Enhancing the Micro-Grid Reliability in Industrial Distribution Feeders by Generating Bus Splitting Model

By

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Institute of Energy Technology (IET)

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Declaration

I hereby declare that the content presented in this thesis has not been previously submitted to fulfill the requirements for an academic degree at this or any other institution of higher education. To the best of my knowledge and belief, this thesis does not include any previously published or authored material by another individual, except where proper references and credentials are provided.

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Dedication

I dedicate this M.Sc. thesis to my parents, Bodiul Alam and Farida Begum, whose unwavering support and encouragement have been my constant pillars of strength throughout my academic journey. I extend my heartfelt gratitude to my wife, Sharifa Khanam Mary, who made countless sacrifices and provided steady support throughout this academic journey.

I am deeply grateful to my elder brother, Dr. Abu Taher, for his invaluable guidance during the formative years of my education, which laid the foundation for my pursuit of knowledge.

I also extend my heartfelt thanks to the Institute of Energy Technology (IET) at Chittagong University of Engineering and Technology (CUET) for providing me with a nurturing academic environment where I could embark on this educational journey. This institute’s support has been instrumental in shaping this thesis, and I am truly fortunate to have been a part of this department.

Approval by the Supervisor

This is to certify that Abu Naser has conducted this work under my direct supervision, following to all the relevant Academic Ordinances of the Chittagong University of Engineering and Technology. Consequently, he is deemed qualified to submit the following thesis in pursuit of the degree of Master of Science in Energy Technology.

Dr. Nur Mohammad
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Acknowledgment

I would like to express my sincere appreciation and gratitude to my mentor and guide, Dr. Nur Mohammad, Professor and Head of the Department of Electrical and Electronic Engineering at Chittagong University of Engineering and Technology (CUET). Special thanks go to my dedicated supervisor, Dr. Nur Mohammed, whose mentorship and guidance have played a key role in helping me bridge the gap between industrial challenges and academic solutions.

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সারাংশ

এই থিসিসের মূল লক্ষ্য হলো, বাংলাদেশের চট্টগ্রাম রপ্তানি প্রক্রিয়াকরণ এলাকায় (CEPZ) অবস্থিত আনুমানিক ১৬৫টি এবং কর্ণফুলী রপ্তানি প্রক্রিয়াকরণ এলাকায় (KEPZ) অবস্থিত আরো প্রায় ৭০টি অনুরূপ রপ্তানিমুখী শিল্প প্রতিষ্ঠানসমূহে নিরবচ্ছিন্ন ও মান-সম্পন্ন বিদ্যুৎ সরবরাহের জন্য এর Industrial Micro-Grid (IMG) এর স্থিতিশীলতা অন্বেষণ ও নিয়ন্ত্রণ সংশ্লিষ্ট বিষয়াদি বিশ্লেষণ করা। আলোচ্য ইন্ডাস্ট্রিয়াল মাইক্রো-গ্রিড গঠিত হয়েছে প্রতিটি ৮.৭৩ মেগাওয়াট ক্ষমতা সম্পন্ন ৫ (পাঁচ) টি এবং প্রতিটি ৯.৩৪ মেগাওয়াট ক্ষমতা সম্পন্ন স্বতন্ত্র আরো ৩টি প্রাকৃতিক গ্যাস (NG) নির্ভর অন্তর্দহ (IC) ধরনের ইঞ্জিন চালিত সর্বমোট ৮টি বৈদ্যুতিক জেনারেটর সমন্বয়ে গঠিত বিদ্যুৎ উৎপাদন কেন্দ্র, যা সংযুক্ত রয়েছে প্রায় ৮০ কিঃ মিঃ বিস্তৃত মিশ্র ধরণের (overhead & underground type) ১১ কেভি ভোল্টেজের বিতরণ নেটওয়ার্কের সাথে এবং ৩টি স্থানীয় ৩৩ কেভি জাতীয় গ্রীডের লুপের সাথে। এই জেনারেটরগুলিকে স্বনিয়ন্ত্রিতভাবে গ্রীড বিযুক্ত থেকে Island Mode অপারেশনে চালু রেখে কিংবা গ্রীডের সাথে সমাপতিত (synchronized) অবস্থায় চালিয়ে CEPZ এর ১৫টি এবং KEPZ এর অনুরূপ ৮টি ১১ কেভি ভোল্টেজের ন্যূনতম ২.৫ মেগাওয়াট থেকে সর্বোচ্চে ৫.২ মেগাওয়াট ক্ষমতার প্রতিটি শিল্প বিতরণ ফিডারের মাধ্যমে ইন্ডাস্ট্রিসমূহে বিদ্যুৎ বিতরণ করা হয়ে থাকে। এই পুরো Industrial Micro-Grid-টির প্রায় সমূদয় বৈদ্যুতিক শক্তির চাহিদার যোগান প্রাকৃতিক গ্যাস ভিত্তিক IC Engine চালিত আলোচ্য নিবেদিত (dedicated) ৭২ মেগাওয়াট (১০০ মেগাওয়াটে উন্নয়ন প্রস্তাবিত) ক্ষমতা সম্পন্ন বিদ্যুৎ উৎপাদন কেন্দ্রের উপরই মূলতঃ নির্ভরশীল। CEPZ এবং KEPZ এ অবস্থিত শতভাগ রপ্তানিমুখী শিল্প প্রতিষ্ঠান সমূহের জন্য নিরবচ্ছিন্ন ও নির্ভরযোগ্য বিদ্যুৎ সরবরাহ অত্যন্ত জরুরী এবং সম্মিলিতভাবে ইন্ডাস্ট্রিগুলোর মোট সর্বোচ্চ ১০০ মেগাওয়াটের বিদ্যুৎ চাহিদা রয়েছে, যার মধ্যে ৭২ মেগাওয়াট সরবরাহ পাওয়া যায় আভ্যন্তরীণভাবে এই বিদ্যুৎ কেন্দ্রের উৎস হতে এবং বাদবাকী ২৮ মেগাওয়াটের ঘাটতি চাহিদা আঞ্চলিক জাতীয় গ্রীড থেকে back-feed এর মাধ্যমে আহরণ করে মেটানো হয়। জোনে সর্বোচ্চ বৈদ্যুতিক চাহিদা পরিলক্ষিত হয় সকাল ৮টা থেকে শুরু হয়ে সন্ধ্যা ৬টা অবধি এবং এ সময়ে বিদ্যুতের চাহিদা থাকে প্রায় শতভাগ। পরবর্তীতে চাহিদা ধীরে ধীরে হ্রাস পেতে থাকে এবং যা পরিশেষে সর্বোচ্চ চাহিদার মাত্র ৩০-৩৫% এ নেমে আসে। নিরবচ্ছিন্ন বিদ্যুৎ সরবরাহের একান্ত চাহিদার বিপরীত সর্বাধুনিক প্রযুক্তি সম্বলিত এই নিবেদিত (dedicated) বিদ্যুৎ উৎপাদন কেন্দ্র থাকা সত্ত্বেও, মূলতঃ বিতরণ প্রান্তের ভোক্তা পর্যায়ে সৃষ্ট বিভিন্ন ধরণের উদ্ভূত ত্রুটির (fault) কারণে এই ইন্ডাস্ট্রিয়াল মাইক্রো-গ্রীডে ঘন ঘন বিদ্যুৎ বিভ্রাট ঘটে থাকে যা প্রত্যাশিত নিরবচ্ছিন্ন বিদ্যুৎ সরবরাহ'কে যৌক্তিকভাবে চ্যালেঞ্জের মুখোমুখি করে তোলে। এই সমস্যাটি সহনীয় পর্যায়ে হ্রাস কল্পে একটি কৌশলী উপায় প্রয়োগের চিন্তা করা হয় যার নামকরণ করা হয় **"Generating Bus Splitting (GBS) Model"**, যা প্রচলিত গতানুগোতিক ইন্ডাস্ট্রিয়াল মাইক্রে-গ্রিড পরিচালন প্রাকটিসের বাহিরে চিন্তা প্রসূত প্রায় একটি মৌলিক ধারণাও বলা যেতে পারে। কৌশলগত এ ধারণায় প্রস্তাব করা হয় যে, একক নিরবচ্ছিন্ন Central Generating Bus (CGB) থেকে এক বা একাধিক মাষ্টার ফিডারকে বিকেন্দ্রীকরণ পূর্বক সরিয়ে পৃথকভাবে সিস্টেমে সন্নিবেশিত করা যাতে করে সৃষ্ট ত্রুটির বোঝাও কেন্দ্রীভূত না হয়ে সমানুপাতে বন্টিত হয়ে সার্বিক বিদ্যুৎ কেন্দ্র blackout এর বিপর্যয়ে পর্যবসিত না হতে পারে। এই ধারণা প্রযুক্ত ১১ কেভি জেনারেশন বাস পরিবর্তনের ফলে আরো যে সকল আনুষঙ্গিক সুবিধাদি উপলব্ধ হয় তাদের মধ্যে রয়েছে গ্রীড স্থানান্তর জনিত লস কম হওয়া, গ্রীড সরবরাহ বৃদ্ধি পাওয়া, আইএমজি'র (IMG) পূর্ণ blackout ঝুঁকি হ্রাস এবং বিদ্যুৎ প্রবাহে বিঘ্ন অবস্থার দ্রুত উত্তরণে বর্ধিত সুবিধা প্রদান ইত্যাদি।

Abstract

This thesis aims to explore the stability and control of an Industrial Micro-Grid (IMG) system engaged to provide uninterrupted and high-quality power to around 165 export-oriented industries in Chattogram Export Processing Zone (CEPZ) and 70 similar industries in Karnaphuli Export Processing Zone (KEPZ) located in Chattogram, Bangladesh. The Industrial Micro-Grid model consists of 5 (five) natural gas (NG) fired IC Engine based Generating Sets (GS), each having a capacity of 8.73 MW and 3 (three) others of 9.34 MW individual capacity along with a span of around 80 running KM mixed mode (O/H & U/G) 11 KV distribution network with 3 (three) 33 KV regional national grid connectivity all together. These generators could be operated in either island or grid mode to supply independently power to 15 industrial distribution 11KV feeders of CEPZ and 08 identical feeders of KEPZ having capacity ranging from 2.5 to 5.2 MW of load in each. This entire IMG is mostly dependable on a dedicated 72 MW IC engine based natural gas fired power plant to meet its most of the energy demands. The uninterrupted and reliable power supply is crucial for the operation of export-oriented industries within CEPZ and KEPZ, which collectively demand a maximum of 100 MW of which 72 MW is made available from its internal power generating source and additional 28 MW is sourced from the regional national grid of electricity. Despite the constant demand for uninterrupted power, frequent tripping of this IMG due to various faults mainly originating from consumer ends has posed a significant challenge for its trusted reliability. To mitigate this issue within a tolerable limit, a tactful unique solution called "Generating Bus Splitting (GBS)," was conceived which involves the proposal of disintegrating & relocating of one master feeder from its Central Generation Bus (CGB) to rationally distribute fault burden concentration. This modification also offers several advantages, including grid shifting loss reduction, improved grid dispatch, reduced total blackout risks of the entire IMG, and enhanced emergency power interruption handling capabilities.

Table of Contents

List of Figures

List of Tables

Nomenclature

BEPZA	Bangladesh Export Processing Zones Authority
EPZ	Export Processing Zone
CEPZ	Chattogram Export Processing Zone
CAIDI	Customer Average Interruption Duration Index
CCU	Central Controlling Unit
CHP	Combined Heat and Power
CGB	Central Generation Bus
CGS	Central Generating Station
DEN	Distributed Energy Network
DER	Distributed Energy Resource
DMT	Definite Minimum Time
EM Relay	Electromechanical Relay
ETAP	Electrical Transient and Analysis Program
GC-IMG	Grid-Connected Industrial Micro-Grid
GBS	Generating Bus Splitting
KEPZ	Karnaphuli Export Processing Zone
LBS	Load Break Switches
IC-Engine	Internal Combustion Engine
IMG	Industrial Micro-Grid
IIMG	Islanded Industrial Micro-Grid
IDF	Industrial Distribution Feeders
IDMT	Inverse Definite Minimum Time

LOTO	Lock Out Tag Out
RAMG	Remote Area Micro-Grids
RMG	Renewable Energy Micro-Grids
RMG	Resilience Micro-Grids
ROCOF	Rate of Change of Frequency
RNG	Regional National Grid
SAIDI	System Average Interruption Duration Index
SAIFI	System Average Interruption Frequency Index
SCADA	Supervisory Control and Data Acquisition
SLD	Single Line Diagram
VCB	Vacuum Circuit Breaker

Chapter 1: Introduction

Chapter 1 serves as the foundational introduction of this thesis, providing essential background information and context. In section 1.1, it highlights the significance of Export Processing Zones (EPZs) of Bangladesh emphasizing their reliance on a 24/7 basis stable power supply for export-oriented industries. In section 1.2 contains the detailed overview of the entire Industrial Micro-Grid (IMG). The primary problem statement is articulated in section 1.3, focusing on the instability of the Industrial Micro-Grid (IMG) in these zones and its adverse effects on industrial operations.

The section 1.4 represents the four specific objectives of the research, which include investigating the causes of IMG tripping incidents, proposing the solution of Generating Bus Splitting (GBS) model, assessing the impact of GBS on industrial micro-grid stability, and quantifying the techno-economic benefits of implementing GBS model. In section 1.5, the scope of the study is clearly defined, encompassing technical and economic aspects related to industrial micro-grid stability and GBS model implementation. The chapter also provides a roadmap for the thesis in section 1.6, outlining the organization of subsequent chapters, which will explore into the literature review, methodology, results with discussion and conclusion.

1.1 Background

Micro-Grids/ Industrial Micro-Grids have emerged as a vital component of modern electrical power systems, offering localized, decentralized, and often different energy solutions. They are particularly relevant in scenarios where ensuring a consistent and reliable power supply is top. Such scenarios are commonplace in industrial settings, where the continuous operation of machinery and processes is critical for productivity, product quality, and ultimately, economic competitiveness.

In industrial distribution systems, Distribution Feeders (DF) plays a crucial role in delivering power from the source to the end-users, which in this case are export-oriented industries. These industries rely heavily on a stable and high-quality power supply to meet their production targets, comply with international standards, and remain competitive in the global market. Disruptions or interruptions in power supply can have severe consequences, including production downtime, product defects, and financial losses etc.

The Chattogram Export Processing Zone (CEPZ) and Karnaphuli Export Processing Zone (KEPZ) in Chattogram, Bangladesh, are vital industrial hubs for our country & housing numerous export-oriented industries. These zones house a large number of export-oriented industries engaged in various sectors, including manufacturing, textiles, electronics and many more.

The industrial distribution feeders in this study cater to around 235 export-oriented industries. These industries collectively represent a significant economic sector, contributing to both local and national economies. Given their strategic importance, there is an uncompromising demand for uninterrupted and high-quality power supply, regardless of external factors such as grid disturbances, faults, or fluctuations in load demand.

1.2 A Typical IMG Overview

A visual representation of the Industrial Micro-Grid (IMG) system structure, providing a comprehensive overview of its key components and their interconnections is presented here. A clear understanding of this system's architecture is vital for materialistic its functionality and efficiency. As we explore the diagram below, we will uncover the various elements that contribute to the successful operation of an industrial micro-grid, shedding light on the vital role it plays in modern energy management and sustainability practices.

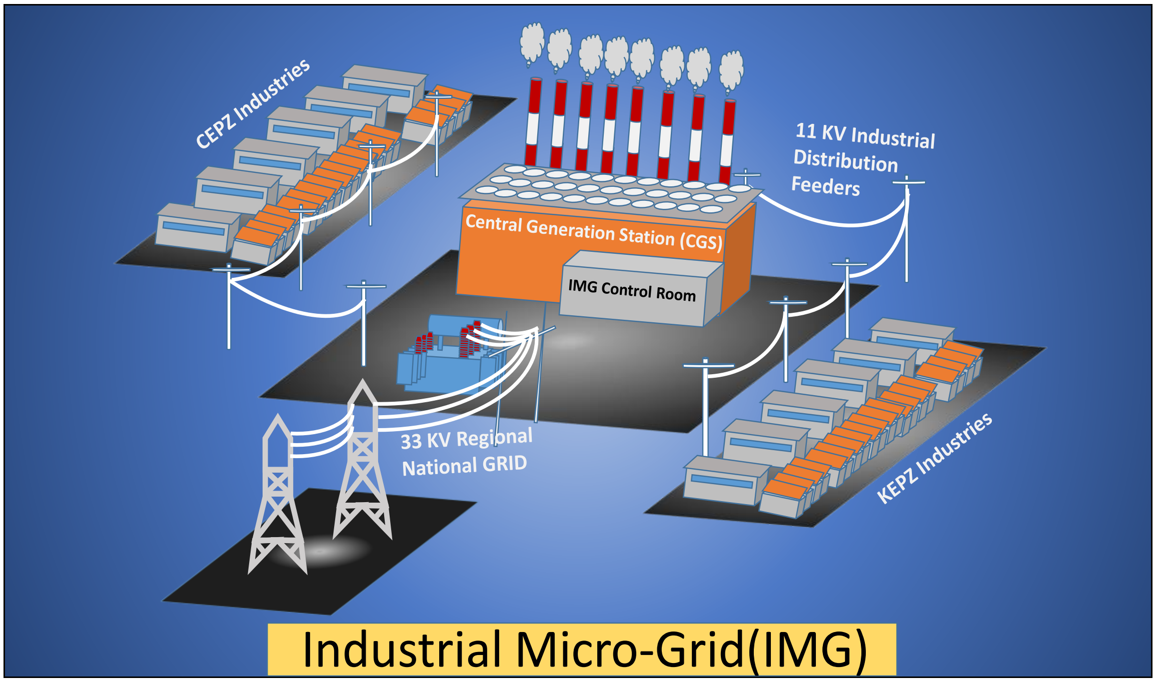

Fig. 1.1: A Typical Structural Overview of an IMG System

The table provided below offers a comprehensive overview of the Chittagong Export Processing Zone (CEPZ) & Karnaphuli Export Processing Zone (KEPZ), which operates under the control of BEPZA (Bangladesh Export Processing Zones Authority). It presents data on cumulative investment in million US dollars, cumulative employment figures, and cumulative exports in million US dollars, year by year. This data serves to emphasize the vital role that CEPZ & KEPZ plays in facilitating investment, generating employment opportunities, and boosting exports, underlining its importance in the economic landscape of Bangladesh and the importance of keeping the connected IMG interruption free or within a tolerable limit for the both the Export Processing Zones.

Table 1.1: Year-wise Cumulative Performance Metrics of Chittagong Export Processing Zone (CEPZ) [1].

Year	Investment Cumulative (Million US $)	Employment Cumulative (Employment No.)	Export Cumulative (Million US $)
1983-84	0.87	624	0.16
1984-85	2.47	1780	4.61
1985-86	6.07	2512	12.21
1986-87	12.71	3240	27.47
1987-88	14.5	3438	41.4
1988-89	17.22	4207	57.48
1989-90	25.8	7001	91.69
1990-91	47.85	9364	139.67
1991-92	71.51	14614	216.67
1992-93	93.56	17728	343.71
1993-94	122.74	20814	484.07
1994-95	150.41	25111	671.05
1995-96	166.54	30986	934.84
1996-97	189.42	39574	1278.15
1997-98	232.02	46993	1728.15
1998-99	268.12	54741	2180.68
1999-00	283.3	57707	2706.77
2000-01	307.61	68556	3327.13
2001-02	329.98	75089	3935.83
2002-03	372.12	83221	4577.11
2003-04	427.55	85698	5256.11
2004-05	472.86	94419	6028.5
2005-06	508.82	104155	6901.53
2006-07	541.44	116984	7873.07
2007-08	667.9	123789	8990.24
2008-09	715.12	138612	10178.38
2009-10	772.64	150783	11511.91
2010-11	858.48	166452	13178.79
2011-12	960.23	176274	15062.6
2012-13	1094.06	185006	17157.72
2013-14	1203.52	182621	19419.342
2014-15	1355.54	190815	21803.099
2015-16	1466.25	196969	24222.81
2016-17	1556.83	199757	26476.97
2017-18	1643.02	201798	28919.97
2018-19	1718.71	203865	31310.86
2019-20	1772.07	175878	33403.31
2020-21	1860.6	158794	35,522.77
2021-22	1949.45	177905	38112.56
2022-23	2036.08	172880	40531.76

Table 1.2: Year-wise Cumulative Performance Metrics of Karnaphuli Export Processing Zone (KEPZ) [2].

Year	Investment Cumulative (Million US $)	Employment Cumulative (Employment No.)	Export Cumulative (Million US $)
2006-07	1.91	174	00
2007-08	20.25	2990	9.86
2008-09	48.15	5403	48.99
2009-10	87.73	11674	105.8
2010-11	135.29	19781	243.96
2011-12	217.12	26830	489.01
2012-13	263.05	39070	868.62
2013-14	307.72	45645	1395.48
2014-15	372.53	54812	2105.22
2015-16	433.04	63118	2928.5
2016-17	484.36	67629	3781.58
2017-18	535.03	71641	4760.5
2018-19	585.93	76903	5833.95
2019-20	611.54	69364	6761.57
2020-21	648.51	73781	7858.06
2021-22	693.66	81100	9306.74
2022-23	723.28	72132	10492.3

1.2.1 Empowering Industrial Success with a Resilient IMG

The success and competitiveness of the industries within CEPZ and KEPZ depend heavily on the availability of a reliable and uninterrupted power supply. These industries operate on tight schedules, and even minor disruptions in power can lead to significant production losses, missed deadlines, and financial setbacks. Moreover, maintaining the quality and consistency of power supply is critical, as many of these industries engage in precision manufacturing processes that demand a stable electrical environment. To ensure the uninterrupted and high-quality power supply required by these industries, an Industrial Micro-Grid (IMG) system has been established. A comprehensive overview of the said industrial micro-grid along with distribution feeders & connected industries within is represented below:

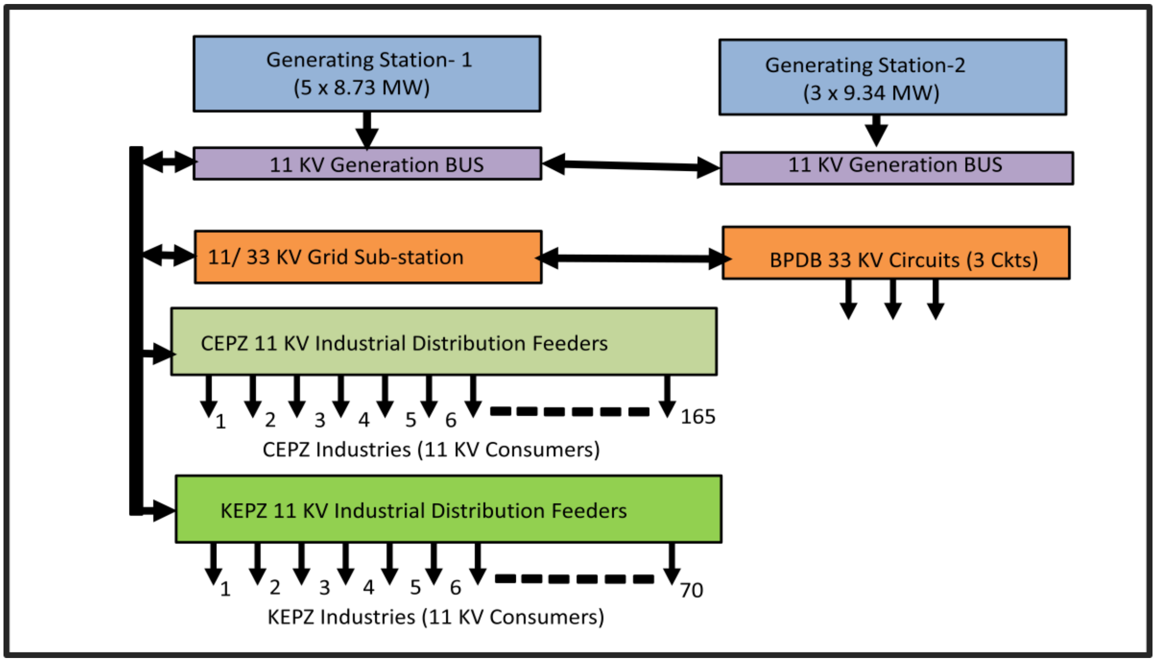

Fig. 1.2: Overview of Industrial Distribution Feeders and Connected Industries in an IMG Network

1.2.2 Technical Specifications of IMG Components and SLD

This comprehensive table presents the technical specifications of the Industrial Micro-Grid (IMG) components and equipment, which constitute the foundation of the described IMG. The table includes the names of components or equipment, their respective technical specifications, along with approximate size and quantity. The size/quantity of IMG components may vary based on specific applications, but a more or less similar arrangement will be required to establish an Industrial Micro-Grid.

Table 1.3: Major Components/ Equipments of a Typical IMG

Sl. No.	Equipment/ Component	Technical Specification	Quantity/ Size	Remarks
01	Generating Set (GS)	Engine Model: W20V34SG Type: V-Type Operating Speed: 750 rpm Rated capacity: 8.73 MW	05 nos.	Natural gas fired IC engine
		Alternator model: ABB AMG 1120MM08 DSE Rated voltage: 11 KV Rated frequency: 50 Hz Insulation Class : F	05 nos.	Synchronous generator
02	Generating Set (GS)	Engine model: B34:40V20AG2 Type: V-Type Operating Speed: 750 rpm Rated capacity: 9.34 MW	03 nos.	Natural gas fired IC engine
		Alternator model: ABB AMG 1120MM08 DSE Rated voltage: 11 KV Rated frequency: 50 Hz Insulation Class : F	03 nos.	Synchronous generator
03	Master Feeder (MF)	Nominal Current: 2000A Short Circuit Breaking Current: 31.5 KA Rated voltage: 11 KV Rated frequency: 50 Hz	04 nos. (CEPZ) 03 nos. (KEPZ)	ABB, Switzerland
04	Industrial Distribution Feeder (IDF)	Nominal Current: 1250A Short Circuit Breaking Current: 31.5 KA Rated voltage: 11 KV Rated frequency: 50 Hz	15 nos. (CEPZ) 08 nos. (KEPZ)	ABB, Switzerland
05	Bus Coupler (BC)	Normal Current: 4000A Short Circuit Breaking Current: 31.5 KA Rated voltage: 11 KV Rated frequency: 50 Hz	03 nos. (GS-1 side) 02 nos. (GS-2 side)	ABB, Switzerland
06	Auxiliary Transformer (AT)	Rated capacity 1) 1250 KVA 2) 750 KVA Rated capacity 3) 1250 KVA 4) 1250 KVA Rated voltage: 11 KV/440 V Rated frequency: 50 Hz	04nos.	03 nos.(operational) Energypac-02 nos. AEG-01 nos. 01 nos. (standby) Energypac
07	Power Transformer (PTx)	Rated voltage: 33 KV/11 KV Rated capacity: 20/25 MVA Rated frequency: 50 Hz	03 nos.	Energypac & CHINT Rated MVA: 20/25
08	Overhead Transmission & Distribution (T&D) Line	Merlin Cable Rating: 519 Amps Insulation cable(D-62) Rating: 340A Grosbeak Rating: 789A Rated voltage: 11 KV	45 KM (approximate)	CEPZ
			35 KM (approximate)	KEPZ

A detailed Single Line Diagram (SLD) of the entire industrial micro-grid is appended below which comprises the items/ equipments listed in the table above:

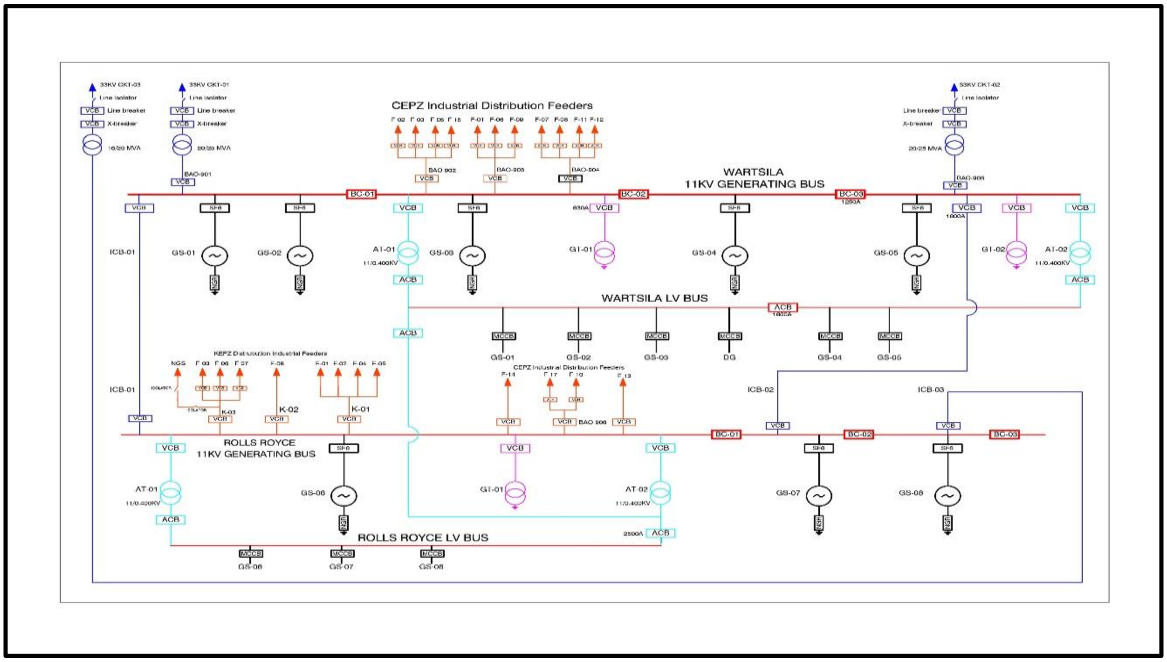

Fig. 1.3: Comprehensive Single Line Diagram (SLD) for the Industrial Micro-Grid System

However, due to various faults mainly originated from different industrial corners this Industrial Micro-Grid (IMG) experiences frequent tripping incidents, which disrupt industrial operations and lead to economic losses. These recurring incidents have become a significant challenge for the Export Processing Zones (EPZs), as they not only hamper the efficiency of manufacturing processes but also result in financial setbacks. Addressing and mitigating these tripping incidents has become a top priority for the EPZs, as it seeks to ensure the uninterrupted operation of industries within its purview and maintain its annual export target.

1.3 Present State of the Problem

The main problem addressed in this thesis is the less stability of the described Industrial Micro-Grid (IMG) serving CEPZ and KEPZ caused by various faults mostly within different industrial settings, leading to power interruptions for the industrial consumers.

Ensuring a continuous and dependable power supply is of paramount importance for the efficient functioning of export-oriented industries situated in the CEPZ and KEPZ. These industrial zones collectively necessitate a maximum electrical load of 100 MW to meet their production needs [3]. This power demand is met through a combination of internal power generation, with 72 MW originating from their own power plant, and an additional 28 MW sourced from the regional national grid. The demand for electricity within these zones experiences a distinct pattern throughout the day. Peak demand occurs during the hours from 8 AM to 6 PM when the load reaches its maximum, reaching 100%. Conversely, during off-peak hours, the load gradually tapers down to a maximum of 30-35% of the peak demand, as represented in the load vs. time curve below. This dynamic load profile presents a significant challenge for ensuring stable and efficient power distribution within these industrial areas:

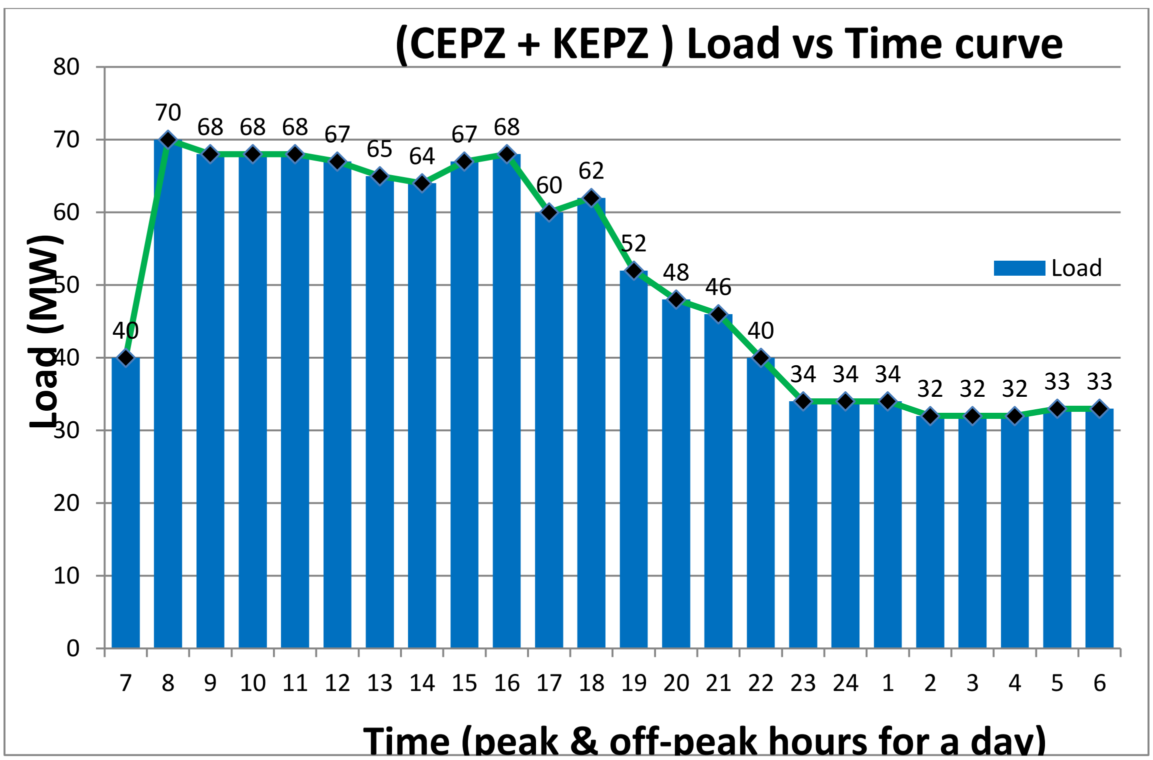

Fig. 1.4: Load Behavior Analysis, Peak and Off-peak Energy Consumption by CEPZ and KEPZ

Frequent tripping of IMG poses significant disruptions to the industrial processes and operations dependent on the micro-grid system. Industries, particularly export-oriented ones, rely on a seamless and uninterrupted power supply to maintain consistent production levels, ensure product quality, and meet delivery deadlines. The consequences of IMG tripping are far-reaching, leading to production downtime, damage to goods in progress, and potential financial losses.

The graph below provides a visual representation of a critical scenario within an economic zone. It vividly demonstrates how the interruption of the industrial micro-grid, which serves as a backbone for power supply to various facilities and operations within the zone, can have an instantaneous and extensive impact [4]. When the Industrial Micro-Grid (IMG) experiences disruptions, it disrupts the functionality of all components and activities across the entire economic zone. This highlights the supreme importance of ensuring a resilient and uninterrupted power supply infrastructure to sustain the continuous operation and productivity of the zone.

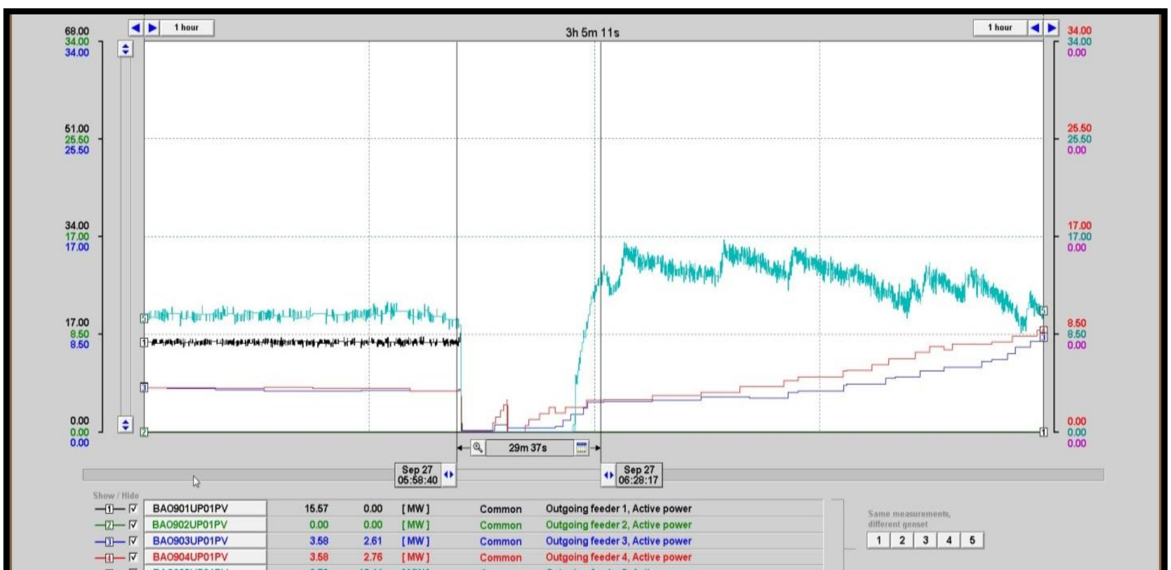

Fig. 1.5: A Typical IMG Interruption Paralyzes the Economic Zone for the Time Being

The graph below illustrates how an interruption in the Industrial Micro-Grid (IMG) can immediately halt all operations within the entire economic zone.

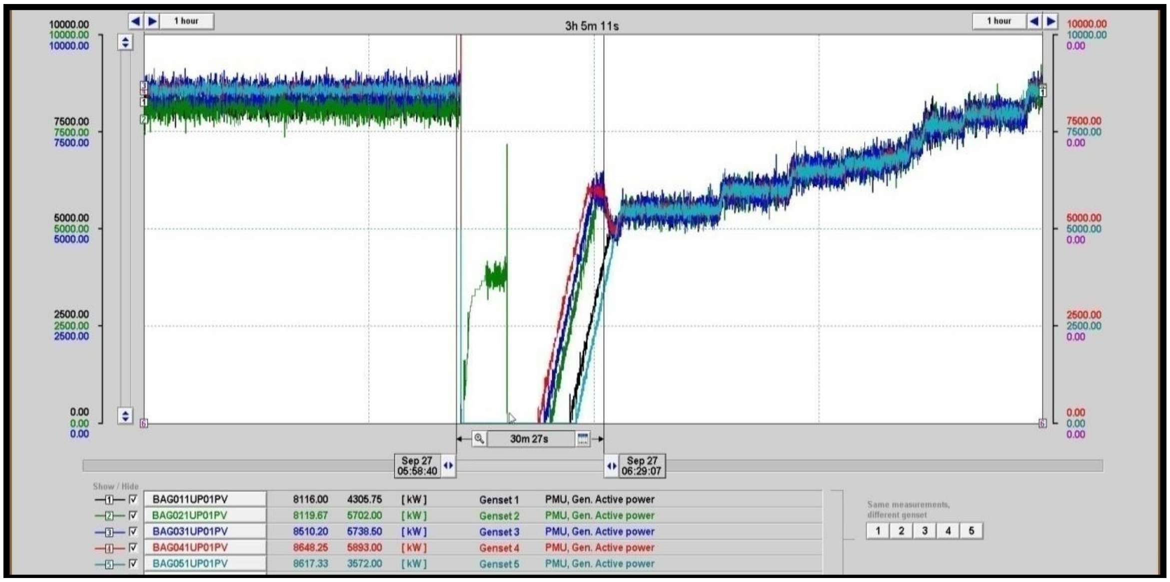

Fig. 1.6: IMG Disruption and the Ripple Effect on Regaining Stability of Economic Zone Operations

1.4 Objectives

This section outlines the specific objectives of the thesis, including investigating the causes of Industrial Micro-Grid (IMG) tripping incidents, evaluating the feasibility of GBS model, and assessing its impact on Industrial Micro-Grid stability. The primary objectives of this research are as follows:

1. To investigate the causes of less stability in the Industrial Micro-Grid (IMG) serving CEPZ and KEPZ.
2. To propose and implement a solution called "Generating Bus Splitting (GBS)" to reduce tripping incidents and enhance the stability of IMG.
3. To assess the impact of GBS model on the reliability and stability of industrial processes.
4. To evaluate the techno-economic benefits of implementing GBS model in terms of reduced downtime and economic losses.

1.5 Significance of the Work

Beyond assessing the technical effectiveness of the "Generating Bus Splitting" model, the next research objective is to comprehensively analyze the benefits it can bring to the Industrial Micro-Grid (IMG) system and the industries it serves. This analysis will encompass a range of aspects, including:

- Whole IMG blackout risk reduction
- Reduction of generation loss associated with each grid shifting in handling peak & off-peak hours
- Enhance additional grid dispatch even in peak hours
- Handling of emergency back-feed power will be maximized
- Reduced IMG disturbance enhances the stability of the regional national grid

These research objectives are closely aligned with the core problem of frequent IMG tripping. By evaluating the stability, proposing a viable solution, and assessing its benefits, this study aims to provide practical insights and recommendations for addressing this persistent challenge. Ultimately, the research objectives are motivated by the need to ensure a reliable and high-quality power supply to the industrial distribution feeders, mitigating operational disruptions, financial losses, and environmental concerns.

1.6 Scope of the Study

This thesis focuses on the Industrial Micro-Grid (IMG) serving CEPZ and KEPZ in Chattogram, Bangladesh. It specifically addresses the stability and control issues within the micro-grid and the implementation of Generating Bus Splitting (GBS) model as a solution to make it more reliable. The research encompasses system modeling, stability analysis, the micro-grid's configuration, and the economic aspect of GBS model and performance evaluation. The scope of the study extends to evaluating the economic impact of power interruptions and the potential economic benefits of implementing Generating Bus Splitting (GBS) as a solution. This involves analyzing the direct and indirect costs associated with power disruptions, such as losses in production, equipment damage, and overall economic consequences for industries within the zones. While the primary focus is technical aspects related to the micro-grid's stability and reliability of GBS, the economic implications and feasibility will also be explored. This includes the causes of Industrial Micro-Grid (IMG) tripping incidents and the evaluation of GBS as a mechanism to reduce their frequency. The proposed modification, "Generating Bus Splitting," involves the relocation of one master feeder within the Industrial Micro-Grid system. The study will comprehensively investigate the impact of this modification on system behavior and performance. This study also pertains to the power supply needs of approximately 235 export-oriented industries connected to the Industrial Micro-Grid (IMG). These industries rely on continuous and reliable power for their operations. The research aims to address the challenges faced by this specific industrial sector and ensure the uninterrupted supply of power to meet their production requirements.

1.7 Organization of the Thesis

The organization of this thesis is designed to provide a comprehensive and structured exploration of the key aspects of Industrial Micro-Grid (IMG) systems, its tripping pattern & frequency, and the innovative approach of Generating Bus Splitting (GBS) model in enhancing system resilience and stability.

The remainder of this thesis is organized as follows:

- **Chapter 2** reviews the relevant literatures of Industrial Micro-Grid (IMG) systems, associated tripping fault patterns and different IMG stability procedures.
- **Chapter 3** outlines the methodology employed in this research, including data collection, system modeling, implementation of Generating Bus Splitting (GBS) model within the Industrial Micro-Grid (IMG) and stability analysis.
- **Chapter 4** presents the results of stability analysis and performance evaluation, along with a discussion of the findings.
- **Chapter 5** concludes the thesis by summarizing the findings, discussing contributions and implications, and suggesting on future research directions.

Chapter 2: Literature Review

The Literature Review chapter plays a crucial role in providing a comprehensive understanding of the existing body of knowledge related to the research topic, "Enhancing the Micro-Grid Reliability in Industrial Distribution Feeders by Generating Bus Splitting Model. It serves as the foundation upon which the current study is built and highlights the gaps, trends, and areas of interest within the field. The section 2.1 looks at Micro-Grid systems, while 2.2 cover different types of Micro-Grids, including Industrial Micro-Grids (IMG). Then in section 2.3 emphasizes the benefits of Micro-Grids, focusing on reliable power supply and cost reduction. Section 2.4 discusses the challenges faced by Industrial Micro-Grids, considering technical, economic, operational, regulatory, and environmental aspects. The section 2.5 explores power quality and reliability, emphasizing stable voltage and frequency. On the other hand, in section 2.6 examines the reliability indices, highlighting the importance of metrics like SAIDI, SAIFI & CAIDI for assessing power distribution systems. Current research study on IMG stability is discussed in section 2.7 and finally, section 2.8 provides a brief summary of the key points of the following chapters.

2.1 Industrial Micro-Grid Systems

This section of the chapter provides a thorough overview of Industrial Micro-Grid (IMG) systems. It covers the fundamental concepts, definitions, and classifications of IMGs [5]. It explores how IMGs differ from traditional centralized power grids and their significance in providing localized and resilient power solutions.

2.1.1 Definition of Industrial Micro-Grid

Industrial Micro-Grids are localized, self-contained, and often independent electrical systems that supply power to industrial facilities or clusters of industries. They are designed to ensure a reliable, resilient, and efficient energy supply to meet the specific needs of industrial processes. Industrial Micro-Grids typically incorporate a combination of distributed energy networks (DENs) [6], advanced control systems, and energy storage to optimize energy generation and consumption when necessary within an industrial setting.

2.1.2 Key Characteristics of IMG

- **Localized Generation**: Industrial micro-grids often include on-site power generation sources, such as gas engines/ turbines, combined heat and power (CHP) systems, solar panels, wind turbines, or backup generators etc.
- **Advanced Control**: They are equipped with sophisticated control and automation systems to manage the generation, distribution, and consumption of energy within the micro-grid, ensuring its stability and efficiency. The IMGs are also designed to export excess power to the main national/ regional grid and conversely, when required, they can receive power from the grid through net metering facilities using advanced control & monitoring systems.
- **Resilience**: Industrial micro-grids are designed to continue operating during grid outages, minimizing disruptions to critical industrial processes.
- **Optimization**: These micro-grids aim to optimize energy usage, reduce costs, and lower greenhouse gas emissions by intelligently balancing energy supply and demand by enhancing their reliability & stability.
- **Customization**: Industrial Micro-Grids (IMGs) are customized to the specific energy needs of the industries they serve, accommodating variable loads and ensuring high-quality & uninterrupted power supply.

2.2 Types of Micro-Grid and Industrial Micro-Grid

The classification of various types of micro-grids/ industrial micro-grid is visually represented below, providing a comprehensive overview of the different categories and their distinguishing features. Micro-grids, which are decentralized energy systems capable of operating independently or in conjunction with the main grid, come in various forms to specific applications and requirements. This classification serves as a valuable reference for understanding the diverse landscape of micro-grid configurations and their suitability for various contexts, from remote off-grid locations to urban environments with advanced energy infrastructure. The pattern of the discussed Industrial Micro-Grid (IMG) types is highlighted with orange color in the figure below:

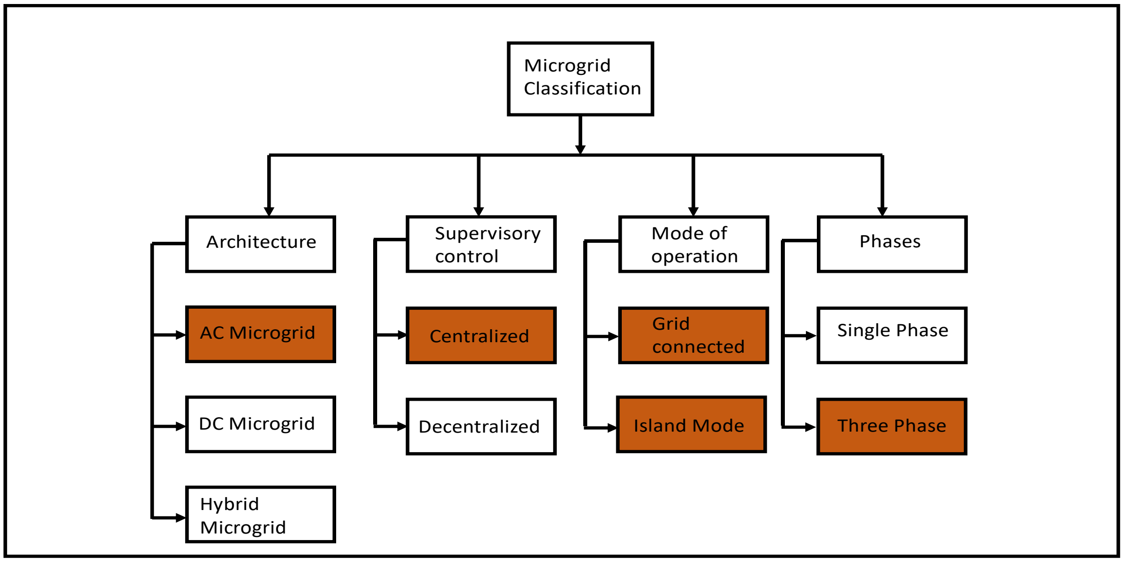

Fig. 2.1: Classification of Micro-Grid/ Industrial Micro-Grid. [7]

2.2.1 Islanded Industrial Micro-Grids (IIMG)

Islanded Industrial Micro-Grids (IIMGs) are self-contained electrical systems that can operate independently with its associated industrial feeders. They are designed to provide power to industrial facilities even when the main grid is unavailable. Islanded Industrial Micro-Grids often rely on a combination of distributed energy resources (DERs) and energy storage systems.

2.2.2 Grid-Connected Industrial Micro-Grids (GCIMG)

Grid-Connected Industrial Micro-Grids (GCIMGs) are integrated with the main or regional national grid (RNG) but have the capability to operate autonomously in the event of a grid outage or any other practical necessity. They can feed excess power into the national grid (NG) or draw power from the grid when needed. This type of IMG is often used for optimizing energy costs and improving reliability and stability. For example, a large manufacturing facility in an economic zone could operate a Grid-Connected Industrial Micro-Grid. During periods of high electricity demand, the micro-grid can draw power from the main grid, while during off-peak hours or outages; it can rely on on-site generation sources like natural gas engines, turbines or combined heat and power (CHP) systems etc.

2.2.3 Resilience Micro-Grids

Resilience Micro-Grids (RMGs) are designed with a primary focus on maintaining power supply in critical situations, such as natural disasters or emergencies. These micro-grids prioritize reliability and often incorporate redundant generation sources and energy storage systems. For example, a hospital in a hurricane-prone region could implement a resilience micro-grid. It would include backup generators, energy storage, and renewable energy sources to ensure continuous power for life-saving medical equipment and facilities during severe weather events or any other extra ordinary situations.

2.2.4 Renewable Energy Micro-Grids

Renewable Energy Micro-Grids (REMGs) are primarily relying on clean and sustainable energy sources such as solar, wind, and hydropower. They aim to minimize carbon emissions and reduce reliance on fossil fuels for industrial power generation. An eco-friendly industrial park might implement a renewable energy micro-grid powered by a combination of solar panels and wind turbines. Excess energy generated during sunny or windy periods can be stored for later use or fed back into the grid through net metering facilities to address its surplus/ shortage power.

2.2.5 Combined Heat and Power (CHP) Micro-Grids

CHP micro-grids, also known as cogeneration systems, simultaneously produce electricity and useful heat from a single energy source, such as natural gas. They are highly efficient and can provide both electricity and thermal energy for industrial processes. A food processing plant could operate a CHP micro-grid. Natural gas-powered generators would produce electricity while capturing waste heat to provide hot water and steam for cooking and sterilization processes.

2.2.6 Remote Area Micro-Grids (RAMG)

Remote Area Micro-Grids (RAMGs) are deployed in locations far from the main electrical grid. They are essential for providing power to remote communities, mining operations, or research facilities where grid access is limited or unavailable. An off-grid research station in Antarctica relies on a remote area micro-grid powered by solar panels, wind turbines, and backup generators to support scientific experiments and provide essential heating and lighting in extreme conditions.

These different types of Industrial Micro-Grids (IMGs) cater to a variety of industrial needs and challenges, showcasing the versatility and adaptability of micro-grid solutions in ensuring reliable, efficient, and sustainable power supply for industrial applications. The choice of IMG type depends on factors such as location, energy requirements, environmental goals, and resilience needs.

2.3 Benefits of Industrial Micro-Grid

The implementation of Industrial Micro-Grids in Export Processing Zones (EPZs) in Bangladesh offers a wide range of benefits that contribute to the economic growth and sustainability of these industrial zones [8]. Here are some key benefits of industrial micro-grids with respect to EPZs in Bangladesh:

2.3.1 Reliable and Uninterrupted Power Supply

EPZs are home to export-oriented industries that require a constant and reliable power supply to maintain production schedules and meet export targets. Industrial micro-grids ensure uninterrupted power even during grid outages or fluctuations, minimizing production disruptions.

2.3.2 Energy Cost Reduction

By integrating renewable energy sources such as solar panels into the micro-grid, EPZs can reduce their reliance on expensive grid electricity and fossil fuels. This can lead to significant cost savings over time, making businesses within the EPZs more competitive in the global market.

2.3.3 Improved Energy Efficiency

Industrial Micro-Grids (IMGs) allow for efficient energy management and optimization. Advanced control systems can balance energy generation and consumption, reducing wastage and optimizing the use of distributed energy resources.

- **Lower Environmental Impact**: Incorporating renewable energy sources and reducing reliance on fossil fuels not only reduces energy costs but also lowers greenhouse gas emissions. This aligns with global sustainability goals and contributes to a greener and more environmentally friendly image for EPZ industries.
- **Enhanced National Grid Resilience**: Bangladesh is prone to natural disasters, which can lead to grid failures. Industrial Micro-Grids (IMGs), when designed with resilience in mind, can continue to operate during such emergencies, ensuring the continuous operation of EPZ industries.
- **Local Economic Development**: The implementation and maintenance of industrial micro-grids can create local job opportunities in EPZs, including skilled positions for system operators, technicians, and maintenance personnel. This contributes to the economic development of the surrounding communities.
- **Energy Independence**: EPZs with their own micro-grids have greater control over their energy supply, reducing their vulnerability to energy price fluctuations in the national grid. This energy independence allows for better long-term planning and budgeting.
- **Attracting Foreign Investment**: A reliable and sustainable power supply, coupled with lower energy costs, makes EPZs in Bangladesh more attractive to

foreign investors. It encourages the establishment of new industries and expansion of existing ones within the EPZs.

- **Regulatory Compliance**: Industrial micro-grids can help EPZs meet and exceed energy efficiency and environmental regulations, ensuring that industries within the zones adhere to international standards and trade agreements.

In conclusion, Industrial Micro-Grids (IMGs) in Export Processing Zones in Bangladesh offer a great solution to the energy challenges faced by export-oriented industries. They not only ensure a stable and reliable power supply but also contribute to cost savings, environmental sustainability, and economic development. The adoption of industrial micro-grids aligns with the broader goals of Bangladesh to promote renewable energy and attract foreign investment, making EPZs more competitive on the global stage.

2.4 Industrial Micro-Grid Challenges

Industrial Micro-Grids (IMGs), while offering numerous benefits, also encounter a set of unique challenges that must be addressed to ensure their effective operation and maximize their advantages. These challenges can be categorized into various aspects:

2.4.1 Technical Challenges

- **Load Variability & Characteristics:** Industrial facilities often have highly variable loads, which can pose challenges for micro-grid stability and control. A manufacturing plant may have variable load profiles due to different production processes running simultaneously. An analysis of the distinctive load characteristics of industrial facilities, which often include variable and high-power demands.
- **Reliability Requirements:** Reliability requirements are top in industrial micro-grids within economic zones, where uninterrupted power supply is critical for sustaining manufacturing and industrial operations. These micro-grids must be designed to ensure a high level of reliability, minimizing downtime and production disruptions. Robust backup systems, advanced monitoring, and control mechanisms are essential to maintain consistent power delivery, protection

against potential outages and grid disturbances. Reliability in such contexts is not just a matter of convenience but a fundamental economic driver, supporting productivity, competitiveness, and the overall success of industries operating within these zones.

- **Grid Integration:** Integrating the micro-grid with the main/ regional national grid while maintaining operational independence requires advanced control systems. Ensuring a faultless transition between grid-connected and islanded modes during grid disturbances.
- **Distributed Energy Resource Management:** Coordinating and optimizing multiple distributed energy resources, including solar, wind, and backup generators, for efficient power generation. Balancing the use of solar power during the day with backup generators at night to meet 24/7 energy demand.

2.4.2 Economic Challenges

- Initial Capital Costs: The upfront costs of establishing an Industrial Micro-Grid, including generation, storage, and control infrastructure, can be substantial. Purchasing and installing generation units, establishing distribution network and different kind of control & protection hardwires.
- Return on Investment (ROI): Demonstrating a favorable ROI for the micro-grid investment can be challenging, especially for industries with low profit margins. Calculating the payback period for the micro-grid infrastructure and ensuring it aligns with the industry's financial goals to be considered before implementing any IMG.

2.4.3 Operational Challenges

a) Maintenance and Reliability: Ensuring the ongoing reliability of micro-grid components and performing regular schedule & unscheduled maintenance. Conducting routine checks on generators, switchgear equipments, distribution feeders, O/H & U/G cables and DC systems to prevent any unexpected failure.

b) Skill and Expertise: Acquiring and retaining skilled personnel with expertise in micro-grid operation and control. Training technicians and operators in advanced control systems and IMG integration are very essential parts of the entire process.

2.4.4 Regulatory and Policy Challenges

a) Regulatory Compliance: Adhering to local regulations and standards related to micro-grid operation, safety, and environmental impact. Complying with emissions limits and safety codes in the operation of backup generators.

b) Grid Interconnection Rules: Navigating complex regulations governing grid interconnection, tariff structures, and power purchase agreements. Negotiating fair rates for selling excess power back to the main grid.

2.4.5 Environmental and Sustainability Challenges

a) Carbon Emissions Reduction: Meeting sustainability goals and reducing carbon emissions while ensuring a reliable power supply. Balancing the integration of different types of energy sources with backup generators to minimize carbon footprint can be a great solution in addressing such issues.

b) Resource Availability: Depending on the location, the availability of energy resources like natural gas and fossil fuel can be inconsistent.

Addressing these challenges requires a multidisciplinary approach involving engineering, finance, policy, and operations. Overcoming these hurdles is essential to fully harness the benefits of Industrial Micro-Grids (IMGs) in enhancing reliability, sustainability, and economic efficiency for export-oriented industries within Export Processing Zones (EPZs) in Bangladesh and similar industrial zones globally.

2.5 Power Quality and Reliability

This part of the literature review explores the concepts of power quality and reliability, as they are central to the research objectives. It includes discussions on:

2.5.1 Power Quality Metrics

An overview of power quality metrics, such as voltage stability, frequency stability, and harmonic distortion, and their relevance to industrial power systems.

2.5.2 Voltage Stability of IMG

Voltage stability refers to the ability of the power system to maintain a steady voltage level within acceptable limits [9]. It is often quantified using a voltage stability index. For simple example voltage protection scheme for this Industrial Micro-Grid (IMG) is appended in the table below:

Table 2.1: Comprehensive Overview of Voltage Protection in a Typical IMG

Sl. No.	Protection Scheme	Standard	Magnitude	Time delay (ms)	PT Ratio	Actual Value (KV)
01	Phase to phase Under Voltage 1st stage (U<)	ANSI 27	87	10	11KV/ 110V	8.7
02	Phase to phase Under Voltage 2nd stage (U<<)		85	0	11KV/ 110V	8.5
03	Phase to phase Over Voltage 1st stage (U>)	ANSI 59	121	3000	11KV/ 110V	12.1
04	Phase to phase Over Voltage 2nd stage (U>>)		130	500	11KV/ 110V	13.0

Suppose we are monitoring the voltage at a specific point within an industrial micro-grid system, and we have recorded the following voltage measurements over a period of time:

- Voltage Measurement 1: 10.936 KV
- Voltage Measurement 2: 11.050 KV
- Voltage Measurement 3: 10.885 KV

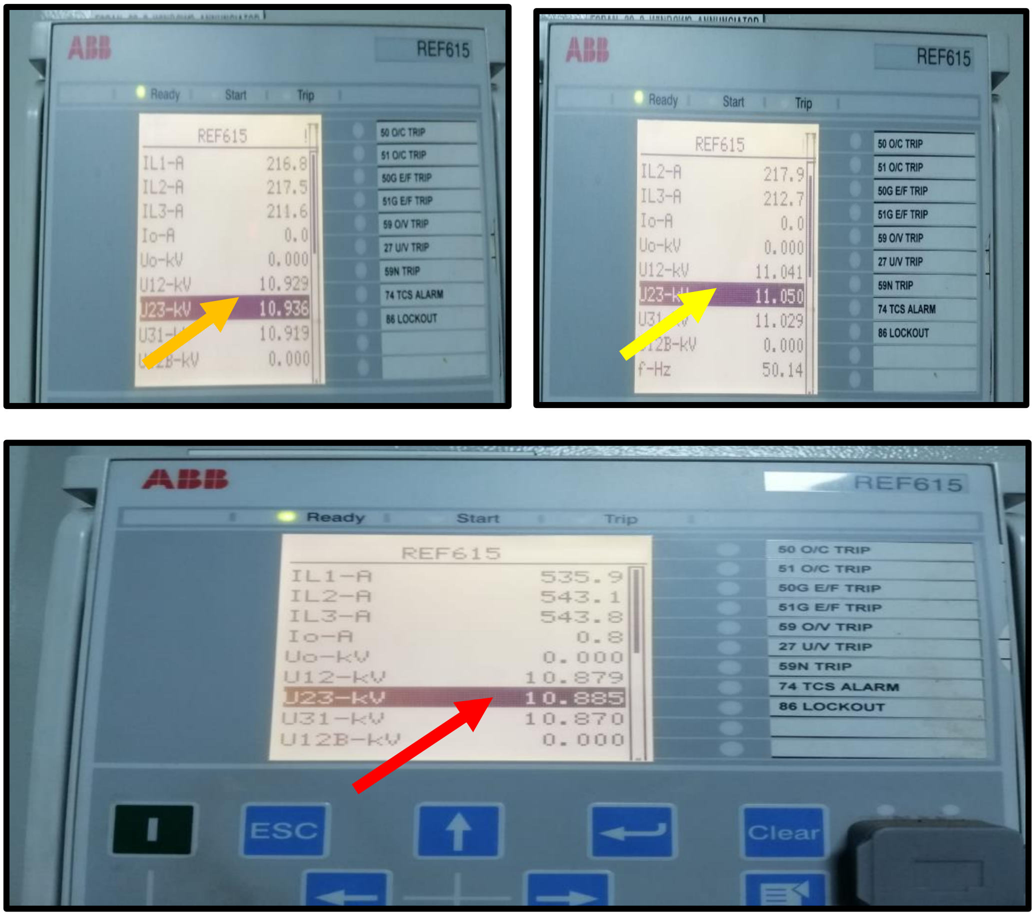

Fig. 2.2: IMG Feeder Voltage under Different Operating Condition

To calculate the average voltage and assess voltage stability:

Average Voltage = (Voltage Measurement 1 + Voltage Measurement 2 + Voltage Measurement 3)/ 3

Average Voltage = (10.936 KV + 11.050 KV + 10.885 KV)/ 3
= 32.871 KV/ 3
= 10.957 KV

In this case, the average micro-grid voltage is 10.957 KV. To assess voltage stability, we would compare this value to acceptable voltage limits specified by standards and regulations after implementation of GBS model. If the average voltage remains within these limits, the system is considered to have good voltage stability for any mentioned Industrial Micro-grid (IMG).

2.5.3 Frequency Stability of IMG

Frequency stability refers to the ability of the power system to maintain a stable frequency, typically 48 to 52 Hz for similar industrial micro-grid [10], depending on the different operational situations. The frequency stability index is typically the deviation from the nominal frequency. For simple example frequency protection scheme for this Industrial Micro-Grid (IMG) is appended in the table below:

Table 2.2: Comprehensive Overview of Frequency Protection in a Typical IMG

Sl. No.	Protection Scheme	Standard	Magnitude	Time delay (ms)	System Frequency (Hz)	Actual Value (Hz)
01	Under Frequency 1st stage (f<)	ANSI 81L	48.5	3000	50	48.5
02	Under Frequency 2nd stage (f<<)		48	200	50	48
03	Over Frequency 1st stage (f>)	ANSI 81H	52	1000	50	51.5
04	Over Frequency 2nd stage (f>>)		52	1000	50	52
05	Rate of change of frequency (ROCOF), df/dt	ANSI 81R	1.1 Hz	1000	50	1.1 Hz/s

Suppose we are monitoring the frequency of a power system, and we have the following frequency measurements over a period of time:

- Frequency Measurement 1: 50.18 Hz
- Frequency Measurement 2: 50.13 Hz
- Frequency Measurement 3: 50.23 Hz

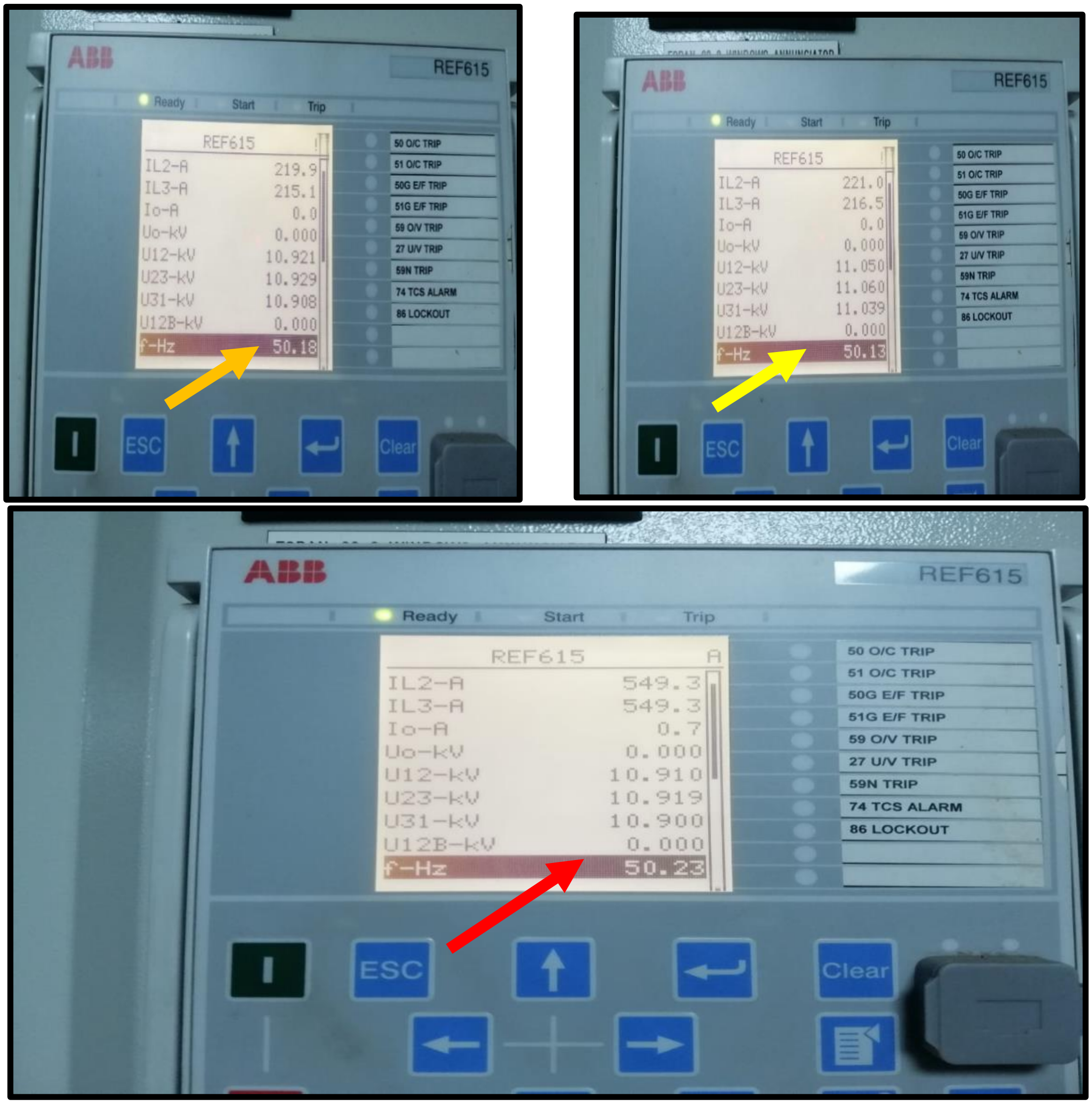

Fig. 2.3: IMG Feeder Frequency under Different Operating Condition

To calculate the average frequency and assess frequency stability:

Average Frequency = (Frequency Measurement 1 + Frequency Measurement 2 + Frequency Measurement 3) / 3

Average Frequency = (50.13 Hz + 50.18 Hz + 50.23/ 3
= 150.54 Hz
= 50.18

In this case, the average micro-grid frequency is 50.18 Hz. To assess its frequency stability, we would compare this value to acceptable frequency limits specified by standards and regulations after implementation of GBS. If the average frequency remains within these limits, the system is considered to have good frequency stability for the mentioned industrial micro-grid.

2.6 Reliability Indices

Explanation of reliability indices like SAIDI (System Average Interruption Duration Index), SAIFI (System Average Interruption Frequency Index) and CAIDI (Customer Average Interruption Duration Index), which quantify the reliability of power distribution systems [11]. These three parameters indices are commonly used to quantify the reliability of power distribution systems.

- SAIDI (System Average Interruption Duration Index)
- SAIFI (System Average Interruption Frequency Index)
- CAIDI (Customer Average Interruption Duration Index)

2.6.1 System Average Interruption Duration Index (SAIDI)

SAIDI represents the average duration of interruptions experienced by customers in a specified period, typically measured in minutes per customer per year. According to IEEE Standard 1366-1998, SAIDI for an Industrial Micro-Grid can be calculated as below:

$$\text{SAIDI} = \frac{\Sigma\, U_i\, N_i}{N_T}$$

Where $\mathbf{N_i}$ is the number of customers and $\mathbf{U_i}$ is the annual outage time for location **i** and $\mathbf{N_T}$ is the total number of customers served by an IMG.

To calculate SAIDI for this industrial micro-grid, we can consider the following formula:

SAIDI = (Total Duration of Interruptions) / (Total Number of Customers)

Let's consider an example:

Suppose an industrial micro-grid serving 200 customers experienced a total of 2,0000 minutes of interruptions over the course of one year.

SAIDI = (2,0000 minutes)/ (200 customers) = 100 minutes per customer per year. This means, on average, each customer in this micro-grid experienced 100 minutes of power interruptions in a year.

2.6.2 System Average Interruption Frequency Index (SAIFI)

The System Average Interruption Frequency Index (SAIFI) is commonly used as a reliability index by electric power utilities. SAIFI is the average number of interruptions that a customer would experience over the course of a year. According to IEEE Standard 1366-1998, SAIFI for an Industrial Micro-Grid can be calculated as below:

$$SAIFI = \frac{\sum \lambda_i N_i}{\sum N_i}$$

Where λ_i is the failure rate and N_i is the number of customers for location **i** served by an IMG.

SAIFI = (Total Number of Interruptions) / (Total Number of Customers).

Let's continue with the same example:

In the same industrial micro-grid, there were a total of 20 power interruptions over the course of one year.

SAIFI = (20 interruptions) / (200 customers) = 0.10 interruptions per customer per year. This means, on average, each customer in this micro-grid experienced 0.10 interruptions in a year.

These reliability indices provide quantitative measures of the power distribution system's performance in terms of interruptions. Lower values of SAIDI and SAIFI indicate higher reliability, which is essential for industrial micro-grids to ensure uninterrupted power supply to critical industries. These indices are valuable tools for utilities and system operators to assess and improve the reliability of their distribution networks.

2.6.3 Customer Average Interruption Duration Index (CAIDI)

CAIDI, the Customer Average Interruption Duration Index, serves as a frequently employed reliability metric within the domain of electric power utilities. It stands interlinked with SAIDI and SAIFI, with its computation defined by the average outage duration experienced by any individual customer. Moreover, CAIDI can be interpreted as the mean restoration time for an IMG in the event of whole blackout. According to IEEE Standard 1366-1998, CAIDI can be calculated as

$$\text{CAIDI} = \frac{\Sigma\, U_i\, N_i}{\Sigma\, \lambda_i\, N_i}$$

Where λ_i is the failure rate and N_i is the number of customers and U_i is the annual outage time for location **i** of any IMG

2.7 Revisiting Methods for Enhancing IMG Reliability

Enhancing power distribution network stability is an ongoing area of research and development. Some methods and results for improving stability and reliability, considering SAIDI, SAIFI, CAIDI metrics and some other IMG reliability enhancement methods are discussed below:

2.7.1 IMG Reliability through FGMO

Enhancing micro-grid stability through Free Governing Mode Operation (FGMO) involves employing sophisticated control algorithms to manage the power flow and frequency regulation within the micro-grid [12]. By closely monitoring and adjusting the power output of generators, FGMO helps maintain a stable frequency and voltage level [13], thereby ensuring the reliability and resilience of the micro-grid system, especially during fluctuations and disturbances.

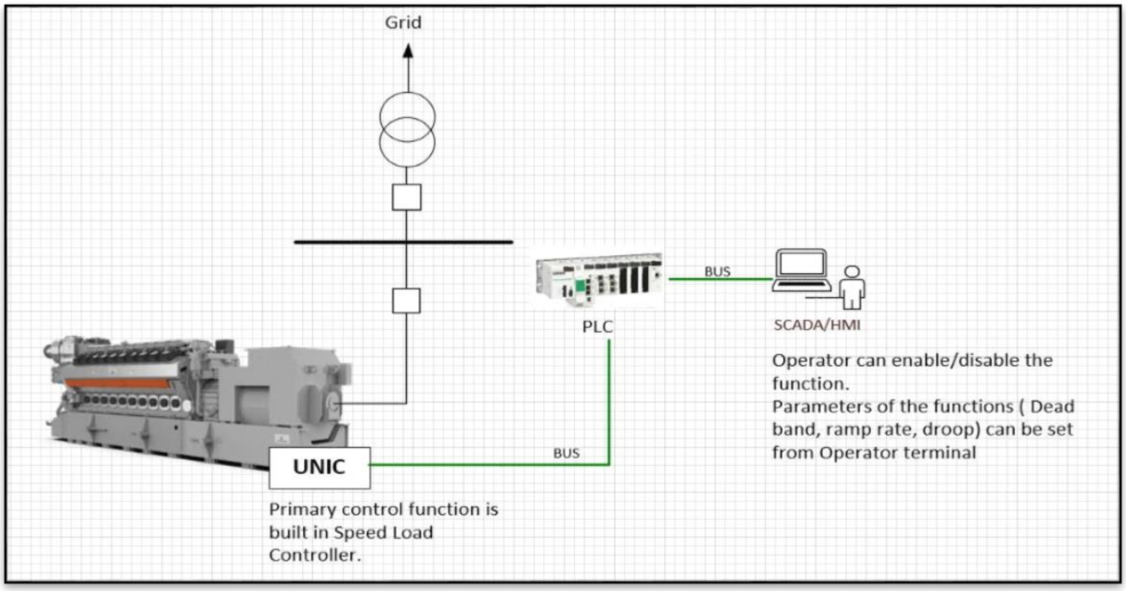

Fig. 2.4: Incorporating FGMO in IMG

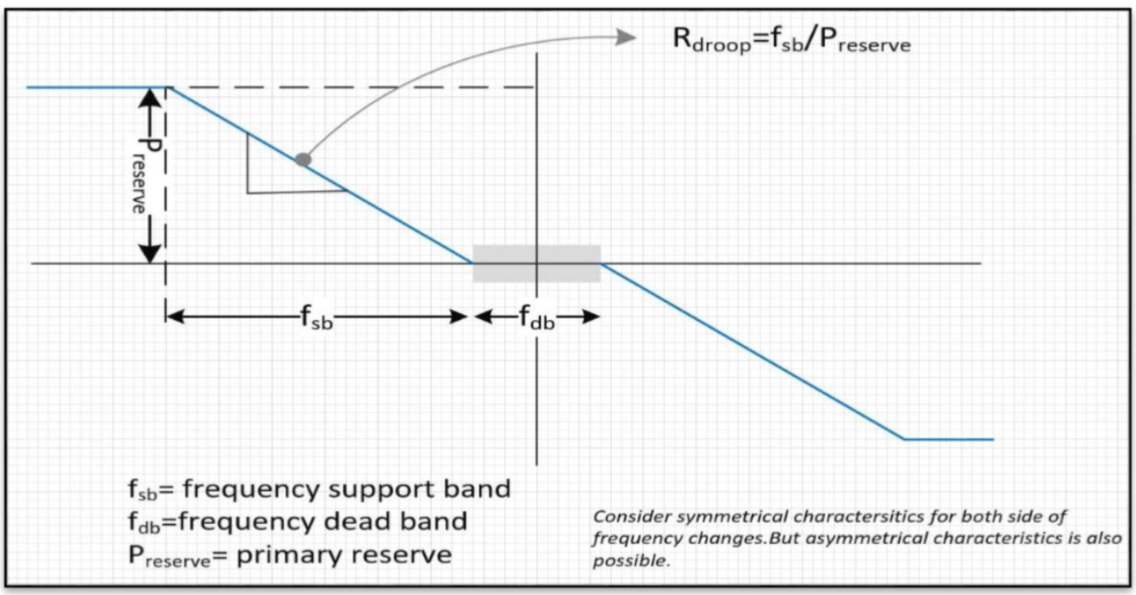

Fig. 2.5: Frequency VS Load Characteristics in FGMO

Table 2.3: FGMO Functional Parameters

Droop	Adjustable	2-12%
Ramp rate	Adjustable	Genset dependent Maximum is 2%/sec
Dead band	Adjustable	0-0.5Hz
Frequency measurement accuracy		<0.02%

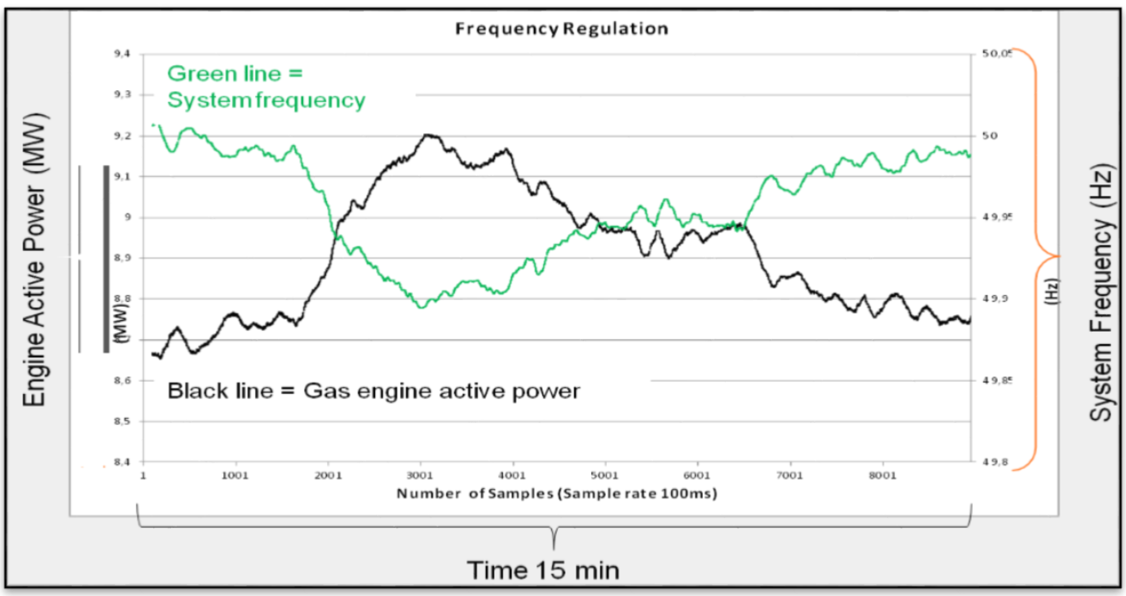

Fig. 2.6: FGMO Regulation with 10% Primary Reserve.

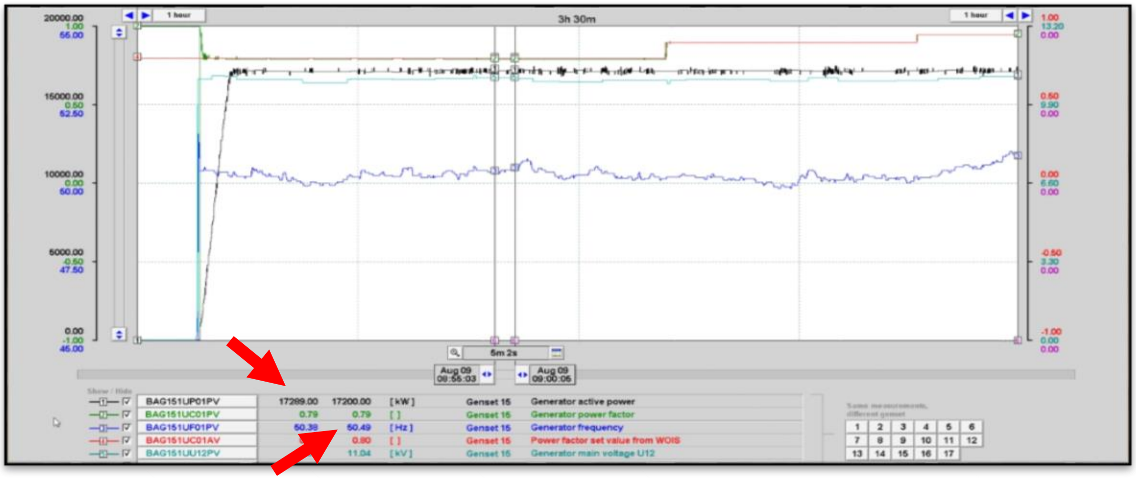

Fig. 2.7: Real World Frequency VS Load Characteristics in FGMO

Additionally, integrating smart technologies and energy storage systems can further improve the effectiveness of FGMO in enhancing micro-grid stability.

2.7.2 Integration of Renewable Energy

Renewable energy integration plays a crucial role in enhancing the stability of industrial micro-grids. By incorporating renewable sources like solar, wind, or hydropower into the micro-grid system, industries can achieve a more sustainable and reliable energy supply. Incorporating renewable energy enhances overall resilience and reliability of the micro-grid by reducing the vulnerability to disruptions in the energy supply chain.

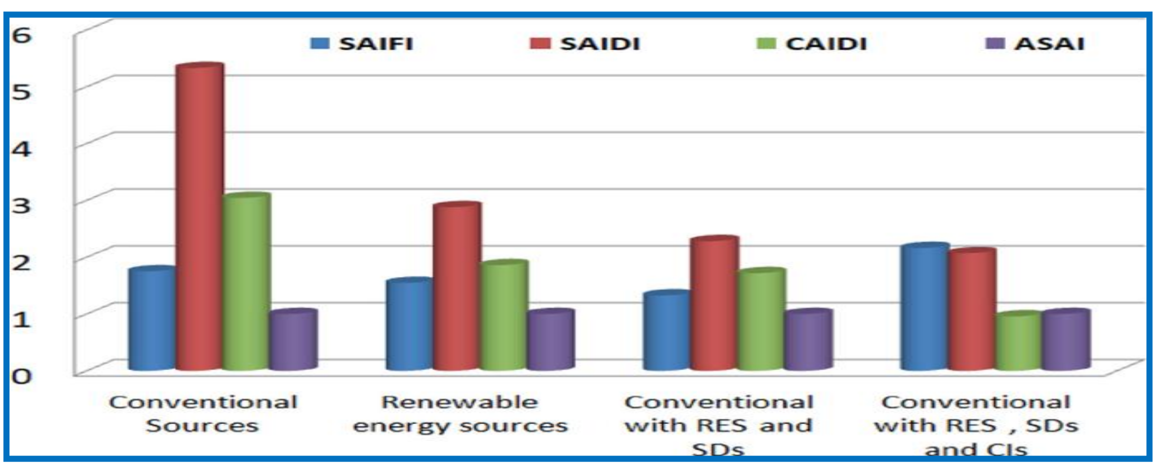

Fig. 2.8: Reliability Assessment of IMG with Renewable Energy Sources, Storage Devices, and Cyber Intrusion [14]

The integration of renewable energy into industrial micro-grids offers substantial benefits, including enhanced environmental sustainability, reduced dependence on fossil fuels, and alignment with regulatory standards. However, it presents several notable challenges, such as the intermittency and variability of renewable sources, dependencies on weather conditions, added infrastructure costs, complex grid management requirements, land use concerns, limitations in energy storage technology, and a complex regulatory environment. Careful planning and mitigation strategies are essential to navigate these disadvantages and fully realize the advantages of renewable energy integration while ensuring the stability of industrial micro-grid systems.

2.7.3 Placement of Distributed Generation

Distribution generation enhances grid reliability by strategically placing power generation sources within the distribution system. In the assessed case, introducing distribution generation at various distances from the substation, can significantly improve system reliability [15][16].

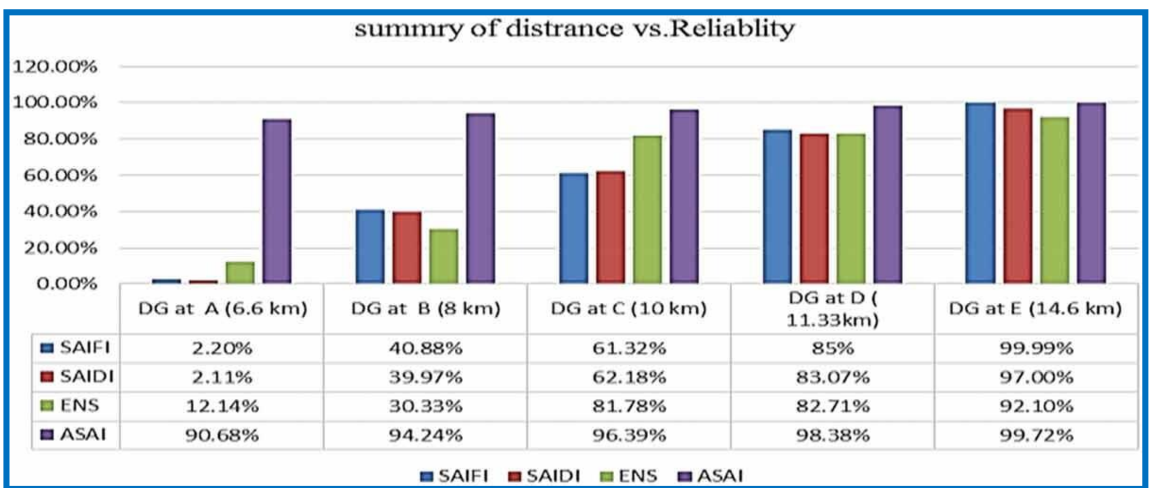

Fig. 2.9: Distance VS Reliability Index for Distributed Generation System [17]

2.7.4 Automatic Generation Control (AGC)

AGC systems adjust the generation output of power plants to match the load demand, maintaining system frequency and stability.

The AGC system has two primary tasks: Load Frequency Control (LFC) and Economic Dispatch (ED). LFC manages the system's frequency and power interchange by adjusting generating unit outputs. It involves three levels: primary, where governors respond quickly to frequency changes; secondary, where the control center corrects deviations; and tertiary, where the control center optimizes unit outputs for efficiency. ED allocates load demand among units in a cost-effective manner. The control center calculates each unit's optimal output considering their costs and limitations. Depending on system design, ED can be integrated with or separate from LFC.

2.7.5 Advanced Fault Detection and Localization

- Utilizing advanced sensors and communication systems to quickly detect and locate faults in the network under a common control and protection scheme [18].
- Implementing automated fault isolation and restoration systems, reducing SAIDI and SAIFI values.
- Using machine learning algorithms to predict potential faults and take preventive measures.

2.7.6 Smart Grid Technologies

The smart grid is often characterized as a self-contained distribution system that can generate power from diverse sources, including renewables and energy storage [19]. Its adoption grants unparalleled control and management capabilities to both suppliers and consumers. In contrast to traditional grids with one-way communication, the smart grid operates as a sophisticated network with numerous two-way interactions between equipment and supply chain actors.

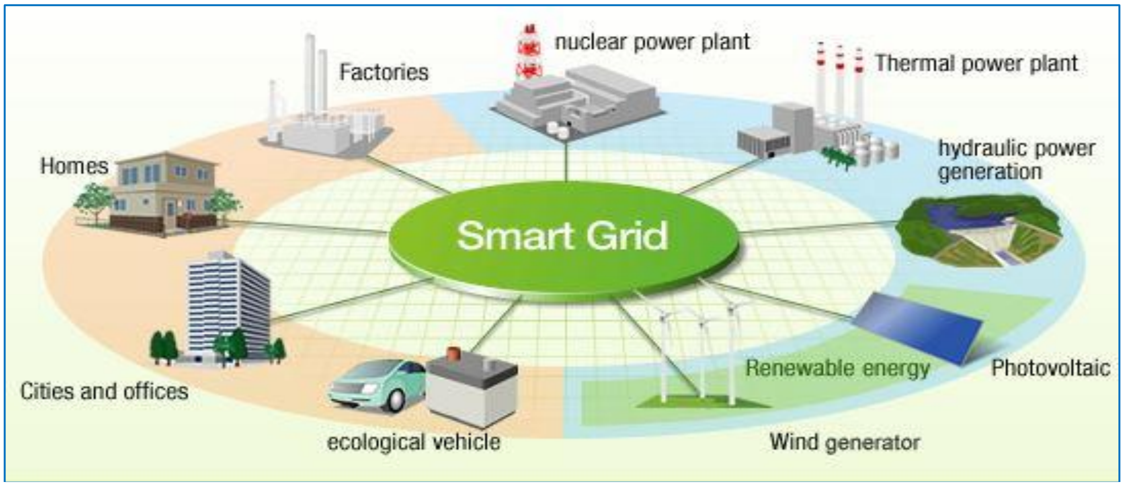

Fig. 2.10: Smart Grid Technology and Applications [20]

- Deploying smart meters and devices for real-time monitoring and control of the distribution network.
- Implementing demand response programs to manage load during peak periods.
- Integrating renewable energy sources and energy storage for grid stability.

2.7.7 Predictive Maintenance and Condition Monitoring

- Using data analytics and machine learning to predict equipment failures and perform maintenance proactively.
- Applying condition-based monitoring to identify and replace deteriorating components. In addition to this, conducting thermal imaging and vibration analysis for early fault detection.

2.7.8 Micro-grids and Decentralized Energy Sources

- Establishing micro-grids to provide localized power during network disruptions.
- Integrating decentralized energy sources, such as solar and wind, to reduce dependency on centralized power generation.

2.7.9 Resilience Planning and Disaster Preparedness

- Developing comprehensive resilience plans for natural disasters and extreme weather events.
- Implementing grid hardening measures, such as underground cabling and reinforced infrastructure.

Recent research results have shown that the combination of these methods can lead to substantial improvements in SAIDI, SAIFI, and CAIDI values, resulting in more reliable and stable power distribution networks. The specific values achieved will vary depending on the characteristics of the network and the extent of the enhancements implemented.

2.8 Summary

By thoroughly reviewing the existing literature, this chapter equips the reader with a comprehensive understanding of the industrial micro-grid landscape, its challenges, and the potential of Generating Bus Splitting (GBS) as a solution. The Literature Review chapter serves as a crucial foundation for the current study on "Enhancing the Micro-Grid Reliability in Industrial Distribution Feeders by Generating Bus Splitting Model." It not only offers an in-depth understanding of the research field but also identifies gaps and trends. It introduces Industrial Micro-Grid (IMG) systems, highlighting their role in providing resilient power solutions for industrial applications. Additionally, it categorizes various types of Micro-Grids, emphasizing their benefits such as reliable power supply and reduced energy costs. However, the chapter also delineates the challenges faced by IMGs, encompassing technical, economic, operational, regulatory, and environmental aspects. Moreover, it delves into power quality and reliability, emphasizing stable voltage and frequency, while highlighting reliability indices, including SAIDI, SAIFI and CAIDI for assessing power distribution systems. These insights culminate in a holistic overview that lays the groundwork for the subsequent chapters, offering a comprehensive understanding of IMGs and their implications in the industrial context.

Chapter 3: Methodology

The following chapter outlines the comprehensive methodology employed to investigate the Industrial Micro-Grid (IMG) and propose a viable solution to enhance its stability and resilience. Both Section 3.1 and Section 3.2 start with a focus on data collection through site visits of both the Export Processing Zones (EPZs) under the coverage of the mentioned Industrial Micro-Grid (IMG). This is followed by corresponding system modeling and simulation in Section 3.3 using ETAP & WECS-8000, WOIS and PCM-600 in some other different part of this study. Emphasizing the significance of primary data collected through extensive site visits, interviews, and load profile data, the section highlights the meticulous process of developing a detailed model using the above mentioned advanced simulation tools. In section 3.4 implementation processes of the Generating Bus Splitting model in IMG are described. Furthermore, in section 3.5 it explains the fundamental principles and technical particulars underlying the GBS Model, showing its potential to significantly improve the IMG's operational efficiency. Additionally, we tried to focus on the grounds behind selecting GBS model as the proposed solution will also be discussed. Through a carefully planned implementation strategy, the methodology aims to not only enhance the understanding of the IMG's functionality but also provide practical solutions to mitigate potential disruptions and boost the IMG's reliability. Finally, section 3.6 represents the summary of this chapter.

3.1 Data Collection

The acquisition of primary data for the Industrial Micro-Grid (IMG) system in the Chittagong Export Processing Zone (CEPZ) and the Karnaphuli Export Processing Zone (KEPZ) entailed a meticulous and comprehensive approach. This study involved an extensive examination of various operational and maintenance scenarios within the IMG framework. Notably, the primary data collection process was multi-faceted, drawing from various sources to ensure a comprehensive understanding. The principal sources of primary data included site visits and visual inspections, which formed the foundation of the data collection process. These meticulous site visits and inspections were very instrumental in evaluating the infrastructure and operational aspects of the IMG, setting the stage for the subsequent analysis and implementation strategies.

3.1.1 Obtaining IMG Primary Data

Primary data collection for this study involved a comprehensive and exhaustive process that covered various aspects of the Industrial Micro-Grid (IMG) system in CEPZ and KEPZ associated its different operational & maintenance scenarios. The primary data sources include:

3.1.2 IMG Site Visits

Extensive site visits were conducted for the entire Industrial Micro-Grid (IMG) i.e. almost all types of industries of both CEPZ and KEPZ. These visits served as the foundation of data collection. During site visits, the following activities were carried out:

3.1.3 Visual Inspection of Industries and CGS under IMG

A thorough visual inspection of the entire Industrial Micro-Grid (IMG) infrastructure, including its Central Generating Station (CGS), control & protection schemes, end user substations & switchgears, both O/H & U/G distribution networks, was conducted to assess their condition, layout, and configuration & for finding an effective solution to reduce the IMG’s interruption into a tolerable limit. During the door-to-door survey, close examination was conducted for all industrial distribution feeders focusing primarily on the IMG feeder load patterns, end-user switchgear, and substation conditions.

For ready reference, the details of sub-station & switchgear components with their functionalities of the industries connected with a single industrial distribution feeder are presented below which is typically more or less same for industries under other feeders as well.

Table 3.1: Switch-Gear and Substation Conditions under a Typical IMG Feeder

Sl. No.	Name of the Industries	O/H line to isolator	Drop out fuse	Lightning arrester	Transformer & HT cable (isolator to VCB)	VCB condition & relay settings
01	M/s. Universal Jeans Ltd. (Unit-1)	OK	OK	OK	2000 KVA Dry type	VCB 630A EM relay EP
02	M/s. Universal Jeans Ltd. (Unit-2)	OK	OK	OK	2000 KVA Dry type	VCB 630A Siemens
03	M/s. Universal Jeans Ltd. (Unit-3)	OK	OK	OK	1000 KVA Dry type	VCB 630A Relay Local
04	M/s. Universal Jeans Ltd. (Unit-4)				1000 KVA Dry type	VCB 630A Relay Local
05	M/s. Patenga Footwear Ltd.	OK	01 no damage	OK	750 KVA	LBS
06	M/s Unity Accessories Pvt Ltd	OK	OK	OK	500 KVA	LBS
07	M/s Section Seven Apparels Ltd.	Operate excess bad need to shift	OK	Need proper wiring	1600 KVA	VCB 630 A EP
08	M/s Merim co. ltd (Unit-1, 2&3).	Operating handle clearance is low	OK	OK	1250 KVA HT cable heat-shrink problem	VCB 630 A Local relay
09	M/s Merim co. ltd (Unit-1, 2&3).	Operating handle clearance is low	OK	OK	1250 KVA	VCB 630 A Local relay
10	M/s. Sanco Corporation Co. ltd.	Need repair	OK	01 no damage	1000 KVA	VCB 630 A EM relay faulty (suspected)

3.1.4 Collected Data Measurements and Analysis

Data measurements were taken at critical points within the micro-grid system to capture key parameters such as voltage levels, frequency limits, current flows, fault conditions & whole IMG interruption frequency & pattern. These measurements were used to validate simulation results and real-world performance.

3.1.5 Discussions with IMG Key Personnel

In-depth discussions and interviews were held with key personnel, including micro-grid operators, maintenance staffs, and technical experts. These discussions provided valuable insights into the day-to-day operation & maintenance (O&M) of the micro-grid, the challenges faced, and the potential benefits of implementing Generating Bus Splitting (GBS) model to make it further stable.

3.1.6 IMG Load Profile Data

Real-time load profile data from the distribution feeders within this Industrial Micro-Grid (IMG) were collected over a specified period. These data included information on load patterns, load fluctuations, and peak demand periods, feeder tripping causes etc. Load profile data were instrumental in understanding the dynamic nature of industrial power consumption.

Hourly individual feeder loads for all 11kV industrial distribution feeders over a 24-hour working day of the IMG are summarized in the table below. This was strategically very vital in selecting the splitting point while implementing the GBS model in this/ similar IMG network [21][22].

Table 3.2: Hourly Individual Loads of IMG 11kV Feeders (Feeder 01 to Feeder 08) in a Single Working Day

Time (Hr)	Load															
	SL-1		SL-2		SL-3		SL-4		SL-5		SL-6		SL-7		SL-8	
	Fedder 01		Fedder 02		Fedder 03		Fedder 05		Fedder 06		Fedder 07		Fedder 08		Fedder09	
	Amp	MW	Amp	MW	Amp	MW	Amp	MW	Amp	MW	Amp	MW	Amp	MW	Amp	MW
0:00	108	1.89	70	1.23	100	1.75	58	1.02	45	0.79	52	0.91	29	0.51	108	1.89
1:00	101	1.77	65	1.14	92	1.61	65	1.14	42	0.74	50	0.88	26	0.46	106	1.86
2:00	102	1.79	64	1.12	102	1.79	58	1.02	47	0.82	48	0.84	22	0.39	109	1.91
3:00	102	1.79	62	1.09	97	1.7	54	0.95	48	0.84	48	0.84	20	0.35	109	1.91
4:00	95	1.67	62	1.09	97	1.7	60	1.05	45	0.79	48	0.84	19	0.33	104	1.82
5:00	90	1.58	62	1.09	97	1.7	66	1.16	43	0.75	49	0.86	19	0.33	94	1.65
6:00	88	1.54	62	1.09	97	1.7	72	1.26	41	0.72	50	0.88	19	0.33	94	1.65
7:00	104	1.82	87	1.53	124	2.18	74	1.3	38	0.67	75	1.32	47	0.82	114	2
8:00	220	3.86	192	3.37	232	4.07	132	2.32	85	1.49	70	1.23	100	1.75	130	2.28
9:00	214	3.75	255	4.47	278	4.88	192	3.37	126	2.21	83	1.46	182	3.19	187	3.28
10:00	214	3.75	260	4.56	276	4.84	198	3.47	128	2.25	90	1.58	190	3.33	190	3.33
11:00	215	3.77	164	2.88	279	4.89	192	3.37	132	2.32	120	2.11	188	3.3	190	3.33
12:00	216	3.79	162	2.84	253	4.44	195	3.42	130	2.28	122	2.14	186	3.26	191	3.35
13:00	215	3.77	260	4.56	226	3.96	190	3.33	126	2.21	90	1.58	190	3.33	190	3.33
14:00	232	4.07	222	3.89	216	3.79	176	3.09	145	2.54	140	2.46	182	3.19	181	3.18
15:00	246	4.32	248	4.35	260	4.56	196	3.44	170	2.98	155	2.72	189	3.32	180	3.16
16:00	245	4.3	245	4.3	255	4.47	185	3.25	162	2.84	160	2.81	172	3.02	171	3
17:00	244	4.28	249	4.37	235	4.12	179	3.14	148	2.6	110	1.93	169	2.96	166	2.91
18:00	185	3.25	240	4.21	185	3.25	182	3.19	145	2.54	80	1.4	128	2.25	152	2.67
19:00	97	1.7	208	3.65	87	1.53	170	2.98	98	1.72	58	1.02	111	1.95	142	2.49
20:00	98	1.72	75	1.32	98	1.72	85	1.49	62	1.09	59	1.04	95	1.67	132	2.32
21:00	146	2.56	78	1.37	111	1.95	74	1.3	58	1.02	61	1.07	88	1.54	94	1.65
22:00	146	2.56	78	1.37	111	1.95	74	1.3	55	0.96	61	1.07	88	1.54	94	1.65
23:00	117	2.05	65	1.14	100	1.75	57	1	49	0.86	58	1.02	33	0.58	118	2.07

Table 3.3: Hourly Individual Loads of IMG 11kV Feeders (Feeder 09 to Feeder 17) in a Single Working Day

Time (Hr)	Load													
	SL-9		SL-10		SL-11		SL-12		SL-13		SL-14		SL-15	
	Fedder 10		Fedder 11		Fedder 12		Fedder 13		Fedder 14		Fedder 15		Fedder 17	
	Amp	MW	Amp	MW	Amp	MW	Amp	MW	Amp	MW	Amp	MW	Amp	MW
0:00	32	0.56	47	0.82	150	2.63	55	0.96	45	0.79	35	0.61	64	1.12
1:00	23	0.4	46	0.81	145	2.54	55	0.96	90	1.58	33	0.58	70	1.23
2:00	28	0.49	48	0.84	140	2.46	55	0.96	37	0.65	34	0.6	66	1.16
3:00	28	0.49	45	0.79	128	2.25	55	0.96	37	0.65	33	0.58	50	0.88
4:00	25	0.44	40	0.7	126	2.21	54	0.95	31	0.54	33	0.58	48	0.84
5:00	25	0.44	38	0.67	124	2.18	52	0.91	36	0.63	32	0.56	45	0.79
6:00	30	0.53	38	0.67	120	2.11	52	0.91	30	0.53	31	0.54	50	0.88
7:00	97	1.7	77	1.35	190	3.33	94	1.65	124	2.18	33	0.58	65	1.14
8:00	242	4.25	120	2.11	220	3.86	249	4.37	232	4.07	42	0.74	130	2.28
9:00	276	4.84	191	3.35	285	5	258	4.53	278	4.88	114	2	192	3.37
10:00	281	4.93	192	3.37	279	4.89	259	4.54	276	4.84	115	2.02	198	3.47
11:00	278	4.88	190	3.33	288	5.05	256	4.49	279	4.89	114	2	185	3.25
12:00	274	4.81	192	3.37	286	5.02	253	4.44	253	4.44	116	2.04	195	3.42
13:00	229	4.02	190	3.33	288	5.05	241	4.23	226	3.96	112	1.96	190	3.33
14:00	226	3.96	184	3.23	282	4.95	223	3.91	216	3.79	108	1.89	180	3.16
15:00	285	5	185	3.25	305	5.35	252	4.42	260	4.56	118	2.07	196	3.44
16:00	288	5.05	172	3.02	285	5	255	4.47	255	4.47	117	2.05	188	3.3
17:00	194	3.4	143	2.51	278	4.88	210	3.68	235	4.12	119	2.09	179	3.14
18:00	160	2.81	140	2.46	251	4.4	208	3.65	185	3.25	108	1.89	182	3.19
19:00	99	1.74	120	2.11	180	3.16	128	2.25	117	2.05	98	1.72	170	2.98
20:00	92	1.61	70	1.23	158	2.77	133	2.33	72	1.26	87	1.53	85	1.49
21:00	83	1.46	72	1.26	160	2.81	102	1.79	50	0.88	55	0.96	74	1.3
22:00	39	0.68	72	1.26	160	2.81	54	0.95	57	1	55	0.96	70	1.23
23:00	38	0.67	72	1.26	147	2.58	50	0.88	44	0.77	35	0.61	57	1

3.2 Obtaining IMG Secondary Data

In addition to the comprehensive primary data collection, the acquisition of secondary data for the Industrial Micro-Grid (IMG) was crucial in obtaining a holistic perspective of its operational dynamics. The IMG management's historical records played a pivotal role in this process, offering valuable insights into the system's performance over time. These records comprised detailed accounts of various aspects of the IMG's operation and performance, contributing to a clear understanding of its historical context and challenges. Among the key elements of the secondary data were the records of IMG interruptions and fault incident logs, both of which provided essential information for the comprehensive analysis of the IMG's performance and the identification of critical areas for improvement and intervention [23]. By meticulously examining these records, the study aimed to uncover recurring patterns and underlying causes behind disruptions, enabling a strategic approach to enhancing the IMG's operational resilience and reliability. Historical records were also obtained from the Industrial Micro-Grid (IMG) management. These records included:

3.2.1 IMG Interruption Data

Detailed records of past power interruptions in IMG, including the date, time, duration, and causes of interruptions were collected & reviewed. This data helped identify trends and patterns in IMG tripping incidents.

3.2.2 Fault Incident Logs

Logs of fault incidents, including information on fault locations, fault types, and response times, were examined. This data provided insights into the nature of faults in this industrial micro-grid. In order to enhance the reliability and resilience of the IMG power supply, a detailed analysis of past power interruptions has been conducted.

The table below provides a comprehensive overview of these interruptions for a 30 working-day period in March 2022, presenting key information including the date, time, duration, and underlying causes. This analysis serves as a valuable resource for understanding historical interruption patterns and working towards improved power supply stability [24].

Table 3.4: Comprehensive Analysis of IMG Power Interruptions

Sl. No.	Date	IMG Tripping Records		IMG Interruption Duration (min)	Alarm/Causes
		From	To		
01	06.03.2022	09:42	10:05	23	Earth fault in IMG feeder-05 2^{nd} stage (ie>>) Magnitude: 14.54 KA
02	10.03.2022	07:50	08:09	19	Over current in IMG master feeder, 1^{st} stage (i>) Magnitude: 3.32 KA
03	15.03.2022	07:10	07:31	21	33 KV Ckt-1 site high earth fault & sudden imbalance in system frequency.
04	17.03.2022	12:07	12:23	16	33 KV Ckt-2 site earth fault & sudden load swing as grid dispatch was 6.6 MW
05	19.03.2022	19:34	19:49	15	High earth fault in IMG feeder-09, 2^{nd} stage (ie>>) Magnitude: 15.25 KA
06	27.03.2022	01:29	01:48	19	33 KV Ckt-1 site high earth fault & sudden imbalance in system frequency. df/dt = 1.4 Hz/s

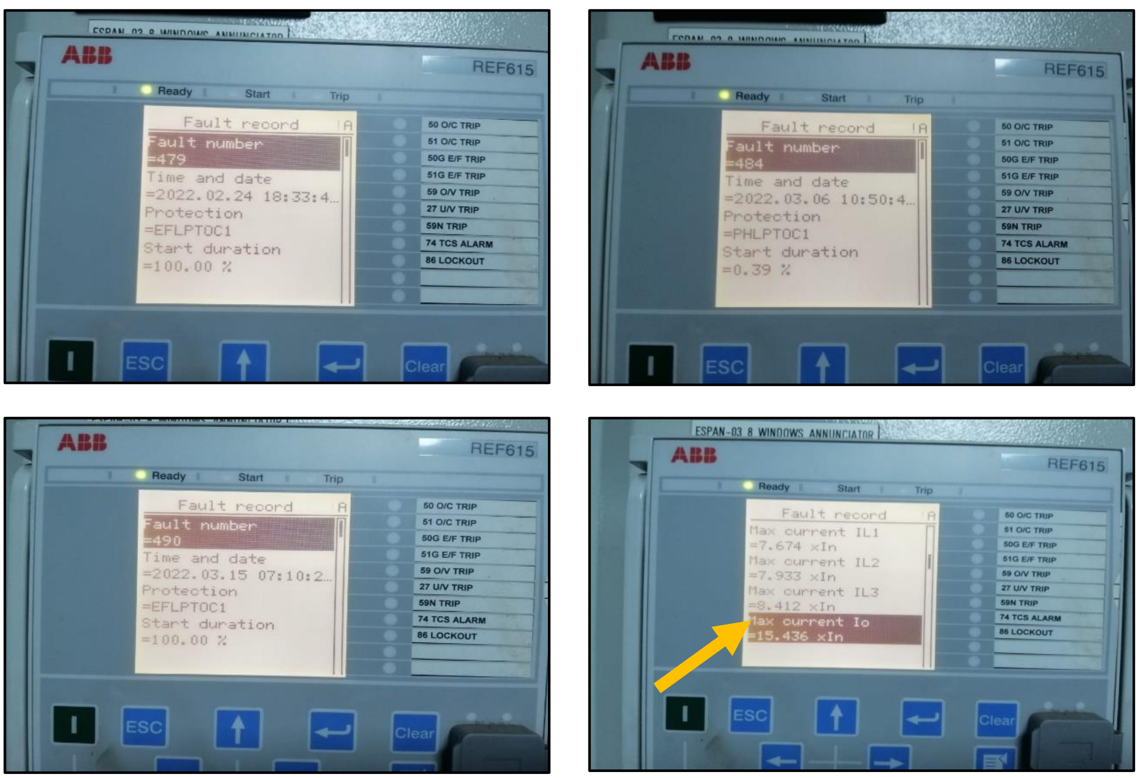

Fig. 3.1: IMG Interruption Fault Records & Pattern

3.3 System Modeling

Based on our collected data, we considered a prototype or mostly similar model to our IMG for having a better understanding of the practical field implementation of our proposed Generating Bus Splitting (GBS) model.

3.3.1 GBS Model Development

A comprehensive model of the Industrial Micro-Grid (IMG) was developed to simulate its behavior under various operating conditions. The modeling process included the creation of a detailed representation of the micro-grid's components, including generating sets, distribution feeders, transformers, and protective devices [25]. The following steps were undertaken:

3.3.2 IMG Component Characterization

- **Generating Sets (GS)**: Detailed data of the eight (08) Natural Gas (NG) fired IC Engine based Generating Sets (GS) were incorporated into the model. This included information on generator ratings, impedance values, and control system parameters.
- **Industrial Distribution Feeders (IDF)**: The layout and parameters of the 09 industrial distribution feeders serving CEPZ were accurately modeled. This involved capturing the feeder's length, line impedance, load distribution, and connection points.
- **Transformers**: The transformers within the micro-grid, including their ratings and impedance values, were included in the model to accurately represent voltage transformations.

3.3.3 Pre-study of GBS by Simulation Model

Electrical Transient and Analysis Program (ETAP), powerful simulation software, was employed to build and simulate the micro-grid model. This software allowed for the creation of a detailed network model that could replicate the behavior of the actual system [26].

3.3.4 IMG Simulation Scenarios

The Industrial Micro-Grid (IMG) model was subjected to various simulation scenarios to assess its performance and stability. These scenarios included:

3.3.4.1 Base Case Simulation

A base case simulation was conducted to represent this micro-grid's behavior under typical operating conditions. This scenario served as a benchmark for evaluating the effects of GBS implementation.

3.3.4.2 Fault Analysis through Simulation

Fault scenarios, including short-circuit faults, were simulated to evaluate fault currents and assess the system's protective devices' performance [27][28]. These simulations helped identify critical fault locations and determine the adequacy of protection measures.

Three phase bolted short circuit IEC 60909 (CASE: 01)

- Utility : Grid-02 CB Open and All Bus Coupler are closed in CGS
- Fault at Bus Segment-01

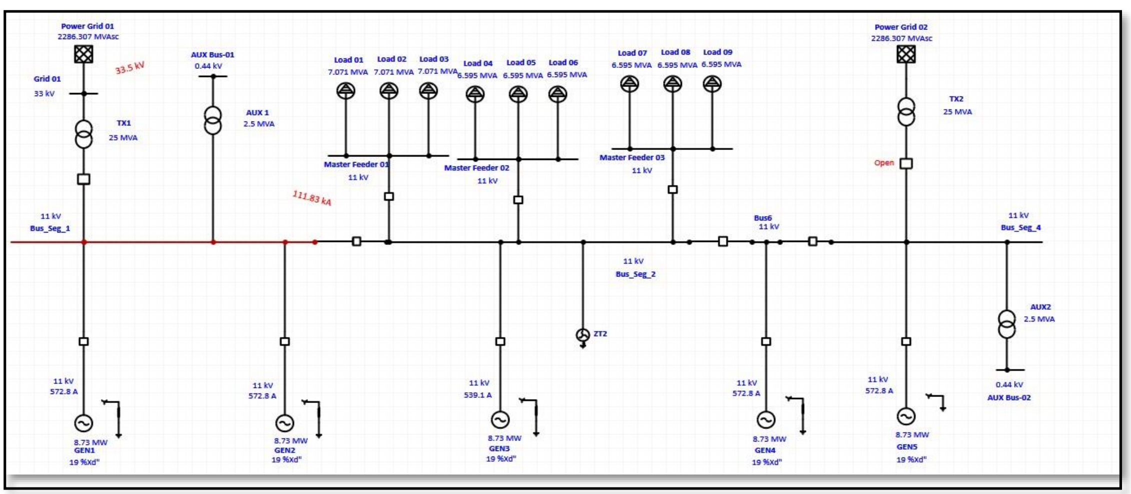

Fig. 3.2**:** Peak Fault Current as Per IEC 60909, 111.39KA (Pre-GBS model)

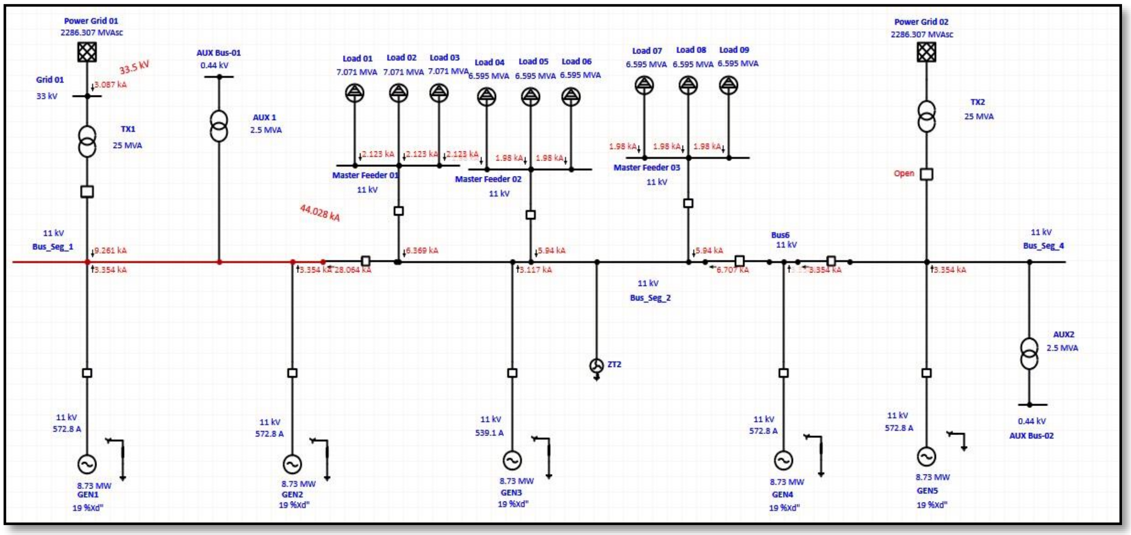

Fig. 3.3: Initial Symmetrical Fault Current, 44.028 KA (Pre-GBS model)

Three phase bolted short circuit as per IEC 60909

- Utility : 02 CB closed and Bus Coupler-02 of IMG's CGS is Open

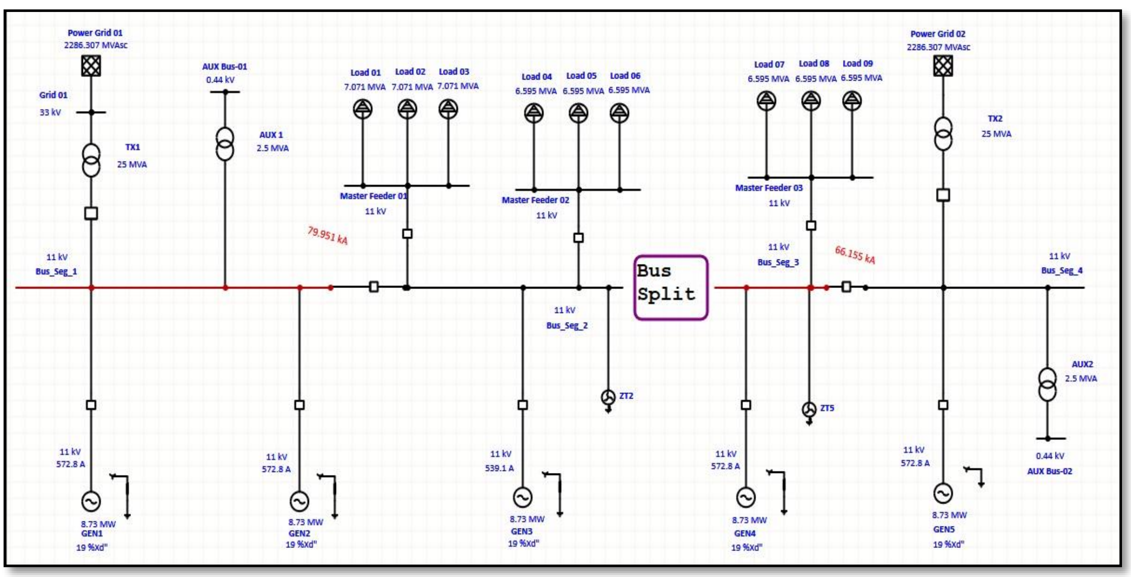

Fig. 3.4**:** Peak fault current as per IEC 60909, 79.951 KA & 66.155KA (Post-GBS model)

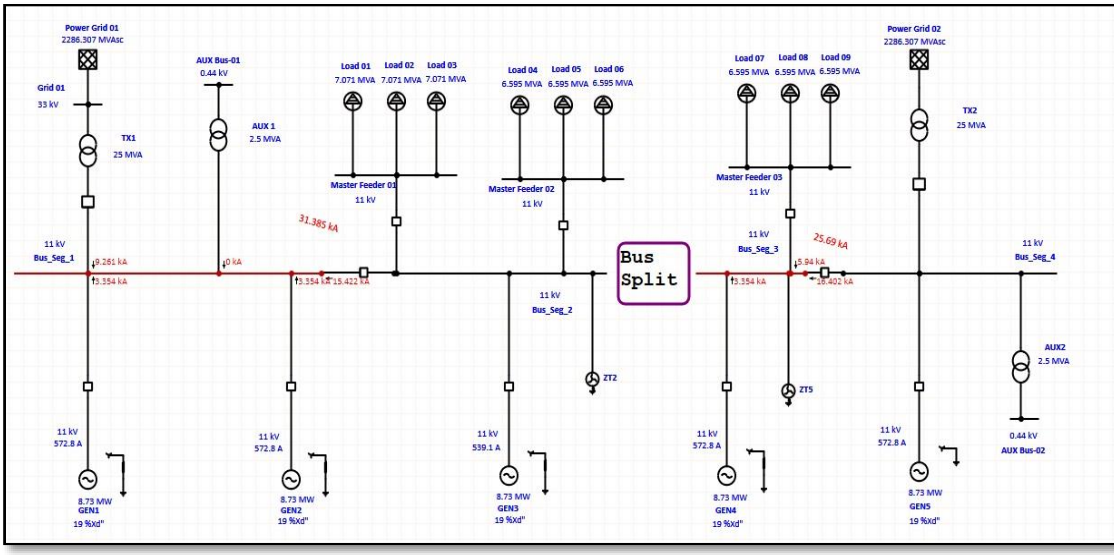

Fig. 3.5**:** Initial symmetrical fault current, 31.385 KA and 25.69 KA
(Post-GBS model)

Based on above GBS model, splitting the IMG network X/R will also be decreased.

- X/R ratio does not affect the Symmetrical RMS Current.
- X/R ratio affects Peak Current. High X/R ratio high peak current.
- Higher X/R ratio case, for selecting CB higher making current required

What exactly is the X/R Ratio?

The X/R ratio is used to measure the relationship between the inductive reactance (X) and the resistance (R) within an electrical system. Understanding the X/R ratio holds significance for various reasons. This ratio plays a crucial role in determining the peak asymmetrical fault current, which can often exceed the symmetrical fault current by a significant margin.

In the event of a short circuit, the overall current is composed of two elements:

- The AC component, which fluctuates in a sinusoidal pattern with time (also referred to as the symmetrical current)
- The DC component, which is non-periodic and diminishes exponentially with a time constant of L/R (where L/R is directly proportional to X/R).

DC component causes the symmetrical current to deviate from symmetry, resulting in an asymmetrical current flow. The X/R ratio directly impacts the intensity of the DC component, thereby influencing the total current magnitude.

The Importance of X/R Ratio:

1. **Protection Choice:** A higher X/R ratio impacts protective device selection, crucial for preventing damage and ensuring safety.
2. **System Performance:** X/R ratio influences voltage stability and response to switching events, optimizing overall electrical system performance.
3. **Troubleshooting Tool:** Abnormal X/R ratios signal issues, aiding quick corrections for seamless operations.

Inductive equipment like transformers and motors typically has a low X/R ratio. During short circuits, the combined AC and DC components determine when a circuit breaker should interrupt the current flow.

3.3.5 Transient Stability Analysis

The model was modified to incorporate the proposed Generating Bus Splitting (GBS) solution. GBS implementation involves the proposal of disintegrating & relocating of one master feeder from its Central Generation Bus (CGS) to rationally distribute fault burden concentration to reduce fault currents. Transient stability analysis was performed to assess this industrial micro-grid's behavior under sudden disturbances or changes in operating conditions [29][30]. This analysis helped ensure the system's stability during transient events. As Per IEC61363 Transients Short circuit analysis is represented below:

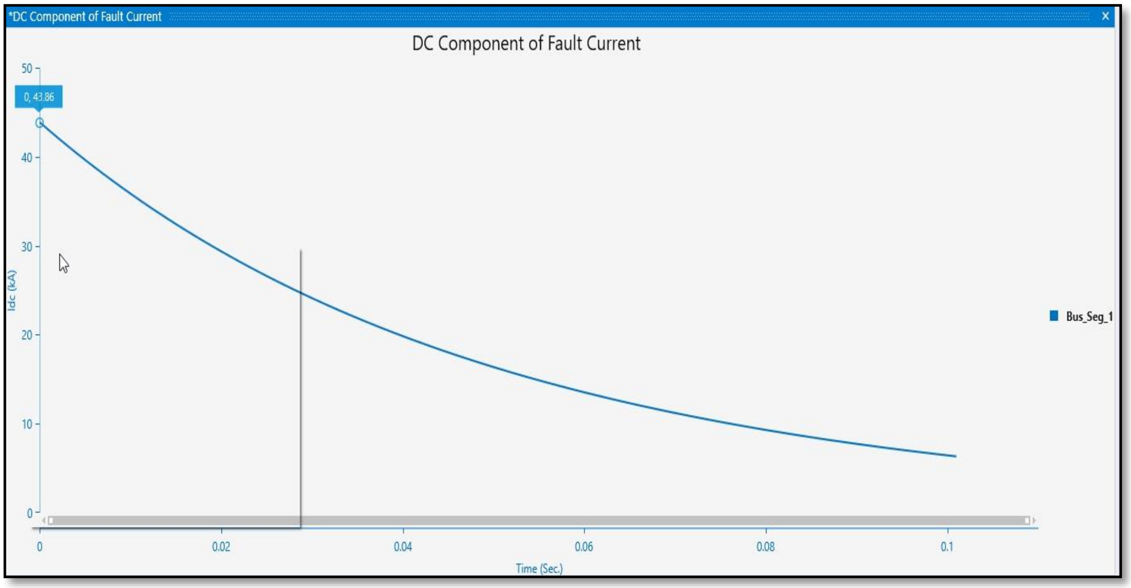

Fig. 3.6: DC Component of fault current, 43.86 KA (in pre-GBS model)

As Per IEC61363 Transients Short circuit analysis is also represented below

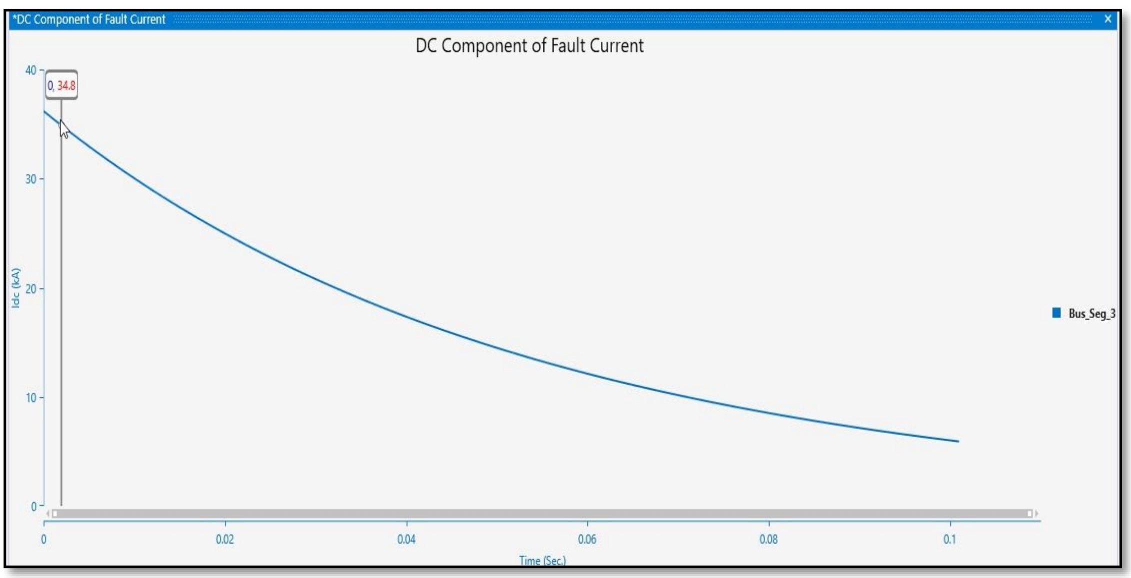

Fig 3.7: DC Component of fault current, 34.8 KA (in post-GBS model)

3.3.6 Data Integration

The model's accuracy and effectiveness were further enhanced by integrating real-world data collected during site visits and load profile measurements. Actual operating parameters and historical data were used to calibrate the model, ensuring that it closely mirrored the behavior of the physical industrial micro-grid.

3.3.7 Validation

To validate the accuracy of the model, simulation results were compared with real-world data collected from the micro-grid. This validation process helped ensure that the model faithfully represented the system's behavior and response to various scenarios.

3.4 GBS Model Implementation

This section introduces the concept of Generating Bus Splitting (GBS) model as a potential solution to the challenges faced by Industrial Micro-Grids due to different types of fault both from generation & distribution sides of the IMG. It includes a detailed explanation of the fundamental principles of GBS, including how it operates and its role in enhancing micro-grid stability.

Generating Bus Splitting (GBS) model was implemented in the Industrial Micro-Grid (IMG) control system using appropriate hardware and software. The GBS involves the disintegrating & relocating of one master feeder from one portion of its Central Generation Bus (CGS) to another to rationally distribute fault burden concentration to reduce the whole IMG tripping frequency [31]. Generating Bus Splitting (GBS) model is a strategy used in electrical distribution systems, particularly in the context of micro-grids, to enhance fault tolerance, stability, and reliability irrespective of entire IMG collapse. GBS model involves dividing a micro-grid or electrical network into smaller buses, each with its own generating, control and protection systems. Here are the principles of GBS model and how it works:

The Generating Bus Splitting (GBS) model principle described below outlines the modifications to the existing Central Generation Station’s 11KV generating bus (CGS-1) of IMG to enhance its reliability, operational and maintenance efficiency. The primary objective of the Generating Bus Splitting (GBS) principle is to enhance the reliability of power supply to all the industries connected with mentioned industrial micro-grid by splitting its Central Generation Station (CGS) into two separate units, namely Generating Bus-1 (GB-1) and Generating Bus-2 (GB-2).

3.4.1 Existing IMG Setup

Currently, during IMG peak hours, Central Generation Station (CGS) operates in parallel with 33KV grid circuit-1(regional national grid-1) or 33KV grid circuit-2 (regional national grid-2), supporting up to 10 industrial distribution feeders. However, this configuration poses a risk of power interruption to all connected industrial feeders in the event of a CGS or IMG trip due to any reason, as all three master feeders share the same 11KV bus section.

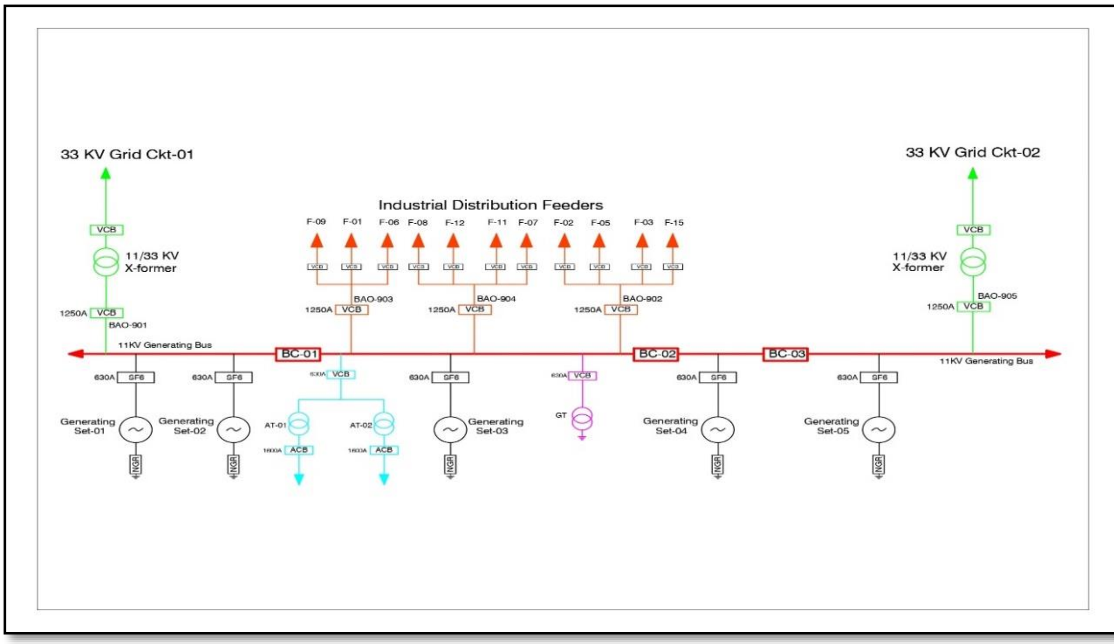

Fig. 3.8: Pre-GBS layout of Central Generation Station (CGS).

3.4.2 Proposed GBS Model

The basic idea of this GBS model is to split 11 KV generation bus of the Central Generation Station (CGS) of this industrial micro-grid into two separate units/ sections, Generating Bus-1 (GB-1) and Generating Bus-2 (GB-2), by relocating one master feeder to a new bus section. This model will provide the following advantages:

In Central Generation Station-1 (GU-1, GU-2, and GU-3) will run in island mode or parallel with the 33KV grid circuit-1 supporting a maximum of 2 master feeders along with 7 industrial distribution feeders of IMG.

On the other hand, in Central Generation Station-2 (GU-4 and GU-5) will be running in island mode or parallel with the 33KV grid circuit-2, supporting a maximum of one master feeders along with 5 industrial distribution feeders of IMG.

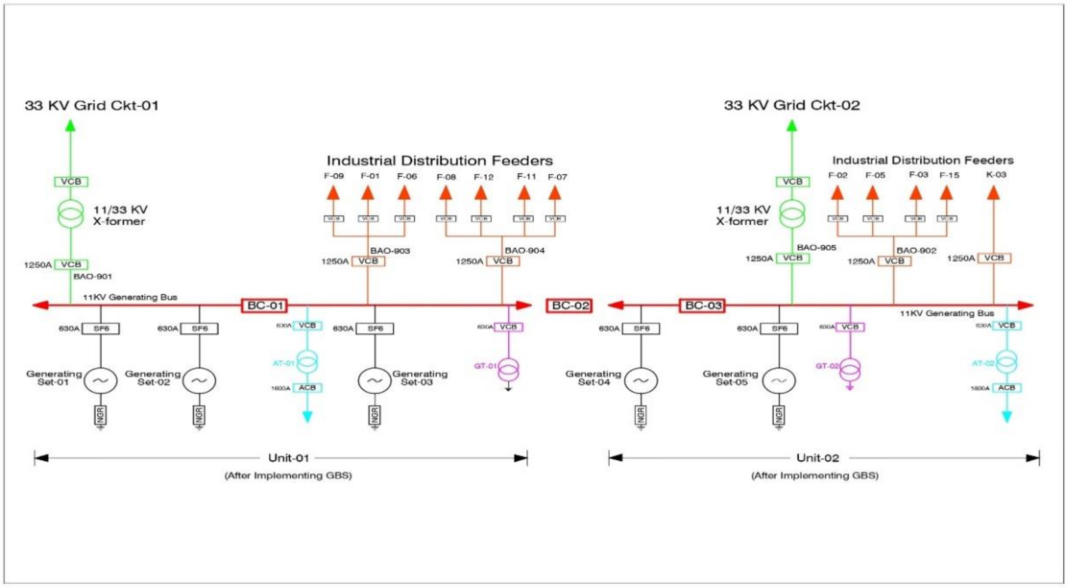

Fig. 3.9: Post-GBS layout of Central Generation Station (CGS).

3.4.3 Crisis and Grid Back-feed Handling

In the event of a severe fault causing the entire industrial micro-grid to go out of operation, the proposed GBS model allows for a total of double back-feed from either regional national grid to handle the crisis. This ensures a quick restoration of power to the maximum number of industrial distribution feeders immediately after an interruption.

3.4.4 Grid Independence

CGS-1 and CGS-2 of the described industrial micro-grid can be operated independently with their respective regional national grids during IMG peak hours, minimizing the risk of a complete IMG blackout in case of a grid failure. The separate auxiliary and grounding transformers for each proposed generating station enhance operational and maintenance flexibility.

3.4.5 Re-Coupling Option

Both the generating sections can be easily re-coupled together as & when necessary by simply synchronizing the existing bus coupler, providing flexibility in managing the power generation & distribution configuration for the entire Industrial Micro-Grid (IMG) [32].

3.5 Functioning of GBS Model

Generating Bus Splitting model is a valuable technique for improving the reliability and fault tolerance of integrated electrical distribution systems by disintegrating. The model is especially applicable & will be proved economical in some critical applications such as industrial micro-grids where each interruption of power imposes huge financial losses in production line. Working methods of GBS model in any IMG are described in the following sub-sections

3.5.1 Disintegrating the IMG Network

GBS model starts by dividing the electrical network into independent smaller bus sections. The division could be chosen at a strategic point in the network where generation and load are interconnected and mostly balanced as well.

3.5.2 Control and Protection

Each bus section is equipped with its own control and protection systems along with completely separate auxiliary transformer (AT) & grounding transformer (GT) of its own. On the other hand, each splitted bus section of the whole IMG will hypothetically be like an independent power generating system which will have its own relays, circuit breakers, and monitoring devices that can detect abnormal conditions such as overloads and faults [33].

3.5.3 Monitoring and Feedback Actions

The control and protection systems continuously monitor the electrical parameters of their respective buses, such as voltage, current, and frequency. They also monitor & compare for any deviations from normal operating values & send to feedback to respective control module for further necessary action [34].

3.5.4 Fault Detection

When a fault is detected in any of the bus sections, the control and protection systems act swiftly to isolate the faulty bus by keeping other part of the IMG safe & running. This isolation may involve opening circuit breakers automatically or disconnecting the faulty section from the rest of the IMG network.

3.5.5 Selective Restoration

After isolation, efforts can be focused on restoring power to the affected bus section of the IMG. Meanwhile, the other parts of the micro-grid keep continuing to operate without any interruption, ensuring power supply to essential loads under its respective IMG part.

3.6 Technical Preparation for Implementing GBS Model

The successful implementation of Generating Bus Splitting (GBS) Model in an Industrial micro-Grid (IMG) is the result of a meticulously planned and executed process, emphasizing safety, technical precision and effective collaboration. This project began with formal approval and evolved through a series of technical preparations that laid the groundwork for the transformation of the power distribution system. From adapting the Single Line Diagram (SLD) to configuring protection systems and conducting different testing, each step in this model was undertaken with meticulous attention to detail. Furthermore, collaboration with the primary power generation source & end users for the entire IMG played a key role in ensuring the perfect integration of GBS Model. In this article, we provide an overview of the technical preparations and steps taken to implement GBS model, shedding light on the complex but successful transition to a more reliable and resilient power distribution system for the whole IMG network [35]. Based on the discussion above so far, here are the steps to be taken to implement Generating Bus Splitting (GBS) model practically in an Industrial Micro-Grid network:

3.6.1 Preparing a Modified SLD

The SLD was modified to reflect the changes required for implementing GBS model to this Industrial Micro-Grid (IMG). Feedback was obtained from the different concern bodies of the IMG authority.

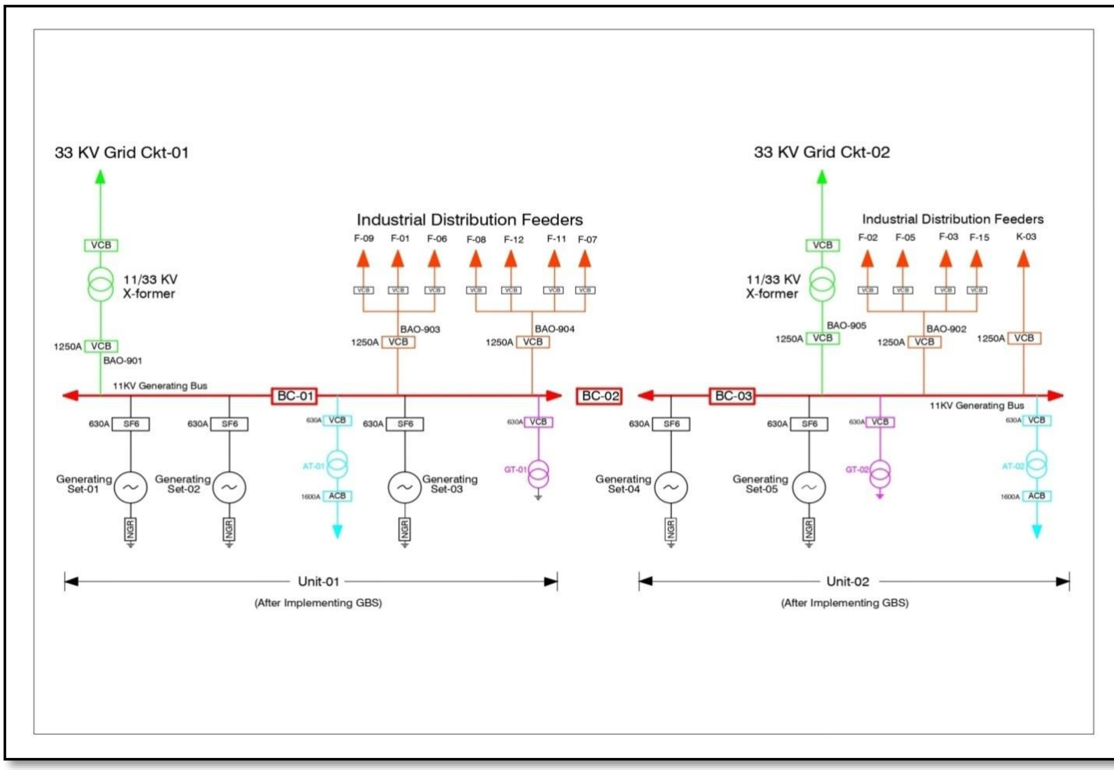

Fig. 3.10: Modified SLD for Implementing GBS in an IMG.

3.6.2 List of Spares

A list of spares with all specifications and technical details was prepared which is appended in the table below.

Table 3.5: List of Spare Parts with Specifications and Technical Details Required for GBS Implementation in Similar IMG

Sl. No.	Name of Spares	Technical Specifications	Quantity (Approximate)
1	VCB with panel	Rated voltage:12KV, Rated current:2000 A Rated impulse withstand voltage: 75KV Rated short circuit breaking current: 31.5 KA Standard: IEC 62271-100	1
2	VCB with panel	Rated voltage: 12KV, Rated current: 630 A Rated impulse withstand voltage: 75 KV Rated short circuit breaking current: 31.5 KA Standard: IEC 62271-100	2
4	Auxiliary transformer	Rated voltage: 11/ 0.415 KV, current: 39.36/1043 Amp, power: 750 KVA, frequency: 50 Hz Standard: BS 171/IEC-76 Type of cooling: ONAN Impedance voltage: % 5 Vector group: Dyn 11	2 nos.
5	Grounding transformer	Rated power: 200 KVA, frequency: 50 Hz Rated current: 10.49/ 278.24 Amp Standard: BS 171/IEC-76 Type of cooling: ONAN Vector group: Dyn 11	1 nos.
6	HT cable	1*185 sq. mm Copper cond. XLPE insulated, un-armoured cables	265 meter
7	LT cable	1*400 sq. mm Copper cond. PVC insulated, armoured cables	340 meter
8	Control cable	1*1.5 sq. mm, 1.1 kV Copper cond. XLPE insulated, armoured cables	160 meter
9	Control cable	2*2.5 sq. mm, 1.1 kV copper cond. XLPE insulated, armoured cables	195 meter
10	Overcurrent & Earth fault protection relay	ABB REF-615 Product version: 5.0 FP1	1 nos.
11	Overcurrent & Earth fault protection relay	ABB REF-610 Product version: A/31.03.2005	2 nos.
12.	Energy meter	Type: A1800, Model: A830RALN-X s200 5000 imp/ KWh, 5000 imp/ KVarh 3x58/100.....277/ 480 V 50 Hz, 5(6) A	2 nos.

3.6.3 Carrying out I/O Tests

An Input/ Output (I/O) chart for IMG's master feeder, generating units (GU-4 & GU-5), and corresponding separate Auxiliary Transformer (AT) & Grounding Transformer (GT) arrangements was created to ensure proper functioning of signals related to the after implementing GBS model to this Industrial Micro-Grid and represented the same in the table below:

Table 3.6: Input/output (I/O) Chart for IMG's Master Feeder and Generating Units (GU-4 & GU-5) with Separate AT & GT Arrangements

Sl. No.	I/O Signal List	Requirements
1	Local Opening	Command
2	Remote Opening	Command
3	Local Closing	Command
4	Remote Closing	Command
5	External Closing	Command
6	CB Closing Blocking Magnet	Interlock
7	CB Truck Blocking Magnet	Interlock
8	Earth Switch Closing Magnet	Interlock
9	CB Under voltage Release	Interlock
10	CB OFF	Status
11	CB ON	Status
12	CB CFC Protection TRIP	Status
13	E/S Open	Status
14	E/S Close	Status
15	CB in Test Position	Status
16	CB in Service Position	Status
17	Internal Relay Faulty	Status
18	MCB Opened	Status
19	Over current Protection Trip (50/51)	Status
20	Earth fault Protection Trip (50N/51N)	Status
21	Local Mode	Status
22	Remote Mode	Status
23	CB Spring Discharged	Status

3.6.4 Shutdown and Safety Procedures

The implementation of GBS model in an operational IMG required proper isolation/ shutdown of that that specific part of the Central Generation Bus (GBS) of its Generating

Station and all other power sources connected through industrial distribution feeders. Safety procedures were strictly followed, including:

- Normal shutdown of respective Generating Units of IMG's Central Generating Station (CGS).
- Isolation of related industrial feeders and regional grid breakers, followed by tagging and disengaging isolators along with proper Lock Out Tag Out (LOTO) system.
- Applying proper grounding protections for the entire working area.

3.6.5 Cable Laying and Testing

Power cables were removed from the existing 11 KV master feeder and associated Auxiliary & Grounding transformer feeders. New power cables were laid and subjected to continuity checks and insulation resistance tests. Cable terminations to the new panels of Master feeder, Grounding, and Auxiliary transformer feeders were completed.

3.6.6 Protection Configuration and Sustainability Testing

Protection settings for individual Master Feeders (MF) and Industrial Distribution Feeders (IDF) in different Numerical Relays (NR) were configured. This mainly included directional overcurrent (O/C) and earth fault (E/F) protection settings.

3.6.7 Types of Over-current and Earth Fault Protection

Timing curves in IMG switchgear protection are used to determine the operating times of protective devices in response to fault conditions. These curves help ensure that protective devices operate quickly and selectively to isolate and clear faults while minimizing unnecessary tripping of the whole Industrial Micro-Grid. Several types of timing curves are commonly used in switchgear protection [36][37]. Here are equations for some of these timing curves:

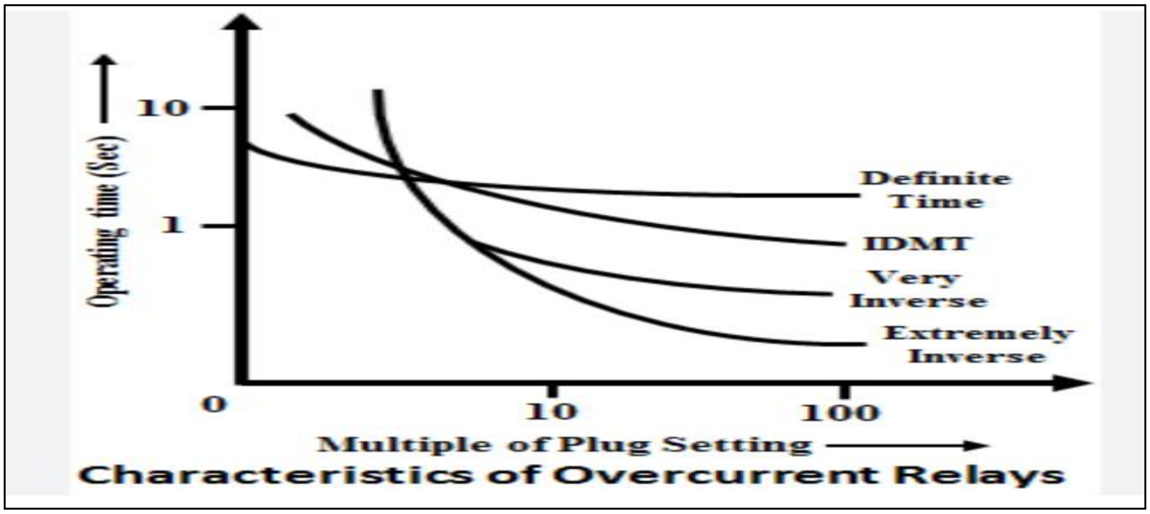

Fig. 3.11: Characteristics of Over-Current Relay for IDMT and DMT Settings [38]

Inverse-Time Over-current (IDMT) Curve:

Equation: $T = K / (I^n - 1)$ ----------------- (1)
Where:
T = Operating time of the protective device (in seconds)
K = Time multiplier constant
I = Current flowing through the protective device (in amperes)
n = Curve exponent (typically between 0.8 and 2.0)

Definite-Time Curve:

Equation: $T = K$ ----------------- (2)
Where:
T = Operating time of the protective device (in seconds)
K = Constant time delay (in seconds)
Instantaneous Curve:
Equation: $T = 0$ ----------------- (3)

In this case, the protective device operates instantaneously (zero time delay) when the current exceeds the pickup setting.

Inverse Definite Minimum Time (IDMT) Curve:
Equation: $T = (K_1 + K_2) / (I^n - 1)$ ----------------- (4)
Where:
T = Operating time of the protective device (in seconds)
K_1 = Minimum time delay constant
K_2 = Additional time delay constant
I = Current flowing through the protective device (in amperes)

n = Curve exponent

Very Inverse-Time Overcurrent Curve:

Equation: T = K / (I^(n+1) - 1) ----------------- (5)
Where:
T = Operating time of the protective device (in seconds)
K = Time multiplier constant
I = Current flowing through the protective device (in amperes)
n = Curve exponent (typically between 0.8 and 2.0)

Extremely Inverse-Time Overcurrent Curve:

Equation: T = K / (I^(n+2) - 1) ----------------- (6)

Where:

T = Operating time of the protective device (in seconds)

K = Time multiplier constant

I = Current flowing through the protective device (in amperes)

n = Curve exponent (typically between 0.8 and 2.0)

The specific values of K, K_1, K_2, and n in these equations depend on the protective device's characteristics and the protection scheme in use. Different types of protection devices, such as overcurrent relays, can have unique timing curve characteristics to suit the requirements of the power system being protected. The choice of timing curve is crucial in ensuring effective fault detection and system protection.

After being study the above protection schemes carefully, we found the following protection to be suitable for our model to be implemented which are grouped together & represented below.

The table below presents the directional overcurrent (O/C) & earth fault (E/F) protection settings of the GBS model feeder in similar IMG facilities:

Table 3.7**:** Protection Settings for GBS Industrial Distribution Feeder

Sl. No.	Protection Scheme	Standard	Magnitude	Time delay (ms)	CT Ratio	Protection types
01	Directional overcurrent 1st stage (i>)	ANSI 67	0.22In to 0.65In	N/A	600/5	IDMT (0.025)
02	Directional overcurrent 2nd stage (i>>)		1.5In	20 to 50	600/5	DMT
03	Earth fault 1st stage (ie>)	ANSI 50N/51N	0.1Ien	10	50/5	IDMT (0.025)
04	Earth fault 2nd stage (ie>>)		0.1Ien	0	50/5	DMT

The table below presents the over-current (O/C) & earth fault (E/F) protection settings of the GBS feeders in similar IMG facilities:

Table 3.8: Protection Settings for GBS Master Feeder

Sl. No.	Protection Scheme	Standard	Magnitude	Time delay	CT Ratio	Protection types
01	Directional overcurrent 1st stage (i>)	ANSI 67	0.77In	N/A	2000/5	IDMT (0.025)
02	Directional overcurrent 2nd stage (i>>)		1.5In	40 ms	2000/5	DMT
03	Earth fault 1st stage (ie>)	ANSI 50N/51N	0.25Ien	N/A	50/5	IDMT (0.025)
04	Earth fault 2nd stage (ie>>)		0.75Ien	300 ms	50/5	DMT

Workability of the above configured settings was tested using a relay test set, and results were recorded accordingly for future references.

3.6.8 Collaboration with IMG Stakeholders

Collaborative efforts were made with the Generating Units supplier team to incorporate necessary changes in PLC logic, SLD extension in SCADA, and Plant CCU panels to ensure the proper functioning of the modified system.

3.6.9 Post GBS Trial Run

Few trial runs of the modified system were conducted in both Island & grid mode operation. The CGS was run with split Units, along with associated generating units, and IMG feeders connected. Successful synchronization with the grid and export of power were tested. The system's ability to return to Island mode operation was also verified.

It was carefully considered every possible outcomes even for various operating conditions & associated matters thereto that might take place after implementing of Bus Splitting model. Based on that we put forward with some suggestions that are not in every day operational practices in the existing classical power plant operation that was also demonstrated here.

When CGS-2 runs parallel to the grid/ in island mode alongside two Generating Units, GU-4 and GU-5, operating at their full rated capacity of 8.73 MW each, and if the IMG feeder demands more power than the combined generation capacity, the system is designed to draw that excess power from the connected regional national grid 33KV ckt-2 [39]. In such scenarios, if the grid trips, an instantaneous overloading will trigger an IMG blackout. A preferential load-shedding scheme is designed to tackle this critical situation, which will selectively disconnect the corresponding load feeder from this section of the IMG to prevent a complete blackout [40][41].

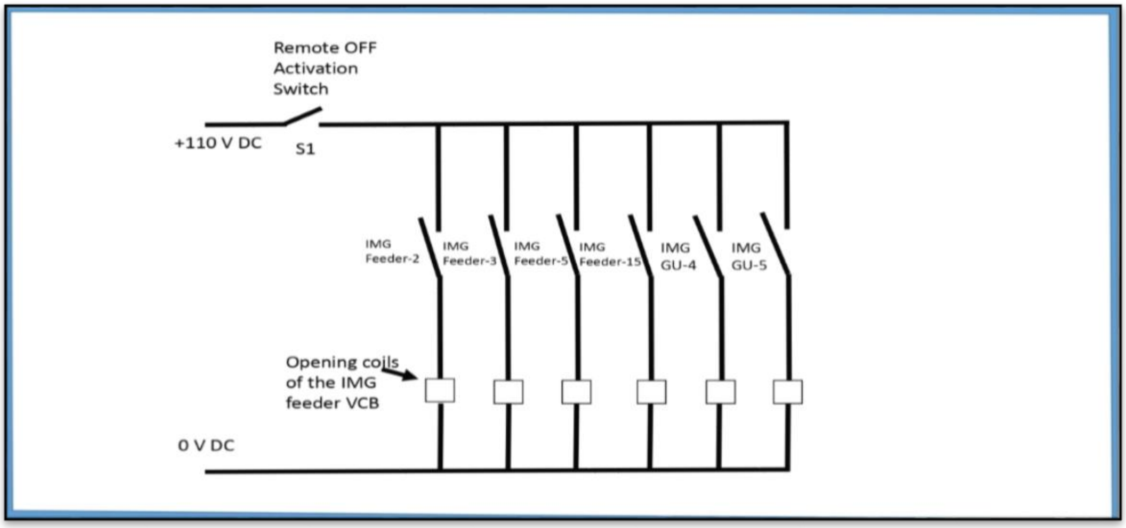

Fig. 3.12: IMG Feeder Remote Controlling Arrangement for Island Mode Operation

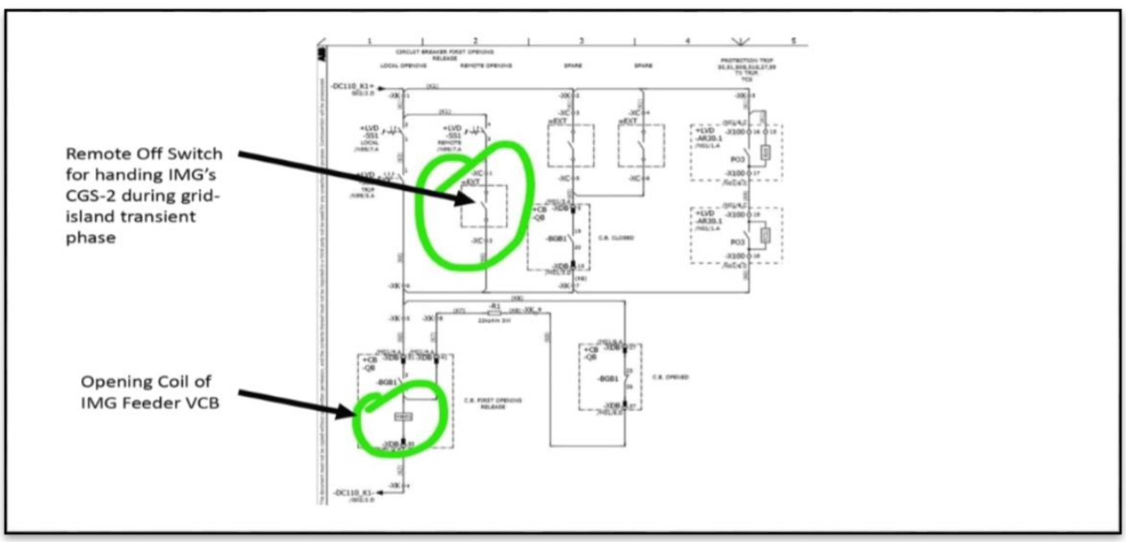

Fig. 3.13: IMG Feeder Remote Controlling Mechanism for Running in Island Mode [ABB, AIS, drawing no-E19038 and 42]

On the other hand, during IMG off-peak hours and weekly holidays, when GU-4 and GU-5 run parallel to the grid at their full rated capacity, and the IMG experiences low demand, a significant amount of load is being fed/ exported to the grid. If the grid trips, the sudden load reduction or fluctuation in the respective generating unit will tend to cause a generation trip due to a significant load swing if it island mode switching is not handled properly [43][44]. A preferential generation-shedding scheme is suggested and designed to address this critical situation, which will selectively disconnect the corresponding generating unit/s from this section of the IMG to prevent a complete blackout.

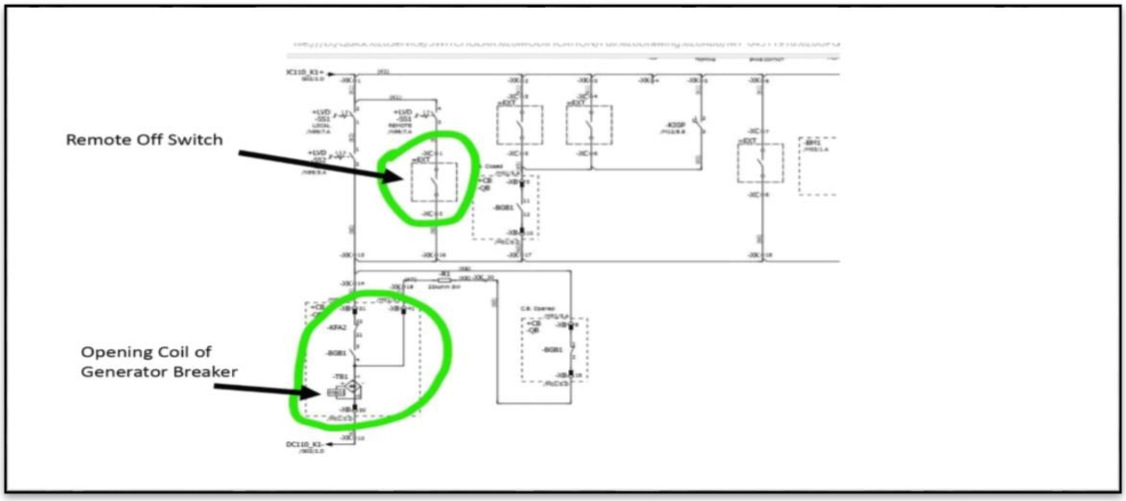

Fig. 3.14: Remote Controlling Mechanism of CGS Generating Units for Running in Island Mode [ABB, AIS, drawing no-E19038 and 45]

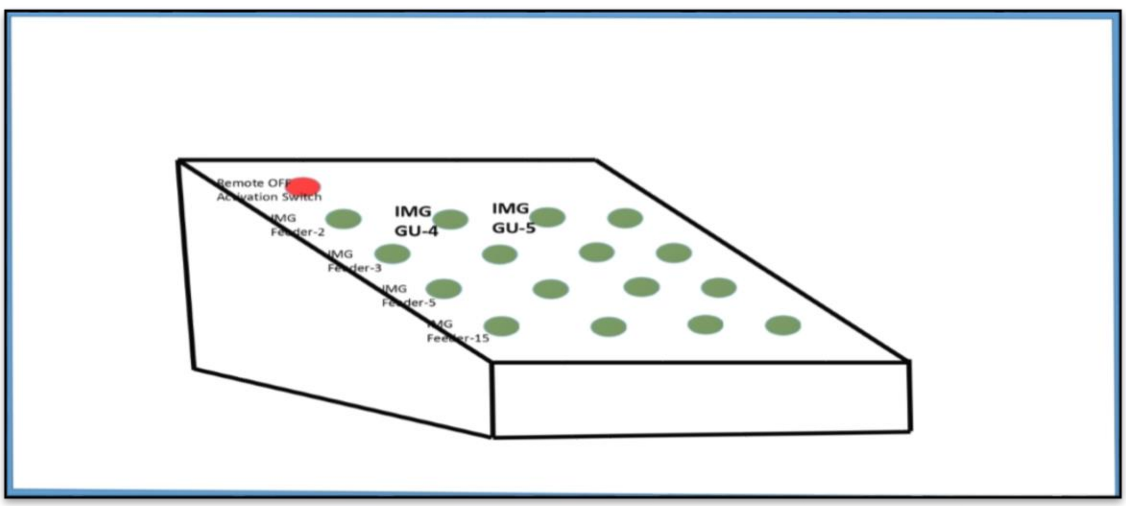

Fig. 3.15: IMG Feeder/GU Controller in Grid-Island Mode Switching Phase

These steps demonstrate a comprehensive process for implementing Generating Bus Splitting (GBS) model practically in an industrial micro-grid network for enhancing the reliability of the IMG along with safety and financial benefits of relevant stakeholders [46].

3.6.10 GBS Model Implementing Flowchart

Presented below is a comprehensive flowchart that illustrates the step-by-step process for implementing a Generating Bus Splitting (GBS) Model for enhancing micro-grid stability in industrial distribution feeder network:

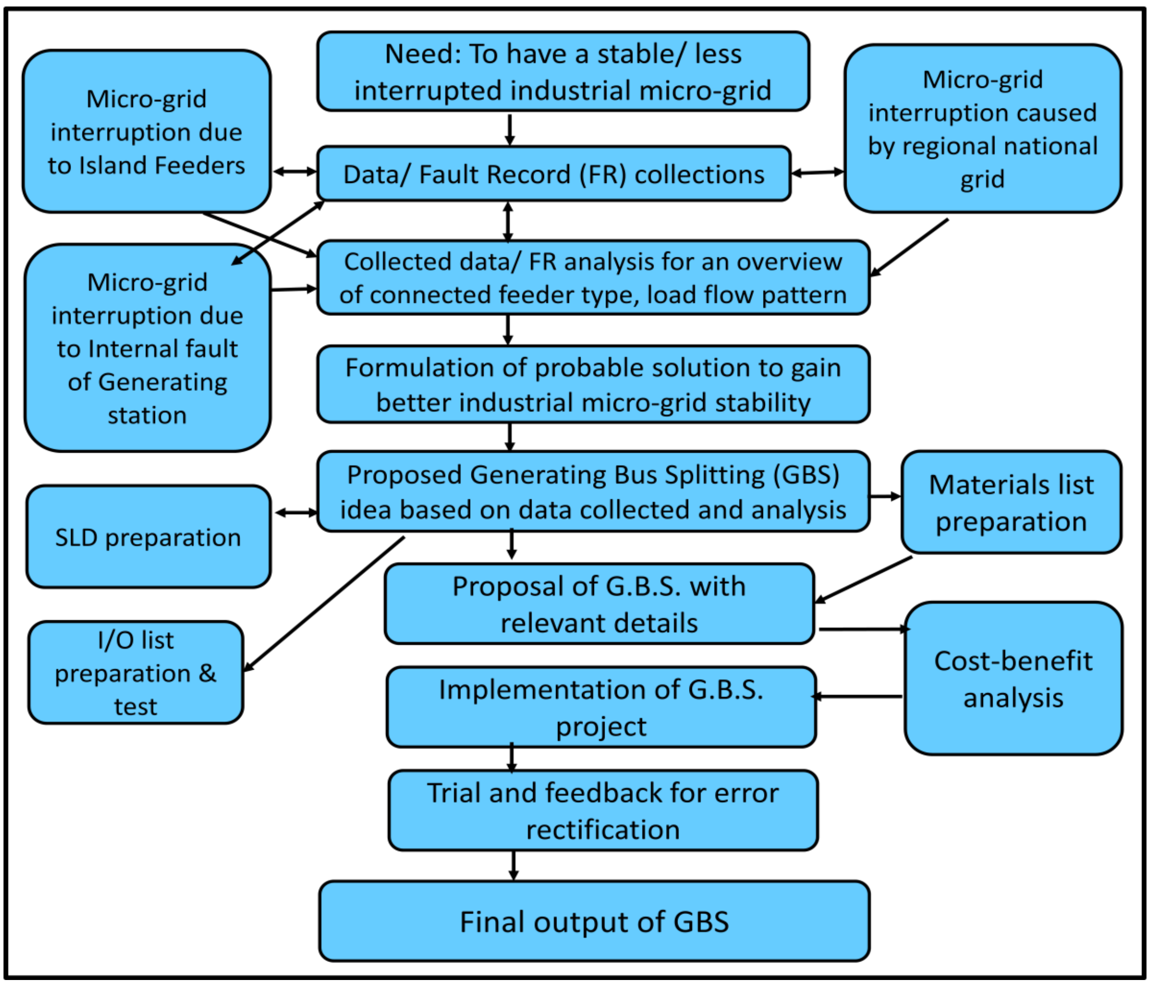

Fig. 3.16: Flowchart of GBS Model Implementation in Industrial Micro-Grid

3.7 Summary

Chapter 3 investigates into the detailed methodology adopted for the study. The chapter begins by explaining the data collection methods, focusing on primary data gathered from site visits, interviews with key personnel, and load profile data from the Industrial Micro-Grid (IMG). The site visits included visual inspections of the infrastructure, documenting the condition of various components, and recording parameters of different industrial distribution feeders. The subsequent section outlines the development of a comprehensive model using Electrical Transient and Analysis Program (ETAP) software, detailing the various components and simulation scenarios undertaken to assess the IMG's reliability and performance. The chapter is also emphasized the implementation of the Generating Bus Splitting (GBS) Model as a solution to enhance the IMG's stability and resilience. It provides a comprehensive understanding of the principles behind the GBS model and its operational mechanics. Technical preparations and safety procedures for the implementation of the GBS model even in an operational IMG are meticulously detailed, including the modification of the Single Line Diagram (SLD), configuration and testing of protection schemes, and collaboration with stakeholders. Overall, this chapter presents a thorough and structured approach to data collection, system modeling, and the practical implementation of the GBS model, showcasing a well-organized and comprehensive research methodology.

Chapter 4: Results and Findings

In this chapter, the results of the investigation into the stability and control of the Industrial Micro-Grid (IMG) serving the Chattogram Export Processing Zone (CEPZ) and Karnaphuli Export Processing Zone (KEPZ) are presented. In section 4.1, the improvement of stability and reliability of the Industrial Micro-Grid (IMG) are represented after the implementation of the Generating Bus Splitting (GBS) model. Subsequently, section 4.2 discusses the economic benefits associated with the implementation of GBS in any Industrial Micro-Grid. Various performance metrics of the GBS model are also addressed in Section 4.3, followed by a chapter summary in section 4.4.

4.1 Stability and Reliability of IMG

The implementation of the Generating Bus Splitting (GBS) Model within the Industrial Micro-Grid (IMG) system yielded significant improvements in stability and reliability, as evidenced by the following key findings:

4.1.1 Whole IMG Blackout Risk Reduction

The GBS Model solution successfully mitigated the frequency of tripping incidents within the IMG, thereby minimizing disruptions to industrial operations. The analysis revealed a notable decrease in the occurrence of system faults and subsequent power interruptions, leading to increased overall system reliability. Specifically, in the event of a grid collapse or any other severe fault, the entire IMG previously faced a blackout, and all connected feeders also experienced power interruptions, as all three master feeders were on the same 11KV bus. However, going forward, the CGS will be operated as two individual units, which allows for the independent operation of two units with two 33kv grid circuits. Consequently, the risk of simultaneous tripping of the two separate units has been significantly reduced.

4.1.2 Grid Shifting Loss Reduction

Before implementing GBS model, grid shifting of two Generating Units (GU) was required every morning (except on holidays) around 0800 hrs to meet IMG's peak hour's demand. However, after implementing the GBS model, it is no longer necessary to repeat this practice since one IMG master feeder has been relocated to the extended bus section under GU-4 & GU-5. As a result, the day's production losses due to unloading and loading of around 16 MW grid dispatch for nearly half an hour duration will be overcome.

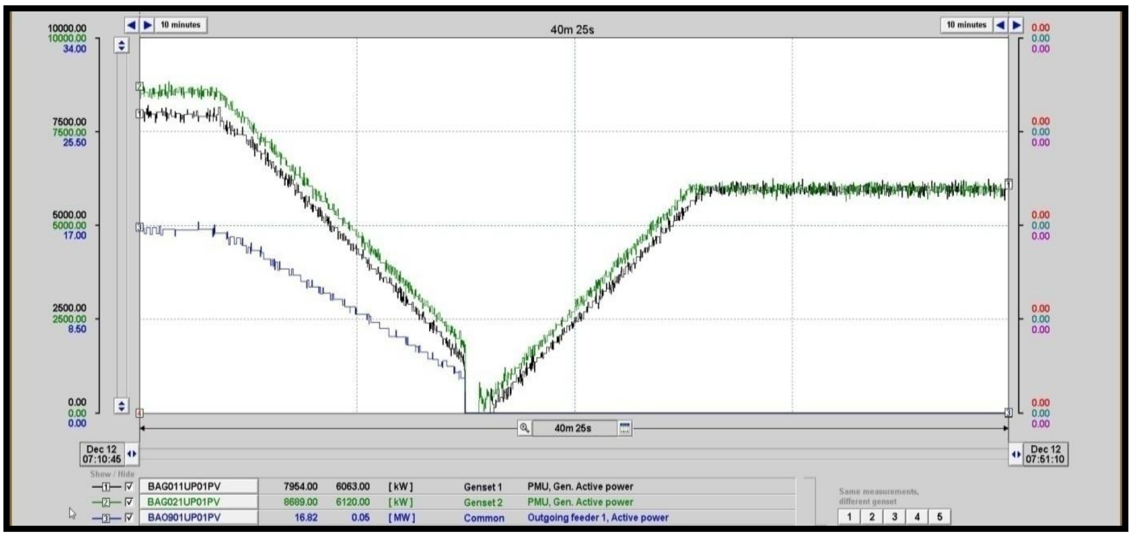

Fig. 4.1: Generation Loss during Grid Shift in Pre GBS

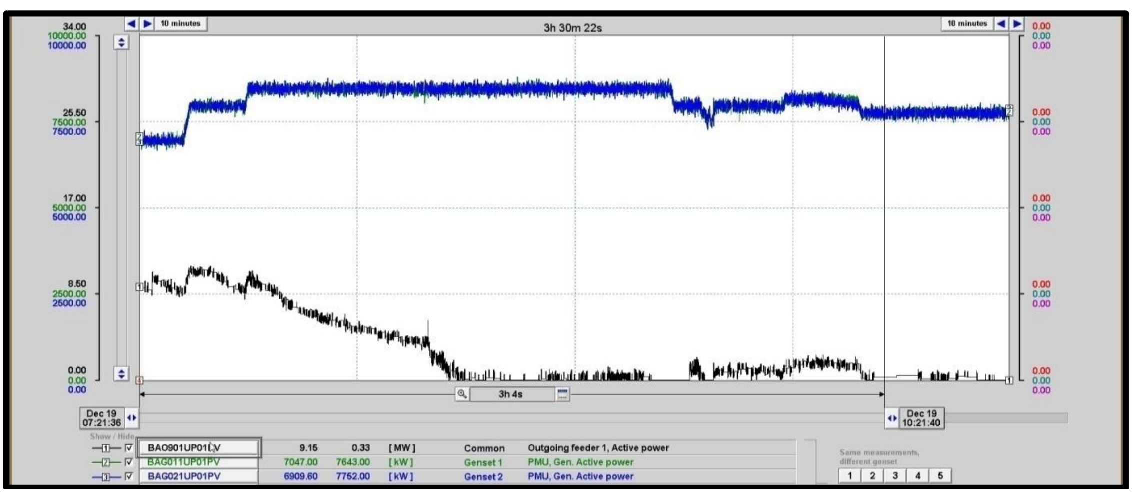

Fig. 4.2: Minimizing Generation Loss by Implementing GBS Model

4.1.3 Additional Grid Dispatch in Day Time

Every day, it is possible to achieve extra grid load dispatch because both 33 kV regional ckt-1 and 33 kV regional ckt-2 can be kept in operation even during the daytime due to this new arrangement.

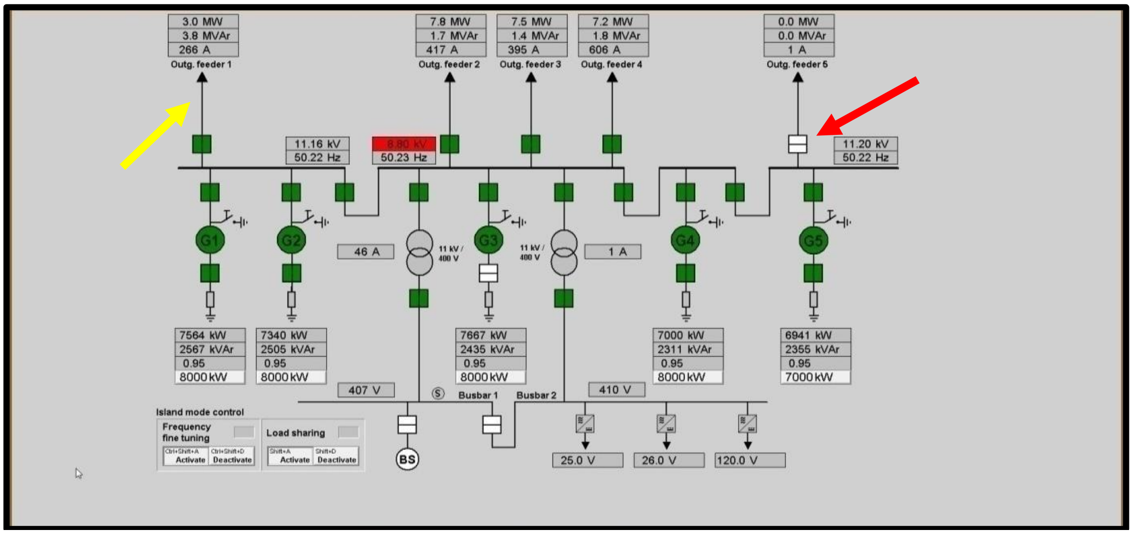

Fig. 4.3: Constraint of Grid Dispatch before GBS Implementation

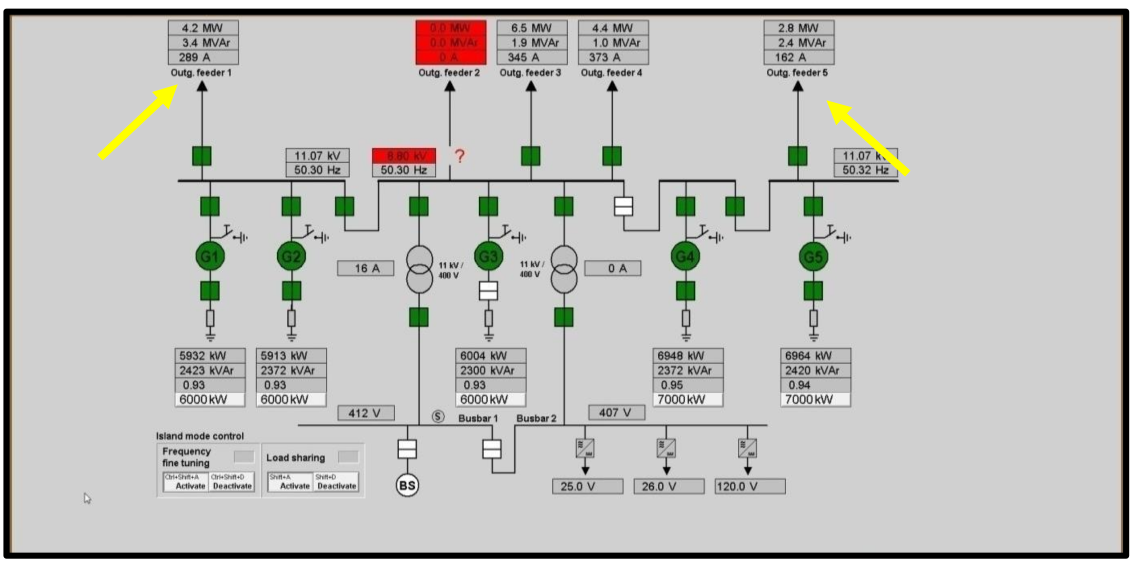

Fig. 4.4: Enhanced Additional Grid Dispatch after GBS

4.1.4 Emergency Handling by Maximum Grid Back-Feed

In emergencies, such as when the entire CGS of IMG goes out of operation due to a severe fault/ during any other scheduled maintenance period, the previous arrangement allowed for a maximum back feed of only around 17 MW to handle the crisis. This back feed was feasible from either 33 kV regional ckt-1 or 33 kV regional ckt-2, as all three IMG master feeders were in the same bus section. However, with the GBS model arrangement, a total of approximately double the previous capacity, namely a maximum of around 34 MW back feed, could be made available to handle any crisis. This enhancement was possible because one of the IMG master feeders (BAO-902) has already been shifted to the extended new bus. Consequently, the maximum number of IMG feeders could be brought back into operation immediately after any internal severe fault/ during maintenance period.

4.2 Economic Benefits of GBS Implementation

The implementation of GBS not only improved the stability and reliability of the IMG but also led to substantial economic benefits. The reduction in power interruptions and downtime resulted in significant cost savings for the industries within the zones, contributing to increased productivity, reduced equipment damage, and minimized financial losses associated with production disruptions.

These findings underscore the effectiveness of the GBS Model in addressing the stability and reliability challenges of the IMG system, ultimately fostering a more resilient and sustainable power supply infrastructure for the export-oriented industries in the CEPZ and KEPZ zones. The economic implications of GBS model implementation were a critical aspect of this research. Economic benefits stemming from GBS were assessed, and the results are as follows:

4.2.1 Reduction in Downtime

The decreased frequency of IMG tripping incidents resulted in a significant reduction in production downtime. Industries within the CEPZ and KEPZ reported fewer instances of halted operations due to power interruptions.

4.2.2 Lower Equipment Damage

With a more stable power supply to any IMG, ensures less equipment damage of the connected industries. Frequent power interruption hampers the harmony of production line in the industries and may cause damage the products under process at the time of IMG interruption. Hence, IMG stability on the other hand, reduction of power interruption will lead to reduced maintenance and replacement costs for industries.

4.2.3 Enhanced Productivity

GBS allowed for more predictable and consistent production processes, enhancing overall productivity within the zones.

The results presented in this chapter demonstrate the effectiveness of Generating Bus Splitting (GBS) Model in addressing the challenges of frequent tripping incidents within the Industrial Micro-Grid (IMG) and its significant positive impact on stability, system performance, and economic viability. The subsequent chapter will provide a comprehensive conclusion, summarizing the key findings and their implications for the CEPZ and KEPZ industrial sectors.

4.3 Performance Metrics of GBS Model

Present a set of performance metrics used to quantitatively evaluate the system's performance. These metrics may include but are not limited to:

Frequency Deviation: Analyze how frequency deviations from the nominal value are affected by the proposed modification. Assess whether the system can maintain a stable frequency during load variations and found within nominal system frequency range which represented in the trend curve below:

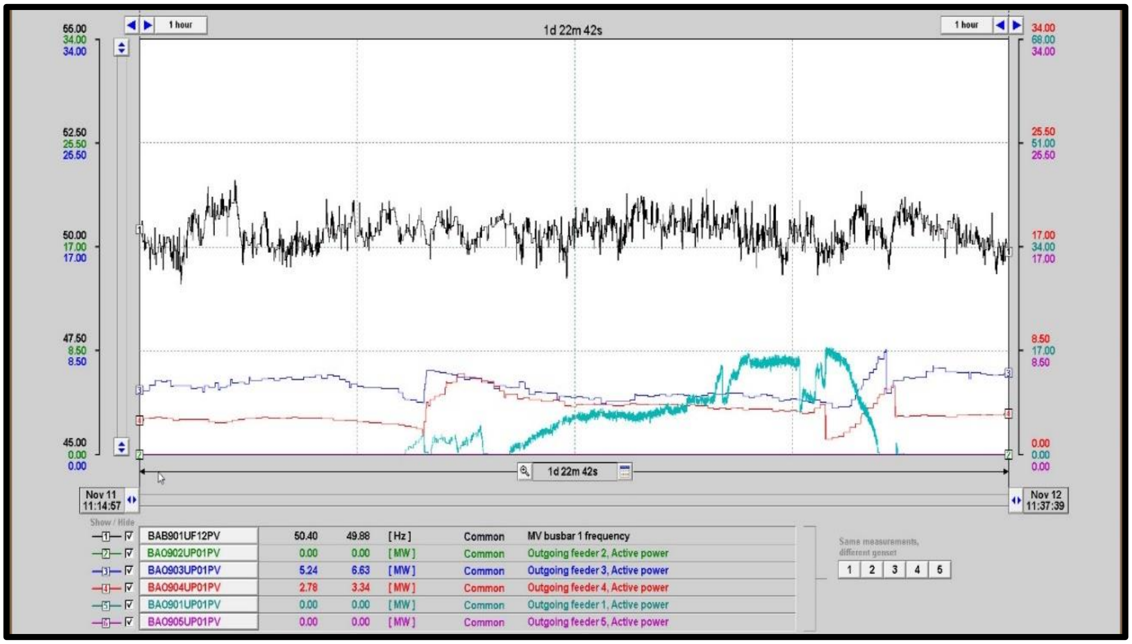

Fig. 4.5: System Frequency during IMG Load Variations

Voltage Profile: Evaluate changes in voltage profiles across the distribution feeders before and after the modification. Examine how voltage levels at various points within the system are affected and found within nominal system voltage range which represented in the trend curve below:

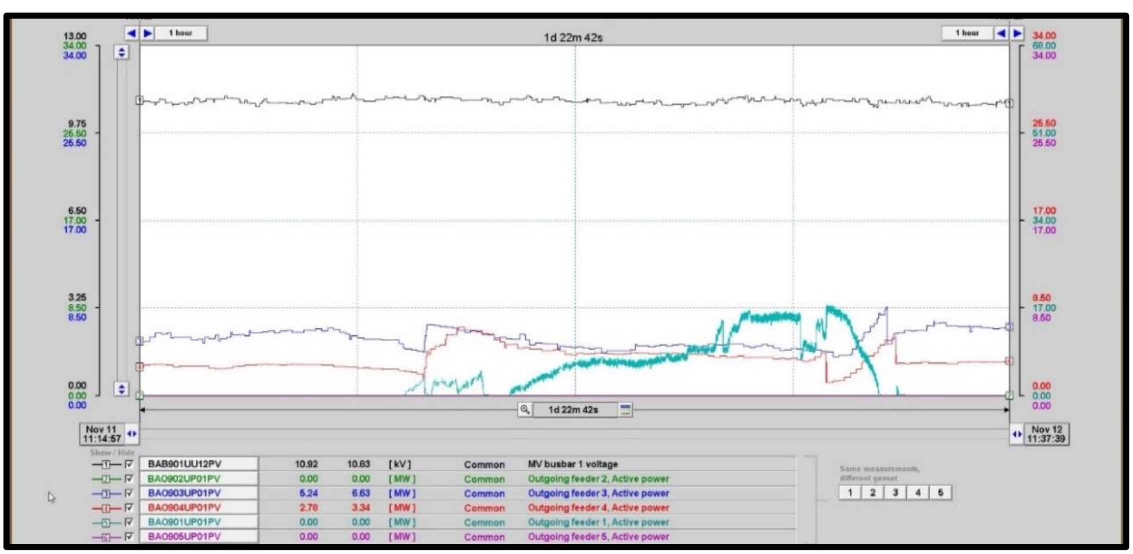

Fig. 4.6: System Voltage during IMG Load Variations

4.3.1 System Average Interruption Duration Index (SAIDI)

In this study, real-time "System Average Interruption Duration Index (SAIDI)" & "System Average Interruption Frequency Index (SAIFI)" values for an Industrial Micro-Grid (IMG) were analyzed over a quarter period of time, January-2022 to March-2022, both before and after the implementation of a Generating Bus Splitting (GBS). SAIDI represents the average duration of interruptions experienced by customers in a specified period for an IMG, here it is typically measured in minutes per customer for the duration of three months, and then multiplied by four to obtain SAIDI for one year according to IEEE Standard 1366-1998.

Table 4.1: SAIDI before Implementation of GBS in Industrial Micro-Grid

Sl. No.	Date	IMG Blackout Duration		Total IMG Interruption (min)	SAIDI (before GBS)
		From	To		
01	04.01.2022	7:10	7:35	25	For a quarter, SAIDI = 379/235 = 1.61 So, for a year it will be =1.61x4 = 6.44
02	07.01.2022	17:54	18:18	24	
03	12.01.2022	06:16	06:42	26	
04	12.01.2022	05:58	06:22	24	
05	21.01.2022	21:43	21:58	15	
06	24.01.2022	21:35	21:55	20	
07	25.01.2022	21:28	21:55	27	
08	25.01.2022	03:25	03:45	20	
09	30.01.2022	18:06	18:25	19	
10	05.02.2022	11:25	11:45	20	
11	13.02.2022	16:48	17:13	25	
12	25.02.2022	20:20	20:48	28	
13	21.03.2022	04:05	04:30	25	
14	23.03.2022	07:36	07:58	22	
15	25.03.2022	06:16	06:40	24	
16	26.03.2022	10:44	10:59	15	
17	28.03.2022	07:04	07:24	20	
Quarterly total IMG interruption duration:				379	

To calculate SAIDI for this industrial micro-grid before implementing GBS model, we can consider the following formula: SAIDI = (Total Duration of Interruptions) / (Total Number of Customers). For example, this IMG is serving around 235 customers &

experienced a total of 379 minutes of interruptions over a quarter period of time mentioned above.

SAIDI = (379 minutes)/ (235 customers) = 1.61 minutes per customer per quarter. This means, on average, each customer in this Industrial Micro-Grid experienced 1.61 minutes of power interruptions in a quarter.

So, according to IEEE Standard 1366-1998, SAIDI before implementing GBS model = 1.61x4 = 6.44

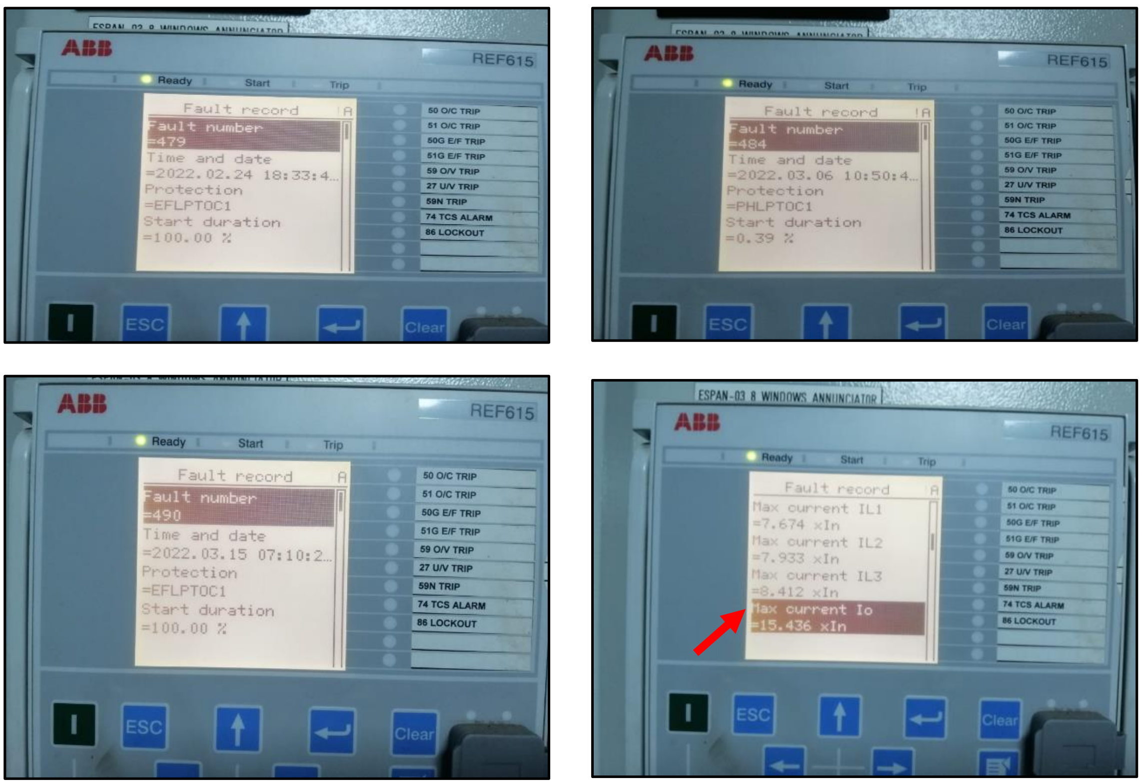

Fig. 4.7: IMG Interruption Fault Records and Pattern (Pre GBS)

The results, as presented in the table below, clearly demonstrate a noteworthy reduction in SAIDI after the GBS implementation. These findings strongly support the conclusion that the implementation of the GBS has significantly and rapidly improved the reliability and stability of similar Industrial Micro-Grid.

Table 4.2: SAIDI after Implementation of GBS in Industrial Micro-Grid

Sl. No.	Date	IMG Blackout Duration		Total IMG Interruption Duration (min)	SAIDI (after GBS)
		From	To		
01	03.01.2023	18:47	19:03	16	For a quarter SAIDI = 188/235 = 0.8
02	05.01.2023	05:03	05:18	15	
03	09.01.2023	14:21	14:38	17	
04	10.02.2023	01:47	02:04	17	
05	14.02.2023	06:51	07:06	15	
06	19.02.2023	10:31	10:47	16	
07	20.02.2023	05:04	05:19	15	
08	25.02.2023	08:26	08:40	14	So, for a year it will be = 0.8x4 = 3.2
09	06.03.2023	09:42	09:58	16	
10	11.03.2023	07:50	08:05	15	
11	17.03.2023	12:07	12:23	16	
12	19.03.2023	07:34	07:50	16	
Quarterly total IMG interruption duration:				**188**	

To calculate SAIDI for this industrial micro-grid after implementing GBS model, we can consider the following formula:

SAIDI = (Total Duration of Interruptions) / (Total Number of Customers)

Suppose This IMG is serving around 235 customers & they experienced a total of 188 minutes of interruptions over a quarter period of time mentioned above.

SAIDI = (188 minutes)/ (235 customers) = 0.8 minutes per customer per quarter. This means, on average, each customer in this Industrial Micro-Grid experienced 0.8 minutes of power interruptions in a quarter.

So, according to IEEE Standard 1366-1998, SAIDI after implementing GBS model will be = 0.8x4 = 3.2

After implementing GBS, the frequency of entire IMG interruptions and the magnitude of fault currents improved significantly, as represented in the pictures below:

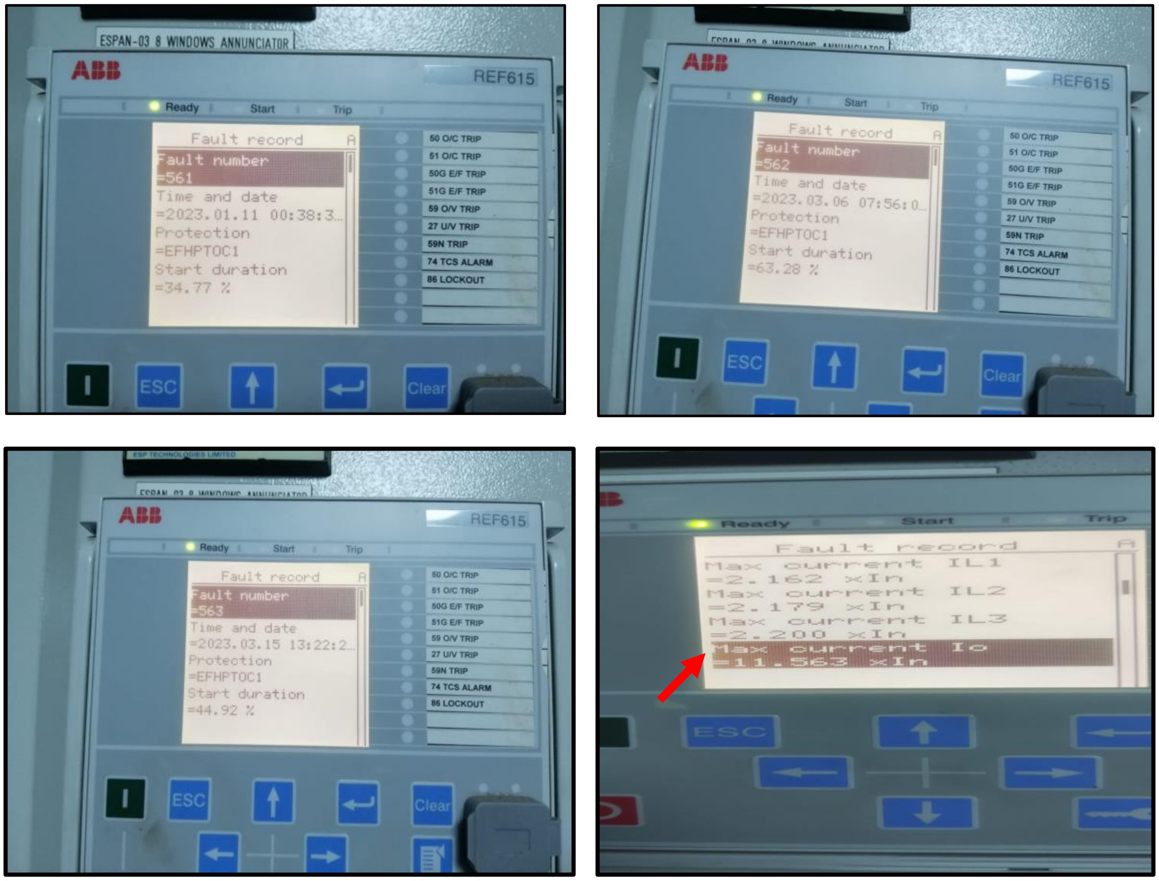

Fig. 4.8: IMG Interruption Fault Records & Pattern (Post GBS)

4.3.2 System Average Interruption Frequency Index (SAIFI)

In this study, real-time System Average Interruption Frequency Index (SAIFI) values for an Industrial Micro-Grid (IMG) were analyzed over a quarter period of time, January-2023 to March-2023, both before and after the implementation of a Generating Bus Splitting (GBS) for the duration of three months, and then multiplied by four to obtain SAIFI for one year according to IEEE Standard 1366-1998. The results, as presented in the tables below, clearly demonstrate a noteworthy reduction in SAIFI after the GBS implementation. These findings strongly support the conclusion that the implementation of the GBS has significantly and rapidly improved the reliability and stability of similar Industrial Micro-Grid.

Table 4.3: SAIFI before Implementation of GBS in Industrial Micro-Grid

Sl. No.	Date	IMG Blackout Duration		IMG Blackout Counting	SAIFI (before GBS)
		From	To		
01	07.01.2022	17:39	17:54	1	For a quarter SAIFI = 17/235 = 0.07
02	07.01.2022	17:54	18:08	1	
03	12.01.2022	06:16	06:32	1	
04	12.01.2022	05:58	06:12	1	
05	21.01.2022	21:43	21:58	1	
06	24.01.2022	21:35	21:51	1	
07	25.01.2022	21:28	21:45	1	So, for a year it will be = 0.07x4 = 0.28
08	25.01.2022	03:25	03:41	1	
09	30.01.2022	18:06	18:20	1	
10	05.02.2022	11:25	11:42	1	
11	13.02.2022	16:48	17:03	1	
12	25.02.2022	20:20	20:42	1	
13	21.03.2022	04:05	04:22	1	
14	23.03.2022	07:36	07:54	1	
15	25.03.2022	06:16	06:32	1	
16	26.03.2022	10:44	10:58	1	
17	28.03.2022	07:04	07:20	1	
Quarterly total IMG interruption counting:				**17**	

SAIFI = (Total Number of Interruptions) / (Total Number of Customers)

In the same industrial micro-grid, there were a total of 17 power interruptions over a quarter period of time.

SAIFI = (17 interruptions) / (235 customers) = 0.07 interruptions per customer per quarter. This means, on average, each customer in this IMG experienced 0.07 interruptions in a quarter duration.

So, according to IEEE Standard 1366-1998, SAIFI before implementing GBS model will be = 0.07x4 = 0.28

The results, as presented in the table below, clearly demonstrate a noteworthy reduction in SAIFI after the GBS implementation. These findings strongly support the conclusion that the implementation of the GBS has significantly and rapidly improved the reliability and stability of similar Industrial Micro-Grid.

Table 4.4: SAIFI after Implementation of GBS in Industrial Micro-Grid

Sl. No.	Date	IMG Blackout Duration		IMG Blackout Counting	SAIFI (after GBS)
		From	To		
01	03.01.2023	18:47	19:03	1	For a quarter, SAIFI = 12/235 = 0.05
02	05.01.2023	05:03	05:18	1	
03	09.01.2023	14:21	14:38	1	
04	10.02.2023	01:47	02:04	1	
05	14.02.2023	06:51	07:06	1	
06	19.02.2023	10:31	10:47	1	
07	20.02.2023	05:04	05:19	1	So, for a year it will be = 0.05x4 = 0.20
08	25.02.2023	08:26	08:40	1	
09	06.03.2023	09:42	09:58	1	
10	11.03.2023	07:50	08:05	1	
11	17.03.2023	12:07	12:23	1	
12	19.03.2023	07:34	07:50	1	
Quarterly total IMG interruption counting:				**12**	

SAIFI = (Total Number of Interruptions) / (Total Number of Customers)

In the same industrial micro-grid, there were a total of 12 power interruptions over a quarter period of time. SAIFI = (12 interruptions) / (235 customers) = 0.05 interruptions per customer per quarter

This means, on average, each customer in this IMG experienced 0.05 interruptions in a quarter.

So, according to IEEE Standard 1366-1998, SAIFI after implementing GBS model will be = 0.05x4 = 0.20

4.3.3 Customer Average Interruption Duration Index (CAIDI)

Customer Average Interruption Duration Index (CAIDI) is a reliability indicator in the field of electrical power distribution. It is used to estimate the average time it takes for the IMG to restore power after an outage. It is computed by dividing the System Average Interruption Duration Index (SAIDI) by the System Average Interruption Frequency Index (SAIFI).

CAIDI before implementing GBS model for this IMG is

= SAIDI (Pre-GBS)/SAIFI (Pre-GBS)

=6.44/0.28

= 23

This means that, on average, it takes around 23 minutes to restore IMG power per customer after an outage before implementing GBS model.

CAIDI after implementing GBS model for this IMG is

= SAIDI (post-GBS)/SAIFI (post-GBS)

=3.2/0.20

= 16

This means that, on average, it takes 16 minutes to restore IMG power per customer after an outage after implementing GBS model.

CAIDI gives an idea of how efficiently the IMG is restoring power to its customers after an outage, providing a measure of the system's reliability. A lower CAIDI value generally indicates a more efficient and reliable power restoration system for any IMG.

4.3.4 Comparison with Reliability Triangle

A comparative representation of all three reliability indexes (SAIDI, SAIFI, and CAIDI) of IMG in both pre- and post-GBS implementation is appended in the table below:

Table 4.5: Comparison of SAIDI, SAIFI & CAIDI in Pre & Post GBS Model

Sl. No.	IMG Reliability Index	Pre-GBS Model	Post-GBS Model
1	System Average Interruption Duration Index (SAIDI)	**6.44**	**3.2**
2	System Average Interruption Frequency Index (SAIFI)	**0.28**	**0.20**
3	Customer Average Interruption Duration Index CAIDI)	**23**	**16**

The reliability triangle in the context of electrical power distribution systems is based on three key metrics: SAIDI, SAIFI, and CAIDI. These metrics are used to measure the reliability and performance of a power distribution system for any industrial micro-grid. These three metrics, SAIDI, SAIFI, and CAIDI, collectively form the reliability triangle in the context of power distribution systems. They are crucial for power utilities and regulatory authorities to monitor and improve the reliability and performance of electrical distribution systems, ensuring that customers receive a consistent and reliable power supply. Improvements in these metrics can lead to enhanced customer satisfaction and overall system reliability. In the initial state, the industrial micro-grid we exhibited here relatively lower stability, evidenced by the SAIDI of 6.44, SAIFI of 0.28, and CAIDI of 23.

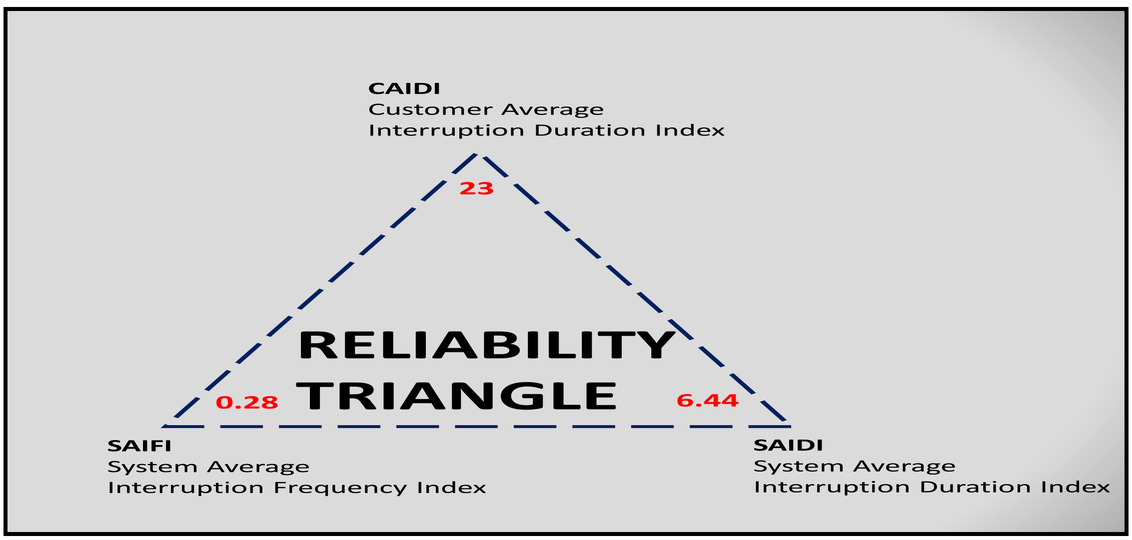

Fig. 4.9: Reliability Triangle before Implementing GBS to the IMG

However, after the successful implementation of the Generating Bus Splitting (GBS) model, significant improvements were observed, with the SAIDI reduced to 3.2, SAIFI to 0.20, and CAIDI to 20. The introduction of the GBS model has evidently enhanced the micro-grid's stability and performance, leading to a notable reduction in power outages and interruptions. The decreased SAIDI value indicates a substantial improvement in the average outage duration, while the lower SAIFI value reflects fewer interruptions experienced by each customer. Furthermore, the improved CAIDI value demonstrates the micro-grid's enhanced efficiency in restoring power after outages. This successful integration of the GBS model has substantially bolstered the micro-grid's overall reliability, ensuring a more consistent and dependable power supply and ultimately resulting in heightened customer satisfaction and operational effectiveness.

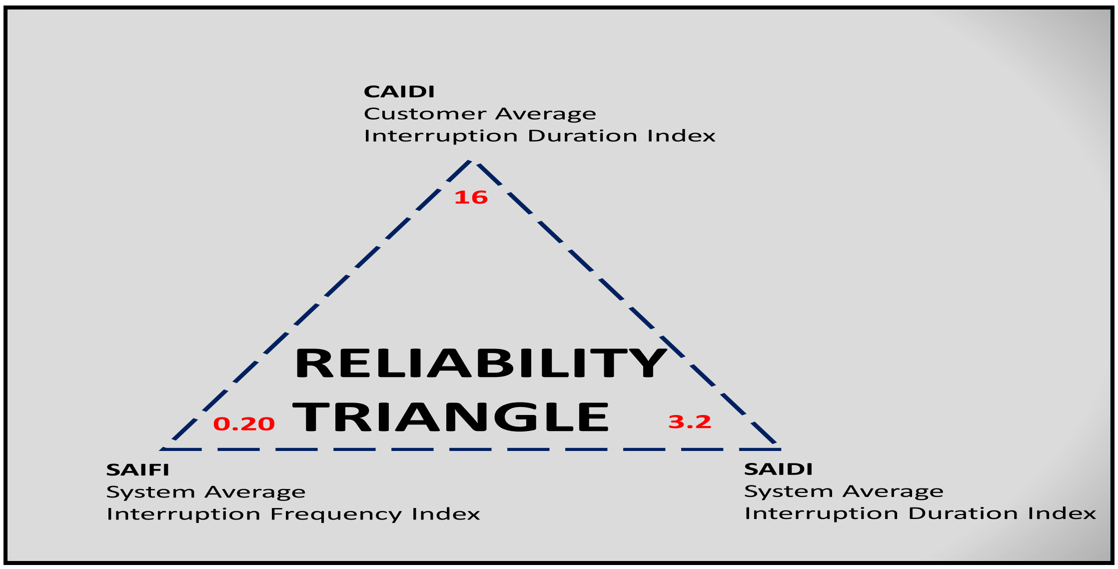

Fig. 4.10: Reliability triangle after implementing GBS to the IMG

4.4 Summarizing the Results and Findings

These reliability indices provide quantitative measures of the power distribution system's performance in terms of interruptions. Lower values of SAIDI & SAIFI indicate higher reliability, which is essential for any Industrial Micro-Grids to ensure uninterrupted power supply to critical industries. These indicators are valuable tools for utilities and system operators to assess and improve the reliability of any IMG distribution networks.

This chapter's findings underline the transformative impact of the Generating Bus Splitting (GBS) Model on the Industrial Micro-Grid (IMG), demonstrating its effectiveness in enhancing stability, reliability, and economic viability for any IMG facility. Notably, the various performance metrics, including the reduction in System

Average Interruption Duration Index (SAIDI) and System Average Interruption Frequency Index (SAIFI), provide quantitative evidence of the system's improved performance of post-GBS implementation. The subsequent chapter will offer a comprehensive conclusion, summarizing the overarching implications of the research and discussing potential avenues for further enhancements in the IMG's power distribution network.

Chapter 5: Conclusion

In this chapter, section 5.1 provides a summary, while key insights are presented in Section 5.2. The section 5.3 offers recommendations, followed by a discussion of the study's limitations in Section 5.4. Section 5.5 suggests directions for future research, and lastly, section 5.6 discusses the overall impact of the research.

5.1 Summary

In this concluding chapter, we summarize the key findings and the implications of this research. Our investigation into enhancing Industrial Micro-Grid (IMG) stability in industrial distribution network by implementing “Generating Bus Splitting (GBS)” model has yielded significant insights in real life practice. We began by recognizing the essentiality of uninterrupted and high-quality power supply for the numerous export-oriented industries in Chattogram Export Processing Zone (CEPZ) and Karnaphuli Export Processing Zone (KEPZ). The existing Industrial Micro-Grid (IMG), even when equipped with the Generating Station of world's most advanced Generating Units (GU) and control systems from Wartsila Finland and Rolls-Royce Norway, has been facing frequent tripping incidents. These incidents primarily arise from various technical faults originating from IMG's industrial corners, leading to instability in the IMG and subsequent economic losses. The primary objective of this study was to mitigate these issues and enhance the reliability of the Industrial Micro-Grid (IMG) through implementing a realistic solution.

Our methodology involved data collection, fault analysis, and the design and implementation of Generating Bus Splitting (GBS). We evaluated the impact of GBS on fault current, power interruption probability, and overall IMG stability. The results indicate a substantial reduction in fault current, a decrease in power interruption probability, and improved grid stability following GBS model implementation.

5.2 Key Insights

Key Insights from the proposed "Generating Bus Splitting (GBS)" model for this Industrial Micro-Grid (IMG) are appended below:

1. The micro-grid faced frequent tripping incidents due to technical faults mainly from industrial corners, leading to instability and economic losses.
2. The thesis focuses on the stability and control of an Industrial Micro-Grid (IMG) serving Chattogram Export Processing Zone (CEPZ) and Karnaphuli Export Processing Zone (KEPZ) in Bangladesh as well as in the other corner of the country having similar arrangements.
3. The IMG consists of 5 natural gas-fired IC Engine based Generating Sets (GS) with 8.73 MW each and 3 others of 9.34 MW individual capacity, along with a 11 KV industrial distribution network and 33 KV regional national grid connectivity.
4. The uninterrupted power supply is crucial for the operation of around 165 export-oriented industries in CEPZ and 70 industries in KEPZ, with a maximum combined demand of 100 MW.
5. The principle goal of proposed solution "Generating Bus Splitting (GBS)" is to reduce interruption within a tolerable limit for enhancing IMG & regional national grid stability.

5.3 Recommendations

Based on our findings and the success of GBS in achieving its objectives, we offer the following recommendations:

- **Adoption of GBS**: We recommend the adoption of Generating Bus Splitting (GBS) in similar industrial micro-grids facing frequent tripping incidents. GBS has proven to be an effective solution in reducing fault currents and enhancing IMG & regional national grid stability as well.
- **Regulatory Considerations**: Policymakers and regulatory bodies should consider incentivizing and facilitating the implementation of GBS in industrial micro-grids.

This would contribute to the reliability of power supply to industries, fostering economic growth and attract more foreign investment.

- **Maintenance and Monitoring**: Ongoing monitoring and maintenance of the GBS system are crucial to ensure its continued effectiveness. Industries and power plant operators should prioritize regular inspections and necessary upkeeps.

5.4 Limitations of the Study

It's important to acknowledge the limitations of this study. The research may not account for all possible variables and conditions that could possibly affect the Industrial Micro-Grid system's stability and control. Additionally, the proposed GBS model may not universally apply to all micro-grid configurations. For example, it would not be applicable to Industrial Micro-Grids that do not have their own power-generating facility; i.e., IMGs are solely operated by grid power supply.

5.5 Recommendation for Future Study

Since this study has provided valuable insights, further research is encouraged to explore the applicability of GBS in diverse micro-grid scenarios and its potentials for integration with renewable energy sources could also be thought of. The other Economic Zones operating in the country that are of same types of power instability could think to capitalize the concept of GBS model under this study and customize it further according to their system may also be the beneficiaries as well. Similarly, up-coming installations could think of this model from the very beginning by adapting with their design for having desired outcomes since inception.

5.6 Overall Impact

This research has broader implications beyond the specific industrial zones studied. The successful implementation of GBS offers an outline for improving industrial micro-grid stability in various contexts. It demonstrates how innovative solutions can address critical challenges in the power sector, ultimately benefiting industrial productivity and regional economic development.

In conclusion, the implementation of Generating Bus Splitting (GBS) has been a transformative step towards enhancing IMG stability and reducing its tripping incidents. This study stands as a testament to the effectiveness of engineering solutions in addressing complex power grid challenges. By providing a reliable and uninterrupted power supply to industries in any IMG, proposed GBS model contributes to their growth, productivity, and long-term sustainability. It is our hope that the insights gained from this research will inspire similar initiatives and innovations in the field of power distribution and Industrial Micro-Grid (IMG) stability.

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Appendices

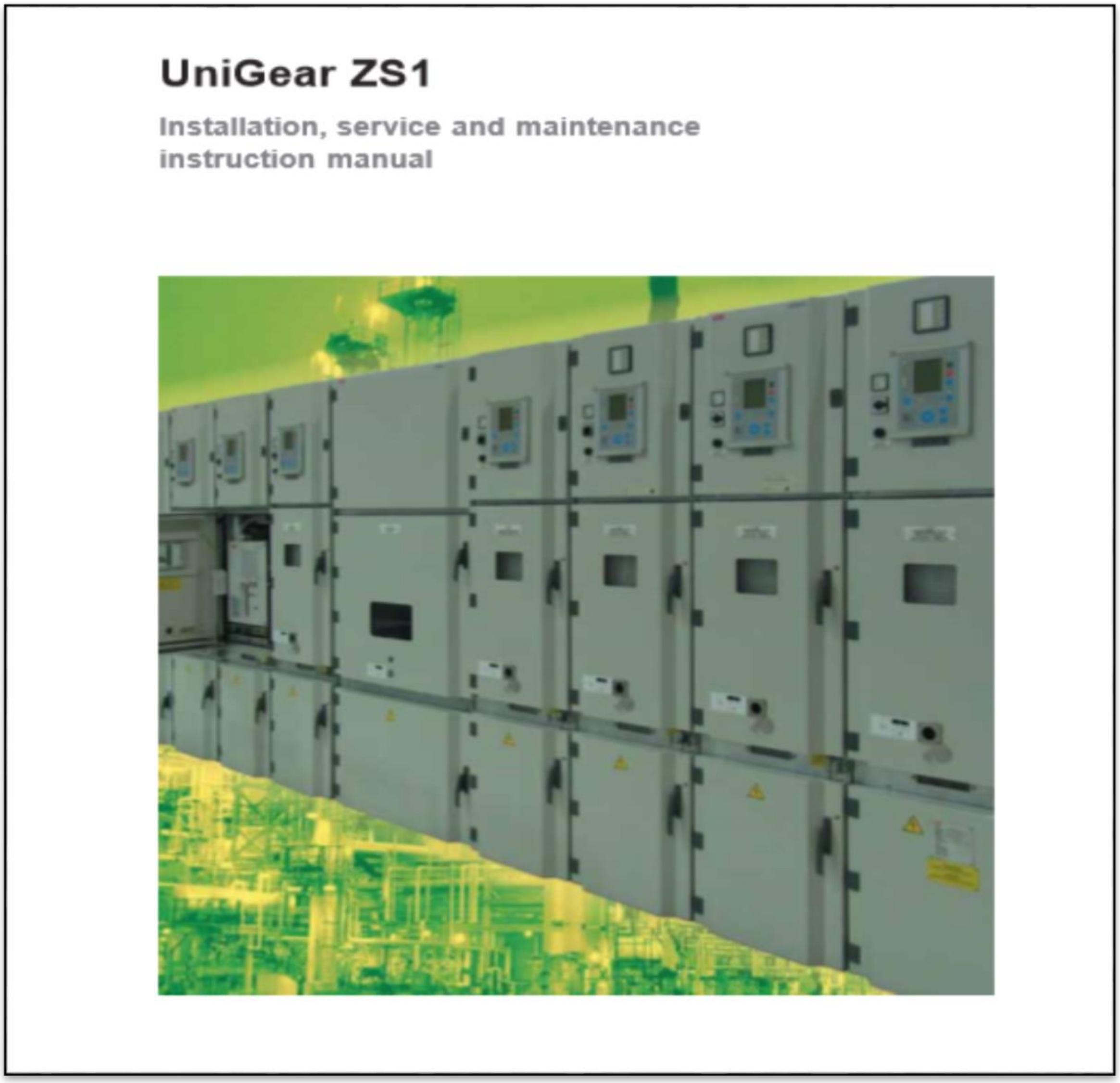

Fig. A01: Medium Voltage (MV) Switchgear

Figure 9: Withdrawable part with circuit-breaker, type VD4, operating mechanism side
13.15 Withdrawable assembly

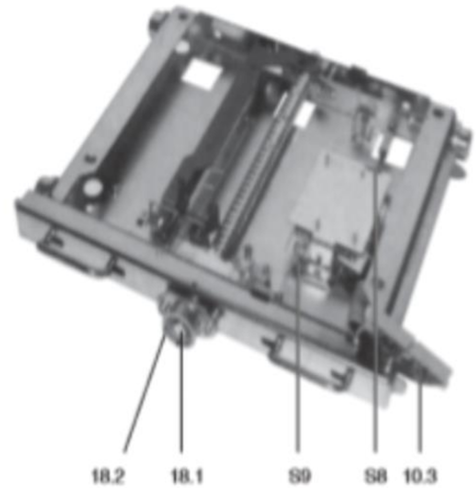

Figure 10: Withdrawable assembly for circuit-breaker, with auxiliary switches
S8 Test position indicator
S9 Service position indicator
10.3 Control wiring plug connector for Withdrawable assembly
18.1 Square spigot
18.2 Hole in spindle for insertion lever spindle

Figure 11: V-Contact VSC type vacuum contactor – front view
91.13 Signalling device ON/OFF
91.14 Operating cycle counter

Figure 12: V-Contact type vacuum contactor – pole side
91.15 MV fuses
91.13 Signalling device ON/OFF
91.14 Operating cycle counter

Fig. A02: Circuit Breaker Module (MV)

Fig. A03: Feeder Control and Protection Relay (REF-615, ABB)

615 series overview

Overview

615 series is a product family of IEDs designed for protection, control, measurement and supervision of utility substations and industrial switchgear and equipment. The design of the IEDs has been guided by the IEC 61850 standard for communication and interoperability of substation automation devices.

The IEDs feature draw-out-type design with a variety of mounting methods, compact size and ease of use. Depending on the product, optional functionality is available at the time of order for both software and hardware, for example, autoreclosure and additional I/Os.

The 615 series IEDs support a range of communication protocols including IEC 61850 with GOOSE messaging, IEC 60870-5-103, Modbus® and DNP3.

- The Wärtsilä 34SG was developed in response to the market need for bigger gas engines.
- The Wärtsilä 34SG lean-burn gas engine utilizes the frame of the new Wärtsilä 32 diesel/heavy fuel engine with its advanced integrated lube oil and cooling water channels. The bore has been increased to 340 mm to fully utilize the power potential of this engine block.

WÄRTSILÄ

User's Manual

November 2012

Synchronous Machine
AMG 1120SM08 DSE

Serial no. 4629264-74
ABB ref. 3976HG401-411
Project: United

ABB

1 PERFORMANCE DATA (Calculated values)

TYPE

Type designation: AMG 1120MM08 DSE

RATINGS

Output:	10913	kVA	Direction of rotation		
Duty:	S1		(Facing drive end):	CCW	
Voltage:	11000	V	Stored energy constant		
Current:	573	A	(Rotative energy divided		
Power factor:	0,80		by rated effect):	0,61	s
Frequency:	50	Hz	Weight:	27000	kg
Speed:	750	rpm	Inertia:	2150	kgm^2
Overspeed:	900	rpm	Protection by enclosure:	IP23	
			Cooling method:	IC0A1	
			Mounting arrangement:	IM1101	

STANDARDS

Applicable standard:	IEC
Marine classification:	None
Hazardous area classification:	None
Temperature rise stator / rotor:	F/F
Insulation class:	F

ENVIRONMENTAL CONDITIONS (max. values)

Ambient temperature:	50	°C	Altitude:	1000	masl
Coolant temperature:		°C			

ASSUMED DATA

Driving equipment:	Wärtsilä 20V34SG	
Appr. mec. power:	8955	kW

EFFICIENCY in %

	load:	110 %	100 %	75 %	50 %	25 %
Efficiency @ power factor	0,80	97,43	97,48	97,51	97,22	95,70
Efficiency @ power factor	1,00	98,14	98,18	98,17	97,92	96,67

REACTANCES in %

XD (U):	223,9	XD' (S):	32,6	XQ'' (S):	23,7	X0 (U):	12,4
XQ (U):	112,6	XD'' (S):	21,1	X2 (S):	22,4	XP (S):	26,9
X1 (U):	18,1	(S) = Saturated value, (U) = Unsaturated value					

TIME CONSTANTS (SEC.) AT 75 °C

TD0':	6,358	TD':	1,019	TQ0'':	0,1277	TA:	0,148
TD0'':	0,02314	TD'':	0,01512	TQ'':	0,0295		

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34SG-200143 Main Data, Operating Data and General Design 01

01. Main Data, Operating Data and General Design

01.1 Main data for Wärtsilä 20V34SG

Cylinder bore . . . . 340 mm
Stroke . . . . 400 mm
Piston displacement per cylinder . . . . 36.32 l

Firing order	
Engine type	Clockwise rotation
20V34SG	A1-B1-A7-B7-A3-B3-A9-B9-A5-B5-A10-B10-A4-B4-A8-B8-A2-B2-A6-B6

Lubricating oil volume in the engine	
Engine type	20V34SG
App. oil volume in litres Wet sump	4680
Oil volume between max. and min. marks appr. litres/mm	650 6

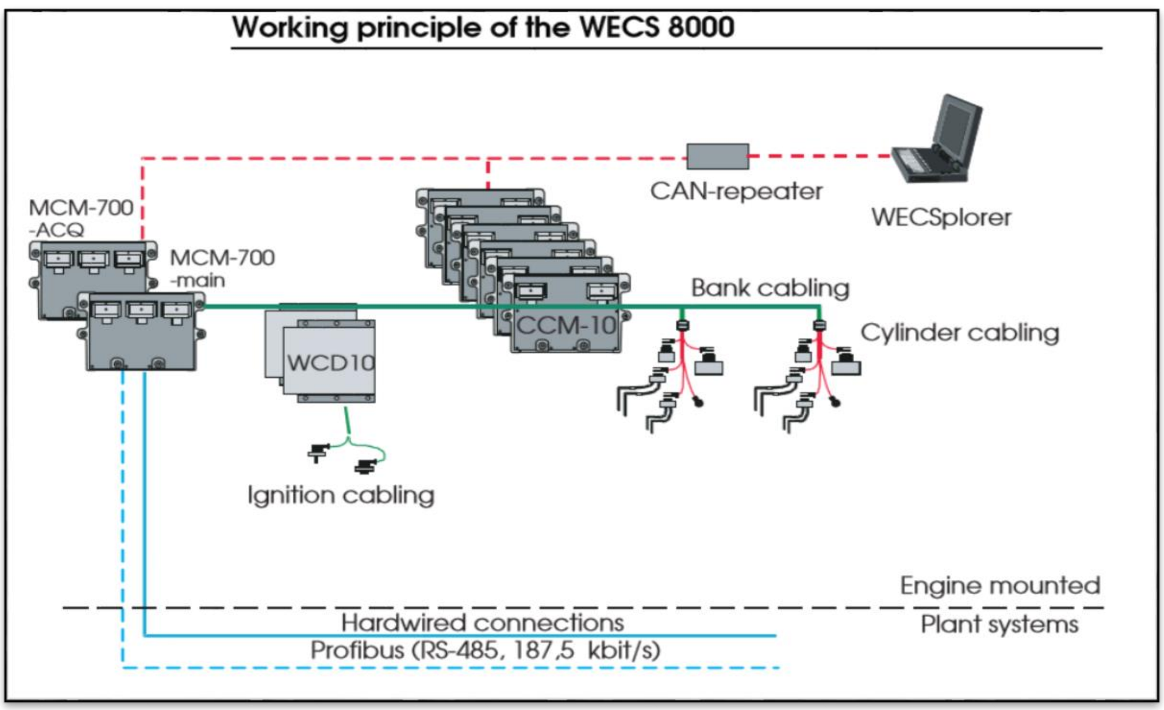


Fig. A04: Working Principle of Wartsila Engine Control System

Engine speed and load control

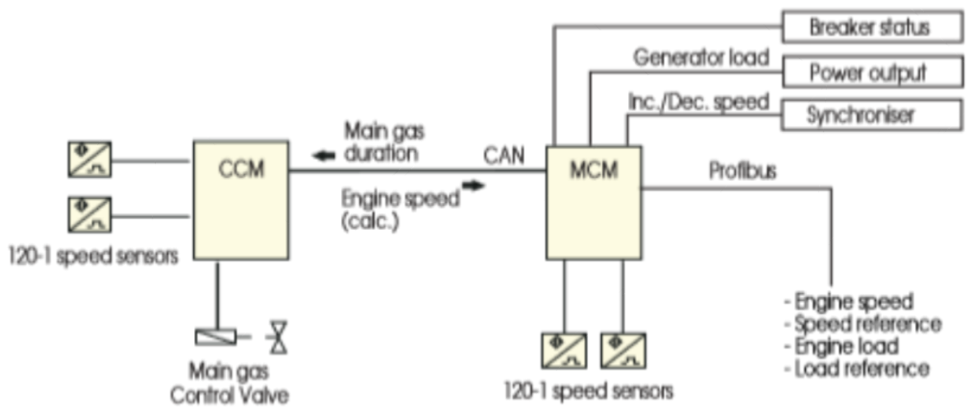


Fig 23-24 402595

23.10.1 Engine speed control

The speed reference is compared with the measured engine speed. The difference between these signals constitutes the input to a PID-controller. The regulation output of this controller will accordingly vary, to sustain the reference level. This output will control the opening duration of the gas valves. If load control mode is selected, another PID control loop becomes active.

The PID-controller has different sets of dynamic parameters for operation with the generator breaker open (speed dependent mapping) and closed (load dependent mapping) to obtain an optimal stability under all conditions. Some adaptive speed deviation dependent features are also provided, to minimise large speed fluctuations in island mode.

To prevent the excessive engine speed increase during accidental opening of the generator breaker, the output of the PID-controller is temporarily set to zero.

Two fuel limiters are available. The start fuel limiter is only active in during engine start, up to a speed level of rated - 20 rpm. The start fuel limiter settings are engine speed dependent (8-point table), and the limiter works in combination with a speed reference ramp, also used at engine start. Another fuel limiter limits the max. fuel demand (gas valve opening time) when the generator breaker is closed, to prevent too rich air/fuel ratio.

23. WECS 8000

23.1 General

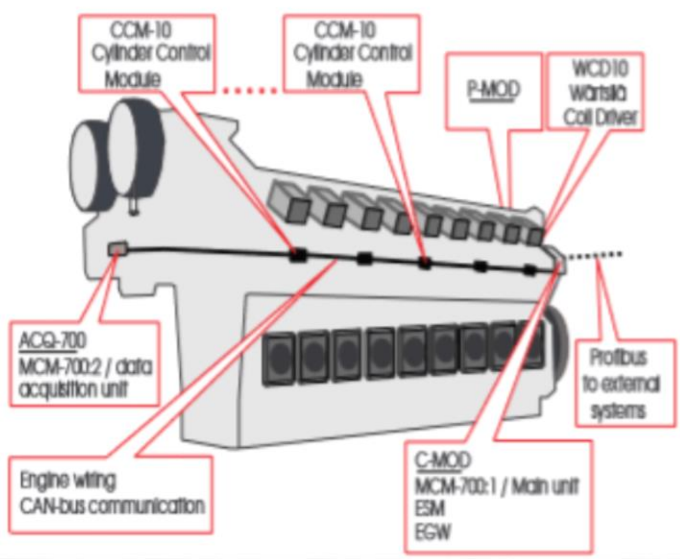
This chapter describes the function of the WECS 8000 (Wärtsilä Engine Control System) engine control and monitoring system.

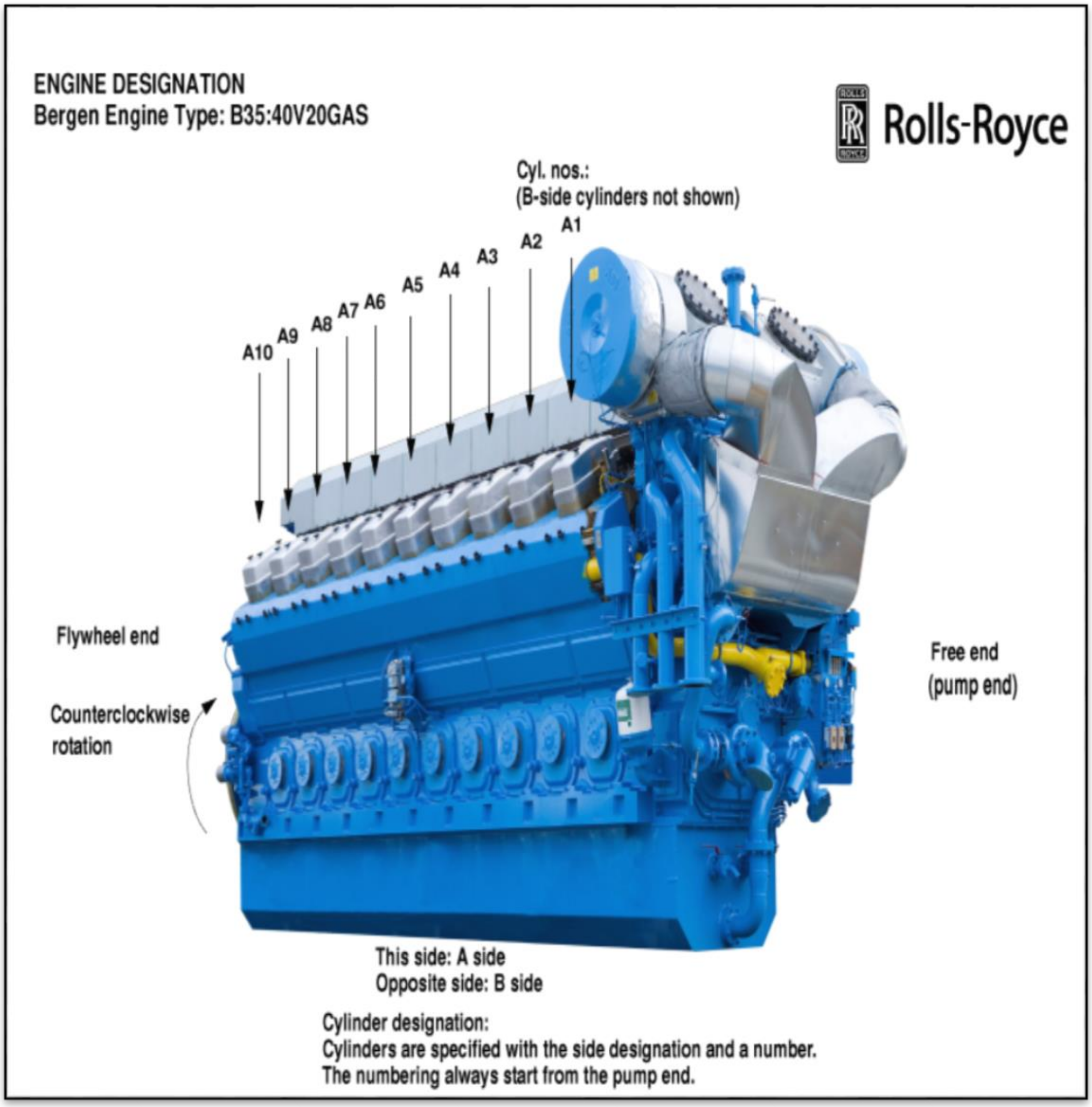
23.2 System configuration

23.2.1 General

The WECS 8000 is a distributed engine control system for monitoring and control of all engine functions. The system monitors and controls gas, air, ignition, knock, speed, load, diagnostics and communication with plant control systems. The system consists of several hardware modules, interconnected by engine wiring. The modules communicates with each other by two communication buses based on *CAN protocol*. An overview of the system is shown in the figure below.

Main components in the WECS 8000




ENGINE DESIGNATION
Bergen Engine Type: B35:40V20GAS
Rolls-Royce
Cyl. nos.:
(B-side cylinders not shown)
A1
A2
A3
A4
A5
A6
A7
A8
A9
A10
Flywheel end
Counterclockwise
rotation
Free end
(pump end)
This side: A side
Opposite side: B side
Cylinder designation:
Cylinders are specified with the side designation and a number.
The numbering always start from the pump end.

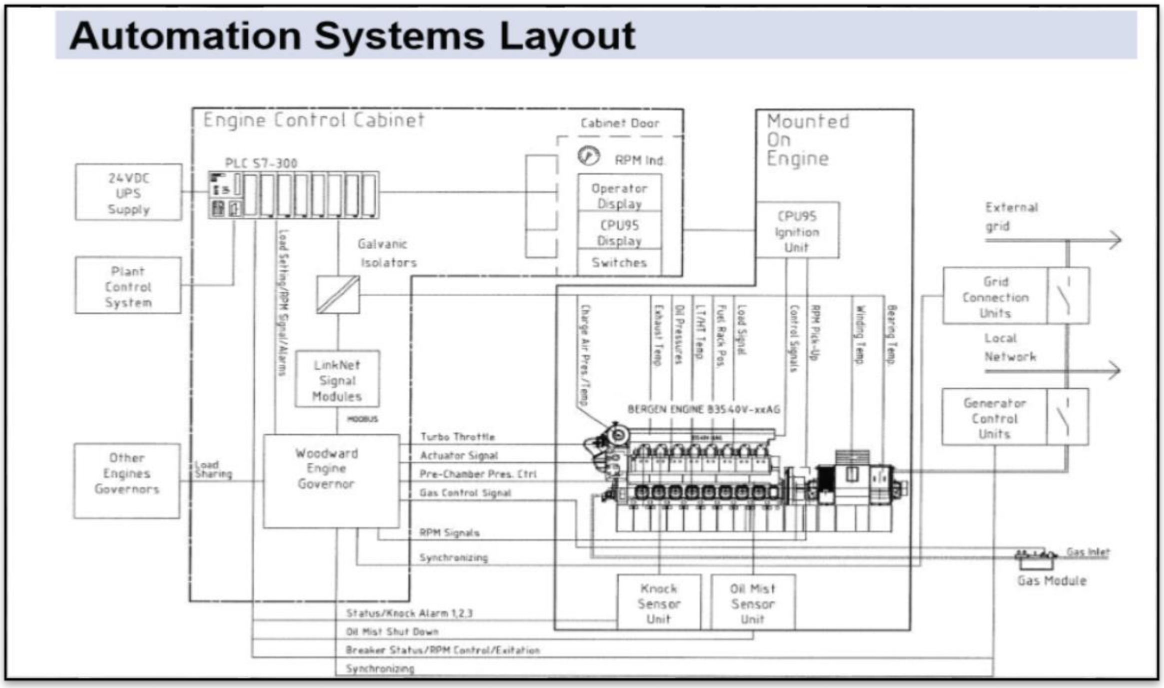


Fig. A05: Engine Automation Control System Layout

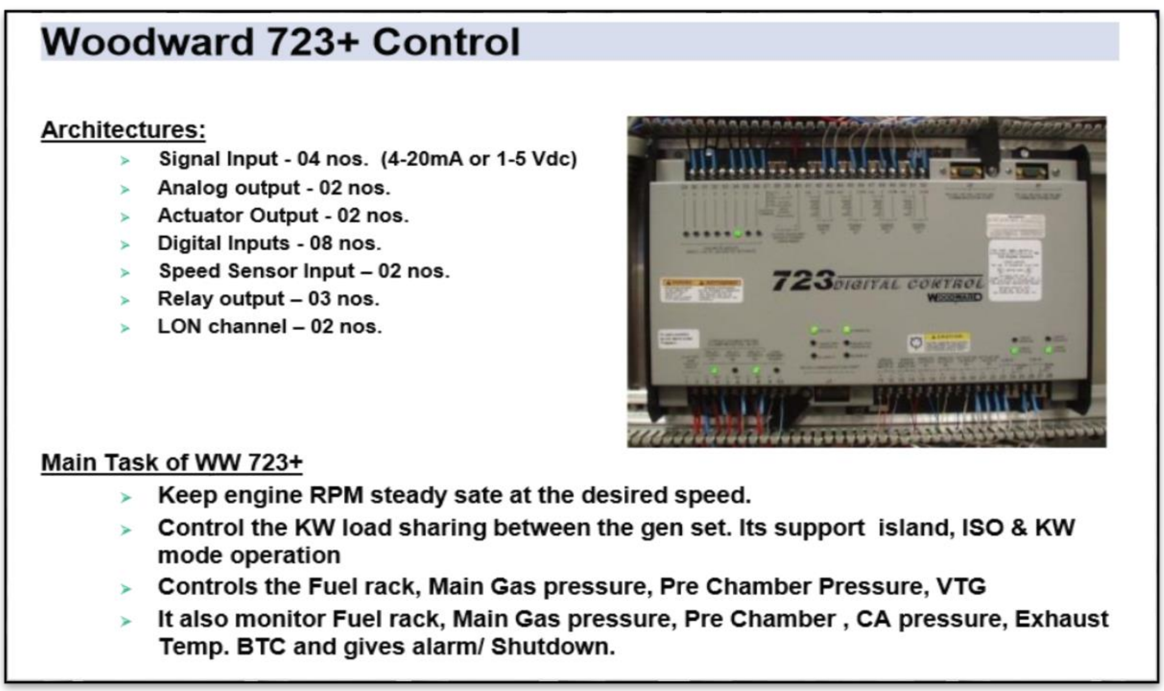


Fig. A06: Engine Control Unit.

Enhancing Micro-Grid Stability in Industrial Distribution Feeders by Generating Bus Splitting (GBS)

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