Design of an IoT Based Autonomous Vehicle with the Aid of Computer Vision

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***Abstract*—A web controlled and partially autonomous vehicle system is presented in this paper. It highlights the idea to develop a remote controlled car which can be driven from anywhere using internet over a secured server. This car will also have limited automation features like traffic light detection, obstacle avoidance system and lane detection system so that it can drive itself safely in case of connectivity failure. The main goal here is to minimize the risk of human life and ensure highest safety during driving. At the same time the car will assure comfort and convenience to the controller. A miniature car including the above features has been developed which showed optimum performance in a simulated environment. The system mainly consists of a Raspberry Pi, an Arduino, a Picamera, a sonar module, a web interface and internet modem. The Raspberry Pi was mainly used for the Computer Vision algorithms and for streaming video through internet. The proposed system is very cheap and very efficient in terms of automation.**

***Index Terms*—Internet of Things(IoT), Raspberry PI, Arduino Uno, Computer Vision, OpenCV, Sonar Module, Picamera, Machine Learning, Python, Apache Web Server.**

I. Introduction

With the ever-growing technological advancement, human civilization is looking for automation in every sphere of life. Automated car is one of the latest trends which has been massively recognized by people all around the world as they want maximum security and comfort during driving. Nowadays, road accident is one of the prime concerns for the people. It became very frequent and uncertain. Most of the road accidents occur due to lack of abidance of the traffic rules. Most of the time, the drivers become drowsy or distracted during driving and eventually hit objects ahead of them. If the driving process can be handled with the aid of Computer Vision and efficient sensors then the risk of human mistakes can be highly reduced. Besides, sometimes it gets necessary to access the car from a remote location in order to reduce hassles. In this case, it would be a lot more convenient if the car could be viewed from a remote computer and driven by interaction through the computer keyboard. This could be as easy as playing a computer game. Our work is based on Internet of Things technology and Computer Vision to remotely control our vehicle and automation features.

Since 1920 the research for vehicle automation has been conducted on, although first promising trials took place around 1950s. During 1980 with Carnegie Mellon University's Navlab and ALV [1], [2] the first ever autonomous car has been seen. This has paved the way for the companies to work on autonomous vehicle research. In July 2013, Vislab demonstrated BRAIVE a vehicle that moved autonomously on a mixed traffic route. Cities like Belgium, France, Italy and the UK are planning to operate transport systems for driver less cars. Germany, Netherlands and Spain have allowed testing robotic cars in traffic.

Google self-driving car is a recent trend. Sebastian Thrun, professor of Stanford University and his team have developed the algorithm and led the development of the Google self-driving car [3]. Google self-driving cars are designed to navigate safely through city streets. They have sensors designed to detect objects as far as two football fields away in all directions, including human and vehicles. It will be marketed by 2020. Tesla motors will be fully driver less within two years and will compete with the Google car. So far these prototypes also have a live driver inside them to acquire test data. If a live driver can be substituted with an online driver then the risk of human life damage can be avoided.

Society of Automotive Engineers (SAE) has classified automated vehicles into six categories from level-0 (No automation) to level-5 (Full automation). In this paper we have worked with the level-3 (Conditional automation). In this level the driver can safely turn their attention in a familiar place and good weather condition. This is by far the most secure driving system as we can not put confidence into fully automated vehicles yet. Besides the cost behind Google car or Tesla wheels is supposed to be out of reach for most people.

The driving becomes a lot boring during traffic jam. In this situation traffic light detection system and obstacle detection comes in handy. Researches have been done regarding traffic light detection using heuristic models and color segmentation [4], [5]. However in this paper a Haar Cascade Classifier is developed with respect to the working environment which can easily be extended to work in real life environment by collecting a lot more frames from the environment and by using powerful computer.

Various lane detection techniques have been observed. Lane detection techniques using OpenCV based on Receiver Operating Characteristic curve and Detection Error Trade-off

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curve [6] and using perspective image [7] have already been worked on. In this paper lane detection is done using canny edge algorithm and Hough line transformation which has shown good rate of success in the working condition. So far many related works are done involving remote controlling an autonomous car using Bluetooth with android or iPhone. Several papers [8], [9] have been published regarding autonomous car and obstacle avoidance system which lack either versatile control over internet or live video streaming. Concepts from papers [10], [11], [12] like home surveillance system, automatic toll collection, obstacle avoidance system are combined to further develop the idea. A sample car was built for the purpose of testing in a created environment. This car successfully achieved its goal.

II. Proposed Method

The overall work can be divided into two major categories. The methodology is briefly shown in Fig. 1.

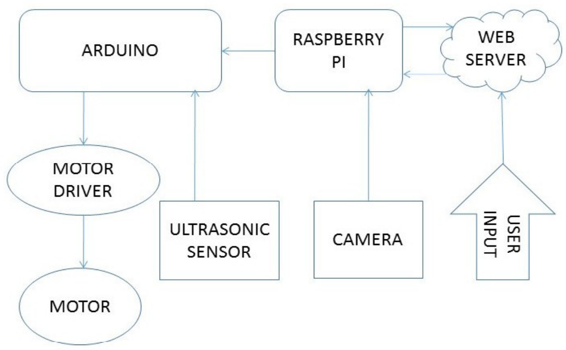

Fig. 1. Working procedure

Firstly the car can be remotely controlled through Internet using a web browser. In case of connectivity failure it can act autonomously in a good weather condition. The proposal consists of complex Computer Vision algorithms and video transmission with Internet. Raspberry pi and Arduino are the main devices to implement the prototype. The Raspberry Pi streams the video to internet. A user can access the streaming using a web browser. It takes a lot of processing power for simultaneously working on video streaming and running Computer Vision. The Raspberry Pi 2 model B is a single-board computer with a powerful processing unit and serial and camera interface (CSI). The Raspberry Pi camera module can be used to take high-definition video. It can be accessed through the V4L (Video for Linux) APIs, and there are numerous third-party libraries built for it, including the Picamera Python library which will be beneficial to the live streaming purpose. Apache is a popular web server application that was installed on the Raspberry Pi to allow it to serve web pages. Apache can serve HTML files over HTTP, and with additional modules can serve dynamic web pages using scripting languages such as python. A web page was hosted that shows the video streaming sent from the Picamera. To access into the web page one only need to know the IP address of the Raspberry Pi and a user name and password to log in. From the web page the car can be fully driven.

For the connectivity failure the car needs to work on its own. It needs to keep itself safe from collision and abide by the traffic rules. The Arduino controls the motor driver circuit. It is connected with sonar, an ultrasonic sensor which evaluates the attributes of a target by interpreting the echoes from radio waves. It is used to detect the distance of obstacles from the car. If an obstacle is detected then the Arduino stops the motor from running operation. Meanwhile the Raspberry Pi uses computer vision algorithms to detect the lane and traffic light signals. Python Open Source Computer Vision (OpenCV) is a library of programming functions mainly aimed at real-time computer vision. It has over 2500 optimized algorithms which can be used for image processing, detection, object identification, classification of actions, traces and other functions. The Raspberry Pi is interfaced with the Arduino with serial communication. It controls the Arduino to run the car accordingly.

A. *Streaming Video and Remote Access*

The Raspberry Pi works on Linux operating system. It can host web pages through Apache server. It responds to requests to serve up web pages, which can be simple HTML or sophisticated web-based apps. To make the Pi capable of hosting websites Apache is installed on it. Apache is a free, open-source HTTP (Hypertext Transfer Protocol) web server application. A website was built for hosting the streamed video and for controlling the car remotely.

MJPG streamer was used to stream video from Raspberry Pi. The easiest way to install it is by using subversion. There is a facility in linux operating system named daemon which runs the selected programs automatically during system boot up. The scripts for MJPG streamer,traffic light detector and lane detector are all run through daemon. So whenever the Raspberry Pi is powered up it automatically keeps streaming the video from its camera to its web server. Now if we type ḧttp://(Raspberry Pi's IP address):port number ẗhen the streaming data can be viewed from any web browser.

The web page hosting the video streaming was developed using python flask framework. From the web page, a python script is used to handle keyboard interruption from the user. This keyboard interruption can be processed and sent through the internet to the remote Raspberry Pi which is located inside the car. The Pi in turn sends signal to Arduino to control the motor through serial communication.

B. *Obstacle Avoidance*

A sonar sensor (HC-SR04) has been used for this purpose. It emits very high frequency (40 KHz) of sound. It has two transducers - a transmitter and a receiver. The "Transmit" transducer sends out a short burst of (8 cycles) of pulse train. The sonar module timing diagram is shown in Fig. 2[13].

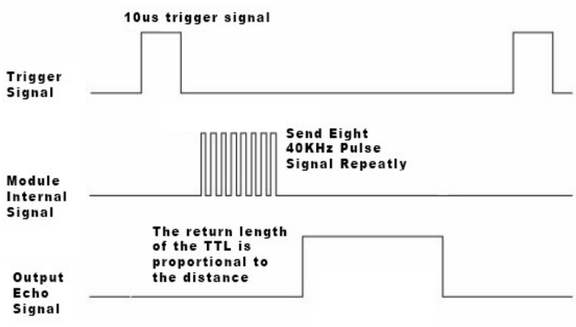

Fig. 2. Timing diagram of a sonar module

The "Receive" transducer in turns wait for an echo. If an object exists on its perimeter an echo bounces back to the "Receive" transducer. Distance of the object is calculated from the following equation.

$$d = v * (t/2) \quad (1)$$

Here d is the distance from object, t is the total time from transmission to reception and v is the velocity of sound which is typically 340 m/s in room temperature.

The sonar is connected with an Arduino which calculates the distance and controls the motor rotation accordingly. The sonar is placed in front of the vehicle and is mounted on a servo motor which can rotate upto 180 degrees. This way if an obstacle comes ahead, then it rotates the sonar and check if the road is clear around. If no obstacle is found then it turns the car and picks an alternative way.

C. Traffic Light Detection

The traffic light detection procedure can be briefly described with Fig. 3.

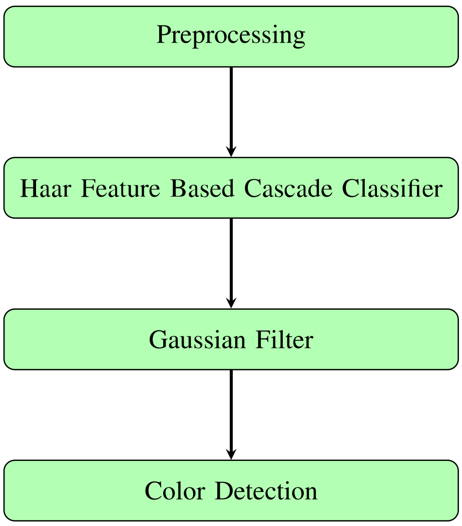

Fig. 3. Traffic light detection process

1) Preprocessing: The image frames captured from the video were converted into gray scale images.

2) Haar Feature-Based Cascade Classifier: Haar feature-based cascade classifier was chosen for traffic light detection. This feature was highly popular for its success on face detection. It has two parts-training and detection. We can generate both using OpenCV. To build a Haar Cascade it was needed to generate some positive images and some negative images. The result is better as much as sample image is generated. However for the processing power limitation of Raspberry Pi only 1000 positive samples and 1000 negative samples were taken.

The positive samples were the images of different traffic light signals in different angle. The negative samples were collected from the related environment where no traffic signals were present. With the utilization of OpenCV_createsamples command many other positive samples were randomly generated superimposing on the negatives. A vector file was created merging all the positive samples. This training part was done using OpenCV_traincascade command. This cascade classifier is used to detect the traffic light post that is the region of interest.

3) Gaussian Filter: To reduce the image noises gaussian blur filter was used.

4) Color Detection: The BGR image was converted to HSV, because it gets much easier to represent the colors in HSV. Then the threshold value for green and red colors were selected individually for the image. And finally the green or red part was extracted.

D. Lane Detection

For the lane detection technique the popular canny edge detection and Hough line transform was used. This algorithm is highly efficient for a road with clearly visible lane marker. In edge detection algorithm the boundaries of an image are generally detected. Canny algorithm is selected for its very low error rate, good localization and minimal response that is only one detector response per edge. For good efficiency several steps are needed to be maintained. Figure. 4. shows the process in a nutshell.

1) Gaussian Filter: Suitable masking was done to filter out the noise from the original image using gaussian filter.

2) Finding Intensity Gradient: After smoothing was done Sobel kernel was used in both horizontal and vertical direction to get the first derivative in both directions. Gradient is the change of brightness in a series of pixels.

3) Removing non Edge: Pixels that were not part of an edge were removed. Thus an image with thin edge is observed.

4) Hysteresis: Canny uses two thresholds. If a pixel gradient is higher than the upper threshold, it is accepted as an edge. Otherwise it is rejected. If a pixel gradient is between the thresholds then it is only accepted if it is connected with a pixel of upper threshold.

5) Hough Line Transformation: After canny edge detection Hough line transformation is applied. Hough transformation is very efficient for detecting any shape if it can be mathematically expressed even if it is a little distorted. To determine the Hough line two parameters are needed- ρ, the perpendicular

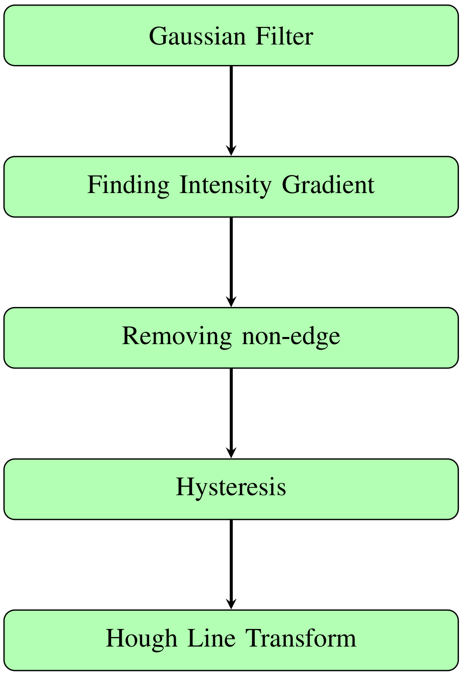

Fig. 4. Lane detection process

distance from origin to the line and θ, the angle formed by this perpendicular line and horizontal axis measured in counter-clockwise. These can form the parametric line equation.

$$\rho = xcos\theta + ysin\theta \quad (2)$$

There exists an OpenCV function for doing this named cv2.HoughLines(). This function takes the ρ,θ as argument. It also takes an extra argument which determines the threshold for allowing a pixel as a line. From the perspective of Bangladesh the drivers always drive through the left side of the road. So it needs to detect the left lane marker.

III. Result

A miniature car including the above features has been developed which showed optimum performance in a simulated environment. The sonar sensor is set up in front of the car. The camera is fixed on the window of the car and the processing units are set within. Fig. 5. shows the implemented model.

Whenever an obstacle was placed in front of the car it reduced its speed and stopped. Some echoes were overlapped and gave back garbage values for a very few time. For better performance multiple sonars can be used. For real life application much efficient and powerful sensor can certainly minimize the hassle.

Python Flask framework was used to host the video sent from the Raspberry Pi. A web page was developed to show the video stream and to provide user interface for supporting the remote control from web page. The MJPG streamer streamed data flawlessly except for that it suffered ms of delay. The video data streamed was 100 ms slow and the commands

Fig. 5. Implemented model

sent from web page consumed another 200 ms. So it overall suffered through 300 milliseconds of delay.

The traffic light detection system was very accurate for the given environment. Although to make it work in the real life environment a lot more training data will be needed. Here 1000 positive and 1000 negative samples have been used to create the classifier. The car could successfully detect the location and interpretation of traffic signal. Fig. 6 shows the traffic light detection obtained from our implemented model.

Fig. 6. Traffic light detection using Haar cascade classifier

The lane detection algorithm worked flawlessly and was able to detect its lane without much of an error. It successfully drove itself in a printed road. Fig. 7, Fig. 8, Fig. 9 show the results of the image processing for detecting lane.

Fig. 7. Original image

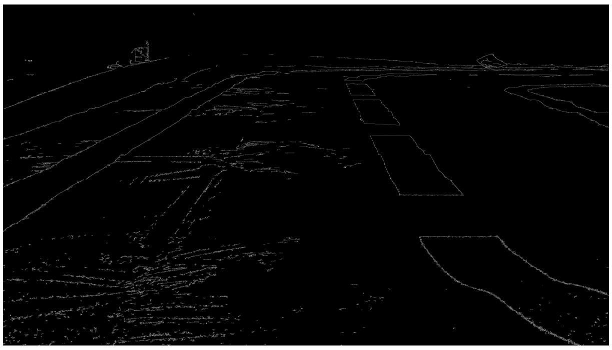

Fig. 8. After canny edge detection

Fig. 9. After Hough transformation and drawing a Hough line

IV. Conclusion

In this paper a method to implement some automation feature in a regular car is described. Utilizing this a small prototype is designed and built. This prototype successfully achieved the goals. However Raspberry Pi maybe powerful but yet we need a much powerful computing machine if we need to implement it on a real car. Or multiple Raspberry Pi could be cascaded to perform different tasks.

As for the cascade classifier we have created for the traffic light detection we need a lot more positive and negative samples from different streets and different weather and light condition if we want to implement it on real life. As the whole system relies heavily on Internet so it would be very convenient in a region where 4G data is available. A fast Internet connection is one of the limitations of this project.

The implemented model is a Level-3 automated car. However if it is to be provided with Level-5 automation a lot more work is to be done. It can not navigate its way to a given location. So a navigation system can be built on top of it. A much better classifier for traffic light detection can be designed to get better performance in a real life scenario.

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New Three Phase Bidirectional Switch Based AC Voltage Controller Topologies

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Abstract—**A new family of three-phase AC voltage controllers has been presented in this paper. The proposed converters consisting of two three-phase modified bidirectional switches have supply and load side neutral connections either directly or indirectly which may be the requirements of three phase AC-AC switched mode voltage controllers in certain applications. Steady state analysis and simulation results are presented in this paper using the Boost topology as an example. Performance of the circuit has been found satisfactory with duty cycle variation. Because the proposed converters employ only two active devices, they can reduce cost and complexity with simple control and improve system reliability.**

Keywords—ac voltage controller; boost converter; pulse width modulation; power quality; switched mode power supply;

I. Introduction

Power utilities deliver AC power at a fixed voltage and frequency. Due to the nature of industrial, commercial, and domestic application requirements of electricity with variable amplitude and/or frequency power conversion is necessary in order to guarantee quality and energy efficient operation of equipment and appliances [1], [2]. The conversion of power may include AC-DC (rectifier), DC-DC (chopper), DC-AC (inverter), and AC-AC at the same (ac voltage controller) or different frequencies (matrix and cycloconverter) [1]-[3]. The AC-AC voltage converter, also known as AC voltage controller, is a kind of power converter that converts a constant voltage and constant frequency AC input supply to a variable voltage AC output delivered to a load through the use of power semiconductor devices. They can be used in light illumination control, industrial heating, power condition and flow control in flexible AC transmission systems, line/bus voltage control for variations in input voltage and load, soft start of AC motors (without v/f control) and their speed control by voltage variation only [4]-[13]. Comprehensive review on single and three phase AC voltage controllers are presented in [14]-[17]. AC voltage converters based on transformers are large and heavy, have sluggish response, include harmonics and need a great number of switches for better regulation [18]. Thyristor based converter topologies give rise to power quality problems and associated effects in supply/load side, machines, transformers, and cables and adversely affect the voltage at the end of common coupling [18], [19]. Bulky and large filters are required for reduction of harmonics and improvement of power factor at input side. The progress in power semiconductor devices and their use as high-power, low-loss and high frequency switching devices with high frequency control results in a variety of AC voltage controller topologies with fewer number of switches, reduction of overall circuit size and volume and improvement of power quality and transient response [20]-[28]. One of the early works available on direct multiple pulse width modulated (MPWM) three-phase AC voltage controller topology was by Mozdzer et al. in [20], where a three-phase AC load is supplied by using six switches, each one was composed of a pair of back to back connected npn transistors and a diode in series with each transistor, counting the total amount of transistors to 12 and also 12 number of diodes. P. D. Ziogas et al. in the 90's, suggested further improvement of AC voltage controller using six switches [21]. Another modification on AC voltage controller was cited by D. Vincenti et al. [22]. This modification substituted the three freewheeling switches in [21] with a unilateral controlled switch and a diode-bridge. As a result the number of switching devices was reduced to four. In [23], S. Srinivasan et. al presented a group of three-phase switch mode AC-AC voltage converters with six AC bi-directional switches, namely – Buck, Boost, Buck-Boost and Ĉuk. In [24], F. Z. Peng et al. replaced the three main switches and the three freewheeling switches used in the AC voltage controllers presented in [23] by two three-phase semi bi-directional switches suggested by D. Vincenti et al. in [22]. Similar two semi bi-directional switch based three-phase Z-source AC voltage converter was proposed by X.P. Fang et. al [25]. The semi bidirectional switch based three phase AC voltage converters of [24], [25] require opening of neutral connection of source and load. They have the disadvantage that if the loads are not balanced, then there will be unbalanced currents which will change phase voltages due to absence of load and source neutral. This shortcoming was overcome in three phase rectifiers [26] and voltage controllers [27], [28] having modular structure in which the converter works on per phase basis. A new true three-phase AC bi-directional switch has been developed consisting of a unidirectional switch included in two three-phase diode bridges. This three-phase AC bi-directional switch allows modular operation even if the converter neutrals (supply and load side) are not connected. As a result three phase output voltages remain same in case of load unbalance.

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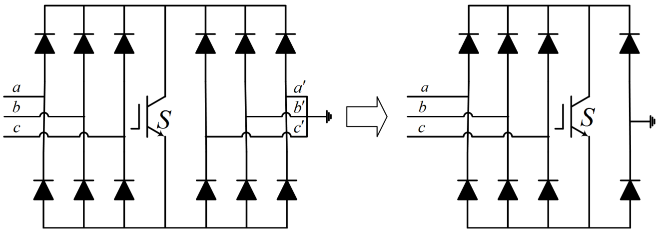

Fig. 1. Three-phase modified bidirectional switch obtained from three phase true bidirectional switch.

In certain applications, it may be necessary to use supply and load neutral points. Investigation has been made to obtain such topologies and in this paper a new group of three phase AC voltage controller topologies has been proposed using two modified three-phase AC bi-directional switches with neutral and less number of diodes. The modified bidirectional switch has been derived from the true three-phase bi-directional switch as shown in Fig. 1. This offers the proposed converters to have supply and load side neutral connections intact with even less utilization of semiconductor devices. Because the proposed converters have neutral connections and employ only two active devices, they can be less costly and can reduce complexity with simple control and enhance reliability of the system.

II. New Three Phase AC-AC Converter Topologies

Using the novel three-phase modified bi-directional switch with neutral new three-phase switch mode AC voltage controllers, namely - Buck, Boost, Buck-Boost, Ĉuk and SEPIC converters, are presented as shown in Figs. 2 - 6 respectively. The proposed converters have only two bidirectional switches - one act as the main switch and the other operates as freewheeling path across the load. Both supply and load sides are connected with neutral either directly or indirectly through the switches. Due to less number of active devices, control becomes easier. Easy control, decreased number of switches and the associated gate drive circuits, availability of source and load side neutral connections make the topologies potential candidates for AC-AC voltage control applications.

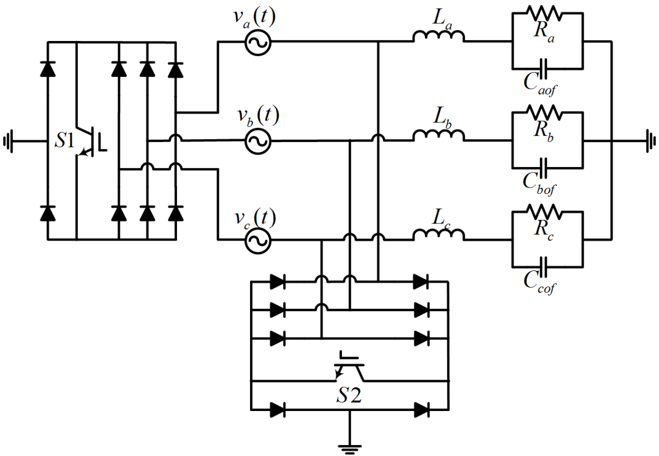

Fig. 2. Three-phase modified Buck AC voltage controller based on two three-phase bi-directional switches with neutral.

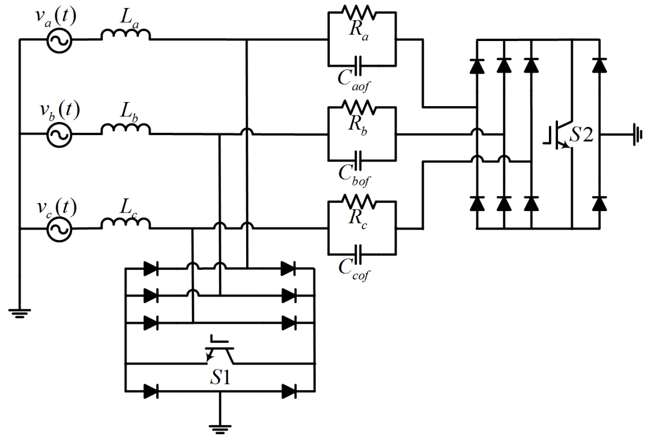

Fig. 3. Three-phase modified Boost AC voltage controller based on two three-phase bi-directional switches with neutral.

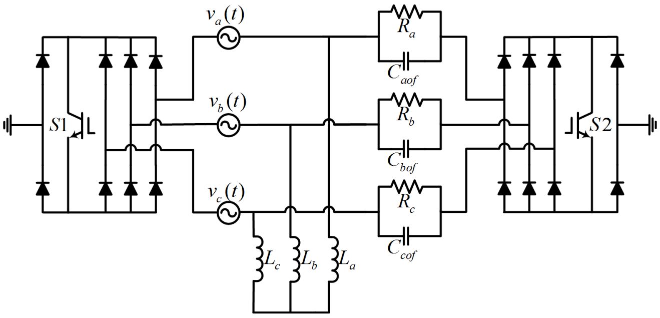

Fig. 4. Three-phase modified Buck-Boost AC voltage controller based on two three-phase bi-directional switches with neutral.

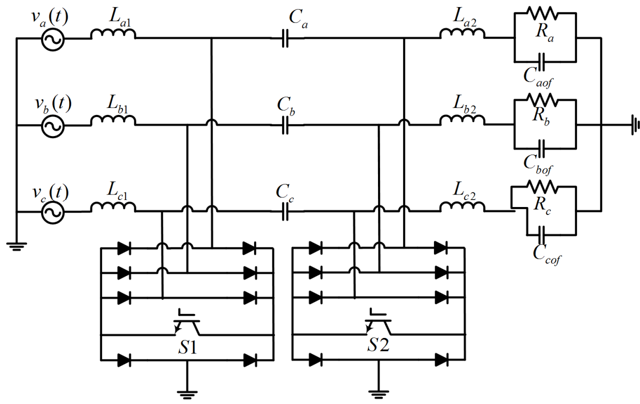

Fig. 5. Three-phase modified Ĉuk AC voltage controller based on two three-phase bi-directional switches with neutral.

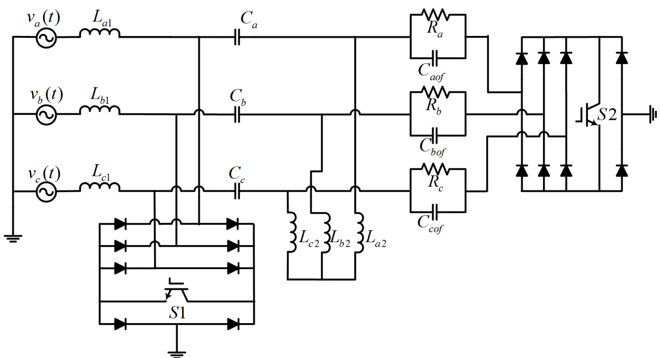

Fig. 6. Three-phase modified SEPIC AC voltage controller based on two three-phase bi-directional switches with neutral.

III. Analysis of Boost AC-AC Converter: An Example

To justify the new three-phase modified AC voltage controller topologies of Figs. 2-6, the three-phase Boost AC voltage controller is analyzed in this paper. Boost converters permits the output voltage to be higher than the input voltage depending on the duty-ratio of the gate signal. As given in Fig. 3, the proposed three-phase Boost AC-AC voltage converter have two three-phase modified bi-directional switches *S1* and *S2* with neutral each consist of a unidirectional switch and 8 number of diodes, three boost inductors L_a, L_b, L_c, output filter capacitors $C_{aof}, C_{bof}, C_{cof}$ and load resistances R_a, R_b, R_c. Here the sources have neutral connection and the loads are placed individually in each phase and connected to neutral through the bidirectional switch $S2$. The two switches act on alternate switching intervals by high frequency pulses at each gate. As the switching frequency is much higher than the AC line frequency of the supply, in a switching period, line frequency variables, such as, input voltage can be considered as constant. Then two equivalent circuits of the two states can be obtained, as shown in Figs. 7 and 8. Suppose the line-frequency input and output voltages of the balanced three-phase Boost AC voltage controller with resistive load are defined as,

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = V_m \begin{bmatrix} sin(\omega t) \\ sin(\omega t - 120^o) \\ sin(\omega t + 120^o) \end{bmatrix} \text{ and } \begin{bmatrix} v_{ao} \\ v_{bo} \\ v_{co} \end{bmatrix} = V_{om} \begin{bmatrix} sin(\omega t) \\ sin(\omega t - 120^o) \\ sin(\omega t + 120^o) \end{bmatrix} \text{ respectively.} \quad (1)$$

In state 1, both in +ve and -ve half cycles of the supply voltage, turning the switch *S1* ON while *S2* is turned OFF during the time DT_S, take apart the input stage from the output. Input provides energy to the boost inductors. Here D is the duty ratio of switch *S1* and T_S is the switching period. Voltage across the inductor can be expressed as,

$$\begin{bmatrix} v_{La} \\ v_{Lb} \\ v_{Lc} \end{bmatrix} = \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \quad (2)$$

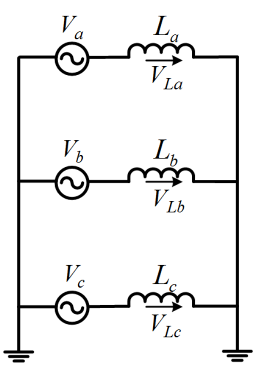

Fig. 7. State 1: switch S1 is ON and S2 is OFF.

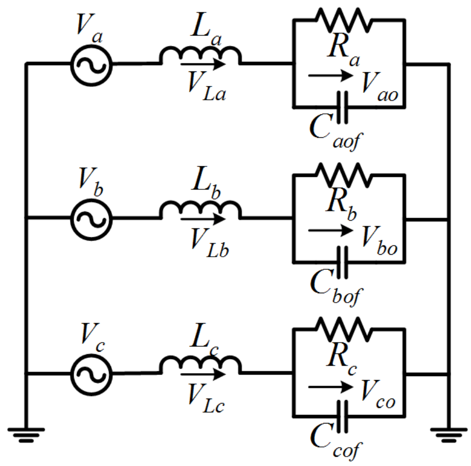

Fig. 8. State 2: switch S1 is OFF and S2 is ON.

In state 2, when the switch *S1* is OFF and *S2* turns ON during the time $(1-D)T_S$, the load gets energy from the supply and the boost inductors. Voltage across the inductor can be expressed as,

$$\begin{bmatrix} v_{La} \\ v_{Lb} \\ v_{Lc} \end{bmatrix} = \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} - \begin{bmatrix} v_{ao} \\ v_{bo} \\ v_{co} \end{bmatrix} \quad (3)$$

In the generalized switching cycle, the inductor volt-second is,

$$\int_t^{t+Ts} \begin{bmatrix} v_{La} \\ v_{Lb} \\ v_{Lc} \end{bmatrix} dt = \int_t^{t+DTs} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} dt + \int_{t+DTs}^{t+Ts} \left(\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} - \begin{bmatrix} v_{ao} \\ v_{bo} \\ v_{co} \end{bmatrix} \right) dt \quad (4)$$

In AC-AC switching converters, in steady state, total volt-second of an inductor over one line frequency AC-cycle should be equal to zero. From volt-second balance,

$$\sum_{i=1}^{n} \int_{t_i}^{t_i+Ts} \begin{bmatrix} v_{La} \\ v_{Lb} \\ v_{Lc} \end{bmatrix} dt = 0 \quad (5)$$

Which implies,

$$\sum_{i=1}^{n} \int_{t_i}^{t_i+DTs} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} dt + \sum_{i=1}^{n} \int_{t_i+DTs}^{t_i+Ts} \left(\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} - \begin{bmatrix} v_{ao} \\ v_{bo} \\ v_{co} \end{bmatrix} \right) dt = 0 \quad (6)$$

Where, $n = \dfrac{AC\ line\ Period, T_l}{Switching\ Period, T_s} = \dfrac{Switching\ frequency, f_s}{AC\ line\ frequency, f_l}$

From equation (6) it is possible to get equation (7),

$$\sum_{i=1}^{n} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} DTs + \sum_{i=1}^{n} \left(\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} - \begin{bmatrix} v_{ao} \\ v_{bo} \\ v_{co} \end{bmatrix} \right) (1-D)Ts = 0 \quad (7)$$

Simplifying we get,

$$\sum_{i=1}^{n}\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} D + \sum_{i=1}^{n}\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix}(1-D) - \sum_{i=1}^{n}\begin{bmatrix} v_{ao} \\ v_{bo} \\ v_{co} \end{bmatrix}(1-D) = 0 \quad (8)$$

This can be written as,

$$\sum_{i=1}^{n}\begin{bmatrix} v_{ao} \\ v_{bo} \\ v_{co} \end{bmatrix} = \frac{1}{(1-D)}\sum_{i=1}^{n}\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \quad (9)$$

with $T_s \rightarrow 0$ or $n \rightarrow \infty$, we can write

$$\sum_{i=1}^{n}\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = V_m \begin{bmatrix} sin(\omega t) \\ sin(\omega t - 120^o) \\ sin(\omega t + 120^o) \end{bmatrix} \quad (10)$$

$$\sum_{i=1}^{n}\begin{bmatrix} v_{ao} \\ v_{bo} \\ v_{co} \end{bmatrix} = \begin{bmatrix} v_{ao} \\ v_{bo} \\ v_{co} \end{bmatrix} = V_{om} \begin{bmatrix} sin(\omega t) \\ sin(\omega t - 120^o) \\ sin(\omega t + 120^o) \end{bmatrix} \quad (11)$$

Thus bearing in mind that the switching period is extremely small compared to the supply line period, the voltage gain expression of the proposed three phase Boost AC voltage controller can be expressed as,

$$\begin{bmatrix} v_{ao} \\ v_{bo} \\ v_{co} \end{bmatrix} = \frac{1}{(1-D)}\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \quad (12)$$

The above input/output relationship indicates that ideally the instantaneous output voltages of the Boost AC voltage controller will be greater than the input voltages. The output voltage can be controlled by duty cycle variation. In practice, switching loss, inductor/capacitor non-idealities, diode/switch conduction losses will cause deviation of ideal gain relationship, which eventually will not allow the circuit to work at high efficiencies at all duty cycles. Almost ideal gain characteristics will be followed near high efficiency operation. A similar analysis applies to other AC-AC converters.

IV. Simulation Results

The proposed three-phase Boost AC voltage controller has been simulated using the application software PSIM version 9.0. The input is a balanced three-phase AC source with peak voltage amplitude of 300V at supply frequency of 50 Hz. The two bi-directional switches are operated in complement by high frequency pulses of 10 KHz. Each Boost inductances has been selected as 7mH, filter capacitances at output are 1μF each and load resistances of 100Ω each. Fig. 9 illustrates the sample three-phase input and output voltages and input currents waveforms of the proposed Boost AC voltage controller with resistive load in open loop control. The wave shapes in the Fig. depicts that the proposed circuit can maintain good power quality by keeping the input currents almost sinusoidal and in phase with input voltage.

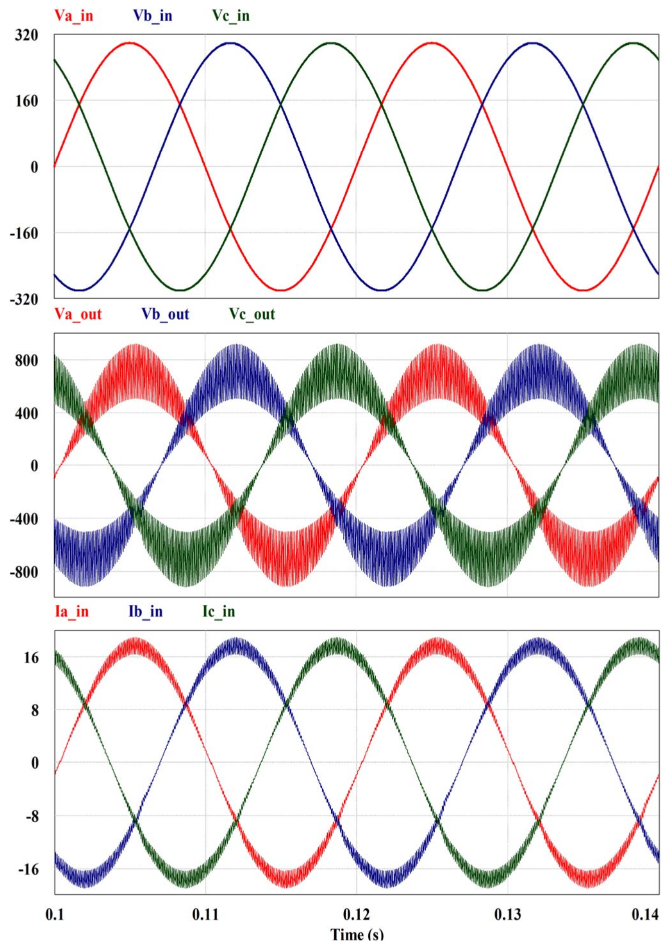

Fig. 9. Typical input and output voltages and input current wave shapes of three-phase modified Boost AC voltage controller at duty cycle D=0.6.

A. *Power Quality with Variation of Duty Cycle*

In open loop condition by varying the duty-ratio of the gate signals of the two bi-directional switches the performance of the proposed three-phase Boost AC voltage controller has been measured in terms of power quality indices such as efficiency(Eff(%)), input power factor (PF), percent Total Harmonic Distortion (THD (%)) of input current, and voltage gain (Vgain). The outcomes of this observation are given in Table I and in Figs. 10 - 13.

TABLE I. PERFORMANCE OF BOOST AC VOLTAGE CONTROLLER UNDER DUTY CYCLE VARIATIONS

Duty Cycle, *D*	**Eff (%)**	**PF**	**THD (%)**	**Vgain**
0.2	99.94	1.00	5.86	1.24
0.3	99.61	1.00	6.21	1.41
0.4	99.31	1.00	6.50	1.64
0.5	98.46	1.00	5.34	1.95
0.6	97.67	0.99	4.43	2.39
0.7	95.01	0.98	2.89	3.09
0.8	90.12	0.91	1.67	4.05

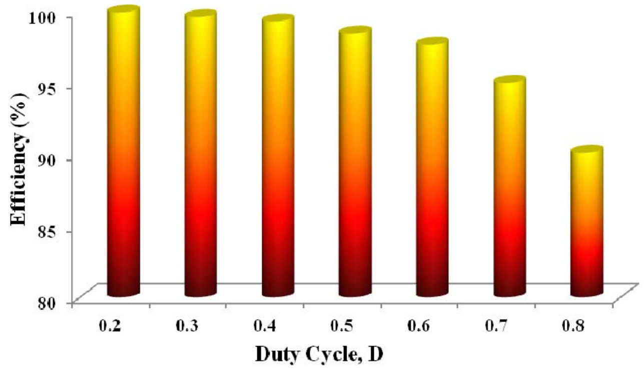

Fig. 10. Performance of three-phase Boost AC voltage controller in terms of efficiency (%) under duty cycle variation.

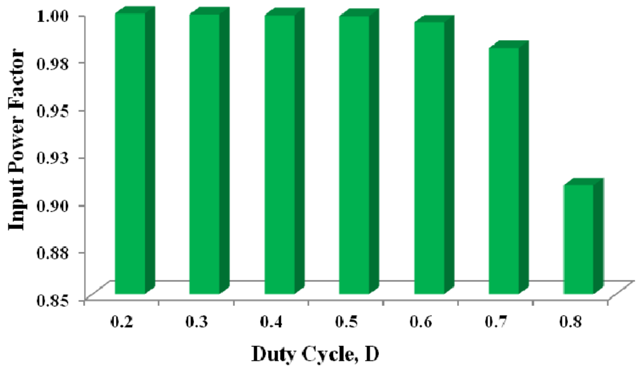

Fig. 11. Performance of three-phase Boost AC voltage controller in terms of input power factor under duty cycle variation.

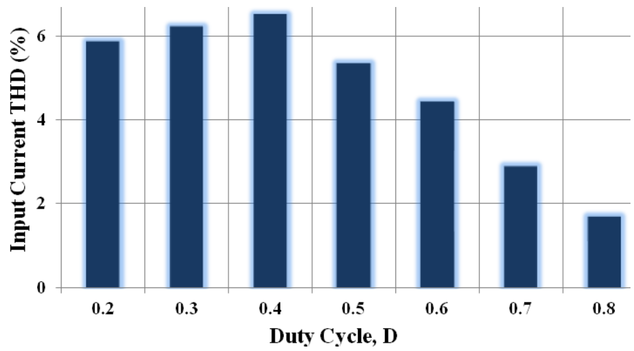

Fig. 12. Performance of three-phase Boost AC voltage controller in terms of input current THD (%) under duty cycle variation.

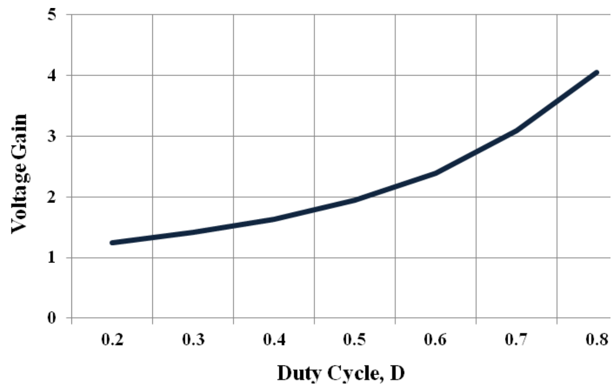

Fig. 13. Performance of three-phase Boost AC voltage controller in terms of voltage gain under duty cycle variation.

In open loop condition with duty-cycle variation the proposed modified Boost AC voltage converter circuit gives high efficiency of more than 90%. The input power factor is almost unity all over the range of duty cycle. The maximum value of input current THD is below 7% at 40% duty-ratio. With duty-cycle variation the voltage at output is always found higher than the input voltage as expected.

V. Conclusion

A novel design of three-phase modified bi-directional switch with neutral has been proposed in this research. The modified bi-directional switch consists of a unidirectional controlled switch enclosed by a three-phase diode bridge the three legs of which are connected to three individual phases and an additional leg of two diodes connected to the source/load side neutral. Based on two new three-phase modified bi-directional switches a new family of three-phase AC voltage controller topologies has been proposed. The proposed converters have supply and load side neutral connections intact and contain less number of diodes. Current ratings of the unidirectional controlled switches (such as IGBTs) used in the proposed converters can be less compare to those employed in the AC voltage controllers having modular structure in which the converters work on per phase basis. Thus overall switching and conduction losses reduce significantly and efficiency of the converters increases. The modified bidirectional switch based converters also give design advantages like simple control, reliable operation, reduction in cost and complexity. The three-phase Boost AC voltage controller circuit has been investigated as an example. Reasonable performance of the converter in terms of power quality has been observed with duty cycle variation. The research outcome is expected to result in a family of simple, cheap, less weight and compact with better power quality AC voltage controller topologies suitable for AC-AC applications. Experimental verification will be conducted in future both in open and closed control to justify the validation of the proposed converter.

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True Three-Phase Bidirectional Switch Based Buck AC Voltage Controller Topology

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***Abstract*—Two bi-directional switch based three-phase buck AC voltage controller is presented in this paper. The operational principle of the proposed three-phase regulator is a direct consequence of using two three-phase bi-directional switches in the buck converter topology. The converter works on per phase basis and therefore three phase output voltages remain same in case of load unbalance. The topology has reduced number of switches for a three-phase AC voltage control having output voltage regulation, input current shaping and power factor improvement capability. Reduced number of switches allows simple control circuit, less switching loss, reliable operation and low cost. Steady state analysis and simulation results of open and closed loop control of the proposed converter are presented in this paper. The voltage mode feedback control method used for controlling the regulator shows acceptable regulation of the converter output voltage. During sudden variation of load or input voltage the controller adjusts the duty cycle to recover to the desired output voltage.**

Keywords—ac voltage controller; automatic voltage control; buck converter; power quality; pulse width modulation;

I. INTRODUCTION

AC voltage controller is a kind of power converter that converts a fixed voltage, fixed frequency AC input supply to a variable voltage AC output delivered to a load through the use of power semiconductor devices [1]. They have applications in light illumination control, industrial heating, power conditioning and power flow control, speed regulation of fans, pumps, and blowers, soft starting of AC motors, etc. [2]-[11]. Transformer based AC voltage controllers are big and weighty, have sluggish response, include harmonics and need a great number of switches for better regulation [12]. Thyristor based converters have poor power quality problems and adversely affect the machines, transformers, and cables and the supply power at the end of common coupling [12], [13]. Bulky and large filters are required to decrease the harmonics and increase the power factor at input side. The progress in power semiconductor devices and their use as high-power, low loss and high frequency switching devices with high frequency control results in a variety of AC voltage controller topologies with fewer number of switches, reduction of overall circuit size and volume and improvement of power quality and transient response [14]-[22]. In [17], S. Srinivasan et. al proposed a group of three-phase switch mode AC-AC voltage converters with six AC bidirectional switches, namely – Buck, Boost, Buck-Boost and Ĉuk. F. Z. Peng et al. in [18], replaced the three main switches and the three freewheeling switches used in the AC voltage controllers presented in [17] by two three-phase semi bi-directional switches each consists of a unidirectional controlled switch enclosed by a three phase diode rectifier bridge. Similar two semi bi-directional switch based three-phase Z-source AC voltage converter was proposed by X.P. Fang et. al [19]. The semi bi-directional switch based three phase AC voltage converters of [18], [19] require opening of neutral connection of source and load. Because of lack of load/source side neutral these topologies have the limitation that in case of unbalanced loads, load currents become unbalanced which also changes the phase voltages. This shortcoming has been overcome in three phase rectifiers [20] and AC voltage controllers [21], [22] having modular structure in which the converter works on per phase basis. A new three phase AC bidirectional switch has been introduced as shown in Fig. 1 which composed of a unidirectional switch enclosed by two three phase diode bridges on either side. This true three-phase AC bidirectional switch allows modular operation even if the converter neutrals are not connected. As a result three phase output voltages remain same in case of load unbalance. Phase by phase modular operation permits the converters to have N number of phases with two bidirectional switches consisting of 2 unidirectional switches and 8N number of diodes.

This paper describes a three-phase switched mode Buck AC voltage controller with two three-phase AC bidirectional switches. Steady state analysis and performance of the converter both in open and closed loop control has been observed. Voltage mode feedback control with simple PI controller has been used for output voltage regulation. of the proposed converter. The controller performance for sudden input voltage and load variation has also been examined.

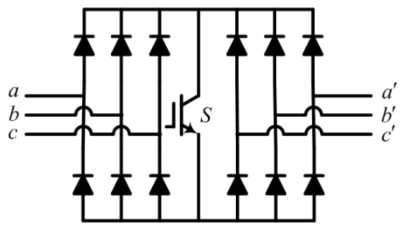

Fig. 1. New three-phase AC bidirectional switch

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II. Three Phase Buck AC Voltage Controller

Buck converter is used as a means of reducing the instantaneous voltage across the load. Fig. 2 illustrates the circuit diagram of the proposed three-phase Buck AC voltage controller. It includes three buck inductors L_a, L_b, L_c, output filter capacitors C_{a_of}, C_{b_of}, C_{c_of}, and load resistances RL_a, RL_b, RL_c, along with two three phase AC bidirectional switches $S1$ and $S2$. The two switches are operated in alternating intervals by applying high frequency pulses at each gate. During the switching interval when the switch $S1$ is ON and $S2$ is OFF, inductor current increases which also passes through the load and back to the source. When switch $S2$ is closed while $S1$ is open inductor current freewheels through the switch *S2* and load. The proposed Buck converter circuit thus operates per phase basis both in positive and negative cycles of input voltages.

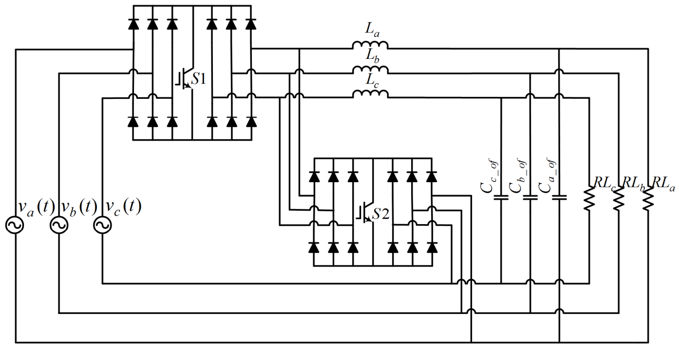

Fig. 2. Proposed three phase Buck AC voltage controller with two three phase AC bidirectional switches.

III. Analysis of Buck AC Voltage Controller

The proposed three phase Buck AC voltage controller can be considered as three single phase AC-AC Buck converter, phase 'a' of which appears as shown in Fig. 3. In phase 'a', two equivalent circuits of the two states can be achieved for a generalized switching cycle, as shown in Fig. 4 and Fig. 5. Since the switching frequency f_s is much higher than the AC line frequency f_l, in a switching period, the line frequency variables (such as input voltage) can be treated as constant.

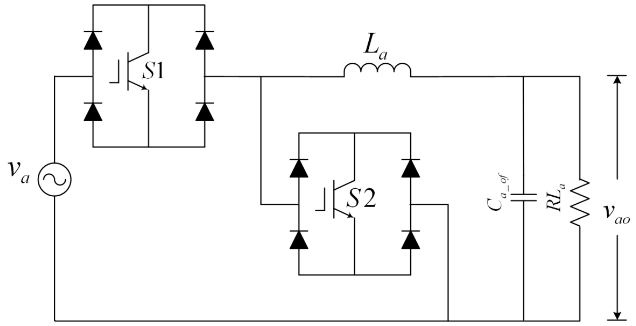

Fig. 3. Equivalent circuit of the phase 'a' of the proposed three-phase Buck AC voltage controller.

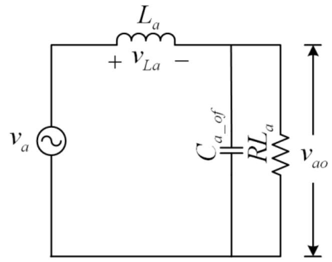

Fig. 4. Single phase equivalent circuit in state 1.

State 1 (S1 ON, S2 OFF): The single-phase equivalent circuit becomes as shown in Fig. 4. Applying KVL, voltage across the inductor can be expressed as,

$$\langle v_{La}\rangle_{T_S} = \langle v_a\rangle_{T_S} - \langle v_{ao}\rangle_{T_S} \qquad (1)$$

State 2 (S1 OFF, S2 ON): The single-phase equivalent circuit turns out to be as shown in Fig. 5. According to KVL, the inductor voltage is,

$$\langle v_{La}\rangle_{T_S} = -\langle v_{ao}\rangle_{T_S} \qquad (2)$$

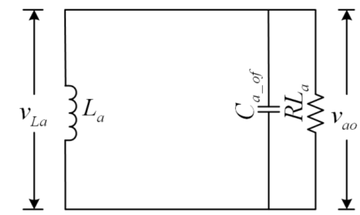

Fig. 5. Single phase equivalent circuit in state 2.

The switching period,

$$T_S = t_{S1} + t_{S2}$$

The duty cycle, *D* of the converter is defined as,

$$D = \frac{t_{S1}}{T_S}$$

The complement of the duty cycle is,

$$(1-D) = \frac{t_{S1}}{T_S}$$

In a generalized switching cycle, the inductor volt-second is,

$$\int_{t}^{t+Ts} \langle v_{La}\rangle_{T_S}\, dt = \int_{t}^{t+DTs} \left(\langle v_a\rangle_{T_S} - \langle v_{ao}\rangle_{T_S}\right) dt + \int_{t+DTs}^{t+Ts} \left(-\langle v_{ao}\rangle_{T_S}\right) dt$$

In AC-AC switching converters, in steady state, total volt-second of an inductor over one line frequency AC-cycle should be equal to zero. From volt-second balance,

$$\sum_{i=1}^{n} \int_{t_i}^{t_i+Ts} \langle v_{La}\rangle_{iT_S}\, dt = 0$$

Here, $n = \dfrac{AC\ line\ Period, T_l}{Switching\ Period, T_S} = \dfrac{Switching\ frequency, f_S}{AC\ line\ frequency, f_l}$

This implies,

$$\sum_{i=1}^{n}\int_{t_i}^{t_i+DTs}\left(\langle v_a\rangle_{iT_S}-\langle v_{ao}\rangle_{iT_S}\right)dt+\sum_{i=1}^{n}\int_{t_i+DTs}^{t_i+Ts}\left(-\langle v_{ao}\rangle_{iT_S}\right)dt=0$$

Which can be expressed as,

$$\sum_{i=1}^{n}\left(\langle v_a\rangle_{iT_S}-\langle v_{ao}\rangle_{iT_S}\right)DTs+\sum_{i=1}^{n}\left(-\langle v_{ao}\rangle_{iT_S}\right)(1-D)Ts=0$$

Simplifying we get,

$$\sum_{i=1}^{n}\langle v_{ao}\rangle_{iT_S}=D\sum_{i=1}^{n}\langle v_a\rangle_{iT_S} \tag{3}$$

with $T_s \rightarrow 0$ or $n \rightarrow \infty$, we can write

$$\sum_{i=1}^{n}\langle v_a\rangle_{iT_S}=v_a=V_{im}\,sin(\omega t),\ \text{and}$$

$$\sum_{i=1}^{n}\langle v_{ao}\rangle_{iT_S}=v_{ao}=V_{om}\,sin(\omega t-\theta)$$

Thus equation (3) can be expressed as,

$$v_{ao}=Dv_a=DV_{im}\,sin(\omega t) \tag{4}$$

In three phase, the voltage gain expression can be written as

$$\begin{bmatrix}v_{ao}\\ v_{bo}\\ v_{co}\end{bmatrix}=D\begin{bmatrix}v_a\\ v_b\\ v_c\end{bmatrix}=DV_{im}\begin{bmatrix}sin\,\omega t\\ sin\left(\omega t-120^o\right)\\ sin\left(\omega t+120^o\right)\end{bmatrix} \tag{5}$$

Equations (4) and (5) respectively define the voltage gain expression of single and three phase Buck AC voltage controller. The input/output relationship indicates that the instantaneous output voltages of the proposed Buck AC voltage controller is lower than input voltages. Controlling the duty ratio of the control signal the output voltage can be controlled in step-down fashion. In practice, switching loss, inductor/capacitor non-idealities, diode/switch conduction losses will cause deviation of ideal gain relationship in practical circuits, which eventually will not allow the circuit to work at high efficiencies at all duty cycles.

IV. THREE-PHASE BUCK REGULATOR WITH FEEDBACK CONTROL

Converter systems require closed loop automatic adjustment of duty cycle to regulate the output voltage within a set limit in spite of fluctuations in supply voltage and in load. Fig. 6 shows the voltage mode feedback control scheme for the proposed three-phase Buck AC voltage controller where the output voltages of the converter were regulated to 150V (peak) from a three-phase balanced inpuy source with peak voltage amplitude of 300V. The feedback signal has been taken as the DC average of the output voltage of a single-phase and is compared with a DC reference signal. The error between the two is compensated by a PI controller. The controller parameters (gain= 1, time constant= 20ms) have been chosen by Ziegler-Nichols tuning method. The controller output is

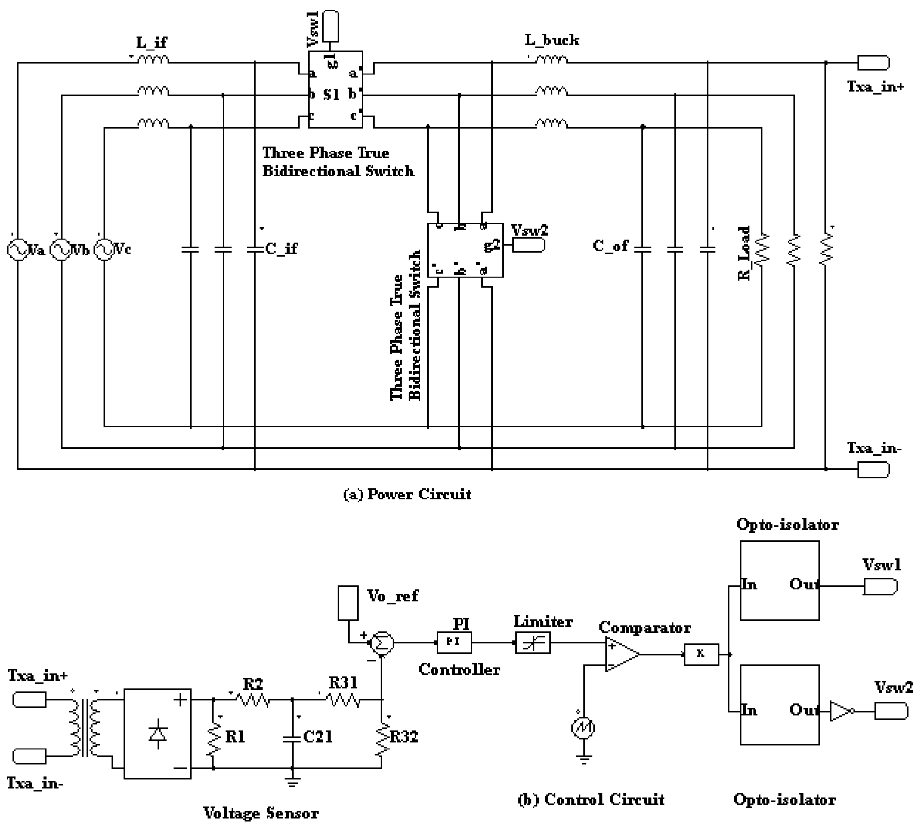

Fig. 6. Voltage mode control of the proposed Buck AC voltage controller with feedback signal taken as DC average of the output voltage of a single phase.

then compared with high frequency triangular wave of 8 kHz to create the desired PWM signals to drive the switches. The generated gate pulses are traversed thru the opto-coupler units to the inputs of two bi-directional switches. In order to make the complimentary gate signal for the bidirectional freewheeling switch one of the gate signals is inverted. In reality commercially existing controller ICs can be employed in this regard with necessary adjustment to acquire the desired inverted gate signal for the freewheeling switch of the three-phase AC voltage controller.

V. SIMULATION RESULTS

The proposed three-phase Buck AC voltage controller has been simulated using PSIM version 9.0 simulation software. In open loop condition the width of the gate pulses is varied and the circuit parameter values are adjusted to get high operating performance from the proposed Buck converter. The circuit parameters and the operating conditions are given in table I below.

TABLE I. CIRCUIT PARAMETERS AND OPERATING CONDITIONS

Source	3-phase balanced ac source Line Frequency: 50 Hz Amplitude: 300V
Switching Frequency	8 kHz
Buck Inductances	4 mH (each)
Input LC Filter	Inductance: 7 mH (each) Capacitance: 1 µF (each)
Output Filter	Capacitance: 1 µF (each)

A. Performance Observation by Varying Duty Ratio

In open loop condition by changing the width of the gate drive signals the performance of the proposed Buck converter has been measured in terms of power quality indices such as efficiency, input power factor, percent Total Harmonic Distortion of input current, and voltage gain. The outcomes of the comparisons are illustrated in Figs. 7 - 10.

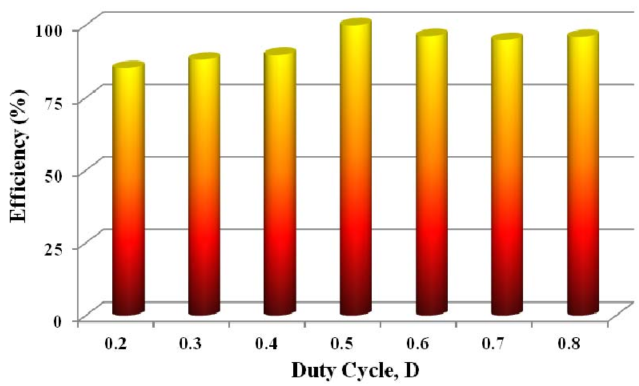

Fig. 7. Performance in terms of efficiency (%) of three-phase Buck AC voltage controller under duty cycle variation.

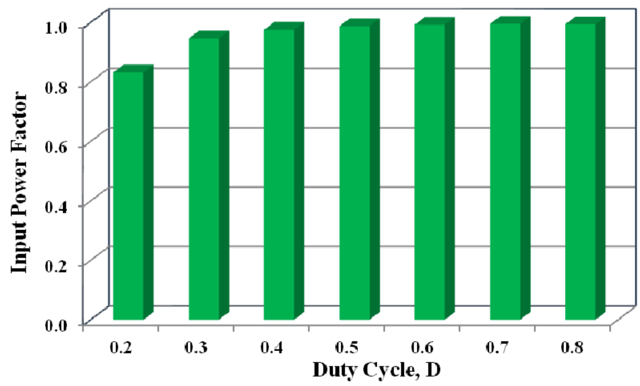

Fig. 8. Performance in terms of input power factor of three-phase Buck AC voltage controller under duty cycle variation.

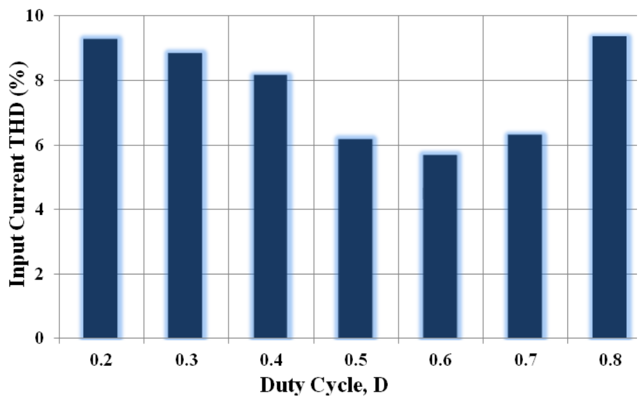

Fig.9. Performance in terms of input current THD (%) of three-phase Buck AC voltage controller under duty cycle variation.

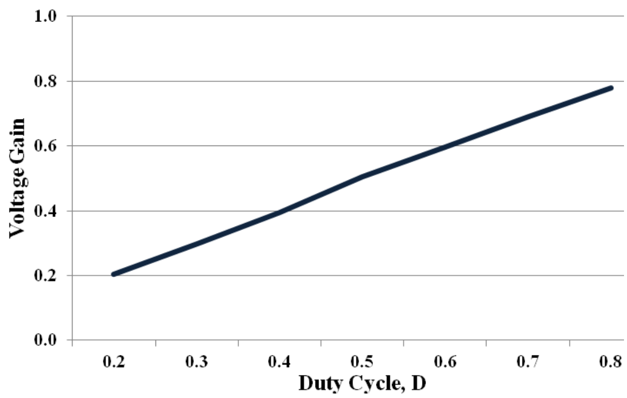

Fig. 10. Performance in terms of voltage gain of three-phase Buck AC voltage controller under duty cycle variation.

In open loop condition with duty cycle variation the proposed three-phase Buck AC-AC converter shows high efficiency operation ranges from 84% to 99%. The power factor is almost unity throughout the range of duty cycle. The input current THDs are found less than 10% all over the duty cycles. The voltage gain with duty cycle variation is linear, follows the theoretical relation of Buck converter.

B. Performance under Closed Loop Control

Fig. 11 shows the typical output voltage and input current wave shapes of the three-phase Buck AC-AC converter, where the output voltage has been controlled at targeted peak value of 150V with voltage mode feedback control using proportional integral (PI) controller. The input current is sinusoidal with percent total harmonic distortion (THD) of 5.4%. The input side power factor has been obtained 0.92 and the efficiency of the converter is 97.05%.

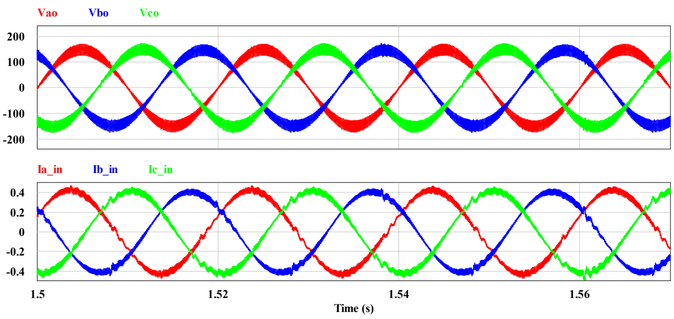

Fig. 11. Controlled output voltage and input current waveforms of the proposed three phase Buck AC-AC converter.

C. Controller Response at Step Load Change

The Proposed Buck converter had experienced sudden load disturbances from the rated load value and the converter performance has been measured under closed loop control. Fig. 12 illustrates the response of output voltage and input current for step changes of load from 100% to 120%. The change of load was occured at 1.5s, where the converter was in steady state. It has been found that the converter shows good response to sudden disturbances in load. This shows the capability of the proposed controller system to accommodate step load change.

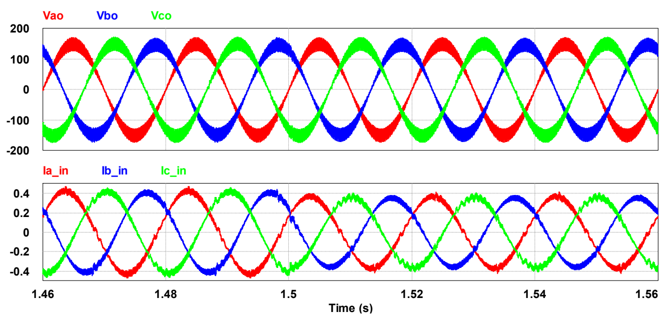

Fig. 12. Response of output voltage and input current wave shapes of Buck converter for sudden load variation at 1.5s.

D. Controller Response at Step Change of Input Voltage

Performance of the converter has also been measured in closed loop condition for sudden change of input voltage from the rated maximum value of 300V. Fig. 13 illustrates the response of the output voltage and input current wave shapes for sudden input voltage change from rated 300V to 330V at 1.5s. It was seen that the output voltage changed momentarily during the input voltage fluctuations. Due to the controller action on the switches, voltage recovered quickly.

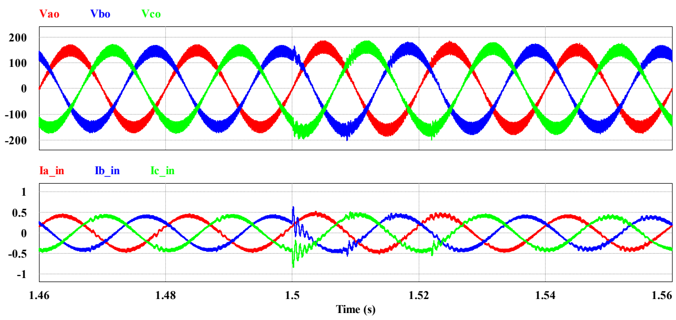

Fig.13. Response of output voltage and input current wave shapes of Buck converter for step input voltage variation at 1.5s.

VI. Conclusion

In this paper a new topology of three-phase PWM switch mode Buck AC voltage controller using two three-phase AC bi-directional switches has been presented. The topology can be well thought-out as direct extension of using two bi-directional AC switches in Buck converter topology. Steady state analysis demonstrates the capability of the proposed converter to reach step-down of the instantaneous output voltages with duty ratio control. Closed loop feedback control of the proposed Buck converter shows that simple PI-controller on one phase can regulate the output voltage of the converter with good accuracy. Performance of the converter in terms of efficiency, input power factor, percent total harmonic distortion of input current, etc. has been found satisfactory both in open and closed loop control. For sudden changes in supply voltage or load the controller adjusts the width of the high frequency gate pulses to obtain the desired output voltage quickly. Since the proposed topology uses only two switches, it has the benefits of having reliable operation, simple control, less conduction and switching losses, and cost and complexity reduction of the overall system. Experimental verification will be done in future to justify the validation of the proposed converter.

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