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Optimizing Induction Wind Energy System with EDLC and PMSG for Efficient Power Control

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ABSTRACT

This paper represents a comprehensive study on the optimization of an Induction Wind Energy System (IWEC) integrated with Electric Double Layer Capacitors (EDLCs) and a Permanent Magnet Synchronous Generator (PMSG) to enhance power control in the quest for sustainable and efficient energy conversion systems. As wind energy plays a pivotal role in the renewable energy landscape, maximizing its conversion efficiency is crucial for a sustainable future. Advanced control strategies and optimization techniques are applied to delve into the intricate details of the IWEC-EDLC-PMSG system, resulting in improved power quality, enhanced transient response, and superior grid integration capabilities. The research demonstrates that this integrated configuration outperforms conventional wind energy systems in terms of efficiency, grid compatibility, and dynamic response. Moreover, the study addresses key aspects like system stability, fault tolerance, and reliability, ensuring the robustness of this innovative solution. In addition to advancing wind energy technology, this research offers valuable insights into integrating energy storage systems and advanced control techniques for efficient power control in renewable energy applications, contributing to a sustainable energy future.

Keywords: Wind energy system, Induction generator, Wind power extraction, and Efficiency improvement.

INTRODUCTION:

Wind energy, a rapidly expanding and vital component of the global renewable energy landscape, has witnessed extraordinary growth in recent years. The year 2021 alone saw a remarkable increase of the 273 terawatt-hours, a 17% surge in electricity generation from wind, the surpassing all other power generation technologies and marking a 45% higher growth rate than in 2020. However, this impressive growth story is not without its challenges. The principal hurdle facing the widespread adoption of wind power lies in its inherent variability and unpredictability, resulting from the capricious nature of wind patterns. Traditionally, Induction Generators (IGs) have been the workhorse of wind farms, but their output fluctuations & reactive power demands during network disturbances pose significant grid integration challenges (V. Yaramasu *et al.,* 2017). This introduction sets the stage for a closer examination of these challenges and the innovative solutions, highlighting the transition towards cost-effective & grid-compliant wind energy technologies, such as Permanent Magnet Synchronous Generators (PMSGs) combined with energy storage solutions. **Fig. 1** shows the overview of global wind energy forecast 2020-2030. The literature review presents an overview of research studies pertaining to various aspects of wind power systems, encompassing stability, control, and the performance enhancement. These studies contribute valuable insights into the challenges and solutions associated with wind energy generation. The following is a summary of the key findings and contributions of each study:

Emphasizes the potential of using Electrical Double Layer Capacitors (EDLCs) in grid-connected wind parks for mitigating fast wind power fluctuations (M. Guohong Wu *et al.,* 2012). It suggests the combining EDLCs with batteries to improve power flow leveling and voltage stability, particularly in the challenging topographical conditions. M. S. Zinat Tasneem *et al.* (2015) study addresses the issue of output fluctuations in wind farms caused by the varying wind speeds, particularly for the fixed-speed wind generators like induction generators (IG) (Hossain *et al*., 2023).

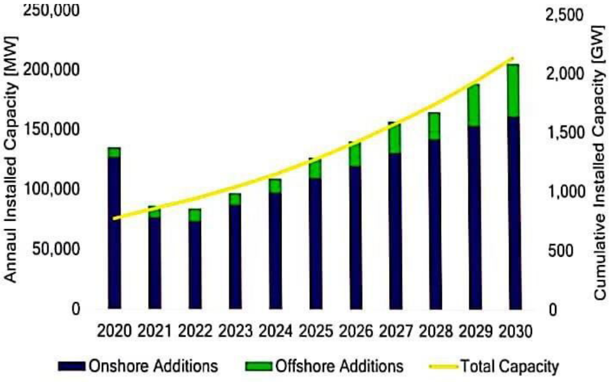

Fig. 1: Global Wind Power Forecast 2020-2030.

The research proposes the integration of Permanent Magnet Synchronous Generators (PMSGs) to smoothen power output and enhance system response during faults. The Sub-synchronous interactions (SSIs) in the wind turbines have received a lot of attention in recent years. The variety of wind power generation types, power grids, & power electronic equipment characterizes these oscillations (L. Reddy *et al.,* 2011). This article (R. Linus *et al.,* 2015) introduces a sensor less hill-climbing algorithm for the grid-connected, field-oriented controlled permanent magnet synchronous generator-based wind energy conversion systems. The algorithm aims to improve the accuracy and speed of initial tracking for the optimal power extraction. S. Vijayalakshmi *et al.* (2011) research underscores the superior performance of PMSGs due to their higher efficiency and lower maintenance requirements, attributed to the absence of rotor current and the ability to operate without a gearbox. The study also discusses maximum power point tracking. Li Wang *et al.* (2012) investigates the use of a Static VAR Compensator (SVC) to enhance the power control that the proposed control scheme can effectively stabilize the system under severe disturbances and the mitigate power fluctuations. Abhishek M Patel *et al.* (2019) focuses on adding PMSGs to induction generators (IGs) to meet reactive power requirements during network disturbances and wind code requirements during network faults. Simulation results indicate that this topology can enhance Low-Voltage Ride-Through (LVRT) performance and the economic benefits. This study (H. Muhammad *et al.,* 2007) investigates the development of a power system model for wind farms and assesses normal and abnormal operations under different wind speed conditions. It concludes that the wind turbines perform within acceptable criteria. B. Anjan *et al.* (1983) adapts a wind turbine-generator system for stability evaluation using a large-scale transient stability computer program. The study includes descriptions of component models, digital model equations, and a versatile wind velocity model capable of simulating various wind variation. C. Maun *et al.* (2004) highlights the importance of the signal stability within a measurement window for enhancing process robustness in power generation. It suggests that assessing grid impedance values at fundamental and harmonic frequencies can aid in power quality monitoring, network component design, control system tuning, and protection configuration. In summary, these research studies collectively contribute to advancing the understanding and performance of wind power systems, covering a wide range of the topics, including stability enhancement, control strategies, and system modeling. Continued research in these areas is essential for the further optimizing wind energy generation and its integration into the global energy landscape. In this paper, the proposed designed wind power generation system model has been simulated and designed by using PSCAD/EMTDC simulation tool. The structure of the paper is organized as follows: Section II covers the proposed wind power generation system model optimization. Then, the corresponding result and the discussion of the paper are concerned in section III. Finally, the conclusion of this presented work is shown in section IV.

Proposed Wind Power Generation System Model

EDLC (Electrical Double Layer Capacitor), which has an extremely high response and long-life cycle but is high cost, is introduced with small capacity for mitigating fast wind power fluctuation only. The new idea is to locate the Permanent Magnet Synchronous Generator (PMSG) near to IG and it has the ability to fulfil the requirements of reactive power during network disturbances. When there is a fault on network reactive power, requirement of IG is fulfilled using a combination of it with PMSG to meet wind grid code requirement. **Fig. 2** shows the schematic diagram of only IG with EDLC.

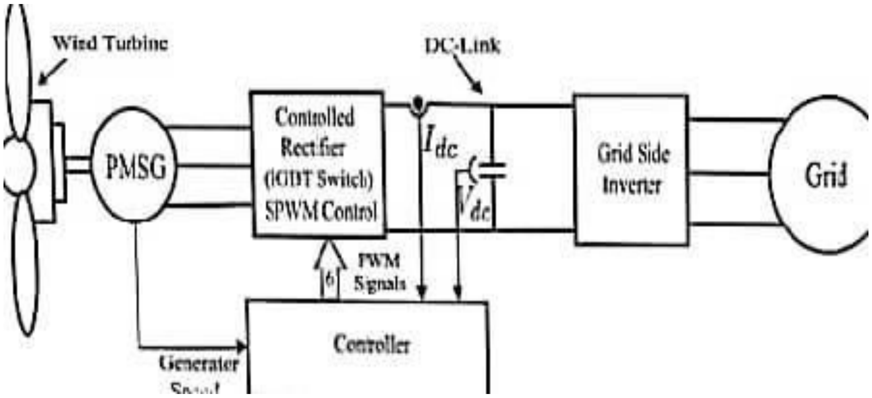

Fig. 2: Block Diagram of Only IG with EDLC Model.

The complete models consist of the Permanent Magnet Synchronous Generator (PMSG) model with two Induction Generators (IGs) connected in series. Here one PMSG rated 3 MA connected to 11.4KV distribution system through a frequency converter, 0.69/11. 4K V step-up transformer and underground cable. Two induction generators connected in series to the high voltage side of the 0.69/11.4K V step-up transformer through 0.69/11.4KV step-up transformers and short underground cables. A capacitor bank has been considered for reactive power compensation at the steady state. The value of capacitor bank is chosen so that power factor of the IG during rated operation becomes unity. The outputs of the wind farm are supplied to the utility grid through a common step-up transformer rated 11.4/66KV. Here system bases used are 6MVA and 9MVA for series models. **Fig. 3** represents the schematic PSMG model. The diagrammatic representation of series connected IG with PMSG is shown in **Fig. 4**.

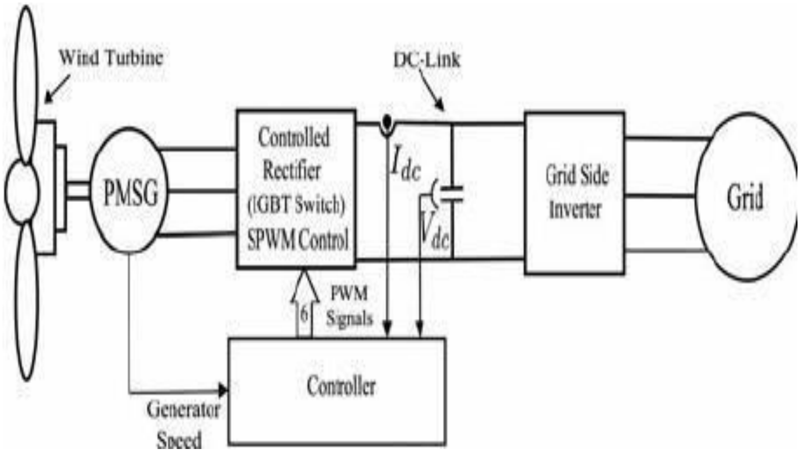

Fig. 3: Block Diagram of PMSG Model.

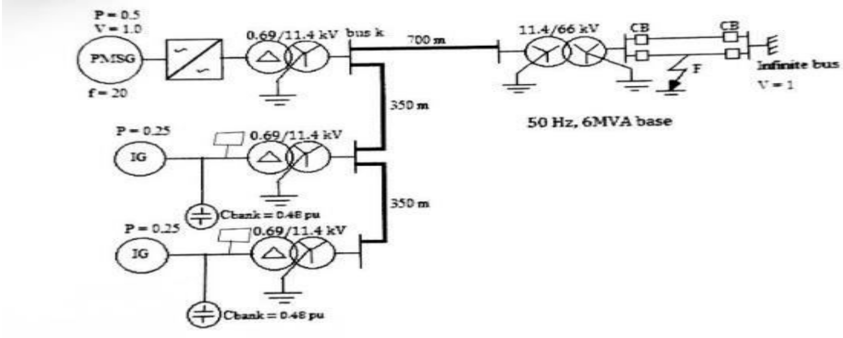

Fig. 4: Block Diagram of Series Connected IG with PMSG.

Modeling for Simulation and Control

In this study new type wind power generating topology is considered which is composed of connecting PMSG with EDLC based IG in the series can mitigate the problems of total power quality. All types of damping are discarded to obtain worst case scenario. Symmetrical three line to ground fault (3LG) is considered as a network disturbance, which occurs at fault point F. the fault occurs at 5s, the circuit breaker of the faulted line is opened at 5.1s and 5.2s the circuit breakers are reclosed. In the simulation study it is assumed that the wind speed is stationary and equivalent to the rated speed of both fixed and variable speed WTGs. This is because it may be considered that wind speed does not change dramatically during the short interval of time of the simulation. **Table 1** shows the case study of wind power system optimization model which divides 5 types A, B, C, D, and E respectively. Simulations have been carried out by using PSCAD/EMTDC.

Table 1: Case Study.

Case 1 IG Only	Case 2 PMSG Only	Case 3 IG + EDLC	Case 4 PMSG + IG
IG (1.5 MVA)	PMSG (3MVA)	3 (MVA)	PMSG (3 MVA)
			IG (1.5 MVA)
			IG (1.5 MVA)

Case 1: IG Only.

Fig. 5, **6** and **7** show the simulation results of this case. These figures show the real power, reactive power and voltage outputs of an Induction generator. From the figures it is clear that when a fault occurs the output of the induction generator changes and returns to the normal condition after a long time. The grid code allows this time to be 3s as stated in the article. So, this system is not fulfilling the grid code requirement for low voltage ride through.

Real Power

The real power output of normal IG can be limited due to the rotor losses and the low power factor.

Reactive Power

The reactive power output of normal IG can be affected by the load characteristics because the rotor cannot provide a constant voltage output.

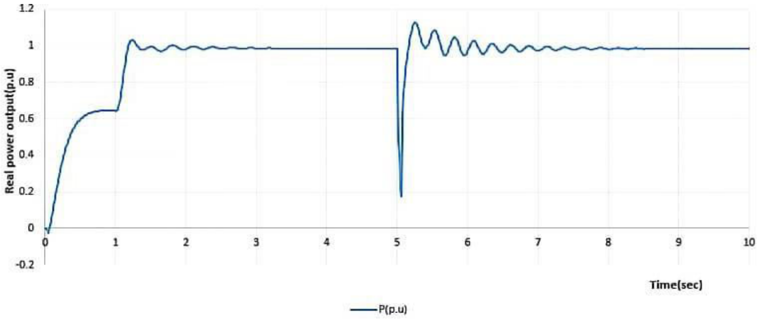

Fig. 5: Real Power Output of Induction Generator.

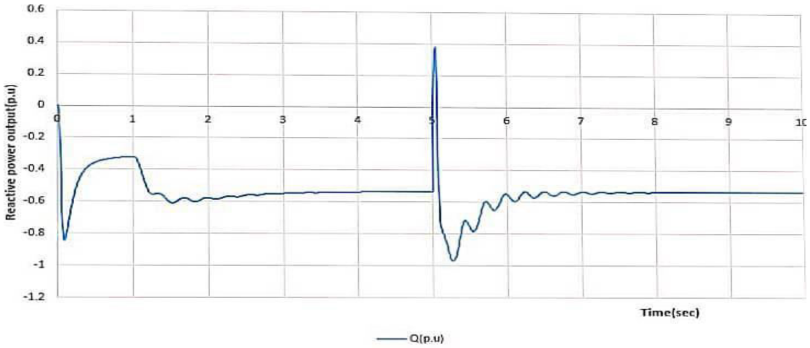

Fig. 6: Reactive Power Output of Induction generator.

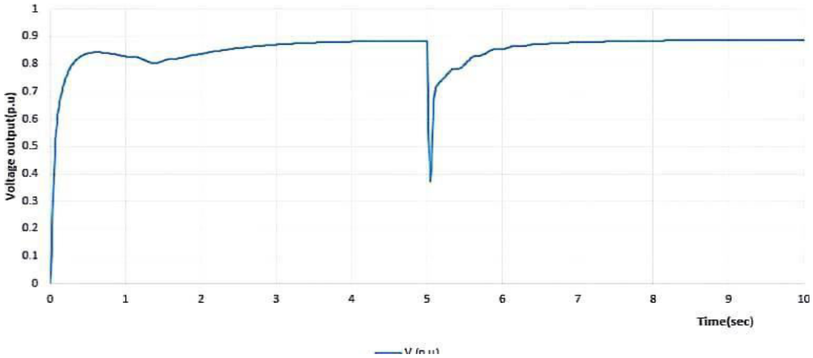

Fig. 7: Voltage Output of Induction Generator.

Voltage Output

The voltage output of normal IG can also be affected by the load variations, which can result in the voltage fluctuations.

Case 2: PMSG Only.

Fig. 8, **9** and **10** show the simulation results of this case. These figures show the real power, reactive power and the voltage outputs of a permanent magnet synchronous generator. After fault this system returns to normal condition within a second. So, it fulfils the grid code requirement and will remain online after the fault, so PMSG can fulfil the necessary LVRT requirement of the system when connected with other wind turbine generators.

Real Power

The real power output of normal PMSG can be higher than the normal IG because the permanent magnet provides a more constant voltage output.

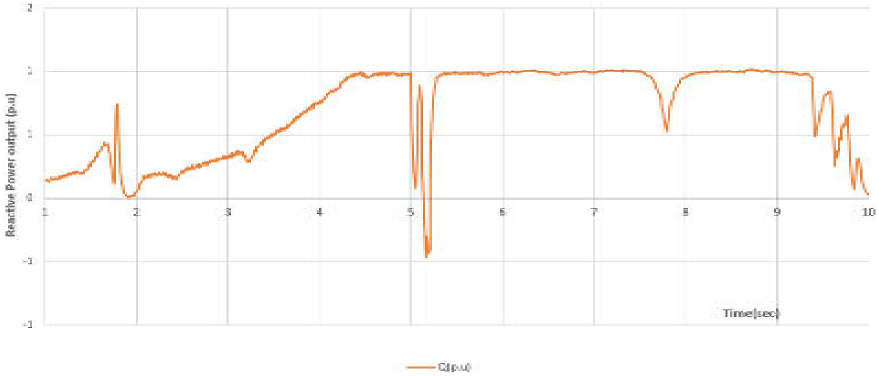

Fig. 8: Reactive Power Output of IG with EDLC.

Voltage Output

The voltage output of normal PMSG can also be more stable than normal IG because the permanent magnet provides a constant voltage output.

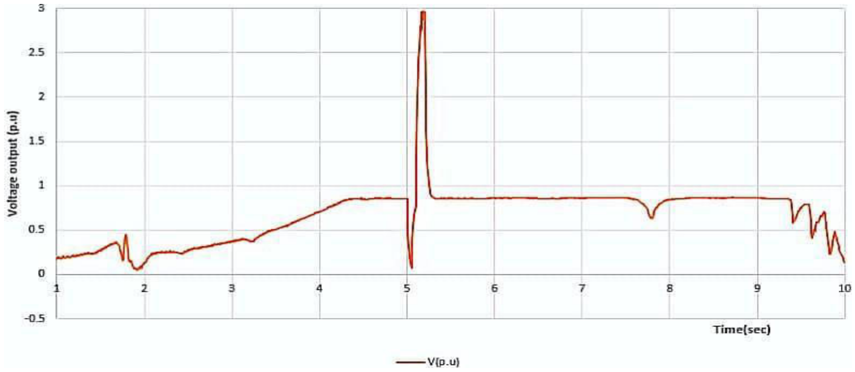

Fig. 9: Voltage Output of PMSG only.

Case 3

IG with EDLC

Fig. 11, **12** and **13** show the simulation results of this case. These figures show the real power, reactive power and voltage outputs of a series connection. It uses the properties of EDLC as a manner to mitigate the fast fluctuations in a small capacity to enhance the LVRT capability of IGs.

Real Power

The real power output of the IG with EDLC can be limited due to the excitation losses in the capacitor.

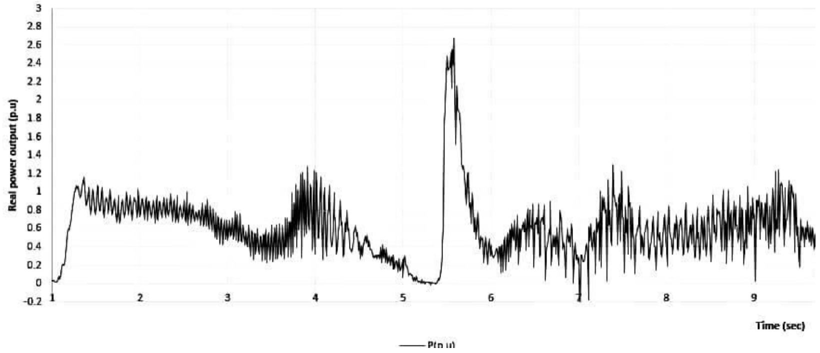

Fig. 10: Real Power Output of IG with EDLC.

Reactive Power

The reactive power output of the IG with EDLC can be affected by the load characteristics because the capacitor cannot provide a constant voltage output.

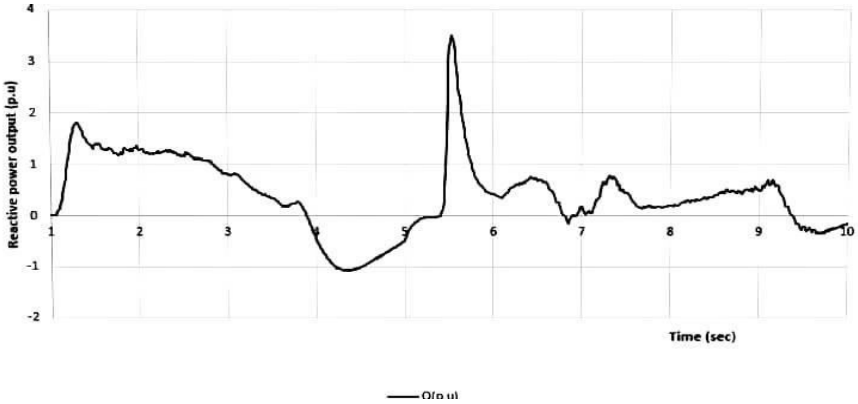

Fig. 11: Reactive Power Output of IG with EDLC.

Voltage Output

The voltage output of the IG with EDLC can also be affected by the load variations, which can result in voltage fluctuations.

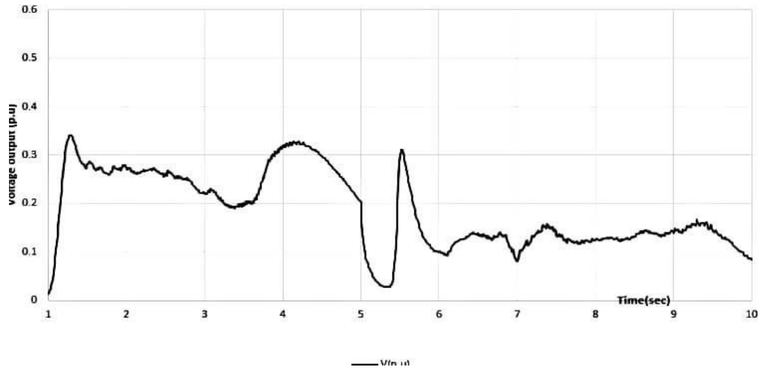

Fig. 12: Voltage Output of IG with EDLC.

Case 4

PMSG and IG

Fig. 13, **14** and **15** show the simulation results of this case. These figures show the real power, the reactive power and voltage outputs of a series connection. It uses the properties of PMSG to enhance the LVRT capability of IGs.

Real power

IG with PMSG is a combination of two types of the generators that can provide the several advantages compared to other generator types. The real power output of IG with PMSG can be higher than other generator types because the PMSG provides a constant voltage output, which results in a more balanced distribution of real and reactive power.

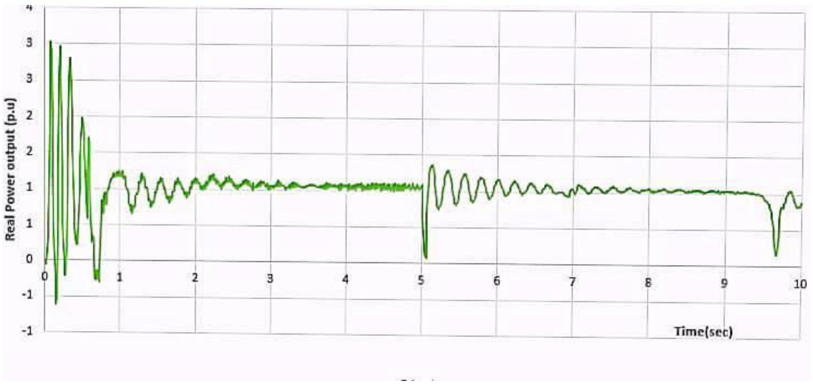

Fig. 13: Real Power Output of IG and PMSG.

Reactive power

The reactive power output of IG with PMSG can be better than other generator types because the PMSG provides a more stable voltage output.

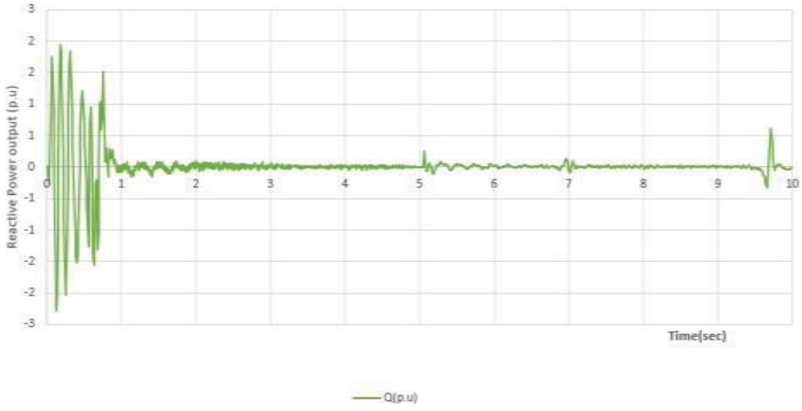

Fig. 14: Reactive Power Output of IG and PMSG.

Voltage Output

The voltage output of IG with PMSG can also be more stable than other generator types because the PMSG provides a constant voltage output.

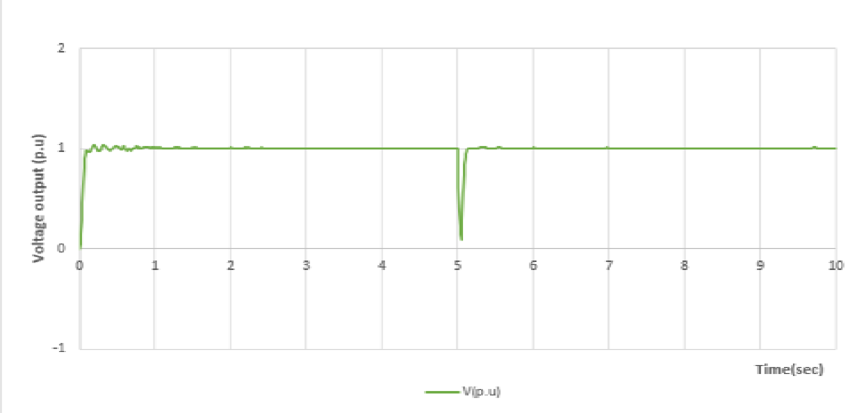

Fig. 15: Voltage Output of IG and PMSG.

Comparison between IG, PMSG, IG with EDLC and IG with PMSG

Real Power

Real power is the actual power that is consumed or delivered to a load. From **Fig. 16** we can say, the real power output of IG with PMSG is higher than other generator types because PMSG provides a constant voltage output, which results in a more balanced distribution of real and reactive power. This means that the generator can supply more real power to the load without exceeding its rated capacity.

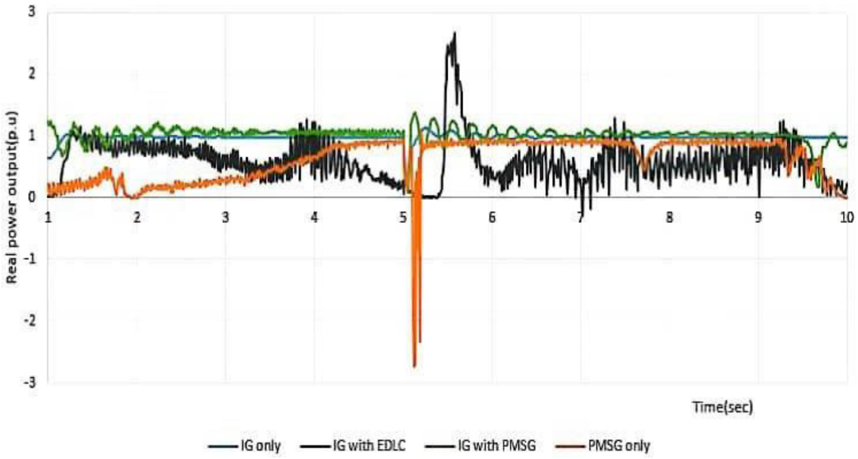

Fig. 16: Real Power Output of IG, PMSG, IG with EDLC and IG with PMSG.

Reactive Power

Reactive power is the power that is exchanged between the generator and the load to maintain the voltage level. From **Fig. 17** we can say, IG with PMSG can provide better reactive power control than other generators because PMSG has a strong magnetic field that maintains the output voltage constant, irrespective of the load variations. This means that the generator can supply more the reactive power to the load when required to maintain the voltage level (Uddin *et al.*, 2021).

Comparison between IG, PMSG, IG with EDLC and IG with PMSG

Real Power

Real power is the actual power that is consumed or delivered to a load. From **Fig.16** we can say, the real power output of IG with PMSG is higher than other generator types because PMSG provides a constant voltage output, which results in a more balanced distribution of real and reactive power. This means that the generator can supply more real power to the load without exceeding its rated capacity.

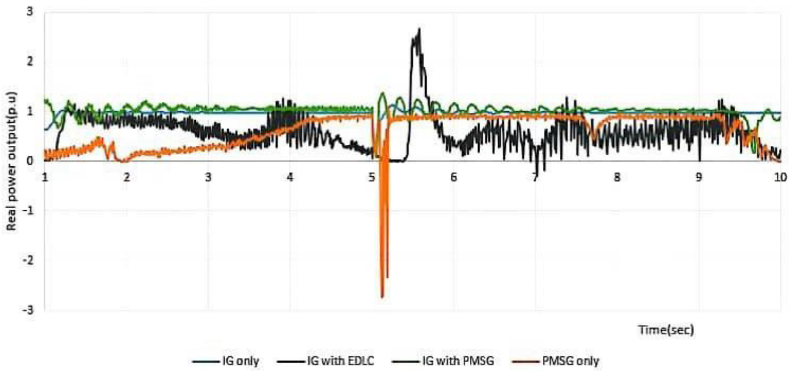

Fig. 17: Real Power Output of IG, PMSG, IG with EDLC and IG with PMSG.

Reactive Power

Reactive power is the power that is exchanged between the generator and the load to maintain the voltage level. From **Fig. 17** we can say, the IG with PMSG can provide better reactive power control than other generators because PMSG has a strong magnetic field that maintains the output voltage constant, irrespective of the load variations. This means that the generator can supply more reactive power to the load when required to maintain the voltage level.

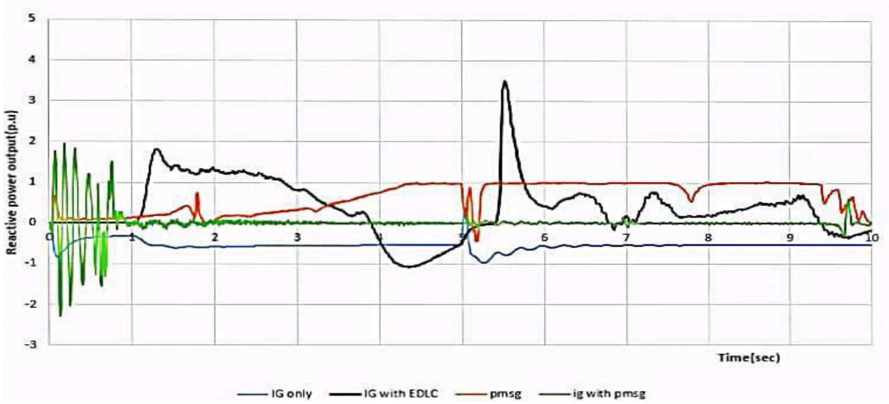

Fig. 18: Real Power Output of IG, PMSG, IG with EDLC and IG with PMSG.

Voltage Output

Voltage output is the magnitude of the voltage produced by the generator. From **Fig.18** we can say, IG with PMSG can provide a more stable voltage output than other generators because the PMSG has a strong magnetic field that the maintains the output voltage constant, irrespective of the load variations. This means that the generator can supply a more stable voltage output to the load even under varying wind speed.

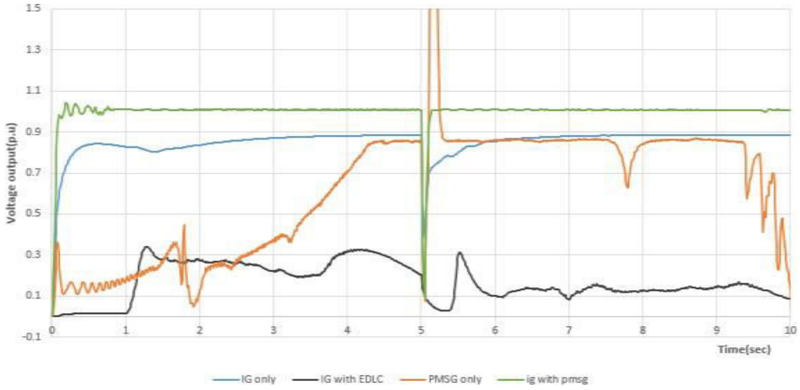

Fig. 19: Voltage Output of IG, PMSG, IG with EDLC and IG with PMSG.

CONCLUSION:

Through a systematic analysis of the proposed system, it is evident that the integration of EDLCs provides a viable solution for mitigating the intermittent nature of wind energy, effectively smoothing power fluctuations and enhancing the overall system performance. The synergy between the PMSG and EDLCs has been demonstrated to improve power quality, reduce grid disturbances, and increase the system's response time to the varying wind conditions. Furthermore, the optimized IWEC system exhibits a notable increase in the energy conversion efficiency, thus making it a promising choice for sustainable wind power generation. The findings of this study underscore the potential of EDLCs as a valuable energy storage component in wind energy systems contributing to a more reliable and efficient renewable energy land-scape. Further research and development in this area will undoubtedly lead to even greater advancements in wind energy technology.

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CONFLICTS OF INTEREST:

The authors declare that they have no conflicts of interest.

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