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Voltage Profile Improvement Techniques of Interconnected Microgrids

Abstract: - In recent years, the adoption of microgrids has emerged as a viable solution to resolve the problems of the traditional power grid. It also provides an optimal way to reduce harmful emissions in the environment. The microgrid (MG) contains Distributed Energy Resources (DERs) and manageable loads, which efficiently work independently and collaboratively on the main grid. The decentralized structure of the microgrids makes them less prone to physical and cyberattacks. Generally, they depend on energy sources like photovoltaics (PVs) to address the emission problems and integrate energy-effective strategies such as heating, cooling and power production. The microgrids reduce the losses incurred during distribution and transmission as they are placed nearer to the loads. These features make the microgrids more reliable and eco-friendly electricity sources. However, the intermittent nature of renewable energy sources (RESs) induces certain limitations for microgrid function, making the energy management process complex. The DERs are incorporated with the Energy Storage Systems (ESSs) to resolve these intermittency challenges, which have increasing maintenance costs. Hence, interconnected multi microgrid (IMMG) schemes are developed which have the capacity of sharing energy with each other during power shortages. Thus, these types of MGs eliminate the intermittency issues of DERs and minimize dependence on ESSs. However, they face issues in preserving the desired voltage profile at the Point of Common Coupling (PCC) due to the presence of multiple sources. This study demonstrates different approaches to enhancing the voltage profile within the interconnected microgrids.

Keywords: Microgrids, Distributed Energy Resources (DERs), Interconnected Multi Microgrids (IMMGs), Total Harmonic Distortion (THD), D-STATCOM, Synchronverters.

I. INTRODUCTION

Compared to conventional grid networks, microgrids contain integrated distributed generation (DG) sources appropriate for delivering power to rural areas [2]. In remote areas, they serve as an eco-friendly solution to resolve the problems associated with power availability. However, the intermittent nature of the RESs in the microgrids demands ESSs, which results in increased maintenance costs and disposal difficulties [3], [4]. This created a demand for a viable solution for handling the intermittency problems. The Interconnected Multi-Microgrid (IMMG) frameworks have improved performance in addressing intermittency problems [5]. Typically, the IMMGs define an interconnected system linking many individual MGs. The MGs are placed closely in this network and connected to a distribution bus. In IMMGs, the optimal collaboration among the MGs enhances the reliability and strength of the power network. In the power network, the IMMGs offer several benefits.

Firstly, the application of IMMGs in the power network offers favorable economic attributes despite working in grid-connected or islanded modes. This is mainly because of the unique energy-sharing mechanism exhibited among the MGs, allowing them to reach power requirements cost-effectively. In addition, this unique energy-sharing characteristic of IMMGs reduces the dependence on traditional fuel production. Moreover, sharing energy with the neighboring MGs reduces the energy loss occurring during transmission and distribution. Secondly, the IMMG concept reduces the stress on the main grid, as it provides energy among the MGs. This helps eliminate power line collisions and enhances the steadiness of both MGs and the extensive grid network. Thirdly, an effective self-healing capability is inherited with the smart multi-MG network, enabling the MG to separate from the faulty grid. Although the IMMGs have numerous benefits, obtaining a reliable and stable functioning is still challenging.

This study concentrates on mitigating the power quality issues introduced by the multiple sources in IMMGs. It also focuses on problems such as power quality enhancement by analyzing techniques that preserve the desired voltage at the PCC. This research explores different voltage profile enhancement approaches for IMMGs, and considers three IMMGs for study. The initial stage of this study concentrates on an IMMG containing two interconnected DC MGs delivering AC loads. In this instance, low-pass filters would be an optimal and economical choice for eliminating the voltage variations. An inexpensive low-pass broadband LC filter was utilized to decrease the broad harmonic frequencies, which in turn minimizes the Total Harmonic Distortion (THD). The next stage of the study concentrates on an IMMG containing two AC MGs. In this instance, a Distribution Static Synchronous Compensator (D-STATCOM) was employed as it exhibits greater efficiency in

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maintaining desired voltage profiles and enhancing power quality [6]-[9]. In addition, different control mechanisms, such as Proportional Integral (PI), fuzzy logic controllers, etc., are developed to maximize the performance of D-STATCOM, especially in AC/DC integrated MGs [10]-[12]. The third phase of the work concentrates on an IMMG containing three MGs, out of which one is a DC MG and the other two are AC MGs. The control mechanism in this case includes the development of synchronverters [13], [14], and nested architectures of synchronous generator (SG) assisted converters. Generally, the synchronverters are employed to stabilize the MG and synchronize the PV modules within the grid networks [15].

To summarize, this study concentrates on strategies for improving the voltage profile of IMMGs. Three different control mechanisms are analyzed for enhancing the voltage profiles: passive LC filter, PI/Fuzzy controlled D-STATCOM, and Synchronverters.

II. EXISTING STUDIES

This section analyzes the existing research works associated with voltage profile improvement in IMMG systems.

In power systems, distorted power quality and voltage stability are the major challenges. To address these issues, Nafeh, Abdelnasser A., Aya Heikal, Ragab A. El-Sehiemy, and Waleed A. A. Salem [16] presented a control strategy, which aims to increase both stability and quality of the voltage in the AC-DC MG network. This work presented advanced fuzzy controllers namely, fuzzy-PI and fuzzy-PID, combined with the DSTATCOM. Also, the study applies the developed strategies in two distinct scenarios (fault and dynamic load conditions). The simulation outcomes proved that the voltage fluctuations were minimized to 0.982% and 0.577%. In addition to this, the dynamic system performance index was enhanced by 6.67% and 5.71% using the above two controllers.

Microgrids offer a prominent solution to numerous issues associated with traditional grid systems like increased energy cost, lack of reliability, etc. However, they face challenges in maintaining power quality due to the intermittent nature of power sources. Hence, Charivil Sojy Rajan and Mabel Ebenezer [17] presented a study using the popular D-STATCOM to enhance voltage profiles in the IMMG scheme. The functioning of the D-STATCOM is regulated by using PI and fuzzy controllers, and they are implemented in the MATLAB/Simulink environment. The experimental evaluation concluded that the fuzzy controlled D-STATCOM offered better performance compared to the PI-based one, making it applicable for achieving enhanced voltage profile at PCC of the IMMG scheme.

The rising demand for power electronic devices increased the distribution of non-linear loads, which distorts the power quality of the distribution frameworks. Manoj Kumar Kar et al. [18] presented a schematic architecture for developing and simulating D-STATCOM for enhancing the power factor. This research aims to apply the compensation efficiency of D-STATCOM to reduce THD in the generated output. This strategy was developed and experimented in MATLAB/Simulink, and the simulation outcomes demonstrated that integration of D-STATCOM effectively enhances the power quality in distribution networks.

Currently, the traditional grid is transforming its typical unidirectional flow into the bidirectional one. The evolution of microgrids showed an optimal efficiency in this conversion. However, the intermittency of its sources degrades the voltage stability of the MGs. Charivil Sojy Rajan and Mabel Ebenezer [19] presented voltage and frequency controlled synchronverters to enhance these distorted voltage profiles at the PCC and load bus of the IMMG scheme. This framework was designed and implemented in the MATLAB/Simulink platform and the outcomes showed that the integration of this control mechanism significantly improved the voltage profiles and minimized the THD.

Santhoshkumar and V. Senthilkumar [20] proposed a controller approach by integrating Whale Optimization and Ant Lion Optimization techniques. The objective of this study is to refine the control variables for optimally managing the grid constraints including voltage, frequency, etc. This hybrid strategy was implemented in the MATLAB/Simulink platform and the implementation results illustrated a stable dynamic performance. However, the frequency response is not satisfactory.

III. STRATEGIES FOR IMPROVING VOLTAGE PROFILE IN IMMGS

This study analyzes three distinct controller strategies for enhancing power quality in the IMMG systems. First case focuses on improving the voltage profile using passive filter in IMMG containing two DC MGs, the second case focuses enhancing voltage profile using PI controlled and fuzzy controlled D-STATCOM in an

IMMG containing two AC MGs, and the third case uses synchronverters for increasing the voltage profile of an IMMG containing two AC and DC MGs. The detailed explanation of the three cases is provided below.

A. Case 1: IMMG consisting of two DC Microgrids-Voltage Profile Improvement using Passive Filter

In this scenario, an IMMG containing two DC MGs (A and B) was modeled and each MG was designed to function independently [1]. However, they are interconnected with each other for sharing the power and load. Each MG is provided with its own DC power source (PV), which generates and stores electrical energy. Also, power converters along with energy storage units are employed to control and store the excessive energy generated during the peak-off periods. Also, a charge controller was used to regulate the charging and discharging of energy within the IMMG system. Fig. 1 presents the systematic architecture of the IMMG with two DC microgrids.

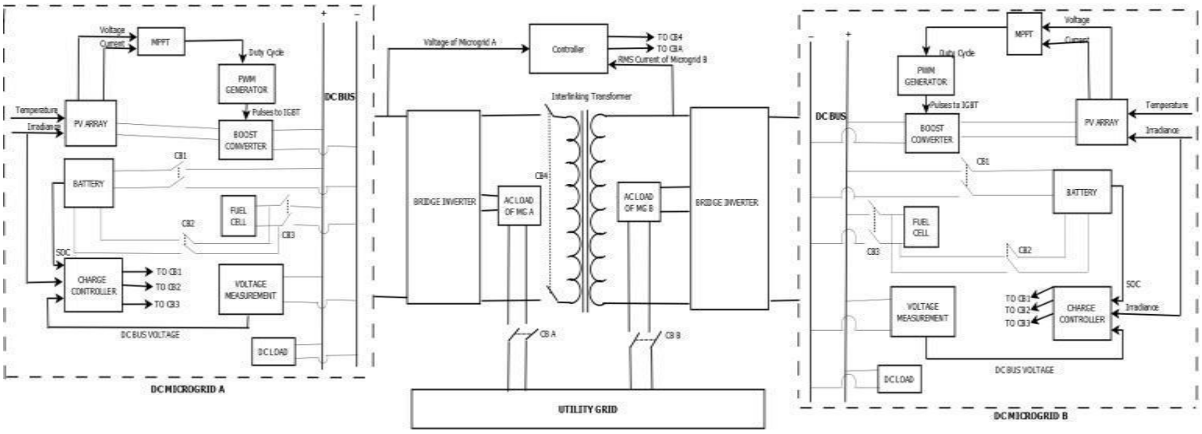

Fig. 1. Schematic Architecture of Interconnected DC Microgrids

1) Harmonic assessment using FFT

The harmonic assessment was performed utilizing the Fast Fourier Transform (FFT) to examine the quality of the electrical signal. In power systems, harmonics define the components, which are integer multiples of the fundamental frequencies that disturbs the normal functioning of the devices by distorting the waveform of the electrical signal. The FFT algorithm decomposes the time domain signal into frequency domain. The FFT outcome provides the amplitude and phases of the signal at various frequencies. This frequency spectrum is then analyzed to measure the THD and determine the overall harmonic content in the input signal.

a) Harmonic analysis without filter

A harmonic assessment was made, concentrating on a three-phase AC load within MG A of the IMMG model. Fig. 2 presents the interconnected DC MGs with filter. A DC bus with a stable 400 V was provided on each side of the MG, under the co-ordinated operation of battery and PV modules. Consider a grid-connected function scenario, where the utility grid delivers energy in case of emergencies (when both the interconnected MGs fail). An FFT assessment was conducted utilizing Powergui in MATLAB/Simulink (Fig. 3), and it demonstrated that only 0.19% THD was observed in this scenario, eliminating the need for filters.

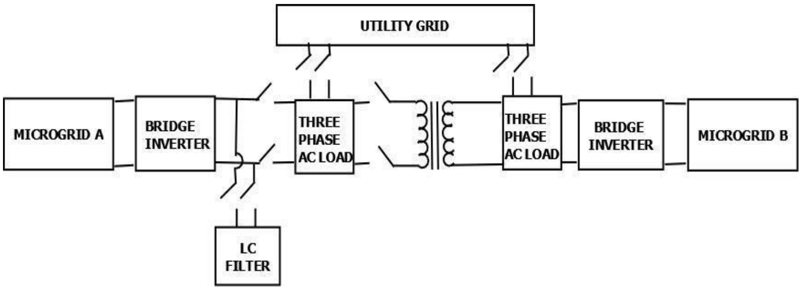

Fig. 2. DC IMMG with Filter

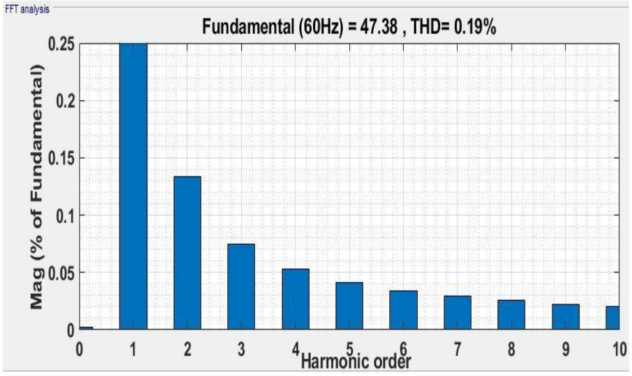

Fig. 3. FFT Assessment

Consequently, the FFT-based harmonic assessment was conducted in the standalone functioning mode of MG A. Firstly, the THD was measured without applying the LC filter. Fig. 4 examines the FFT window of a single-phase AC load current of MG A without LC filter. Fig. 5 depicts the FFT spectrum of the AC load current without a filter, and a THD of 92.52% was observed in this scenario. This high percentage of THD increases the possibility of damaging the micro sources within the MG. The increasing non-linearity of the load leads to rapid increase of the THD value (beyond the calculated value). The fluctuations in the load power are presented in Fig. 6.

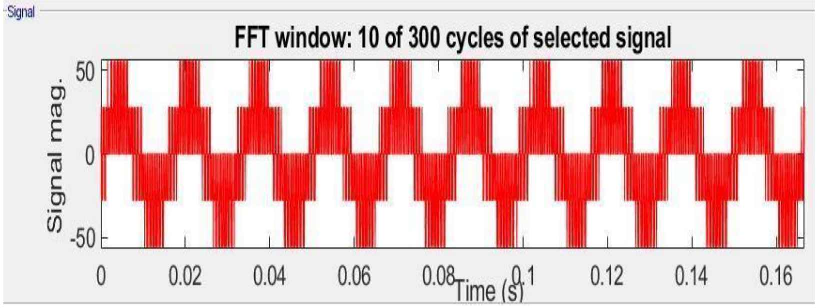

Fig. 4. FFT Window of single-phase of the AC Load Current of MG A without filter

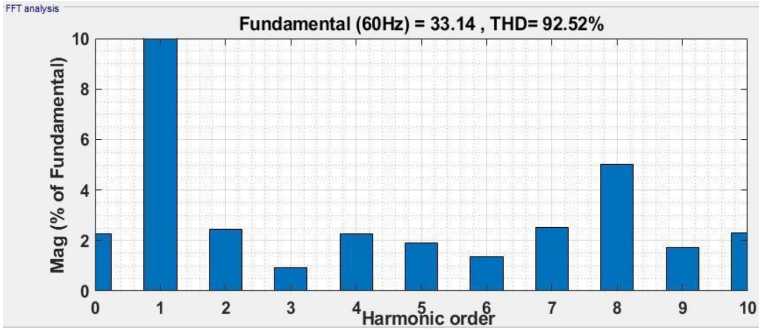

Fig. 5. Harmonic Assessment of the AC load Current of MG A without Filter

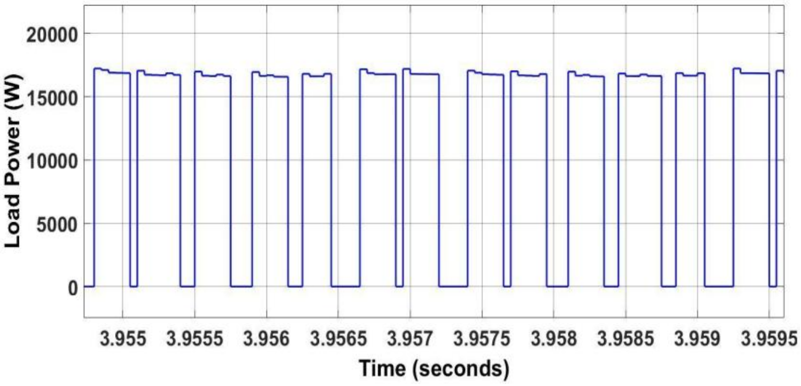

Fig. 6. Fluctuating Load Power

b) LC filter design

The LC filter contains two major components including inductors (L) and capacitors, which is used widely to attenuate particular frequency bands of the signal. These two components are passive elements with conflicting features that is; the capacitor blocks the DC element but passes AC current at high frequencies. In contrast, the inductor passes the DC current but passes AC current less easily at high frequency. Thus, the combination of these two components cut off the harmonic or specific band of frequencies from the signal, and it is developed by the equations (1), (2), and (3)

$$f_c \leq \frac{1}{10} f_{SW} \tag{1}$$

$$L < \frac{0.03U_{inv}}{2\pi f I_{L\max}} \tag{2}$$

$$C = \frac{1}{(2\pi f_c)^2 L} \tag{3}$$

Where f_c indicates cut-off frequency, U_{inv} denotes the inverter's DC input voltage, f_{sw} represents switching frequency, and I_{Lmax} defines maximum load current. By applying this filter, the harmonic frequency bands are cut off from the voltage profile of the IMMG system.

c) Harmonic assessment with LC filter

The modeled LC filter is placed between the three-phase AC load and inverter. The main objective of utilizing this filter is to mitigate THD. Figs. 7 and 8 depict the FFT window and harmonic spectrum. This assessment shows that the THD was reduced to 7.32%, and it achieved constant load power, which is presented in Fig. 9. However, the obtained load power showed non-pure sinusoidal features because of the minor DC offset. This attribute illustrates the presence of certain even harmonics in the load power.

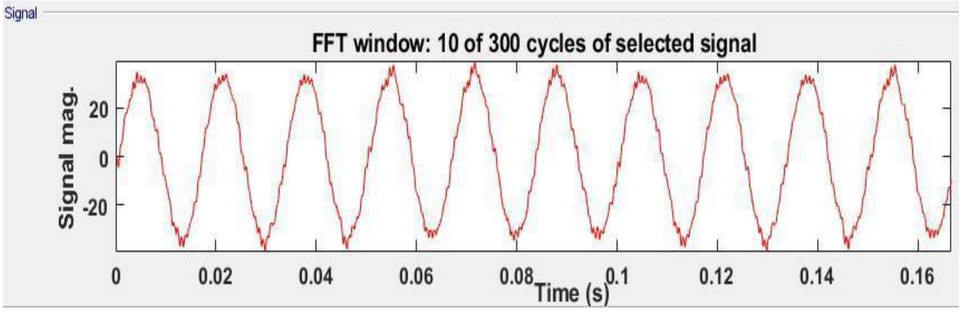

Fig. 7. FFT window of AC current (MG A with filter)

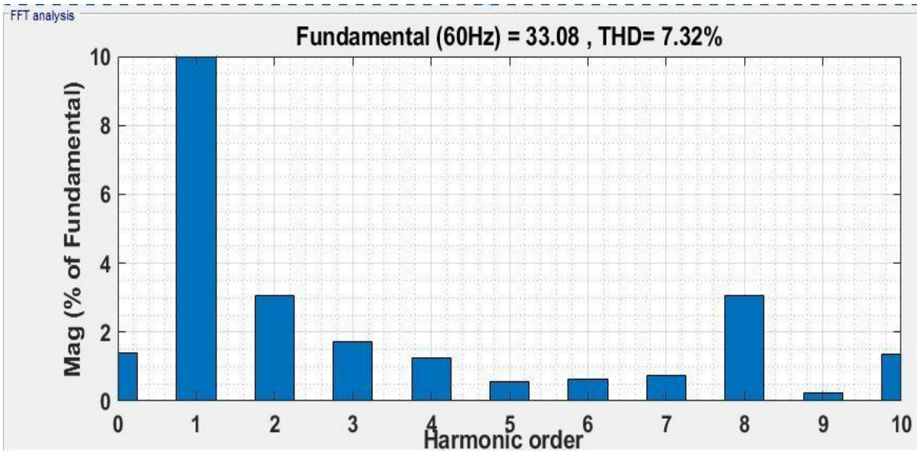

Fig. 8. THD assessment of AC Load Current of MG A with LC Filter

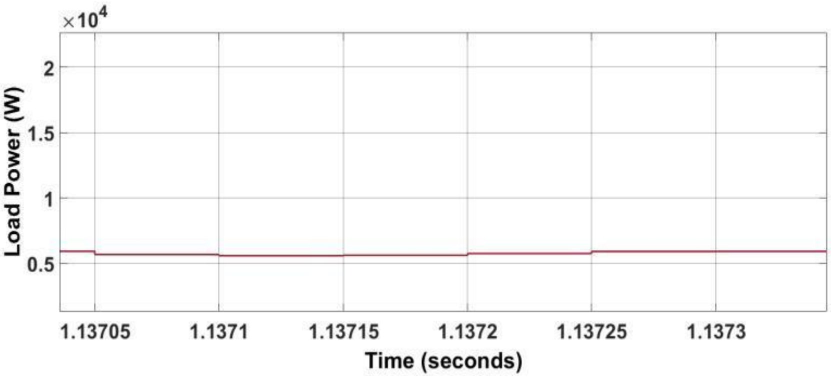

Fig. 9. Load power assessment

From the above analysis, it is evident that the THD was high without filter when compared to that with an LC filter. The high THD leads to potential fluctuations in the load power, creating damage to the IMMG devices. Thus, the application of LC filters enhances the overall stability and quality of voltage profile in IMMG systems.

B. Case 2: IMMG consisting of two AC Microgrids-Comparison of PI Controlled and Fuzzy Controlled D-STATCOM for Voltage Profile Improvement

1) IMMG System

In the IMMG under study, the utility grid is provided with a 120 kV sinusoidal source, and at PCC the distribution transformer is rated at 47 MVA with a proportion of 120/25 kV. A D-STATCOM was employed for maintaining the PCC AC bus voltage at 25kV. This helps in compensating the deficiency of the reactive power by mitigating the harmonic flow to the source in the grid network. This in turn potentially mitigates problems like overheating of transformers and other adverse impacts. Also, the D-STATCOM controls the PCC voltage by delivering or absorbing the reactive power by mitigating the harmonics in the current flow.

A continuous wind speed of 13 m/s was fed into the Doubly Fed Induction Generator (DFIG). Then, the reference value for reactive power input (Q_{ref}) was estimated from the PI/fuzzy logic controller. Consequently, varying wind speed was given as input to operate the induction generator wind turbine (IGWT), as presented in Fig. 10.

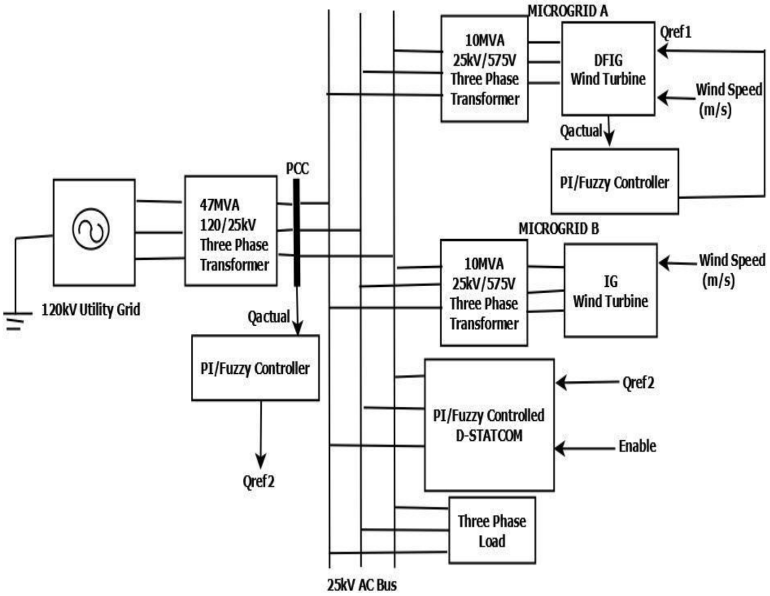

Fig. 10. Schematic structure of IMMG

2) PI Controlled D-STATCOM

In power systems, a PI controlled D-STATCOM is an approach employed for improving the system stability. The D-STATCOM is a three-phase shunt connected equipment, which contains voltage source converter (VSC) and DC link capacitor. The shunt configuration used in D-STATCOM enables it to produce and absorb reactive power effectively. The working of this is almost identical to the synchronous compensator. Here, the AC terminals of the VSC are connected to the PCC via inductance.

In PI-controlled D-STATCOM, the VSC component injects the compensated current into the grid, which is regulated by the PI controller. The PI controller works in accordance with two principles namely, proportional (P) and integral control (I). The P component reacts to the immediate error between the reference and actual grid voltage values and produces output signal proportional to the observed error. This mechanism helps the system to respond rapidly to the changing grid conditions. Consequently, the I component integrates the error over time and eliminates the steady-state error. The combination of the P and I terms allow the D-STATCOM to regulate the system voltages/currents and facilitates signal conditioning during fluctuating loads [6].

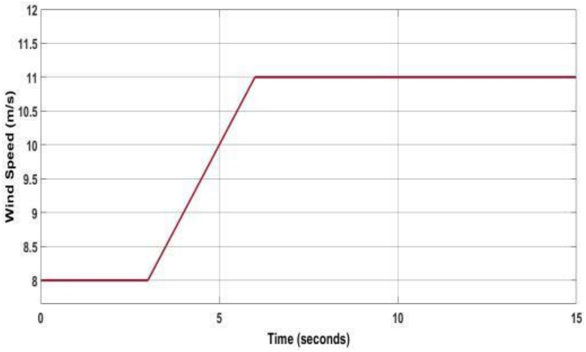

Fig. 11. Input wind speed

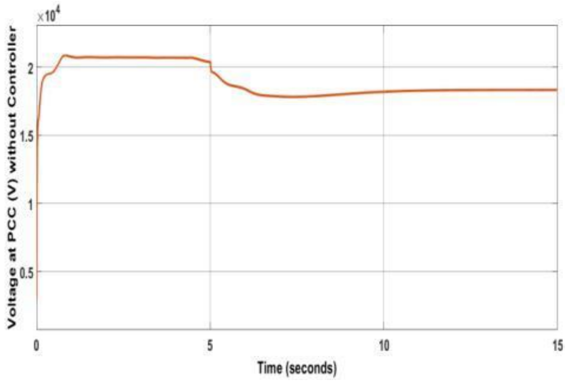

Fig. 12. PCC voltage without controller

As presented in Figure 11, the wind speed of the IGWT accelerates continuously from 8m/s to 11m/s within 4-6 seconds. Eventually, the MG B load was elevated, which reduced the voltage at the PCC, as presented in Fig. 12. The analysis shows that the voltage dropped notably below 20kV and failed to recover the PCC voltage level without a controller.

3) Simulation Outcomes and Analysis

The PCC voltage exceeds 20 kV within a couple of seconds by using the PI-assisted D-STATCOM, as displayed in Figs. 13 and 14. Fig. 15 displays the three-phase rotor current, rotor speed in the MG A, and the active and reactive power outcomes of the WT-DFIG. Fig. 16 presents the FFT assessment of PCC voltage. Fig. 17 illustrates the real power, rotor speed, reactive power, and pitch of the IGWT in MG B.

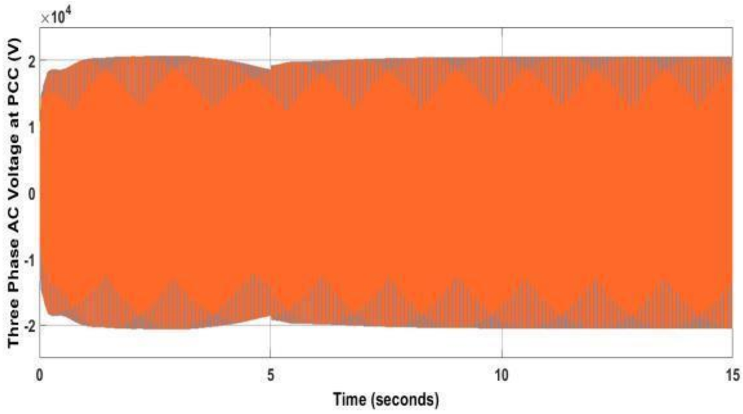

Fig. 13. Three phase AC voltage at PCC with PI Controller

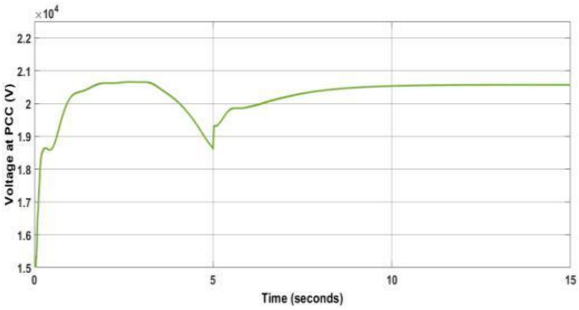

Fig. 14. PCC voltage with PI Controller

The above assessments demonstrated that the PCC voltage was restored rapidly within 2-3 seconds to a value greater than 20 kV. This demonstrates rapid response of the system, highlighting the effectiveness of using controllers. In addition, it should be noted that before stabilization, the speed of the rotor varies between a margin of 1.21 and 1.17 pu over 20 seconds. Moreover, both the active and reactive power outcomes remained at 0.5 pu.

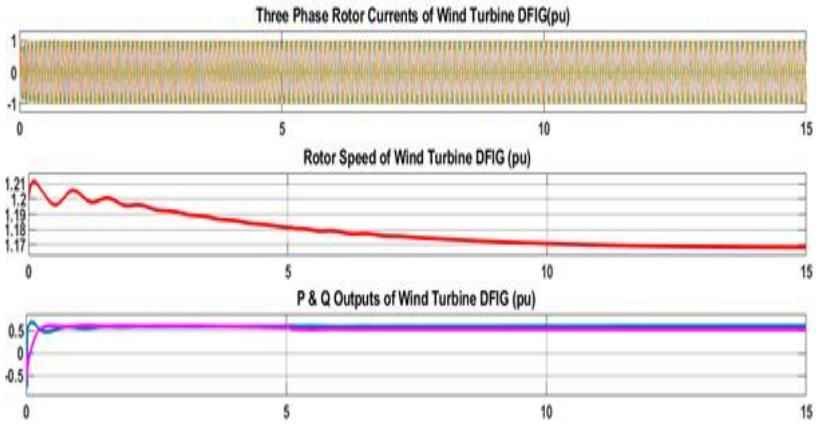

Fig. 15. Response of WT-DFIG with PI Controller (MG A)

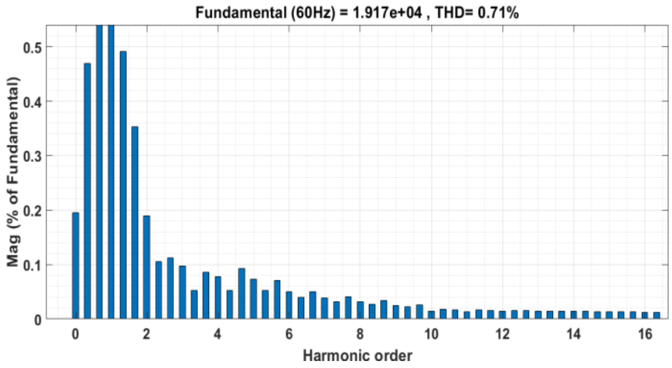

Fig. 16. FFT assessment with PI Controller

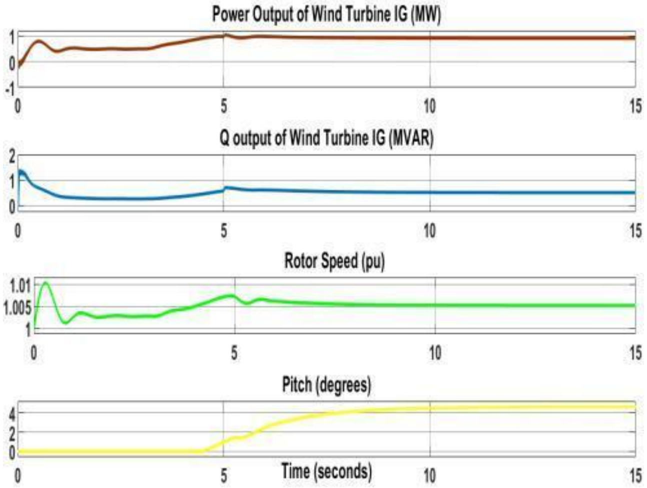

Fig. 17. Resultant waveforms of WTIG (MG B)

The FFT assessment on the PCC voltage illustrated that the basic components of approximately 19kV with 0.7% THD follow voltage restoration in the initial 3 cycles. The waveforms shown in Fig. 17 highlight that the resultant power of the WTIG balances at 1 MW with a reactive power outcome of 0.8 MVAR attained within 5 seconds. Consequently, the rotor speed was balanced to 1 pu in 5 seconds, and it is noted that the variations in pitch are visible at high wind speed.

4) Fuzzy Controlled D-STATCOM

The fuzzy controlled D-STATCOM is used in electrical systems for regulating the voltage profiles optimally under changing grid conditions. The fuzzy controlled D-STATCOM integrates the fuzzy logic controller (FLC) and D-STATCOM for compensating the voltage profiles in IMMG systems. The FLC circuit contains four modules namely, fuzzification interface, rule base, an inference engine, and a defuzzification interface. Unlike the PI controller, the FLC approach is more flexible and adaptable, as it functions by defining linguistic variables. The fuzzification interface transforms the input constraints like voltage error into fuzzy sets using membership functions. The rule base component contains a sequence of fuzzy rules, which demonstrate how the compensating current needs to be adjusted to mitigate fluctuations. The inference engine component applies the fuzzy logic principles and determines the output fuzzy set based on the current input variables, while the defuzzification interface converts the fuzzy output into crisp values appropriate for controlling the D-STATCOM.

In the presented fuzzy-based D-STATCOM design, input 1 denotes the error (V_{ref}-V_{actual}), encircling 7 constraints that range from -0.1 to 0.1. On the other hand, input 2 indicates the error deviations, and it contains 5 variables ranging from -0.1 to 0.6. The resultant of the system is the reactive power reference containing 5 variables, which range from -0.1 to 0.6. The inputs of this system were connected to a sequence of IF/THEN control protocols, and the linguistic variables of the system are framed as Negative Large (NL), Negative (N), Negative Zero (NZ), Zero (Z), Positive Zero (PZ), Positive (P) and Positive Large (PL). Typically, the fuzzy system contains a dataset along with the rule base. Here, 10 rules are framed for controlling the PCC voltage and presented in Table 1. The Mamdani inference was used as the controller mechanism, and the bisector strategy was implemented to perform the de-fuzzification process.

Table 1. Fuzzy Rules

	Error							
Error Deviations		**NL**	**N**	**NZ**	**Z**	**PZ**	**P**	**PL**
	NL	NL	x	x	x	x	x	x
	N	x	N	N	x	x	x	x
	Z	x	x	Z	Z	Z	x	x
	P	x	x	x	x	Z	x	x
	PL	x	x	x	x	P	P	PL

5) Simulation Results and Assessment

The PCC voltage rapidly increased beyond 20kV when the wind speed of the MG WT increased from 8 to 11m/s, as shown in Figs. 18 and 19. The PI-based system has shown a functional delay of 2 to 3 seconds, but the fuzzy-based system illustrated an immediate response. This highlights its greater efficiency in handling dynamic input variations. Consequently, the FFT assessment (Fig. 20) was conducted, and it demonstrated that this system obtained 20.85kV fundamental component and 0.16% THD in its initial three cycles following voltage restoration. These outcomes and assessments reveal that utilizing the fuzzy controller model increases the power quality.

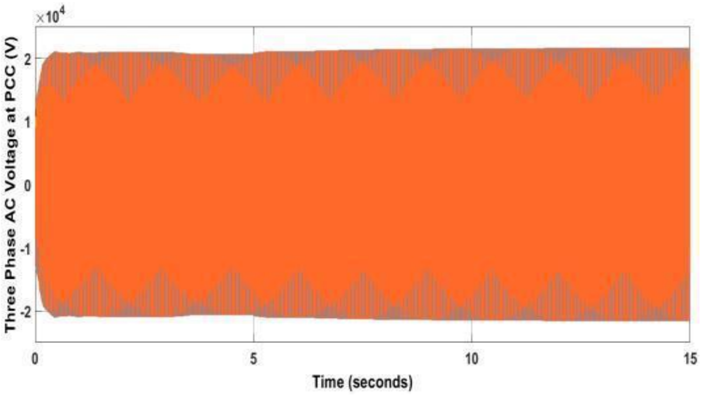

Fig. 18. Three phase AC voltage at PCC with FLC

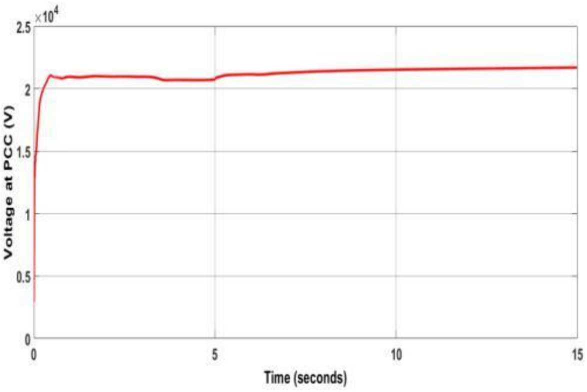

Fig. 19. PCC voltage (with FLC)

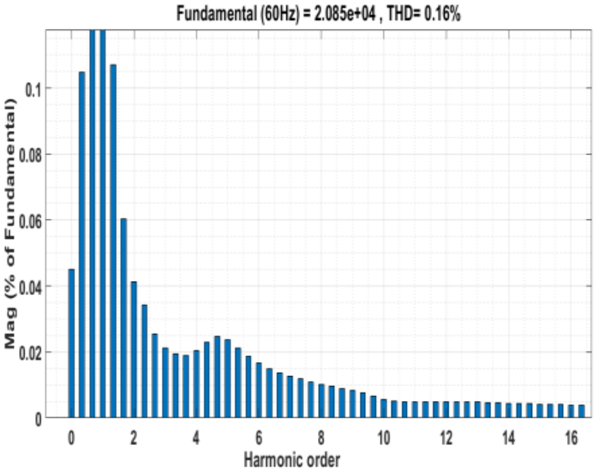

Fig. 20. FFT assessment (with FLC)

This analysis proves that the system offered optimal outcomes than the PI-based system in terms of reactive power, rotor speed, and real power output, as shown in Fig. 21.

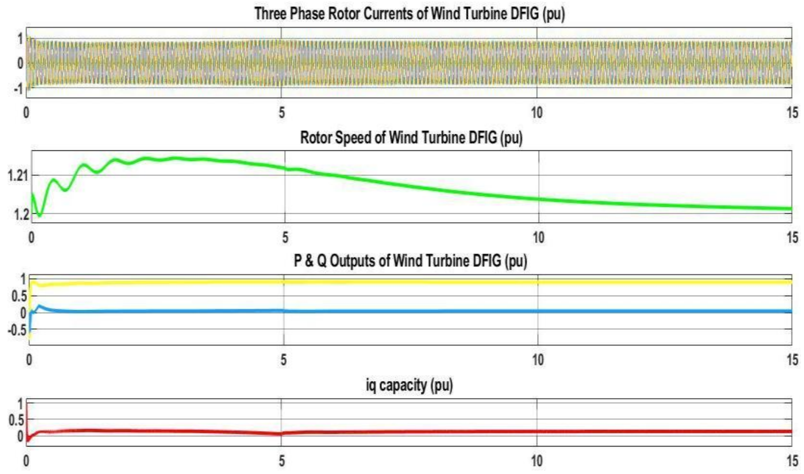

Fig. 21. Outcome of WT-DFIG with FLC (MG A)

Moreover, in a fuzzy-based approach, the rotor speed variation was within a narrow margin (between 1.21 and 1.2 pu). This small deviation indicates the stable and balanced state of the system. Also, the real power outcome maintains a constant value of approximately 1pu. In contrast, the PI-based scheme offered significant deviations in the rotor speed ranging between 1.21 and 1.17 pu, with a real power of 0.5pu. Comparatively, the fuzzy model reduced the reactive power output to around 0 from 0.5pu, highlighting improved power quality. These scenarios are displayed in Fig. 21.

6) Comparative Evaluation

This subsection analyzes the performance of both PI and fuzzy schemes. Table 2 presents the comparative evaluation, providing different constraints investigated to evaluate the performance comparison between the PI and fuzzy controller models in the D-STATCOM system. The values of these constraints achieved in each instance demonstrated the efficiency of the fuzzy-controlled D-STATCOM in an IMMG framework. The significant improvement in the system performance, such as immediate response, reduced THD of the PCC voltage, and fundamental component of the PCC voltage, demonstrated its proficiency in enhancing the IMMG voltage profile.

Table 2. Comparative assessment of PI controlled and fuzzy-controlled D-STATCOM

Constraints	**PI D-STATCOM**	**Fuzzy D-STATCOM**	**Analysis**
Fundamental Component of PCC voltage (kV)	19.17	20.85	Enhanced PCC voltage profile
Response Time (s)	2-3	Immediate	Improved response time
THD of PCC Voltage (%)	0.71	0.16	Minimal THD
Deviation of Rotor Speed of WT-DFIG (pu)	1.21-1.17	1.21-1.2	Achieved almost constant rotor speed
Real Power outcome of WT- DFIG (pu)	0.5	1	High real power outcome
Reactive Power outcome of WT-DFIG (pu)	0.5	Almost equivalent to 0	Minimal

C. Case 3: IMMG consisting of two AC and one DC Microgrid-Voltage Profile Improvement using Synchronverters

1) IMMG under study

The systematic architecture of an IMMG containing 3 MGs is presented in Fig. 22. The 3 MGs are named A, B, and C and they were designed with their own local load. However, the IMMG model also collaboratively shares a common load. In addition, this system has the flexibility and ability to function in an island or grid-interconnected mode, depending upon the requirements. One of the biggest advantages of this configuration is its efficiency in resolving the power shortage within each MG; that is, if one of the MGs faces power deficiency, it can take on power from a neighboring MG or the utility grid.

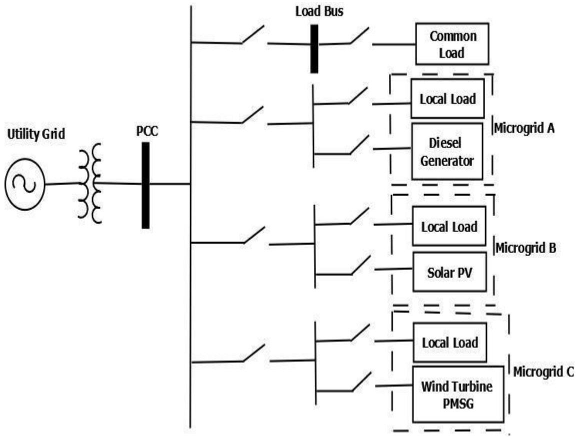

Fig. 22. Architecture of IMMG with two AC and one DC MGs

Fig. 23 depicts the detailed architecture of the IMMG with two AC and one DC MGs. Here, a 25 kV load was applied to the three phase AC bus voltage. The MG A was provided with a diesel generator that enables it to deliver energy to the AC bus via a three phase transformer. In contrast, the MG B contains a PV array; here, the power is delivered to the AC bus via VSC and a 3-phase transformer. Consequently, the Perturb and Observe approach was employed for tracking the maximum power point (MPP) of the PV units. To precisely track MPP, an ideal duty cycle was provided to the boost converter IGBTs as input. The MG C uses the wind turbine Permanent Magnet Synchronous Generator (PMSG) as the power source and delivers energy to the AC bus via a converter, 3 phase transformer, and filters. In addition, the controlled synchronverter was deployed to manage PCC voltage and load bus voltage. Moreover, the utility grid is considered the AC source and power is supplied through the three phase transformer. A three phase RLC load is used as the system load.

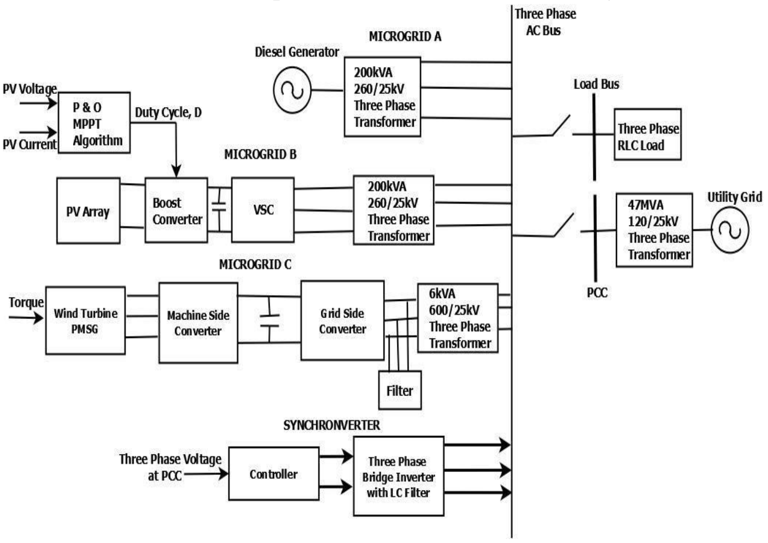

Fig. 23. Systematic block diagram of the IMMG

2) Synchronverter

This model contains components like a regulator, LC filter, three-phase inverter, and two power modules. Typically, the inverter current waveform and output voltage will be non-sinusoidal; therefore, the model uses an LC filter to smooth those waveforms. Then, the sinusoidal PWM generator produces pulses with the reference signal to stimulate the IGBTs of the three phase inverter. The architecture outlining the frequency and voltage control loop of the synchronverter controller is provided in Fig. 24.

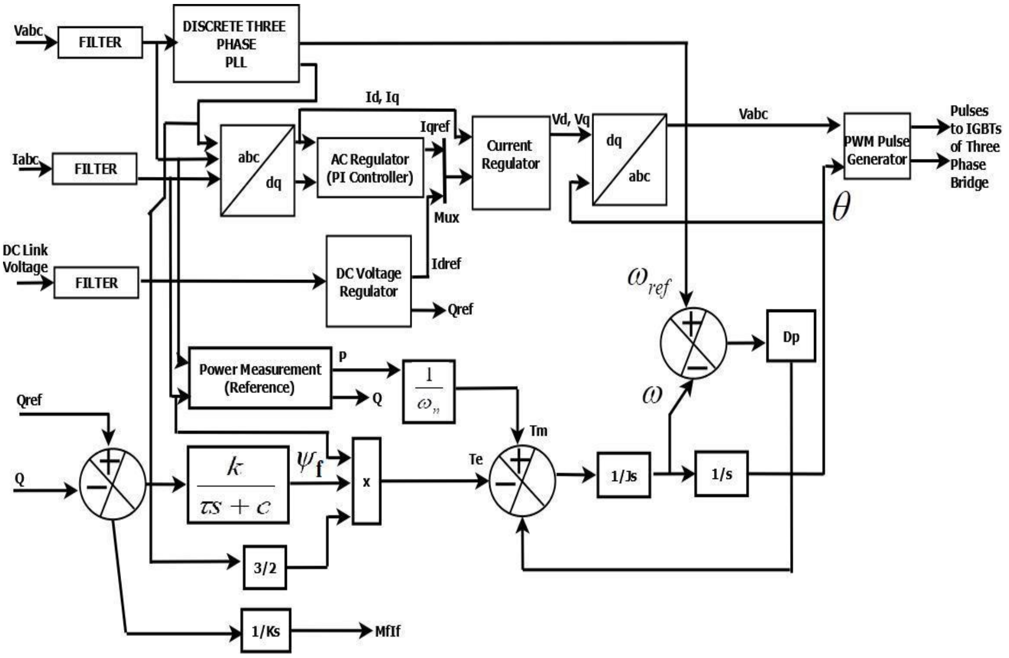

Fig. 24. Structure of the frequency and voltage controlled Synchronverter

3) Simulation Outcomes

In the IMMG framework, the frequency and voltage-controlled synchronverter is responsible for handling the stability challenges associated with the voltage profile in both load bus and PCC. Three different cases are investigated:

a) Starting Transients

During the startup phase, the waveform experienced significant transients, which are illustrated in Figs. 25 and 26. However, the controlled synchronverter quickly restores the load absolute power to 20kW within 0.05 seconds. Also, the current in the three-phase load bus was balanced in less than 0.2 seconds.

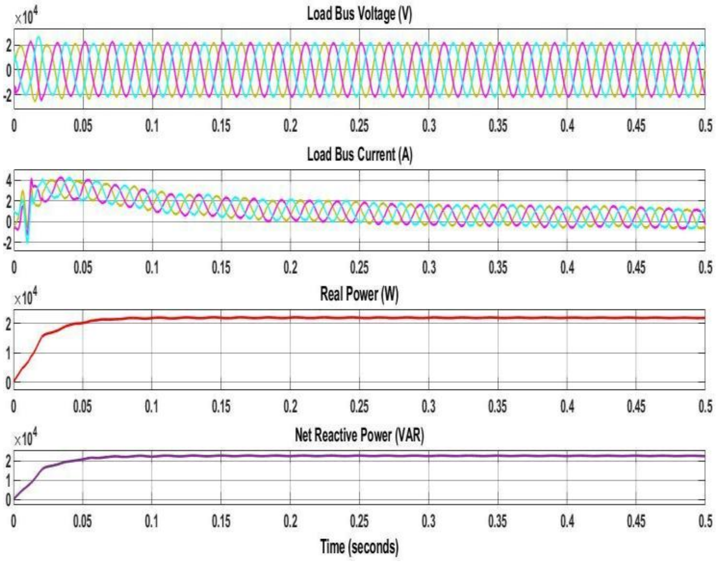

Fig. 25. Load bus constraints

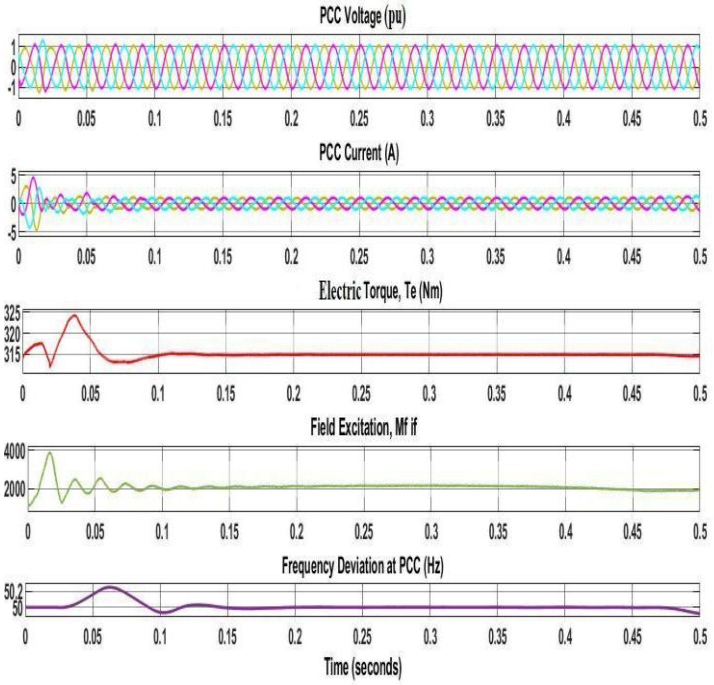

Fig. 26. Variation of PCC Voltage, Current, and Frequency

In addition, the three phase current and PCC voltage achieved a balanced phase in less than 0.05 seconds, and the synchronverter electric torque was balanced at 315 Nm in 0.1 seconds, as demonstrated in Figure 26. Moreover, the frequency is set back to 50 Hz, and field excitation attains its steady phase in less than 0.15 and 0.1 seconds, respectively.

b) Load variation

In this case, the load is exclusively triggered at 0.5 seconds, as presented in Fig. 27. After stimulating the load, significant transients are observed in the waveforms, as shown in Figs. 27 and 28. Owing to this, the synchronverter starts functioning rapidly and restores the waveforms to their standard values. The frequency was returned to 50 Hz in 1 second.

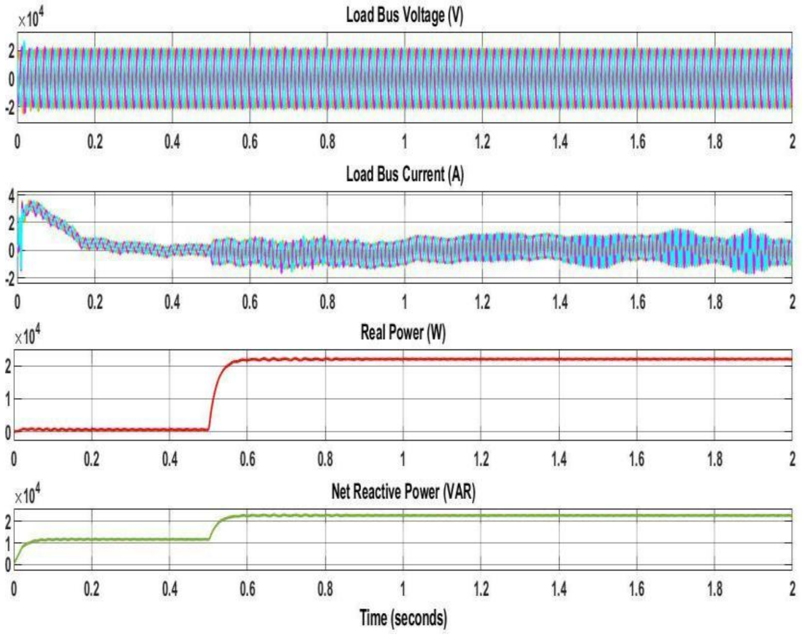

Fig. 27. Load bus constraints

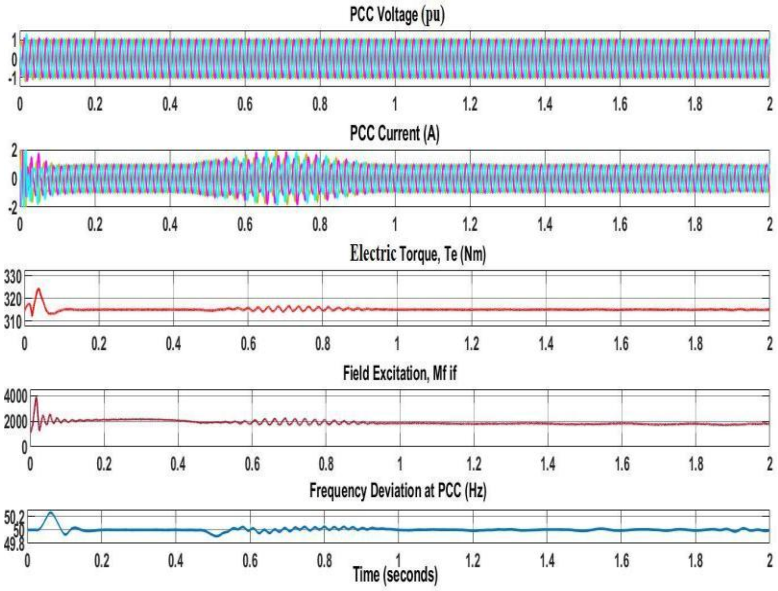

Fig. 28. Variation of PCC Voltage, Current and Frequency

c) Varying torque input of the WT PMSG

In this instance, the pitch angle regulator manages the input torque of the WT PMSG. This scenario is presented visually in Fig. 29. This regulator accepts the real rotor speed and reference speed as inputs and produces the wind speed, pitch angle, and rotor speed as outputs. These outcomes are given as input to the turbine to produce the mechanical torque fed into the PMSG unit. Fig. 30 depicts the electromagnetic torque and mechanical torque.

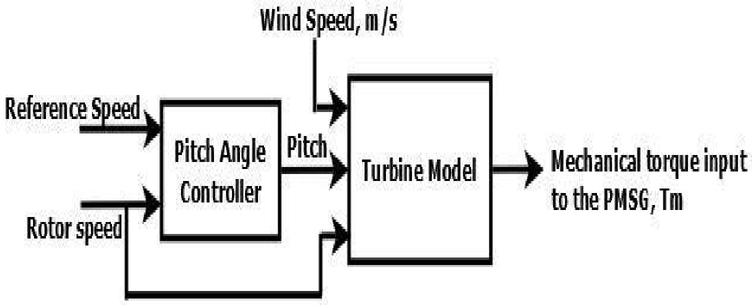

Fig. 29. Systematic structure of Pitch Angle regulator

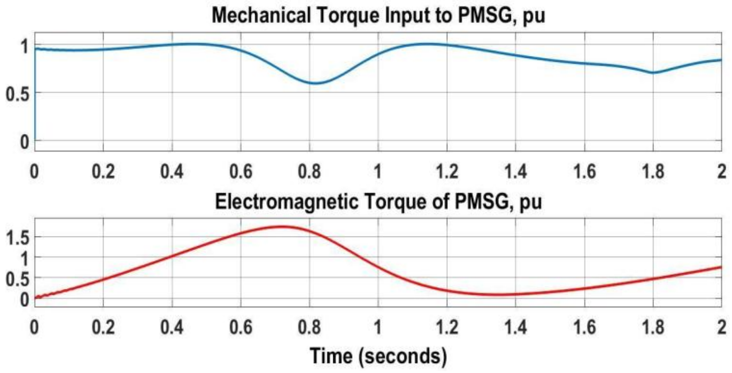

Fig. 30. Input Mechanical Torque and Electromagnetic Torque of PMSG

Fig. 31 shows a minor influence on the load bus variables. In addition, the electromagnetic torque diminished between 0.8 and 0.12 seconds, as demonstrated in Fig. 32. This reduction of electromagnetic torque illustrates that during this time, a significant transient existed in the PCC current, field excitation, electric torque, and frequency. However, the synchronverter rapidly redirects these variables to their normal values.

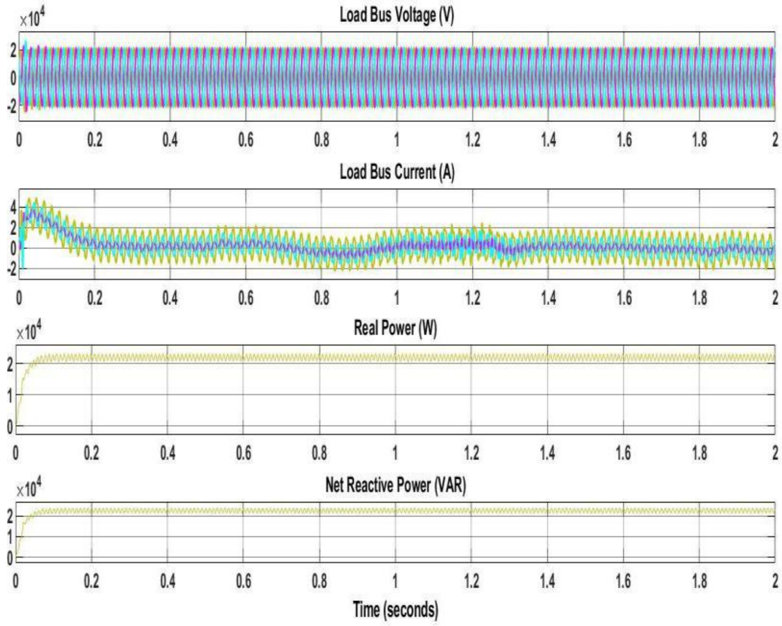

Fig. 31. Load bus parameters

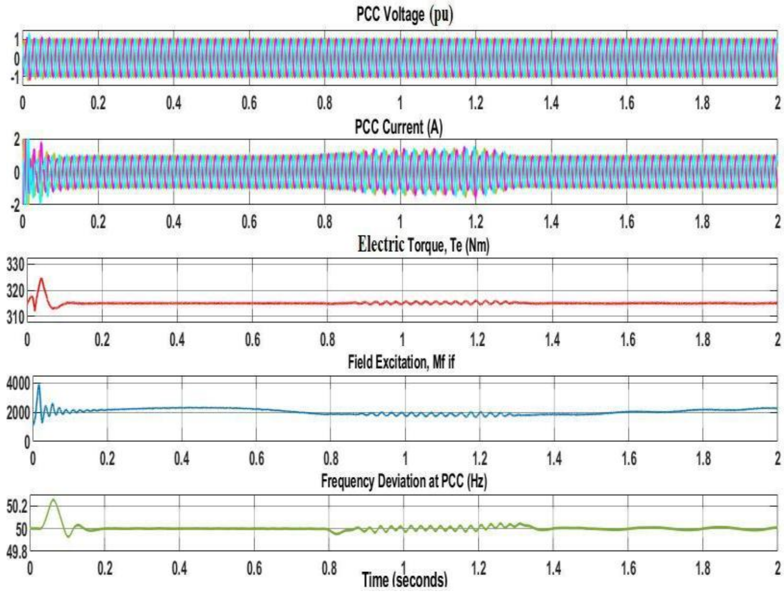

Fig. 32. PCC Voltage, Current and Frequency deviation

IV. CONCLUSIONS

In conclusion, the paper has provided a comprehensive overview of voltage profile improvement techniques for interconnected microgrids, highlighting the significance of maintaining stable voltage levels within these complex systems. Three cases of IMMGs were analyzed. The first case was an IMMG consisting of two DC microgrids. In this case, a passive filter is designed for voltage profile improvement as it is the most economical solution. The second case is an IMMG consisting of two AC microgrids. PI and Fuzzy-controlled D-STATCOMs have been proposed, and effective solutions for voltage profile improvement have been found in this scenario. Simulation results proved the Fuzzy-controlled D-STATCOM to be a better solution than the PI-controlled one. The third case is an IMMG with two AC and one DC microgrid. Synchronverter control has been proposed and found to be effective in this case. A detailed examination of various approaches shows that a diverse range of solutions exists to address voltage profile challenges in interconnected microgrids. Furthermore, the analysis presented in this paper highlights the significance of selecting the best approach considering the demands and features of the IMMG under construction. While some techniques prioritize response time and cost-effectiveness, others prioritize reliability and scalability. Therefore, carefully evaluating these factors is essential in designing effective voltage profile improvement strategies.

REFERENCES

[1] C Sojy Rajan, Mabel Ebenezer, “Modeling Operation & Simulation of Interconnected DC Microgrids” 2020 IEEE International Conference on Power Instrumentation Control & Computing (PICC2020), Government Engineering College, Thrissur, Dec 2020.

[2] Adam Hirsch, Yael Parag, Josep Guerrero, “Microgrids: A review of technologies, key drivers, and outstanding issues”, Renewable and Sustainable Energy Reviews, vol. 90, pp. 402–411, July 2018.

[3] N. Hatziargyriou, H. Asano, R. Iravani, and C. Marnay, “Microgrids,” IEEE Power Energy Mag., vol. 5, no. 4, pp. 78–94, Jul./Aug. 2007.

[4] Y. Yolda, A. Önen, S. M. Muyeen, A. V. Vasilakos, and Alan, “Enhancing smart grid with microgrids: Challenges and opportunities," Renew. Sustain. Energy Rev., vol. 72, pp. 205_214, May 2017.

[5] Hualei Zou, Shiwen Mao, Yu Wang, and et al., “A Survey of Energy Management in Interconnected Multi-Microgrids”, IEEE Access Special Section on Urban Computing & Intelligence, Vol. 7, pp. 72158-72169, 2019.

[6] Poornima S, Joise K George, “Power Factor Improvement Using PI Controlled DSTATCOM”, International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering, Vol.5, Issue 8, August 2016.

[7] N Raveendra, V Madhusudhan, A Jaya Laxmi, “PI and Fuzzy Controlled D-STATCOM based on Power Quality Theory”, International Conference on Energy, Communication, Data Analytics and Soft Computing (ICECDS), June 2018.

[8] Juan Shi, Amin Noshadi, Akhtar Kalam, Peng Shi, “Fuzzy logic control of DSTATCOM for improving power quality and dynamic performance”, 2015 Australasian Universities Power Engineering Conference (AUPEC), Nov. 2015.

[9] Lavanya R Shekar, S Sumana, R Dhanalakshmi, “Voltage Regulation Using DSTATCOM in Distribution Grid for Enhancement of Power Quality”, 2018 2nd International Conference on Trends in Electronics and Informatics (ICOEI), Dec. 2018.

[10] Subhadip Bhattacharya, Benjamin A. Shimray, “Power quality improvement and mitigation of harmonic distortion using DSTATCOM with PI and Fuzzy Logic Controller”, 2017 International Conference on Smart grids, Power and Advanced Control Engineering (ICSPACE), April 2018.

[11] Epsita Das, Swaraj Basak, Swarnabha Sarkar;Biswarup Ganguly, Ambarnath Banerji, Sujit. K. Biswas, “Fuzzy PID Controlled DSTATCOM for Delivering Quality Power”, 2020 IEEE VLSI Device Circuit and System (VLSI DCS)

[12] Ahmed Hussain Elmetwaly; Azza Ahmed Eldesouky; Abdelhay Ahmed Sallam, “An Adaptive D-FACTS for Power Quality Enhancement in an Isolated Microgrid”, IEEE Access, Vol.8, March 2020.

[13] Q.C. Zhong and G. Weiss, “Synchronverters: Inverters that mimic synchronous generators,” IEEE Transactions on Industrial Electronics, vol. 58, no. 4, pp. 1259-1267, 2011.

[14] Q.C. Zhong, P.-L. Nguyen, Z. Ma and W. Sheng, “Self-synchronized synchronverters: Inverters without a dedicated synchronization unit,” IEEE Transactions on Power Electronics, vol. 29, no. 2, pp. 617-630, 2014.

[15] Purvi Chandrakar, Saptadip Saha, Priyanath Das, Ankit Singh, Sajal Debbarma, “Grid Integration of PV System using Synchronverter”, 2018 International Conference on Computation of Power, Energy, Information and Communication (ICCPEIC), 2018.

[16] Nafeh, Abdelnasser A., Aya Heikal, Ragab A. El-Sehiemy, and Waleed A. A. Salem, "Intelligent fuzzy-based controllers for voltage stability enhancement of AC-DC micro-grid with D-STATCOM." Alexandria Engineering Journal 61, no. 3 (2022): 2260-2293.

[17] Rajan, Charivil Sojy, and Mabel Ebenezer. "Fuzzy controlled D-STATCOM to improve the PCC voltage profile of a multi-microgrid interconnection scheme." In Control Applications in Modern Power Systems: Select Proceedings of EPREC 2021, pp. 219-232. Singapore: Springer Nature Singapore, 2022.

[18] Kar, Manoj Kumar, Sanjay Kumar, and Arun Kumar Singh. "Power quality improvement of an interconnected grid system using PWM technique of D-STATCOM." In Recent Advances in Power Electronics and Drives: Select Proceedings of EPREC 2021, pp. 31-41. Singapore: Springer Nature Singapore, 2022.

[19] Rajan, Charivil Sojy, and Mabel Ebenezer. "Voltage Profile Improvement of a Multi Microgrid Interconnection Scheme using Synchronverters." In 2022 IEEE International Conference on Signal Processing, Informatics, Communication and Energy Systems (SPICES), vol. 1, pp. 217-222. IEEE, 2022.

[20] Santhoshkumar, Thenpennaisivem, and V. Senthilkumar. "Transient and small signal stability improvement in microgrid using AWOALO with virtual synchronous generator control scheme." ISA transactions 104 (2020): 233-244.