

**DEVELOPMENT OF A MODEL OF ENERGY SAVING ELECTRO-
HYDRAULIC POWER-STEERING SYSTEM**

**MASTER OF SCIENCE IN ENERGY TECHNOLOGY
M.Sc (ET)**



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DEVELOPMENT OF A MODEL OF ENERGY SAVING ELECTRO-HYDRAULIC POWER-STEERING SYSTEM

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APPROVAL

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DEDICATION

This thesis is dedicated to my parents.
For their endless love, support and encouragement

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First of all, I wish to express my gratitude to the Almighty for giving me patience in ensuring the successful completion of the thesis. I would like to express my sincere appreciation to my thesis supervisor Dr. Md. Tazul Islam, Professor, Department of Mechanical Engineering, CUET for his instructions, inspiration and support. I sincerely would like to express my gratitude to my thesis Co-supervisor, Syed Masrur Ahmmad, Associate Professor, Department of Mechanical Engineering, CUET for his instructions and support to complete my research work. I sincerely would like to express my gratitude to the Director, Faculty Members, Officials and Staffs of Institute of Energy Technology, CUET for their suggestions, support and help to use the laboratory facilities in completing the thesis work.

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ABSTRACT

Automobile steering system is used to steer a vehicle to the desired path. In mechanical steering system, the driver's physical effort is used to steer front wheels. But during parking or at slow speeds, steering becomes difficult and energy-consuming because of high friction. Conventional power steering uses hydraulic power to reduce steering effort. The objective of this work is to develop an energy-saving model of electro-hydraulic power steering system of vehicle that can save energy and also provide a good steering feel to driver according to vehicle speed and steering rate. Similar systems can be found in Ford, Volkswagen, Audi, and Nissan cars. At first, the model was simulated in Matlab software and then hardware was developed. A set of experiments has been carried out to setup the electro-hydraulic power steering (EHPS) system test bench. The pressure developed in hydraulic chamber is proportional to motor speed. So, the motor speed is controlled via PID controller to regulate the hydraulic pressure according to vehicle speed and steering rate. Fuzzy-logic is applied to tune the proportional (K_p) and integral (K_i) gain of the PID controller. Experimental results show that the response of the system is fast because of the use of fuzzy logic, which improves the steering feel. An Arduino microcontroller is used to implement the fuzzy-PID algorithm to control the DC motor. The experimental results show that the energy consumption of the proposed model is low compared to conventional hydraulic power steering. Power consumption is calculated for five different torques: 0 Nm, 3.98 Nm, 4.23 Nm, 4.48 Nm, and 5.23 Nm. At high vehicle speeds, the proposed model can save more energy. If set point is greater than current motor speed (set point is 45 and current RPS is 22), then PID saves 0.038505Wh more electrical energy than fuzzy-PID at 0 Nm torque for 10 sec, but it can't develop the right hydraulic pressure at the right time. If the set point is less than the current motor speed, then fuzzy-PID saves 0.02599 Wh of electrical energy compared to PID at 0 Nm torque for 10 sec, and it can provide sufficient hydraulic power at the right time. For energy saving electrohydraulic power steering system, the correlation of electric power with voltage, current, motor speed, and vehicle speed at 0 Nm torque is $P_g = -181.823 - 33.4625v + 23.8562i + 0.46321V$ and the correlation of hydraulic power with hydraulic pressure, pump discharge rate, motor speed, and vehicle speed at 3.98 Nm torque is $P_{h8} = -4.2179 + 2.3687p + 0.0241V$.

সারসংক্ষেপ

অটোমোবাইল স্টিয়ারিং সিস্টেম গাড়ির দিক পরিবর্তনে ব্যবহৃত হয়। মেকানিক্যাল স্টিয়ারিং সিস্টেমে গাড়ির সামনের চাকা ঘুরানোর জন্য চালকের শারীরিক শক্তি ব্যবহৃত হয়। কিন্তু পার্কিংয়ের সময় বা গাড়ি ধীর গতিতে উচ্চ ঘর্ষণের কারণে স্টিয়ারিং কঠিন হয় এবং শক্তি খরচ হয়। কনভেনশনাল পাওয়ার স্টিয়ারিং সিস্টেমে স্টিয়ারিং শক্তি কমাতে হাইড্রোলিক পাওয়ার ব্যবহৃত হয়। এই গবেষণার উদ্দেশ্য হলো, একটি এনার্জি সেভিং ইলেকট্রো-হাইড্রোলিক পাওয়ার স্টিয়ারিং সিস্টেম মডেল তৈরি করা যা শক্তির ব্যবহার কমাতে পারে এবং গাড়ির গতি এবং স্টিয়ারিং রেট অনুযায়ী চালককে একটি ভাল স্টিয়ারিং ফিলিং প্রদান করতে পারে। ফোরড, ভক্সওয়াগেন, অডি ও নিসান গাড়ীতে এই ধরনের সিস্টেমটি ব্যবহৃত হয়। প্রথমত মডেলটি ম্যাটল্যাব সফটওয়্যারে সিমুলেশন করা হয় এবং পরবর্তীতে যন্ত্রাংশ সমন্বয় করা হয়। ইলেকট্রো-হাইড্রোলিক পাওয়ার স্টিয়ারিং সিস্টেম টেস্ট বেঞ্চ সেটআপ করার জন্য কিছু এক্সপেরিমেন্ট করা হয়। হাইড্রোলিক চেম্বারে সৃষ্ট চাপ মোটর স্পিডের সমানুপাতিক। সুতরাং, গাড়ির গতি এবং স্টিয়ারিং রেট অনুযায়ী হাইড্রোলিক চাপ নিয়ন্ত্রণ করতে পিআইডি কন্ট্রোলার দিয়ে মোটরের স্পিড কন্ট্রোল করা হয়। পিআইডি কন্ট্রোলারের প্রপোরশনাল (K_p) এবং ইন্টিগ্রাল (K_i) গেইন টিউন করার জন্য ফাজি লজিক প্রয়োগ করা হয়। পরীক্ষালব্ধ ফলাফলে প্রতীয়মান হয় যে, ফাজি লজিক ব্যবহারের ফলে সিস্টেমের রেসপন্স খুব দ্রুত হয় এবং এটি স্টিয়ারিং ফিলিংকে উন্নত করে। ডিসি মোটর কন্ট্রোল ও ফাজি-পিআইডি অ্যালগরিদম প্রয়োগ করার জন্য আরডুনো মাইক্রোকন্ট্রোলার ব্যবহার করা হয়। পরীক্ষালব্ধ ফলাফলে, প্রচলিত হাইড্রোলিক পাওয়ার স্টিয়ারিংয়ের তুলনায় নতুন মডেলের শক্তি খরচ কম প্রতীয়মান হয়। পাঁচটি ভিন্ন ভিন্ন টর্কে ০, ৩.৯৮, ৪.২৩, ৪.৪৮ ও ৫.২৩ নিউটন-মিটারে শক্তির মান হিসাব করা হয়। এই মডেলটি গাড়ির উচ্চ গতিতে আরো বেশি পরিমাণে শক্তি সাশ্রয় করতে পারে। যদি সেট পয়েন্ট মোটরের বর্তমান স্পিডের চেয়ে বেশি হয়, সেট পয়েন্ট ৪৫ এবং বর্তমান আরপিএস ২২ হয়, তাহলে ফাজি-পিআইডির তুলনায় পিআইডি ০.০৩৮৫০৫ ওয়াট-আওয়ার পরিমাণ বেশি বৈদ্যুতিক শক্তি সাশ্রয় করে, ১০ সেকেন্ডের জন্য শূন্য নিউটন-মিটার টর্কে। কিন্তু এটি সঠিক সময়ে সঠিক পরিমাণে হাইড্রোলিক প্রেসার তৈরি করতে পারে না। অন্যদিকে, ফাজি-পিআইডি সঠিক সময়ে সঠিক পরিমাণে হাইড্রোলিক প্রেসার তৈরি করতে পারে, যা স্টিয়ারিং ফিলিংকে উন্নত করে। যদি সেট পয়েন্ট বর্তমান মোটর স্পিডের চেয়ে কম হয়, সেট পয়েন্ট ২২ এবং বর্তমান আরপিএস ৪৫ হয়, তাহলে পিআইডির তুলনায় ফাজি-পিআইডি ০.০২৫৯৯ ওয়াট-আওয়ার পরিমাণ বেশি বৈদ্যুতিক শক্তি সাশ্রয় করে, ১০ সেকেন্ডের জন্য শূন্য নিউটন-মিটার টর্কে এবং এটি সঠিক সময়ে পর্যাপ্ত পরিমাণ হাইড্রোলিক শক্তি প্রদান করতে পারে। শূন্য নিউটন-মিটার টর্কে এনার্জি সেভিং ইলেকট্রো-হাইড্রোলিক পাওয়ার স্টিয়ারিং সিস্টেমের জন্য ইলেকট্রিক পাওয়ার, ভোল্টেজ, কারেন্ট, মোটর স্পিড ও গাড়ির গতির ইকুয়েশন হলো পাওয়ার (ইলেকট্রিক) = $-১৮১.৮২৩ - ৩৩.৪৬২৫V + ২৩.৮৫৬২i + ০ + ০.৪৬৩২১V$ এবং ৩.৯৮ নিউটন-মিটার টর্কে হাইড্রোলিক পাওয়ার, হাইড্রোলিক প্রেসার, পাম্প ডিসচার্জ রেট, মোটর স্পিড এবং গাড়ির গতির ইকুয়েশন হলো পাওয়ার (হাইড্রোলিক) = $-৪.২১৭৯ + ২.৩৬৮৭p + ০ * q + ০ * n + ০.০২৪১V$ ।

LIST OF PUBLICATIONS

1. Robin Barua, Md. Mizanur Rahman, Md. Tazul Islam, Syed Masrur Ahmmad, Rasel Sen, Saswata Dutta, Simulation and Modeling of an Energy Saving Electro-hydraulic Power Steering System of Vehicle, IMEOM, Dhaka, Bangladesh, December 26-27, 2022.
2. Robin Barua, Md. Tazul Islam, Syed Masrur Ahmmad, Md. Masum Rana, Rasel Sen, Md. Mizanur Rahman, Conventional power steering system of vehicle and continuous improvement, ICMIEE, 2022 22-24 December, 2022, Khulna, Bangladesh.
3. Md. Mizanur Rahman, Robin Barua, Md. Tazul Islam, Nur Mohammad, Simulation of an Energy Saving Egg Incubator, IMEOM, Dhaka, Bangladesh, December 26-27, 2022.

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LIST OF ABBREVIATIONS

ECU	Electrical Control Unit
EHPS	Electro Hydraulic Power Steering
HPS	Hydraulic Power Steering
EPS	Electric Power Steering
EHPV	Electro Hydraulic Proportional Valve
PID	Proportional Integral Derivative
ODE	Ordinary Differential Equation
PS	Power Steering
MDPS	Motor Driven Power Steering
RPS	Rotation Per Second
PWM	Pulse Width Modulation
ADC	Analog to Digital Converter
LPM	Liter Per Minute

NOMENCLATURE

Symbol	Meaning [Unit]
$\dot{P}_a$	Derivative of pressure of chamber A [pa]
$\dot{P}_b$	Derivative of pressure of chamber B [pa]
β	Bulk modulus [N/m^2]
V	Fluid volume of half cylinder [m^3]
Q_{pump}	Pump discharge rate, [m^3/s]
A_p	Effective piston area, [m^2]
B_r	Cylinder bore radius, [m]
R_r	Rod radius, [m]
x_p	Piston position, [m]
$\dot{x}_p$	Piston speed, [ms ⁻¹]
F_p	Force developed on piston, [N]
P_a	Pressure of chamber A, [pa]
P_b	Pressure of chamber B, [pa]
m	mass of piston and load, [kg]
$\ddot{x}_p$	acceleration, [m/s ²]
F_{load}	Tire load, [N]
$F_{\text{fric},v}$	Viscous friction, [N]
$F_{\text{fric},c}$	Coulomb friction, [N]
$F_{\text{fric},s}$	Stribeck friction, [N]
k	Tire stiffness,[N/m]
F_{fric}	Summation of friction force, [N]
k_v	Viscous friction coefficient (hydraulic viscosity), [kg/s]
τ_s	Stribeck velocity, [m/s]
n	Motor Speed [RPS]
v	Voltage [V]
i	Current [A]
P	Electric Power [W]
V	Vehicle Speed [km/h]
P_h	Hydraulic Power [W]

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND AND MOTIVATION

Automobile steering system is most important as it controls the vehicle's direction according to driver's steering wheel direction. It ensures vehicle's safety and controllability. If the steering system is not properly designed, the steering may be pulled to one side. The known problems of steering system are excessive steering effort or excessive steering wheel free-play [1]. The two basic types of steering system are: manual or mechanical steering system and power steering system.

A vane pump directly driven from vehicle engine delivers hydraulic power to hydraulic chamber to drive steering gear to steer the front wheels of vehicle [2]. Plenty of vehicles with conventional power steering system are still on road. But in conventional power steering system, the amount of hydraulic power generated is proportional to engine speed. And engine driven pump runs during non-steering condition which consumes power from the vehicle engine. At high speed, energy consumption increases, which can be saved. At low speed, vane pump's delivery flow rate is minimum. Therefore, the amount of hydraulic power generated is minimum which is not sufficient to move the front wheels comfortably. At high speed, flow rate increases and assist hydraulic power increases. In conventional power steering system, assist effort doesn't vary as preferred [3]. Driver feels very light steering. But driving comfort means high-speed steering feel and low-speed steering portability, which plays an important role on driver's behavior [4]. By controlling motor speed with an electrical control unit (ECU), the flow rate is changed to give right amount of force as per demand. According to vehicle speed and steering rate, motor speed is controlled as well as the developed hydraulic power is controlled to provide driver a good steering feel. Also, energy can be saved by operating motor at minimum speed at high speed. Typically, a 12V battery is used as a power source to drive the electric motor. So, EHPS is suitable for small and medium sized vehicles. Researchers have tested the driver's preferred steering torque in different speed conditions for better steering feeling.

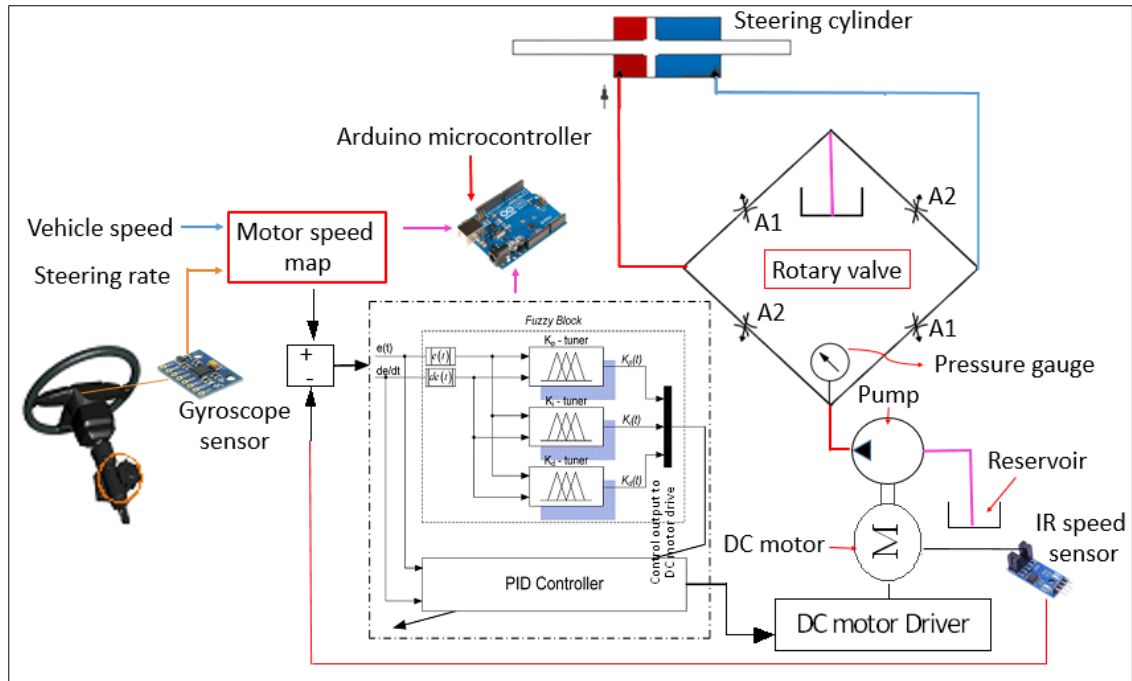


Figure 1.1: Schematic Diagram of Energy Saving Electro-Hydraulic Power Steering System

Figure 1.1 shows the schematic diagram of an energy saving electrohydraulic power steering system. The energy consumption can be reduced at different speed conditions by properly tuning the motor speed map. A hydraulic system is a non-linear system. So fuzzy adaptive PID can properly handle the non-linear behavior. This research aims to develop a motor speed control strategy of electro-hydraulic power steering system for energy saving operation and steering feel improvement.

1.2 MECHANICAL STEERING SYSTEM

In mechanical-steering system, the vehicle's front wheels are turned with driver's physical effort. The mechanical steering system as shown in Figure 1.2 consists of a steering wheel, a steering column, a steering gear box, pitman arms (used in recirculating ball steering gear), tie rods, steering arms, road wheels, and other mechanical linkages [5]. When driver turns the steering wheel, it turns the steering column. The turning motion acts on the steering gear and moves the pitman arm. This movement moves the tie rods and connected steering arms and turns the road wheels. The mechanical steering system consists of various components that can be grouped into three sections, which are:

- a. Steering gear box
- b. Steering wheel and column

c. Mechanical linkages

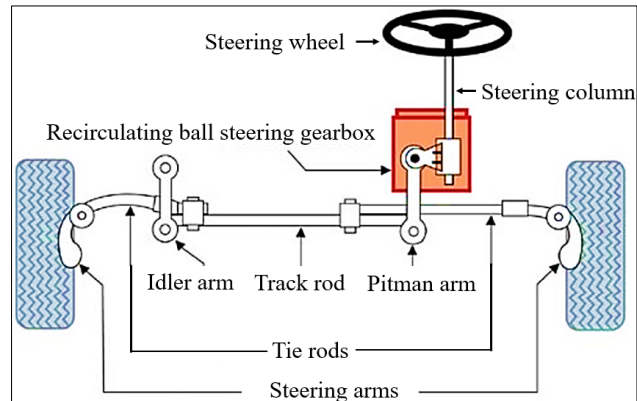


Figure 1.2: Mechanical Steering System

1.2.1 Steering Gearbox:

Steering gear amplifies the physical effort of driver. The basic function of a steering gearbox is to convert rotational displacement into linear displacement. When driver turns the steering wheel right or left, the steering shaft or steering column rotates the inside steering gear and converts the rotational displacement into linear displacement. Efficient steering gear design was the only way to reduce physical effort. But after introducing hydraulic power to the mechanical steering system, the driver's physical effort was reduced a lot, and this system is known as power steering. There are four types of steering gear that are mostly used [6]:

- a. Worm and sector gear
- b. Worm and roller gear
- c. Re-circulating ball type steering gear and
- d. Rack and pinion gear

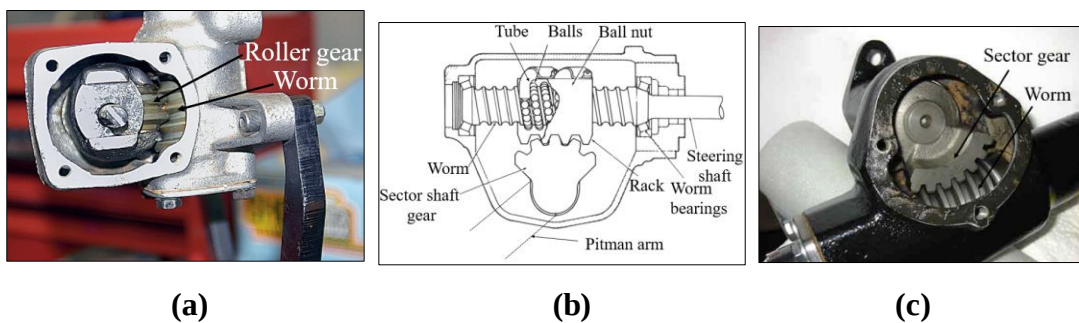


Figure 1.3: (a) Worm and Roller Gear, (b) Re-Circulation Ball Type Steering Gear and (c) Worm and Sector Gear

The steering gear works as a gear reduction between its input and output. The gear ratio varies from 12:1 to 30:1, depending on the load on the road wheels.

Worm and Sector

In worm and sector gear operation, the worm is connected to the end of the steering column, in Figure 1.3C. So, when the driver turns the steering wheel, the column itself rotates the worm and the sector gear. The sector gear is a section of the full gear and has external teeth. The teeth are meshed with worm gear. The sector gear rotates along its axis and moves the pitman arm connected to it. And the pitman arm is connected to the tie rod on the other side. This converts the sector shaft's angular motion into linear motion.

Worm and Roller

Worm and roller steering gear is similar to worm and sector gear. In Figure 1.3C, a toothed roller is mounted on the roller shaft, and a worm is mounted at the end of the steering shaft. If the worm rotates, the roller rotates with it, which forces the pitman arm to rotate. Variable steering is possible in this type of design [7]. Variable steering is helpful at different speeds. The steering gear ratio can be high or low in different positions to control the vehicle's wheel rotation speed faster or lower.

Re-Circulating Ball Steering Gear

Figure 1.3B shows a rectangular-shaped internally grooved ball nut rack mounted over a worm gear. The worm gear is fitted inside the ball nut rack, and there are dozens of ball bearings between the worm gear and the internal groove of the ball nut to reduce friction. The ball nut rack has gear teeth on the outside to engage with the sector. The sector moves the pitman arm. Both the ball and nut have round shaped threads to fit the balls in. The worm gear is placed in the steering gearbox with ball bearings at the bottom and top, so it can rotate along its axis but not vertically. So, if the worm gear rotates and goes up or down, then the ball bearings are forced against the tube inside the nut. This forces the nut as well as the rack to move up or down along the worm gear. The ball bearings move around the worm gear, go out through a tube, and again come back into the worm gear. Balls are continuously recirculated through the system.

Cam and Lever

The cam and lever steering gear is similar to the worm and sector. In Figure 1.4, the worm and sector are replaced by a cam and a lever, respectively. The cam is cylindrical and grooved so that the stud can move along with it. The groove is narrower at the center than at the ends. This provides non-reversibility in the center part of the cam, where most of the car's steering takes place. The twin levers are mounted on the cross shaft and are located so that the studs engage the cam from the side. When the cam is turned, the studs move along the cam groove to cause the lever to swing through an arc, thus turning the cross shaft.

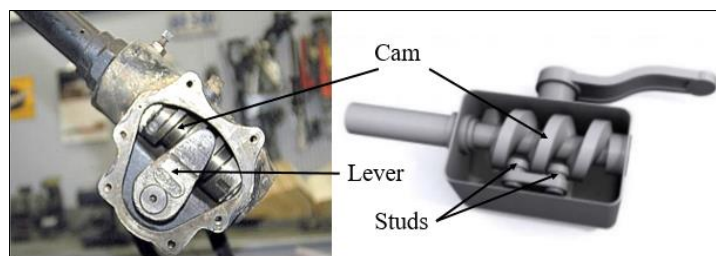


Figure 1.4: Cam and Lever

Rack And Pinion Linkage

The rack and pinion is less complex than other steering gearboxes. It has a reduced number of friction points as compared to a parallelogram steering linkage. A flat rack is connected to road wheel with tie rods and steering arms. A pinion gear is attached at the end of the steering shaft. In Figure 1.5, the pinion gear moves clockwise or anticlockwise over the rack gear, and the rack gear converts this rotational motion into linear motion as left or right.

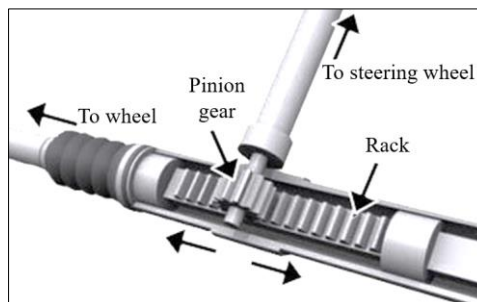


Figure 1.5: Rack and Pinion Gear

The teeth of pinion gear are meshed with the teeth of flat rack gear. The pinion gear is mounted on bearings in the gear housing. The steering gear is mounted so that the tie

rods are parallel to the lower control arms. The tie rods are connected the same way as the parallelogram steering linkage. The inner side of the tie rods is connected to the rack with a spring-loaded ball socket. Rack moves horizontally on bushings in the steering gearbox. In rack and pinion steering gear, tie rods are directly connected to the steering rack in the steering gear. So, it provides good steering feel but transfers more shock from the road wheel to the steering wheel.

1.2.2 Steering Wheel and Column:

The steering wheel helps turn the road wheels left or right. The steering wheel is connected to the road wheels with a set of mechanical linkages and steering gear [8].

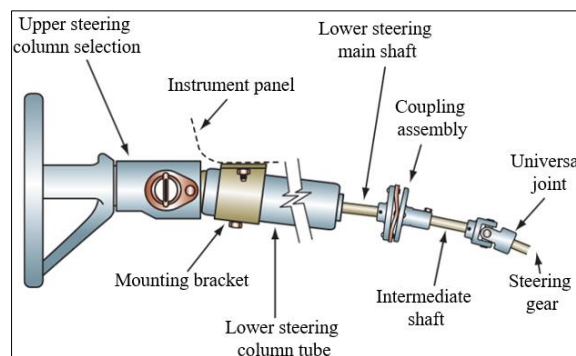


Figure 1.6: Steering Wheel and Column

The steering column connects the steering wheel to the steering gear. The lower steering shaft and the intermediate shaft from the steering gear are connected through a universal joint or flexible coupling. Bearings support the steering shaft as it rotates clockwise or anticlockwise in the steering column. There are different designs of steering columns, such as conventional or non-tilt steering columns, tilt steering columns, and telescoping steering columns. Figure 1.6 shows a tilting steering column. There is an air bag equipped on the upper side of the steering wheel to give protection to the driver's side, and in most vehicles, there is another air bag on the instrument panel for passenger side protection when involved in a collision.

1.2.3 Steering Linkages

The steering linkage connects the steering gear to the front wheels.

Parallelogram Steering Linkage:

It is common in mechanical steering systems. In parallelogram steering linkage, the pitman arm from the steering gear is connected to one end of the center link [9]. A

pivoted idler arm bolted to the chassis supports the other end of the center link. Tie rods connect the center link to the steering arm. The steering arms are attached to the steering wheels. Pivoted ball studs are mounted on the inner ends of the tie rods. The outer ends of the tie rods are threaded into the tie rod adjusting sleeves. The outer tie rod contains pivoted ball studs, and these tapered ball studs fit into the matching tapered openings in the end of the steering arm.

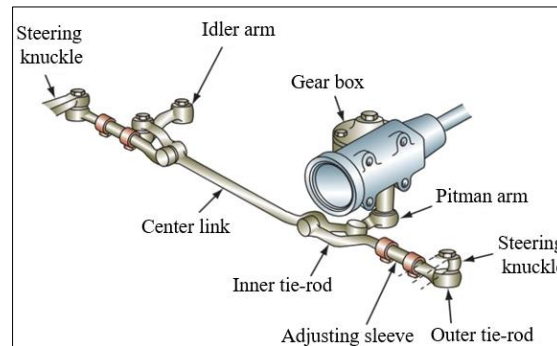


Figure 1.7: Parallelogram Steering Linkage

The pitman arm and idler arm keep the center link and tie rods at the right height so that the tie rods are parallel to the lower control arms [10]. Upper and lower control arms control lateral (side-to-side) wheel movement. If the front wheels hit a bump, then the road wheels go up and down. So the lower control arms make an arc with respect to the wheels up and down movement. But the tie rods are designed to always be parallel with the control arms. So the tie rods also make an arc with the steering arms, just as the control arms do.

Center Link:

It provides the connection between the right and left side steering components and enables them to act as a single unit. It controls the wheel movement with a sideways steering linkage. When direction changes, the pitman arm moves the center link and also the right and left tie rods.



Figure 1.8: Center Link

There are two types of center links: wear-type and non-wear-type. A non-wear-type center link has tapered openings on both ends. The pitman arm and idler arm have stud balls to fit into this opening. The other wear type center link has ball sockets in both ends, and a tapered stud extends from the socket. This tapered stud fits into the openings of the pitman arm and idler arm. They are more prone to stress and corrosion. They are designed to absorb road irregularities and reduce vibration feedback to the steering wheel.

Tie Rods:

It makes a connection between the center link and the steering arms. It transmits force from the center link to the steering arms. Steering arms turn the steering knuckles to move the vehicle's wheels.



Figure 1.9: Tie Rods

Tie rods consist of inner and outer tie rods. The inner tie rod is connected to the center link, or rack. Outer tie rods provide a link between the steering knuckle and other steering components. In rack and pinion steering systems, the outer tie rod end is connected directly to the inner tie rod end, and in steering box systems, the outer tie rod is connected to the inner tie rod end with adjustment sleeves.

Idler Arm:

It is connected from the center link to the vehicle body to support the center link at the right height. It allows the center link to move sideways but keeps the vehicle body isolated from this movement. Internal bearings reduce the friction of joints.



Figure 1.10: Idler Arm

Steering Knuckle:

It is the pivot point of the steering system. It allows the wheel to turn. It supports the weight of the car. The suspension system is also connected to the steering knuckle through upper and lower ball joints.

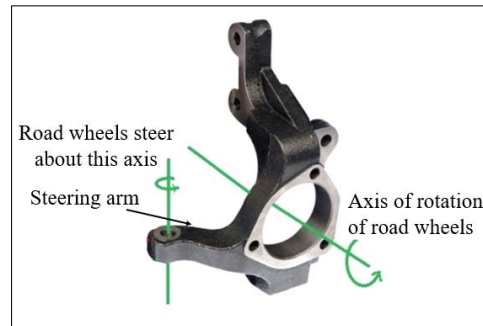


Figure 1.11: Steering Knuckle

Steering Damper:

In the event of road irregularities, the front wheels transfer a shock to the steering wheel. To minimize this shock, a steering damper or shock absorber is used in some parallelogram steering linkages or rack and pinion steering systems. This is connected by one of the steering links to the chassis or frame.

1.3 STEERING GEOMETRY

Steering geometry is a geometric arrangement of linkages within lengths and angles to provide directional stability. Ackerman, Anti-Ackerman and Davis steering Geometry, shown in Figure 1.12, are used to follow a curve while avoiding sideways slip.

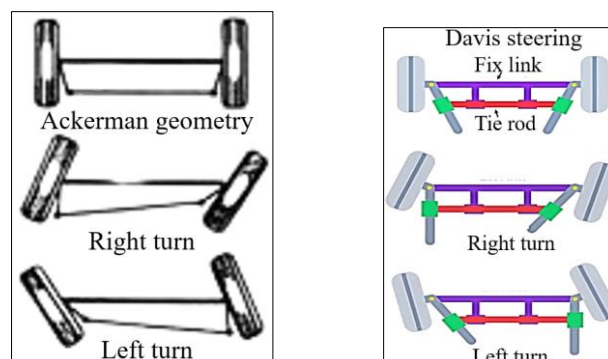


Figure 1.12: Ackerman and Davis Steering Geometry.

Ackerman steering is suitable for low-speed maneuvering. For high-speed cornering, some race cars use anti-Ackerman geometry. Davis steering has superior cornering and

small turning radius maneuverability. Camber angle, castor angle, king pin inclination, toe in, and toe out are the factors of steering geometry [11, 12].

1.3.1. Ackerman Steering:

If the fixed link and tie rod lengths are equal in length, the steering arms are parallel, and both wheels turn at the same angle. If the tie rod is shorter than the fix link, like a trapezoidal shape, both wheels turn at different angles when steered. This is called Ackerman steering.

$$\cotangent(o) - \cotangent(i) = \frac{Track}{Base} \quad (1)$$

As shown in Figure 1.13, o denotes outer wheel angle and i denotes inner wheel angle. For example, when the inner wheel lock angle is 30.52°, the outer wheel lock angle is 21.89°.

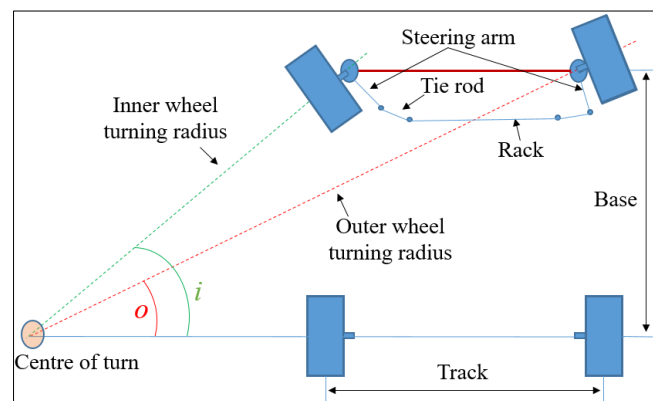


Figure 1.13: Ackerman Steering System.

When the inner wheel turning radius is 2.3 meters, the outer wheel turning radius is 3.37 meters.

1.4 POWER STEERING

In order to steer the front wheels easily, hydraulic power is used in power steering as a supplementary power. It is a basic hydraulic application of Pascal's law. Pascal's law states that force is equal to pressure multiplied by piston area [13]. 90% of vehicle steering systems are engine driven power steering systems. A fixed displacement vane pump, directly driven by the vehicle's internal combustion engine, delivers fluid to the steering gear to generate hydraulic force. The vane pump is driven by the vehicle's internal combustion engine. So pump output is proportional to vehicle speed. An open-

center rotary valve, directly operated by the driver, provides hydraulic force to the right or left chamber port according to the steering wheel's turning direction. It uses hydraulic power to reduce the driver's physical effort to steer the wheel. It is also known as a hydraulic power steering system (HPS). The parts of a hydraulic steering system are the mechanical part and the hydraulic part. All the mechanical parts are the same as in the mechanical steering system. The hydraulic part consists of a rotary valve, a steering pump, a reservoir and hoses for the steering pump, hydraulic pipelines, a pressure relief valve, and a hydraulic piston. Two standard designs are used in mechanical power steering: re-circulating ball gear power steering and rack and pinion gear power steering. Re-circulating ball gear type power steering is more assistive than rack-and-pinion type power steering, so it is more common in the commercial vehicle sector. Rack and pinion steering systems are used in the passenger car segment. With the increase in vehicle weight and to reduce steering effort, hydraulic power steering (HPS) is used as an addition to mechanical power steering. Rack and pinion hydraulic power steering is more dominant than re-circulating ball hydraulic power steering systems because of its low cost. The supply flow rate can be controlled in some HPS to activate variable assistance.

1.4.1 Steering Vane Pump and Hydraulic Assembly:

The power steering pump compresses the hydraulic fluid to develop pressure in the piston to turn the vehicle wheel. The pump is driven by the engine and connected to the crankshaft with a belt. The pump runs when the engine is running. The fluid pressure developed by the pump is proportional to the vehicle's engine speed. If the engine runs at high speed, then high pressure is generated, so a pressure relief valve is mounted at the pressure tube to keep the pressure below a set point. When the steering wheel is fully turned in the right or left direction and the road wheel reaches the stop point, the pressure builds up, and the pressure relief valve relieves the excessive pressure. There are two lines. Pressure line and return line.

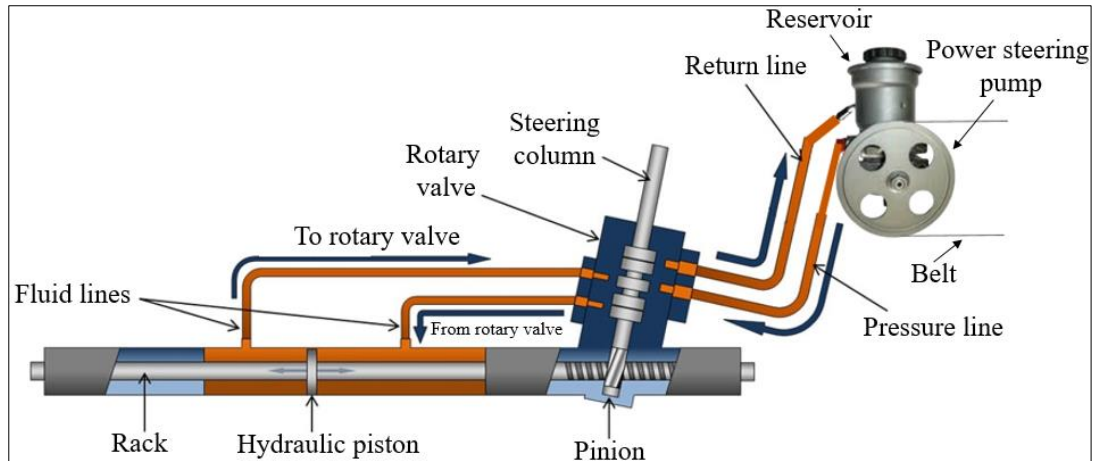


Figure 1.14: Steering Pump and Hydraulic Assembly (Front View)

One side of the pressure line is connected to the vane pump outlet port, and the other side is connected to the rotary valve, as shown in Figure 1.14. And for the return line, one side of the line is connected to the reservoir, and the other side is connected to the rotary valve. There are two fluid lines in Figure 1.14. One side of the fluid line is connected to the right and left pistons, and the other side is connected to the rotary valve. According to Figure 1.14, fluid from the power steering vane pump is coming to the rotary valve. And as it is steering left, fluid from the rotary valve is coming to the piston's left chamber, and from the right chamber, fluid is going to the rotary valve and then to the reservoir.

1.4.2 Reservoir:

There are two connecting ports in the reservoir. Through the suction tube port, an engine-driven pump sucks oil from the reservoir and forces the fluid to the steering gear. From the steering gear, the oil returns to the reservoir through the return tube.



Figure 1.15: Reservoir

A power steering fluid change is necessary when it gets contaminated and dirty. The dirty fluid can be replaced with fresh oil through the reservoir cap.

1.4.3 Power Steering Cooler:

The fluid circulates continuously forward and backward through the hose pipe and steering gear. Due to the continuous operation, the fluid gets hot. Hot fluid increases wear and tear on the pump and gearbox. The cooler is connected in series with the return line. Coolers reduce the oil temperature by about 70–80 degrees, reduce the interval between fluid replacements, and make the components last longer. EHPS saves more power than HPS. In HPS, an engine-driven pump runs if power steering is not needed. So it's a waste of energy. But in EHPS, the electric motor pump only works when power assistance is needed.

1.5 ROTARY VALVE

A rotary valve senses the driver's applied force or torque and directs fluid to the steering gear to turn the steering wheel [14]. And the fluid flow rate depends on the torque applied to the torsion bar. The flow rate through a rotary valve is nearly equal to the flow rate of a hydraulic pump. A rotary valve [15] is located between the input shaft and the pinion or worm gear. It consists of a cylindrical inner spool and an outer cylindrical sleeve. Both spool and sleeve rotate in the valve housing if the steering wheel is turned.

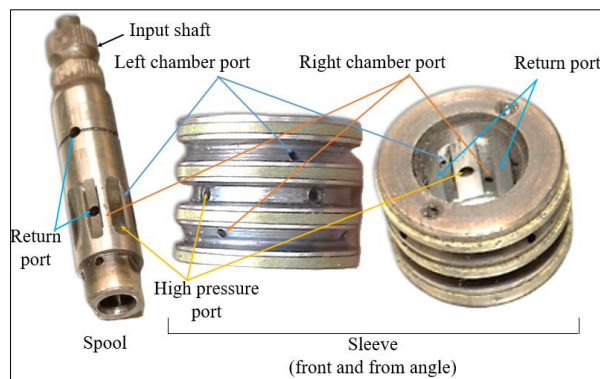


Figure 1.16: Spool and Sleeve.

But a slight relative rotation between them before contacting a stop on a pinion or worm gear activates the rotary valve. A torsion bar, a thin steel rod inside the spool, twists when torque is applied. This twist makes the relative rotation and controls the opening area between the spool valve and sleeve. When the input shaft contacts the stop on the pinion or worm gear, maximum hydraulic assist force is provided. In case of hydraulic

power failure, the system can be used mechanically as a manual steering system with physical effort.

1.5.1 Rotary Valve Operation:

In the straight-ahead position, the steering wheel does not twist the torsion bar, so the torsion bar also does not rotate the directional rotary spool valve that is connected to it. So the flow through the high-pressure line coming from the vane pump is divided equally in the top and bottom areas of the piston but builds no pressure on either side as the return path is open and fluid returns back to the reservoir through the return line. If the driver turns the steering wheel left, it twists the torsion bar left, and the torsion bar rotates the spool valve left. And fluids from the pump through the high pressure line go to the piston top area and build enough pressure to move the piston, and the fluid from the piston bottom returns to the reservoir through the return line. When the driver makes a right turn, the torsion bar twists the spool valve right, and fluid through the high pressure line goes to the piston bottom and builds pressure. The piston now moves up, and fluid from the piston bottom returns to the reservoir through the return line. If the front wheels hit a bump, then the front wheels turn in the opposite direction of the turning direction. So the re-circulating ball tends to move in the opposite direction and force oil into the inlet port, and the driver feels a kickback on the steering wheel. So a poppet valve in the inlet fitting closes and prevents kickback.

1.5.2 Neutral, Left and Right Turn:

In an open center rotary valve, when the steering wheel stays in neutral position, as shown in Figure 1.17 A, no relative rotation occurs between spool and sleeve.

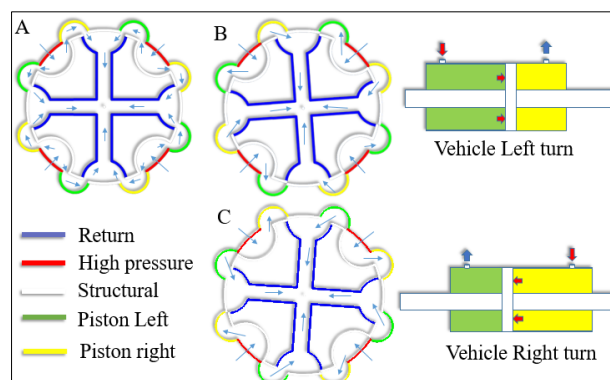


Figure 1.17: Rotary Valve Fluid Flow Diagram.

So, the open orifice area is the same, and fluid supplied by the pump through the high pressure line equally passes to piston right and piston left and returns to the reservoir through the return line. Hence, no pressure difference is developed between the right and left chambers, and no assistance is provided. For a vehicle left turn, when the driver turns the steering wheel anti-clockwise, the road wheels turn as shown in Figure 1.17, the torsion bar twists anti-clockwise, and relative rotation occurs between spool and sleeve. As shown in Figure 1.17 B, the open orifice area of high pressure to the piston left increases and the piston left to the return or reservoir decreases. And the open orifice area of high pressure to piston right decreases and piston right to return increases. This develops a pressure difference between the right and left chambers. Pressure differences multiplied by the effective piston area are the hydraulic forces that work on the piston to make a left turn. Force acts on the piston in the same direction as the driver turns the steering wheel [16]. Vice-versa happens for vehicle right turns, as shown in Figure 1.17 C. If the steering wheel is fully turned left or right and the road wheels reach the stop point, pressure rises, and the relief valve releases the excessive pressure.

1.6 ELECTRO-HYDRAULIC POWER STEERING SYSTEM (EHPS)

EHPS uses all the conventional components of HPS without an engine-driven hydraulic pump. A motor-pump is driven electronically through a DC motor to supply hydraulic power. The main difference between HPS and EHPS is that EHPS saves energy more than HPS, and the assistive torque on the road wheel varies according to vehicle speed. In HPS, pumps run continuously, whether steering occurs or not. But in EHPS, the pump stops running if there is no steering. The components are an open center rotary valve, steering column and linkage, rack and pinion gear, and power cylinder. The working principle of EHPS is the same as that of HPS. The rack is divided into two sides. Both outer ends are connected to the pinion side, and the middle side is the power cylinder side. The rack works as a hydraulic piston and is sealed inside the power cylinder. The rack is not rotatable. Two pressure sensors, one in each chamber, sense the pressure between the chambers, and the ECU utilizes the differential pressure and sends a control signal to the bi-directional dc motor. A rack position sensor senses the current rack position and sends the signal to the ECU. An angle sensor or encoder measures the steering wheel position and steering rate per degree.

1.7 BOOST CURVE

The boost curve is an important characteristic of a steering system. In EHPS, it's the relationship between steering input torque and assistive output pressure. And in electric power steering (EPS), the boost curve is the relation between steering wheel inputs and the electric motor's output torque. To improve the steering feel in different driving conditions, like parking and normal driving, the assistive power should be different.

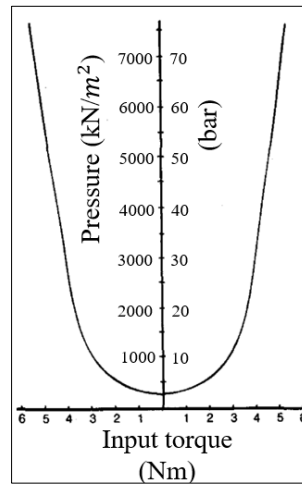


Figure 1.18: Input Torque Vs Pressure Curve.

The boost curve is different for different categories of cars. The more torque applied to the torsion bar, the more the orifice area is opened. The more the orifice area is opened, the more fluid enters the chamber, and thus the pressure is increased. The torque vs. pressure (assist power) curve is known as the boost curve in HPS systems, as shown in Figure 1.18 [17]. From Table 1.1 given below, after 2 Newton-meters (Nm), a small amount of change in Nm changes a large amount of pressure. Valve geometry or torsion bar strength can change the boost curve [18]. Conventional power steering has a fixed boost curve [19].

Table 1.1: Input Torque vs Pressure Data.

Input torque (Nm)	Pressure (bar)
0	2.5
1	3.5
2	5.7
3	11
4	27
5	57

1.8 OPEN-CENTRE HYDRAULIC SYSTEM

In an open-center hydraulic system, fluid returns back to the reservoir through a valve, so there is no pressure rise in the chamber [19]. Constant-flow pumps are used in these systems, and assistive power is always constant. Assistive power variation is necessary during high-speed driving and parking maneuvers. For heavy vehicles, an EHPV is mounted in parallel with a rotary valve to vary the assistive power by regulating the flow rate [20]. There are four valves in a wheatstone bridge-type valve connection. Each valve area depends on valve geometry. In the majority of cases, symmetrical valve areas are equal. The areas are a function of spool valve displacement (x_v). An open-center system is efficient for single functions but not for multiple functions. In neutral, fluid flows from the pump to the reservoir. The mathematical modeling [21] of an open-center rotary valve is given below:

Valve Orifice Area, $A_1 = A_1(x_v)$, $A_2 = A_2(-x_v)$

Pump discharge, $Q_{\text{pump}} = D\omega$

$$\text{Input Flow Rate, } Q_1 = \begin{cases} CA_1 \sqrt{\frac{2(P_{\text{supply}} - P_a)}{\rho}}, & x_v \geq 0 \\ CA_2 \sqrt{\frac{2(P_a - P_{\text{tank}})}{\rho}}, & x_v < 0 \end{cases}$$

$$\text{Output Flow Rate, } Q_2 = \begin{cases} CA_1 \sqrt{\frac{2(P_b - P_{\text{tank}})}{\rho}}, & x_v \geq 0 \\ CA_2 \sqrt{\frac{2(P_{\text{supply}} - P_b)}{\rho}}, & x_v < 0 \end{cases}$$

Pressure dynamic equation:

$$\text{Supply pressure, } \dot{P}_s = \begin{cases} \frac{\text{Beta}}{v_{\text{Pipe}}} (Q_{\text{pump}} - Q_1), & x_v \geq 0 \\ \frac{\text{Beta}}{v_{\text{Pipe}}} (Q_{\text{pump}} - Q_2), & x_v < 0 \end{cases}$$

$$\text{Chamber A Pressure, } \dot{P}_a = \frac{\text{Beta}}{v_{\text{Pipe}} + v_{\text{ch1}} + A_1 x_p} (Q_1 - A_1 \dot{x}_p)$$

$$\text{Chamber B Pressure, } \dot{P}_b = \frac{\text{Beta}}{v_{\text{Pipe}} + v_{\text{ch2}} - A_2 x_p} (A_2 \dot{x}_p - Q_2)$$

Where, P_{supply} =supply pressure (pa); P_a =chamber A pressure (pa); P_b =chamber B pressure (pa); P_{tank} =reservoir pressure (pa); Q_{pump} =supply flow rate (m^3/s);

Q_1 =input flow rate (m^3/s); Q_2 =output flow rate (m^3/s); Beta=bulk modulus;

x_p =piston displacement; $\dot{x}_p$ =piston velocity; x_v =spool displacement; ρ =fluid density;

C=valve coefficient; v_{ch1} =initial volume of chamber A; v_{ch2} =initial volume of chamber B; v_{pipe} =pipe volume.

1.9 CLOSE-CENTRE HYDRAULIC SYSTEM

In a closed-center hydraulic system, pressure is controlled independently [22, 23]. In the neutral position, there is no flow through the valve to the reservoir, so the pressure is increased [19]. Variable displacement pumps are used in these systems. The valve opening is a simple linear second-order differential equation. Mathematical modeling of a closed center valve is given below:

$$\begin{aligned} \text{Pump Discharge, } Q_{pump} &= D\omega \\ \text{Input Flow Rate, } Q_1 &= \begin{cases} CA_1 \sqrt{\frac{(P_{supply} - P_a)}{\rho}}, & x_v \geq 0 \\ CA_2 \sqrt{\frac{(P_a - P_{tank})}{\rho}}, & x_v < 0 \end{cases} \\ \text{Output Flow Rate, } Q_2 &= \begin{cases} CA_1 \sqrt{\frac{(P_b - P_{tank})}{\rho}}, & x_v \geq 0 \\ CA_2 \sqrt{\frac{(P_{supply} - P_b)}{\rho}}, & x_v < 0 \end{cases} \end{aligned}$$

1.10 PID CONTROLLER

A proportional integral derivative (PID) controller is a control loop feedback controller. A PID controller calculates an error value as the difference between a measured process variable and a desired set point. The controller tries to minimize the error by adjusting the proportional, integral, and derivative values, denoted P, I, and D. The proportional term (P) corresponds to proportional control. The integral term (I) gives a control action that is proportional to the time integral of the error. The derivative term (D) is proportional to the time derivative of the control error. This term allows for the prediction of future errors. [24]

$$PID(t) = K_p(e(t)) + K_i \int (e(t)) dt + K_d \left(\frac{d(e(t))}{dt} \right)$$

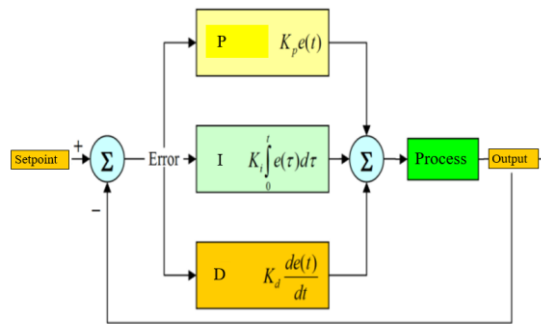


Figure 1.19: PID Controller

1.10.1 Proportional Controller:

The Proportional term produces an output value that is proportional to the current error value. A high proportional gain results in a large change in the output for a given change in the error. If the proportional gain is too high, the system can become unstable. The proportional response can be adjusted by multiplying the error by a constant K_p , called the proportional gain constant.

$$P = K_p (e(t))$$

1.10.2 Proportional Integral Controller:

An integral controller can eliminate the steady-state error that occurs with a proportional controller. The main function of the integral action is to make sure that the process output agrees with the set point in steady state. With Proportional control, there is normally a control error in steady state. Integral control action is expressed as follows:

$$PI = K_p (e(t)) + K_i \int (e(t)) dt$$

1.10.3 Proportional Derivative Controller:

The purpose of the derivative action is to improve close-loop stability. Because of the process dynamics, it will take some time before a change in the control variable is noticeable in the process output. Thus, the control system will be late in correcting an error. The action of a controller with proportional and derivative may be interpreted as if the control is made proportional to the predicted process output, where the prediction is made by extrapolating the error by the tangent to the error curve.

$$PD = K_p (e(t)) + K_d \left(\frac{de(t)}{dt} \right)$$

1.11 FUZZY LOGIC

Fuzzy logic is one of the most popular new technologies. To understand fuzzy logic, it is important to discuss fuzzy sets. In a fuzzy set, we name all the elements of the universe and supplement them with a number between 0 and 1. This number demonstrates to what degree this generic element belongs to the defined fuzzy set. Actually, according to this definition, we just add to every element a number that constitutes the membership degree of this element. Actually, a fuzzy set is given by its membership function [25].

1.11.1 Linguistic Variables:

To specify rules for the rule base, the expert will use a "linguistic description"; hence, linguistic expressions are needed for the inputs and outputs and the characteristics of the inputs and outputs. "Linguistic variables" (constant symbolic descriptions of what are in general time-varying quantities) are used to describe fuzzy system inputs and outputs [26].

1.11.2 Membership Functions:

The simplest membership functions are formed using straight lines. Of these, the simplest is the triangular membership function, which has the function name trimf. It is nothing more than a collection of three points for a triangle. The trapezoidal membership function, trapmf, has a flat top and really is just a truncated triangle curve. These straight line membership functions have the advantage of simplicity.

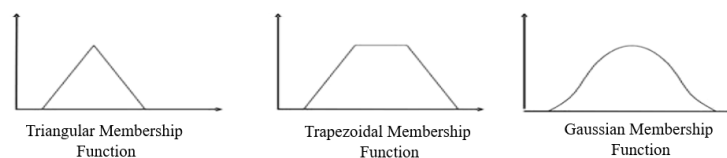


Figure 1.20: Membership Functions

1.11.3 Fuzzification:

The first block of the fuzzy controller is fuzzification, which converts each piece of input data to degrees of membership by looking up one or several membership functions. The fuzzification block thus matches the input data with the conditions of the rules to determine how well the condition of each rule matches that particular input

instance. There is a degree of membership for each linguistic term that applies to that input variable.

1.11.4 The Basics of Fuzzy Logic:

A fuzzy controller is a controller that is intended to manage some vaguely known or vaguely described process. The controller can be used with the process in two modes: Feedback mode, when the fuzzy controller acts as a control device, and feed-forward mode, where the controller can be used as a prediction device. The plant output is denoted by $\Delta u(k)$, the input is denoted by $e(k)$, and the reference input to the fuzzy controller is denoted by $\Delta e(k)$. The fuzzy controller has four main components.

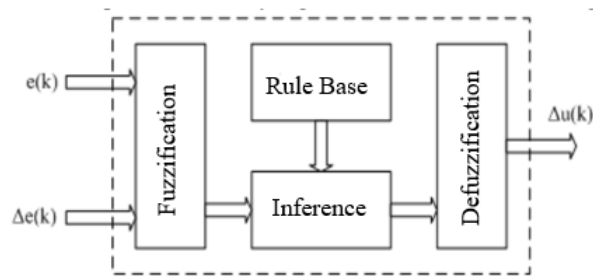


Figure 1.21: Fuzzy Logic Diagram

Inference Mechanism

The inference mechanism, or engine, is the processing program in a fuzzy control System. It derives a conclusion from the facts and rules contained in the knowledge base using various human expert techniques.

Rule-base

A group of rules may use several variables, both in the condition and the conclusion of the rules. They are based on a set of rules that a human expert would follow in diagnosing a problem.

Defuzzification

Defuzzification is a process that maps a fuzzy set to a crisp set and has attracted far less attention than other processes involved in fuzzy systems and technologies. The four most common defuzzification methods are:

1. Maximum membership method.
2. Center of gravity method.

3. Weight average method.

1.12 MATLAB

MATLAB (matrix laboratory) is a fourth-generation high-level programming language and interactive environment for numerical computation, visualization, and programming. MATLAB is developed by MathWorks. It allows matrix manipulations, plotting of functions and data, implementation of algorithms, creation of user interfaces, interfacing with programs written in other languages, including C, C++, Java, and FORTRAN; analyzing data, developing algorithms, and creating models and applications. It has numerous built-in commands and math functions that help in mathematical calculations, generating plots, and performing numerical methods. The diagram in the figure shows the main features and capabilities of MATLAB [27].

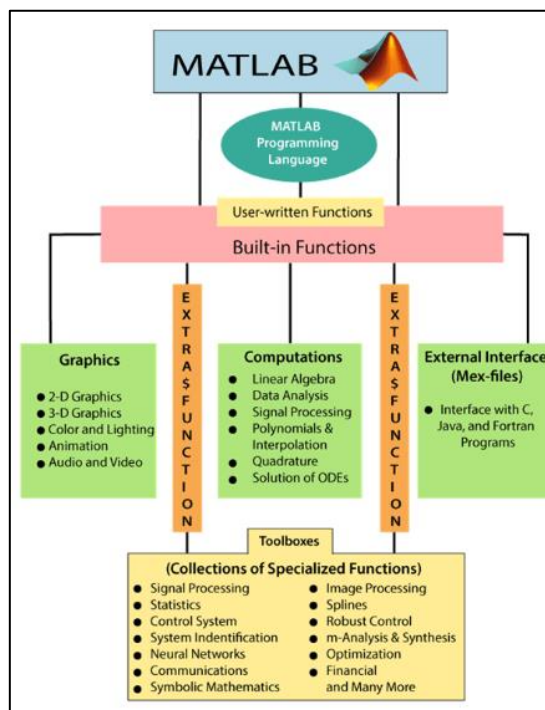


Figure 1.22: Schematic Diagram of Matlab Main Features [27]

MATLAB's built-in functions provide excellent tools for linear algebra computations, data analysis, signal processing, optimization, numerical solutions of ordinary differential equations (ODEs), quadrature, and many other types of scientific calculations. Most of these functions use state-of-the-art algorithms. There are numerous functions for 2-D and 3-D graphics, as well as animations. There are also various optional "toolboxes" available from the developers of MATLAB. These

toolboxes are a collection of functions written for primary applications such as symbolic computations, image processing, statistics, control system design, and neural networks. The necessary building component of MATLAB is the matrix. The fundamental data type is an array. Vectors, scalars, real matrices, and complex matrices are all automatically handled as special cases of the primary data type. The built-in functions are optimized for vector functions. Therefore, Vectorized commands or codes run much faster in MATLAB.

1.12.1 Simulink:

Simulink is a block diagram environment used to design systems with multidomain models, simulate before moving to hardware, and deploy without writing code [28]. Simulink allows to incorporate MATLAB algorithms into models as well as export the simulation results into MATLAB for further analysis [29]. It is basically a graphical block diagramming tool with a customizable set of block libraries. It is a simulation and model-based design environment for dynamic and embedded systems, integrated with MATLAB. Simulink, also developed by MathWorks, is a data flow graphical programming language tool for modeling, simulating, and analyzing multi-domain dynamic systems.

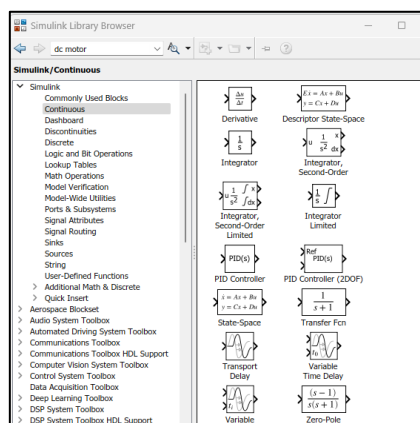


Figure 1.23: Matlab Simulink Library

1.12.2. Simulink PID:

The PID Controller block implements a PID controller (PID, PI, PD, P only, or I only). The block is identical to the Discrete PID Controller block with the Time domain parameter set to Continuous-time.

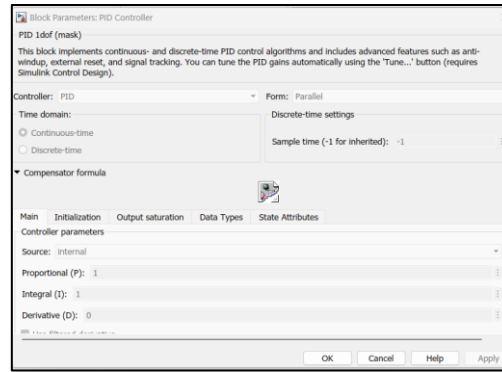


Figure 1.24: Matlab Simulink Library

The block output is a weighted sum of the input signal, the integral of the input signal, and the derivative of the input signal. The weights are the proportional, integral, and derivative gain parameters. The block supports several controller types and structures.

1.12.3 Matlab Fuzzy Toolbox:

In recent years, the number and variety of applications of fuzzy logic have increased significantly. The applications range from consumer products such as cameras, camcorders, washing machines, and microwave ovens to industrial process control, medical instrumentation, decision-support systems, and portfolio selection.

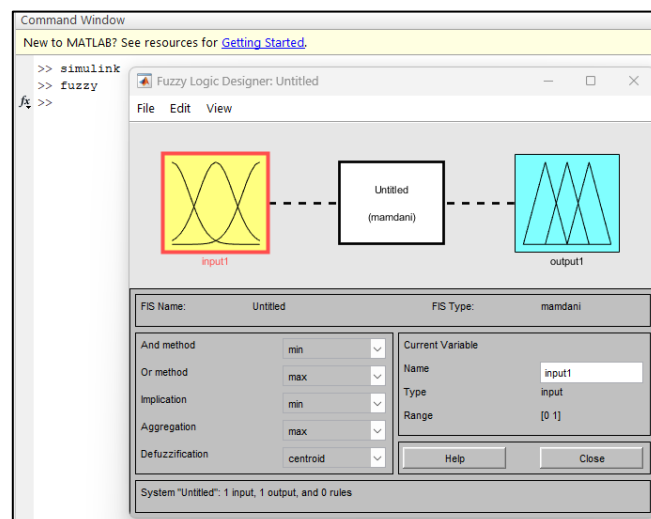


Figure 1.25: Matlab Fuzzy Toolbox

The Fuzzy Logic Toolbox provides MATLAB functions, apps, and a Simulink block for analyzing, designing, and simulating fuzzy logic systems. It allows to specify and configure inputs, outputs, membership functions, and rules for type-1 and type-2 fuzzy inference systems. The toolbox automatically tunes the membership functions and rules of a fuzzy inference system from the data. Additionally, the fuzzy inference system can be used as a support system to explain AI-based black-box models.

1.13 Specific Objectives and Possible Outcomes

Specific Objectives:

Specific objectives of this research are:

1. Propose and modeling of a new closed loop electro-hydraulic circuit.
2. Comparison between new and old power steering system.
3. Develop motion control strategy for energy saving operation.
4. Design and fabrication of model of the proposed power steering system.

Possible Outcomes:

The following outcomes can be achieved with the help of this project:

1. Minimize the cost and fuel consumptions of power assisting-based vehicles.
2. High performance energy saving solution.

1.14 THESIS OUTLINE

Chapter-1: The introduction chapter contains background and motivation, mechanical steering system, steering geometry, power steering, rotary valve, electro hydraulic power steering system (EHPS), boost curve, open-centre hydraulic system, close-centre hydraulic system, pid controller, fuzzy logic, matlab, specific objectives and possible outcomes of the study.

Chapter-2: Literature Review consist of hydraulic power and steering gear, EHPS and control strategy, energy saving techniques and steering feel improvement.

Chapter-3: Materials and Methodology consists of research study sites and equipment collection, designed components of electrohydraulic power steering system, experimental setup and methodology ,steering torque calculation, data acquisition software, experimental data plot in matlab and stepinfo, dc motor parameter estimation, electrical connection, fuzzy PID experimental and simulation.

Chapter-4: Result and Discussion.

Chapter-5: Conclusion and Recommendations.

CHAPTER 2

LITERATURE REVIEW

Tracking back to the XIX century, there was a long tradition of hydraulics. Before the First World War, the first mechanical-hydraulic designs were made. Control of the displacement of huge masses is enabled with a handy mechanical lever [30]. With traditional engines, power steering (PS) systems are currently used in many kinds of vehicles. To defend humans against pollution, electric and hybrid vehicles have been developed in recent years. The basic need for power steering is to augment the force exerted on the steering wheel by drivers to steer the vehicle's wheels with minimal effort and comfort against resistance. Power steering system development has been led by the limitations of manual power steering when used in heavy-duty vehicles. The front axle load of heavy-duty vehicles made manual steering impractical. Calculation shows that manual steering of a 2WS vehicle weighing 3000kg with a front wheel axle weight of 1100 kg at a friction coefficient of 0.7 requires 18.98 kg of steering effort at stationary [31]. So steering is a difficult task for drivers, especially at low and zero vehicle speeds.

In the 1920s, the first nut-and-bolt type non-commercial power steering unit was invented by Francis W. Davis [32]. Efficient steering gear can improve overall power steering efficiency. The evolution shows that worm-sector and screw-nut types of gearing with plain sliding surfaces are only 20% efficient. Then updated cams and levers with anti-friction bearings and worm-rollers were introduced, but they are not still efficient enough. Later, a ball-nut design was developed where a train of balls was used between the nut and the screw. This increased the overall efficiency to 75%. Modern steering gear in commercial vehicles is classified into two groups: steering box and rack and pinion types. Worm and sector, screw and nut, recirculating ball, cam and peg, and worm and roller are the types of steering boxes. Rack and pinion was introduced in the late 1960s in medium performance sports cars [33]. Rack and pinion are used in most modern cars. The rack and pinion converts the rotational motion of the steering wheel to linear motion to turn the road wheels and provides a gear reduction for easy steering [34]. To reduce the steering effort of driver later hydraulic power was used to drive the steering gear.

The first motor driven power steering (MDPS) was developed for the Subaru XT in Japan, where a 12V motor is installed to drive the vane pump instead of the vehicle engine [35]. A controller decreases the motor speed to decrease power assist at high speed and provides a natural steering sensation. The motor takes power from the alternator, which becomes a load on the engine. But the test result shows that MDPS consumes less fuel as compared to conventional power steering.

An EHPS for the medium-duty truck FL 60 model was developed, in which the gross weight of the vehicle is 23400 pounds and the front axle weight is 7900 pounds. The result shows that the motor-driven pump unit can supply a maximum of 5 lpm at 150 bar pressure, which is equivalent to 750 watts of power, which is the working power of the system [36]. As power is limited, so is the speed of steering. The result shows that at low speeds, conventional power steering is more energy efficient, and at high speeds, EHPS is more efficient.

Motor speed control is very important in the EHPS system. A fuzzy-PID control strategy was implemented to control the speed of a brushless DC motor [37]. Motor speed has been increased above normal speed using the field weakening method. The motor speed has been smoothly controlled under different load conditions. Motor speed control is the key to the performance of the EHPS system.

Not only energy savings but also conventional HPS can provide obstacle avoidance support at high speed. If a vehicle travels at high speed and suddenly an obstacle comes up that needs to be avoided, then a higher flow rate of supply develops higher pressure, and rack speed gets higher. So, obstacles can be avoided. To provide this rapid response at high speed in the system, steering wheel angular velocity, motor speed, and vehicle speed are the parameters that have to be used [38].

An induction motor control strategy was simulated for EHPS, which can obtain a good control effect [39]. Fujita (2001) developed a control method for brushless DC motors for Hydraulic-electric power steering systems to achieve steering feel and save energy [40]. An electric power steering system was implemented on a light commercial vehicle [41]. A brushless DC motor was used, torque was controlled to provide steering feel,

and the motor was directly connected to the recirculating ball gear. For automobiles with a 42 V dc supply, an electric driven pump unit was developed for the EHPS system, which was driven by an interior-type synchronous motor [42].

The hydraulic actuator of the rack-and-pinion steering system used in light-weight vehicles is a symmetrical actuator. Alaydi et al. simulated and experimented with a symmetrical actuator model where friction force and piston dynamic equations are included [43]. An electro-hydraulic actuator model simulation was done, with special attention given to the friction model [44].

A directional control valve, or steering rotary valve, is a major part of the power steering system. The pressure developed in a piston depends on the valve structure as well. Xu and Xu (2021) analyzed the power steering valve, where force, pressure, and torque relations are discussed [45]. A fuzzy-adaptive PID control algorithm was used for motor speed control, and calculations were done for the power consumption at different vehicle speeds [46].

In an EHPS system, for obstacle avoidance, high rack force is needed, so power consumption will be high. High-power motor pump units, ranging from 500W to 900W, have been developed for commercial vehicles [47]. A positive displacement pump is used in the EHPS system, and the motor is controlled using a pulse-width modulation signal. The differential pressure developed in the piston creates the actuating force to move the front wheels [48]. The relationship between discharge flow rate and motor speed was tested [49].

Techniques are being applied to the power steering system for two reasons: to give the driver a good steering feel and to reduce vehicle fuel consumption, as well as carbon dioxide emissions. Different hydraulic circuits with different techniques were tested by researchers to regulate flow rate to generate sufficient force in EHPS.

A closed-center rotary valve technique was applied to a conventional engine-driven vehicle with a front weight of 720 kg [50]. The vane pump is disconnected from the vehicle's engine. A motor-pump was used to supply fluid, and a closed-center rotary valve instead of a regular open-center valve was used to change the flow direction. In

a closed center servo valve at neutral position, pressure to the right or left chamber orifice is closed. And chambers for reservoir lines are opened. So, at neutral, fluid can't pass to the right or left chamber, and fluid can't return to the reservoir. Electrical energy consumption has been reduced by operating the motor and pump at an extremely low speed in neutral.

The most commonly used energy-saving technique is the flow control by changing motor speed. The vane pump is also disconnected from the vehicle's engine. One way is that an external motor can be set in position, and the vane pump's pulley can be connected to the motor with a belt. Another way is that, for compactness and to increase mechanical efficiency, an electric motor-driven power steering pump unit can be developed and used. Most of the motors that have been used are brushless and powered by 12 V DC voltage. But for electric vehicles and 42-volt automobiles, induction motors and permanent magnet synchronous motors can be used [39, 42]. An ECU controls the speed of the motor as per demand. In this system, the pump flow rate is proportional to the motor speed. In this circuit, the more the motor can be controlled efficiently, the more energy can be saved. Energy savings also depend on the desired steering torque. Obviously, energy has to be saved by fulfilling the driver's desired steering torque. For example, the desired steering torque is 3.924 Nm at 30 km/h and a 90° steering rate [51]. But if the motor speed is kept lower than the desired speed, the driver will feel steering torque greater than 3.924 Nm. This will decrease energy consumption but cause a bad steering feel. A vehicle speed sensor is used to regulate the motor's speed. But using a steering rate sensor and an angle sensor, energy can be saved further. Because desired steering torque also depends on steering rate and steering angle. The system parameters of some experiments are given in Table 2.1.

Table 2.1: System Parameters of EHPS (Flow Control via Motor Speed).

Voltage (V)	Power (watt)	Pressure (bar)	Flow rate (l/min)	Motor speed (rpm)	Ref.
12	1202	150	8.3	2200	[36]
42	1500	120	-	4000	[42]
-	1152	80	7	-	[52]

The flow control using bypass proportional valve is an energy saving technique. According to proportional valve connections, this technique has been categorized as Type A and Type B, as shown in Figure 2.1. In Type A, an electrohydraulic proportional

valve (EHPV) is connected in parallel with an open center rotary valve. A regular engine-driven vane pump has been used here. So, pump flow is constant, and it works as normal HPS at low speed. But, at high speed, regulating the flow rate via EHPV according to vehicle speed and steering rate provides a good steering feel. In Type B, flow rate is regulated via motor speed and EHPV [53, 54]. EHPV is connected in series with a closed center rotary valve.

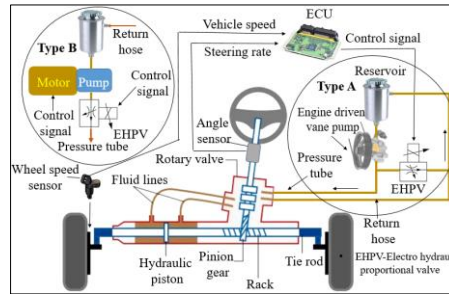


Figure 2.1: Proportional Valve EHPS

The use of closed-loop rotary valve is a way of energy saving in power steering system. In this system, the response is fast because it uses an accumulator and a closed-loop rotary valve. And it can save more energy by turning off the motor and providing the right amount of assistance as per demand. Only a 500-watt motor is sufficient for a 2700-kg front-load vehicle.

The closed loop system is similar to Type B EHPS in Figure 2.1. The difference is that no rotary valve is used. Instead, two closed center solenoid valves control the pressure of each chamber [22]. By controlling the orifice size of both valves, the pressure difference is controlled. Variable assist force is provided according to vehicle speed and steering torque. A torque sensor has been used here. This is a very energy efficient system. It consumes 75% less energy compared to a traditional HPS system. Auto restoration of the steering wheel to center is performed. The pump is driven by the vehicle combustion engine.

The electro-magnetic clutch system is another energy saving technique. In this circuit [55], an electromagnetic clutch is installed between the vane pump and pulley.

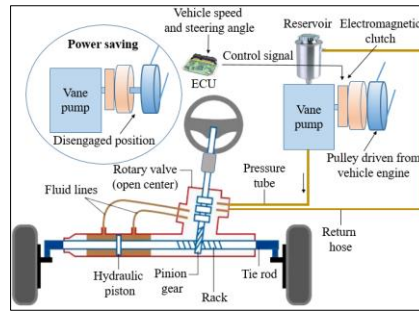


Figure 2.2 EHPS with Electromagnetic Clutch

The vehicle's engine always drives the pulley by a belt. If the vehicle speed is greater than 40 kilometers per hour (kmph) and the steering angle exceeds 7° , the clutch system connects the pulley to the vane pump. And fluid is supplied to the circuit. If vehicle speed is greater than 40 kmph and steering angle is less than 7° , the clutch system detects it as power saving mode, as shown in Figure 2.2, and disconnects the vane pump from the pulley.

All the systems described above improve steering feel. The more sensors added to the system, the more steering feel is gained. It also depends on efficiently controlling all electrical equipment. Steering feel is a function of vehicle speed, steering rate, and steering angle. The driver's desirable steering torque is the steering feel. A system that can keep the steering torque stable at the target value can provide good steering feel. Measuring the force at the rack and pinion gear via a torque sensor and making a closed-loop circuit can give more precise and desirable torque. Desirable steering torque can vary from person to person. But by testing the desirable torque of different drivers, an average value can be found. Now, various control algorithms are being applied to the ECU to satisfy different characteristic curves like motor speed vs. vehicle speed, motor speed vs. steering rate, and steering torque vs. hydraulic pressure.

Similar Electro-Hydraulic power systems can be found in Nissan, Audi, Volkswagen, Mazda, and Peugeot cars. In Nissan, the system provides a natural and smooth feel, improving fuel economy. A power pack generates hydraulic power. A bi-directional motor pump is used to supply hydraulic power according to the steering wheel's right and left turns [55]. In Audi, a demand-controlled vane pump is used to supply the fluid needed for a given operating point. An electric pump unit is used in the Audi A2-2005 Model car. In Volkswagen cars, similar steering systems are fitted, supplied by Koyo and TRW. The Volkswagen Polo Model has an electric power steering pump for

variable assistance. The Mazda 3 has a similar electric motor power steering pump unit. The Peugeot 308 model has an electric power steering pump.

The above-mentioned technique has reduced the energy consumption, but a tuned motor speed map can reduce the energy consumption even more. Also, an overshoot-free and fast motor speed control can provide a good steering feel for the driver at different vehicle speeds. Also, the energy consumption at different steering torques is different, which has not been calculated to the best of our knowledge. Therefore, in this research, a tuned motor speed map with an overshoot-free motor speed controller is implemented on the electro-hydraulic power steering system for good steering feel and energy saving operation at different vehicle speed. Also, the power consumption and motor speed response are compared among different controllers. The power consumption is also calculated for different steering torques.

CHAPTER 3

MATERIALS AND METHODOLOGY

3.1 RESEARCH STUDY SITES AND EQUIPMENT COLLECTION:

This experimental research study was performed on an electrohydraulic power steering test bench at the Institute of Energy Technology Laboratory, Chittagong University of Engineering & Technology (CUET). The electric-driven pump unit is collected from ship marine equipment in Kodomtoly, Chattogram. The electro- hydraulic system, consisting of rack and pinion steering gear with power cylinder and tie rod, hoses, steering wheel setup, road wheels, and ball joints, was collected from Muradpur, Chattogram. The electronic parts, consisting of an Arduino microcontroller, motor controller, sensors, and measuring devices, were collected from Ice Factory Road, Chattogram. The test bench frames were built in Betagi, Rangunia, and some corrections were made in Pahartoli, CUET.

3.2 DESIGNED COMPONENTS OF ELECTROHYDRAULIC POWER STEERING SYSTEM:

3.2.1 Motor Selection:

As the motor is the main actuator in EHPS, motor selection is very important when designing EHPS. Because all motor properties such as torque, shape, and iron loss need to be suitable for this system. As a 12V supply is available in the vehicle, we have selected a 12V, 800W motor. In Figure 3.1, the motor operates at 12 volts and is rated at 800 watts. It is a brush motor. The maximum power output is 837.80 W. The efficiency of the motor is 66.47% [56]. The maximum rpm at unload is 5298 rpm. The maximum torque is rated at 2.41 Nm.



Figure 3.1: Model: 12V 800W, MCA1201V, N0204

空载点 (Unload) :		
转速 (n)	=	5298 (rpm)
电流 (I)	=	13.480 (A)
最大扭矩点 (Max_Torque)		
转矩 (M)	=	2.410 (N.m)
电流 (I)	=	135.590 (A)
转速 (n)	=	3319 (rpm)
效率 (Eff)	=	50.90 (%)
输出功率 (P2)	=	837.80 (W)
最大效率点 (Max_Efficiency)		
效率 (Eff)	=	66.47 (%)
转速 (n)	=	4575 (rpm)
转矩 (M)	=	0.802 (N.m)
电流 (I)	=	48.130 (A)
输出功率 (P2)	=	384.20 (W)
最大输出功率点 (Max_Pout)		
效率 (Eff)	=	50.90 (%)
转速 (n)	=	3319 (rpm)
转矩 (M)	=	2.410 (N.m)
电流 (I)	=	135.590 (A)
输出功率 (P2)	=	837.80 (W)

Figure 3.2: Manufacturer Datasheet

3.2.2 Hydraulic Power Calculation:

Hydraulic Power (in kW) = $(P \cdot Q) / 600$;

Where, P is the pressure in bar;

Q=Pump discharge or flow rate, in liters per minute.

The relief pressure in power steering is 80 bar at 7 lpm [52].

Therefore, $P = (80 \cdot 7) / 600$

Hydraulic power, P = 0.93 kilowatts

Therefore, 930 watts of power is needed to drive the steering system. But as motors are not 100% efficient, if we select 66% efficiency, then we have to select

Power = $(930 \text{ Watt}) / 0.66 = 1409 \text{ Watt}$ rated motor for real vehicle implementation. But as we are working on a test bench, we have selected this motor of 800 watts, which is also available in Bangladesh.

From the manufacture datasheet in Figure 3.2, the motor is 66.47% efficient, and the maximum output is 837.80 W.

So, Power = $(837.80 \cdot 0.6647) = 556 \text{ W}$ of hydraulic power is available for our experiment on the test bench.

3.2.3 Gear Pump:

A Gear Pump is one kind of pump that converts mechanical energy into hydraulic energy with the help of gear networks [57]. It is a mechanical device that is used to deliver pressurized fluid in the required quantity. A pump is needed to deliver a specific fluid at a specific pressure at a specific discharge rate. Pumps mainly convert mechanical energy into hydraulic energy. Electrical energy is generally used to move the prime mover.

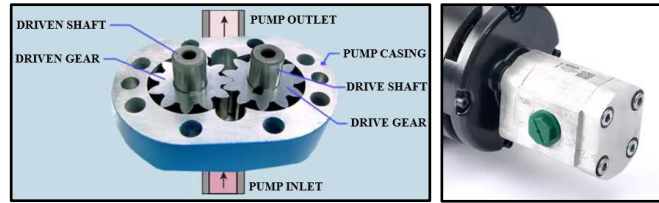


Figure 3.3: Gear Pump Parts

3.2.4 Pump Discharge Rate Calculation:

After positioning the power steering system in the frame, we tested the pump discharge rate. As we are controlling the pump as well as the motor speed with the Arduino microcontroller. We have given a 100% duty PWM signal so that we can measure the maximum flow rate. The pump outlet is connected to the steering pressure port, and the steering return hose pipe is open. We have taken a 500-ml cylindrical empty fluid tube and connected it to the return open hose. When we run the motor, it drives the pump, and the pump delivers the fluid from the reservoir to the steering valve. We have kept the rotary valve or steering wheel in neutral position so that the maximum fluid flows to the return port and to the fluid tube. We have watched the time when the motor starts. As the motor started, the fluid tube was being filled with steering fluid. In the meantime, we saw the rpm on the computer's Arduino serial monitor. When the tube is filled, we stop the motor and watch the time again. We have tested twice. The result is the same. It takes 15 seconds to fill up the 500-ml fluid tube.

Therefore, pump discharge rate (max) = 2 lpm = $(0.002 \text{ m}^3)/60 \text{ sec} = 3.33 \times 10^{-5} \text{ m}^3/\text{s}$.
The motor's rpm is 5340 rpm (89 rps).

3.2.5 Power Steering Fluid:

Power Steering Fluid is specially designed for use in power steering and suspension units [58]. It is a premium, fully synthetic oil to offer maximum wear protection, long service life. It minimizes viscosity loss. Its density is 0.883 g/ml at 15⁰ C, and its flash point is 180⁰ C [59].



Figure 3.4: Power Steering Fluid

3.2.6. Electrical Components:

Arduino

Arduino is an open-source electronics platform based on easy-to-use hardware and software. The main component on the Arduino board – the ATmega328P Microcontroller [60]. UNO uses a 28-pin DIP version of the ATmega328P. The Atmega328P is pre-programmed with a bootloader that allows to directly upload the program to the Arduino through USB. The Arduino UNO has 14 digital I/O pins and 6 Analog inputs. There are 6 PWM I/O pins. The digital I/O pins are 5V logic level, and the Analog pins can be used as digital I/O too. Arduino UNO supports 6 channel 10 bit ADC inputs through A0-A5, which can be sampled and analyzed using UNO.

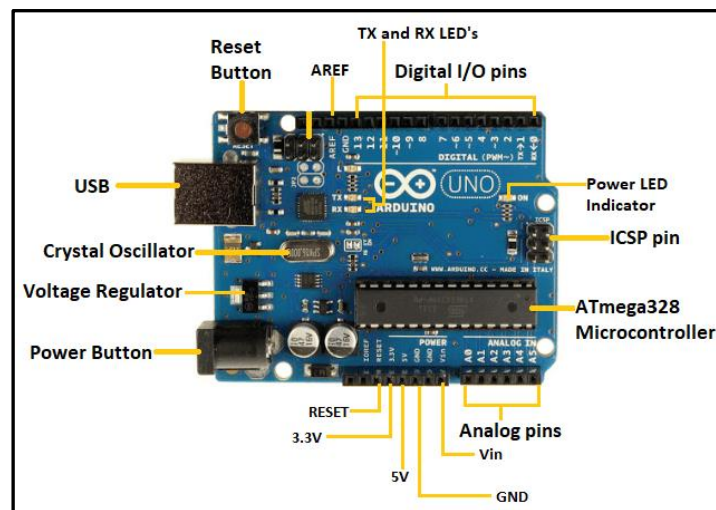


Figure 3.5: Arduino UNO Microcontroller

The Arduino environment can be extended through the use of libraries, just like most programming platforms. Libraries provide extra functionality. The Library is considered an advanced feature that extends the capabilities of the Arduino IDE. It means that the libraries provide extra functionality to the Arduino programming platform. The libraries in Arduino are written in C or C++ and allow to manipulate data and work with the hardware [61]. The clock speed of Arduino Uno is 16 MHz.

Battery

The automotive batteries are recharged from the vehicle alternator and are referred to as SLI, starting (S), lighting (L), and ignition (I) batteries [56]. Car batteries are designed especially to give high current, known as cranking amps, to start a vehicle's engine. Also, it provides power to the vehicle's electrical system [62]. This is a Hamko

brand battery that is especially designed for cars. The capacity of this battery is 12 V, 45 AH+. It is a rechargeable lead-acid battery.



Figure 3.6: Model: Hamko NS 60L Car Battery

Motor Controller Selection

The DC motor takes a maximum of 66 A. In Figure 3.7, a motor controller is shown, which is a PWM speed controller. There is a potentiometer knob to change the output duty cycle. This motor speed controller controls the speed of the motor by Pulse-width modulation. The motor can be run in one direction. The specification of the controller is given. There are twelve MOSFETS. Eight MOSFETS are connected in parallel. The working voltage is between DC 10 and 55 V, and the continuous current load capacity is 60 A. Maximum power is 3300W. We have modified this controller as there is no control option or connection port to connect with Arduino [63].

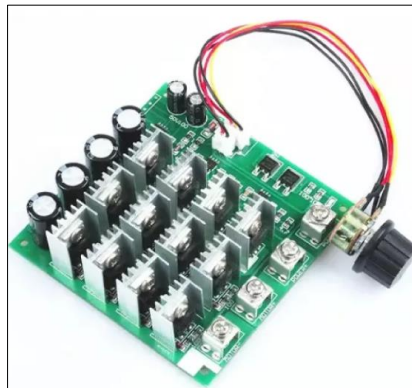


Figure 3.7: DC Motor Speed Controller.

Gyroscope sensor

Gyroscopes are devices that are attached to a frame and can detect angular velocity if the frame is rotated [64]. Gyros are commonly used to provide an estimate of the rate of rotation about a particular axis. The MPU6050 IMU has both a 3-Axis accelerometer

and a 3-Axis gyroscope integrated on a single chip. The gyroscope measures rotational velocity, or the rate of change of the angular position over time, along the X, Y, and Z axes. It uses MEMS technology and the Coriolis Effect for measuring. The full scale ranges of GY521 output are +/- 250, +/- 500, +/- 1000, and +/- 2000.

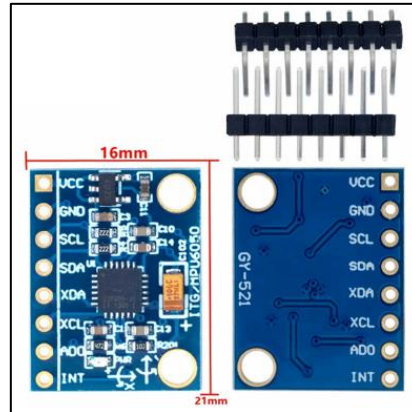


Figure 3.8: Gyroscope GY 521

Motor RPS Measurement: IR Speed Sensor

This 4-pin infrared speed sensor module is used in speed control applications. It is powered by any of the 3.3V or 5V supplies and gives digital output, which can be easily read with the help of the interrupt function on the microcontroller. To power this sensor, we have to connect either a 3.3V or 5V supply to the VCC pin and the GND pin to ground. By taking the Digital Output from the DO pin and connecting it to any GPIO pin on the microcontroller, the output can be read by the AttachInterrupt function in Arduino.

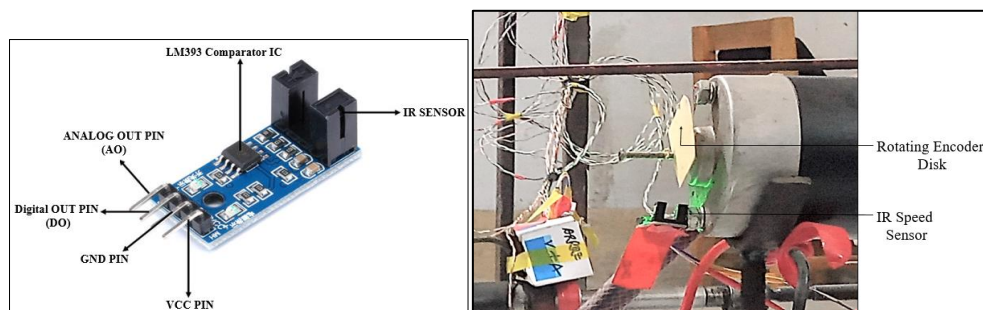


Figure 3.9: IR Speed Sensor

Cable Selection

An electrical cable is an assembly of one or more wires running side by side or bundled together to carry electric current. Electrical cables are used to connect two or more devices and transfer electrical signals or power from one device to the other. As we

have 12V and 800W. So the maximum current consumption is 66 A. We have tried different cables [65–66]. But they became hot and were burned because of low ratings. So we have tried the 6 RM cable [67], and it can handle the current.

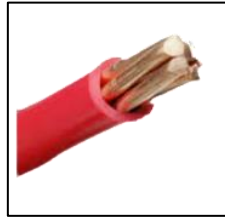


Figure 3.10: 6 RM Cable

3.2.7 Measuring Devices

Multimeter

A multimeter is a measuring instrument that can measure multiple electrical properties. A typical multimeter can measure voltage, current and resistance, in which case it is also known as a volt-ohm-milliammeter (VOM). Digital multimeters have numeric displays, and they are more precise and physically robust. In our work, we will measure voltage, current, and resistance and do continuity tests.



Figure 3.11: Digital Multimeter

Shunt Resistor

Most ammeters have a built-in resistor to measure the current. However, when the current is too high for the ammeter, a different setup is required. The solution is to place the ammeter in parallel with an accurate shunt resistor [68]. Another term that is sometimes used for this type of resistor is ammeter shunt. A shunt resistor is used to measure electric current. This is done by measuring the voltage drop across the resistor. There are four terminals. Two terminals are used as the main current port, and the other two terminals are used for sensing output. The two ports show different results.

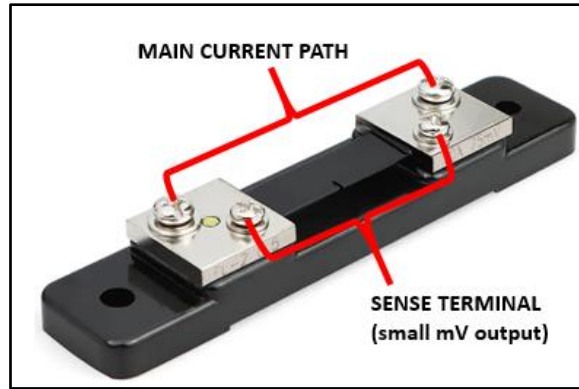


Figure 3.12: Shunt Resistor 50A, 75 mV.

Current Measuring

The current through the motor is the main power consumes in an energy saving electrohydraulic system. The motor is taking power from the battery, but there is a motor controller between the 12V battery and the 800W dc motor. The controller works as an electrical switch between the motor and battery. MOSFETs work as switches in motor controllers. So very little power is consumed to drive the MOSFET, but the main power is consumed by the electrical motor. As in a series circuit, the amount of current is the same through any component [69]. So we have connected the shunt resistor between the motor and controller in negative line, and the voltage drop across the shunt resistor is measured by a multimeter. The shunt resistor voltage drop is 75 mV at 50 A current. So if the voltage drop measured by the multimeter of the shunt resistor is 20 mV, then current consumption is

$$\text{Current (A)} = \frac{50 \text{ (A)}}{75 \text{ (mV)}} * 20 \text{ (mV)} = 13.33 \text{ A}$$

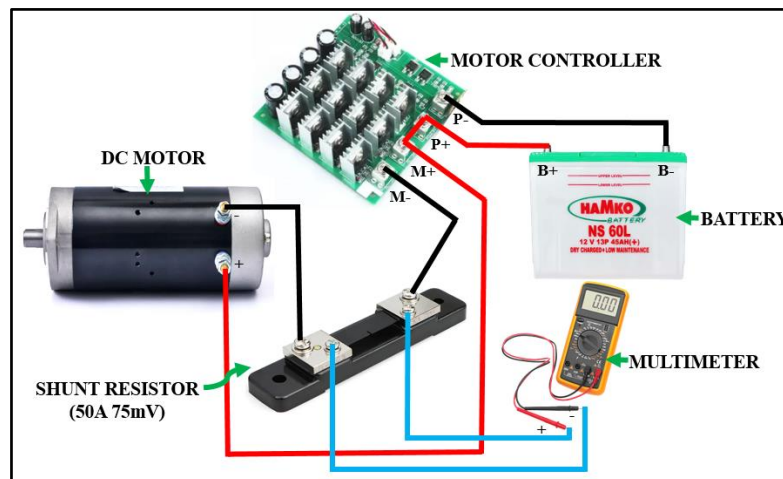


Figure 3.13: Current Measurement with Shunt and Multimeter.

Pressure Gauge

A pressure gauge is installed in the pressure line to measure the developed pressure by the DC motor pump and to calculate the hydraulic power.



Figure 3.14: Pressure Gauge

3.2.8 PWM Motor Control:

Pulse-width modulation (PWM) is a method for controlling DC power [70]. The average voltage supplied to the load is controlled by switching the supply voltage between 0 and 100%. The longer the switch is on, the higher the voltage supplied to the load. PWM is particularly suited for motors. The aim of the PWM method here used is to control the speed of the pump motor. The PWM signal technique is an energy-efficient control method.

3.2.9 ENERGY SAVING ELECTRO HYDRAULIC POWER STEERING SYSTEM SETUP DIAGRAM:

Figure 3.15 shows the setup diagram of the electrohydraulic power steering system. The model shown in the Figure 3.15 is similar to a conventional power steering system. But the modification is that the vane pump and reservoir have been disconnected from pressure hoses. Fluid from the DC pump comes to the rotary valve through a pressure tube. The driver operates the rotary valve via the steering wheel and steering column and changes the direction of fluid according to the steering wheel's direction. An Arduino UNO microcontroller has been used to take data from sensors and give control signals to a DC motor. The setup diagram of an energy-saving electrohydraulic power steering system can be divided into three systems. The steering system, hydraulic

system, and electric system. The red dotted lines show the hydraulic connection, and the plain blue lines show the electrical connection. The hydraulic system consists of a DC motor pump, pressure tubes, return hoses, fluid lines, and a rotary valve. The electric system can be divided into two parts. The two parts are the sensing part and the control part. In the sensing part, the electrical sensors are used, which are a gyroscope and a potentiometer as a vehicle speed regulator. In the control parts, an Arduino microcontroller and a PWM controller are used. The steering system consists of a steering wheel, steering column, rack and pinion, road wheels, and mechanical linkages. The reservoir is filled with power steering fluid. The DC motor pump delivers fluid to the rotary valve through the pressure tube. According to the steering wheel direction, the fluid delivered by the DC motor pump develops hydraulic pressure in the right and left chambers. The fluid comes back to the reservoir through the return hose. In normal power steering operation, when there is no steering operation, the fluid delivered by the DC motor pump through the pressure tube and the fluid coming back through the return hose are the same. When steering occurs, the delivered flow and return flow are not the same. The return hose fluid flow is regulated according to steering torque. In energy-saving power steering, the pump flow is regulated. The car battery (45 Ah) is the main power source for this model.

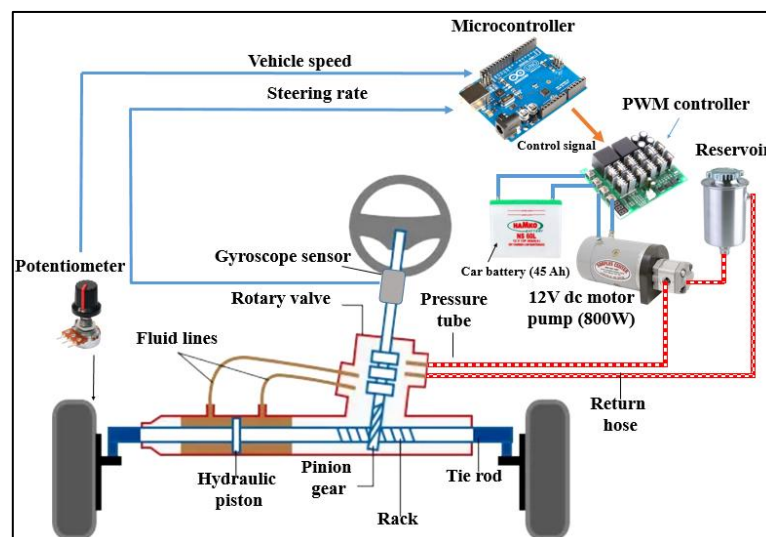


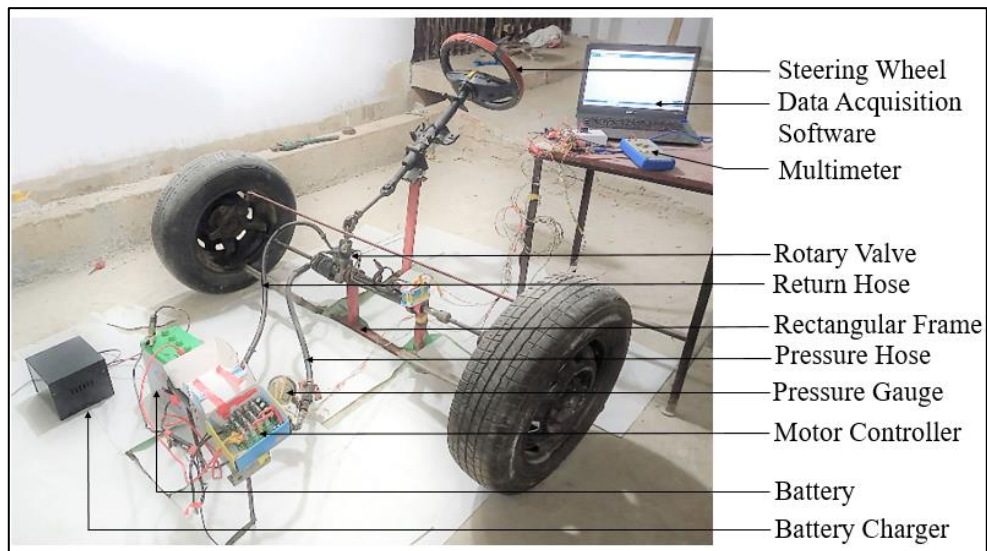
Figure 3.15: Setup Diagram of Electro-Hydraulic Power Steering System

A steering rate sensor is used in this model to detect a high steering rate at high vehicle speeds. As in energy-saving operations, the speed of the motor decreases with the increase in vehicle speed. So at high speed, if suddenly an obstacle comes up, the driver

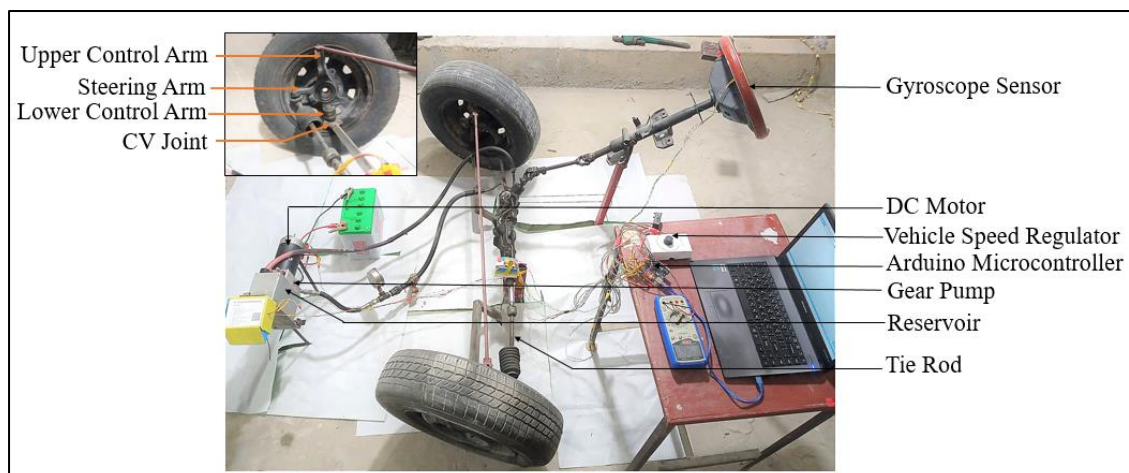
tends to turn the steering wheel too quickly. So to supply sufficient power at quick turns, we should increase the pump discharge rate as well as motor speed.

3.3 EXPERIMENTAL SETUP AND METHODOLOGY:

Figure 3.16 shows the experimental setup diagram of the energy-saving electrohydraulic power steering system. The mechanical steering system is implemented on an iron frame. The steering system is designed according to Ackerman Steering. In the fabrication process, we first measured the distance between the road wheels by connecting the steering arms with tie rods.



**Figure 3.16: Experimental Setup of Electrohydraulic Power Steering System
(Angle View)**



**Figure 3.17: Experimental Setup of Electrohydraulic Power Steering System
(Side View)**

To build the power steering system frame, using measurement data, we first welded and made a rectangular frame. Then we placed the rectangular frame between two road wheels. Then we have connected the CV (constant velocity) joint to the lower steering arm. Then, placing the rack and pinion at the proper height from the rectangular frame, we positioned the rack and pinion in two U clamps. Then we have made a connection between the CV joint and the rectangular frame. Then, after positioning the rack and pinion, we connected the steering column and positioned it at the right height and angle. We have placed it on the stand with two nuts. The stand is 90 degrees from the ground and connected to the rectangular frame. Figure 3.18 shows the flow chart of an energy-saving electro-hydraulic power steering system. First, the steering torque is selected and applied to the steering wheel. The Arduino UNO has been connected to a computer and has been initialized. As the controller gets power from the computer, the control loop starts to work. It reads data from sensors and displays it on a serial monitor. The data have been collected in Excel Data Streamer. According to the motor speed map, the controller gives a set point, and the fuzzy-PID controller reaches the motor speed at the set point. To measure hydraulic power, the hydraulic pressure has been measured from the pressure gauge, and to measure electric power, the electric current has been measured through the shunt resistor.

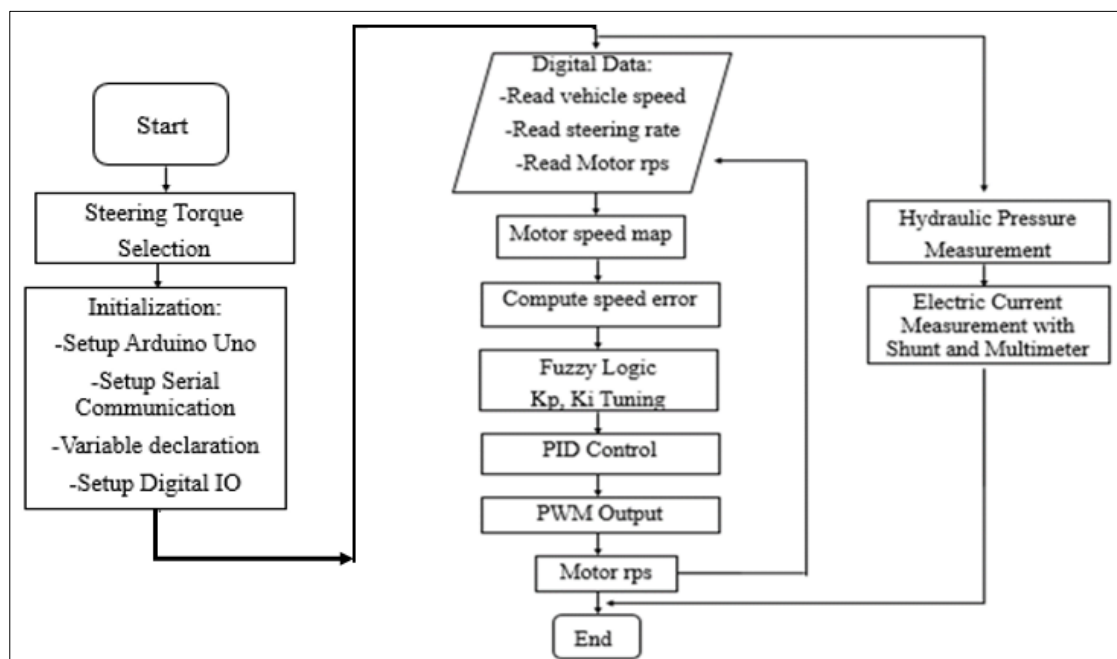


Figure 3.18: Flow Chart of Energy-saving Electro-Hydraulic Power Steering System.

3.4 STEERING TORQUE CALCULATION:

There is a torsion bar inside the rotary valve. To activate the rotary valve, the torsion bar needs to be twisted. The stronger the torsion bar, the more force is needed to twist it. We measure the steering torque to twist the torsion bar to open the rotary valve. The more the vehicle's front axle weighs, the more steering torque is needed, and the more the rotary valve opens.

Torque Equation:

Torque = force * length

$T = F * l * \sin(\theta)$. [71]

We have used an "inch" scale and 1 kg of mass to measure the torque value.

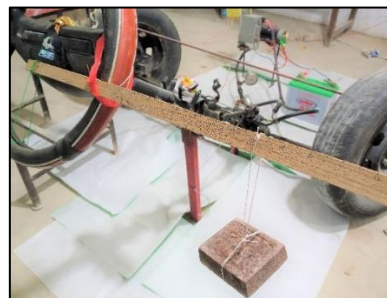


Figure 3.19: Steering Torque Measurement Scale and Mass

3.5 DATA ACQUISITION SOFTWARE:

We have used the Excel data streamer feature to collect input and output data from sensors. Data Streamer is a two-way data transfer for Excel that streams live data from a microcontroller into Excel and sends data from Excel back to the microcontroller. After activating the data streamer add-in from the File, Option setting, we have connected the Arduino Uno. Then we started taking data by clicking Start Data. "We have selected 500 data rows and a data interval of 150 ms (default).

Time	CH1	CH2	CH3	CH4	CH5	CH6	CH7	CH8	CH9	CH10
44.28.2	45	606	0	2.05	44.93	95.18				

Time	CH1	CH2	CH3	CH4	CH5	CH6	CH7	CH8	CH9	CH10
43:42.0	22	606	119	1.57	21.35	57.39	2.700705882			
43:42.1	22	606	119	1.73	21.35	57.77	2.718058825			
43:42.2	22	606	119	1.63	21.32	57.77	2.718058825			
43:42.3	22	606	119	1.33	21.35	57.41	2.713058824			

Figure 3.20: Microsoft Excel Data Streamer Software

We have collected set point, steering angle, vehicle speed, steering rate, motor speed, and PID or fuzzy PID output voltage data simultaneously with respect to time. We have used 7 of the 10 channels.

3.6 EXPERIMENTAL DATA PLOT IN MATLAB AND STEPINFO:

Matlab has a feature called stepinfo, which is used to know curve parameters: rising time, settling time, overshoot, and undershoot. We have used this feature, shown in Figure 3.21, to find the experimental PID and Fuzzy PID curve parameters.

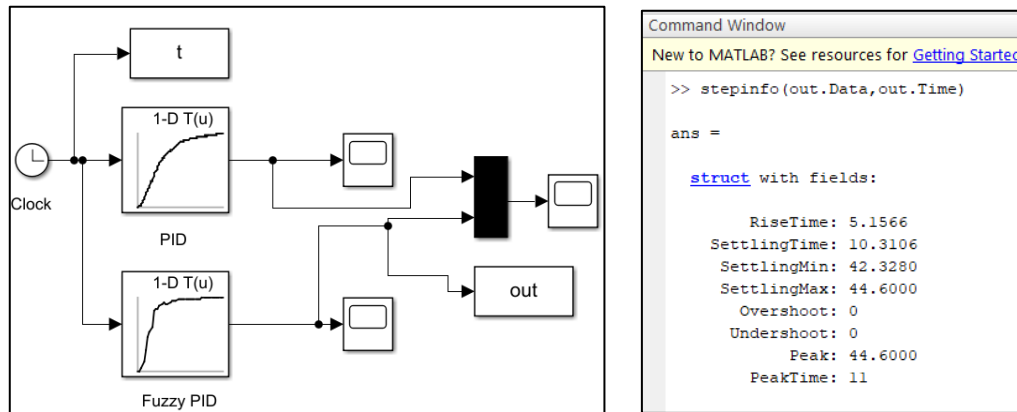


Figure 3.21: Matlab Block and Stepinfo

3.7 DC MOTOR PARAMETER ESTIMATION:

Back emf [72] is the generator output of a motor, and so it is proportional to the motor's angular velocity. It is zero when the motor is first turned on, meaning that the coil receives the full driving voltage and the motor draws maximum current when it is on but not turning. After tuning the parameters, we found this transfer function. The armature resistance is calculated from experimental data. As the motor is 12V and 800W. So, the armature resistance is $R = V/I = 12/66 = 0.26$ ohm.

Moment of inertia of the motor, $J = 0.000117 \text{ kg} \cdot \text{m}^2/\text{s}^2$.

Damping ratio of the mechanical system, $b = 0.00147 \text{ Nms}$

Electromotive force constant (Steering torque = 5.23 Nm), $k_t = 0.033 \text{ Nm/Amp}$

Electromotive force constant (Steering torque = 0 Nm), $k_t = 0.039 \text{ Nm/Amp}$

Motor constant, $k_e = 0.009 \text{ Nm/Amp}$

Electric inductance, $L = 0.117 \text{ H}$

The transfer function is,

$$\frac{\dot{\theta}}{V} = \frac{k_t}{jLs^2 + (jR + bL)s + bR + keKt}$$

$$= \frac{0.033}{0.0000137s^2 + 0.0002s + 0.00068}$$

PID value: $K_p = 0.01$; $K_i = 0.08$; $K_d = 0.09$.

3.8 ELECTRICAL CONNECTION:

Figure 3.22 shows the electrical connection diagram of an energy-saving electro-hydraulic power steering system. The main control board of this circuit is an Arduino Uno. A 12-volt battery powers the DC motor. A computer powers the Arduino UNO through a USB port. Sensor data has been collected through this port. There are three ground pins. If the ultrasonic sonar sensor makes noise, it has to be grounded separately. The DC motor controller is modified, and there are two control pins that have been connected to Arduino pins 9 and 10. It will also work if the control pins are reversed, as the DC motor is a unidirectional motor. A speed-detecting sensor, a gyroscope sensor, a vehicle speed regulator, and the motor controller's ground have been connected to one ground port of the Arduino. The ultrasonic sonar sensor's ground is connected separately unless it makes noise. The dotted line shows the negative line.

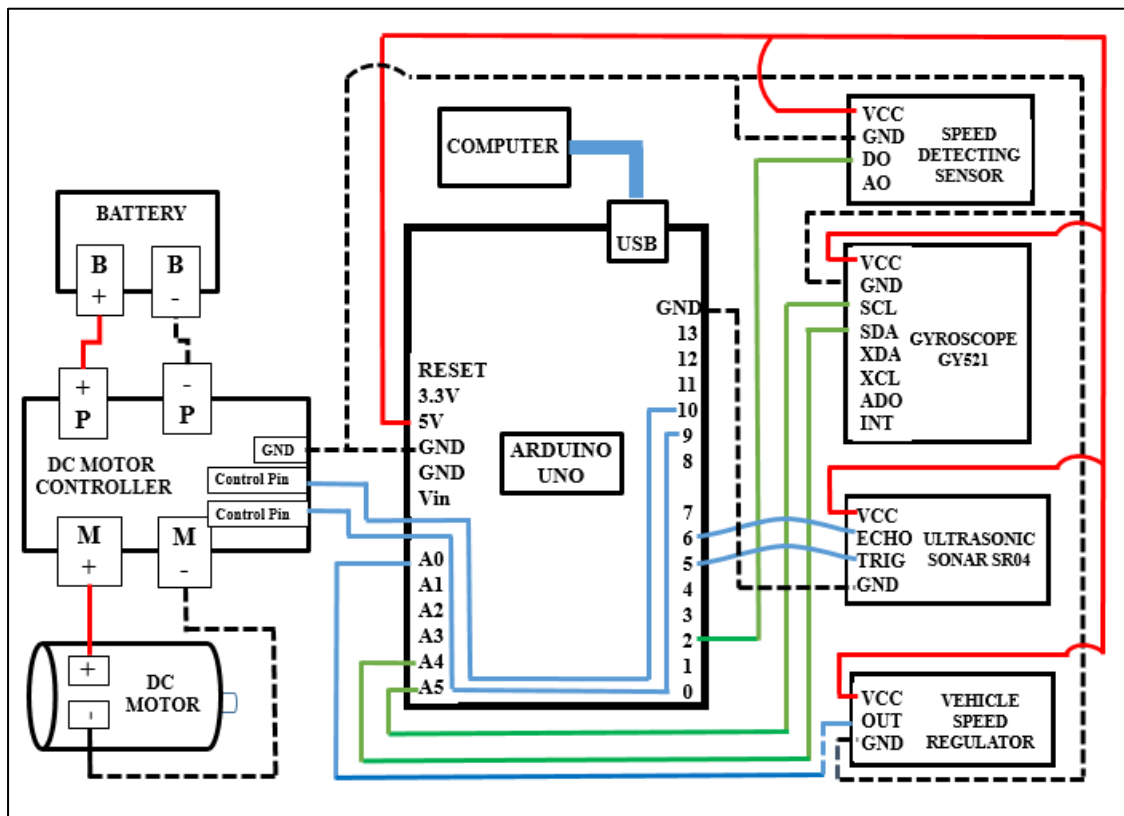


Figure 3.22: Electrical Connection

Vehicle speed and steering rate sensor data are the inputs of the microcontroller. The motor speed signal is the output of the microcontroller. PID control algorithms run on microcontrollers. The hydraulic piston rack moves right or left mechanically according to the driver's steering wheel direction. If the steering wheel stays in neutral, fluid returns to the reservoir through the return hose. If the steering wheel is turned right or left, fluid goes to the right or left piston, respectively, and develops a pressure difference between chambers to create an actuating force. According to vehicle speed and steering rate, a motor speed control signal (PWM signal) has been sent to the motor drive circuit to control the motor speed as well as regulate the pressure difference.

3.9 FUZZY PID EXPERIMENTAL PROCEDURE:

3.9.1 Membership Function

We have selected 7 triangular membership functions. The range is between -90 and 90, as our maximum speed is 90 RPS. There is one input variable and two output variables. The input variable is speed error, and the output variables are kp and ki. In Figure 3.23, the input variable speed error membership functions are enl, enm, ens, eze, eps, epm, and epl. The output variables kp and ki are named sm, md, and bg, and the range is 1 to 5.

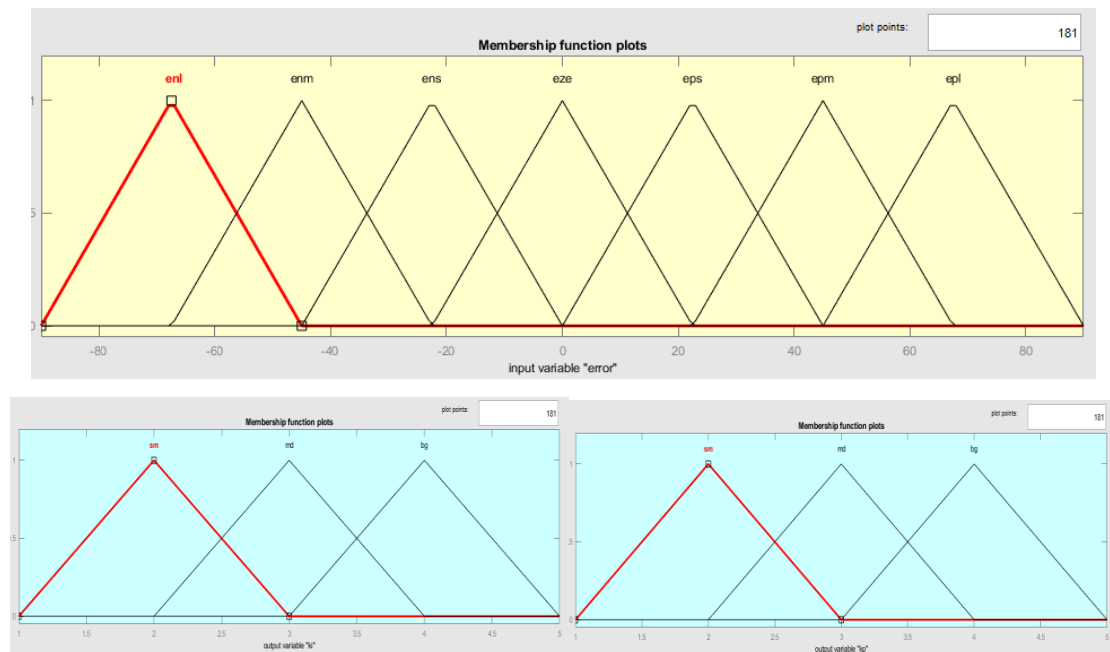


Figure 3.23: Membership Functions of Input and Output Variable

3.9.2 Surface View of Kp and Ki

The surface view is a 2D curve as there is only one input variable. Figure 3.24 shows the surface view of k_p and k_i according to speed error. At different errors, the PID values k_p and k_i change to go to the set point first.

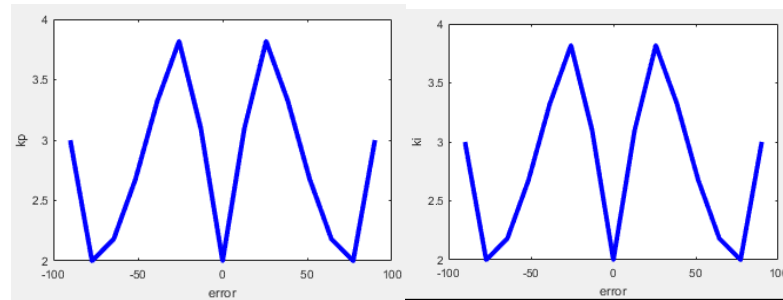


Figure 3.24: Surface view of Kp and Ki

3.9.3 Experimental Fuzzy Rules

Fuzzy rules are the key to getting good output results. As there is one input variable and 7 membership functions, we have set 7 rules. The rules are:

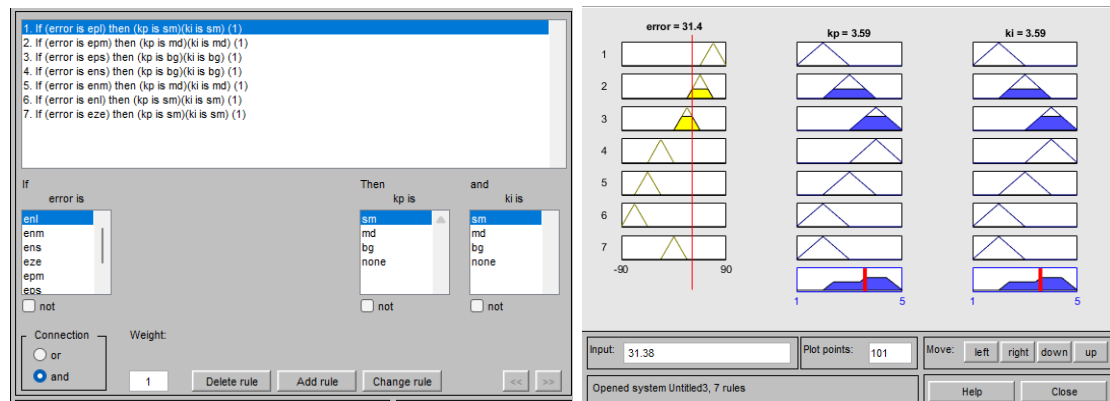


Figure 3.25: Fuzzy Rules

Rule 1: If error is epl then K_p is sm and K_i is sm.

Rule 2: If error is epm, then K_p is md and K_i is md.

Rule 3: If error is eps, then K_p is bg and K_i is bg.

Rule 4: If error is ens, then K_p is bg and K_i is bg.

Rule 5: If error is enm, then K_p is md and K_i is md.

Rule 6: If error is enl, then K_p is md and K_i is md.

Rule 7: If error is eze, then K_p is sm and K_i is sm.

The fuzzy rules and output results are shown in Figure 3.25.

3.10 SIMULATION:

3.10.1 Rack Force Calculation:

Vehicle front axle weight, 500 kg, [73]

Weight on each wheel: 250 kg

The vertical force on each wheel is $250 \times 9.81 \text{ kg} = 2452.5 \text{ N}$.

Steering force of each wheel = Vertical force $\times$ friction coefficient (μ) $= 2452.5 \times 0.8 = 1962 \text{ N}$

Steering rack force to move both wheels $= 1962 \times 2 = 3924 \text{ N}$

3.10.2 Motor Speed Map According to Friction Coefficient, Rack Force and Vehicle Speed:

The friction coefficient decreases with vehicle speed, as shown in Figure 3.26 [74]. The value of rack force in Figure 3.27 is calculated by multiplying the vehicle vertical force (4900 N for 500kg) with the friction coefficient at different vehicle speeds. Steering force is linear with rack force, and it is less than rack force because of the use of steering linkages and rack-pinion gear.

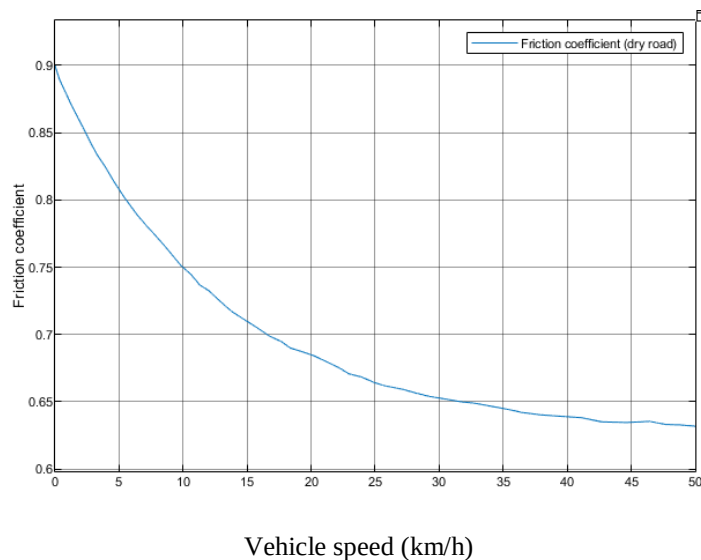


Figure 3.26: Friction Coefficient (Dry Road) vs Vehicle Longitudinal Speed [74]

So, rack force as well as steering force, or steering effort, decrease with vehicle speed. A vehicle's tires develop rack force due to the vertical load, which is F_{load} . At different motor speeds, the developed piston force is calculated. The suitable motor speed, according to the steering rate and the driver's steering feel, needs to be determined. It needs practical implementation to determine the exact value.

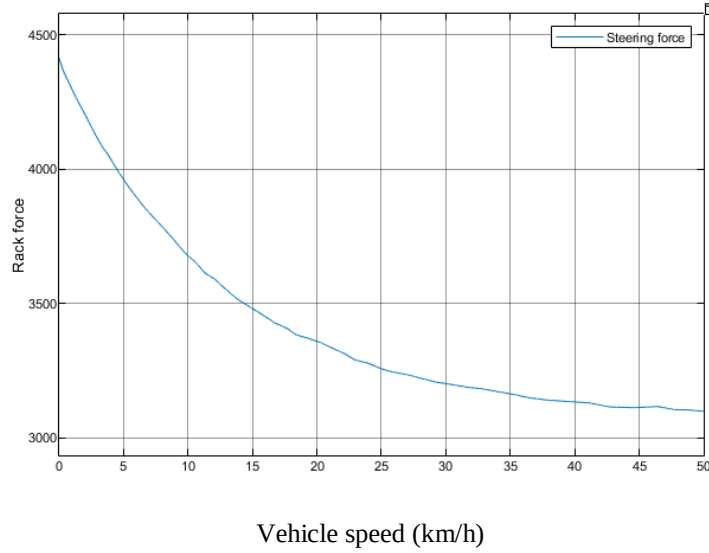


Figure 3.27: Rack Force vs Vehicle Longitudinal Speed

3.10.3 Pressure and Force:

If cylinder pressure develops to 40 bar and piston cross sectional area is 11.4 cm^2 (used in simulation).

$$\begin{aligned} \text{Then, } 40 \text{ bar} &= 40 \times 10^5 \text{ Pascal} = 40 \times 10^5 \text{ Nm}^{-2} = (40 \times 10^5) / (100 \times 100) \text{ Ncm}^{-2} \\ &= 400 \text{ Ncm}^{-2} \end{aligned}$$

$$\text{Force on } 1 \text{ cm}^2 = 400 \text{ N}$$

Therefore, the force on $11.4 \text{ cm}^2 = 400 \times 11.4 = 4560 \text{ N}$ can be developed with 40 bar pressure.

3.10.4 Hydraulic Actuator Model:

The hydraulic actuator used in the EHPS system is a symmetrical actuator, as shown in Figure 3.28. From the continuity of mass equation, we can find the pressure derivative ($\dot{P}_a$ and $\dot{P}_b$) for each chamber [75]. Q_{pump} is the pump discharge rate to chamber A. The equations given below show that pressure rate builds up linearly with pump discharge rate (Q_{pump}). At the neutral position of the steering wheel, the piston stays in the middle. So, both chamber volumes (V) are equal. And it changes as a function of piston position (x_p). The equations for the piston rod moving left to right direction are:

$$\dot{P}_a = \frac{\beta}{V + A_p x_p} (Q_{pump} - A_p \dot{x}_p)$$

$$\dot{P}_b = \frac{\beta}{V - A_p x_p} (A_p \dot{x}_p)$$

$$A_p = \pi * (B_r - R_r)^2$$

Where,

$\dot{P}_a$ = Derivative of pressure of chamber A, [pa]	A_p = Effective piston area, [m ²]
$\dot{P}_b$ = Derivative of pressure of chamber B, [pa]	B_r = Cylinder bore radius, [m]
β = Bulk modulus, [N/m ²]	R_r = Rod radius, [m]
V = Fluid volume of half cylinder, [m ³]	x_p = Piston position, [m]
Q_{pump} = Pump discharge rate, [m ³ /s]	$\dot{x}_p$ = Piston speed, [ms ⁻¹]

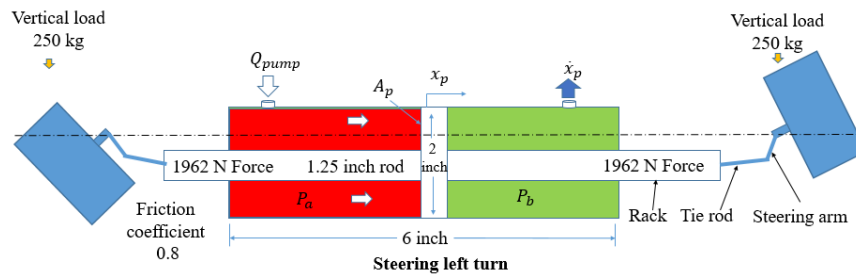


Figure 3.28: Hydraulic actuator model

After calculating the differential pressure of each chamber, we can know the total pressure developed in each chamber by integration. We can now calculate the acting force on the piston by multiplying the effective piston area (A_p) with the pressure difference across chambers. Here the equation,

$$F_p = A_p (P_a - P_b)$$

Where,

F_p = Acting force on piston, [N]
P_a = Pressure of chamber A, [pa]
P_b = Pressure of chamber B, [pa]

The piston motion equation can be developed from Newton's second law. As the piston force will move the tires, it is assumed that tire load F_{load} works as a linear spring load with a stiffness k . Friction force, F_{vcs} between oil seal and piston is also included, which has components of viscous, coulomb, and stribeck (seal) friction. The resulting force equation is,

$$F_p = m\ddot{x}_p + F_{fric} + F_{load}$$

$$F_{load} = kx_p$$

$$F_{vcs} = F_{fric,v} + F_{fric,c} + F_{fric,s}$$

$$F_{fric,v} = k_v(\dot{x}_p)$$

$$F_{fric,c} = k_c \text{sign}(\dot{x}_p)$$

$$F_{fric,s} = k_s \text{sign}(\dot{x}_p) e^{-\frac{|\dot{x}_p|}{\tau_s}}$$

Where,

F_p =Force developed on piston, [N]

m =mass of piston and load, [kg]

$\ddot{x}_p$ =acceleration, [ms^{-2}]

F_{load} =Tire load, [N]

k = Tire stiffness,[Nm^{-1}]

F_{vcs} = Summation of friction force, [N]

F_p =Force developed on piston, [N]

$F_{fric,v}$ =Viscous friction, [N]

$F_{fric,c}$ =Coulomb friction, [N]

$F_{fric,s}$ =Stribeck friction, [N]

k_v = Viscous friction coefficient (hydraulic viscosity), [kgs^{-1}]

τ_s = Stribeck velocity, [ms^{-1}]

F_{vcs} has discontinuity in $\dot{x}_p = 0$, so $\text{sign}(\dot{x}_p)$ has been replaced by $\tanh(\dot{x}_p)$ and discontinuity has been removed [76].

3.10.5 Vane Pump Flow

The vane pump in conventional HPS is a fixed displacement vane pump. The flow rate is proportional to the speed of the vehicle's engine speed. In this model, the vane pump will be driven by a motor. For a single rotation, the displacement of the vane pump is assumed to be $6 \text{ cm}^3 = 6 \times 10^{-6} \text{ m}^3$. Therefore, the flow rate,

$$Q_{pump} = \frac{6 \times 10^{-6} \times \text{Motor rpm}}{60} (\text{m}^3 \text{s}^{-1})$$

CHAPTER 4

RESULT AND DISCUSSION

4.1 MATLAB SIMULATION:

4.1.1 Motor Speed Control with PID

To simulate the motor speed control in Matlab, a dc brush motor's transfer function is used [77], where voltage is the input and angular rotation rate is the output. The speed of the DC brush motor is controlled via the PID control method. Figure 4.1 shows the Matlab block diagram of motor speed control with PID. The DC brush motor's transfer function is,

$$\frac{0.02}{0.008s^2 + 0.12s + 0.4004}$$

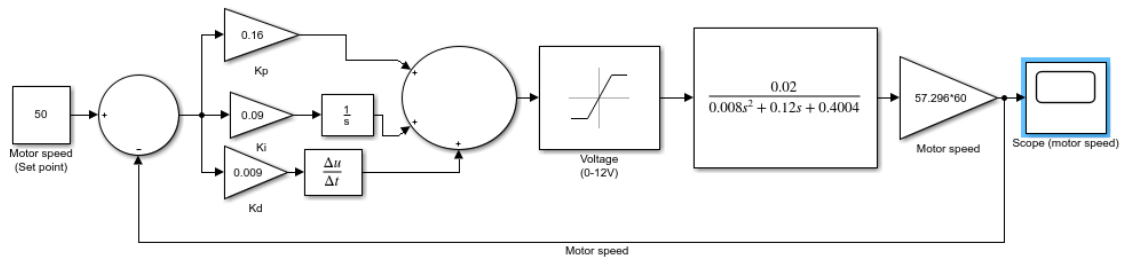


Figure 4.1: PID Motor Speed Control Diagram

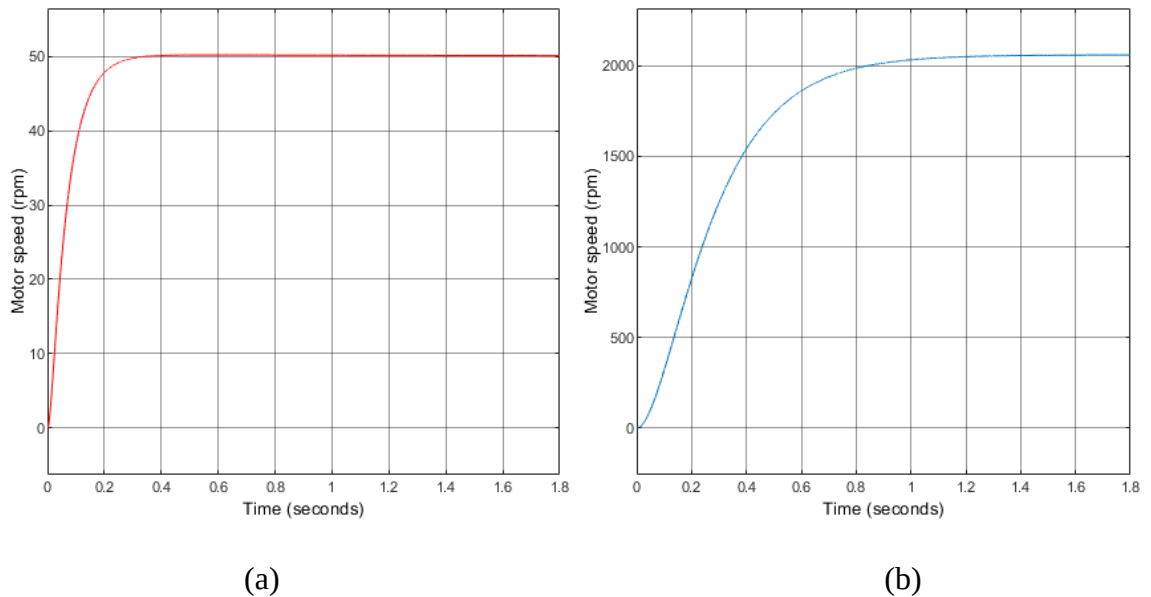


Figure 4.2: (a) Response Curve for 50 rpm and (b) 1500 rpm, for $K_p=0.16$, $K_i=0.09$, $K_d=0.01$

A 12 volt car battery (Li-ion) can be used as a power source, so the output of the PID controller has been limited to 0-12 V. We give 12 V at the transfer function input (open loop) and find the motor speed 2060 rpm. This is the maximum motor speed. We will control the speed between 0-2000 rpm, which is suitable for a vane pump. For closed loop, as shown in Figure 4.2 (a), for motor speed 50 (set point), we have tuned the PID values as $K_p=0.16$, $K_i=0.09$ and $K_d=0.01$. But with increasing motor speed, the overshoot is increasing for the same PID values, for example, 2000 rpm, as shown in Figure 4.2 (b) and for different motor speeds (set point) in Table 4.1. It's because of integral gain. For 500 motor speed, if we replace just the integral gain of 0.09 with 0.060, then the overshoot is reduced. So, to minimize this overshoot for different motor speed set point, we have tuned the integral gain value only for different speed, Table 4.2. We have used a lookup table to set the suitable integral gain for different speeds.

Table 4.1: Parameters of Different Motor Speed Set Point

$K_p=0.16, K_i=0.09, K_d=0.01$									
Parameters	50 rpm	500 rpm	1000 rpm	1200 rpm	1500 rpm	1800 rpm	1850 rpm	1900 rpm	2000 rpm
Rise Time	0.1233	0.1335	0.1756	0.2041	0.2685	0.3654	0.3871	0.4115	0.4755
Settling Time	0.2221	0.2288	1.5884	2.0379	2.6633	3.3760	3.5471	3.8019	6.7093
Settling Min	45.0866	450.75	901.9314	1.0824e+03	1.3524e+03	1.6220e+03	1.6671e+03	1.7113e+03	1.8075e+03
Settling Max	50.0437	507.4828	1.0364e+03	1.2557e+03	1.5956e+03	1.9528e+03	2.0111e+03	2.0545e+03	2.0606e+03
Overshoot	0.0870	1.4893	3.6251	4.6137	6.3376	8.4336	8.6508	8.0616	2.6468
Undershoot	0	0	0	0	0	0	0	0	0
Peak	50.0437	507.4828	1.0364e+03	1.2557e+03	1.5956e+03	1.9528e+03	2.0111e+03	2.0545e+03	2.0606e+03

Table 4.2: Tuned Integral Gain (K_i) for Overshoot Minimization at Different Speed

$K_p=0.16, K_d=0.01$									
Motor speed (rpm)	50	500	1000	1200	1500	1800	1850	1900	2000
Tuned Integral gain (K_i)	0.090	0.060	0.042	0.037	0.031	0.025	0.024	0.023	0.021
Overshoot	0.0870	0.0045	0.0466	0.0543	0.0836	0.0322	0.0204	0.0097	0.0013

4.1.2 Motor Speed Control with Adaptive PID

Figure 4.3 shows the block diagram of the updated integral gain for different motor speeds, which can be called adaptive PID control. Figure 4.4 shows the lookup table output, which has different integral gains at different speeds. For a different motor speed set point (700 rpm), the simulation shows that, in Figure 4.5, the adaptive PID has reduced the overshoot error.

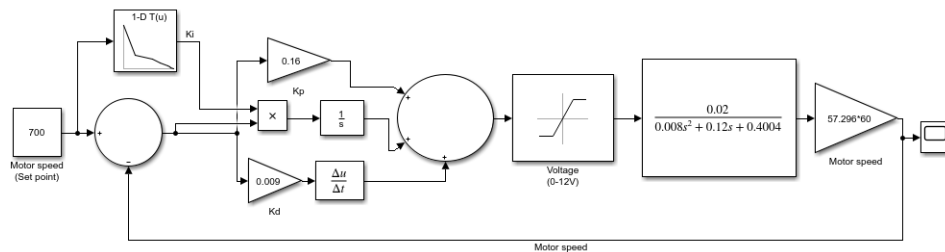


Figure 4.3: Motor Speed Control Diagram with Adaptive PID

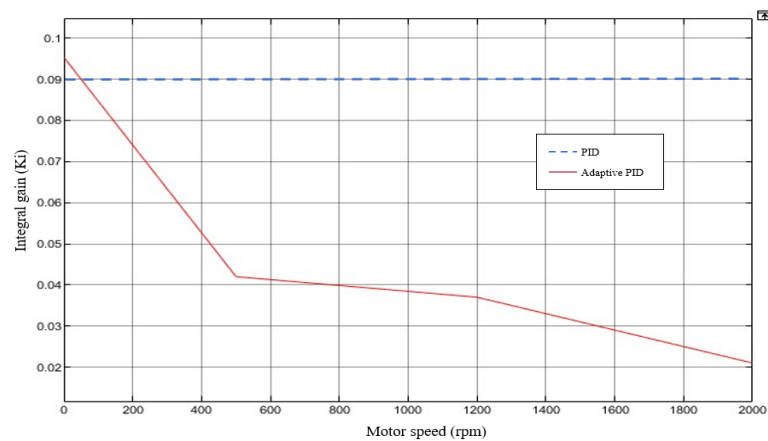


Figure 4.4: Motor speed vs Ki

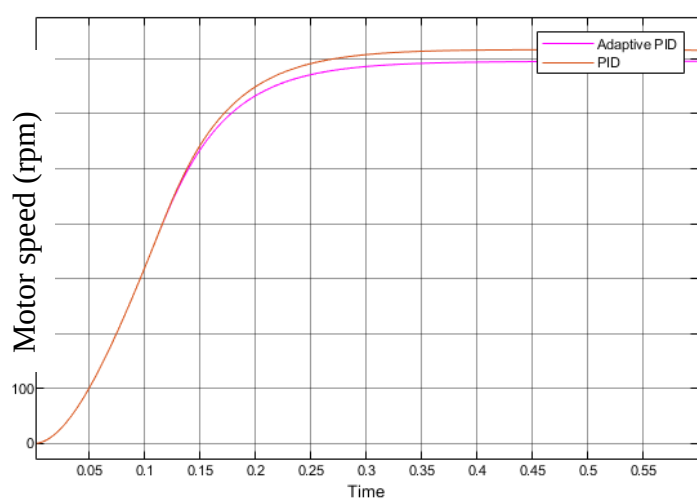


Figure 4.5: Difference between Adaptive PID and PID for Set Point 700 RPM

4.1.3 Hydraulic Force Control with Varying Speed

Figure 4.6 shows the hydraulic pressure and force control of energy-saving electro-hydraulic power steering by controlling the motor speed with adaptive PID. The hydraulic actuator block diagram simulates the hydraulic actuator model. The adaptive PID motor speed control block diagram has been added to the hydraulic actuator model to control the hydraulic pressure and force. Table 4.3 shows the parameters of the hydraulic actuator model.

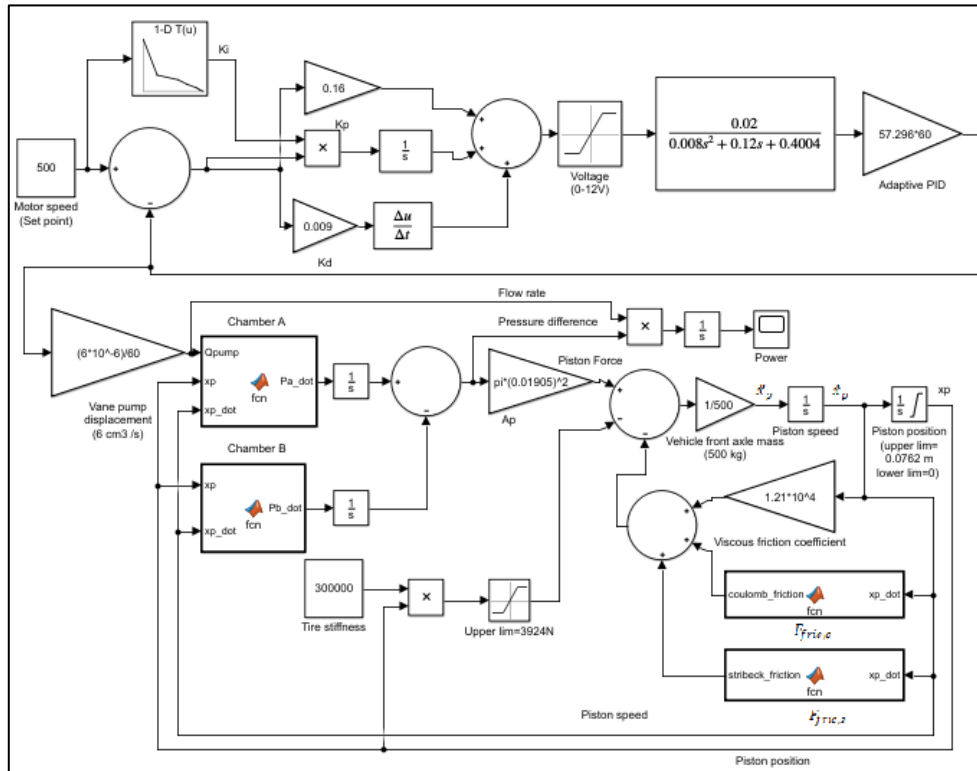


Figure 4.6: Electro-Hydraulic Power Steering Matlab Block Diagram

Table 4.3: Parameters for Hydraulic Actuator Model

Parameters	Value	Parameters	Value
β	$1.5 \times 10^9 \text{ Nm}^{-2}$	B_r	0.0508 m
x_p	0.0762 m	R_r	0.03175 m
A_p	$\pi \times 0.01905^2 \text{ m}^2$	k_v	$1.21 \times 10^4 \text{ kgs}^{-1}$
Q_{pump}	$\frac{6 \times 10^{-6} \times \text{Motor rpm}}{60} \text{ m}^3 \text{ s}^{-1}$	k_c	$1.14 \times 10^3 \text{ N}$
V	$\pi \times 0.01905^2 \times 0.0762 \text{ m}^3$	k_s	244.37 N
k	300000 Nm^{-1}	τ_s	$3.41 \times 10^{-3} \text{ ms}^{-1}$
m	500 kg		

4.2 GRAPHICAL RESULTS

Figure 4.7 shows the graphical results of the energy saving electro-hydraulic power steering system. The friction force changes with time. Therefore, to overcome this friction force, the same amount of piston force is needed. The tire stiffness force (max 3924 N) changes according to piston position (x_p) as well as tire movement. The friction force is the sum of tire stiffness force and Friction_{vcs} force. In Figure 4.8, the Friction_{vcs} force is the sum of viscous, coulumb and stribeck friction forces, and it changes according to piston speed, $\dot{x}_p$. At different motor speed set points, the friction force is different at initial. Then, after 1.7 seconds, it is almost equal.

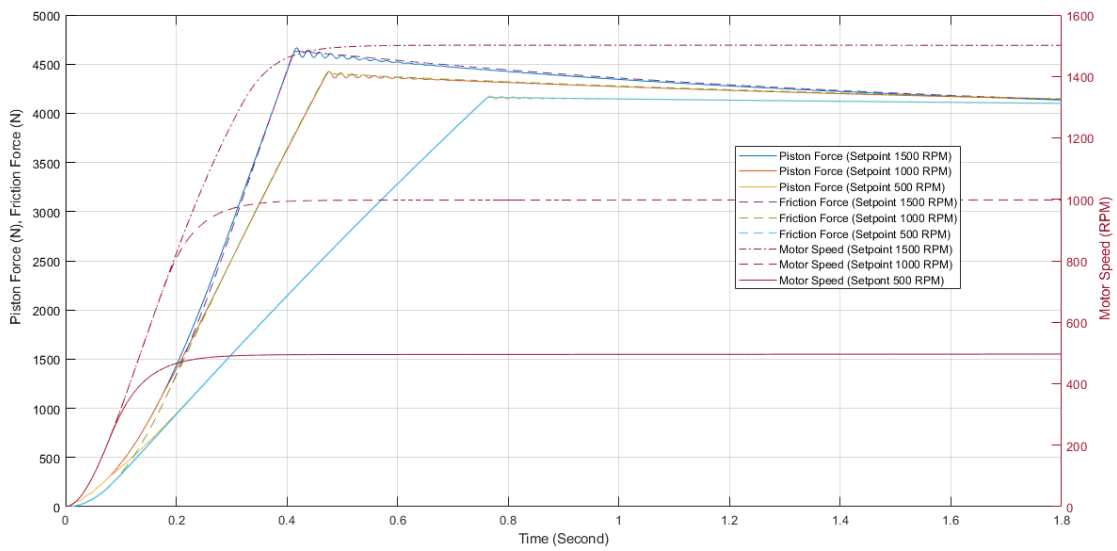


Figure 4.7: Developed Piston Force Corresponding Time at Different Set Point Motor Speed.

4.2.1 Steering Feel at Different Speed and Obstacle Avoidance

As shown in Figure 4.7, piston force is developed at different motor speeds. The higher the motor speed, the higher the piston force that develops. If the driver turns the steering wheel quickly, it will provide fast assistance. If the driver turns at medium speed, the response will be medium.

4.2.2 Low Steering Rate

If we look at Figure 3.27, when vehicle speed is approximately 6 km/h, the rack load is 3924 N at a friction coefficient of 0.8. And the total load is the sum of rack load (tire load) and friction force. If we set the motor speed set point is 500 rpm. Then, at 0.8 sec, as shown in Figure 4.7, the required piston force is developed, which assists the driver

to steer the wheel easily. The rack displacement is 0.013m (0.51 inch) at 0.8 sec, as shown in Figure 4.9. The piston pressure is 36 bar (approximate), and the pump discharge rate is 2.5 liters per minute (lpm), as shown in Figure 4.10.

4.2.3 Medium Steering Rate

If the driver turns the steering wheel quickly, then the microcontroller can detect it via the steering rate sensor and change the motor set point to 1000. Then, as shown in Figure 4.9, we can see that the required rack force develops in 0.47 sec and the rack displacement is 0.013m (0.51 inch) in 0.47 sec. The piston pressure is 38 bar (approximate), and the pump discharge rate is 6 lpm, as shown in Figure 4.10.

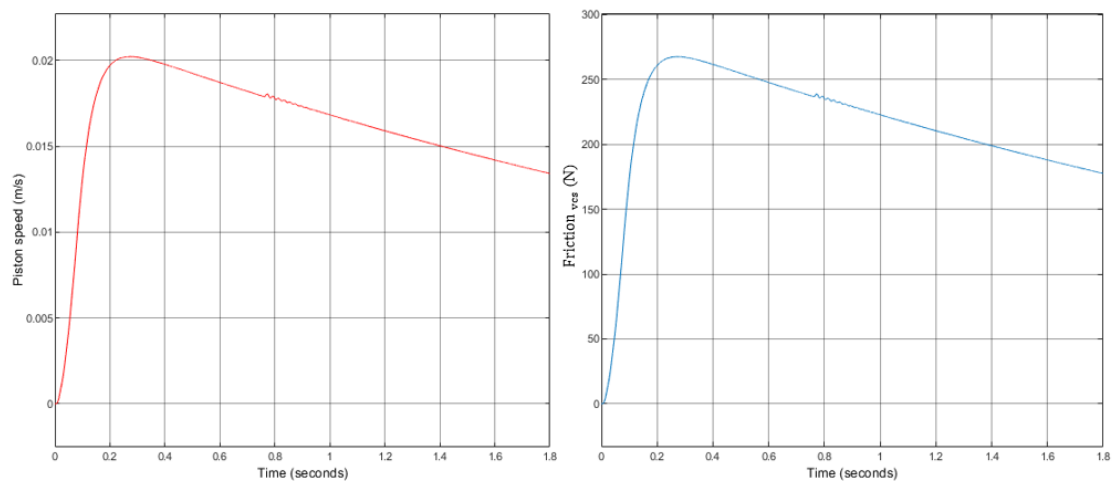


Figure 4.8: Friction and Piston Speed with Time

4.2.4 High Steering Rate

For a high steering rate, motor speed will be high. For 1500 rpm, the rack force develops in 0.41 sec, and the rack displacement is 0.013m (0.51 inch) in 0.41 sec. The piston pressure is 40 bar (approximate), and the pump discharge rate is 9 lpm, as shown in Figure 4.10. Figure 4.8 shows the relationship between friction force and piston speed. Friction force changes as a function of piston speed. As motor speed increases, piston speed also increases, as shown in Figure 4.9.

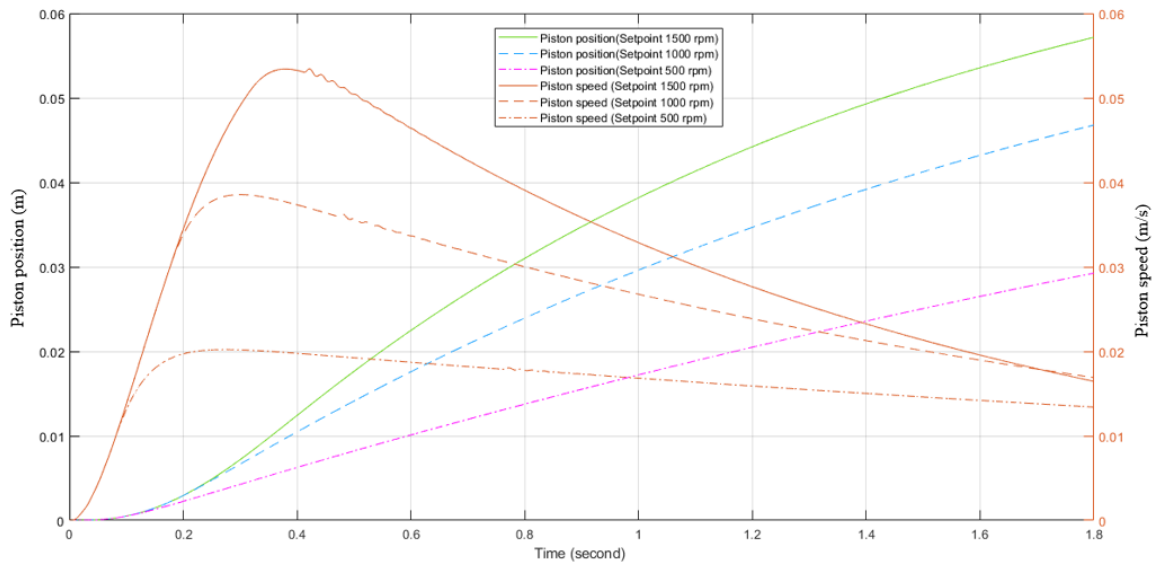


Figure 4.9: Piston Position and Piston Speed at Different Motor Speed Set Point

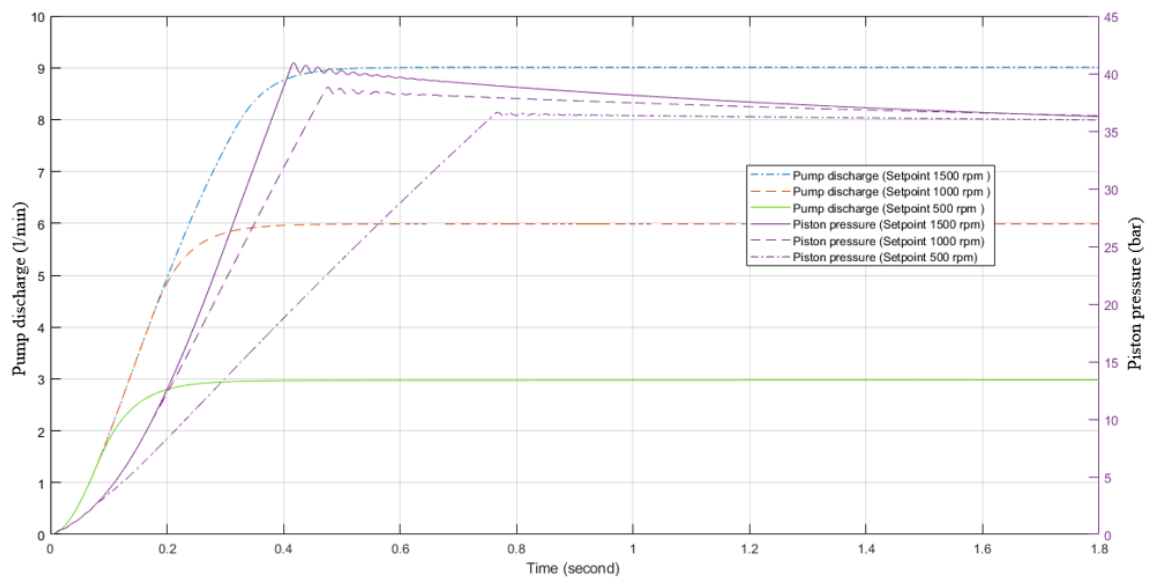


Figure 4.10: Pump Discharge Rate and Piston Pressure at Different Motor Speed

4.2.5 Energy Consumption Comparison

From Figure 4.11, we can see that at 500 rpm for 1 sec, total energy consumption is 108 W. At 1000 rpm, 272 W, and at 1500 rpm, 422 W. If we compare the old power steering system (engine-driven HPS) with our model, we can see that the new model delivers fluid according to demand. Whereas engine driven HPS delivers fluid greater than demand at high speed.

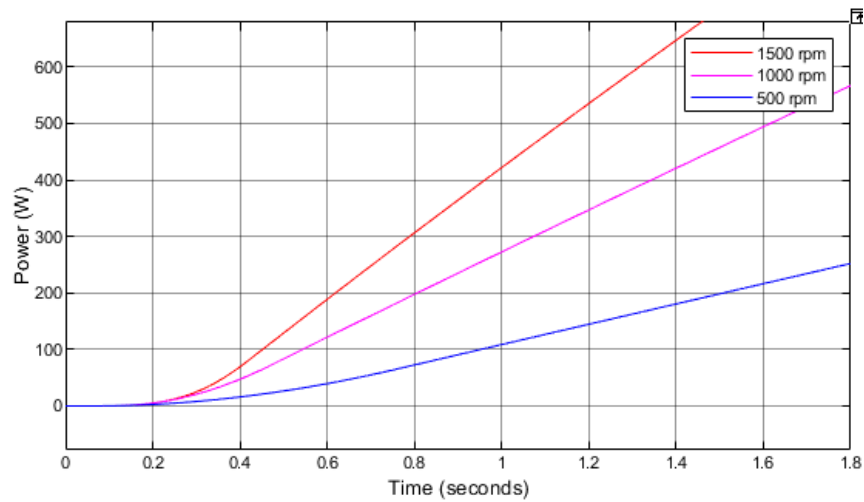


Figure 4.11: Power Consumption at Different Motor Speed

For example, in Figure 3.27, at 50 km/h, the rack force or tire load is 3100 N. In engine-driven power steering, the vane pump speed is proportional to the vehicle speed. The vane pump supplies fluid, which develops piston force quickly. But at high speed, quick response is not necessary unless for obstacle avoidance.

4.3 PID SIMULATION AND PID EXPERIMENTAL COMPARISON

The Matlab simulation shows the simulation of an energy saving electro-hydraulic system. A transfer function represents a linear, time-invariant system in terms of the input-output relationship. To simulate the experiment in Matlab, we have used a transfer function whose parameters are based on experimental devices. The experimental DC motor transfer function has been given in Section 3.2.14. The hydraulic actuator model parameters are the same as Table 4.3, but only the flow rate (Q_{pump}) is changed to 2 lpm at 90 RPS (5400 rpm). After changing the values according to experimental results and running the simulation in Matlab, the simulation and experimental results are given below. Table 4.4 and Figure 4.12 show the results of the motor speed control of the EHPS via PID control. It shows the Matlab simulation and experimental results. The set point of PID control is 45 RPS, and the current speed is 22 RPS. At time = 0 seconds, the set point is set at 45 RPS. The simulation and experimental data are taken for 10 seconds. The mathematical model of a DC motor and speed control with PID is shown in 3.7. The Matlab step info data shows the settling time in simulation is 7.53 and in experiment is 8.65, and the difference is very little. And there is overshoot in simulation.

Table 4.4: Motor Speed of Simulation and Experimental: PID and Fuzzy-PID

Time (Second)	Simulation PID (RPS)	Experimental PID (RPS)	Experimental Fuzzy-PID (RPS)
0	21.82018	21.79	22
0.5	24.59037	22.64	32.52
1	28.38015	25.71	41.3
1.5	32.84935	28.45	42.78
2	37.15545	31.42	44.18
2.5	40.80434	33.94	44.55
3	43.57894	35.96	44.55
3.5	45.45968	37.59	44.78
4	46.55032	38.83	45.07
4.5	47.01658	39.78	45.07
5	47.04064	41.04	45.07
5.5	46.79118	41.82	45.07
6	46.40674	42.44	45.07
6.5	45.98952	42.52	45.07
7	45.60628	43.06	45.07
7.5	45.29342	43.22	45.07
8	45.06411	43.31	45.07
8.5	44.91558	43.68	45.07
9	44.83567	43.82	45.07
9.5	44.80808	43.94	45.07
10	44.81606	44.17	45.07

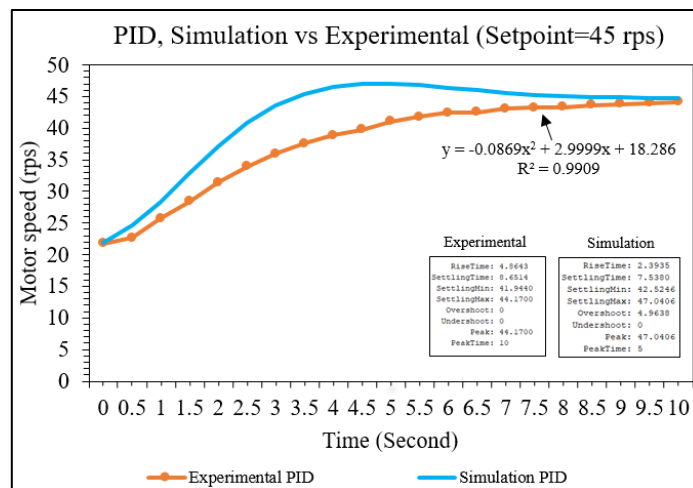


Figure 4.12: Matlab Simulation vs Experimental Results of Motor Speed Control with PID.

The R-square value of the experimental data is 0.9909, which indicates that there is a good correlation. The experimental data follows the second-order polynomial equation. The simulation curve tends to follow the experimental curve.

4.4 MOTOR SPEED AND POWER CONSUMPTION COMPARISON OF EXPERIMENTAL PID AND FUZZY PID (SET POINT= 45 RPS)

4.4.1 Experimental PID and Fuzzy PID Motor Speed Comparison

Figure 4.13 shows the experimental results of PID and fuzzy-PID, and Table 4.4 shows the experimental data. The current speed of the motor is 22 RPS, and the set point has

been changed to 45 RPS. The rise time of the PID is 4.86 sec, and the fuzzy-PID is 1.38 sec, which is fast. Comparing the PID with the fuzzy-PID control, the fuzzy-PID control reduces the settling time and rising time significantly. The fuzzy-PID speed-time characteristics curve follows the 4th-order polynomial equation.

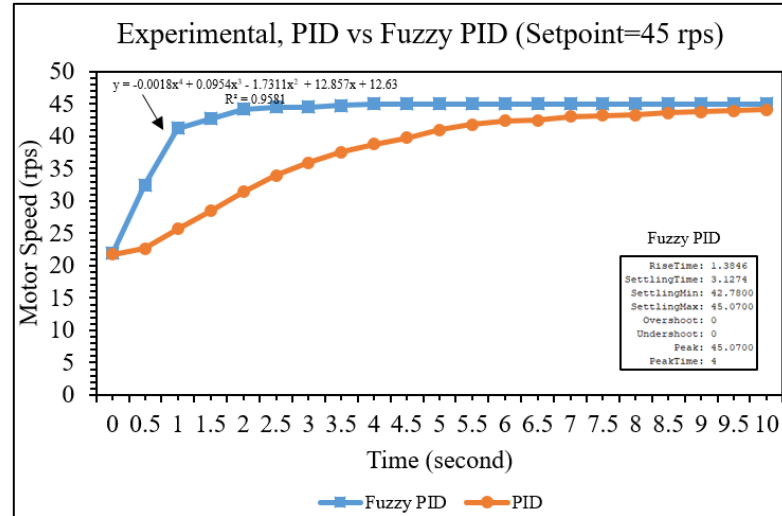


Figure 4.13: PID and Fuzzy-PID Experimental Results of Motor Speed Control.

4.4.2 Electric Power consumption of Experimental PID (Set point=45 RPS)

Figure 4.14 shows the experimental voltage and current of PID with time at Torque = 0 Nm. Table 4.5 shows the experimental data. As the voltage increases, the motor RPS increases, so the current consumption through the motor also increases, and the power consumption, as shown in Figure 4.15, also increases. The voltage and current follows the 2nd order polynomial equation and the R-square value indicates a good correlation. The power consumption at current speed (22 RPS) is 30.65 W, and at set point (45 RPS), the power consumption is 79.25 W.

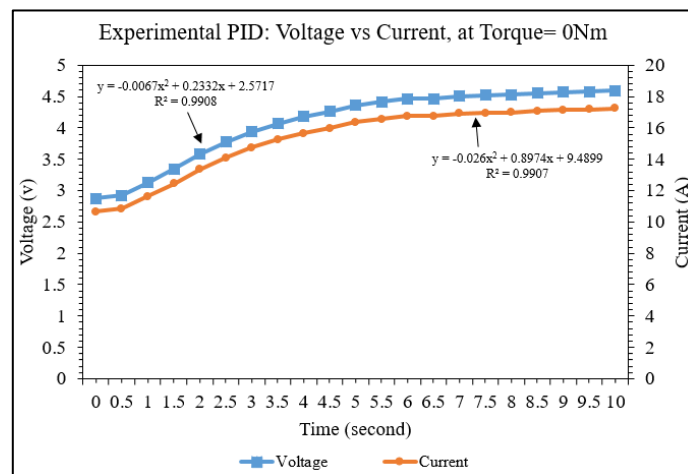


Figure 4.14: Voltage and Current of Experimental PID, at Torque=0 Nm

Table 4.5: Experimental PID: Voltage, Current and Power with Time, Set Point=45 RPS, at Torque= 0 Nm

Time (second)	Motor Speed (RPS)	Voltage (V)	Current (A)	Power (W)
0	21.79	2.8742	10.665	30.65334
0.5	22.64	2.9236	10.86	31.7503
1	25.71	3.126	11.632	36.36163
1.5	28.45	3.3475	12.4514	41.68106
2	31.42	3.5824	13.3444	47.80498
2.5	33.94	3.7725	14.0895	53.15264
3	35.96	3.935	14.733	57.97436
3.5	37.59	4.0694	15.2566	62.08521
4	38.83	4.1774	15.6686	65.45401
4.5	39.78	4.2611	15.9879	68.12604
5	41.04	4.3582	16.3558	71.28185
5.5	41.82	4.4157	16.5733	73.18272
6	42.44	4.4617	16.7473	74.72143
6.5	42.52	4.4663	16.7647	74.87618
7	43.06	4.5077	16.9213	76.27614
7.5	43.22	4.52	16.9652	76.6827
8	43.31	4.5275	16.9916	76.92947
8.5	43.68	4.5575	17.0972	77.92049
9	43.82	4.5675	17.1324	78.25224
9.5	43.94	4.5775	17.1676	78.58469
10	44.17	4.5975	17.238	79.25171

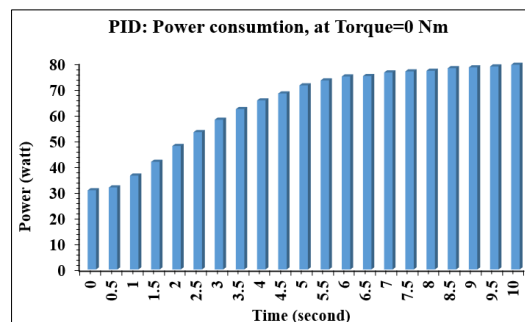


Figure 4.15: Power Consumption of Experimental PID

4.4.3 Electric Power consumption of Experimental Fuzzy-PID (Set point= 45 RPS)

Figure 4.16 shows the experimental voltage and current of fuzzy PID with time at Torque = 0 Nm, and Table 4.6 shows the experimental data. The electrical power consumption of a DC motor is shown in Figure 4.17. The power consumption at current speed (22 RPS) is 30.94 W, and at set point (45 RPS), the power consumption is 81.69 W. The voltage and current follow the 2nd-order polynomial equation, and the R-square value indicates a good correlation.

Table 4.6: Experimental Fuzzy-PID: Voltage, Current and Power with Time, Set point=45 RPS, at Torque= 0 Nm

Time (second)	Motor Speed (RPS)	Voltage (V)	Current (A)	Power (W)
0	22	2.8875	10.7175	30.94678
0.5	32.52	3.664	13.664	50.0649
1	41.3	4.3766	16.4254	71.88741
1.5	42.78	4.4847	16.8343	75.49679
2	44.18	4.5975	17.238	79.25171
2.5	44.55	4.6275	17.3436	80.25751
3	44.55	4.6275	17.3436	80.25751
3.5	44.78	4.645	17.4052	80.84715
4	45.07	4.67	17.4932	81.69324
4.5	45.07	4.67	17.4932	81.69324
5	45.07	4.67	17.4932	81.69324
5.5	45.07	4.67	17.4932	81.69324
6	45.07	4.67	17.4932	81.69324
6.5	45.07	4.67	17.4932	81.69324
7	45.07	4.67	17.4932	81.69324
7.5	45.07	4.67	17.4932	81.69324
8	45.07	4.67	17.4932	81.69324
8.5	45.07	4.67	17.4932	81.69324
9	45.07	4.67	17.4932	81.69324
9.5	45.07	4.67	17.4932	81.69324
10	45.07	4.67	17.4932	81.69324

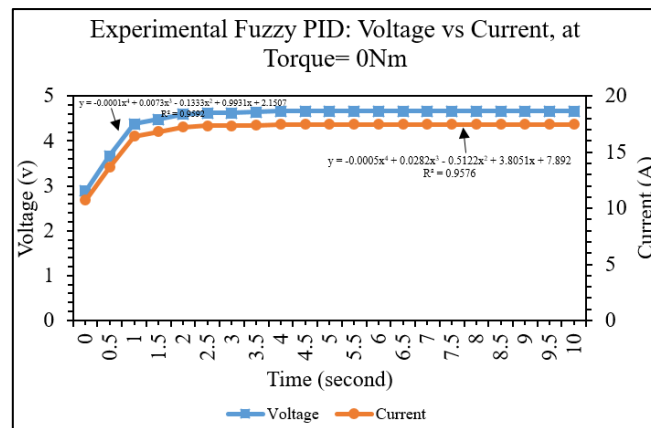


Figure 4.16: Voltage and Current of Experimental Fuzzy-PID

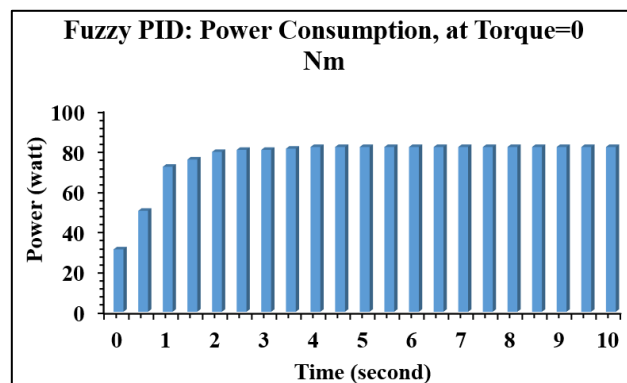


Figure 4.17: Power Consumption of Experimental Fuzzy-PID

4.4.4 Electric Power Consumption Comparison: Experimental PID vs Fuzzy-PID (Set point=45 RPS)

Figure 4.18 shows the comparison of experimental Watt-hour of PID and Fuzzy PID with time at Torque=0 Nm and Table 4.7 shows the experimental data.

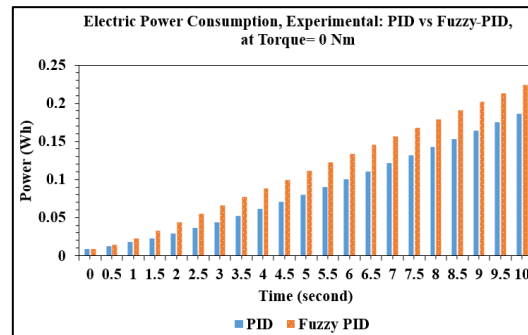


Figure 4.18: Power Consumption Comparison of Experimental PID vs Fuzzy-PID

Table 4.7: Electric Power Consumption in Watt-Hour (Set point=45 RPS) at Torque= 0 Nm

Time (second)	PID Watt-hour (Wh)	Fuzzy PID Watt-hour (Wh)
0	0.008515	0.008596389
0.5	0.012848	0.0142222
1	0.017578	0.02269111
1.5	0.022998	0.032926123
2	0.029212	0.043672546
2.5	0.036223	0.054749575
3	0.04394	0.065896451
3.5	0.052278	0.077084275
4	0.061135	0.088371802
4.5	0.070411	0.099718086
5	0.080092	0.11106437
5.5	0.090124	0.122410654
6	0.100396	0.133756938
6.5	0.110784	0.145103222
7	0.121281	0.156449506
7.5	0.131903	0.16779579
8	0.142571	0.179142073
8.5	0.153324	0.190486111
9	0.164169	0.201833333
9.5	0.175061	0.213180925
10	0.186022	0.224527209

As compared to PID, the watt-hour (Wh) of fuzzy PID is greater than PID. It is because fuzzy-PID consumes power quickly to reach the set point. The total Wh consumed at 10 sec are 0.186022 Wh (PID) and 0.2245 Wh (Fuzzy PID). The PID saves 0.038505 Wh more energy than the fuzzy PID for 10 sec.

4.5 MOTOR SPEED AND POWER CONSUMPTION COMPARISON OF EXPERIMENTAL PID AND FUZZY PID (SET POINT= 22 RPS)

4.5.1 Experimental PID and Fuzzy PID Motor Speed Comparison (Set point=22 RPS)

Table 4.8 and Figure 4.19 show the motor speed vs. time curve of the experimental PID and fuzzy PID of the EHPS. The set point has been changed to 22 RPS from the current motor speed of 45 RPS. Comparing the PID with fuzzy-PID, the fuzzy-PID control reaches the set point quickly. The fuzzy-PID speed-time characteristics curve follows the 4th-order polynomial equation, and the PID control curve follows the 2nd-order polynomial equation.

Table 4.8: Motor Speed of Experimental: PID and Fuzzy-PID

Time (second)	Experimental PID (RPS)	Experimental Fuzzy PID (RPS)
0	44.63	44.89
0.5	44.29	41.93
1	41.57	29.63
1.5	38.6	25.5
2	36.02	24.39
2.5	33.69	23.57
3	31.92	22.89
3.5	30.41	22.28
4	28.94	21.97
4.5	27.68	21.98
5	26.65	22.1
5.5	25.84	22.1
6	25.22	22.1
6.5	24.57	22.1
7	24.08	22.1
7.5	23.72	22.1
8	23.25	22.1
8.5	22.99	22.1
9	22.97	22.1
9.5	22.6	22.1
10	22.5	22.1

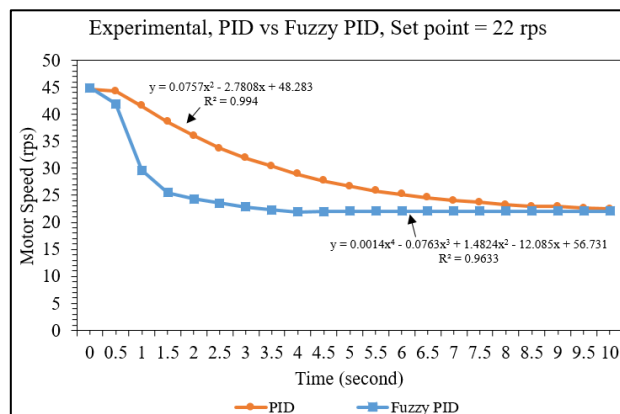


Figure 4.19: PID and Fuzzy-PID Experimental Results of Motor Speed Control (Set Point=22 RPS)

4.5.2 Electric Power consumption of Experimental PID (Set point=22 RPS)

Figure 4.20 shows the experimental voltage and current of PID with time at Torque = 0 Nm. Table 4.9 shows the experimental data. As the voltage decreases, the motor RPS decreases, so the current consumption through the motor also decreases, and the power consumption, as shown in Figure 4.21, also decreases.

Table 4.9: Experimental PID: Voltage, Current and Power with Time, Set point=22 RPS, at Torque= 0 Nm.

Time (second)	Motor Speed (RPS)	Voltage (V)	Current (A)	Power (W)
0	44.63	4.6325	17.3612	80.42576
0.5	44.29	4.6025	17.2556	79.4189
1	41.57	4.3973	16.5037	72.57172
1.5	38.6	4.1585	15.5965	64.85805
2	36.02	3.9375	14.7429	58.05017
2.5	33.69	3.7528	14.0118	52.58348
3	31.92	3.6184	13.4854	48.79557
3.5	30.41	3.505	13.0436	45.71782
4	28.94	3.3875	12.6018	42.6886
4.5	27.68	3.285	12.2164	40.13087
5	26.65	3.2028	11.9136	38.15688
5.5	25.84	3.138	11.676	36.63929
6	25.22	3.0876	11.4912	35.48023
6.5	24.57	3.0348	11.2976	34.28596
7	24.08	3.0053	11.1825	33.60677
7.5	23.72	2.9863	11.1075	33.17033
8	23.25	2.9578	10.995	32.52101
8.5	22.99	2.9426	10.935	32.17733
9	22.97	2.9407	10.9275	32.1345
9.5	22.6	2.9217	10.8525	31.70775
10	22.5	2.916	10.83	31.58028

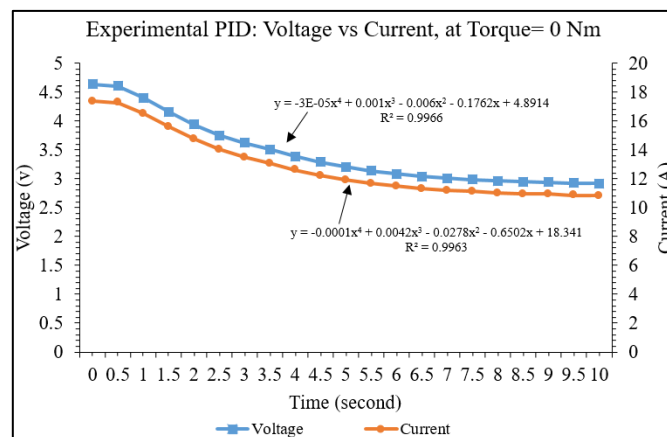


Figure 4.20: Voltage and Current of Experimental PID, at Set Point =22 RPS

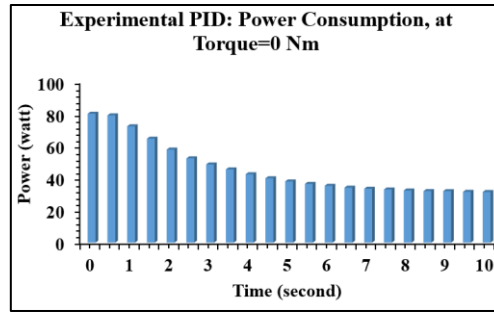


Figure 4.21: Electric Power Consumption of Experimental PID, (Set Point=22 RPS)

The voltage and current follow the 2nd-order polynomial equation, and the R-square value indicates a good correlation. The current speed of the DC motor is 45 RPS, and it has been changed to 22 RPS. The set point is now less than the current speed. The power consumption at current speed (44.63 RPS) is 80.42 W, and at set point (22.5 RPS), the power consumption is 31.48 W.

4.5.3 Electric Power consumption of Experimental Fuzzy-PID (Set point= 22 RPS)

Figure 4.22 shows the experimental voltage and current of Fuzzy PID with time at Torque = 0 Nm, and Table 4.10 shows the experimental data. The electrical power consumption of a DC motor is shown in Figure 4.23.

Table 4.10: Experimental Fuzzy PID: Voltage, Current and Power with Time, Set Point=22 RPS, at Torque=0 Nm

Time (second)	Motor Speed (RPS)	Voltage (V)	Current (A)	Power (W)
0	44.89	4.655	17.4404	81.18506
0.5	41.93	4.4226	16.5994	73.41251
1	29.63	3.4425	12.8086	44.09361
1.5	25.5	3.1092	11.5704	35.97469
2	24.39	3.0243	11.2575	34.04606
2.5	23.57	2.9768	11.07	32.95318
3	22.89	2.9369	10.9125	32.04892
3.5	22.28	2.9027	10.7775	31.28385
4	21.97	2.8837	10.7025	30.8628
4.5	21.98	2.8856	10.71	30.90478
5	22.1	2.8913	10.7325	31.03088
5.5	22.1	2.8913	10.7325	31.03088
6	22.1	2.8913	10.7325	31.03088
6.5	22.1	2.8913	10.7325	31.03088
7	22.1	2.8913	10.7325	31.03088
7.5	22.1	2.8913	10.7325	31.03088
8	22.1	2.8913	10.7325	31.03088
8.5	22.1	2.8913	10.7325	31.03088
9	22.1	2.8913	10.7325	31.03088
9.5	22.1	2.8913	10.7325	31.03088
10	22.1	2.8913	10.7325	31.03088

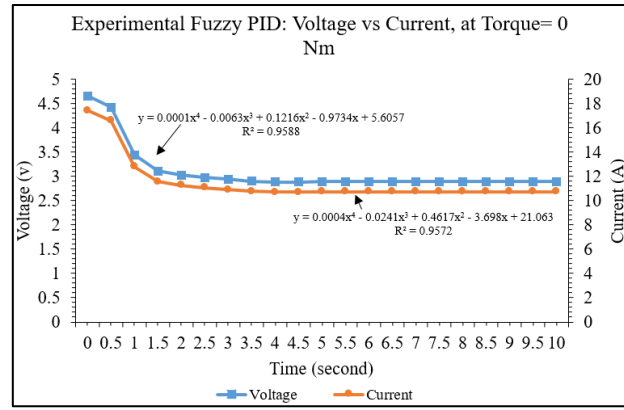


Figure 4.22: Voltage and Current of Experimental Fuzzy PID, at Set Point =22 RPS

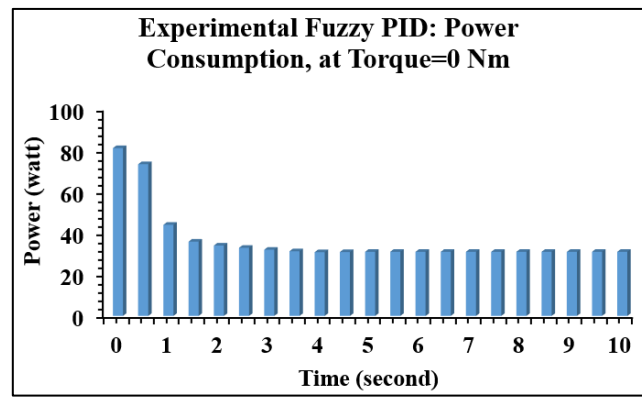


Figure 4.23: Electric Power Consumption of Experimental Fuzzy PID, (Set Point=22 RPS)

The voltage and current follow the 2nd-order polynomial equation, and the R-square value indicates a good correlation. The power consumption at current speed (44.89 RPS) is 81.18 W, and at set point (22.1 RPS), the power consumption is 31.03 W. At torque = 0 Nm, the steering wheel stays in the neutral position.

4.5.4 Electric Power Consumption Comparison: Experimental PID vs Fuzzy-PID (Set point=22 RPS)

Figure 4.24 shows the comparison of experimental Watt-hour of PID and Fuzzy PID with time at Torque = 0 Nm, and Table 4.11 shows the experimental data. As compared to PID, the watt-hour (Wh) of fuzzy PID is less than PID. It is because Fuzzy PID decreases power quickly to reach the set point. The total Wh consumed at 10 sec for PID is 0.147437 Wh and for Fuzzy PID is 0.12144 Wh. The fuzzy PID saves 0.02599 Wh more energy than the PID for 10 sec.

Table 4.11: Electric Power Consumption in Watt-Hour: PID vs Fuzzy PID (Set Point=22 RPS) at Torque= 0 Nm

Time (second)	PID Watt-hour (Wh)	Fuzzy PID Watt-hour (Wh)
0	0.022341	0.022551
0.5	0.033441	0.033287
1	0.043996	0.041448
1.5	0.053539	0.047008
2	0.062075	0.05187
2.5	0.069758	0.056523
3	0.076798	0.061037
3.5	0.083361	0.065435
4	0.089501	0.069751
4.5	0.095252	0.07404
5	0.100689	0.078341
5.5	0.105883	0.082651
6	0.110891	0.086961
6.5	0.115736	0.091271
7	0.120451	0.095581
7.5	0.125088	0.099891
8	0.12965	0.104201
8.5	0.134143	0.10851
9	0.138609	0.11282
9.5	0.143042	0.11713
10	0.147437	0.12144

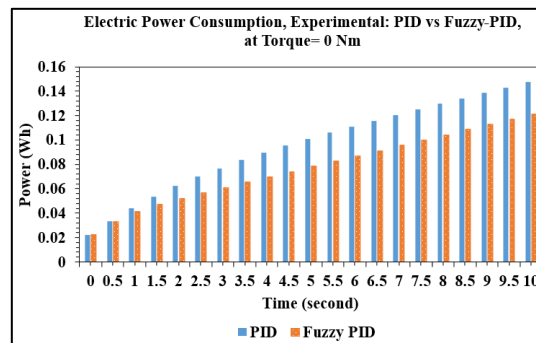


Figure 4.24: Electric Power Consumption Comparison of Experimental PID vs Fuzzy-PID (Set Point =22 RPS)

4.6 ELECTRIC POWER CONSUMPTION of EXPERIMENTAL PID at TORQUE= 3.98, 4.23, 4.48 and 5.23 NM (SET POINT=45 RPS)

Figures 4.25 and 4.26 show the voltage and current profiles vs. time of the experimental PID at Torques of 3.98 Nm, 4.23 Nm, 4.48 Nm, and 5.23 Nm. Tables 4.12 and 4.13 show the experimental data of voltage, current, and power consumption in watts. The voltage and current increase with motor speed. So, the power consumption increases. The voltage and current curve at Torque=3.98 Nm follows the 4th-order polynomial equation. As the PID controller's output voltage increases, the current consumption also increases. The current curve vs. time follows the voltage curve vs. time.

Table 4.12: Experimental PID: Voltage, Current and Power with Time (Set Point=45 RPS), at Torque=3.98 Nm and Torque=4.23 Nm

Experimental PID Set point= 45 RPS	Torque=3.98 Nm				Torque=4.23 Nm			
	Motor Speed (RPS)	Voltage (V)	Current (A)	Power (W)	Motor Speed (RPS)	Voltage (V)	Current (A)	Power (W)
0	21.79	3.0211	11.0525	33.39071	21.79	3.079	12.295	37.85631
0.5	22.64	3.0912	11.4468	35.38435	22.64	3.164	12.72	40.24608
1	25.71	3.3539	12.6211	42.32991	25.71	3.471	14.284	49.57976
1.5	28.45	3.615	13.7545	49.72252	28.45	3.7	15.38	56.906
2	31.42	3.8778	14.8544	57.60239	31.42	3.942	16.468	64.91686
2.5	33.94	4.0946	15.6608	64.12471	33.94	4.194	17.476	73.29434
3	35.96	4.3048	16.4032	70.6125	35.96	4.396	18.38	80.79848
3.5	37.59	4.5008	17.1037	76.98033	37.59	4.659	19.195	89.42951
4	38.83	4.6496	17.6286	81.96594	38.83	4.783	19.815	94.77515
4.5	39.78	4.7714	18.0354	86.05411	39.78	4.878	20.29	98.97462
5	41.04	4.8936	18.5152	90.60598	41.04	5.004	20.508	102.622
5.5	41.82	4.9638	18.8116	93.37702	41.82	5.082	20.664	105.0144
6	42.44	5.024	19.0428	95.67103	42.44	5.144	20.788	106.9335
6.5	42.52	5.032	19.0724	95.97232	42.52	5.152	20.804	107.1822
7	43.06	5.0854	19.2722	98.00685	43.06	5.2	20.906	108.7112
7.5	43.22	5.0998	19.3314	98.58627	43.22	5.2	20.922	108.7944
8	43.31	5.1079	19.3647	98.91295	43.31	5.2	20.931	108.8412
8.5	43.68	5.1412	19.5016	100.2616	43.68	5.2	20.968	109.0336
9	43.82	5.1538	19.5534	100.7743	43.82	5.2	20.982	109.1064
9.5	43.94	5.1646	19.5978	101.2148	43.94	5.2	20.994	109.1688
10	44.17	5.187	19.6846	102.104	44.17	5.217	21.034	109.7344

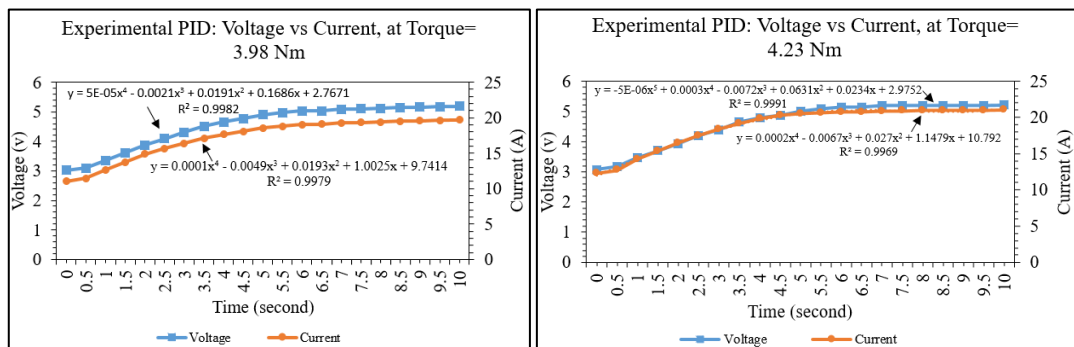


Figure 4.25: Voltage and Current of Experimental PID, at Torque=3.98, 4.23 Nm

At 4.23 Nm torque, the current and voltage curves follow the 4th and 5th order polynomial equations, respectively. The motor speed vs. time curve of the experimental PID for different torques is the same as shown in Figure 4.13. At different torque values, the voltage, current, and power consumption are different. If motor speed is the same, the more torque applied to the steering wheel, the more voltage and current increase, which in turn increases power consumption. At time = 0 second, when the motor speed is at 21.79 RPS, the voltage values at 3.98, 4.23, 4.48, and 5.23 Nm torques are 3.0211, 3.079, 3.1469, and 3.1469, and the current values are 11.0525, 12.295, 12.5029, and 12.9908, respectively. So the power consumption also increases with an increase in torque value. The power consumptions at 3.98, 4.23, 4.48, and 5.23 Nm torques are

33.39071, 37.85631, 39.34538, and 40.88075 W. The voltage and current vs. time characteristics curves of 4.48 Nm and 5.23 Nm follow the 5th-order polynomial equation. The R-square value indicates that there is a good correlation between voltage, current, and time. The maximum power consumption occurs at 10 sec at 44.17 RPS. The PID control takes about 10 seconds to reach the set point. So, the power developed to assist the driver at the right time is not sufficient.

Table 4.13: Experimental PID: Voltage, Current and Power with Time, Set Point=45 RPS, at Torque=4.48 Nm and Torque=5.23 Nm

Experimental PID 22 to 45 RPS	Torque=4.48 Nm				Torque=5.23 Nm			
Time (second)	Motor Speed (RPS)	Voltage (V)	Current (A)	Power (W)	Motor Speed (RPS)	Voltage (V)	Current (A)	Power (W)
0	21.79	3.1469	12.5029	39.34538	21.79	3.1469	12.9908	40.88075
0.5	22.64	3.234	12.93	41.81562	22.64	3.234	13.4328	43.44168
1	25.71	3.551	14.4566	51.33539	25.71	3.551	15.0008	53.26784
1.5	28.45	3.835	15.7415	60.36865	28.45	3.835	16.316	62.57186
2	31.42	4.1278	17.028	70.28818	31.42	4.1036	17.5712	72.10518
2.5	33.94	4.3646	18.036	78.71993	33.94	4.2952	18.4784	79.36842
3	35.96	4.566	18.8344	85.99787	35.96	4.4852	19.3016	86.57154
3.5	37.59	4.7349	19.4642	92.16104	37.59	4.6908	20.0355	93.98252
4	38.83	4.863	19.9437	96.98621	38.83	4.8396	20.5935	99.6643
4.5	39.78	4.958	20.3142	100.7178	39.78	4.9536	21.0288	104.1683
5	41.04	5.1148	20.8576	106.6825	41.04	5.0836	21.546	109.5312
5.5	41.82	5.2084	21.2008	110.4222	41.82	5.1538	21.858	112.6518
6	42.44	5.2828	21.4736	113.4407	42.44	5.214	22.106	115.2607
6.5	42.52	5.2924	21.5088	113.8332	42.52	5.222	22.138	115.6046
7	43.06	5.3572	21.7464	116.4998	43.06	5.2754	22.354	117.9263
7.5	43.22	5.3764	21.8168	117.2958	43.22	5.2898	22.418	118.5867
8	43.31	5.3872	21.8564	117.7448	43.31	5.2979	22.454	118.959
8.5	43.68	5.4316	22.0192	119.5995	43.68	5.3312	22.602	120.4958
9	43.82	5.4484	22.0808	120.305	43.82	5.3438	22.658	121.0798
9.5	43.94	5.4628	22.1336	120.9114	43.94	5.3546	22.706	121.5815
10	44.17	5.4921	22.2348	122.1157	44.17	5.3753	22.798	122.5461

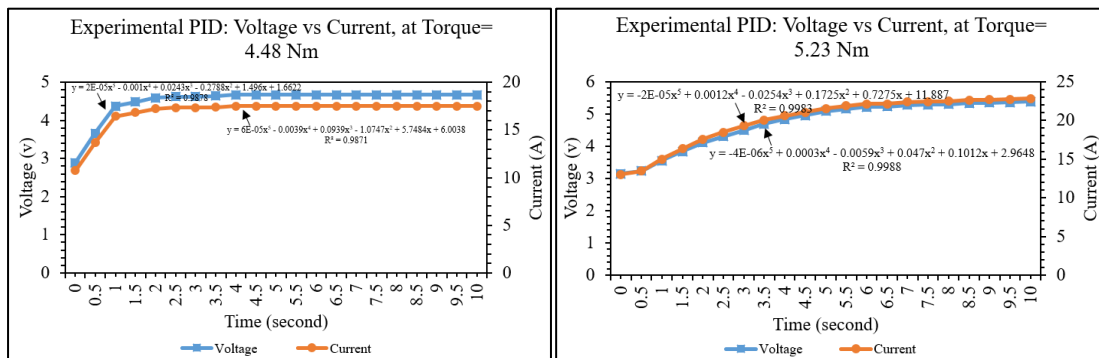


Figure 4.26: Voltage and Current of Experimental PID, at Torque=4.48, 5.23 Nm

But the PID controller can increase the power with the steering torque value. As the steering torque increases, the rotary valve opens more and more, allowing more fluid to pass into the hydraulic chamber. So the pressure load increases, and motor speed tends to decrease. But the PID controller increases the output voltage to keep the motor speed at the set point. So at different torque values, the experimental PID controller can reach the motor's RPS.

4.7 ELECTRIC POWER CONSUMPTION of EXPERIMENTAL FUZZY PID, at TORQUE= 3.98, 4.23, 4.48 and 5.23 NM (SET POINT 45 RPS)

Figures 4.27 and 4.28 show the voltage and current profiles vs. time of the experimental Fuzzy PID at Torques of 3.98 Nm, 4.23 Nm, 4.48 Nm, and 5.23 Nm. Tables 4.14 and 4.15 show the experimental data of voltage, current, and power consumption in watts. The voltage and current increase with motor speed. So, the power consumption increases. The voltage and current curve at Torque = 3.98 Nm follows the 5th-order polynomial equation. As the PID controller's output voltage increases, the current consumption also increases.

Table 4.14: Experimental Fuzzy PID: Voltage, Current and Power with Time, Set Point=45 RPS, at Torque=3.98 Nm and Torque=4.23 Nm

Experimental Fuzzy PID Set Point=45 RPS	Torque=3.98 Nm				Torque=4.23 Nm			
	Motor Speed (RPS)	Voltage (V)	Current (A)	Power (W)	Motor Speed (RPS)	Voltage (V)	Current (A)	Power (W)
0	22	3.04	11.21	34.0784	22	3.1	12.4	38.44
0.5	32.52	3.9716	15.2064	60.39374	32.52	4.052	16.908	68.51122
1	41.3	4.917	18.614	91.52504	41.3	5.03	20.56	103.4168
1.5	42.78	5.058	19.1686	96.95478	42.78	5.178	20.856	107.9924
2	44.18	5.188	19.6884	102.1434	44.18	5.218	21.036	109.7658
2.5	44.55	5.225	19.829	103.6065	44.55	5.255	21.11	110.9331
3	44.55	5.225	19.829	103.6065	44.55	5.255	21.11	110.9331
3.5	44.78	5.248	19.9164	104.5213	44.78	5.278	21.156	111.6614
4	45.07	5.27	20	105.4	45.07	5.3	21.2	112.36
4.5	45.07	5.27	20	105.4	45.07	5.3	21.2	112.36
5	45.07	5.27	20	105.4	45.07	5.3	21.2	112.36
5.5	45.07	5.27	20	105.4	45.07	5.3	21.2	112.36
6	45.07	5.27	20	105.4	45.07	5.3	21.2	112.36
6.5	45.07	5.27	20	105.4	45.07	5.3	21.2	112.36
7	45.07	5.27	20	105.4	45.07	5.3	21.2	112.36
7.5	45.07	5.27	20	105.4	45.07	5.3	21.2	112.36
8	45.07	5.27	20	105.4	45.07	5.3	21.2	112.36
8.5	45.07	5.27	20	105.4	45.07	5.3	21.2	112.36
9	45.07	5.27	20	105.4	45.07	5.3	21.2	112.36
9.5	45.07	5.27	20	105.4	45.07	5.3	21.2	112.36
10	45.07	5.27	20	105.4	45.07	5.3	21.2	112.36

The current curve vs. time follows the voltage curve vs. time. At 4.23 Nm torque, the current and voltage curves follow a 6th-order polynomial equation. The R-square values shown in the graph indicate that there is a good correlation between voltage and current vs. time. The motor speed vs. time curve of the experimental fuzzy PID for different torques is the same as shown in Figure 4.13 for set point 45 RPS. At different torque values, the voltage, current, and power consumption are also different, as is the experimental PID.

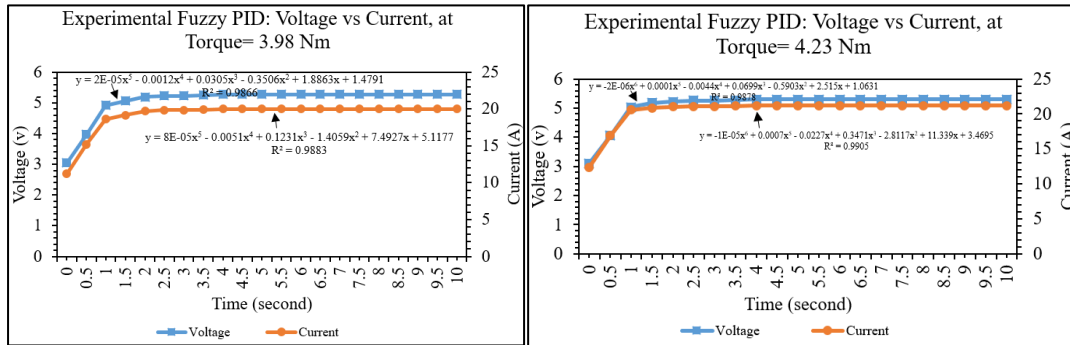


Figure 4.27: Voltage and Current of Experimental Fuzzy PID, at Torque=3.98, 4.23 Nm

Table 4.15: Experimental Fuzzy PID: Voltage, Current and Power with Time, Set Point=45 RPS, at Torque=4.48 Nm and Torque=5.23 Nm

Experimental Fuzzy PID 22 to 45 RPS	Torque=4.48 Nm				Torque=5.23 Nm			
Time (second)	Motor Speed (RPS)	Voltage (V)	Current (A)	Power (W)	Motor Speed (RPS)	Voltage (V)	Current (A)	Power (W)
0	22	3.17	12.61	39.9737	22	3.17	13.1	41.527
0.5	32.52	4.232	17.468	73.92458	32.52	4.1864	17.9672	75.21789
1	41.3	5.146	20.972	107.9219	41.3	5.107	21.65	110.5666
1.5	42.78	5.3236	21.6232	115.1133	42.78	5.248	22.242	116.726
2	44.18	5.4934	22.2392	122.1688	44.18	5.3762	22.802	122.5881
2.5	44.55	5.5415	22.402	124.1407	44.55	5.4095	22.95	124.148
3	44.55	5.5415	22.402	124.1407	44.55	5.4095	22.95	124.148
3.5	44.78	5.5714	22.5032	125.3743	44.78	5.4302	23.042	125.1227
4	45.07	5.6	22.6	126.56	45.07	5.45	23.13	126.0585
4.5	45.07	5.6	22.6	126.56	45.07	5.45	23.13	126.0585
5	45.07	5.6	22.6	126.56	45.07	5.45	23.13	126.0585
5.5	45.07	5.6	22.6	126.56	45.07	5.45	23.13	126.0585
6	45.07	5.6	22.6	126.56	45.07	5.45	23.13	126.0585
6.5	45.07	5.6	22.6	126.56	45.07	5.45	23.13	126.0585
7	45.07	5.6	22.6	126.56	45.07	5.45	23.13	126.0585
7.5	45.07	5.6	22.6	126.56	45.07	5.45	23.13	126.0585
8	45.07	5.6	22.6	126.56	45.07	5.45	23.13	126.0585
8.5	45.07	5.6	22.6	126.56	45.07	5.45	23.13	126.0585
9	45.07	5.6	22.6	126.56	45.07	5.45	23.13	126.0585
9.5	45.07	5.6	22.6	126.56	45.07	5.45	23.13	126.0585
10	45.07	5.6	22.6	126.56	45.07	5.45	23.13	126.0585

At constant motor speed, the more torque applied to the steering wheel, the more voltage and current increase, which also increases power consumption. At time = 0 second, when the motor speed is at 22 RPS, the voltage values at 3.98, 4.23, 4.48, and 5.23 Nm torques are 3.04, 3.1, 3.17, and 3.17, respectively, and the current values are 11.21, 12.4, 12.61, and 13.1. So the power consumption also increases with an increase in torque value. The power consumptions are 34.0784, 38.44, 39.9737, and 41.527 W. The voltage and current vs. time characteristics curve of 4.48 Nm torque follows the 6th order polynomial equation, and the voltage and current vs. time characteristics curve of 5.23 Nm torque follows the 5th and 6th order polynomial equations, respectively. The R-square value indicates that there is a good correlation between voltage, current, and time. The maximum power consumption occurs at 10 sec at 45.07 RPS. The fuzzy PID control takes about 4 seconds to reach the set point. So, the power developed to assist the driver at the right time is sufficient. And fuzzy PID controllers can increase power with steering torque values as well.

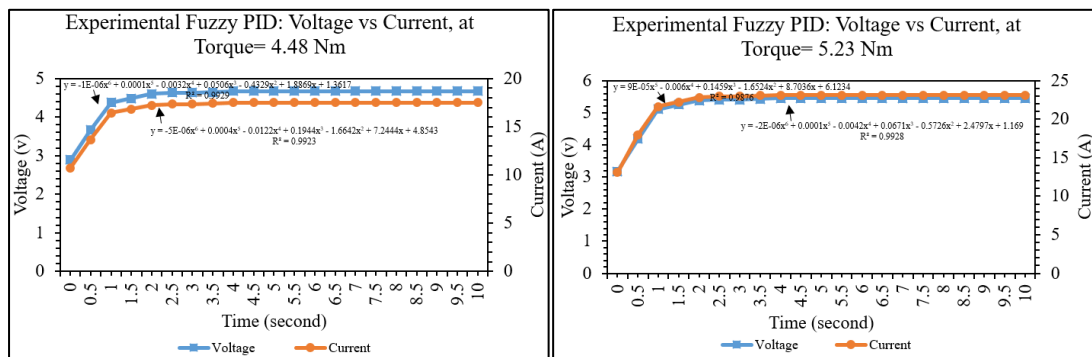


Figure 4.28: Voltage and Current of Experimental Fuzzy PID, at Torque=4.48, 5.23 Nm

As the steering torque increases, the rotary valve opens more and more, allowing more fluid to pass into the hydraulic chamber. So the pressure load increases, and motor speed tends to decrease. But the fuzzy PID controller increases the output voltage to keep the motor speed at the set point. So at different torque values, the experimental fuzzy PID controller can reach the motor RPS faster than PID.

4.8 ELECTRIC POWER CONSUMPTION of EXPERIMENTAL PID, at TORQUE= 3.98, 4.23, 4.48 and 5.23 NM (SET POINT 22 RPS)

Figures 4.29 and 4.30 show the voltage and current profiles vs. time of the experimental PID at Torques of 3.98 Nm, 4.23 Nm, 4.48 Nm, and 5.23 Nm. Tables 4.16 and 4.17 show the experimental data of voltage, current, and power consumption in watts. The

voltage and current decrease with motor speed. So, the power consumption decreases. The voltage and current curves at Torque = 3.98 Nm follow the 5th and 6th-order polynomial equations, respectively. As the PID controller's output voltage decreases, the current consumption also decreases. The current curve follows the voltage curve with time. At 4.23 Nm torque, the current and voltage curves both follow the 5th and 6th order polynomial equations, respectively. The R-square values shown in the graph indicate that there is a good correlation between voltage and current vs. time. The motor speed vs. time curve of the experimental PID for different torques is the same as shown in Figure 4.19 for set point 22 RPS.

Table 4.16: Experimental PID: Voltage, Current and Power with Time, Set Point=22 RPS, at Torque=3.98 Nm and Torque=4.23 Nm

Experimental PID 45 to 22	Torque=3.98 Nm				Torque=4.23 Nm			
Time (second)	Motor Speed (RPS)	Voltage (V)	Current (A)	Power (W)	Motor Speed (RPS)	Voltage (V)	Current (A)	Power (W)
0	44.63	5.233	19.8594	103.9242	44.63	5.263	21.126	111.1861
0.5	44.29	5.199	19.7302	102.5773	44.29	5.229	21.058	110.1123
1	41.57	4.9413	18.7166	92.48434	41.57	5.257	21.114	110.9963
1.5	38.6	4.622	17.532	81.0329	38.6	4.76	19.7	93.772
2	36.02	4.3124	16.4286	70.84669	36.02	4.404	18.41	81.07764
2.5	33.69	4.0721	15.5808	63.44658	33.69	4.169	17.376	72.44054
3	31.92	3.9228	15.0144	58.89849	31.92	3.992	16.668	66.53866
3.5	30.41	3.7928	14.5312	55.11394	30.41	3.841	16.123	61.92844
4	28.94	3.664	13.9554	51.13259	28.94	3.7	15.576	57.6312
4.5	27.68	3.5412	13.4388	47.58948	27.68	3.668	15.072	55.2841
5	26.65	3.445	13.013	44.82979	26.65	3.565	14.66	52.2629
5.5	25.84	3.3656	12.6744	42.65696	25.84	3.484	14.336	49.94662
6	25.22	3.3098	12.4202	41.10838	25.22	3.422	14.088	48.20914
6.5	24.57	3.2513	12.1709	39.57125	24.57	3.357	13.742	46.13189
7	24.08	3.2072	11.9896	38.45305	24.08	3.308	13.448	44.48598
7.5	23.72	3.1776	11.8536	37.666	23.72	3.272	13.26	43.38672
8	23.25	3.14	11.675	36.6595	23.25	3.225	13.025	42.00563
8.5	22.99	3.1192	11.5763	36.10879	22.99	3.199	12.895	41.25111
9	22.97	3.1176	11.5689	36.0672	22.97	3.197	12.885	41.19335
9.5	22.6	3.088	11.432	35.30202	22.6	3.16	12.7	40.132
10	22.5	3.08	11.395	35.0966	22.5	3.15	12.65	39.8475

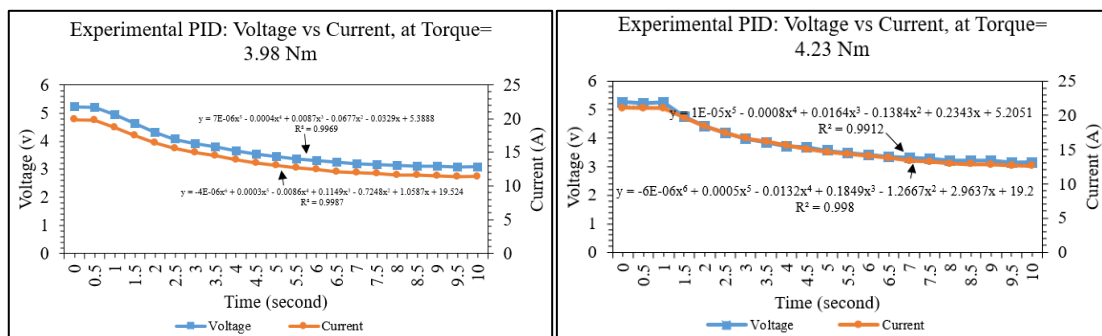


Figure 4.29: Voltage and Current of Experimental PID, at Torque=3.98, 4.23 Nm
At different torque values, the voltage, current, and power consumption are also different. At constant motor speed, the more torque applied to the steering wheel, the

more voltage and current increase, which also increases power consumption. The current speed of the motor is now 44.63 RPS, and the set point is less than the current speed, which is 22 RPS. At time = 0 second, when the motor speed is at 44.63 RPS, the voltage values at 3.98, 4.23, 4.48 and 5.23 Nm torques are 5.233, 5.263, 5.5519 and 5.4167 and current values are 19.8594, 21.126, 22.4372 and 22.982 respectively. So the power consumption also increases with an increase in torque value. The power consumption is maximum at different torques, and the values are 103.9242, 111.1861, 124.5691, and 124.4866 W.

Table 4.17: Experimental PID: Voltage, Current and Power with Time, Set Point=22 RPS, at Torque=4.48 Nm and Torque=5.23 Nm

Experimental PID 45 to 22	Torque=4.48 Nm				Torque=5.23 Nm			
Time (second)	Motor Speed (RPS)	Voltage (V)	Current (A)	Power (W)	Motor Speed (RPS)	Voltage (V)	Current (A)	Power (W)
0	44.63	5.5519	22.4372	124.5691	44.63	5.4167	22.982	124.4866
0.5	44.29	5.5077	22.2876	122.7534	44.29	5.3861	22.846	123.0508
1	41.57	5.1784	21.0908	109.2166	41.57	5.1313	21.758	111.6468
1.5	38.6	4.84	19.854	96.09336	38.6	4.812	20.49	98.59788
2	36.02	4.572	18.8578	86.21786	36.02	4.4926	19.329	86.83747
2.5	33.69	4.3421	17.936	77.87991	33.69	4.2752	18.3884	78.61409
3	31.92	4.1728	17.228	71.889	31.92	4.1436	17.7512	73.55387
3.5	30.41	4.0369	16.624	67.10943	30.41	4.0287	17.2076	69.32426
4	28.94	3.884	15.9718	62.03447	28.94	3.884	16.5512	64.28486
4.5	27.68	3.7548	15.3796	57.74732	27.68	3.7548	15.9464	59.87554
5	26.65	3.645	14.8955	54.2941	26.65	3.645	15.452	56.32254
5.5	25.84	3.564	14.5164	51.73645	25.84	3.564	15.0632	53.68524
6	25.22	3.502	14.2312	49.83766	25.22	3.502	14.7656	51.70913
6.5	24.57	3.4327	13.9107	47.75126	24.57	3.4327	14.4364	49.55583
7	24.08	3.3788	13.6608	46.15711	24.08	3.3788	14.1816	47.91679
7.5	23.72	3.342	13.4772	45.0408	23.72	3.342	13.9944	46.76928
8	23.25	3.295	13.2375	43.61756	23.25	3.295	13.75	45.30625
8.5	22.99	3.269	13.105	42.84025	22.99	3.269	13.6148	44.50678
9	22.97	3.267	13.095	42.78137	22.97	3.267	13.6044	44.44557
9.5	22.6	3.23	12.91	41.6993	22.6	3.23	13.412	43.32076
10	22.5	3.22	12.86	41.4092	22.5	3.22	13.36	43.0192

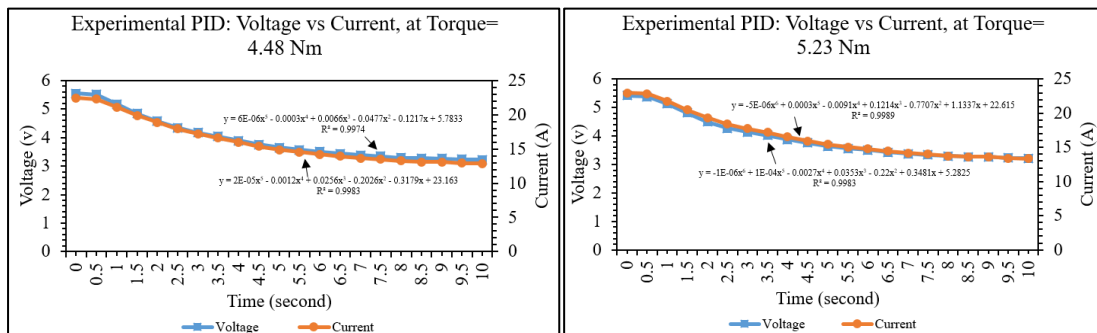


Figure 4.30: Voltage and Current of Experimental PID, at Torque=4.48, 5.23 Nm

The voltage and current vs. time characteristics curve of 4.48 Nm torque both follow the 5th order polynomial equation, and the voltage and current vs. time characteristics curve of 5.23 Nm torque follow the 5th and 6th order polynomial equations, respectively.

The R-square value indicates that there is a good correlation between voltage, current, and time. The minimum power consumption occurs at 10 seconds at 22.5 RPS. The experimental PID control takes about 10 seconds to reach the set point. So, the power developed to assist the driver at the right time is not sufficient. The PID controller increases power with steering torque. As the steering torque increases, the rotary valve opens more and more, allowing more fluid to pass into the hydraulic chamber. So the hydraulic pressure increases, and motor speed tends to decrease. But the PID controller increases the output voltage to keep the motor speed at the set point. So at different torque values, the PID controller can reach the motor speed.

4.9 ELECTRIC POWER CONSUMPTION of EXPERIMENTAL FUZZY PID, at TORQUE= 3.98, 4.23, 4.48 and 5.23 NM (SET POINT=22 RPS)

Figures 4.31 and 4.32 show the voltage and current profiles vs. time of the experimental PID at Torque = 3.98 Nm, 4.23 Nm, 4.48 Nm, and 5.23 Nm. Tables 4.18 and 4.19 show the experimental data of voltage, current, and power consumption in watts. The voltage and current decrease with motor speed.

Table 4.18: Experimental Fuzzy PID: Voltage, Current and Power with Time, Set Point=22 RPS, at Torque=3.98 Nm and Torque=4.23 Nm

Experimental Fuzzy PID Set Point=22 RPS	T=3.98 Nm				T=4.23 Nm			
	Motor Speed (RPS)	Voltage (V)	Current (A)	Power (W)	Motor Speed (RPS)	Voltage (V)	Current (A)	Power (W)
0	44.89	5.259	19.9582	104.9602	44.89	5.289	21.178	112.0104
0.5	41.93	4.9737	18.8534	93.77116	41.93	5.093	20.686	105.3538
1	29.63	3.7267	14.2446	53.08535	29.63	3.763	15.852	59.65108
1.5	25.5	3.335	12.535	41.80423	25.5	3.45	14.2	48.99
2	24.39	3.2351	12.1043	39.15862	24.39	3.339	13.634	45.52393
2.5	23.57	3.1656	11.7966	37.34332	23.57	3.257	13.185	42.94355
3	22.89	3.1112	11.5393	35.90107	22.89	3.189	12.845	40.96271
3.5	22.28	3.0624	11.3136	34.64677	22.28	3.128	12.54	39.22512
4	21.97	3.0373	11.1875	33.97979	21.97	3.097	12.385	38.35635
4.5	21.98	3.0382	11.195	34.01265	21.98	3.098	12.39	38.38422
5	22.1	3.048	11.247	34.28086	22.1	3.11	12.45	38.7195
5.5	22.1	3.048	11.247	34.28086	22.1	3.11	12.45	38.7195
6	22.1	3.048	11.247	34.28086	22.1	3.11	12.45	38.7195
6.5	22.1	3.048	11.247	34.28086	22.1	3.11	12.45	38.7195
7	22.1	3.048	11.247	34.28086	22.1	3.11	12.45	38.7195
7.5	22.1	3.048	11.247	34.28086	22.1	3.11	12.45	38.7195
8	22.1	3.048	11.247	34.28086	22.1	3.11	12.45	38.7195
8.5	22.1	3.048	11.247	34.28086	22.1	3.11	12.45	38.7195
9	22.1	3.048	11.247	34.28086	22.1	3.11	12.45	38.7195
9.5	22.1	3.048	11.247	34.28086	22.1	3.11	12.45	38.7195
10	22.1	3.048	11.247	34.28086	22.1	3.11	12.45	38.7195

So, the power consumption decreases. The voltage and current curve at Torque=3.98 Nm follows the 6th-order polynomial equation. As the fuzzy PID controller's output voltage decreases, the current consumption also decreases. The current curve follows the voltage curve with time. At 4.23 Nm torque, the current and voltage curves both follow a 6th-order polynomial equation. The R-square values shown in the graph indicate that there is a good correlation between voltage and current vs. time. The motor speed vs. time curve of the experimental fuzzy PID (Set Point = 22 RPS) for different torques is the same as shown in Figure 4.19. At different torque values, the voltage, current, and power consumption are also different.

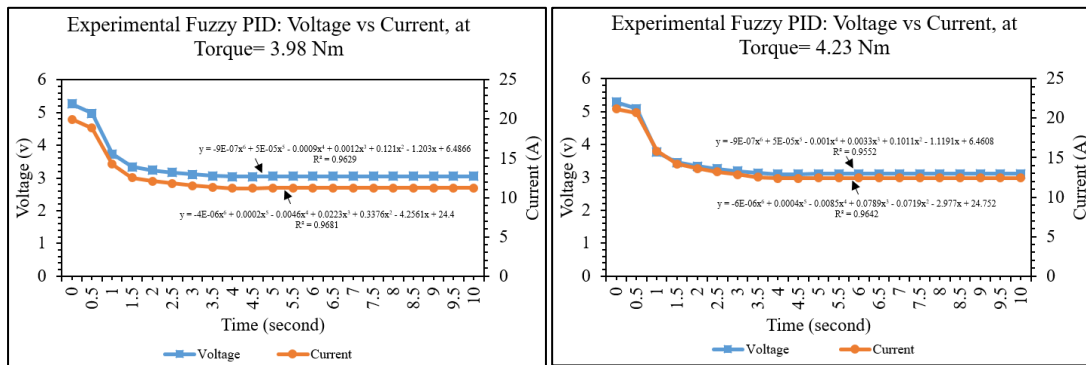


Figure 4.31: Voltage and Current of Experimental Fuzzy PID, at Torque=3.98, 4.23 Nm

Table 4.19: Experimental Fuzzy PID: Voltage, Current and Power with Time, Set Point=22 RPS, at Torque=4.48 Nm and Torque=5.23 Nm

Experimental Fuzzy PID 45 to 22	T=4.48 Nm				T=5.23 Nm			
Time (second)	Motor Speed (RPS)	Voltage (V)	Current (A)	Power (W)	Motor Speed (RPS)	Voltage (V)	Current (A)	Power (W)
0	44.89	5.5857	22.5516	125.9665	44.89	5.4401	23.086	125.5901
0.5	41.93	5.2216	21.2492	110.9548	41.93	5.1637	21.902	113.0954
1	29.63	3.9593	16.2898	64.49621	29.63	3.9593	16.8824	66.84249
1.5	25.5	3.53	14.36	50.6908	25.5	3.53	14.9	52.597
2	24.39	3.4129	13.8189	47.16252	24.39	3.4129	14.3428	48.95054
2.5	23.57	3.327	13.4007	44.58413	23.57	3.327	13.9164	46.29986
3	22.89	3.259	13.055	42.54625	22.89	3.259	13.5628	44.20117
3.5	22.28	3.198	12.75	40.7745	22.28	3.198	13.2456	42.35943
4	21.97	3.1667	12.5947	39.88364	21.97	3.1667	13.0844	41.43437
4.5	21.98	3.1678	12.5998	39.91365	21.98	3.1678	13.0896	41.46523
5	22.1	3.18	12.66	40.2588	22.1	3.18	13.152	41.82336
5.5	22.1	3.18	12.66	40.2588	22.1	3.18	13.152	41.82336
6	22.1	3.18	12.66	40.2588	22.1	3.18	13.152	41.82336
6.5	22.1	3.18	12.66	40.2588	22.1	3.18	13.152	41.82336
7	22.1	3.18	12.66	40.2588	22.1	3.18	13.152	41.82336
7.5	22.1	3.18	12.66	40.2588	22.1	3.18	13.152	41.82336
8	22.1	3.18	12.66	40.2588	22.1	3.18	13.152	41.82336
8.5	22.1	3.18	12.66	40.2588	22.1	3.18	13.152	41.82336
9	22.1	3.18	12.66	40.2588	22.1	3.18	13.152	41.82336
9.5	22.1	3.18	12.66	40.2588	22.1	3.18	13.152	41.82336
10	22.1	3.18	12.66	40.2588	22.1	3.18	13.152	41.82336

If motor speed is constant, the more torque applied to the steering wheel, the more voltage and current increase, which in turn increases power consumption. The voltage and current vs. time characteristics curves of 4.48 Nm torque both follow the 5th and 6th order polynomial equations, respectively, and the current and voltage vs. time characteristics curves of 5.23 Nm torque follow the 5th and 6th order polynomial equations, respectively. The current speed of the motor is now 44.89 RPS, and the set point is less than the current speed, which is 22 RPS. At time = 0 seconds, when the motor speed is at 44.89 RPS, the voltage values at 3.98, 4.23, 4.48, and 5.23 Nm torques are 5.259, 5.289, 5.5857, and 5.4401, and the current values are 19.9582, 21.178, 22.5516, and 23.086 respectively.

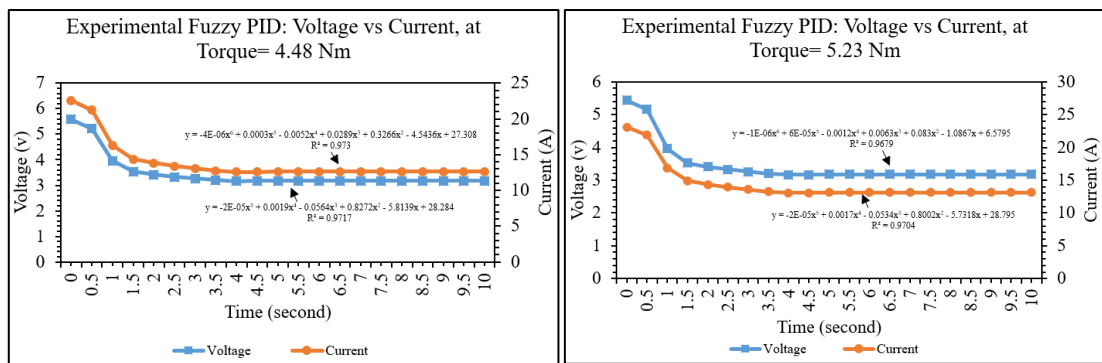


Figure 4.32: Voltage and Current of Experimental Fuzzy PID, at Torque=4.48, 5.23 Nm

So the power consumption also increases with an increase in torque value. The power consumption is maximum at 44.89 RPS, and at different torques, the values are 104.9602, 112.0104, 125.9665, and 125.5901 W. The R-square value indicates that there is a good correlation between voltage, current, and time. The minimum power consumption occurs at 4.5 sec at 22.1 RPS. The experimental fuzzy PID control takes about 4.5 seconds to reach the set point. So, the power developed to assist the driver at the right time is sufficient. The fuzzy PID controller increases power with steering torque. As the steering torque increases, the rotary valve opens more and more, allowing more fluid to pass into the hydraulic chamber. So the hydraulic pressure increases, and motor speed tends to decrease. But the fuzzy PID controller increases the output voltage to keep the motor speed at the set point. So at different torque values, the fuzzy PID controller can reach the motor speed quickly.

4.10 ELECTRIC POWER CONSUMPTION COMPARISON: EXPERIMENTAL PID VS FUZZY-PID AT TORQUE=3.98, 4.23, 4.48 AND 5.23 NM (SET POINT=45 RPS)

The product of voltage and current is the electric power consumption of an energy-saving electro-hydraulic power steering system. We have calculated the power from voltage and current data over time. To calculate the power consumption in watt-hours, we have fed the power signal to the Matlab Simulink integrator block, and the output of the integrator block is the total power in every second. The sampling time we have used in Matlab is 0.5. In the Matlab integrator block, the initial value has been changed to the initial (at 0 second) value. The output of the Integrator block is watt-sec. By dividing the watt-sec by 3600, we have calculated power in watt-hour (Wh). Figures 4.33 and 4.34 show the power consumption comparison of PID and fuzzy PID for a set point of 45 RPS, and Table 4.20 shows the experimental data. The electric power consumption of fuzzy PID is greater than PID at different torques. The graph shows the power consumption in watt-hours for 10 seconds.

Table 4.20: Electric Power Consumption Comparison of Experimental PID vs Fuzzy-PID (Set Point =45 RPS), at Torque=3.98 Nm, 4.23 Nm, 4.48 Nm and 5.23 Nm

Electric power	T=3.98 Nm		T=4.23 Nm		T=4.48 Nm		T=5.23 Nm	
Time (second)	PID (Wh)	Fuzzy PID (Wh)	PID (Wh)	Fuzzy PID (Wh)	PID (Wh)	Fuzzy PID (Wh)	PID (Wh)	Fuzzy PID (Wh)
0	0.009275	0.009466	0.010516	0.010678	0.010929	0.011104	0.011356	0.011535
0.5	0.014051	0.016027	0.015939	0.018105	0.016565	0.019013	0.017211	0.019643
1	0.019448	0.026577	0.022177	0.030044	0.023034	0.031642	0.023927	0.032544
1.5	0.025841	0.039666	0.029572	0.044726	0.030792	0.04713	0.031972	0.048328
2	0.033294	0.053492	0.038032	0.059848	0.039865	0.063608	0.041324	0.064948
2.5	0.041747	0.06778	0.04763	0.075174	0.050213	0.080713	0.051843	0.082082
3	0.051104	0.08217	0.058331	0.090581	0.061651	0.097955	0.063367	0.099325
3.5	0.061353	0.096623	0.070152	0.106039	0.074024	0.115282	0.075906	0.116635
4	0.072391	0.111201	0.082944	0.121596	0.087159	0.132778	0.089353	0.134078
4.5	0.084059	0.12584	0.096399	0.137202	0.100888	0.150355	0.103508	0.151586
5	0.096327	0.140479	0.110399	0.152807	0.115291	0.167933	0.118348	0.169095
5.5	0.109104	0.155118	0.124818	0.168413	0.130368	0.185511	0.133778	0.186603
6	0.122232	0.169757	0.139537	0.184019	0.145914	0.203089	0.149605	0.204111
6.5	0.135541	0.184395	0.154406	0.199624	0.161697	0.220666	0.165637	0.221619
7	0.149012	0.199034	0.169399	0.21523	0.177692	0.238244	0.181855	0.239127
7.5	0.162664	0.213673	0.184503	0.230835	0.193928	0.255822	0.198279	0.256635
8	0.176379	0.228312	0.199617	0.246441	0.21025	0.2734	0.214776	0.274143
8.5	0.190211	0.242951	0.214747	0.262046	0.226732	0.290978	0.231404	0.291651
9	0.204171	0.25759	0.229895	0.277652	0.243392	0.308555	0.24818	0.30916
9.5	0.218199	0.272229	0.245053	0.293257	0.260144	0.326133	0.265032	0.326668
10	0.232318	0.286868	0.260255	0.308863	0.27702	0.343711	0.281985	0.344176

The power consumption of PID at 0 sec for 3.98 Nm, 4.23 Nm, 4.48 Nm, and 5.23 Nm torques is 0.009275, 0.010516, 0.010929, and 0.011356 Wh. And the power

consumption of fuzzy PID at 0 sec for 3.98 Nm, 4.23 Nm, 4.48 Nm, and 5.23 Nm torques is 0.009466, 0.010678, 0.011104, and 0.011535 Wh. As fuzzy PID is faster than PID controllers, its output voltage is always greater to reach the set point quickly. At 10 sec, the power consumption of the PID of 3.98 Nm, 4.23 Nm, 4.48 Nm, and 5.23 Nm torques is 0.232318, 0.260255, 0.27702, and 0.281985 Wh. The power consumption of fuzzy PID at 10 sec for 3.98 Nm, 4.23 Nm, 4.48 Nm, and 5.23 Nm torques is 0.286868, 0.308863, 0.343711, and 0.344176 Wh. In an energy saving power steering system, the motor speed (set point in "RPS") decreases with an increase in vehicle speed (km/h). So, if vehicle speed decreases, then the motor speed set point will be greater than the current motor speed. Then the fuzzy PID will take the motor speed to the set point quickly and consume more electrical energy than the PID. Though in this situation fuzzy PID consumes more power than PID, it can ensure a good steering feel to the driver. On the other hand, lags in providing sufficient power at the right time.

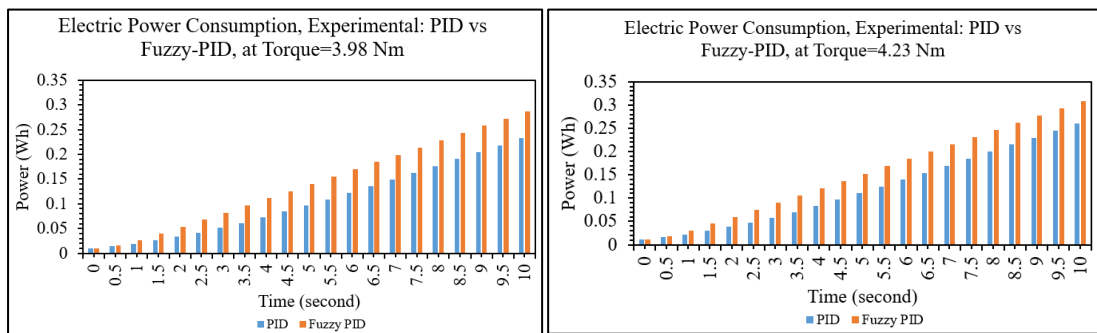


Figure 4.33: Electric Power Consumption Comparison of Experimental PID vs Fuzzy-PID (Set Point =45 RPS), at Torque=3.98, 4.23 Nm

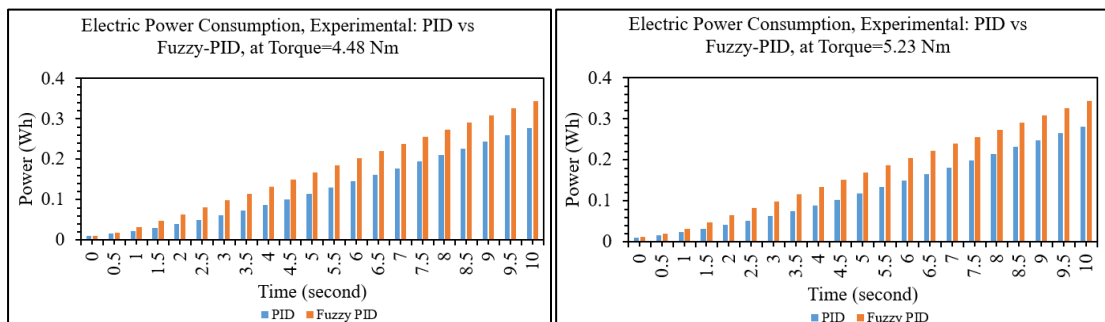


Figure 4.34: Electric Power Consumption Comparison of Experimental PID vs Fuzzy-PID (Set Point =45 RPS), at Torque=4.48, 5.23 Nm

4.11 ELECTRIC POWER CONSUMPTION COMPARISON: EXPERIMENTAL PID VS FUZZY-PID AT TORQUE=3.98, 4.23, 4.48 AND 5.23 NM (SET POINT=22 RPS)

The electric power consumption is calculated as shown in Section 4.10 for set point 22 RPS. In the Matlab integrator block, the initial value has been changed to the initial (time = 0 sec) value. Figures 4.35 and 4.36 show the power consumption comparison of PID and fuzzy PID for set point = 22 RPS, and Table 4.21 shows the experimental data. The graph has been shown in the column chart as a 0.5-second step to easily see the power consumption (Wh) difference. The electric power consumption of fuzzy PID is less than that of PID at different torques. The graph shows the power consumption in watt-hours for 10 seconds. The power consumption of PID at 0 sec for 3.98 Nm, 4.23 Nm, 4.48 Nm, and 5.23 Nm torques is 0.034603, 0.028868, 0.030885, and 0.03458 Wh. And the power consumption of fuzzy PID at 0 sec for 3.98 Nm, 4.23 Nm, 4.48 Nm, and 5.23 Nm torques is 0.034991, 0.02915, 0.031114, and 0.034886 Wh.

Table 4.21: Electric Power Consumption Comparison of Experimental PID vs Fuzzy-PID (Set Point =22 RPS), at Torque=3.98 Nm, 4.23 Nm, 4.48 Nm and 5.23 Nm

Electric power	T=3.98 Nm		T=4.23 Nm		T=4.48 Nm		T=5.23 Nm	
Time (second)	PID (Wh)	Fuzzy PID (Wh)	PID (Wh)	Fuzzy PID (Wh)	PID (Wh)	Fuzzy PID (Wh)	PID (Wh)	Fuzzy PID (Wh)
0	0.028868	0.02915	0.030885	0.031114	0.034603	0.034991	0.03458	0.034886
0.5	0.043208	0.042951	0.046253	0.046209	0.051778	0.051444	0.05177	0.051462
1	0.056754	0.053149	0.061608	0.057667	0.067887	0.063628	0.068068	0.063957
1.5	0.068804	0.059739	0.075828	0.065212	0.082144	0.071627	0.082668	0.072252
2	0.079351	0.065361	0.08797	0.071775	0.094805	0.078422	0.095546	0.079304
2.5	0.088677	0.070674	0.098631	0.077919	0.106201	0.084793	0.107036	0.085918
3	0.097173	0.07576	0.108282	0.083746	0.116601	0.090844	0.117603	0.092203
3.5	0.105091	0.080659	0.117204	0.089314	0.126254	0.09663	0.127525	0.098214
4	0.112469	0.085425	0.125507	0.094702	0.135222	0.102232	0.136803	0.104033
4.5	0.119325	0.090147	0.133348	0.100031	0.14354	0.107773	0.145426	0.10979
5	0.125743	0.094889	0.140816	0.105386	0.151321	0.113341	0.153495	0.115574
5.5	0.131818	0.099651	0.147914	0.110763	0.158684	0.118932	0.161134	0.121383
6	0.137635	0.104412	0.154731	0.116141	0.165738	0.124524	0.168453	0.127192
6.5	0.143238	0.109173	0.161282	0.121519	0.172515	0.130115	0.175486	0.133
7	0.148656	0.113934	0.167575	0.126896	0.179036	0.135707	0.182255	0.138809
7.5	0.153942	0.118696	0.173677	0.132274	0.18537	0.141298	0.18883	0.144618
8	0.159104	0.123457	0.179607	0.137652	0.191526	0.14689	0.195224	0.150427
8.5	0.164157	0.128218	0.185389	0.14303	0.19753	0.152481	0.201461	0.156236
9	0.169169	0.132979	0.191114	0.148407	0.203476	0.158073	0.207638	0.162044
9.5	0.174126	0.13774	0.196762	0.153785	0.209343	0.163664	0.213733	0.167853
10	0.179014	0.142502	0.202316	0.159163	0.215115	0.169256	0.219729	0.173662

As fuzzy PID is faster than a PID controller, its output voltage is always lower to reach the set point quickly as the set point is less than the current motor speed. At 10 sec, the power consumption of the PID of 3.98 Nm, 4.23 Nm, 4.48 Nm, and 5.23 Nm torques

is 0.179014, 0.202316, 0.215115, and 0.219729 Wh. The power consumption of fuzzy PID at 10 sec for 3.98 Nm, 4.23 Nm, 4.48 Nm, and 5.23 Nm torques is 0.142502, 0.159163, 0.169256, and 0.173662 Wh. As in an energy-saving power steering system, the motor speed (set point in "RPS") is inversely proportional to vehicle speed (km/h). So, if vehicle speed increases, the motor speed set point will be less than the current motor speed.

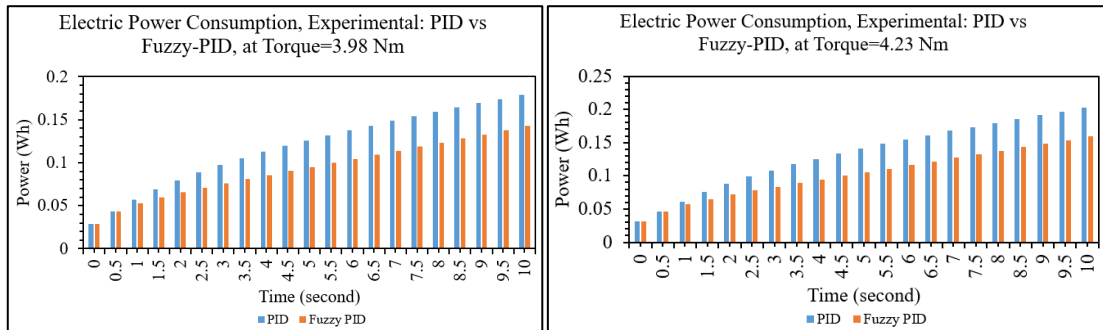


Figure 4.35: Electric Power Consumption Comparison of Experimental PID vs Fuzzy-PID (Set Point =22 RPS), at Torque=3.98, 4.23 Nm

The fuzzy PID will take the motor speed to the set point quickly, so it will consume less electrical energy than the PID. The fuzzy PID not only consumes less energy in this situation but can also provide a good steering feel to the driver.

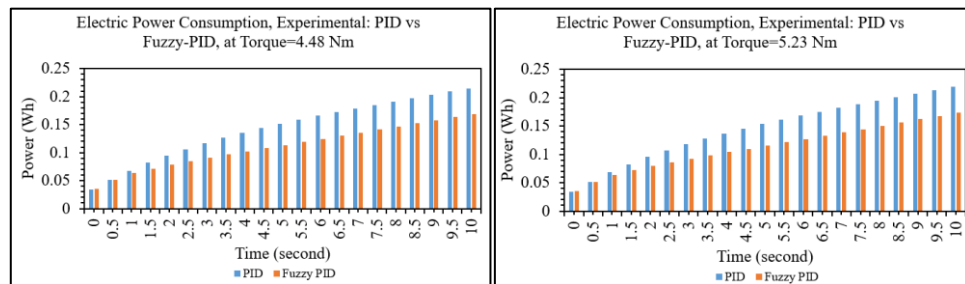


Figure 4.36: Electric Power Consumption Comparison of Experimental PID vs Fuzzy-PID (Set Point =22 RPS), at Torque=4.48, 5.23 Nm

4.12 HYDRAULIC POWER CONSUMPTION OF EXPERIMENTAL PID (SET POINT= 45 RPS), at TORQUE=3.98 NM

The hydraulic power is calculated in Section 3.2.2. The pump discharge rate is proportional to motor RPS and is calculated in Section 3.2.4. Table 4.22, Figure 37 and 4.38 show the experimental data and graph of motor speed, pressure, pump discharge rate, and hydraulic power with time. The motor's current speed is 21.79 RPS, and the power consumption is 0.816105 W.

Table 4.22: Experimental PID: Pressure, Pump Discharge Rate and Power with Time, Set Point=45 RPS, at Torque =3.98 Nm

Time (second)	Motor Speed (RPS)	Hydraulic Pressure (bar)	Pump Discharge Rate (lpm)	Hydraulic Power (watt)
0	21.79	1	0.489663	0.816105
0.5	22.64	1	0.508764	0.84794
1	25.71	1.142	0.577753	1.099656
1.5	28.45	1.69	0.639326	1.800768
2	31.42	2.284	0.706067	2.687763
2.5	33.94	2.788	0.762697	3.543997
3	35.96	3.192	0.80809	4.299038
3.5	37.59	3.518	0.844719	4.95287
4	38.83	3.766	0.872584	5.476921
4.5	39.78	3.956	0.893933	5.893996
5	41.04	4.416	0.922247	6.787739
5.5	41.82	4.728	0.939775	7.405429
6	42.44	4.976	0.953708	7.909417
6.5	42.52	5.008	0.955506	7.975287
7	43.06	5.224	0.96764	8.424923
7.5	43.22	5.288	0.971236	8.559826
8	43.31	5.324	0.973258	8.636046
8.5	43.68	5.472	0.981573	8.951946
9	43.82	5.528	0.984719	9.072545
9.5	43.94	5.576	0.987416	9.176384
10	44.17	5.668	0.992584	9.376613

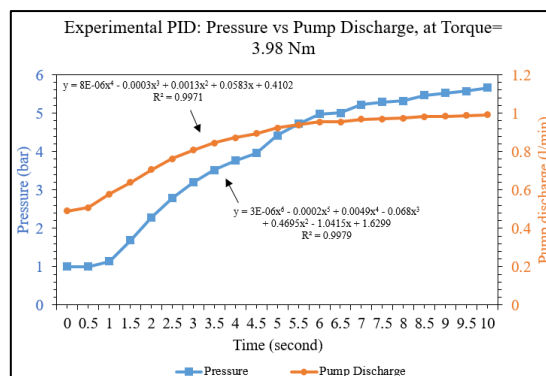


Figure 4.37: Hydraulic Pressure and Pump Discharge Rate of Experimental PID, at Set Point =45 RPS

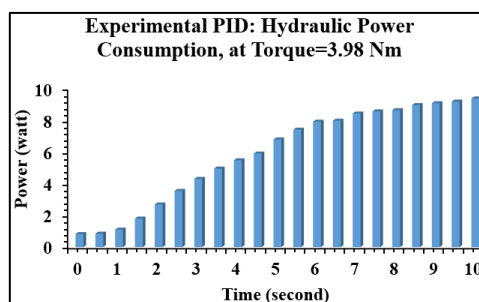


Figure 4.38: Hydraulic Power Consumption of Experimental PID, (Set Point=45 RPS)

After changing the motor set point to 45 RPS, the PID controller increases the motor RPS. So the pump discharge rate increases with time, and the hydraulic power consumption increases. As the motor RPS reaches the set point, the pump discharge rate is constant, and the hydraulic pressure is also constant. So, the hydraulic power consumption is constant with time. The hydraulic pressure follows the 6th order polynomial equation, and the pump discharge rate follows the 4th-order polynomial equation. Both R-squares indicate a good correlation.

4.13 HYDRAULIC POWER CONSUMPTION OF EXPERIMENTAL FUZZY PID (SET POINT= 45 RPS), at TORQUE=3.98 NM

Table 4.23, Figure 4.39, and Figure 4.40 show the experimental data and graph of motor speed, pressure, pump discharge rate, and hydraulic power with time. The motor's current speed is 22 RPS, and the power consumption is 0.82397 W. After changing the motor set point to 45 RPS, the PID controller increases the motor RPS. So the pump discharge rate increases with time, and the hydraulic power consumption increases. As the motor RPS reaches the set point, the pump discharge rate is constant, and so is the hydraulic pressure. So, the hydraulic power consumption is constant with time. The hydraulic pressure and pump discharge rate follow the 5th-order polynomial equation. Both R-squares indicate a good correlation.

Table 4.23: Experimental Fuzzy-PID: Pressure, Pump Discharge Rate and Power with Time, Set Point=45 RPS, at Torque =3.98 Nm

Time (second)	Motor Speed (RPS)	Hydraulic Pressure (bar)	Pump Discharge Rate (lpm)	Hydraulic Power (watt)
0	22	1	0.494382	0.82397
0.5	32.52	2.504	0.730787	3.049816
1	41.3	4.52	0.92809	6.99161
1.5	42.78	5.112	0.961348	8.190688
2	44.18	5.672	0.992809	9.385354
2.5	44.55	5.82	1.001124	9.710899
3	44.55	5.82	1.001124	9.710899
3.5	44.78	5.912	1.006292	9.915332
4	45.07	6	1.011236	10.11236
4.5	45.07	6	1.011236	10.11236
5	45.07	6	1.011236	10.11236
5.5	45.07	6	1.011236	10.11236
6	45.07	6	1.011236	10.11236
6.5	45.07	6	1.011236	10.11236
7	45.07	6	1.011236	10.11236
7.5	45.07	6	1.011236	10.11236
8	45.07	6	1.011236	10.11236
8.5	45.07	6	1.011236	10.11236
9	45.07	6	1.011236	10.11236
9.5	45.07	6	1.011236	10.11236
10	45.07	6	1.011236	10.11236

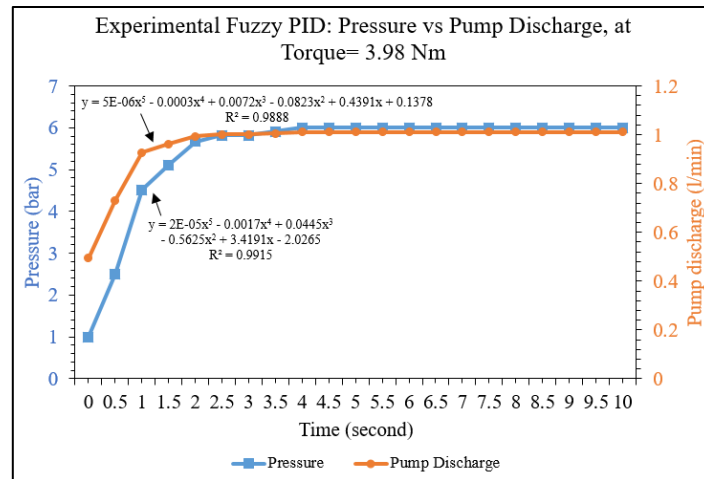


Figure 4.39: Hydraulic Pressure and Pump Discharge Rate of Experimental Fuzzy-PID, at Set Point =45 RPS, at Torque= 3.98 Nm

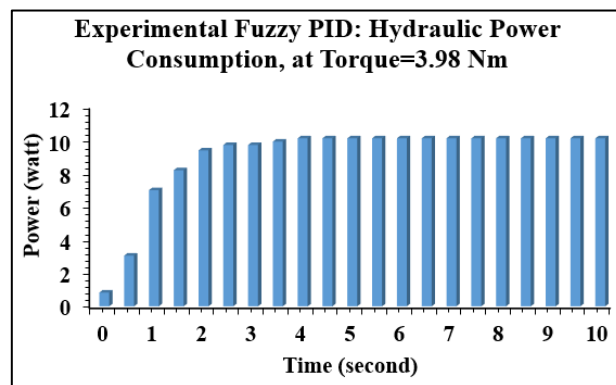


Figure 4.40: Hydraulic Power Consumption of Experimental Fuzzy PID, (Set Point=45 RPS)

4.14 HYDRAULIC POWER CONSUMPTION COMPARISON: EXPERIMENTAL PID VS FUZZY-PID (SET POINT=45 RPS), at TORQUE= 3.98 NM

Matlab's integrator block is used to calculate the hydraulic power consumption in Watt-hours. The sampling time is set at 0.5. In an energy saving electro-hydraulic power steering system, the electrical energy is converted into hydraulic power. The hydraulic power is calculated from the hydraulic pressure and pump discharge rate. Table 4.24 and Figure 4.41 show the hydraulic power consumption comparison of experimental PID vs. Fuzzy-PID at Torque = 3.98 Nm. The power consumption of fuzzy PID is always greater than that of PID as the motor speed set point is greater than the current motor speed and fuzzy PID response is faster than PID.

Table 4.24: Hydraulic power consumption in Watt-hour: PID vs Fuzzy PID (Set point = 45 RPS), at Torque=3.98 Nm

Time (second)	PID (Wh)	Fuzzy PID (Wh)
0	0.000227	0.000229
0.5	0.000342	0.000498
1	0.000478	0.001195
1.5	0.000679	0.00225
2	0.000991	0.00347
2.5	0.001423	0.004796
3	0.001968	0.006145
3.5	0.002611	0.007508
4	0.003335	0.008899
4.5	0.004124	0.010303
5	0.005005	0.011708
5.5	0.005991	0.013112
6	0.007054	0.014517
6.5	0.008157	0.015921
7	0.009296	0.017326
7.5	0.010476	0.01873
8	0.01167	0.020135
8.5	0.012891	0.021539
9	0.014143	0.022944
9.5	0.01541	0.024348
10	0.016699	0.025753

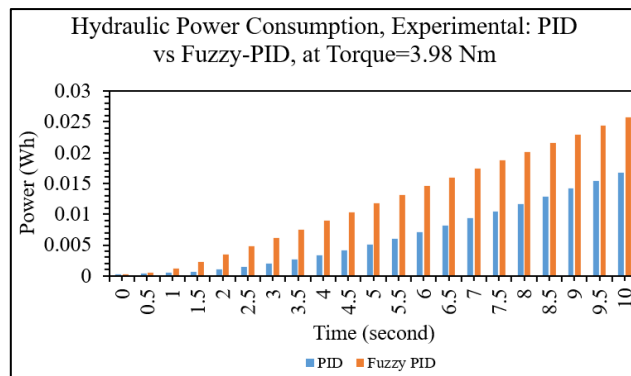


Figure 4.41: Hydraulic Power Consumption Comparison of Experimental PID vs Fuzzy-PID (Set Point =45 RPS), at Torque = 3.98 Nm

At time = 0 sec, the power consumed for PID and fuzzy PID is 0.000227 and 0.000229 Wh, respectively. The power consumption continuously increases unless it reaches the set point. At the set point, at time = 10 sec, the hydraulic power consumed for PID and fuzzy PID is 0.016699 and 0.025753 Wh, respectively.

4.15 Hydraulic Power consumption of Experimental PID (Set point= 22 RPS), at Torque=3.98 Nm

Table 4.25, Figure 4.42, and Figure 4.43 show the experimental data and graph of motor speed, pressure, pump discharge rate, and hydraulic power with time. The motor current speed is 44.63 RPS, and the hydraulic power consumption is 9.781826 W. After

changing the motor set point to 22 RPS, the PID controller decreases the output voltage. So the motor RPS decreases, the pump discharge rate decreases with time, and the hydraulic power consumption decreases. As the motor RPS reaches the set point, the pump discharge rate is constant, and so is the hydraulic pressure. So, the hydraulic power consumption is also constant with time. The hydraulic pressure follows the 6th order polynomial equation, and the pump discharge rate follows the 5th-order polynomial equation. Both R-squares indicate a good correlation between pressure, pump discharge rate, and time. The hydraulic power consumption at time = 0 sec is 9.781826 W, and at set point, at time = 10 sec, it is 0.842697 W.

Table 4.25: Experimental PID: Pressure, Pump Discharge Rate and Power with Time, Set Point=22 RPS, at Torque =3.98 Nm

Time (second)	Motor Speed (RPS)	Hydraulic Pressure (bar)	Pump Discharge Rate (lpm)	Hydraulic Power (watt)
0	44.63	5.852	1.002921	9.781826
0.5	44.29	5.716	0.995281	9.481709
1	41.57	4.628	0.934157	7.205467
1.5	38.6	3.72	0.867416	5.377978
2	36.02	3.204	0.809438	4.3224
2.5	33.69	2.738	0.757079	3.454802
3	31.92	2.384	0.717303	2.850085
3.5	30.41	2.082	0.683371	2.371297
4	28.94	1.788	0.650337	1.938004
4.5	27.68	1.536	0.622022	1.592378
5	26.65	1.33	0.598876	1.327509
5.5	25.84	1.168	0.580674	1.130379
6	25.22	1.044	0.566742	0.98613
6.5	24.57	1	0.552135	0.920225
7	24.08	1	0.541124	0.901873
7.5	23.72	1	0.533034	0.88839
8	23.25	1	0.522472	0.870787
8.5	22.99	1	0.516629	0.861049
9	22.97	1	0.51618	0.8603
9.5	22.6	1	0.507865	0.846442
10	22.5	1	0.505618	0.842697

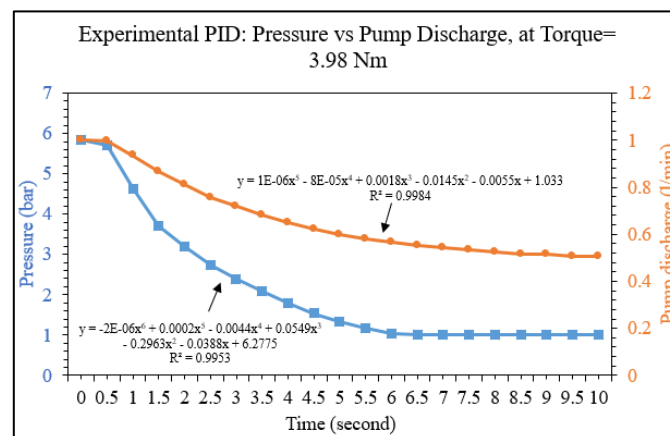


Figure 4.42: Hydraulic Pressure and Pump Discharge Rate of Experimental PID, at Set Point =22 RPS

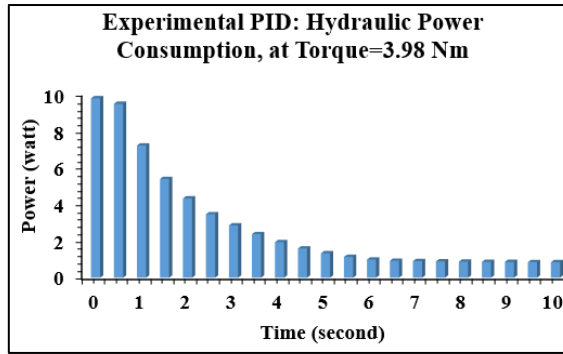


Figure 4.43: Hydraulic Power Consumption of Experimental PID, (Set Point=22 RPS)

4.16 HYDRAULIC POWER CONSUMPTION OF EXPERIMENTAL FUZZY PID (SET POINT= 22 RPS), at TORQUE=3.98 NM

Table 4.26, Figure 4.44, and Figure 4.45 show the experimental graph and data of motor speed, pressure, pump discharge rate, and hydraulic power with time. The motor's current speed is 44.89 RPS, and the power consumption is 10.01366 W. The motor set point has been changed to 22 RPS. So, the PID controller decreases the output voltage, and the dc motor speed decreases. The pump discharge rate decreases with time, and the hydraulic power consumption also decreases. When motor speed reaches the set point speed, the pump discharge rate is constant, and so the hydraulic pressure is constant.

Table 4.26: Experimental Fuzzy-PID: Pressure, Pump Discharge Rate and Power with Time, Set Point=22 RPS, at Torque =3.98 Nm

Time (second)	Motor Speed (RPS)	Hydraulic Pressure (bar)	Pump Discharge Rate (lpm)	Hydraulic Power (watt)
0	44.89	5.956	1.008764	10.01366
0.5	41.93	4.772	0.942247	7.494006
1	29.63	1.926	0.665843	2.137355
1.5	25.5	1.1	0.573034	1.050562
2	24.39	1	0.54809	0.913483
2.5	23.57	1	0.529663	0.882772
3	22.89	1	0.514382	0.857303
3.5	22.28	1	0.500674	0.834457
4	21.97	1	0.493708	0.822846
4.5	21.98	1	0.493933	0.823221
5	22.1	1	0.496629	0.827715
5.5	22.1	1	0.496629	0.827715
6	22.1	1	0.496629	0.827715
6.5	22.1	1	0.496629	0.827715
7	22.1	1	0.496629	0.827715
7.5	22.1	1	0.496629	0.827715
8	22.1	1	0.496629	0.827715
8.5	22.1	1	0.496629	0.827715
9	22.1	1	0.496629	0.827715
9.5	22.1	1	0.496629	0.827715
10	22.1	1	0.496629	0.827715

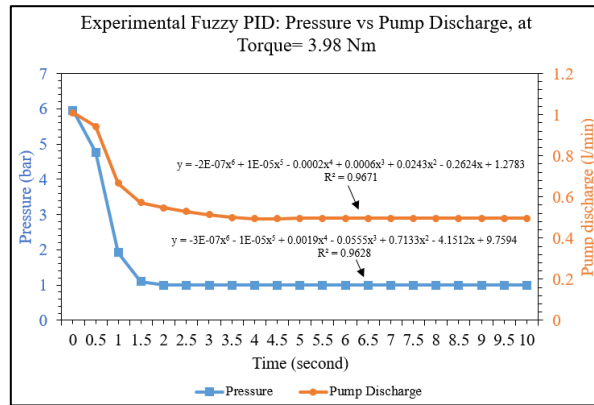


Figure 4.44: Hydraulic Pressure and Pump Discharge Rate of Experimental Fuzzy-PID, at Set Point =22 RPS, at Torque= 3.98 Nm

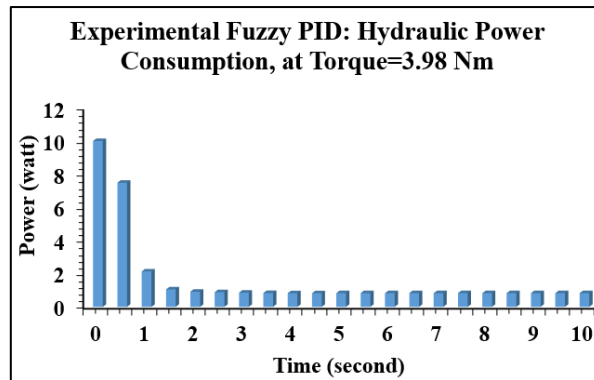


Figure 4.45: Hydraulic Power Consumption of Experimental Fuzzy PID, (Set Point=22 RPS)

So, the hydraulic power consumption is also constant with time. The hydraulic pressure follows the 6th-order polynomial equation, and the pump discharge rate also follows the 6th-order polynomial equation. Both R-squares indicate a good correlation between pressure, pump discharge rate, and time. The hydraulic power consumption at time = 0 sec is 10.01366 W, and at set point, at time = 10 sec, it is 0.827715 W.

4.17 HYDRAULIC POWER CONSUMPTION COMPARISON: EXPERIMENTAL PID VS FUZZY-PID (SET POINT=22 RPS), at TORQUE= 3.98 NM

The power consumption of the energy saving electrohydraulic power steering system depends on vehicle speed (km/h). If the vehicle runs at high speed, then the power consumption (electric and hydraulic) will be low. And if the vehicle runs at low speed, then the electric and hydraulic power consumption will be high. The power consumption also varies according to different control methods. Table 4.27 and Figure

4.46 show the hydraulic power consumption comparison of experimental PID vs. Fuzzy-PID at Torque = 3.98 Nm for set point 22 RPS. The power consumption of fuzzy PID is always less than PID as the motor speed set point is less than the current motor speed. At time = 0 sec, the power consumption for PID and fuzzy-PID is 0.002717 and 0.002782 Wh, respectively. The power consumption continuously decreases unless it reaches the set point of 22 RPS. At the set point, at time = 10 sec, the total hydraulic power consumed for PID and fuzzy PID is 0.010148 and 0.006881 Wh, respectively. Fuzzy PID consumes less power than PID.

Table 4.27: Hydraulic power consumption in Watt-hour: PID vs Fuzzy PID (Set point=22 RPS), at Torque=3.98 Nm

Time (second)	PID (Wh)	Fuzzy PID (Wh)
0	0.002717	0.002782
0.5	0.004055	0.003997
1	0.005214	0.004666
1.5	0.006088	0.004888
2	0.006761	0.005024
2.5	0.007301	0.005149
3	0.007739	0.00527
3.5	0.008102	0.005387
4	0.008401	0.005502
4.5	0.008646	0.005616
5	0.008849	0.005731
5.5	0.00902	0.005846
6	0.009167	0.005961
6.5	0.009299	0.006076
7	0.009426	0.006191
7.5	0.00955	0.006306
8	0.009672	0.006421
8.5	0.009792	0.006536
9	0.009912	0.006651
9.5	0.01003	0.006766
10	0.010148	0.006881

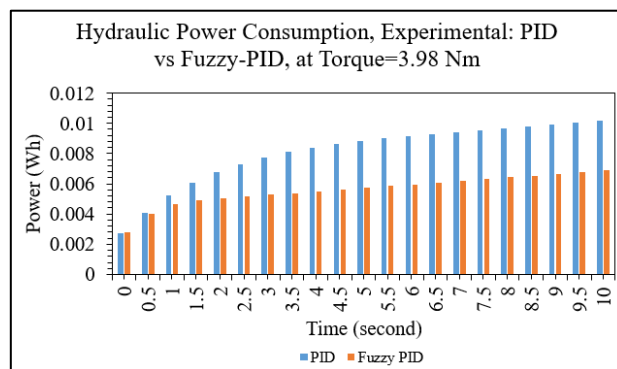


Figure 4.46: Hydraulic Power Consumption Comparison of Experimental PID vs Fuzzy-PID (Set Point =22 RPS), at Torque = 3.98 Nm

4.18 HYDRAULIC POWER CONSUMPTION OF EXPERIMENTAL PID, AT TORQUE= 4.23, 4.48 AND 5.23 NM (SET POINT=45 RPS)

The more torque applied to the steering wheel, the more fluid can pass through the rotary valve to the hydraulic piston chamber. At a fixed motor speed, the pump discharge rate is proportional to the motor speed. According to the rotary valve opening area, the flow through the rotary valve to the piston chamber can be regulated. So, the steering torque applied to the steering wheel regulates the piston chamber flow.

Table 4.28: Experimental PID: Pressure, Pump Discharge Rate and Power with Time at Torque =4.23 Nm, 4.48 Nm and 5.23 Nm (Set Point=45 RPS)

Set Point= 45 RPS		Torque=4.23 Nm			Torque=4.48 Nm			Torque=5.23 Nm		
Time (second)	Motor Speed (RPS)	Hydraulic Pressure (bar)	Pump Discharge Rate (lpm)	Hydraulic Power (watt)	Hydraulic Pressure (bar)	Pump Discharge Rate (lpm)	Hydraulic Power (watt)	Hydraulic Pressure (bar)	Pump Discharge Rate (lpm)	Hydraulic Power (watt)
0	21.79	2.716	0.489663	2.216541	2.716	0.489663	2.216541	5.432	0.489663	4.433082
0.5	22.64	3.056	0.508764	2.591305	3.056	0.508764	2.591305	6.112	0.508764	5.18261
1	25.71	4.284	0.577753	4.125155	4.284	0.577753	4.125155	8.284	0.577753	7.97684
1.5	28.45	5.38	0.639326	5.732622	5.38	0.639326	5.732622	9.38	0.639326	9.994794
2	31.42	6.568	0.706067	7.729085	6.568	0.706067	7.729085	10.568	0.706067	12.4362
2.5	33.94	7.576	0.762697	9.630316	7.576	0.762697	9.630316	11.576	0.762697	14.71496
3	35.96	8.384	0.808091	11.29171	8.384	0.808091	11.29171	12.192	0.808091	16.42039
3.5	37.59	9.036	0.844719	12.72147	9.036	0.844719	12.72147	12.518	0.844719	17.62366
4	38.83	9.532	0.872584	13.86246	9.532	0.872584	13.86246	12.766	0.872584	18.56568
4.5	39.78	9.912	0.893933	14.76777	9.912	0.893933	14.76777	12.956	0.893933	19.30298
5	41.04	10.208	0.922247	15.6905	10.416	0.922247	16.01021	13.416	0.922247	20.62145
5.5	41.82	10.364	0.939775	16.2330	10.728	0.939775	16.80318	13.728	0.939775	21.50206
6	42.44	10.488	0.953708	16.67081	10.976	0.953708	17.4465	13.976	0.953708	22.21504
6.5	42.52	10.504	0.955506	16.72772	11.008	0.955506	17.53034	14.008	0.955506	22.30787
7	43.06	10.612	0.967643	17.11433	11.224	0.967643	18.10133	14.224	0.967643	22.93953
7.5	43.22	10.644	0.971236	17.22973	11.288	0.971236	18.27219	14.288	0.971236	23.12837
8	43.31	10.662	0.973258	17.2948	11.324	0.973258	18.36863	14.324	0.973258	23.23492
8.5	43.68	10.736	0.981573	17.56361	11.472	0.981573	18.76768	14.472	0.981573	23.67554
9	43.82	10.764	0.984719	17.6658	11.528	0.984719	18.91974	14.528	0.984719	23.84333
9.5	43.94	10.788	0.987416	17.75373	11.576	0.987416	19.05054	14.576	0.987416	23.98762
10	44.17	10.834	0.992584	17.92276	11.668	0.992584	19.30246	14.668	0.992584	24.26538

As the derivative of pressure depends on pump discharge rate and steering torque, at different torques, the hydraulic pressure developed is different and the hydraulic power consumption is also different. Figure 4.47 and 4.48, show the hydraulic pressure and pump discharge rate profiles vs. time of experimental PID at Torques of 4.23 Nm, 4.48 Nm, and 5.23 Nm. Table 4.28 shows the experimental data for hydraulic pressure, pump discharge rate, and power consumption in watts. The hydraulic pressure increases with motor speed as well as pump discharge rate. So, the power consumption increases. The pressure curve follows the 6th order polynomial equation, and the pump discharge rate curve follows the 4th order polynomial equation at Torque=4.23 Nm.

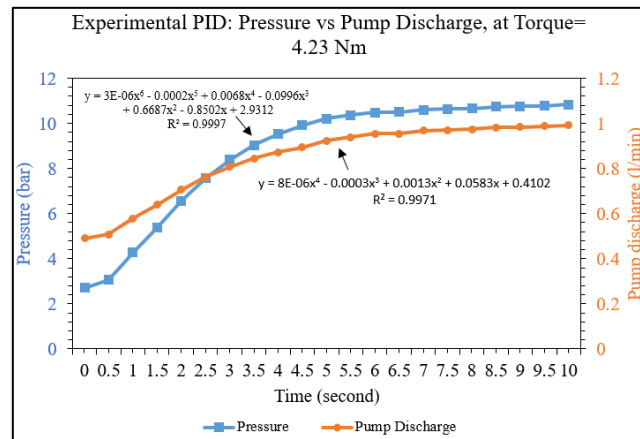


Figure 4.47: Hydraulic Pressure and Pump Discharge Rate of Experimental PID, at Set Point =45 RPS, at Torque=4.23 Nm

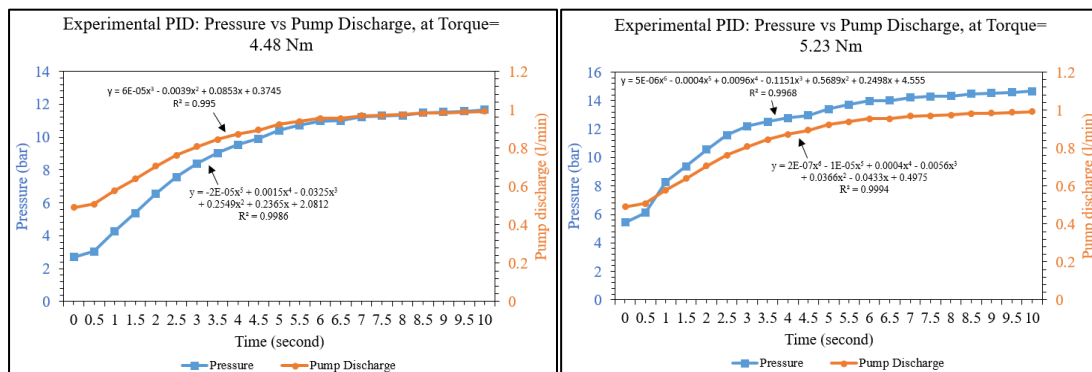


Figure 4.48: Hydraulic Pressure and Pump Discharge Rate of Experimental PID, at Set Point =45 RPS, at Torque=4.48, 5.23 Nm

As the PID controller's output voltage increases, so does the motor speed. The hydraulic pressure curve follows the pump discharge rate curve with time. At 4.48 Nm torque, the hydraulic pressure curve follows the 5th-order polynomial equation, and the pump discharge rate follows the 3rd-order polynomial equation. The R-square values shown in the graph indicate that there is a good correlation between hydraulic pressure and

pump discharge rate vs. time. The motor speed vs. time curve of the experimental PID for different torques is the same as shown in Figure 4.13 for set point 45 RPS. The current speed of the motor is now 21.79 RPS, and the set point is greater than the current speed, which is 45 RPS. At time = 0 second, when the motor speed is at 21.79 RPS, the hydraulic pressure values at 4.23, 4.48, and 5.23 Nm torques are 2.716, 2.716, and 5.432 bar, respectively, and the pump discharge rate is 0.489663 lpm. So the power consumption also increases with an increase in torque value. The power consumption increases with torque values, and at torques of 4.23, 4.48, and 5.23 Nm at a time of 0 sec, the values are 2.216541 W, 2.216541 W, and 4.433082 W. The hydraulic pressure vs. time and pump discharge rate vs. time characteristics curve at 5.23 Nm torque follows the 6th-order polynomial equation.

4.19 HYDRAULIC POWER CONSUMPTION OF EXPERIMENTAL FUZZY PID, AT TORQUE= 4.23, 4.48 AND 5.23 NM (SET POINT=45 RPS)

Figure 4.49 and 4.50 show the hydraulic pressure and pump discharge rate profiles vs. time of experimental fuzzy PID at Torque= 4.23 Nm, 4.48 Nm, and 5.23 Nm of set point =45 RPS. Table 4.29 shows the experimental data for hydraulic pressure, pump discharge rate, and power consumption in watts. The hydraulic pressure increases with motor speed as well as pump discharge rate. So, the power consumption increases. The pressure curve follows the 6th-order polynomial equation, and the pump discharge rate curve also follows the 6th-order polynomial equation at Torque=4.23 Nm. As the fuzzy PID controller's output voltage increases, so does the motor speed. The hydraulic pressure curve follows the pump discharge rate curve with time. At 4.48 Nm torque, the hydraulic pressure curve follows the 6th order polynomial equation, and the pump discharge rate also follows the 6th-order polynomial equation. The R-square values shown in the graph indicate that there is a good correlation between hydraulic pressure and pump discharge rate vs. time. The motor speed vs. time curve of the experimental fuzzy PID for different torques is the same as shown in Figure 4.13 for set point 45 RPS. The current speed of the motor is now 22 RPS, and the set point is greater than the current speed, which is 45 RPS. At time = 0 seconds, when the motor speed is at 22 RPS, the hydraulic pressure values at 4.23, 4.48, and 5.23 Nm torques are 2.8, 2.8, and 5.6 bar, respectively, and the pump discharge rate is 0.494382 lpm.

Table 4.29: Experimental Fuzzy PID: Pressure, Pump Discharge Rate and Power with Time at Torque =4.23 Nm, 4.48 Nm and 5.23 Nm (Set Point=45 RPS)

Set Point= 45 RPS		Torque= 4.23 Nm			Torque= 4.48 Nm			Torque= 5.23 Nm		
Time (second)	Motor Speed (RPS)	Hydraulic Pressure (bar)	Pump Discharge Rate (lpm)	Hydraulic Power (watt)	Hydraulic Pressure (bar)	Pump Discharge Rate (lpm)	Hydraulic Power (watt)	Hydraulic Pressure (bar)	Pump Discharge Rate (lpm)	Hydraulic Power (watt)
0	22	2.8	0.494382	2.307116	2.8	0.494382	2.307116	5.6	0.494382	4.614232
0.5	32.52	7.008	0.730787	8.535587	7.008	0.730787	8.535587	11.008	0.730787	13.4075
1	41.3	10.26	0.92809	15.87034	10.52	0.92809	16.27251	13.52	0.92809	20.91296
1.5	42.78	10.556	0.961348	16.91332	11.112	0.961348	17.80417	14.112	0.961348	22.61091
2	44.18	10.836	0.992809	17.93013	11.672	0.992809	19.31344	14.672	0.992809	24.27749
2.5	44.55	10.91	1.001124	18.20376	11.82	1.001124	19.72213	14.82	1.001124	24.72775
3	44.55	10.91	1.001124	18.20376	11.82	1.001124	19.72213	14.82	1.001124	24.72775
3.5	44.78	10.956	1.006292	18.37489	11.912	1.006292	19.97825	14.912	1.006292	25.00971
4	45.07	11	1.011236	18.53933	12	1.011236	20.22472	15	1.011236	25.2809
4.5	45.07	11	1.011236	18.53933	12	1.011236	20.22472	15	1.011236	25.2809
5	45.07	11	1.011236	18.53933	12	1.011236	20.22472	15	1.011236	25.2809
5.5	45.07	11	1.011236	18.53933	12	1.011236	20.22472	15	1.011236	25.2809
6	45.07	11	1.011236	18.53933	12	1.011236	20.22472	15	1.011236	25.2809
6.5	45.07	11	1.011236	18.53933	12	1.011236	20.22472	15	1.011236	25.2809
7	45.07	11	1.011236	18.53933	12	1.011236	20.22472	15	1.011236	25.2809
7.5	45.07	11	1.011236	18.53933	12	1.011236	20.22472	15	1.011236	25.2809
8	45.07	11	1.011236	18.53933	12	1.011236	20.22472	15	1.011236	25.2809
8.5	45.07	11	1.011236	18.53933	12	1.011236	20.22472	15	1.011236	25.2809
9	45.07	11	1.011236	18.53933	12	1.011236	20.22472	15	1.011236	25.2809
9.5	45.07	11	1.011236	18.53933	12	1.011236	20.22472	15	1.011236	25.2809
10	45.07	11	1.011236	18.53933	12	1.011236	20.22472	15	1.011236	25.2809

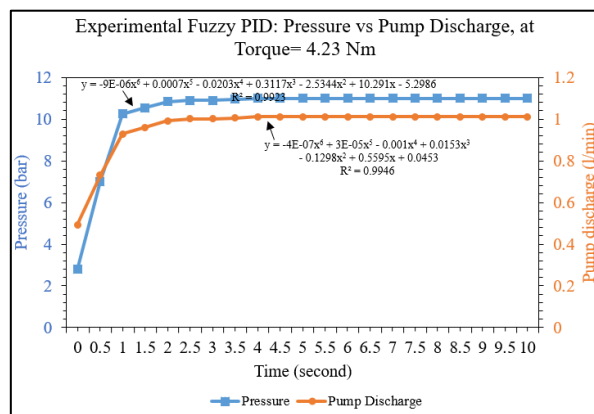


Figure 4.49: Hydraulic Pressure and Pump Discharge Rate of Experimental Fuzzy-PID, at Set Point =45 RPS, at Torque=4.23 Nm

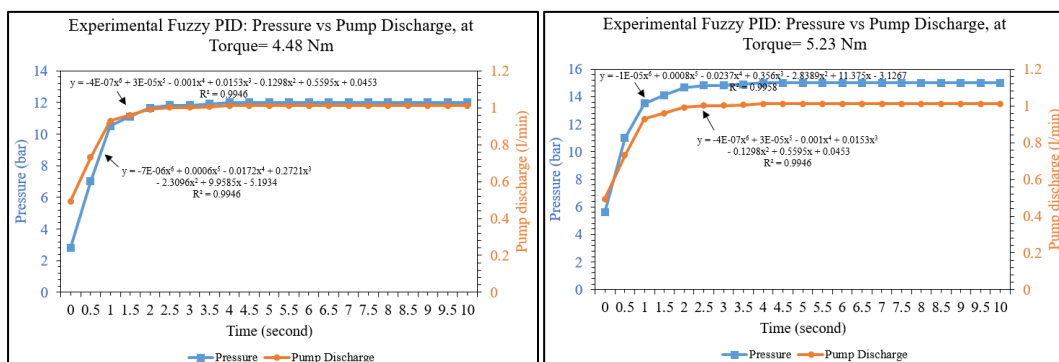


Figure 4.50: Hydraulic Pressure and Pump Discharge Rate of Experimental Fuzzy-PID, at Set Point =45 RPS, at Torque=4.48, 5.23 Nm

So, the power consumption also increases with an increase in torque value. The power consumption increases with torque values, and at torques of 4.23, 4.48, and 5.23 Nm at a time of 0 sec, the values are 2.307116 W, 2.307116 W, and 4.614232 W. The hydraulic pressure vs. time and pump discharge rate vs. time characteristics curve at 5.23 Nm torque follows the 6th-order polynomial equation.

4.20 HYDRAULIC POWER CONSUMPTION OF EXPERIMENTAL PID, AT TORQUE= 4.23, 4.48 AND 5.23 NM (SET POINT=22 RPS)

The pressure developed depends on the pump discharge rate. If the pump discharge rate has been reduced, then the pressure also falls. Figures 4.51 and 4.52 show the hydraulic pressure and pump discharge rate profiles vs. time of experimental PID at Torque= 4.23 Nm, 4.48 Nm, and 5.23 Nm for set point = 22 RPS. Table 4.30 shows the experimental data for hydraulic pressure, pump discharge rate, and power consumption in watts. The hydraulic pressure decreases with a decrease in motor speed as well as pump discharge rate. So, the power consumption decreases. The pressure curve follows the 6th-order polynomial equation, and the pump discharge rate curve also follows the 6th order polynomial equation at Torque = 4.23 Nm. As the PID controller's output voltage decreases, so does the motor speed. The hydraulic pressure curve follows the pump discharge rate curve with time.

Table 4.30: Experimental PID: Pressure, Pump Discharge Rate and Power with Time at Torque =4.23 Nm, 4.48 Nm and 5.23 Nm (Set Point=22 RPS)

Set Point = 22 RPS	Experimental PID	Torque= 4.23 Nm			Torque= 4.48 Nm			Torque= 5.23 Nm		
Time (second)	Motor Speed (RPS)	Hydraulic Pressure (bar)	Pump Discharge Rate (lpm)	Hydraulic Power (watt)	Hydraulic Pressure (bar)	Pump Discharge Rate (lpm)	Hydraulic Power (watt)	Hydraulic Pressure (bar)	Pump Discharge Rate (lpm)	Hydraulic Power (watt)
0	44.63	10.926	1.002921	18.2632	11.852	1.002921	19.81104	14.852	1.002921	24.82565
0.5	44.29	10.858	0.995281	18.01127	11.716	0.995281	19.43452	14.716	0.995281	24.41092
1	41.57	10.314	0.934157	16.05816	10.628	0.934157	16.54704	13.628	0.934157	21.21783
1.5	38.6	9.44	0.867416	13.64734	9.44	0.867416	13.64734	12.72	0.867416	18.38921
2	36.02	8.408	0.809438	11.34293	8.408	0.809438	11.34293	12.204	0.809438	16.46397
2.5	33.69	7.476	0.757079	9.4332	7.476	0.757079	9.4332	11.476	0.757079	14.48039
3	31.92	6.768	0.717303	8.091182	6.768	0.717303	8.091182	10.768	0.717303	12.8732
3.5	30.41	6.164	0.683371	7.020496	6.164	0.683371	7.020496	10.164	0.683371	11.5763
4	28.94	5.576	0.650337	6.043799	5.576	0.650337	6.043799	9.576	0.650337	10.37938
4.5	27.68	5.072	0.622022	5.258163	5.072	0.622022	5.258163	9.072	0.622022	9.40498
5	26.65	4.66	0.598876	4.651273	4.66	0.598876	4.651273	8.66	0.598876	8.643783
5.5	25.84	4.336	0.580674	4.196339	4.336	0.580674	4.196339	8.336	0.580674	8.0675
6	25.22	4.088	0.566742	3.861399	4.088	0.566742	3.861399	8.088	0.566742	7.639676
6.5	24.57	3.828	0.552135	3.52262	3.828	0.552135	3.52262	7.656	0.552135	7.04524
7	24.08	3.632	0.541124	3.275601	3.632	0.541124	3.275601	7.264	0.541124	6.551203
7.5	23.72	3.488	0.533034	3.098703	3.488	0.533034	3.098703	6.976	0.533034	6.197405
8	23.25	3.3	0.522472	2.873596	3.3	0.522472	2.873596	6.6	0.522472	5.747191
8.5	22.99	3.196	0.516629	2.751912	3.196	0.516629	2.751912	6.392	0.516629	5.503823
9	22.97	3.188	0.51618	2.742635	3.188	0.51618	2.742635	6.376	0.51618	5.48527
9.5	22.6	3.04	0.507865	2.573184	3.04	0.507865	2.573184	6.08	0.507865	5.146367
10	22.5	3	0.505618	2.52809	3	0.505618	2.52809	6	0.505618	5.05618

At 4.48 Nm torque, the hydraulic pressure curve follows the 6th-order polynomial equation, and the pump discharge rate follows the 6th-order polynomial equation. The R-square value of 0.9993 in the graph indicates that there is a good correlation between hydraulic pressure and pump discharge rate vs. time. The motor speed vs. time curve of the experimental PID for different torques is the same as shown in Figure 4.19 for set point 22 RPS. The current speed of the motor is now 44.63 RPS, and the set point is less than the current speed, which is 22 RPS. At time = 0 second, when the motor speed is 44.63 RPS, the hydraulic pressure values at 4.23, 4.48, and 5.23 Nm torques are 10.926, 11.852, and 14.852 bar, respectively, and the pump discharge rate is 1.002921 lpm. So the power consumption also increases with an increase in torque value. The power consumption increases with torque values, and at torques of 4.23, 4.48, and 5.23 Nm at a time of 0 sec, the values are 18.2632 W, 19.81104 W, and 24.82565 W. The hydraulic pressure vs. time and pump discharge rate vs. time characteristics curve at 5.23 Nm torque follows the 6th-order polynomial equation.

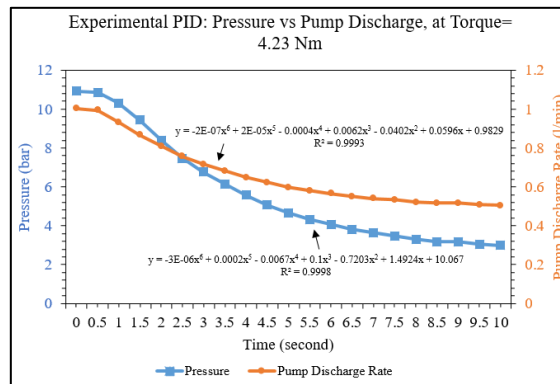


Figure 4.51: Hydraulic Pressure and Pump Discharge Rate of Experimental PID, at Set Point =22 RPS, at Torque=4.23 Nm

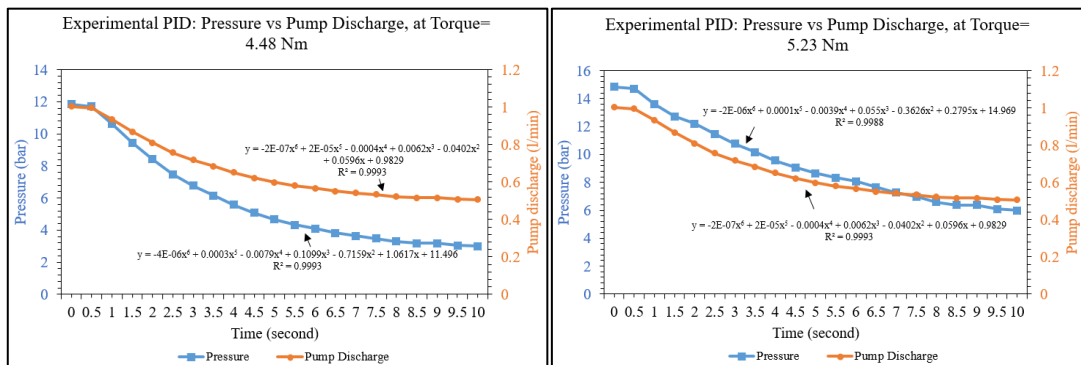


Figure 4.52: Hydraulic Pressure and Pump Discharge Rate of Experimental PID, at Set Point =22 RPS, at Torque=4.48, 5.23 Nm

4.21 HYDRAULIC POWER CONSUMPTION OF EXPERIMENTAL FUZZY PID, AT TORQUE= 4.23, 4.48 AND 5.23 NM (SET POINT=22 RPS)

The pressure curve shows that from a certain value, it gradually decreases and goes to saturation. This is because the fuzzy PID controller controls the motor speed, which also controls the pump discharge rate. So, from a certain value, the fuzzy PID controller increases or decreases the motor speed according to the speed error. Figure 4.53 and 4.54 show the hydraulic pressure and pump discharge rate profile vs. time of experimental fuzzy PID at Torque= 4.23 Nm, 4.48 Nm, and 5.23 Nm for set point = 22 RPS. Table 4.31 shows the experimental data for hydraulic pressure, pump discharge rate, and power consumption in watts. The hydraulic pressure decreases with a decrease in motor speed as well as pump discharge rate. So, the power consumption decreases. The pressure curve follows the 6th-order polynomial equation, and the pump discharge rate curve also follows the 6th-order polynomial equation at Torque = 4.23 Nm. As the PID controller's output voltage decreases, so does the motor speed. The hydraulic pressure curve follows the pump discharge rate curve. At 4.48 Nm torque, the hydraulic pressure curve follows the 6th-order polynomial equation, and the pump discharge rate follows the 6th order polynomial equation.

Table 4.31: Experimental Fuzzy PID: Pressure, Pump Discharge Rate and Power with Time at Torque =4.23 Nm, 4.48 Nm and 5.23 Nm (Set Point=22 RPS)

Set Point= 22 RPS	Experimental fuzzy-PID	Torque=4.23 Nm			Torque=4.48 Nm			Torque=5.23 Nm		
Time (second)	Motor Speed (RPS)	Hydraulic Pressure (bar)	Pump Discharge Rate (lpm)	Hydraulic Power (watt)	Hydraulic Pressure (bar)	Pump Discharge Rate (lpm)	Hydraulic Power (watt)	Hydraulic Pressure (bar)	Pump Discharge Rate (lpm)	Hydraulic Power (watt)
0	44.89	10.978	1.008764	18.45702	11.956	1.008764	20.1013	14.956	1.008764	25.14513
0.5	41.93	10.386	0.942247	16.3103	10.772	0.942247	16.91648	13.772	0.942247	21.62771
1	29.63	5.852	0.665843	6.494186	5.852	0.665843	6.494186	9.852	0.665843	10.93314
1.5	25.5	4.2	0.573034	4.011236	4.2	0.573034	4.011236	8.2	0.573034	7.831461
2	24.39	3.756	0.54809	3.431043	3.756	0.54809	3.431043	7.512	0.54809	6.862085
2.5	23.57	3.428	0.529663	3.026141	3.428	0.529663	3.026141	6.856	0.529663	6.052282
3	22.89	3.156	0.514382	2.705649	3.156	0.514382	2.705649	6.312	0.514382	5.411299
3.5	22.28	2.912	0.500674	2.429939	2.912	0.500674	2.429939	5.824	0.500674	4.859877
4	21.97	2.788	0.493708	2.294096	2.788	0.493708	2.294096	5.576	0.493708	4.588192
4.5	21.98	2.792	0.493933	2.298433	2.792	0.493933	2.298433	5.584	0.493933	4.596866
5	22.1	2.84	0.496629	2.350712	2.84	0.496629	2.350712	5.68	0.496629	4.701423
5.5	22.1	2.84	0.496629	2.350712	2.84	0.496629	2.350712	5.68	0.496629	4.701423
6	22.1	2.84	0.496629	2.350712	2.84	0.496629	2.350712	5.68	0.496629	4.701423
6.5	22.1	2.84	0.496629	2.350712	2.84	0.496629	2.350712	5.68	0.496629	4.701423
7	22.1	2.84	0.496629	2.350712	2.84	0.496629	2.350712	5.68	0.496629	4.701423
7.5	22.1	2.84	0.496629	2.350712	2.84	0.496629	2.350712	5.68	0.496629	4.701423
8	22.1	2.84	0.496629	2.350712	2.84	0.496629	2.350712	5.68	0.496629	4.701423
8.5	22.1	2.84	0.496629	2.350712	2.84	0.496629	2.350712	5.68	0.496629	4.701423
9	22.1	2.84	0.496629	2.350712	2.84	0.496629	2.350712	5.68	0.496629	4.701423
9.5	22.1	2.84	0.496629	2.350712	2.84	0.496629	2.350712	5.68	0.496629	4.701423
10	22.1	2.84	0.496629	2.350712	2.84	0.496629	2.350712	5.68	0.496629	4.701423

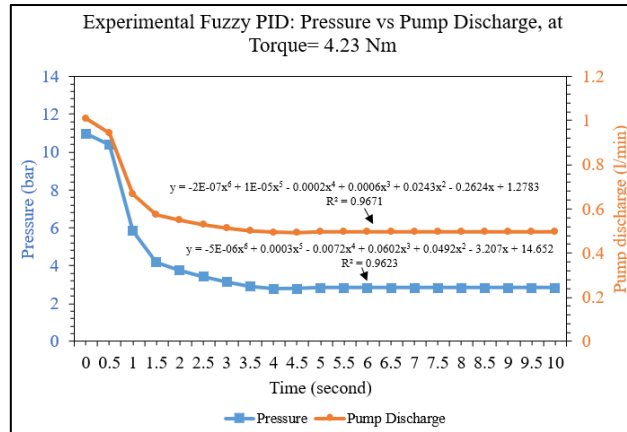


Figure 4.53: Hydraulic Pressure and Pump Discharge Rate of Experimental Fuzzy PID, at Set Point =22 RPS, at Torque=4.23 Nm

The R-square value in the graph indicates that there is a good correlation between hydraulic pressure and pump discharge rate vs. time. The motor speed vs. time curve of the experimental PID for different torques is the same as shown in Figure 4.19 for set point 22 RPS. The current speed of the motor is now 44.89 RPS, and the set point is less than the current speed, which is 22 RPS. At time = 0 second, when the motor speed is 44.89 RPS, the hydraulic pressure values at 4.23, 4.48, and 5.23 Nm torques are 10.978, 11.956, and 14.956 bar, respectively, and the pump discharge rate is 1.008764 lpm.

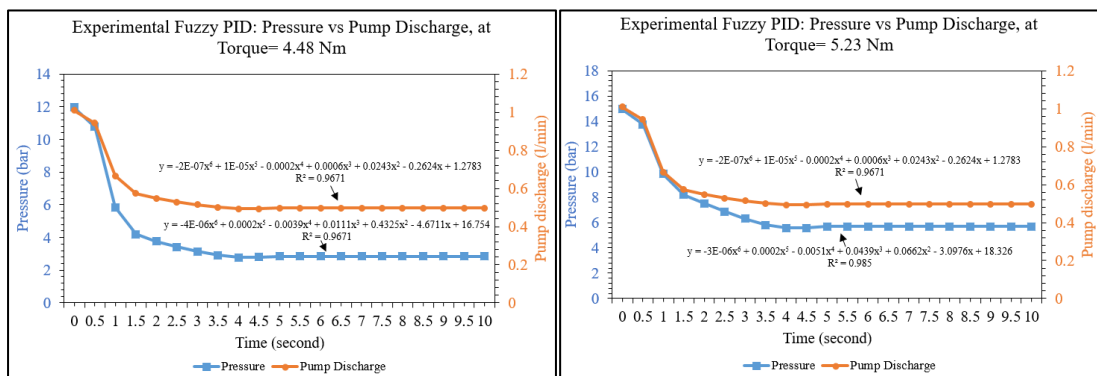


Figure 4.54: Hydraulic Pressure and Pump Discharge Rate of Experimental Fuzzy PID, at Set Point =22 RPS, at Torque=4.48, 5.23 Nm

So the power consumption also increases with an increase in torque value. The power consumption increases with torque values, and at torques of 4.23, 4.48, and 5.23 Nm at a time of 0 sec, the values are 18.45702 W, 20.1013 W, and 25.14513 W. The hydraulic pressure vs. time and pump discharge rate vs. time characteristics curve at 5.23 Nm torque follows the 6th-order polynomial equation.

4.22 HYDRAULIC POWER CONSUMPTION COMPARISON:

EXPERIMENTAL PID VS FUZZY-PID AT TORQUE=4.23, 4.48 AND 5.23 NM (SET POINT=45 RPS)

The product of hydraulic pressure and pump discharge rate is the hydraulic power consumption of the energy-saving electro-hydraulic power steering system. We have calculated the power from pressure and pump discharge rate data over time. To calculate the power consumption in watt-hours, we have fed the power signal to the Matlab Simulink integrator block, and the output of the integrator block is the total power in every second. The sampling time we have used in Matlab is 0.5. In the Matlab integrator block, the initial value has been changed to the initial (time = 0 sec) value. The output of the Integrator block is watt-sec. By dividing the watt-sec by 3600, we have calculated power in watt-hours (Wh). Figure 4.55 and 4.56 show the power consumption comparison of PID and fuzzy PID for a set point of 45 RPS, and Table 4.32 shows the experimental data. The hydraulic power consumption of fuzzy PID is greater than PID at different torques. The graph shows the power consumption in watt-hour for 10 seconds. The power consumption of PID at 0 sec for 4.23 Nm, 4.48 Nm, and 5.23 Nm torques is 0.000616 Wh, 0.000616 Wh, and 0.001231 Wh, respectively. And the power consumption of fuzzy PID at 0 sec for 4.23 Nm, 4.48 Nm, and 5.23 Nm torques is 0.000641 Wh, 0.000641 Wh, and 0.001282 Wh, respectively.

Table 4.32: Hydraulic Power Consumption Comparison of Experimental PID vs Fuzzy-PID at Torque= 4.23 Nm, 4.48 Nm and 5.23 Nm (Set Point =45 RPS)

Set point=45 RPS	Torque=4.23 Nm		Torque=4.48 Nm		Torque=5.23 Nm	
Time (second)	PID (Wh)	Fuzzy PID (Wh)	PID (Wh)	Fuzzy PID (Wh)	PID (Wh)	Fuzzy PID (Wh)
0	0.000616	0.000641	0.000616	0.000641	0.001231	0.001282
0.5	0.00095	0.001394	0.00095	0.001394	0.001899	0.002533
1	0.001416	0.003089	0.001416	0.003117	0.002813	0.004917
1.5	0.002101	0.005365	0.002101	0.005483	0.004061	0.007939
2	0.003035	0.007785	0.003035	0.008061	0.005619	0.011195
2.5	0.004241	0.010294	0.004241	0.010771	0.007504	0.014598
3	0.005694	0.012823	0.005694	0.013511	0.009666	0.018033
3.5	0.007361	0.015363	0.007361	0.016268	0.012031	0.021487
4	0.009208	0.017926	0.009208	0.019059	0.014544	0.024979
4.5	0.011196	0.020501	0.011196	0.021868	0.017173	0.02849
5	0.013311	0.023076	0.013333	0.024677	0.019946	0.032002
5.5	0.015528	0.025651	0.015612	0.027486	0.022871	0.035513
6	0.017813	0.028226	0.01799	0.030295	0.025907	0.039024
6.5	0.020132	0.030801	0.020419	0.033104	0.028999	0.042535
7	0.022482	0.033376	0.022894	0.035913	0.032141	0.046047
7.5	0.024867	0.035951	0.02542	0.038722	0.03534	0.049558
8	0.027265	0.038526	0.027964	0.041531	0.03856	0.053069
8.5	0.029686	0.0411	0.030543	0.04434	0.041818	0.05658
9	0.032132	0.043675	0.03316	0.047149	0.045118	0.060091
9.5	0.034592	0.04625	0.035797	0.049958	0.048439	0.063603
10	0.037069	0.048825	0.03846	0.052767	0.05179	0.067114

As fuzzy PID is faster than PID controllers, its output voltage is always greater to reach the set point quickly. At 10 sec, the power consumption of PID for 4.23 Nm, 4.48 Nm, and 5.23 Nm torques is 0.037069 Wh, 0.03846 Wh, and 0.05179 Wh, respectively. The power consumption of fuzzy PID at 10 sec of 4.23 Nm, 4.48 Nm, and 5.23 Nm torques is 0.048825 Wh, 0.052767 Wh, and 0.067114 Wh. In an energy-saving power steering system, the motor speed (set point in "RPS") decreases with an increase in vehicle speed (km/h). When vehicle speed decreases, the motor speed set point is greater than the current motor speed. The fuzzy-PID takes the motor speed to the set point quickly and consumes more hydraulic energy than the PID. In this situation, fuzzy PID consumes more power than PID, but it ensures a good steering feel for the driver. On the other hand, PID is unable to provide sufficient power at the right time.

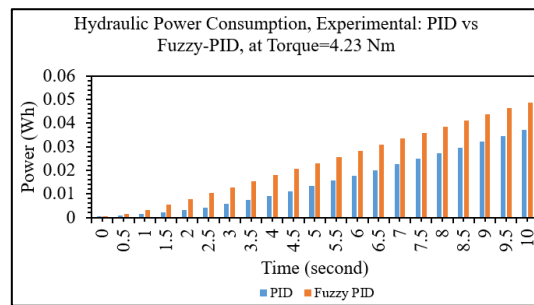


Figure 4.55: Hydraulic Power Consumption Comparison of Experimental PID vs Fuzzy-PID at Torque=4.23 Nm (Set Point =45 RPS)

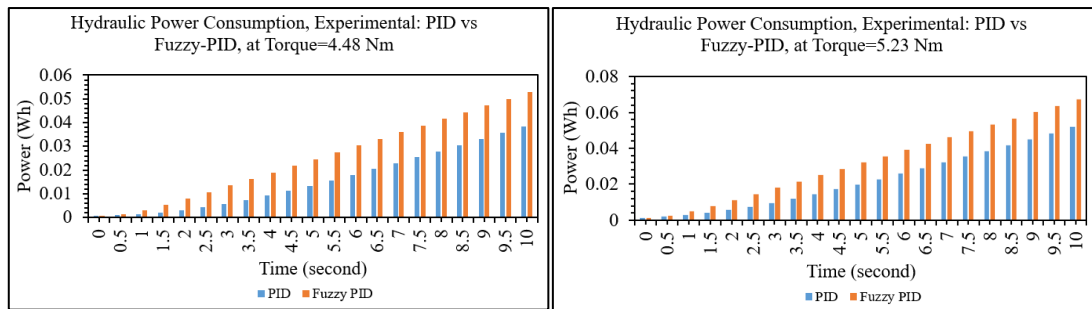


Figure 4.56: Hydraulic Power Consumption Comparison of Experimental PID vs Fuzzy-PID at Torque=4.48, 5.23 Nm (Set Point =45 RPS)

4.23 HYDRAULIC POWER CONSUMPTION COMPARISON: EXPERIMENTAL PID VS FUZZY-PID AT TORQUE=4.23, 4.48 AND 5.23 NM (SET POINT=22 RPS)

Figure 4.57 and 4.58 show the power consumption comparison of PID and fuzzy PID for a set point of 22 RPS, and Table 4.33 shows the experimental data. The power consumption rises as the steering torque input increases. When the driver gives more

steering effort, the fluid passes more in the chamber, which increases pressure. With increasing vehicle front axle loads, the steering effort increases. So the power consumption increases. If steering torque is greater than 5.23 Nm, after a certain Nm torque, the rack and pinion go to the end lock position, and the torsion bar twists to its maximum angle. The rotary valve opens fully, and the pump discharge rate and chamber incoming flow rate are equal. Then maximum hydraulic power is generated, and maximum hydraulic power consumption occurs.

Table 4.33: Hydraulic Power Consumption Comparison of Experimental PID vs Fuzzy-PID at Torque= 4.23 Nm, 4.48 Nm and 5.23 Nm (Set Point =22 RPS)

Set Point=22 RPS	Torque=4.23 Nm		Torque=4.48 Nm		Torque=5.23 Nm	
Time (second)	PID (Wh)	Fuzzy PID (Wh)	PID (Wh)	Fuzzy PID (Wh)	PID (Wh)	Fuzzy PID (Wh)
0	0.005073	0.005127	0.005503	0.005586	0.006896	0.006985
0.5	0.007592	0.007541	0.008228	0.008157	0.010315	0.010233
1	0.009958	0.009125	0.010727	0.009783	0.013484	0.012494
1.5	0.012021	0.009855	0.012824	0.010512	0.016234	0.013797
2	0.013756	0.010371	0.014559	0.011029	0.018655	0.014817
2.5	0.015199	0.01082	0.016002	0.011478	0.020803	0.015714
3	0.016416	0.011218	0.017219	0.011876	0.022703	0.01651
3.5	0.017466	0.011574	0.018269	0.012232	0.024401	0.017224
4	0.018373	0.011903	0.019176	0.01256	0.025926	0.01788
4.5	0.019158	0.012221	0.019961	0.012879	0.0273	0.018518
5	0.019846	0.012544	0.020649	0.013202	0.028553	0.019163
5.5	0.02046	0.012871	0.021263	0.013529	0.029713	0.019816
6	0.02102	0.013197	0.021823	0.013855	0.030804	0.020469
6.5	0.021533	0.013524	0.022336	0.014182	0.031824	0.021122
7	0.022005	0.01385	0.022808	0.014508	0.032768	0.021775
7.5	0.022447	0.014177	0.02325	0.014835	0.033653	0.022428
8	0.022862	0.014503	0.023665	0.015161	0.034483	0.023081
8.5	0.023253	0.01483	0.024056	0.015488	0.035264	0.023734
9	0.023634	0.015156	0.024437	0.015814	0.036027	0.024387
9.5	0.024003	0.015483	0.024807	0.016141	0.036766	0.02504
10	0.024358	0.015809	0.025161	0.016467	0.037474	0.025693

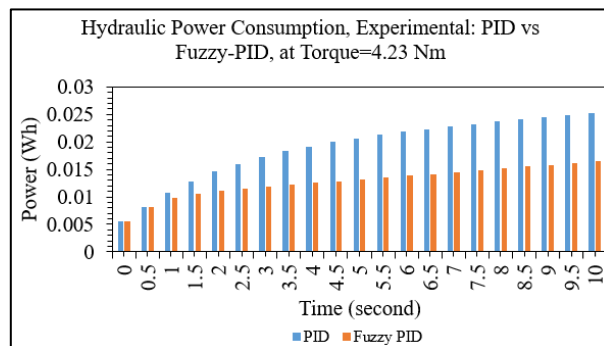


Figure 4.57: Hydraulic Power Consumption Comparison of Experimental PID vs Fuzzy-PID at Torque=4.23 Nm (Set Point =22 RPS)

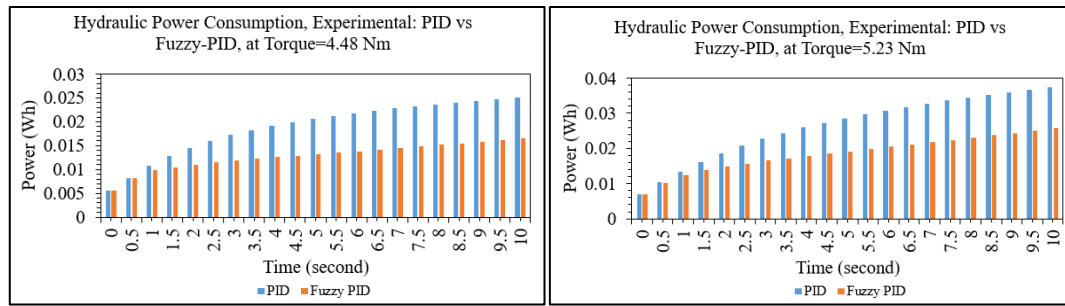


Figure 4.58: Hydraulic Power Consumption Comparison of Experimental PID vs Fuzzy-PID at Torque=4.48, 5.23 Nm (Set Point =22 RPS)

The hydraulic power consumption of fuzzy PID is less than that of PID at different torques. The graph shows the power consumption in watt-hour for 10 sec. Initially, the power consumption of PID at 0 sec for 4.23 Nm, 4.48 Nm, and 5.23 Nm torques is 0.005073 Wh, 0.005503 Wh, and 0.006896 Wh, respectively. And the power consumption of fuzzy PID at 0 sec for 4.23 Nm, 4.48 Nm, and 5.23 Nm torques is 0.005127 Wh, 0.005586 Wh, and 0.006985 Wh. As fuzzy PID is faster than PID controllers, it reduces its output voltage to reach the set point quickly. At 10 sec, the power consumption of the PID of 4.23 Nm, 4.48 Nm, and 5.23 Nm torques is 0.024358 Wh, 0.025161 Wh, and 0.037474 Wh, respectively. The power consumption of fuzzy PID at 10 sec of 4.23 Nm, 4.48 Nm, and 5.23 Nm torques is 0.015809 Wh, 0.016467 Wh, and 0.025693 Wh. In the energy-saving power steering system, the motor speed (set point in "RPS") increases with a decrease in vehicle speed (km/h). When vehicle speed increases from a certain speed, the motor speed set point is less than the current motor speed. The fuzzy PID takes the motor speed to the set point quickly and consumes less hydraulic energy compared to the PID. In this situation, fuzzy PID consumes less power than PID and ensures a good steering feel for the driver.

4.24 ELECTRIC POWER COMPARISON OF DIFFERENT CONTROLLERS AT TORQUE=5.23 NM (SETPOINT=45 AND 22 RPS)

The voltage and current of conventional, manual, PID, and Fuzzy-PID at Torque=5.23 Nm for setpoint 45 RPS are shown in Figure 4.59. The graphs are plotted from experimental data given in Appendix A9 & A10. For conventional controllers, the voltage is constant, so the current is constant. The voltage is constant because to reach the setpoint from 22 RPS, the time required is negligible, as the conventional controller is a PWM controller and there is no control method to reach the setpoint automatically.

For manual control, we modified the conventional PWM controller and connected it to the Arduino. Now, the conventional PWM output signal is off, and the Arduino PWM control signal is given to control the motor speed. So, in manual control, the voltage takes about 1.5 seconds to reach saturation, as the Arduino is loaded with programs. For PID control, it takes 8.5 seconds to reach saturation. For Fuzzy-PID control, it takes about 3 seconds to reach saturation point. The current curve follows the voltage curve in all controllers.

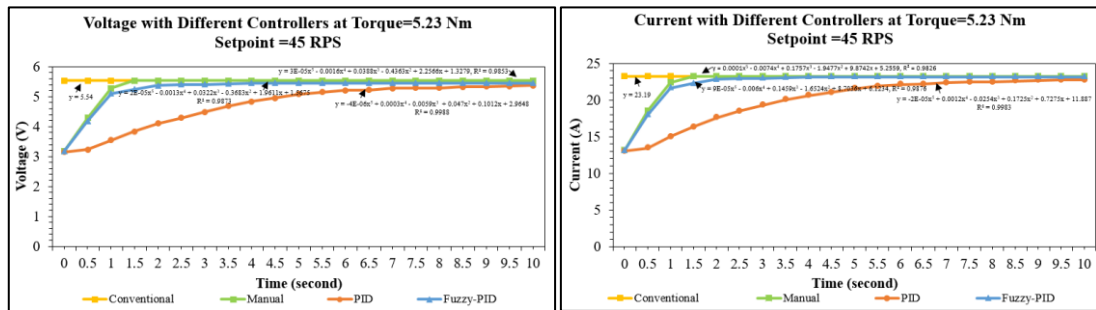


Figure 4.59: Voltage and Current of Different Controllers at Torque=4.23 Nm (Set Point =45 RPS)

For setpoint 22 RPS, the voltage and current curves are now different, as shown in Figure 4.60. Now, the motor speed is 45 RPS, and the setpoint is 22 RPS. The graphs are plotted from Appendix 11 and 12. For conventional, the voltage at 45 RPS is about 5.4 volts. But to reach saturation (3.17 V), the time required is negligible. So the voltage curve is a constant curve, and at Time = 0 sec, the voltage value is 3.17. For manual, PID, and Fuzzy-PID, the voltage gradually decreases, and when motor speed reaches the setpoint, the voltage is constant. The current curve follows the voltage curve.

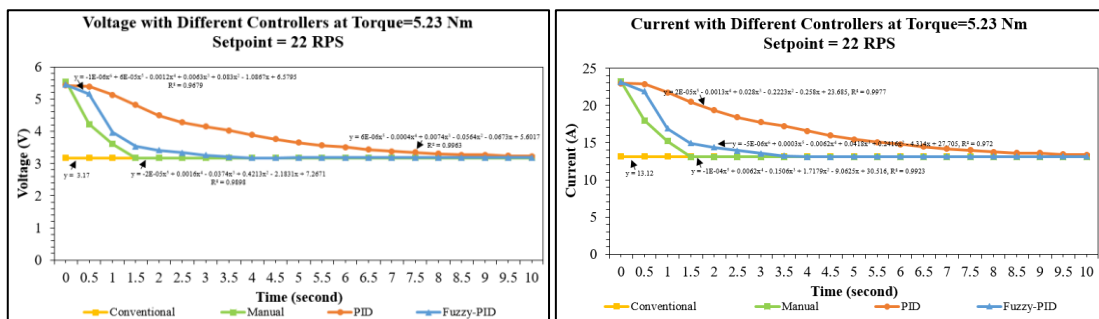


Figure 4.60: Voltage and Current of Different Controllers at Torque=4.23 Nm (Set Point =22 RPS)

Figure 4.61 shows the electric power consumption of different controllers. Power consumption is the product of voltage and current. For setpoint = 45 RPS, for conventional, the power is a constant curve as voltage and current are constant.

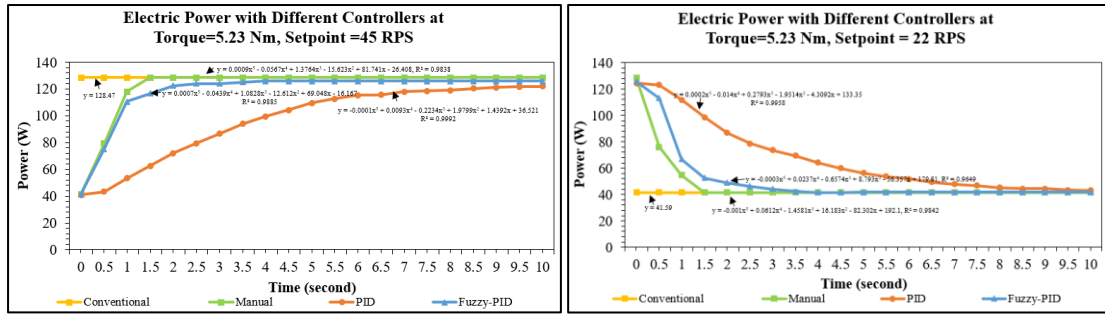


Figure 4.61: Electric Power of Different Controllers at Torque=5.23 Nm (Set Point =45, 22 RPS)

For manual, PID, and Fuzzy-PID, the power consumption gradually increases as voltage and current increase, and when voltage and current are constant, then the power is constant. For 22 RPS, the power consumption is constant for conventional. For the other three controllers, the power consumption gradually decreases. When motor speeds reach the setpoint, power consumption is constant.

4.25 HYDRAULIC POWER COMPARISON OF DIFFERENT CONTROLLERS AT TORQUE=5.23 NM (SETPOINT=45 AND 22 RPS)

The pump discharge rate and hydraulic power of conventional, manual, PID, and Fuzzy-PID at Torque = 5.23 Nm for setpoint 45 RPS are shown in Figure 4.62. The graphs are plotted from experimental data given in Appendix A13 and A14. For conventional, the pump discharge rate is constant, so the hydraulic pressure is constant.

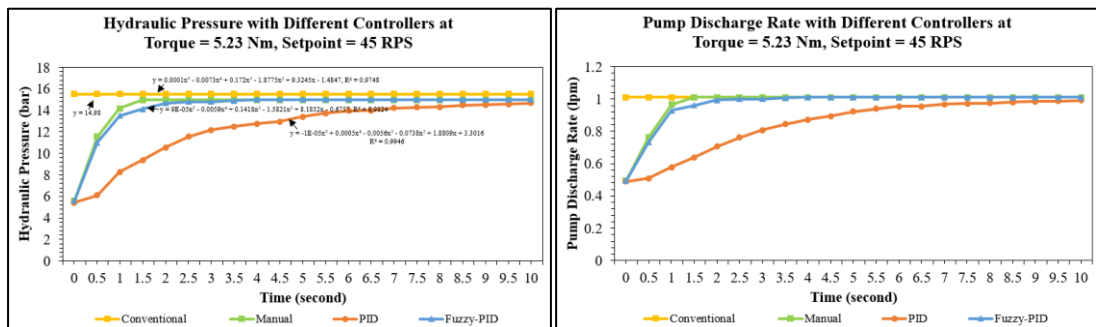


Figure 4.62: Hydraulic Pressure and Pump Discharge Rate of Different Controllers at Torque=4.23 Nm (Set Point =45 RPS)

The hydraulic pressure is constant because to reach the setpoint from 22 RPS, the time required is negligible, as the conventional controller is a PWM controller and there is no control method. It takes about 1.5 seconds for manual to reach the saturation of the hydraulic pressure. The time required for PID control to reach the saturation of

hydraulic pressure is 8.5 seconds. For Fuzzy-PID control, it takes about 3 seconds to reach the hydraulic pressure saturation point.

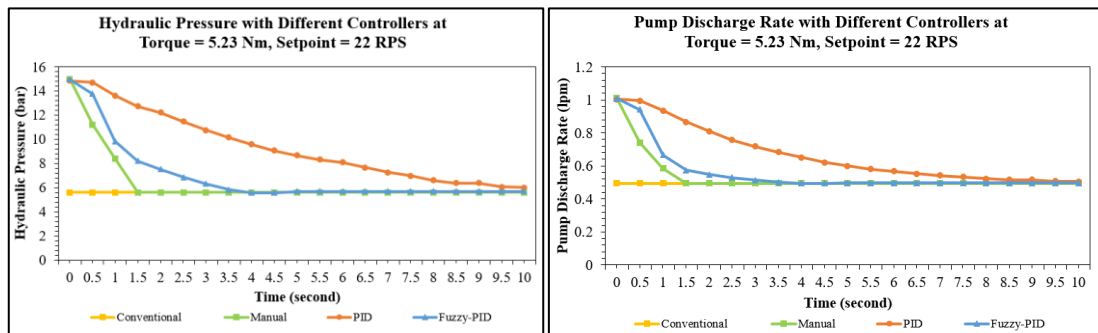


Figure 4.63: Hydraulic Pressure and Pump Discharge Rate of Different Controllers at Torque=4.23 Nm (Set Point =22 RPS)

For setpoint 22 RPS, the pump discharge rate and hydraulic pressure curves are now different, as shown in Figure 4.63. The graphs are plotted from Appendix 15 and 16. For conventional, the hydraulic pressure at 45 RPS is about 14.98 bar. But to reach saturation (5.6 bar), the time required is negligible. So the hydraulic pressure curve is a constant curve, and at Time = 0 sec, the hydraulic pressure value is 5.6 bar. For manual, PID, and Fuzzy-PID the hydraulic pressure gradually decreases, and when motor speed reaches the setpoint, the pressure is constant. The hydraulic pressure curve follows the pump discharge rate curve. Figure 4.64 shows the hydraulic power consumption of different controllers. Power consumption is the product of hydraulic pressure and pump discharge rate. For setpoint = 45 RPS, for conventional, the power is a constant curve as pressure and pump discharge rate are constant.

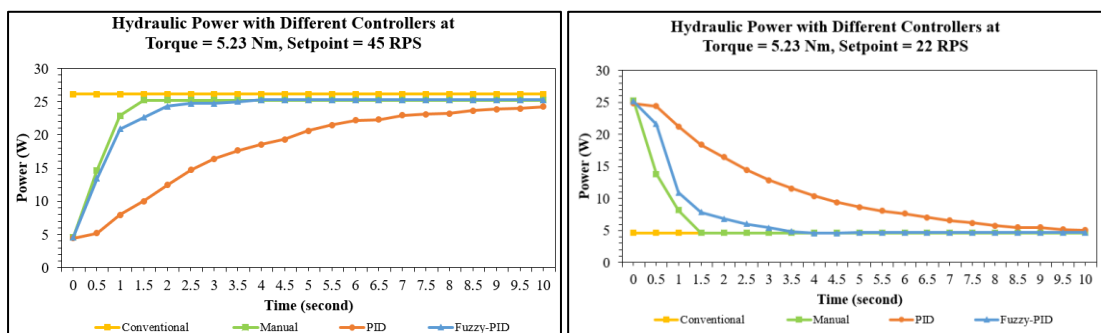


Figure 4.64: Hydraulic Power of Different Controllers at Torque=5.23 Nm (Set Point =45, 22 RPS)

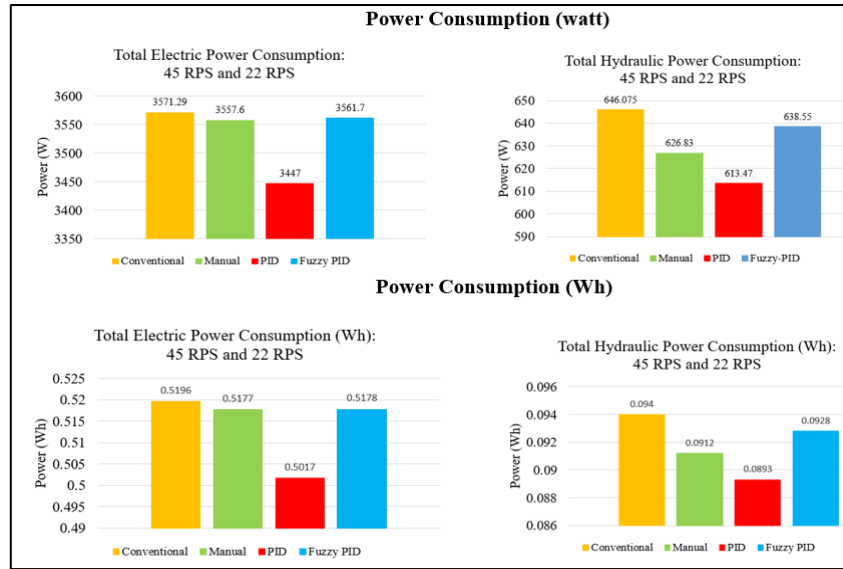


Figure 4.65: Total Electric and Hydraulic Power consumption of Different Controllers at Torque=5.23 Nm (Set Point =45 and 22 RPS)

For manual, PID, and Fuzzy-PID, the power consumption gradually increases as pressure and pump discharge rate gradually increase, and when pressure and pump discharge rate are constant, then the power is constant. For 22 RPS, the hydraulic power consumption is constant for conventional. For manual, PID, and Fuzzy-PID, the power consumption gradually decreases. When motor speeds reach the setpoint, power consumption is constant. Figure 4.65 shows the power consumption in watts and watt-hours. The total electric power in watts is the sum of the power consumption of 45 RPS and 22 RPS. The total hydraulic power in watts is the sum of the power consumption of 45 RPS and 22 RPS. The power consumption in watt-hours is calculated using Matlab. First, power consumption is calculated in watt-sec by integrating the power consumption from 0 to 10 sec. Then, by dividing the result by 3600, watt-sec has been converted to watt-hour.

4.26 ELECTRIC POWER AND HYDRAULIC POWER COMPARISON AT DIFFERENT VEHICLE SPEED OF DIFFERENT CONTROLLERS AT TORQUE=5.23 NM

Figures 4.66, 4.67, and 4.68 are plotted from Appendix 5, 6, 7, and 8. Figure 4.66 shows the voltage and current of conventional, manual, PID, and Fuzzy-PID at different vehicle speeds at Torque=5.23 Nm. In conventional control, with an increase in vehicle speed, the motor speed increases. Therefore, the voltage and current increase with vehicle speed. For manual, PID, and Fuzzy-PID the voltage and current decrease with

vehicle speed. The voltage and current for manual, PID, and Fuzzy-PID controllers are almost the same.

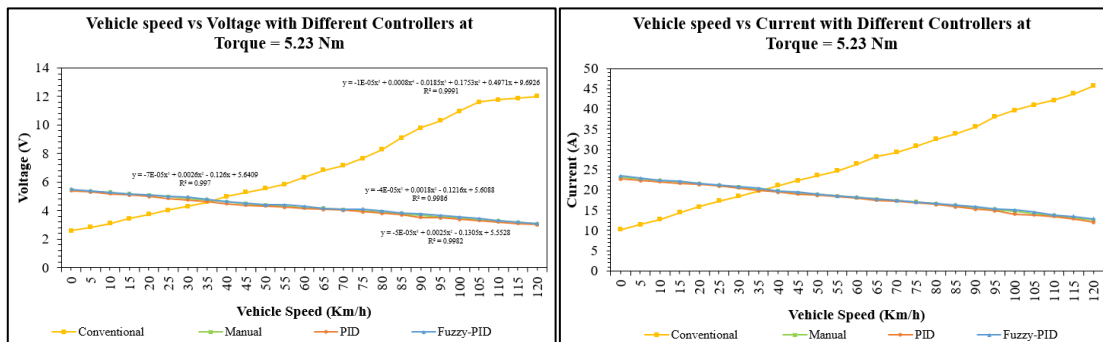


Figure 4.66: Voltage and Current of Different Controllers according to Vehicle Speed at Torque=5.23 Nm

Figure 4.67 shows the hydraulic pressure and pump discharge rate of conventional, manual, PID, and Fuzzy-PID at different vehicle speeds at Torque=5.23 Nm. In conventional control, the motor speed decreases with vehicle speed. So, hydraulic pressure and pump discharge rate increase. For manual, PID, and Fuzzy-PID, motor speed decreases with vehicle speed. So, the pump discharge rate decreases, and hydraulic pressure decreases. The pump discharge rate and hydraulic pressure for manual, PID, and Fuzzy-PID controllers are almost the same.

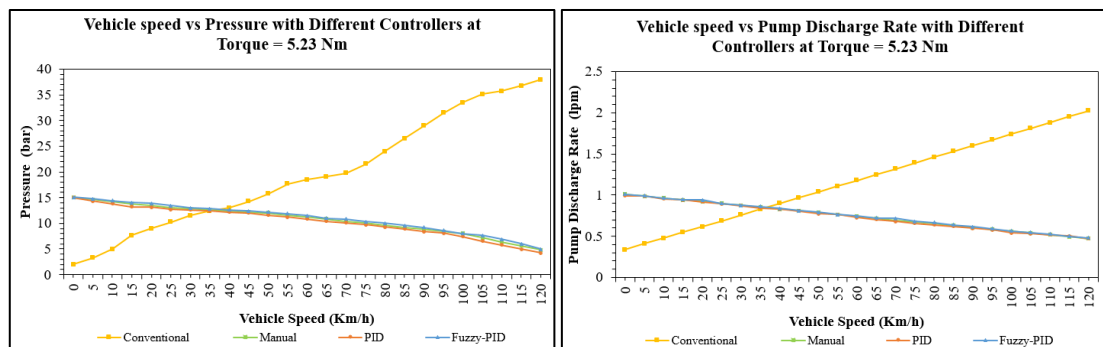


Figure 4.67: Hydraulic Pressure and Pump Discharge Rate of Different Controllers according to Vehicle Speed at Torque=5.23 Nm

Figure 4.68 shows the electric power and hydraulic power consumption for conventional, manual, PID, and Fuzzy-PID at different vehicle speeds at Torque=5.23 Nm. In conventional control, voltage, current, hydraulic pressure, and pump discharge rate increase. So, electric and hydraulic power consumption increase with vehicle speed. For manual, PID, and Fuzzy-PID, voltage, current, pump discharge rate, and

hydraulic pressure decrease. So, electric and hydraulic power consumption decrease with vehicle speed.

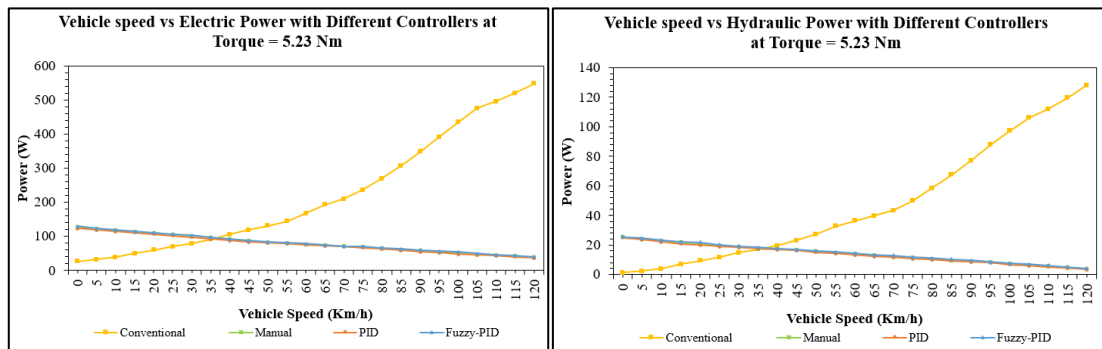


Figure 4.68: Hydraulic Power and Electric Power of Different Controllers according to Vehicle Speed at Torque=5.23 Nm

4.27 Possible Fuel Consumption

Input Thermal power (Q) required: [55]

= Pump Hydraulic Output Power ÷ (Pump Efficiency * IC Engine Thermal Efficiency * Belt Transmission efficiency)

Conventional: $47.68 / (0.3 \times 1 \times 1) = 158.93$ Watts of thermal power

Based on the higher calorific value of fuel, the mass flow rate of fuel required to produce this thermal power is calculated as follows:

Mass Flow (M) rate (Kg /sec) = (Q) watts of heat Thermal Power Q (J/sec) ÷ Higher Calorific value of fuel (Joules per Kg)

M_d (Kg /sec) (for Diesel) = $158.93 \div (44.8 \times 10^6) = 3.54 \times 10^{-6}$ kg/sec

M_g (Kg/sec) (for Gasoline) = $158.93 \div (47.3 \times 10^6) = 3.36 \times 10^{-6}$ kg/sec

Table 4.34: Possible Fuel Consumption

Type	Average Hydraulic Power (P, watt)	Input Thermal Power of IC Engine (Q, watt)	Diesel (kg/sec)	Gasoline (kg/sec)
Conventional	47.68	158.93	3.54×10^{-6}	3.36×10^{-6}
Manual	13.99	46.63	1.04×10^{-6}	0.985×10^{-6}
PID	13.42	44.73	0.998×10^{-6}	0.945×10^{-6}
Fuzzy- PID	14.44	48.1	1.07×10^{-6}	1.01×10^{-6}

4.28 Motor Speed Map

The engine rotational speed is linear to vehicle speed [78]. The speed of the vane pump is proportional to engine speed. In our experiment, we have replaced. For conventional power steering, the vane pump speed is proportional to the engine speed. Figure 4.69 shows the vehicle speed vs. motor speed curve. At 0 km/h, the rotational speed of the motor is 15 RPS, and it increases according to vehicle speed. At 20 km/h, the motor speed is 90 RPS. The equation of vehicle speed and motor speed for conventional power steering is $y = 0.625x + 15$.

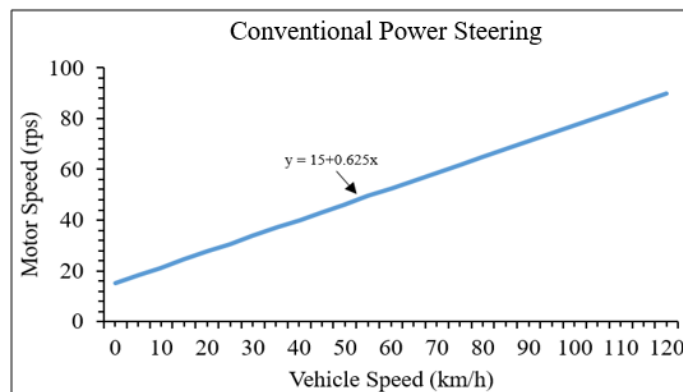


Figure 4.69: Conventional Power Steering: Vehicle speed vs Motor Speed

For energy-saving operation, at 0 km/h vehicle speed, the motor speed is set at 45 RPS, and with increasing vehicle speed, the motor speed decreases. At 120 km/h vehicle speed, the speed is set at 21 RPS.

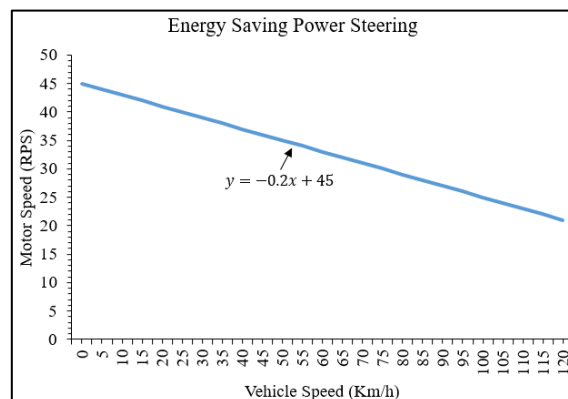


Figure 4.70: Energy Saving Power Steering: Vehicle speed vs Motor Speed

The motor speed is calculated according to vehicle speed [79].

The maximum motor speed is 100% at 90 RPS.

At 0 km/h vehicle speed, motor speed is 50% at 45 RPS.

At 20 km/h vehicle speed, motor speed is 40% at 36 RPS.

At 40km/h vehicle speed, motor speed is 37.5% at 33.75 RPS.

At 60 km/h vehicle speed, motor speed is 32.5% at 29.25 RPS.

At 80km/h vehicle speed, motor speed is 31.2% at 28.08 RPS.

At 100 km/h vehicle speed, motor speed is 30% at 27 RPS.

Vehicle speed is between 0-120 km/h.

Figure 4.70 shows the relation between vehicle speed and motor speed for energy-saving operation, and the equation is $y = -0.2x + 45$ when steering rate is less than 100 degree/sec.

4.29 Conventional and Energy Saving Power Steering System

Tables 4.35 and 4.36 show the chart of electric power and hydraulic power of conventional and energy saving power steering system data at Torque= 0 Nm. The parameters of electric power are vehicle speed, motor speed, voltage, current, and power. And the parameters of hydraulic power are vehicle speed, motor speed, pressure, pump discharge rate, and power. The vehicle speed and motor speed are the same for both electric and hydraulic power.

Table 4.35: Electric Power and Hydraulic Power at different vehicle speed and motor speed of Conventional Power Steering at Torque=0 Nm

Vehicle speed (km/h)	Motor Speed (RPS)	Electric Power			Hydraulic Power		
		Voltage (V)	Current (A)	Power (W)	Pressure (bar)	Pump Discharge Rate (lpm)	Power (W)
0	15	2.4	8.53	20.472	0	0.337079	0
5	18.2	2.64	9.64	25.4496	0	0.408989	0
10	21.2	2.84	10.53	29.9052	0	0.476404	0
15	24.5	3.03	11.28	34.1784	0	0.550562	0
20	27.5	3.27	12.16	39.7632	0	0.617978	0
25	30.6	3.52	13.1	46.112	0	0.68764	0
30	33.8	3.76	14.04	52.7904	0	0.759551	0
35	36.9	4.01	15.03	60.2703	0	0.829213	0
40	40	4.28	16.06	68.7368	0	0.898876	0
45	43.1	4.51	16.93	76.3543	0	0.968539	0
50	46.2	4.76	17.81	84.7756	0	1.038202	0
55	49.4	5.03	18.75	94.3125	0	1.110112	0
60	52.5	5.27	19.3	101.711	0	1.179775	0
65	55.6	5.52	19.86	109.6272	0	1.249438	0
70	58.7	5.84	20.9	122.056	0	1.319101	0
75	61.9	6.17	21.81	134.5677	0	1.391011	0
80	65	6.49	22.6	146.674	0	1.460674	0
85	68.1	6.93	23.46	162.5778	0	1.530337	0
90	71.2	7.35	24.24	178.164	0	1.6	0
95	74.4	7.77	24.88	193.3176	0	1.67191	0
100	77.5	8.25	25.53	210.6225	0	1.741573	0
105	80.6	8.78	26.17	229.7726	0	1.811236	0
110	83.7	9.42	26.7	251.514	0	1.880899	0
115	86.9	10.1	27.21	274.821	0	1.952809	0
120	90	10.77	27.66	297.8982	0	2.022472	0
				Total=3046 W			

Table 4.36: Electric Power and Hydraulic Power at Different Vehicle Speed and Motor Speed of Energy Saving Power Steering at Torque=0 Nm

Energy Saving Power Steering, Torque=0 Nm							
Vehicle speed (km/h)	Motor Speed (RPS)	Electric Power			Hydraulic Power		
		Voltage (V)	Current (A)	Power (W)	Pressure (bar)	Pump Discharge Rate (lpm)	Power (W)
0	45	4.65	17.46	81.189	0	1.011236	0
5	44	4.58	17.18	78.6844	0	0.988764	0
10	43	4.5	16.9	76.05	0	0.966292	0
15	42	4.43	16.62	73.6266	0	0.94382	0
20	41	4.35	16.34	71.079	0	0.921348	0
25	40	4.28	16.06	68.7368	0	0.898876	0
30	39	4.19	15.73	65.9087	0	0.876404	0
35	38	4.11	15.4	63.294	0	0.853933	0
40	37	4.02	15.06	60.5412	0	0.831461	0
45	36	3.94	14.73	58.0362	0	0.808989	0
50	35	3.85	14.4	55.44	0	0.786517	0
55	34	3.78	14.1	53.298	0	0.764045	0
60	33	3.7	13.81	51.097	0	0.741573	0
65	32	3.63	13.52	49.0776	0	0.719101	0
70	31	3.55	13.22	46.931	0	0.696629	0
75	30	3.48	12.93	44.9964	0	0.674157	0
80	29	3.39	12.62	42.7818	0	0.651685	0
85	28	3.31	12.32	40.7792	0	0.629213	0
90	27	3.22	12.01	38.6722	0	0.606742	0
95	26	3.14	11.7	36.738	0	0.58427	0
100	25	3.05	11.4	34.77	0	0.561798	0
105	24	3	11.17	33.51	0	0.539326	0
110	23	2.94	10.94	32.1636	0	0.516854	0
115	22	2.88	10.72	30.8736	0	0.494382	0
120	21	2.83	10.49	29.6867	0	0.47191	0
				Total= 1317 W			

Table 4.37: Electric Power and Hydraulic Power at Different Vehicle Speed and Motor Speed of Conventional Power Steering at Torque=3.98 Nm

Vehicle speed (km/h)	Motor Speed (RPS)	Electric Power			Hydraulic Power		
		Voltage (V)	Current (A)	Power (W)	Pressure (bar)	Pump Discharge Rate (lpm)	Power (W)
0	15	2.49	8.73	21.7377	0	0.337079	0
5	18.2	2.73	9.84	26.8632	0.64	0.408989	0.436255
10	21.2	2.97	10.91	32.4027	1	0.476404	0.794007
15	24.5	3.25	12.14	39.455	1	0.550562	0.917603
20	27.5	3.52	13.36	47.0272	1.5	0.617978	1.544944
25	30.6	3.81	14.59	55.5879	2.12	0.68764	2.429663
30	33.8	4.08	15.61	63.6888	2.76	0.759551	3.493933
35	36.9	4.42	16.81	74.3002	3.38	0.829213	4.671236
40	40	4.8	18.13	87.024	4	0.898876	5.992509
45	43.1	5.09	19.29	98.1861	5.24	0.968539	8.458577
50	46.2	5.39	20.4	109.956	6.48	1.038202	11.21258
55	49.4	5.72	21.46	122.7512	7.76	1.110112	14.35745
60	52.5	6.09	22.53	137.2077	8.5	1.179775	16.71348
65	55.6	6.47	23.6	152.692	9.12	1.249438	18.99146
70	58.7	6.88	24.63	169.4544	9.74	1.319101	21.41341
75	61.9	7.36	25.72	189.2992	10.38	1.391011	24.06449
80	65	7.85	26.8	210.38	11	1.460674	26.77903
85	68.1	8.44	27.83	234.8852	11.62	1.530337	29.63753
90	71.2	9.03	28.85	260.5155	12.24	1.6	32.64
95	74.4	9.66	29.87	288.5442	12.88	1.67191	35.89034
100	77.5	10.42	30.86	321.5612	13.5	1.741573	39.18539
105	80.6	11.12	31.85	354.172	14.12	1.811236	42.62442
110	83.7	11.44	32.8	375.232	14.74	1.880899	46.20742
115	86.9	11.73	34.16	400.6968	15.38	1.952809	50.057
120	90	12	35.73	428.76	16	2.022472	53.93258
				Total= 4302 W			Total: 492 W

Table 4.38: Electric Power and Hydraulic Power at Different Vehicle Speed and Motor Speed of Energy Saving Power Steering at Torque=3.98 Nm

Vehicle speed (km/h)	Motor Speed (RPS)	Electric Power			Hydraulic Power		
		Voltage (V)	Current (A)	Power (W)	Pressure (bar)	Pump Discharge Rate (lpm)	Power (W)
0	45	5.27	20	105.4	6	1.011236	10.11236
5	44	5.17	19.62	101.4354	5.6	0.988764	9.228464
10	43	5.08	19.25	97.79	5.2	0.966292	8.374532
15	42	4.98	18.88	94.0224	4.8	0.94382	7.550562
20	41	4.89	18.5	90.465	4.4	0.921348	6.756554
25	40	4.8	18.13	87.024	4	0.898876	5.992509
30	39	4.67	17.7	82.659	3.8	0.876404	5.550562
35	38	4.55	17.28	78.624	3.6	0.853933	5.123596
40	37	4.43	16.85	74.6455	3.4	0.831461	4.71161
45	36	4.31	16.42	70.7702	3.2	0.808989	4.314607
50	35	4.18	16	66.88	3	0.786517	3.932584
55	34	4.1	15.68	64.288	2.8	0.764045	3.565543
60	33	4.01	15.36	61.5936	2.6	0.741573	3.213483
65	32	3.93	15.04	59.1072	2.4	0.719101	2.876404
70	31	3.84	14.72	56.5248	2.2	0.696629	2.554307
75	30	3.76	14.4	54.144	2	0.674157	2.247191
80	29	3.67	13.98	51.3066	1.8	0.651685	1.955056
85	28	3.57	13.57	48.4449	1.6	0.629213	1.677903
90	27	3.48	13.16	45.7968	1.4	0.606742	1.41573
95	26	3.38	12.74	43.0612	1.2	0.58427	1.168539
100	25	3.29	12.33	40.5657	1	0.561798	0.93633
105	24	3.2	11.96	38.272	1	0.539326	0.898876
110	23	3.12	11.58	36.1296	1	0.516854	0.861423
115	22	3.04	11.21	34.0784	1	0.494382	0.82397
120	21	2.95	10.46	30.857	1	0.47191	0.786517
				Total= 1613 W			Total= 96 W

At Torque=0 Nm Torque, there is no steering operation, and we have increased the vehicle speed from 0 km/h to 120 km/h linearly. The motor's speed also increases as the vehicle's speed increases. The voltage increases with vehicle speed, and the current also increases. Because the voltage and current are proportional to motor speed. So power consumption also increases. The total electric power consumption in watts from 0 km/h to 120 km/h at vehicle speed is 3046 W. In hydraulic power, with vehicle speed, the motor speed also increases. The pump discharge rate is proportional to the motor speed. But as at Torque=0 Nm, there is no steering operation, the pump flow returns to the reservoir, hence no pressure develops at all. The pressure that develops in the chamber is atmospheric pressure, which is negligible. Hence, the hydraulic power, which is the product of pressure and pump discharge rate, is zero. In energy-saving power steering, the total power consumed at 0 km/h to 120 km/h vehicle speed is 1317 W, which is 1729 W less power than conventional. Tables 4.37 and 4.38 show the chart of electric power and hydraulic power of conventional and energy saving power steering system data at Torque= 3.98 Nm. There is steering operation at Torque= 3.98 Nm. So though the vehicle speed, motor speed, and pump discharge rate are the same at 0 Nm and 3.98 Nm Torque, the flow rate in the chamber is different. At high torque,

more fluid comes into the hydraulic chamber, which increases the hydraulic pressure. As the hydraulic power increases, the hydraulic power also increases. The relation between hydraulic and electric power is that, with increasing hydraulic load, the electric load also increases. So the voltage and current, as well as power consumption, increase according to vehicle speed. In conventional, the total electric power consumption in watts from 0 km/h to 120 km/h at vehicle speed is 4302 W. In energy-saving power steering, the total electric power consumed at 0 km/h to 120 km/h vehicle speed is 1613 W, which is 2689 W less power than conventional. For hydraulic power, the total power consumption for conventional is 492 W, and for energy savings, it is 96 W.

4.30 BOOST CURVE

In a power steering system, the boost curve is defined by the assistive pressure for a given torsion bar torque. In conventional power steering systems, the pressure control is purely hydro-mechanical [80]. The steering torque determines the amount of fluid that passes to the hydraulic chamber. In conventional power steering, at a fixed vehicle speed, if the steering torque is applied more, then more fluid enters the hydraulic chamber, which results in an increase in hydraulic pressure. As the hydraulic pressure rises, the mechanical load on the DC motor increases, which results in an increase in electric current. Figures 4.71, 4.72, 4.73, and 4.74 have been plotted from Tables 4.35, 4.36, 4.37, 4.38, and Tables A1–A6 (Appendix A). Figures 4.71 and 4.72 show hydraulic pressure and current at different torque values at different vehicle speeds for conventional power steering. In conventional power steering, at 0 km/h vehicle speed, the motor speed is 15 RPS. So the pump discharge rate is 0.337079 lpm. In Figure 4.71, we can see there is no pressure developed before 4 Nm torque. After 4 Nm of torque, the pressure increases, and at 5.23 Nm of torque, the pressure is 2 bar. At 10 km/h and 0 to 3.98 Nm torque, the pressure linearly increases. The slope increases when torque is applied greater than 3.98 Nm, and at 5.23 Nm torque, the pressure developed is 4.96 bar. The motor runs at 15 RPS speed, so at 0 km/h vehicle speed, it consumes current at 0 Nm torque. The slope of current vs. hydraulic pressure is different at torque less than 3.98 Nm and torque greater than 3.98 Nm. At greater than 3.98 Nm of torque, the tangent of current vs. torque changes.

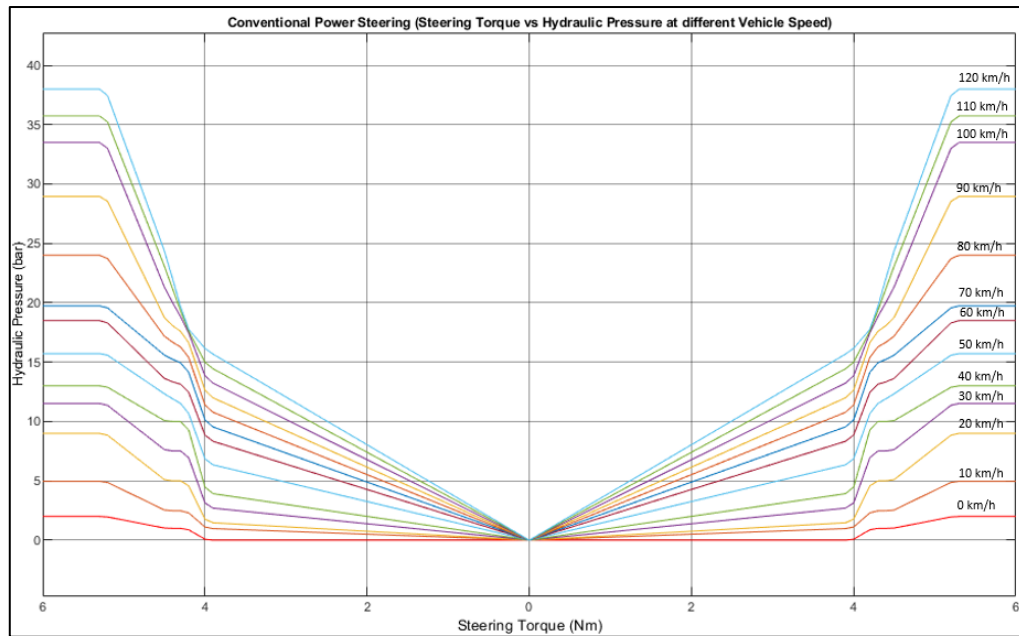


Figure 4.71: Conventional Power Steering: Steering Torque vs Hydraulic Pressure at Different Vehicle Speed

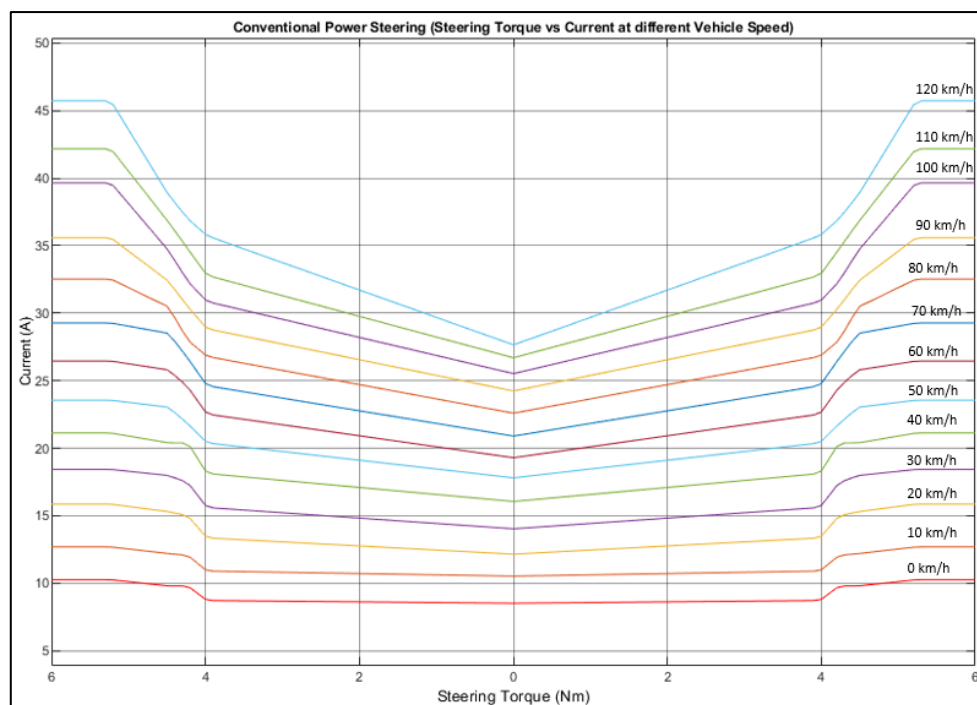


Figure 4.72: Conventional Power Steering: Steering Torque Vs Current at Different Vehicle Speed

In energy-saving power steering, in Figure 4.73, the boost curves show that at 0 km/h vehicle speed, the hydraulic pressure is highest, and at 120 km/h high vehicle speed, the hydraulic pressure curve is minimum. Figure 4.74 shows the current consumption vs. steering curve.

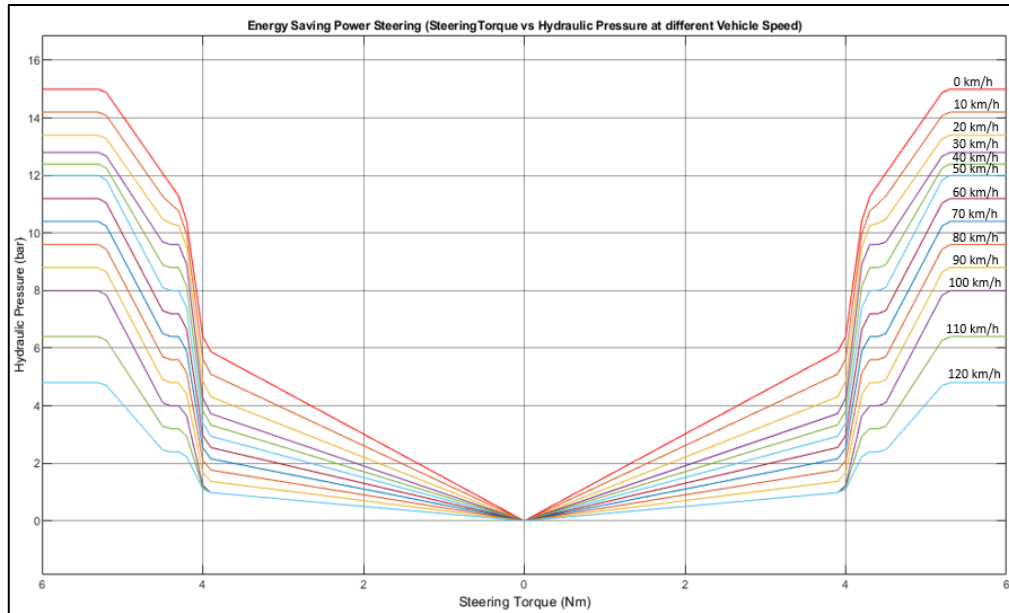


Figure 4.73: Energy Saving Power Steering: Steering Torque vs Hydraulic Pressure at Different Vehicle Speed

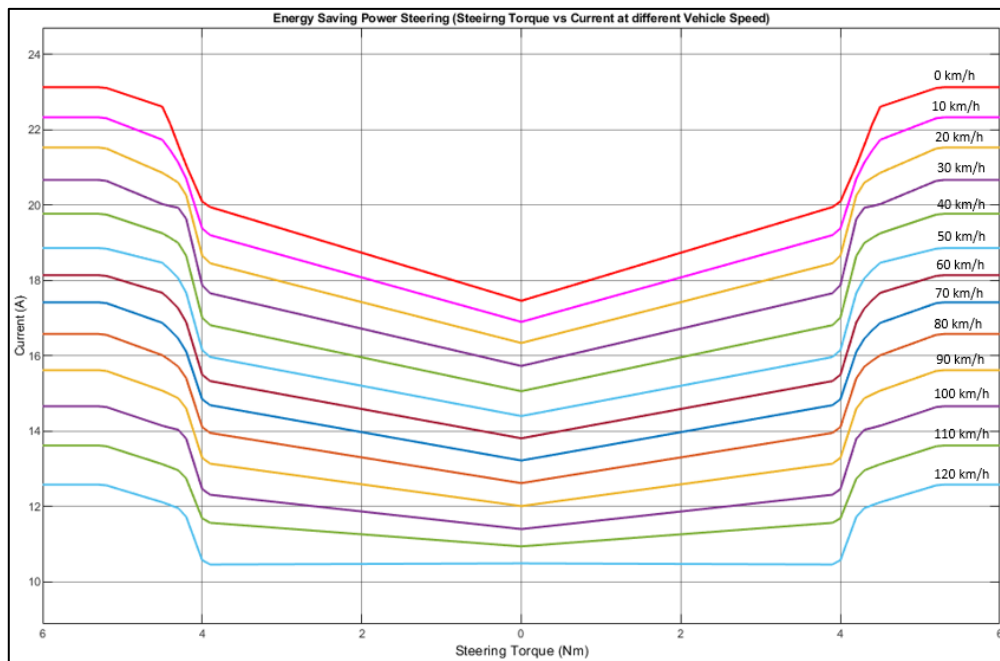


Figure 4.74: Energy Saving Power Steering: Steering Torque Vs Current at Different Vehicle Speed

In energy-saving power steering, at low vehicle speeds, the current consumption is maximum, and at high vehicle speeds, the current consumption is minimum. At high vehicle speeds, to give the driver a good steering feel and to reduce energy consumption, we have designed the motor speed map, which reduces the motor speed. With increasing vehicle speed, preferred steering torque needs to be increased, which means motor speed needs to be decreased.

4.31 REGRESSION ANALYSIS

Tables 4.39 and 4.41 show the regression analysis of electric power and hydraulic power, respectively, for conventional power steering systems. We have used the regression analysis feature of Microsoft Excel to estimate the relationships between two or more variables. There are two basic terms: the dependent variable and the independent variable. Table 4.40 and Table 4.42 show the regression analysis of electric and hydraulic power, respectively, of an energy-saving power steering system. In conventional and energy-saving power steering, for electric power consumption, the dependent variable is power and the independent variables are voltage, current, motor speed, and vehicle speed. In conventional and energy-saving power steering, for electric power consumption, the dependent variable is power and the independent variables are voltage, current, motor speed, and vehicle speed.

Table 4.39: Conventional Power Steering, Regression Analysis of Power (p, watt) with Voltage (v, volt), Current (i, amp), Motor Speed (n, RPS) and Vehicle Speed (V, km/h), at Torque= 0 Nm.

Model No.	Form of Equation	Equation Constants		Multiple R	R Square	Adjusted R Square
		m_i	k_1			
1	$P_1 = m_1 v + k_1$	$m_1 = 34.1053$	-72.82	0.99852	0.99703	0.9969
$P_1 = -72.82 + 34.1053v$						
2	$P_2 = m_1 i + k_1$	$m_1 = 13.1982$	-128.475	0.9549	0.91194	0.90811
$P_2 = -128.475 + 13.1982i$						
3	$P_3 = m_1 n + k_1$	$m_1 = 3.5188$	-62.88	0.9732	0.94719	0.9449
$P_3 = -62.88 + 3.5188n$						
4	$P_4 = m_1 V + k_1$	$m_1 = 2.1978$	-10.0129	0.97315	0.94702	0.94472
$P_4 = -10.0129 + 2.1978V$						
5	$P_5 = m_1 v + m_2 i + k_1$	$m_1 = 39.6055$ $m_2 = -2.3012$	-60.5791	0.99941	0.9982	0.99872
$P_5 = -60.5791 + 39.6055v - 2.3012i$						
6	$P_6 = m_1 v + m_2 n + k_1$	$m_1 = 41.6678$ $m_2 = -0.81478$	-73.2223	0.9994	0.99879	0.99868
$P_6 = -73.2223 + 41.6678v - 0.81478n$						
7	$P_7 = m_1 v + m_2 V + k_1$	$m_1 = 41.6538$ $m_2 = -0.50805$	-85.4358	0.9994	0.99879	0.99869
$P_7 = -85.4358 + 41.6538v - 0.50805V$						
8	$P_8 = m_1 v + m_2 i + m_3 n + m_4 V + k_1$	$m_1 = 38.6781$ $m_2 = -3.2738$ $m_3 = 1.0038$ $m_4 = -0.40819$	-65.0457	0.9994	0.9988	0.9985
$P_8 = -65.0457 + 38.6781v - 3.2738i + 1.0038n - 0.40819V$						

Table 4.40: Energy Saving Power Steering, Regression Analysis of Power (p, watt) with Voltage (v, volt), Current (i, amp), Motor Speed (n, RPS) and Vehicle Speed (V, km/h), at Torque= 0 Nm.

Model No.	Form of Equation	Equation Constants		Multiple R	R Square	Adjusted R Square
		m_i	k_1			
1	$P_1 = m_1v + k_1$	$m_1 = 28.1638$	-51.8257	0.99765	0.9953	0.9951
$P_1 = -51.8257 + 28.1638v$						
2	$P_2 = m_1i + k_1$	$m_1 = 7.373$	-49.5686	0.9980	0.9960	0.9958
$P_2 = -49.5686 + 7.373i$						
3	$P_3 = m_1n + k_1$	$m_1 = 2.20439$	-20.0266	0.99606	0.99213	0.99178
$P_3 = -20.0266 + 2.20439n$						
4	$P_4 = m_1V + k_1$	$m_1 = -0.44088$	79.1712	0.99606	0.99213	0.99178
$P_4 = 79.1712 - 0.44088V$						
5	$P_5 = m_1v + m_2i + k_1$	$m_1 = -59.7913$ $m_2 = 23.019$	-44.6841	0.99831	0.99663	0.99632
$P_5 = -60.5791 + 39.6055v - 2.3012i$						
6	$P_6 = m_1v + m_2n + k_1$	$m_1 = 56.4201$ $m_2 = -2.2163$	-83.5739	0.9981	0.9963	0.9960
$P_6 = -83.5739 + 56.4201v - 2.2163n$						
7	$P_7 = m_1v + m_2V + k_1$	$m_1 = 56.4201$ $m_2 = 0.44327$	-183.309	0.99818	0.99636	0.99603
$P_7 = -183.309 + 56.4201v + 0.44327V$						
8	$P_8 = m_1v + m_2i + m_3n + m_4V + k_1$	$m_1 = -33.4625$ $m_2 = 23.8562$ $m_3 = 0$ $m_4 = 0.46321$	-181.823	0.9988	0.9977	0.9498
$P_8 = -181.823 - 33.4625v + 23.8562i + 0n + 0.46321V$						

In the Tables, the Multiple R is the Correlation Coefficient that measures the strength of a linear relationship between dependent and independent variables. The larger the absolute value, the stronger the relationship is. 1 means a strong positive relationship, -1 means a strong negative relationship, and 0 means no relationship at all [81]. In Table 4.39, Table 4.40, Table 4.41, and Table 4.42, there are eight correlations. The maximum value of Multiple R in Table 4.39 is 0.99852, and the minimum value is 0.9549, which indicates a good positive correlation. The Multiple R of Table 4.40, Table 4.41, and Table 4.42 also show good positive correlations. R Square signifies the Coefficient of Determination, which shows the goodness of fit. It shows how many points fall on the regression line. In our experiments, the values of R square in Table 4.39, Table 4.40, Table 4.41, and Table 4.42 are between 0.91194 and 0.9977, which is an excellent fit.

Table 4.41: Conventional Power Steering, Regression Analysis of hydraulic Power (p, watt) with hydraulic pressure (p, bar), pump discharge rate (q, lpm), Motor Speed (n, RPS) and vehicle Speed (V, km/h), at Torque= 3.98 Nm.

Model No.	Form of Equation	Equation Constants		Multiple R	R Square	Adjusted R Square
		m_i	k_1			
1	$P_{h1} = m_1p + k_1$	$m_1 = 3.2167$	-5.406	0.9755	0.9517	0.9496
$P_{h1} = -5.406 + 3.2167p$						
2	$P_{h2} = m_1q + k_1$	$m_1 = 33.0203$	-19.2587	0.9772	0.9549	0.9529
$P_{h2} = -19.2587 + 33.0203q$						
3	$P_{h3} = m_1n + k_1$	$m_1 = 0.7420$	-19.2587	0.9772	0.9549	0.9529
$P_{h3} = -19.2587 + 0.7420n$						
4	$P_{h4} = m_1V + k_1$	$m_1 = 0.4634$	-8.1105	0.9771	0.9547	0.9528
$P_{h4} = -8.1105 + 0.4634V$						
5	$P_{h5} = m_1p + m_2q + k_1$	$m_1 = 1.0819$ $m_2 = 21.9884$	-14.6873	0.9776	0.9560	0.9520
$P_{h5} = -14.6873 + 1.0819p + 21.9884q$						
6	$P_{h6} = m_1p + m_2n + k_1$	$m_1 = 1.0819$ $m_2 = 0.4941$	-14.6873	0.9777	0.9560	0.9520
$P_{h6} = -14.6873 + 1.0819p + 0.4941n$						
7	$P_{h7} = m_1p + m_2V + k_1$	$m_1 = 1.1031$ $m_2 = 0.3055$	-7.2461	0.9777	0.9559	0.9519
$P_{h7} = -7.2461 + 1.1031p + 0.3055V$						
8	$P_{h8} = m_1p + m_2q + m_3n + m_4V + k_1$	$m_1 = 1.299$ $m_2 = 0$ $m_3 = 20.6703$ $m_4 = -12.6341$	-317.5863	0.9788	0.9581	0.9045
$P_{h8} = -317.5863 + 1.299p + 0q + 20.6703n - 12.6341V$						

Adjusted R-squared is a modified version of R-squared that has been adjusted for the number of predictors in the model. The adjusted R-squared increases when the new term improves the model more than would be expected by chance. It decreases when a predictor improves the model by less than expected. Typically, the adjusted R-squared is positive, not negative. It is always lower than R-squared [82]. In Tables 4.39, 4.40, 4.41, and 4.42, the minimum and maximum adjusted R square values are 0.9045 and 0.99872, respectively.

Table 4.42: Energy Saving Power Steering, Regression Analysis of hydraulic Power (P_h , watt) with hydraulic pressure (p, bar), pump discharge rate (q, lpm), Motor Speed (n, RPS) and vehicle Speed (V, km/h), at Torque= 3.98 Nm.

Model No.	Form of Equation	Equation Constants		Multiple R	R Square	Adjusted R Square
		m_i	k_1			
1	$P_{h1} = m_1 p + k_1$	$m_1 = 1.8098$	-1.2022	0.9965	0.9931	0.9928
$P_{h1} = -1.2022 + 1.8098p$						
2	$P_{h2} = m_1 q + k_1$	$m_1 = 16.5128$	-8.3802	0.9640	0.9294	0.9263
$P_{h2} = -8.3802 + 16.5128q$						
3	$P_{h3} = m_1 n + k_1$	$m_1 = 0.3710$	-8.3802	0.9640	0.9294	0.9263
$P_{h3} = -8.3802 + 0.3710n$						
4	$P_{h4} = m_1 V + k_1$	$m_1 = -0.0742$	8.3180	0.9640	0.9294	0.9263
$P_{h4} = 8.3180 - 0.0742V$						
5	$P_{h5} = m_1 p + m_2 q + k_1$	$m_1 = 2.3687$ $m_2 = -5.3796$	1.2221	0.9985	0.9970	0.9968
$P_{h5} = 1.2221 + 2.3687p - 5.3796q$						
6	$P_{h6} = m_1 p + m_2 n + k_1$	$m_1 = 2.3687$ $m_2 = -0.1208$	1.2221	0.9985	0.9970	0.9968
$P_{h6} = 1.2221 + 2.3687p - 0.1208n$						
7	$P_{h7} = m_1 p + m_2 V + k_1$	$m_1 = 2.3687$ $m_2 = 0.0241$	-4.2179	0.9985	0.9970	0.9968
$P_{h7} = -4.2179 + 2.3687p + 0.0241V$						
8	$P_{h8} = m_1 p + m_2 q + m_3 n + m_4 V + k_1$	$m_1 = 2.3687$ $m_2 = 0$ $m_3 = 0$ $m_4 = 0.0241$	-4.2179	0.9985	0.9970	0.9059
$P_{h8} = -4.2179 + 2.3687p + 0q + 0n + 0.0241V$						

4.32 Pearson Correlation Coefficient

A Pearson Correlation Coefficient measures the linear association between two variables. The correlation coefficient r_{xy} (also called Pearson's product moment correlation after Karl Pearson) is calculated by

$$r_{xy} = \frac{44623}{\sqrt{12681 \times 165774}} = 0.9732$$

$$r_{xy} = \frac{\sum((X - X_{\text{mean}}) * (Y - Y_{\text{mean}}))}{\sqrt{\sum(X - X_{\text{mean}})^2 \sum(Y - Y_{\text{mean}})^2}} \quad [83]$$

The correlation coefficient may take any value between -1 and +1. Assumptions: linear relationship between x and y, continuous random variables, both variables must be normally distributed, x and y must be independent of each other. Table 4.43 and Table

4.44 calculate the correlation coefficient of motor speed and electric power of conventional and energy saving power steering, respectively, at Torque= 0 Nm. First, we have calculate the mean of both the X and Y values.

Table 4.43: Pearson Correlation Coefficient of Motor Speed and Electric Power of Conventional Power Steering at Torque= 0 Nm

Motor Speed (X, rps)	Electric Power (Y, watt)	$(X - X_{mean})$	$(Y - Y_{mean})$	$(X - X_{mean}) * (Y - Y_{mean})$	$(X - X_{mean})^2$	$(Y - Y_{mean})^2$
15	20.472	-37.5	-101.378	3801.675	1406.25	10277.5
18.2	25.4496	-34.3	-96.4004	3306.534	1176.49	9293.037
21.2	29.9052	-31.3	-91.9448	2877.872	979.69	8453.846
24.5	34.1784	-28	-87.6716	2454.805	784	7686.309
27.5	39.7632	-25	-82.0868	2052.17	625	6738.243
30.6	46.112	-21.9	-75.738	1658.662	479.61	5736.245
33.8	52.7904	-18.7	-69.0596	1291.415	349.69	4769.228
36.9	60.2703	-15.6	-61.5797	960.6433	243.36	3792.059
40	68.7368	-12.5	-53.1132	663.915	156.25	2821.012
43.1	76.3543	-9.4	-45.4957	427.6596	88.36	2069.859
46.2	84.7756	-6.3	-37.0744	233.5687	39.69	1374.511
49.4	94.3125	-3.1	-27.5375	85.36625	9.61	758.3139
52.5	101.711	0	-20.139	0	0	405.5793
55.6	109.6272	3.1	-12.2228	-37.8907	9.61	149.3968
58.7	122.056	6.2	0.206	1.2772	38.44	0.042436
61.9	134.5677	9.4	12.7177	119.5464	88.36	161.7399
65	146.674	12.5	24.824	310.3	156.25	616.231
68.1	162.5778	15.6	40.7278	635.3537	243.36	1658.754
71.2	178.164	18.7	56.314	1053.072	349.69	3171.267
74.4	193.3176	21.9	71.4676	1565.14	479.61	5107.618
77.5	210.6225	25	88.7725	2219.313	625	7880.557
80.6	229.7726	28.1	107.9226	3032.625	789.61	11647.29
83.7	251.514	31.2	129.664	4045.517	973.44	16812.75
86.9	274.821	34.4	152.971	5262.202	1183.36	23400.13
90	297.8982	37.5	176.0482	6601.808	1406.25	30992.97
$X_{mean}=52.5$	$Y_{mean}=121.85$			$\Sigma = 44622.54$	$\Sigma = 12680.98$	$\Sigma = 165774.5$

Table 4.44: Pearson Correlation Coefficient of Motor Speed and Electric Power of Energy Saving Power Steering at Torque= 0 Nm

Motor Speed (X, rps)	Electric Power (Y, watt)	$(X - X_{mean})$	$(Y - Y_{mean})$	$(X - X_{mean}) * (Y - Y_{mean})$	$(X - X_{mean})^2$	$(Y - Y_{mean})^2$
45	81.189	12	28.479	341.748	144	811.0534
44	78.6844	11	25.9744	285.7184	121	674.6695
43	76.05	10	23.34	233.4	100	544.7556
42	73.6266	9	20.9166	188.2494	81	437.5042
41	71.079	8	18.369	146.952	64	337.4202
40	68.7368	7	16.0268	112.1876	49	256.8583
39	65.9087	6	13.1987	79.1922	36	174.2057
38	63.294	5	10.584	52.92	25	112.0211
37	60.5412	4	7.8312	31.3248	16	61.32769
36	58.0362	3	5.3262	15.9786	9	28.36841
35	55.44	2	2.73	5.46	4	7.4529
34	53.298	1	0.588	0.588	1	0.345744
33	51.097	0	-1.613	0	0	2.601769
32	49.0776	-1	-3.6324	3.6324	1	13.19433
31	46.931	-2	-5.779	11.558	4	33.39684
30	44.9964	-3	-7.7136	23.1408	9	59.49962
29	42.7818	-4	-9.9282	39.7128	16	98.56916
28	40.7792	-5	-11.9308	59.654	25	142.344
27	38.6722	-6	-14.0378	84.2268	36	197.0598
26	36.738	-7	-15.972	111.804	49	255.1048
25	34.77	-8	-17.94	143.52	64	321.8436

24	33.51	-9	-19.2	172.8	81	368.64
23	32.1636	-10	-20.5464	205.464	100	422.1546
22	30.8736	-11	-21.8364	240.2004	121	476.8284
21	29.6867	-12	-23.0233	276.2796	144	530.0723
$X_{mean}=33$	$Y_{mean}=52.71$			$\Sigma=2865.71$	$\Sigma=1300$	$\Sigma=6367.29$

$$r_{xy} = \frac{2865.7}{\sqrt{1300 * 6367.3}} = 0.996$$

Next, we calculated the difference between each of the individual X and Y values and their respective means. Then, we calculated the remaining values needed to complete the Pearson Correlation Coefficient formula. Then, we calculated the sums of the last three columns. Then, we put the values in the equation for the Pearson Correlation Coefficient and get the correlation coefficient.

Table 4.45: Pearson Correlation Coefficient of Motor Speed and Hydraulic Power of Conventional Power Steering at Torque= 5.23 Nm

Motor Speed (X, rps)	Hydraulic Power (Y, watt)	(X- X_{mean})	(Y- Y_{mean})	(X- X_{mean})*(Y- Y_{mean})	(X- X_{mean}) ²	(Y- Y_{mean}) ²
15	1.123596	-37.5	-46.5864	1746.99	1406.25	2170.293
18.2	2.235805	-34.3	-45.4742	1559.765	1176.49	2067.902
21.2	3.938277	-31.3	-43.7717	1370.055	979.69	1915.964
24.5	6.973783	-28	-40.7362	1140.614	784	1659.439
27.5	9.269663	-25	-38.4403	961.0084	625	1477.66
30.6	11.73573	-21.9	-35.9743	787.8365	479.61	1294.148
33.8	14.58337	-18.7	-33.1266	619.468	349.69	1097.374
36.9	17.10944	-15.6	-30.6006	477.3688	243.36	936.3944
40	19.47566	-12.5	-28.2343	352.9293	156.25	797.1782
43.1	22.98667	-9.4	-24.7233	232.3993	88.36	611.2432
46.2	27.2009	-6.3	-20.5091	129.2073	39.69	420.6232
49.4	32.6373	-3.1	-15.0727	46.72536	9.61	227.1862
52.5	36.3764	0	-11.3336	0	0	128.4504
55.6	39.81543	3.1	-7.89457	-24.4732	9.61	62.32422
58.7	43.39843	6.2	-4.31157	-26.7318	38.44	18.58966
61.9	49.89094	9.4	2.180936	20.5008	88.36	4.756483
65	58.42697	12.5	10.71697	133.9621	156.25	114.8534
68.1	67.53888	15.6	19.82888	309.3305	243.36	393.1843
71.2	77.22667	18.7	29.51667	551.9617	349.69	871.2336
74.4	87.83101	21.9	40.12101	878.6501	479.61	1609.696
77.5	97.23783	25	49.52783	1238.196	625	2453.006
80.6	106.0177	28.1	58.30768	1638.446	789.61	3399.785
83.7	112.0389	31.2	64.32888	2007.061	973.44	4138.204
86.9	119.6421	34.4	71.9321	2474.464	1183.36	5174.227
90	128.0899	37.5	80.37989	3014.246	1406.25	6460.926
$X_{mean}=52.5$	$Y_{mean}=47.71$			$\Sigma=21639.97$	$\Sigma=12681$	$\Sigma=39504$

$$r_{xy} = \frac{21640}{\sqrt{12681*39504}}=0.96$$

In Table 4.43, our result is 0.9732, or 97.32%. Since this value is close to 1, this is an indication that motor speed and electric power are strongly positively correlated. Tables 4.45 and 4.46 calculate the correlation coefficient of motor speed and hydraulic power of conventional and energy-saving power steering, respectively, at Torque= 5.23 Nm and the result shows a strong correlation between motor speed and hydraulic power.

Table 4.46: Pearson Correlation Coefficient of Motor Speed and Hydraulic Power of Energy Saving Power Steering at Torque= 5.23 Nm

Motor Speed (X, rps)	Hydraulic Power (Y, watt)	(X- X_{mean})	(Y- Y_{mean})	(X- X_{mean})*(Y- Y_{mean})	(X- X_{mean}) ²	(Y- Y_{mean}) ²
45	25.2809	12	11.2909	135.4908	144	127.4844
44	24.05993	11	10.06993	110.7692	121	101.4034
43	22.86891	10	8.878914	88.78914	100	78.83511
42	21.70787	9	7.717865	69.46079	81	59.56544
41	20.57678	8	6.586779	52.69423	64	43.38566
40	19.47566	7	5.485655	38.39959	49	30.09242
39	18.69663	6	4.706629	28.23978	36	22.15236
38	17.93258	5	3.942584	19.71292	25	15.54397
37	17.18352	4	3.193521	12.77408	16	10.19857
36	16.44944	3	2.459438	7.378315	9	6.048836
35	15.73034	2	1.740337	3.480674	4	3.028773
34	14.77154	1	0.781536	0.781536	1	0.610798
33	13.8427	0	-0.1473	0	0	0.021698
32	12.94382	-1	-1.04618	1.04618	1	1.094492
31	12.07491	-2	-1.91509	3.830187	4	3.667584
30	11.23596	-3	-2.75404	8.262135	9	7.584764
29	10.42697	-4	-3.56303	14.25213	16	12.69521
28	9.64794	-5	-4.34206	21.7103	25	18.85348
27	8.898876	-6	-5.09112	30.54674	36	25.91954
26	8.179775	-7	-5.81022	40.67157	49	33.75871
25	7.490637	-8	-6.49936	51.99491	64	42.24172
24	6.47191	-9	-7.51809	67.66281	81	56.52168
23	5.513109	-10	-8.47689	84.76891	100	71.85769
22	4.614232	-11	-9.37577	103.1334	121	87.90502
21	3.775281	-12	-10.2147	122.5766	144	104.3405
$X_{mean}=33$	$Y_{mean}=13.99$			$\Sigma =1118.42$	$\Sigma =1300$	$\Sigma =964.81$

$$r_{xy} = \frac{1118.4}{\sqrt{1300 * 964.81}} = 0.99$$

4.33 Comparison Result with Existing Work

Table 4.47 shows the comparative result of relevant existing work with the present work. The energy saving percentage of the proportional solenoid valve controlled technique is 48 because the power source is the same as conventional. The solenoid valve reduced energy consumption by bypassing the main flow rate. Though the same motor speed control technique is used in the proposed work and Gupta et al. But the percentage is greater in the proposed work. Because the motor speed map used in the proposed work is energy efficient. Table 4.48 shows a comparison of motor speed

response between proposed and existing works. An overshoot free motor speed control in the EHPS system can provide a good steering feel for the driver. All the work in Table 4.48 used the Fuzzy-PID control method. The proposed work has no overshoot (negligible), but the other two works have overshoot, which causes a bad steering feel.

Table 4.47: Energy Savings Comparison with Existing Works

The Work	Technique	Control Method	Energy savings over conventional (Hydraulic)
Kozuma et al.,[84]	Proportional Solenoid Valve Control		48%
Gupta et al.,[36]	Motor Speed Control		60 %
Proposed Work	Motor Speed Control	Fuzzy-PID	69.71%

Table 4.48: Motor Speed Response Comparison with Existing Works

The Work	Technique	Control Method	Overshoot	
			PID	Fuzzy-PID
Dong,W., Song, J., Cheng,S., Yu, L., Lu, Z., [37]	Motor Speed Control	Fuzzy-PI	Overshoot and reverse overshoot	Overshoot and reverse overshoot is minimized
Yong,C.,[85]	Motor Speed Control	Fuzzy-PID	Overshoot	Overshoot is minimized
Proposed Work	Motor Speed Control	Fuzzy-PID	No Overshoot	No Overshoot and settling time is reduced

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 CONCLUSION

This research has experimented an energy-saving model of hydraulic power steering system by electrification of the hydraulic power steering system. In engine driven power steering, the energy to drive power steering comes from the vehicle's engine. The power consumption is proportional to the vehicle speed. As the speed of the vehicle increases, the vane pump discharge rate also increases. So, the power consumption increases.

The energy-saving electro-hydraulic model was simulated in Matlab. The hydraulic model and the motor control algorithm have been combined and run simultaneously. The speed of the motor is controlled using a PID controller and an adaptive PID controller. The integral error of the PID at different motor speed set point is minimized using adaptive PID, where the different integral gain at different motor speed set point is estimated by trial and error during simulation. The simulation result shows that the pump discharge rate increases with motor speed. So, the hydraulic pressure as well as the hydraulic force increases. The piston speed follows the pump discharge rate curve. When the pump discharge rate is constant, the piston speed decreases and goes to saturation point.

In our thesis, energy is saved in the power steering system by controlling the motor speed. We have replaced the vane pump with a DC motor pump. The energy source of the DC motor pump is a 45-Ah Lithium-ion car battery. We have controlled the pump discharge rate by controlling the speed of the DC motor. An Arduino microcontroller and a PWM controller have been used to control the speed of the DC motor. We have used the PID control method to control the DC motor speed. We have calculated the preferred motor speed with respect to vehicle speed. At different vehicle speeds, the recommended motor speed is different. So, the PID controller set point is different at different vehicle speeds. The PID controller can reach the set point, but the response is not fast. The fast response of this system ensures a good steering feel. Steering feel is defined as the comfortable steering effort of a driver where steering is not too light or

too tight. The steering becomes very light with increasing motor speed. The PID controller can't provide a good steering feel, though it can save energy. To improve the steering feel, we have applied fuzzy-logic to tune the PID parameters. We have tuned the proportional and integral gain of PID using fuzzy logic. The input of the fuzzy logic block is the difference between the set point and process variable, and the outputs of the fuzzy block are the proportional gain and integral gain. The results show that the system responds faster than PID.

The energy consumption of this system has been divided into electrical power and hydraulic power. We have tested the electric and hydraulic power consumption of the system for 0 Nm, 3.98 Nm, 4.23 Nm, 4.48 Nm, and 5.23 Nm torques. The results show that power consumption is different at different torques. The vehicle speed range is 0-120 Km/h. For conventional power steering systems, the vehicle speed (x) and motor speed (y) equation is $y = 0.625x + 15$, and for energy-saving power steering, the vehicle speed (x) and motor speed (y) equation is $y = -0.2x + 45$. The results show that power consumption has been reduced using PID and Fuzzy-PID controllers as compared to conventional controllers.

We have experimented with two different motor speed set points: 22 RPS and 45 RPS. For 45 RPS, the set point is 45 RPS and the current speed is 22 RPS. For 22 RPS, the set point is 22 RPS and the current speed is 45 RPS. Using PID and Fuzzy-PID controllers, the total electric and hydraulic power consumption in watt-hours has been reduced as compared to the conventional. Though Fuzzy-PID consumes more power than PID, it ensures a good steering feel, and power consumption has been reduced as compared to the conventional.

5.1.1 Key Findings

1. Motor speed determines the power consumption of an energy-saving electrohydraulic power steering system.
2. In energy-saving power steering, power consumption decreases with vehicle speed.
3. Power consumption increases with steering torque.
4. Fuzzy PID responds faster than PID and can provide a good steering feel.
5. The settling time has been reduced using Fuzzy PID.

5.1.2 Limitations

1. The battery power is limited.
2. The hydraulic pressure is limited to 40 bar.

5.1.3 Future Work

The power source in our experiment is a DC power source, and the actuator is a DC motor. As high-power DC motors are not available in our country, we can use AC motors. Because high power AC motors are available in our country and the cost is low as compared to DC motors. The high hydraulic pressure can be generated using high-power AC motors. Inverters can be used to convert the DC supply into AC. Motor speed maps can be fine-tuned using neural networks.

5.2 RECOMMENDATIONS

1. Energy saving power steering saves energy (watts) compared to conventional power steering. The fuzzy-PID algorithm controls the motor speed efficiently. The hydraulic and electric power consumption have been reduced.
2. The battery and motor power have to be calculated according to the vehicle's front axle weight.

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APPENDIX A

Table A1: Electric Power and Hydraulic Power at Different Vehicle Speed and Motor Speed of Conventional Power Steering at Torque=4.23 Nm

Conventional Power Steering, Torque=4.23 Nm							
Vehicle speed (km/h)	Motor Speed (RPS)	Electric Power			Hydraulic Power		
		Voltage (V)	Current (A)	Power (W)	Pressure (bar)	Flow rate (lpm)	Power (W)
0	15	2.58	9.8	25.284	1	0.337079	0.561798
5	18.2	2.82	10.86	30.6252	1.64	0.408989	1.117903
10	21.2	3.08	12.07	37.1756	2.48	0.476404	1.969139
15	24.5	3.43	13.74	47.1282	3.8	0.550562	3.486891
20	27.5	3.67	15	55.05	5	0.617978	5.149813
25	30.6	3.92	16.23	63.6216	6.24	0.68764	7.151461
30	33.8	4.25	17.46	74.205	7.52	0.759551	9.5197
35	36.9	4.6	18.87	86.802	8.76	0.829213	12.10652
40	40	4.98	20.4	101.592	10	0.898876	14.98127
45	43.1	5.22	20.93	109.2546	10.62	0.968539	17.14315
50	46.2	5.51	21.81	120.1731	11.24	1.038202	19.44899
55	49.4	5.9	23.26	137.234	11.88	1.110112	21.98022
60	52.5	6.28	24.53	154.0484	13	1.179775	25.5618
65	55.6	6.66	25.71	171.2286	14.12	1.249438	29.40345
70	58.7	7.04	26.66	187.6864	14.74	1.319101	32.40592
75	61.9	7.5	27.72	207.9	15.38	1.391011	35.65625
80	65	8	28	224	16	1.460674	38.95131
85	68.1	8.49	29.66	251.8134	16.62	1.530337	42.39034
90	71.2	9.01	30.48	274.6248	17.24	1.6	45.97333
95	74.4	9.58	31.25	299.375	17.88	1.67191	49.82292
100	77.5	10.04	32.36	324.8944	18	1.741573	52.24719
105	80.6	10.5	33.56	352.38	18	1.811236	54.33708
110	83.7	11.06	34.76	384.4456	18	1.880899	56.42697
115	86.9	11.56	35.92	415.2352	18	1.952809	58.58427
120	90	12	37	444	18	2.022472	60.67416
				Total= 4579 W			Total= 690 W

Table A2: Electric Power and Hydraulic Power at Different Vehicle Speed and Motor Speed of Energy Saving Power Steering at Torque=4.23 Nm

Energy Saving Power Steering, Torque=4.23 Nm							
Vehicle speed (km/h)	Motor Speed (RPS)	Electric Power			Hydraulic Power		
		Voltage (V)	Current (A)	Power (W)	Pressure (bar)	Flow rate (lpm)	Power (W)
0	45	5.3	21.2	112.36	11	1.011236	18.53933
5	44	5.2	21	109.2	10.8	0.988764	17.79775
10	43	5.2	20.9	108.68	10.6	0.966292	17.07116
15	42	5.1	20.7	105.57	10.4	0.94382	16.35955
20	41	5	20.5	102.5	10.2	0.921348	15.66292
25	40	4.9	20.4	99.96	10	0.898876	14.98127
30	39	4.8	19.9	95.52	9.6	0.876404	14.02247
35	38	4.7	19.4	91.18	9.2	0.853933	13.09363
40	37	4.6	18.9	86.94	8.8	0.831461	12.19476
45	36	4.4	18.4	80.96	8.4	0.808989	11.32584
50	35	4.3	17.9	76.97	8	0.786517	10.48689
55	34	4.2	17.5	73.5	7.6	0.764045	9.677903
60	33	4.1	17.1	70.11	7.2	0.741573	8.898876
65	32	4	16.7	66.8	6.8	0.719101	8.149813
70	31	3.9	16.3	63.57	6.4	0.696629	7.430712
75	30	3.8	16	60.8	6	0.674157	6.741573
80	29	3.7	15.6	57.72	5.6	0.651685	6.082397
85	28	3.7	15.2	56.24	5.2	0.629213	5.453184
90	27	3.6	14.8	53.28	4.8	0.606742	4.853933
95	26	3.5	14.4	50.4	4.4	0.58427	4.284644
100	25	3.4	14	47.6	4	0.561798	3.745318
105	24	3.3	13.4	44.22	3.6	0.539326	3.235955
110	23	3.2	12.9	41.28	3.2	0.516854	2.756554
115	22	3.1	12.4	38.44	2.8	0.494382	2.307116
120	21	3	11.9	35.7	2.4	0.47191	1.88764
				Total= 1829 W			Total= 237 W

Table A3: Electric Power and Hydraulic Power at Different Vehicle Speed and Motor Speed of Conventional Power Steering at Torque=4.48 Nm

Conventional Power Steering, Torque=4.48 Nm							
Vehicle speed (km/h)	Motor Speed (RPS)	Electric Power			Hydraulic Power		
		Voltage (V)	Current (A)	Power (W)	Pressure (bar)	Flow rate (lpm)	Power (W)
0	15	2.58	9.8	25.284	0	0.337079	0
5	18.2	2.82	10.95	30.879	1.28	0.408989	0.872509
10	21.2	3.08	12.2	37.576	2.48	0.476404	1.969139
15	24.5	3.43	13.88	47.6084	3.8	0.550562	3.486891
20	27.5	3.74	15.3	57.222	5	0.617978	5.149813
25	30.6	4.05	16.7	67.635	6.24	0.68764	7.151461
30	33.8	4.35	17.98	78.213	7.52	0.759551	9.5197
35	36.9	4.66	19.2	89.472	8.76	0.829213	12.10652
40	40	4.98	20.4	101.592	10	0.898876	14.98127
45	43.1	5.36	21.76	116.6336	11.24	0.968539	18.14397
50	46.2	5.73	23.04	132.0192	12.24	1.038202	21.17933
55	49.4	6.09	24.24	147.6216	12.88	1.110112	23.83041
60	52.5	6.56	25.8	169.248	13.5	1.179775	26.54494
65	55.6	7.06	27.35	193.091	14.24	1.249438	29.65333
70	58.7	7.55	28.51	215.2505	15.48	1.319101	34.03281
75	61.9	8.06	29.55	238.173	16.38	1.391011	37.97461
80	65	8.56	30.46	260.7376	17	1.460674	41.38577
85	68.1	9.2	31.41	288.972	17.62	1.530337	44.9409
90	71.2	9.83	32.36	318.0988	18.48	1.6	49.28
95	74.4	10.46	33.34	348.7364	19.76	1.67191	55.06157
100	77.5	11.12	34.63	385.0856	21	1.741573	60.95506
105	80.6	11.68	35.89	419.1952	22.12	1.811236	66.77423
110	83.7	11.74	36.74	431.3276	22.74	1.880899	71.28607
115	86.9	11.85	37.73	447.1005	23.38	1.952809	76.09446
120	90	12	38.76	465.12	24	2.022472	80.89888
				Total= 5111 W			Total= 793 W

Table A4: Electric Power and Hydraulic Power at Different Vehicle Speed and Motor Speed of Energy Saving Power Steering at Torque=4.48 Nm

Energy Saving Power Steering, Torque=4.48 Nm							
Vehicle speed (km/h)	Motor Speed (RPS)	Electric Power			Hydraulic Power		
		Voltage (V)	Current (A)	Power (W)	Pressure (bar)	Flow rate (lpm)	Power (W)
0	45	5.6	22.6	126.56	12	1.011236	20.22472
5	44	5.47	22.16	121.2152	11.6	0.988764	19.1161
10	43	5.35	21.72	116.202	11.2	0.966292	18.03745
15	42	5.23	21.28	111.2944	10.8	0.94382	16.98876
20	41	5.11	20.84	106.4924	10.4	0.921348	15.97004
25	40	4.98	20.4	101.592	10	0.898876	14.98127
30	39	4.88	20.01	97.6488	9.6	0.876404	14.02247
35	38	4.78	19.62	93.7836	9.2	0.853933	13.09363
40	37	4.67	19.24	89.8508	8.8	0.831461	12.19476
45	36	4.57	18.85	86.1445	8.4	0.808989	11.32584
50	35	4.47	18.46	82.5162	8	0.786517	10.48689
55	34	4.37	18.06	78.9222	7.6	0.764045	9.677903
60	33	4.28	17.66	75.5848	7.2	0.741573	8.898876
65	32	4.18	17.26	72.1468	6.8	0.719101	8.149813
70	31	4.09	16.86	68.9574	6.4	0.696629	7.430712
75	30	4	16.46	65.84	6	0.674157	6.741573
80	29	3.89	16	62.24	5.6	0.651685	6.082397
85	28	3.79	15.53	58.8587	5.2	0.629213	5.453184
90	27	3.68	15.06	55.4208	4.8	0.606742	4.853933
95	26	3.58	14.59	52.2322	4.4	0.58427	4.284644
100	25	3.48	14.13	49.1724	4	0.561798	3.745318
105	24	3.37	13.62	45.8994	3.6	0.539326	3.235955
110	23	3.27	13.11	42.8697	3.2	0.516854	2.756554
115	22	3.17	12.61	39.9737	2.8	0.494382	2.307116
120	21	3.06	12.1	37.026	2.4	0.47191	1.88764
				Total= 1938 W			Total= 241 W

Table A5: Electric Power and Hydraulic Power at Different Vehicle Speed and Motor Speed of Conventional Power Steering at Torque=5.23 Nm

Conventional Power Steering, Torque=5.23 Nm							
Vehicle speed (km/h)	Motor Speed (RPS)	Electric Power			Hydraulic Power		
		Voltage (V)	Current (A)	Power (W)	Pressure (bar)	Flow rate (lpm)	Power (W)
0	15	2.58	10.26	26.4708	2	0.337079	1.123596
5	18.2	2.82	11.41	32.1762	3.28	0.408989	2.235805
10	21.2	3.08	12.69	39.0852	4.96	0.476404	3.938277
15	24.5	3.43	14.4	49.392	7.6	0.550562	6.973783
20	27.5	3.74	15.86	59.3164	9	0.617978	9.269663
25	30.6	4.04	17.28	69.8112	10.24	0.68764	11.73573
30	33.8	4.28	18.43	78.8804	11.52	0.759551	14.58337
35	36.9	4.6	19.72	90.712	12.38	0.829213	17.10944
40	40	4.98	21.13	105.2274	13	0.898876	19.47566
45	43.1	5.28	22.37	118.1136	14.24	0.968539	22.98667
50	46.2	5.56	23.56	130.9936	15.72	1.038202	27.2009
55	49.4	5.83	24.71	144.0593	17.64	1.110112	32.6373
60	52.5	6.32	26.46	167.2272	18.5	1.179775	36.3764
65	55.6	6.83	28.2	192.606	19.12	1.249438	39.81543
70	58.7	7.15	29.28	209.352	19.74	1.319101	43.39843
75	61.9	7.66	30.79	235.8514	21.52	1.391011	49.89094
80	65	8.28	32.53	269.3484	24	1.460674	58.42697
85	68.1	9.09	33.85	307.6965	26.48	1.530337	67.53888
90	71.2	9.79	35.59	348.4261	28.96	1.6	77.22667
95	74.4	10.3	38.06	392.018	31.52	1.67191	87.83101
100	77.5	10.98	39.66	435.4668	33.5	1.741573	97.23783
105	80.6	11.6	41.02	475.832	35.12	1.811236	106.0177
110	83.7	11.76	42.18	496.0368	35.74	1.880899	112.0389
115	86.9	11.89	43.83	521.1387	36.76	1.952809	119.6421
120	90	12	45.73	548.76	38	2.022472	128.0899
				Total= 5543 W			Total= 1192 W

Table A6: Electric Power and Hydraulic Power at Different Vehicle Speed and Motor Speed of Energy Saving Power Steering at Torque=5.23 Nm

Energy Saving Power Steering, Torque=5.23 Nm							
Vehicle speed (km/h)	Motor Speed (RPS)	Electric Power			Hydraulic Power		
		Voltage (V)	Current (A)	Power (W)	Pressure (bar)	Flow rate (lpm)	Power (W)
0	45	5.45	23.13	126.0585	15	1.011236	25.2809
5	44	5.36	22.73	121.8328	14.6	0.988764	24.05993
10	43	5.27	22.33	117.6791	14.2	0.966292	22.86891
15	42	5.17	21.93	113.3781	13.8	0.94382	21.70787
20	41	5.08	21.53	109.3724	13.4	0.921348	20.57678
25	40	4.98	21.13	105.2274	13	0.898876	19.47566
30	39	4.86	20.67	100.4562	12.8	0.876404	18.69663
35	38	4.74	20.22	95.8428	12.6	0.853933	17.93258
40	37	4.62	19.77	91.3374	12.4	0.831461	17.18352
45	36	4.49	19.32	86.7468	12.2	0.808989	16.44944
50	35	4.37	18.86	82.4182	12	0.786517	15.73034
55	34	4.3	18.5	79.55	11.6	0.764045	14.77154
60	33	4.22	18.14	76.5508	11.2	0.741573	13.8427
65	32	4.15	17.78	73.787	10.8	0.719101	12.94382
70	31	4.07	17.42	70.8994	10.4	0.696629	12.07491
75	30	4	17.06	68.24	10	0.674157	11.23596
80	29	3.89	16.58	64.4962	9.6	0.651685	10.42697
85	28	3.79	16.1	61.019	9.2	0.629213	9.64794
90	27	3.68	15.62	57.4816	8.8	0.606742	8.898876
95	26	3.58	15.14	54.2012	8.4	0.58427	8.179775
100	25	3.48	14.66	51.0168	8	0.561798	7.490637
105	24	3.37	14.14	47.6518	7.2	0.539326	6.47191
110	23	3.27	13.62	44.5374	6.4	0.516854	5.513109
115	22	3.17	13.1	41.527	5.6	0.494382	4.614232
120	21	3.06	12.58	38.4948	4.8	0.47191	3.775281
				Total= 1979 W			Total= 349 W

Table A7: Electric Power and Hydraulic Power at Different Vehicle Speed and Motor Speed of Energy Saving Power Steering (PID) at Torque=5.23 Nm

PID T=5.23 Nm							
Vehicle speed (km/h)	Motor Speed (RPS)	Voltage (V)	Current (A)	Power (W)	Pressure (bar)	Flow rate (lpm)	Power (W)
0	45	5.4	22.75	122.85	14.98	0.992584	24.78152
5	44	5.3	22.35	118.455	14.3	0.987416	23.53341
10	43	5.18	22	113.96	13.8	0.955506	21.97663
15	42	5.1	21.7	110.67	13.2	0.939775	20.67506
20	41	5	21.33	106.65	13.1	0.916404	20.00816
25	40	4.86	20.97	101.9142	12.7	0.893933	18.92157
30	39	4.75	20.5	97.375	12.6	0.872584	18.32427
35	38	4.63	19.9	92.137	12.4	0.844719	17.45753
40	37	4.49	19.5	87.555	12.2	0.830112	16.87895
45	36	4.38	19	83.22	12	0.80809	16.1618
50	35	4.31	18.7	80.597	11.6	0.773483	14.95401
55	34	4.25	18.4	78.2	11.2	0.762697	14.237
60	33	4.17	18	75.06	10.8	0.728539	13.11371
65	32	4.09	17.51	71.6159	10.4	0.706067	12.2385
70	31	4.02	17.3	69.546	10.1	0.683371	11.50341
75	30	3.91	16.87	65.9617	9.7	0.658427	10.64457
80	29	3.81	16.4	62.484	9.3	0.639326	9.909551
85	28	3.7	15.88	58.756	8.9	0.622022	9.226667
90	27	3.52	15.3	53.856	8.4	0.598876	8.38427
95	26	3.5	14.9	52.15	8.1	0.580674	7.839101
100	25	3.39	14	47.46	7.4	0.541124	6.673858
105	24	3.3	13.8	45.54	6.5	0.533034	5.774532
110	23	3.2	13.5	43.2	5.8	0.516629	4.994082
115	22	3.1	12.9	39.99	5	0.505618	4.213483
120	21	3	12	36	4.2	0.47191	3.303371
				1915.2			335.72

Table A8: Electric Power and Hydraulic Power at Different Vehicle Speed and Motor Speed of Energy Saving Power Steering (Fuzzy-PID) at Torque=5.23 Nm

Fuzzy PID T=5.23 Nm							
Vehicle speed (km/h)	Motor Speed (RPS)	Voltage (V)	Current (A)	Power (W)	Pressure (bar)	Flow rate (lpm)	Power (W)
0	45	5.5	23.5	129.25	15.1	1.012809	25.48903
5	44	5.38	22.9	123.202	14.8	0.993258	24.50037
10	43	5.27	22.4	118.048	14.4	0.966292	23.19101
15	42	5.18	22.1	114.478	14	0.945618	22.06442
20	41	5.1	21.7	110.67	13.9	0.942247	21.82873
25	40	5	21.3	106.5	13.4	0.900674	20.11506
30	39	4.96	20.8	103.168	13	0.878652	19.03745
35	38	4.79	20.4	97.716	12.8	0.861124	18.37064
40	37	4.65	19.8	92.07	12.6	0.839101	17.62112
45	36	4.5	19.5	87.75	12.4	0.809438	16.72839
50	35	4.4	19	83.6	12.2	0.791011	16.0839
55	34	4.4	18.5	81.4	11.9	0.764944	15.17139
60	33	4.3	18.2	78.26	11.5	0.743596	14.25225
65	32	4.17	17.8	74.226	11	0.721348	13.22472
70	31	4.09	17.4	71.166	10.8	0.717303	12.91146
75	30	4.1	17	69.7	10.3	0.681573	11.70034
80	29	3.96	16.7	66.132	10	0.665843	11.09738
85	28	3.84	16.3	62.592	9.6	0.638652	10.21843
90	27	3.76	15.8	59.408	9.2	0.616629	9.454981
95	26	3.64	15.4	56.056	8.6	0.594607	8.522697
100	25	3.56	15.1	53.756	8	0.566742	7.556554
105	24	3.45	14.5	50.025	7.6	0.54809	6.942472
110	23	3.3	13.8	45.54	6.9	0.529663	6.091124
115	22	3.2	13.5	43.2	6	0.500674	5.006742
120	21	3.1	12.9	39.99	5	0.482247	4.018727
				2017.9			361.19

Table A9: Electric Power (Conventional and Manual) at Torque=5.23 Nm, Setpoint=45 RPS

T=5.23 Nm, Conventional, 22 to 45 RPS					T=5.23 Nm, Energy saving with manual, 22 to 45 RPS				
Time (s)	Motor Speed (RPS)	Voltage (V)	Current (A)	Power (W)	Time(s)	Motor Speed (RPS)	Voltage (V)	Current (A)	Power (W)
0	45	5.54	23.19	128.4726	0	22	3.17	13.1	41.527
0.5	45	5.54	23.19	128.4726	0.5	33.9	4.295	18.4784	79.36473
1	45	5.54	23.19	128.4726	1	43	5.275	22.35	117.8963
1.5	45	5.54	23.19	128.4726	1.5	45	5.54	23.19	128.4726
2	45	5.54	23.19	128.4726	2	45	5.54	23.19	128.4726
2.5	45	5.54	23.19	128.4726	2.5	45	5.54	23.19	128.4726
3	45	5.54	23.19	128.4726	3	45	5.54	23.19	128.4726
3.5	45	5.54	23.19	128.4726	3.5	45	5.54	23.19	128.4726
4	45	5.54	23.19	128.4726	4	45	5.54	23.19	128.4726
4.5	45	5.54	23.19	128.4726	4.5	45	5.54	23.19	128.4726
5	45	5.54	23.19	128.4726	5	45	5.54	23.19	128.4726
5.5	45	5.54	23.19	128.4726	5.5	45	5.54	23.19	128.4726
6	45	5.54	23.19	128.4726	6	45	5.54	23.19	128.4726
6.5	45	5.54	23.19	128.4726	6.5	45	5.54	23.19	128.4726
7	45	5.54	23.19	128.4726	7	45	5.54	23.19	128.4726
7.5	45	5.54	23.19	128.4726	7.5	45	5.54	23.19	128.4726
8	45	5.54	23.19	128.4726	8	45	5.54	23.19	128.4726
8.5	45	5.54	23.19	128.4726	8.5	45	5.54	23.19	128.4726
9	45	5.54	23.19	128.4726	9	45	5.54	23.19	128.4726
9.5	45	5.54	23.19	128.4726	9.5	45	5.54	23.19	128.4726
10	45	5.54	23.19	128.4726	10	45	5.54	23.19	128.4726
			Total:	2697.92				Total:	2551.29

Table A10: Electric Power (PID and Fuzzy-PID) at Torque=5.23 Nm, Setpoint=45 RPS

T=5.23 Nm, PID, 22 to 45 RPS					T=5.23 Nm, Fuzzy PID, 22 to 45 RPS				
Time (s)	Motor Speed (RPS)	Voltage (V)	Current (A)	Power (W)	Time(s)	Motor Speed (RPS)	Voltage (V)	Current (A)	Power (W)
0	21.79	3.1469	12.9908	40.88075	0	22	3.17	13.1	41.527
0.5	22.64	3.234	13.4328	43.44168	0.5	32.52	4.1864	17.9672	75.21789
1	25.71	3.551	15.0008	53.26784	1	41.3	5.107	21.65	110.5666
1.5	28.45	3.835	16.316	62.57186	1.5	42.78	5.248	22.242	116.726
2	31.42	4.1036	17.5712	72.10518	2	44.18	5.3762	22.802	122.5881
2.5	33.94	4.2952	18.4784	79.36842	2.5	44.55	5.4095	22.95	124.148
3	35.96	4.4852	19.3016	86.57154	3	44.55	5.4095	22.95	124.148
3.5	37.59	4.6908	20.0355	93.98252	3.5	44.78	5.4302	23.042	125.1227
4	38.83	4.8396	20.5935	99.6643	4	45.07	5.45	23.13	126.0585
4.5	39.78	4.9536	21.0288	104.1683	4.5	45.07	5.45	23.13	126.0585
5	41.04	5.0836	21.546	109.5312	5	45.07	5.45	23.13	126.0585
5.5	41.82	5.1538	21.858	112.6518	5.5	45.07	5.45	23.13	126.0585
6	42.44	5.214	22.106	115.2607	6	45.07	5.45	23.13	126.0585
6.5	42.52	5.222	22.138	115.6046	6.5	45.07	5.45	23.13	126.0585
7	43.06	5.2754	22.354	117.9263	7	45.07	5.45	23.13	126.0585
7.5	43.22	5.2898	22.418	118.5867	7.5	45.07	5.45	23.13	126.0585
8	43.31	5.2979	22.454	118.959	8	45.07	5.45	23.13	126.0585
8.5	43.68	5.3312	22.602	120.4958	8.5	45.07	5.45	23.13	126.0585
9	43.82	5.3438	22.658	121.0798	9	45.07	5.45	23.13	126.0585
9.5	43.94	5.3546	22.706	121.5815	9.5	45.07	5.45	23.13	126.0585
10	44.17	5.3753	22.798	122.5461	10	45.07	5.45	23.13	126.0585
			Total:	2030.24				Total:	2478.8

**Table A11: Electric Power (Conventional and Manual) at Torque=5.23 Nm,
Setpoint=22 RPS**

T=5.23 Nm, Conventional, 45 to 22 RPS					T=5.23 Nm, Energy saving with manual, 45 to 22 RPS				
Time (s)	Motor Speed (RPS)	Voltage (V)	Current (A)	Power (W)	Time(s)	Motor Speed (RPS)	Voltage (V)	Current (A)	Power (W)
0	22	3.17	13.12	41.5904	0	45	5.54	23.19	128.4726
0.5	22	3.17	13.12	41.5904	0.5	33	4.22	18	75.96
1	22	3.17	13.12	41.5904	1	26	3.6	15.2	54.72
1.5	22	3.17	13.12	41.5904	1.5	22	3.17	13.1	41.527
2	22	3.17	13.12	41.5904	2	22	3.17	13.1	41.527
2.5	22	3.17	13.12	41.5904	2.5	22	3.17	13.1	41.527
3	22	3.17	13.12	41.5904	3	22	3.17	13.1	41.527
3.5	22	3.17	13.12	41.5904	3.5	22	3.17	13.1	41.527
4	22	3.17	13.12	41.5904	4	22	3.17	13.1	41.527
4.5	22	3.17	13.12	41.5904	4.5	22	3.17	13.1	41.527
5	22	3.17	13.12	41.5904	5	22	3.17	13.1	41.527
5.5	22	3.17	13.12	41.5904	5.5	22	3.17	13.1	41.527
6	22	3.17	13.12	41.5904	6	22	3.17	13.1	41.527
6.5	22	3.17	13.12	41.5904	6.5	22	3.17	13.1	41.527
7	22	3.17	13.12	41.5904	7	22	3.17	13.1	41.527
7.5	22	3.17	13.12	41.5904	7.5	22	3.17	13.1	41.527
8	22	3.17	13.12	41.5904	8	22	3.17	13.1	41.527
8.5	22	3.17	13.12	41.5904	8.5	22	3.17	13.1	41.527
9	22	3.17	13.12	41.5904	9	22	3.17	13.1	41.527
9.5	22	3.17	13.12	41.5904	9.5	22	3.17	13.1	41.527
10	22	3.17	13.12	41.5904	10	22	3.17	13.1	41.527
Total:				873.39	Total:				1006.63

**Table A12: Electric Power (PID and Fuzzy-PID) at Torque=5.23 Nm,
Setpoint=22 RPS**

T=5.23 Nm, PID, 45 to 22 RPS					T=5.23 Nm, Fuzzy PID, 45 to 22 RPS				
Time (s)	Motor Speed (RPS)	Voltage (V)	Current (A)	Power (W)	Time(s)	Motor Speed (RPS)	Voltage (V)	Current (A)	Power (W)
0	44.63	5.4167	22.982	124.4866	0	44.89	5.4401	23.086	125.5901
0.5	44.29	5.3861	22.846	123.0508	0.5	41.93	5.1637	21.902	113.0954
1	41.57	5.1313	21.758	111.6468	1	29.63	3.9593	16.8824	66.84249
1.5	38.6	4.812	20.49	98.59788	1.5	25.5	3.53	14.9	52.597
2	36.02	4.4926	19.329	86.83747	2	24.39	3.4129	14.3428	48.95054
2.5	33.69	4.2752	18.3884	78.61409	2.5	23.57	3.327	13.9164	46.29986
3	31.92	4.1436	17.7512	73.55387	3	22.89	3.259	13.5628	44.20117
3.5	30.41	4.0287	17.2076	69.32426	3.5	22.28	3.198	13.2456	42.35943
4	28.94	3.884	16.5512	64.28486	4	21.97	3.1667	13.0844	41.43437
4.5	27.68	3.7548	15.9464	59.87554	4.5	21.98	3.1678	13.0896	41.46523
5	26.65	3.645	15.452	56.32254	5	22.1	3.18	13.152	41.82336
5.5	25.84	3.564	15.0632	53.68524	5.5	22.1	3.18	13.152	41.82336
6	25.22	3.502	14.7656	51.70913	6	22.1	3.18	13.152	41.82336
6.5	24.57	3.4327	14.4364	49.55583	6.5	22.1	3.18	13.152	41.82336
7	24.08	3.3788	14.1816	47.91679	7	22.1	3.18	13.152	41.82336
7.5	23.72	3.342	13.9944	46.76928	7.5	22.1	3.18	13.152	41.82336
8	23.25	3.295	13.75	45.30625	8	22.1	3.18	13.152	41.82336
8.5	22.99	3.269	13.6148	44.50678	8.5	22.1	3.18	13.152	41.82336
9	22.97	3.267	13.6044	44.44557	9	22.1	3.18	13.152	41.82336
9.5	22.6	3.23	13.412	43.32076	9.5	22.1	3.18	13.152	41.82336
10	22.5	3.22	13.36	43.0192	10	22.1	3.18	13.152	41.82336
Total:				1416.82	Total:				1082.89

Table A13: Hydraulic Power (Conventional and Manual) at Torque=5.23 Nm, Setpoint=45 RPS

T=5.23 Nm, Conventional, 22 to 45 RPS					T=5.23 Nm, Energy saving with manual, 22 to 45 RPS				
Time (s)	Motor Speed (RPS)	Pressure (bar)	Flow rate (lpm)	Power (W)	Time (s)	Motor Speed (RPS)	Pressure (bar)	Flow rate (lpm)	Power (W)
0	45	14.98	1.011	25.2413	0	22	5.6	0.494382	4.614232
0.5	45	14.98	1.011	25.2413	0.5	33.9	11.57	0.7617	14.68812
1	45	14.98	1.011	25.2413	1	43	14.2	0.9663	22.8691
1.5	45	14.98	1.011	25.2413	1.5	45	14.98	1.011	25.2413
2	45	14.98	1.011	25.2413	2	45	14.98	1.011	25.2413
2.5	45	14.98	1.011	25.2413	2.5	45	14.98	1.011	25.2413
3	45	14.98	1.011	25.2413	3	45	14.98	1.011	25.2413
3.5	45	14.98	1.011	25.2413	3.5	45	14.98	1.011	25.2413
4	45	14.98	1.011	25.2413	4	45	14.98	1.011	25.2413
4.5	45	14.98	1.011	25.2413	4.5	45	14.98	1.011	25.2413
5	45	14.98	1.011	25.2413	5	45	14.98	1.011	25.2413
5.5	45	14.98	1.011	25.2413	5.5	45	14.98	1.011	25.2413
6	45	14.98	1.011	25.2413	6	45	14.98	1.011	25.2413
6.5	45	14.98	1.011	25.2413	6.5	45	14.98	1.011	25.2413
7	45	14.98	1.011	25.2413	7	45	14.98	1.011	25.2413
7.5	45	14.98	1.011	25.2413	7.5	45	14.98	1.011	25.2413
8	45	14.98	1.011	25.2413	8	45	14.98	1.011	25.2413
8.5	45	14.98	1.011	25.2413	8.5	45	14.98	1.011	25.2413
9	45	14.98	1.011	25.2413	9	45	14.98	1.011	25.2413
9.5	45	14.98	1.011	25.2413	9.5	45	14.98	1.011	25.2413
10	45	14.98	1.011	25.2413	10	45	14.98	1.011	25.2413
			Total	530.06				Total	496.51

Table A14: Hydraulic Power (PID and Fuzzy-PID) at Torque=5.23 Nm, Setpoint= 45 RPS

T=5.23 Nm, PID, 22 to 45 RPS					T=5.23 Nm, Fuzzy-PID, 22 to 45 RPS				
Time (s)	Motor Speed (RPS)	Pressure (bar)	Flow rate (lpm)	Power (W)	Time (s)	Motor Speed (RPS)	Pressure (bar)	Flow rate (lpm)	Power (W)
0	21.79	5.432	0.489663	4.433082	0	22	5.6	0.494382	4.614232
0.5	22.64	6.112	0.508764	5.18261	0.5	32.52	11.008	0.730787	13.4075
1	25.71	8.284	0.577753	7.97684	1	41.3	13.52	0.92809	20.91296
1.5	28.45	9.38	0.639326	9.994794	1.5	42.78	14.112	0.961348	22.61091
2	31.42	10.568	0.706067	12.4362	2	44.18	14.672	0.992809	24.27749
2.5	33.94	11.576	0.762697	14.71496	2.5	44.55	14.82	1.001124	24.72775
3	35.96	12.192	0.80809	16.42039	3	44.55	14.82	1.001124	24.72775
3.5	37.59	12.518	0.844719	17.62366	3.5	44.78	14.912	1.006292	25.00971
4	38.83	12.766	0.872584	18.56568	4	45.07	15	1.011236	25.2809
4.5	39.78	12.956	0.893933	19.30298	4.5	45.07	15	1.011236	25.2809
5	41.04	13.416	0.922247	20.62145	5	45.07	15	1.011236	25.2809
5.5	41.82	13.728	0.939775	21.50206	5.5	45.07	15	1.011236	25.2809
6	42.44	13.976	0.953708	22.21504	6	45.07	15	1.011236	25.2809
6.5	42.52	14.008	0.955506	22.30787	6.5	45.07	15	1.011236	25.2809
7	43.06	14.224	0.96764	22.93953	7	45.07	15	1.011236	25.2809
7.5	43.22	14.288	0.971236	23.12837	7.5	45.07	15	1.011236	25.2809
8	43.31	14.324	0.973258	23.23492	8	45.07	15	1.011236	25.2809
8.5	43.68	14.472	0.981573	23.67554	8.5	45.07	15	1.011236	25.2809
9	43.82	14.528	0.984719	23.84333	9	45.07	15	1.011236	25.2809
9.5	43.94	14.576	0.987416	23.98762	9.5	45.07	15	1.011236	25.2809
10	44.17	14.668	0.992584	24.26538	10	45.07	15	1.011236	25.2809
			Total:	378.37				Total:	488.93

Table A15: Hydraulic Power (Conventional and Manual) at Torque=5.23 Nm, Setpoint=22 RPS

T=5.23 Nm, Conventional, 45 to 22 RPS					T=5.23 Nm, Energy saving with normal, 45 to 22 RPS				
Time (s)	Motor Speed (RPS)	Pressure (bar)	Flow rate (lpm)	Power (W)	Time (s)	Motor Speed (RPS)	Pressure (bar)	Flow rate (lpm)	Power (W)
0	22	5.6	0.4944	4.6144	0	45	14.98	1.011	25.2413
0.5	22	5.6	0.4944	4.6144	0.5	33	11.2	0.7415	13.84133
1	22	5.6	0.4944	4.6144	1	26	8.4	0.5842	8.1788
1.5	22	5.6	0.4944	4.6144	1.5	22	5.6	0.4944	4.6144
2	22	5.6	0.4944	4.6144	2	22	5.6	0.4944	4.6144
2.5	22	5.6	0.4944	4.6144	2.5	22	5.6	0.4944	4.6144
3	22	5.6	0.4944	4.6144	3	22	5.6	0.4944	4.6144
3.5	22	5.6	0.4944	4.6144	3.5	22	5.6	0.4944	4.6144
4	22	5.6	0.4944	4.6144	4	22	5.6	0.4944	4.6144
4.5	22	5.6	0.4944	4.6144	4.5	22	5.6	0.4944	4.6144
5	22	5.6	0.4944	4.6144	5	22	5.6	0.4944	4.6144
5.5	22	5.6	0.4944	4.6144	5.5	22	5.6	0.4944	4.6144
6	22	5.6	0.4944	4.6144	6	22	5.6	0.4944	4.6144
6.5	22	5.6	0.4944	4.6144	6.5	22	5.6	0.4944	4.6144
7	22	5.6	0.4944	4.6144	7	22	5.6	0.4944	4.6144
7.5	22	5.6	0.4944	4.6144	7.5	22	5.6	0.4944	4.6144
8	22	5.6	0.4944	4.6144	8	22	5.6	0.4944	4.6144
8.5	22	5.6	0.4944	4.6144	8.5	22	5.6	0.4944	4.6144
9	22	5.6	0.4944	4.6144	9	22	5.6	0.4944	4.6144
9.5	22	5.6	0.4944	4.6144	9.5	22	5.6	0.4944	4.6144
10	22	5.6	0.4944	4.6144	10	22	5.6	0.4944	4.6144
Total				96.9	Total:				130.32

Table A16: Hydraulic Power (PID and Fuzzy-PID) at Torque=5.23 Nm, Setpoint= 22 RPS

T=5.23 Nm, PID, 45 to 22 RPS					T=5.23 Nm, Fuzzy PID, 45 to 22 RPS				
Time (s)	Motor Speed (RPS)	Pressure (bar)	Flow rate (lpm)	Power (W)	Time (s)	Motor Speed (RPS)	Pressure (bar)	Flow rate (lpm)	Power (W)
0	44.63	14.852	1.002921	24.82565	0	44.89	14.956	1.008764	25.14513
0.5	44.29	14.716	0.995281	24.41092	0.5	41.93	13.772	0.942247	21.62771
1	41.57	13.628	0.934157	21.21783	1	29.63	9.852	0.665843	10.93314
1.5	38.6	12.72	0.867416	18.38921	1.5	25.5	8.2	0.573034	7.831461
2	36.02	12.204	0.809438	16.46397	2	24.39	7.512	0.54809	6.862085
2.5	33.69	11.476	0.757079	14.48039	2.5	23.57	6.856	0.529663	6.052282
3	31.92	10.768	0.717303	12.8732	3	22.89	6.312	0.514382	5.411299
3.5	30.41	10.164	0.683371	11.5763	3.5	22.28	5.824	0.500674	4.859877
4	28.94	9.576	0.650337	10.37938	4	21.97	5.576	0.493708	4.588192
4.5	27.68	9.072	0.622022	9.40498	4.5	21.98	5.584	0.493933	4.596866
5	26.65	8.66	0.598876	8.643783	5	22.1	5.68	0.496629	4.701423
5.5	25.84	8.336	0.580674	8.0675	5.5	22.1	5.68	0.496629	4.701423
6	25.22	8.088	0.566742	7.639676	6	22.1	5.68	0.496629	4.701423
6.5	24.57	7.656	0.552135	7.04524	6.5	22.1	5.68	0.496629	4.701423
7	24.08	7.264	0.541124	6.551203	7	22.1	5.68	0.496629	4.701423
7.5	23.72	6.976	0.533034	6.197405	7.5	22.1	5.68	0.496629	4.701423
8	23.25	6.6	0.522472	5.747191	8	22.1	5.68	0.496629	4.701423
8.5	22.99	6.392	0.516629	5.503823	8.5	22.1	5.68	0.496629	4.701423
9	22.97	6.376	0.51618	5.48527	9	22.1	5.68	0.496629	4.701423
9.5	22.6	6.08	0.507865	5.146367	9.5	22.1	5.68	0.496629	4.701423
10	22.5	6	0.505618	5.05618	10	22.1	5.68	0.496629	4.701423
Total:				235.1	Total:				149.62

Table A17: Pearson Correlation Coefficient of Motor Speed and Voltage of Conventional Power Steering at Torque= 0 Nm

Motor Speed (X, rps)	Voltage (Y, watt)	(X- X_{mean})	(Y- Y_{mean})	(X- X_{mean})*(Y- Y_{mean})	(X- X_{mean}) ²	(Y- Y_{mean}) ²
15	2.4	-37.5	-3.3084	124.065	1406.25	10.94551
18.2	2.64	-34.3	-3.0684	105.2461	1176.49	9.415079
21.2	2.84	-31.3	-2.8684	89.78092	979.69	8.227719
24.5	3.03	-28	-2.6784	74.9952	784	7.173827
27.5	3.27	-25	-2.4384	60.96	625	5.945795
30.6	3.52	-21.9	-2.1884	47.92596	479.61	4.789095
33.8	3.76	-18.7	-1.9484	36.43508	349.69	3.796263
36.9	4.01	-15.6	-1.6984	26.49504	243.36	2.884563
40	4.28	-12.5	-1.4284	17.855	156.25	2.040327
43.1	4.51	-9.4	-1.1984	11.26496	88.36	1.436163
46.2	4.76	-6.3	-0.9484	5.97492	39.69	0.899463
49.4	5.03	-3.1	-0.6784	2.10304	9.61	0.460227
52.5	5.27	0	-0.4384	0	0	0.192195
55.6	5.52	3.1	-0.1884	-0.58404	9.61	0.035495
58.7	5.84	6.2	0.1316	0.81592	38.44	0.017319
61.9	6.17	9.4	0.4616	4.33904	88.36	0.213075
65	6.49	12.5	0.7816	9.77	156.25	0.610899
68.1	6.93	15.6	1.2216	19.05696	243.36	1.492307
71.2	7.35	18.7	1.6416	30.69792	349.69	2.694851
74.4	7.77	21.9	2.0616	45.14904	479.61	4.250195
77.5	8.25	25	2.5416	63.54	625	6.459731
80.6	8.78	28.1	3.0716	86.31196	789.61	9.434727
83.7	9.42	31.2	3.7116	115.8019	973.44	13.77597
86.9	10.1	34.4	4.3916	151.071	1183.36	19.28615
90	10.77	37.5	5.0616	189.81	1406.25	25.61979
$X_{mean} = 52.5$	$Y_{mean} = 5.7084$			$\Sigma = 1318.9$	$\Sigma = 12681$	$\Sigma = 142.1$

$$r_{xy} = \frac{1318.9}{\sqrt{12681 \times 142.1}} = 0.9825$$

Table A18: Pearson Correlation Coefficient of Motor Speed and Current of Conventional Power Steering at Torque= 0 Nm

Motor Speed (X, rps)	Current (Y, watt)	(X- X_{mean})	(Y- Y_{mean})	(X- X_{mean})*(Y- Y_{mean})	(X- X_{mean}) ²	(Y- Y_{mean}) ²
15	8.53	-37.5	-10.437	391.3875	1406.25	108.931
18.2	9.64	-34.3	-9.327	319.9161	1176.49	86.99293
21.2	10.53	-31.3	-8.437	264.0781	979.69	71.18297
24.5	11.28	-28	-7.687	215.236	784	59.08997
27.5	12.16	-25	-6.807	170.175	625	46.33525
30.6	13.1	-21.9	-5.867	128.4873	479.61	34.42169
33.8	14.04	-18.7	-4.927	92.1349	349.69	24.27533
36.9	15.03	-15.6	-3.937	61.4172	243.36	15.49997
40	16.06	-12.5	-2.907	36.3375	156.25	8.450649
43.1	16.93	-9.4	-2.037	19.1478	88.36	4.149369
46.2	17.81	-6.3	-1.157	7.2891	39.69	1.338649
49.4	18.75	-3.1	-0.217	0.6727	9.61	0.047089
52.5	19.3	0	0.333	0	0	0.110889
55.6	19.86	3.1	0.893	2.7683	9.61	0.797449
58.7	20.9	6.2	1.933	11.9846	38.44	3.736489

61.9	21.81	9.4	2.843	26.7242	88.36	8.082649
65	22.6	12.5	3.633	45.4125	156.25	13.19869
68.1	23.46	15.6	4.493	70.0908	243.36	20.18705
71.2	24.24	18.7	5.273	98.6051	349.69	27.80453
74.4	24.88	21.9	5.913	129.4947	479.61	34.96357
77.5	25.53	25	6.563	164.075	625	43.07297
80.6	26.17	28.1	7.203	202.4043	789.61	51.88321
83.7	26.7	31.2	7.733	241.2696	973.44	59.79929
86.9	27.21	34.4	8.243	283.5592	1183.36	67.94705
90	27.66	37.5	8.693	325.9875	1406.25	75.56825
$X_{mean} = 52.5$	$Y_{mean} = 18.9672$			$\Sigma = 3308.655$	$\Sigma = 12680.98$	$\Sigma = 867.86$

$$r_{xy} = \frac{3308.7}{\sqrt{12681 \times 867.86}} = 0.9973$$

Table A19: Pearson Correlation Coefficient of Motor Speed and Electric Power of Conventional Power Steering at Torque= 5.23 Nm

Motor Speed (X, rps)	Electric Power (Y, watt)	(X- X_{mean})	(Y- Y_{mean})	(X- X_{mean})*(Y- Y_{mean})	(X- X_{mean}) ²	(Y- Y_{mean}) ²
15	26.4708	-37.5	-195.279	7322.97	1406.25	38133.97
18.2	32.1762	-34.3	-189.574	6502.381	1176.49	35938.23
21.2	39.0852	-31.3	-182.665	5717.408	979.69	33366.43
24.5	49.392	-28	-172.358	4826.024	784	29707.28
27.5	59.3164	-25	-162.434	4060.84	625	26384.67
30.6	69.8112	-21.9	-151.939	3327.46	479.61	23085.4
33.8	78.8804	-18.7	-142.87	2671.662	349.69	20411.72
36.9	90.712	-15.6	-131.038	2044.193	243.36	17170.96
40	105.2274	-12.5	-116.523	1456.533	156.25	13577.52
43.1	118.1136	-9.4	-103.636	974.1822	88.36	10740.5
46.2	130.9936	-6.3	-90.7564	571.7653	39.69	8236.724
49.4	144.0593	-3.1	-77.6907	240.8412	9.61	6035.845
52.5	167.2272	0	-54.5228	0	0	2972.736
55.6	192.606	3.1	-29.144	-90.3464	9.61	849.3727
58.7	209.352	6.2	-12.398	-76.8676	38.44	153.7104
61.9	235.8514	9.4	14.1014	132.5532	88.36	198.8495
65	269.3484	12.5	47.5984	594.98	156.25	2265.608
68.1	307.6965	15.6	85.9465	1340.765	243.36	7386.801
71.2	348.4261	18.7	126.6761	2368.843	349.69	16046.83
74.4	392.018	21.9	170.268	3728.869	479.61	28991.19
77.5	435.4668	25	213.7168	5342.92	625	45674.87
80.6	475.832	28.1	254.082	7139.704	789.61	64557.66
83.7	496.0368	31.2	274.2868	8557.748	973.44	75233.25
86.9	521.1387	34.4	299.3887	10298.97	1183.36	89633.59
90	548.76	37.5	327.01	12262.88	1406.25	106935.5
$X_{mean} = 52.5$	$Y_{mean} = 221.75$			$\Sigma = 91317.27$	$\Sigma = 12681$	$\Sigma = 703689.3$

$$r_{xy} = \frac{91317}{\sqrt{12681 \times 703689}} = 0.9666$$

Table A20: Pearson Correlation Coefficient of Motor Speed and Electric Power of Energy Saving Power Steering at Torque= 5.23 Nm

Motor Speed (X, rps)	Electric Power (Y, watt)	$(X - X_{mean})$	$(Y - Y_{mean})$	$(X - X_{mean}) * (Y - Y_{mean})$	$(X - X_{mean})^2$	$(Y - Y_{mean})^2$
45	126.0585	12	46.8685	562.422	144	2196.656
44	121.8328	11	42.6428	469.0708	121	1818.408
43	117.6791	10	38.4891	384.891	100	1481.411
42	113.3781	9	34.1881	307.6929	81	1168.826
41	109.3724	8	30.1824	241.4592	64	910.9773
40	105.2274	7	26.0374	182.2618	49	677.9462
39	100.4562	6	21.2662	127.5972	36	452.2513
38	95.8428	5	16.6528	83.264	25	277.3157
37	91.3374	4	12.1474	48.5896	16	147.5593
36	86.7468	3	7.5568	22.6704	9	57.10523
35	82.4182	2	3.2282	6.4564	4	10.42128
34	79.55	1	0.36	0.36	1	0.1296
33	76.5508	0	-2.6392	0	0	6.965377
32	73.787	-1	-5.403	5.403	1	29.19241
31	70.8994	-2	-8.2906	16.5812	4	68.73405
30	68.24	-3	-10.95	32.85	9	119.9025
29	64.4962	-4	-14.6938	58.7752	16	215.9078
28	61.019	-5	-18.171	90.855	25	330.1852
27	57.4816	-6	-21.7084	130.2504	36	471.2546
26	54.2012	-7	-24.9888	174.9216	49	624.4401
25	51.0168	-8	-28.1732	225.3856	64	793.7292
24	47.6518	-9	-31.5382	283.8438	81	994.6581
23	44.5374	-10	-34.6526	346.526	100	1200.803
22	41.527	-11	-37.663	414.293	121	1418.502
21	38.4948	-12	-40.6952	488.3424	144	1656.099
$X_{mean} = 33$	$Y_{mean} = 79.19$			$\Sigma = 4704$	$\Sigma = 1300$	$\Sigma = 17129$

$$r_{xy} = \frac{4704}{\sqrt{1300 * 17129}} = 0.99$$

APPENDIX B

Arduino Programming Code (PID)

```
#include <PID_v1.h>//PID library
#include <Adafruit_MPU6050.h>// Gyroscope library
#include <Adafruit_Sensor.h>//Gyroscope library
#include <Wire.h>
Adafruit_MPU6050 mpu;
//Define Variables we'll be connecting to
int trigPin = 5;  // Ultrasonic Trigger
int echoPin = 6;  // Ultrasonic Echo
const byte ENCODER = 2;// connected to encoder
const byte MOTOR1 = 9;//connected to motor controller
const byte MOTOR2 = 10;//connected to motor controller
long duration, cm, inches;
double Setpoint, Input, Output;
//Specify the links and initial tuning parameters
double Kp=0.1, Ki=1, Kd=0.09;
PID myPID(&Input, &Output, &Setpoint, Kp, Ki, Kd, DIRECT);
unsigned long microsPerRev = 1000000;//Encoder
void isrRotation() // counts from the speed sensor
{
    static unsigned long lastMicros = 0;
    unsigned long currentMicros = micros();
    microsPerRev = currentMicros - lastMicros;
    lastMicros = currentMicros;
}
void setup()
{
    Serial.begin(9600);
    mpu.begin();//Gyroscope begin
    mpu.setGyroRange(MPU6050_RANGE_500_DEG); // set gyro range to +- 500
    deg/s.
    mpu.setFilterBandwidth(MPU6050_BAND_21_HZ);// set filter bandwidth to 21 Hz.
```

```

//Setpoint = 0;//PID setpoint
myPID.SetMode(AUTOMATIC);//turn the PID on.
pinMode(ENCODER, INPUT_PULLUP); // Enable the pullup resistor for the
encoder interrupt pin.
pinMode(MOTOR1, OUTPUT); // Connected to motor controller.
pinMode(MOTOR2, OUTPUT); // Connected to motor controller.
pinMode(trigPin, OUTPUT);//Ultrasonic trigger
pinMode(echoPin, INPUT);//Ultrasonic echo
pinMode(A0, INPUT);//vehicle speed
pinMode(A1, INPUT);//current
attachInterrupt(digitalPinToInterrupt(ENCODER), isrRotation, RISING); // increase
counter when speed sensor pin goes High
Serial.println("Start");
Serial.println("ISR set");
Serial.println("Starting Motor");
Serial.println("Motor On");
delay(5000);
}
unsigned long lastMillis = 0;
int steering_angle;
void loop()
{
  digitalWrite(trigPin, LOW);// Give a short LOW pulse beforehand to ensure a clean
HIGH pulse:
  delayMicroseconds(5);
  digitalWrite(trigPin, HIGH);
  delayMicroseconds(10);// The sensor is triggered by a HIGH pulse of 10 or more
microseconds.
  digitalWrite(trigPin, LOW);
  pinMode(echoPin, INPUT);
  duration = pulseIn(echoPin, HIGH);
  cm = (duration/2) / 29.1; // Divide by 29.1 or multiply by 0.0343
  steering_angle=map(cm,15,27,-520,520);
  inches = (duration/2) / 74; // Divide by 74 or multiply by 0.0135

```

```

int pot=analogRead(A0);//Potentiometer read as vehicle speed
int v_speed=map(pot, 0,1023,0,120);
int current=analogRead(A1); //Shunt voltage reading for current measure
sensors_event_t a, g, temp; //Gyroscope setting
mpu.getEvent(&a, &g, &temp);
double steering_rate=abs ((g.gyro.x))*57.3;
//if (v_speed>=60 && steering_rate>=300)
//{
//Setpoint=70-(v_speed/5);
//}
//else{
//Setpoint=45-(v_speed/5);
//}
Setpoint=45-(v_speed/5);
if( millis() - lastMillis >= 100) //Encoder for motor rps
{
lastMillis += 100;
noInterrupts();// Protect the microsPerRev variable from being updated while reading
unsigned long upr = microsPerRev;
interrupts();
float rps = 1000000.0f / (float)upr;
Input = rps; //PID input
myPID.Compute();
analogWrite(MOTOR1, Output);
analogWrite(MOTOR2, Output);
Serial.print(Setpoint);
Serial.print(",");
Serial.print(steering_angle);
Serial.print(",");
Serial.print(v_speed);
Serial.print(",");
Serial.print(steering_rate);
Serial.print(",");
Serial.print(rps);

```

```

Serial.print(",");
Serial.println(Output);
}
}

void setMotorSpeed( byte pwm)
{
}

```

Arduino Programming Code (Fuzzy PID)

```

#include <PID_v1.h> //PID library
#include <Adafruit_MPU6050.h> // Gyroscope library
#include <Adafruit_Sensor.h> //Gyroscope library
#include <Wire.h>
#include <Fuzzy.h>
Fuzzy* fuzzy = new Fuzzy();
float err=0;
Adafruit_MPU6050 mpu;
//Define Variables we'll be connecting to
int trigPin = 5; // Ultrasonic Trigger
int echoPin = 6; // Ultrasonic Echo
const byte ENCODER = 2; // connected to encoder
const byte MOTOR1 = 9; //connected to motor controller
const byte MOTOR2 = 10; //connected to motor controller
long duration, cm, inches;
double Setpoint, Input, Output;
//Specify the links and initial tuning parameters
double Kp=0.1, Ki=1, Kd=0.09;
PID myPID(&Input, &Output, &Setpoint, Kp, Ki, Kd, DIRECT);
unsigned long microsPerRev = 1000000; //Encoder
void isrRotation() // counts from the speed sensor
{
    static unsigned long lastMicros = 0;
    unsigned long currentMicros = micros();
    microsPerRev = currentMicros - lastMicros;
}

```

```

    lastMicros = currentMicros;
}

void setup()
{
    Serial.begin(9600);
    mpu.begin();//Gyroscope begin
    mpu.setGyroRange(MPU6050_RANGE_500_DEG); // set gyro range to +- 500
deg/s.
    mpu.setFilterBandwidth(MPU6050_BAND_21_HZ);// set filter bandwidth to 21 Hz.
    //Setpoint = 0;//PID setpoint
    // initilizing fuzzy papmeters
    FuzzyInput* e = new FuzzyInput(1);
    FuzzySet* enl = new FuzzySet(-90, -67.5, -67.5, -45);
    e->addFuzzySet(enl);
    FuzzySet* enm = new FuzzySet(-67.5, -45, -45, -22.5);
    e->addFuzzySet(enm);
    FuzzySet* ens = new FuzzySet(-45, -22.5, -22.5, 0);
    e->addFuzzySet(ens);
    FuzzySet* eze = new FuzzySet(-22.5, 0, 0, 22.5);
    e->addFuzzySet(eze);
    FuzzySet* eps = new FuzzySet(0, 22.5, 22.5, 45);
    e->addFuzzySet(eps);
    FuzzySet* epm = new FuzzySet(22.5, 45, 45,67.5 );
    e->addFuzzySet(epm);
    FuzzySet* epl = new FuzzySet(45, 67.5, 67.5,90 );
    e->addFuzzySet(epl);
    fuzzy->addFuzzyInput(e);
    // initilizing fuzzy papmeters
    FuzzyOutput* KP = new FuzzyOutput(1);
    FuzzySet* kpsm = new FuzzySet(1, 2, 2, 3 );
    KP->addFuzzySet(kpsm);
    FuzzySet* kpmd = new FuzzySet(2, 3, 3, 4);
    KP->addFuzzySet(kpmd);
    FuzzySet* kpbg = new FuzzySet(3, 4, 4, 5);

```



```

KP->addFuzzySet(kpbg);
fuzzy->addFuzzyOutput(KP);
// initilizing fuzzy papmeters
FuzzyOutput* KI = new FuzzyOutput(2);
FuzzySet* kism = new FuzzySet(1, 2, 2, 3);
KI->addFuzzySet(kism);
FuzzySet* kimd = new FuzzySet(2, 3, 3, 4);
KI->addFuzzySet(kimd);
FuzzySet* kibg = new FuzzySet(3, 4, 4, 5);
KI->addFuzzySet(kibg);
fuzzy->addFuzzyOutput(KI);
// initiating fuzzy rules
FuzzyRuleAntecedent* if_e_pl = new FuzzyRuleAntecedent();
if_e_pl->joinSingle(epl);
FuzzyRuleConsequent* then_kpsm_and_kism = new FuzzyRuleConsequent();
then_kpsm_and_kism->addOutput(kpsm);
then_kpsm_and_kism->addOutput(kism);
FuzzyRule* fuzzyRule01 = new FuzzyRule(1, if_e_pl, then_kpsm_and_kism);
fuzzy->addFuzzyRule(fuzzyRule01);
FuzzyRuleAntecedent* if_e_pm = new FuzzyRuleAntecedent();
if_e_pm->joinSingle(epm);
FuzzyRuleConsequent* then_kpmd_and_kimd = new FuzzyRuleConsequent();
then_kpmd_and_kimd->addOutput(kpmd);
then_kpmd_and_kimd->addOutput(kimd);
FuzzyRule* fuzzyRule02 = new FuzzyRule(2, if_e_pm, then_kpmd_and_kimd);
fuzzy->addFuzzyRule(fuzzyRule02);
FuzzyRuleAntecedent* if_e_ps = new FuzzyRuleAntecedent();
if_e_ps->joinSingle(eps);
FuzzyRuleConsequent* then_kpbg_and_kibg = new FuzzyRuleConsequent();
then_kpbg_and_kibg->addOutput(kpbg);
then_kpbg_and_kibg->addOutput(kibg);
FuzzyRule* fuzzyRule03 = new FuzzyRule(3, if_e_ps, then_kpbg_and_kibg);
fuzzy->addFuzzyRule(fuzzyRule03);
FuzzyRuleAntecedent* if_e_ns = new FuzzyRuleAntecedent();

```

```

if_e_ns->joinSingle(ens);
FuzzyRule* fuzzyRule04 = new FuzzyRule(4, if_e_ns, then_kpbg_and_kibg);
fuzzy->addFuzzyRule(fuzzyRule04);
FuzzyRuleAntecedent* if_e_nm = new FuzzyRuleAntecedent();
if_e_nm->joinSingle(enm);
FuzzyRule* fuzzyRule05 = new FuzzyRule(5, if_e_nm,
then_kpmd_and_kimd); fuzzy->addFuzzyRule(fuzzyRule05);
FuzzyRuleAntecedent* if_e_nl = new FuzzyRuleAntecedent();
if_e_nl->joinSingle(enl);
FuzzyRule* fuzzyRule06 = new FuzzyRule(6, if_e_nl, then_kpsm_and_kism);
fuzzy->addFuzzyRule(fuzzyRule06);
FuzzyRuleAntecedent* if_e_ze = new FuzzyRuleAntecedent();
if_e_ze->joinSingle(eze);
FuzzyRule* fuzzyRule07 = new FuzzyRule(7, if_e_ze, then_kpsm_and_kism);
fuzzy->addFuzzyRule(fuzzyRule07);


myPID.SetMode(AUTOMATIC);//turn the PID on.
pinMode(ENCODER, INPUT_PULLUP); // Enable the pullup resistor for the
encoder interrupt pin.
pinMode(MOTOR1, OUTPUT); // Connected to motor controller.
pinMode(MOTOR2, OUTPUT); // Connected to motor controller.
pinMode(trigPin, OUTPUT);//Ultrasonic trigger
pinMode(echoPin, INPUT);//Ultrasonic echo
pinMode(A0, INPUT);//vehicle speed
pinMode(A1, INPUT);//current
attachInterrupt(digitalPinToInterrupt(ENCODER), isrRotation, RISING); // increase
counter when speed sensor pin goes High
Serial.println("Start");
Serial.println("ISR set");
Serial.println("Starting Motor");
Serial.println("Motor On");
delay(5000);
}

```

```

unsigned long lastMillis = 0;
int steering_angle;
void loop()
{
    digitalWrite(trigPin, LOW); // Give a short LOW pulse beforehand to ensure a clean
    HIGH pulse:
    delayMicroseconds(5);
    digitalWrite(trigPin, HIGH);
    delayMicroseconds(10); // The sensor is triggered by a HIGH pulse of 10 or more
    microseconds.
    digitalWrite(trigPin, LOW);
    pinMode(echoPin, INPUT);
    duration = pulseIn(echoPin, HIGH);
    cm = (duration/2) / 29.1; // Divide by 29.1 or multiply by 0.0343
    steering_angle=map(cm,15,27,-520,520);
    inches = (duration/2) / 74; // Divide by 74 or multiply by 0.0135
    int pot=analogRead(A0); //Potentiometer read as vehicle speed
    int v_speed=map(pot, 0,1023,0,120);
    int current=analogRead(A1); //Shunt voltage reading for current measure
    sensors_event_t a, g, temp; //Gyroscope setting
    mpu.getEvent(&a, &g, &temp);
    double steering_rate=abs ((g.gyro.x))*57.3;
    //if (v_speed>=60 && steering_rate>=300)
    //{
    //Setpoint=70-(v_speed/5);
    //}
    //else{
    //Setpoint=45-(v_speed/5);
    //}
    Setpoint=45-(v_speed/5);
    if( millis() - lastMillis >= 100) //Encoder for motor rps
    {
        lastMillis += 100;
        noInterrupts(); // Protect the microsPerRev variable from being updated while reading

```

```

unsigned long upr = microsPerRev;
interrupts();
float rps = 1000000.0f / (float)upr;
Input = rps;
err = Setpoint -rps;
fuzzy->setInput(1, err);
fuzzy->fuzzify();
// Set output vlaue: output
Kp = (double)fuzzy->defuzzify(1);
Ki = (double)fuzzy->defuzzify(2)*3;
myPID.SetTunings(Kp, Ki, Kd);
myPID.Compute();
analogWrite(MOTOR1, Output);
analogWrite(MOTOR2, Output);
Serial.print(Setpoint);
Serial.print(",");
Serial.print(steering_angle);
Serial.print(",");
Serial.print(v_speed);
Serial.print(",");
Serial.print(steering_rate);
Serial.print(",");
Serial.print(rps);
Serial.print(",");
Serial.println(Output);
}
}
void setMotorSpeed( byte pwm)
{}

```