JEATSA JOURNAL
JOURNAL OF ENGINEERING ADVANCES AND TECHNOLOGIES FOR SUSTAINABLE APPLICATIONS
Volume 1, Issue 2 (April, 2025)
Print ISSN: 3062-5629 Online ISSN: 3062-5637
Open Access
https://jeats.journals.ekb.eg/

Enhancing Voltage Stability in PV/Wind Power Systems with STATCOM Utilizing Fuzzy Controller

Ahmed A. Zaki Diab [a,1,*], *Ibram Y. Fawzy* [a,2], *Ahmed M. Elsawy* [a,3], *Ayat G. Abo El-Magd* [b,4]

[a] *Electrical Engineering Department, Faculty of Engineering, Minia University, Minia 61111, Egypt*
[b] *El-Minia High Institute of Engineering and Technology, New Minya, 61111 Minia, Egypt*

[1] a.diab@mu.edu.eg; [2] ibramyehia@yahoo.com ; [3] ahmed.elsawy@mu.edu.eg ; [4] yassen_mk_2012@yahoo.com

[*] Corresponding author: a.diab@mu.edu.eg

Received 29-09-2024
Revised 16-10-2024
Accepted: 1-11-2024
Published: April-2025

Print ISSN: 3062-5629
Online ISSN: 3062-5637

Abstract- Renewable energy sources (RES) has gained pivotal importance due to the depletion of fossil fuels, coupled with increasing electricity demand and escalating environmental concerns. The integration of renewables into power systems significantly impacts grid performance. Addressing transient performance issues remains a critical area that requires further investigation. This paper explores the deployment of a Static Synchronous Compensation Device (STATCOM) utilizing a controller based on fuzzy logic (FLC) to tackle voltage stability issues in the IEEE nine-bus investigation, specifically considering the incorporation of Photovoltaic (PV) and Wind energy. The STATCOM based on FLC is considered as a dynamic voltage recovery aimed at sustaining voltage stability, thus preservation of RES through and after occurring disturbances. A virtual simulation is performed utilizing Matlab/Simulink environment with Proportional Integrative (PI) controller and with FLC of the STATCOM under different conditions to prominence the variation which the offered STATCOM presents concerning transient stability. The study aims to illustrate the effectiveness of FLC over PI controller for enhancing the system stability at different locations using STATCOM device. The obtained results inspect that STATCOM contributes better response through FLC under abnormal conditions as compared to PI controller.

Keywords- *Power System, renewable energy sources (RES), Wind, PV, STATCOM, PI Controller, Fuzzy Logic Controller (FLC), Faults, and Voltage Stability.*

I. *INTRODUCTION*

As the global population and industrial advancements continue to grow, the demand for energy is rising, while fossil energy reserves are being depleted at an alarming rate. Currently, although fossil fuels like coal, oil, and natural gas are still utilized for energy generation, their rapid exhaustion is prompting a greater shift toward renewable energy sources (RES) [1].

RES include solar, wind, hydropower, geothermal energy, and biomass. Technologies based on renewable energy can transform these resources into various forms, including electricity, heat, chemicals, and mechanical power. Embracing renewable energy has the potential to promote energy independence and improve safety in energy production [2].

In recent years, RES have made significant advancements to address the growing energy demand. Energy has increasingly become a focal point for researchers and policymakers alike. Fossil fuels such as coal, oil, and natural gas remain significant contributors to the energy landscape both globally and nationally. However, as these resources deplete, there is a rising shift toward sustainable energy sources, along with increased efforts to develop them. One of the key benefits of

JEATSA JOURNAL
JOURNAL OF ENGINEERING ADVANCES AND TECHNOLOGIES FOR SUSTAINABLE APPLICATIONS
Volume 1, Issue 2 (April, 2025)
Print ISSN: 3062-5629 Online ISSN: 3062-5637
Open Access
https://jeats.journals.ekb.eg/

renewable energy is its ability to integrate into hybrid systems with other energy sources. Typically, hybrid energy systems consist of two or more distinct energy production methods that work together to provide electricity or thermal energy. There is considerable research underway into hybrid systems that combine wind and solar energy from renewable sources [1, 3].

RES including solar and wind, have emerged as appealing options for energy generation due to their lack of pollution and widespread availability across the globe [4, 5]. They provide the most economical solution for addressing power supply shortages in remote regions lacking access to the utility grid [5, 6]. Research and the utilization of RES have garnered growing interest in recent times [7-9].

As electricity demand rises, power systems are becoming increasingly complex. Traditional methods aimed at preventing voltage instability and collapses in these expanding systems have, at times, struggled to address their needs effectively. Today, the implementation of Flexible AC Transmission Systems (FACTS) allows for quicker and more efficient resolution of issues in complex and burgeoning networks. Furthermore, when utilized correctly, FACTS devices enhance the power system stability and maximize the use of available resources [1, 10].

Voltage instability could be effectively tackled by incorporating a device from the FACTS family like static VAR compensators (SVC) and static synchronous compensators (STATCOM) could effectively mitigate voltage instability during faults. These FACTS devices manage the voltage's amplitude and phase within the network, offering reactive power compensation and enhancing voltage levels at various nodes within the electrical network [11-13].

STATCOM is highly effective in reactive power compensation, voltage regulation, and enhancing grid stability, thereby contributing to the reliability of modern power systems [14].While many research studies have employed traditional control circuits, such as PI controllers for FACTS devices, these controllers face limitations due to their fixed parameters, leading to suboptimal performance under varying abnormal conditions [11].

Different types of reactive compensation devices encompass STATCOM, shunt capacitors, saturation reactors, and synchronous condensers. The STATCOM offers several benefits, including the ability to compensate reactive power in both directions, a broad operating range, rapid response times, minimal energy storage requirements, and greater control flexibility compared to traditional compensators [15-17]

With the rising need for stable and reliable electrical power transmission, utilities and industries are turning to advanced technologies like STATCOM to effectively manage voltage and reactive power along transmission lines [18, 19].

STATCOMs offer operational flexibility by enabling smooth integration with existing infrastructure and supporting various control schemes to enhance performance across different operating conditions [18, 20].

The selection of converter configuration is a crucial factor. The two available configurations are voltage source converters and current source converters, each incorporating passive storage elements: a capacitor for voltage source converters and an inductor for current source converters. Typically, voltage source converters are favored because they offer a more compact design, reduced heat generation, and lower costs for capacitors compared to inductors of the same rating [21].

The VSC control method is a commonly used approach for managing STATCOM systems. This technique utilizes a VSC within the STATCOM to generate a controlled AC voltage at the point of connection. To maintain the desired voltage levels and power factor, the VSC control system constantly monitors grid voltage and current, adjusting the inverter's output voltage as necessary. PI controllers are often implemented and created control signals to adjust the inverter output based on the difference between a reference voltage and the actual grid voltage, which they continuously evaluate [22].

The use of STATCOM's fuzzy logic controller (FLC) has garnered significant attention. One key advantage of fuzzy logic controllers over PI controllers is their ability to operate without needing precise mathematical model values, allowing them to manage nonlinearity effectively with vague inputs. The Mamdani type FLC is the most widely used and has demonstrated superior performance in STATCOM applications compared to PI controllers [23, 24]. Despite its many advantages, FLCs do have some drawbacks. These include the complex nature of designing the rule base and the need for specialized knowledge in fuzzy logic systems [25]. Fuzzy systems are regarded as intelligent systems that leverage data and reasoning to tackle complex issues, which requires considerable engineering expertise for adequate explanation [26, 27].

Several works reviews associated to this paper are specified as follows:-

H. Bakır and A. A. Kulaksız (2018) presented a model

JEATSA JOURNAL
JOURNAL OF ENGINEERING ADVANCES AND TECHNOLOGIES FOR SUSTAINABLE APPLICATIONS
Volume 1, Issue 2 (April, 2025)
Print ISSN: 3062-5629 Online ISSN: 3062-5637
Open Access
https://jeats.journals.ekb.eg/

and analysis of a hybrid RES integrated with STATCOM in MATLAB/SIMULINK. The study examines how STATCOM influences the hybrid RES. Through supplying reactive power compensation in transmission networks, STATCOM either absorbs or generates the required reactive power within the system [1].

J. Bhukya, and P. Singh (2024) explored the complexities of power system stability, particularly examining the challenges associated with the integration of RES, with a primary emphasis on wind power under different operating conditions [28].

R. Somalwar and M. Khemariya (2012) presented FACTS controllers aimed at resolving instability challenges. The FACTS devices could also be employed to manage power flows and enhance stability. The research investigated how FACTS devices can be utilized to improve system stability [29].

I. Hamdan, A. M. Ibrahim, and O. Noureldeen (2020) presented the use of STATCOM for reactive power compensation, aiming to improve Fault Ride-Through (FRT) capabilities and boost the performance of a hybrid power system integrated with the grid. This system merges photovoltaic as well as wind power during transient disturbances in the grid [30].

D. S. Ahmed, and A. F. Marhoon (2024) utilized STATCOM to enhance the voltage stability within a power grid integrating RES. The STATCOM-based modular multilevel converter is specifically considered to improve the quality of the output voltage while minimizing the need for filters. Controllers based on PI, as well as integral sliding mode (ISM) strategies, were developed. The results indicated that the STATCOM effectively enhances performance in this hybrid system, utilizing both PI and ISM controllers [31] .

M. P. Donsion, J. Guemes, and J. Rodriguez (2007) focused on FACTS technologies aimed to enhance the system power quality. The study examines how impedance, current, and voltage can be optimized through the use of FACTS units for boosting system performance. [32].

A. M. Ibrahim, I. Hamdan, L. Nasrat, and M. A. Ismeil (2022) presented an optimal design for a STATCOM aimed at improving the performance of a hybrid power system combining wind and PV energy in the Gabal El Zayt area, situated along the Red Sea coast in Egypt [33].

S. Akter, A. Saha, and P. Das (2012) offered various FACTS technologies model and simulation, including STATCOM , aimed at enhancing the stability and capacity of the power network [34].

K. Mohd and U. Ansari (2014) discussed the integration of a STATCOM into the power network to enhance dynamic voltage regulation for the wind farm, manage power flow in the transmission lines, alleviate congestion, and enhance damping of power oscillations. Simulation results indicate that the addition of STATCOM devices markedly enhances the performance of both the wind farm and the overall power network during transient disturbances [35].

S. Shinde, R. Gandhi, G. S. Margarat, Y. Khairnar, H. M. Al-Jawahry, M. Landage, and K. K. Naidu (2024) presented an overview of different FACTS devices, detailing their operating principles, functionalities, and contributions to improving power system stability. It also explored various control strategies implemented for FACTS devices, including voltage and reactive power control, as well as their effectiveness in sustaining grid stability [36].

B. Bouhadouza, A. Gherbi, and H. Mellah (2013) presented the FACTS technologies importance for stability enhancing in the presence of faults, as well as for managing the incorporation of renewables, particularly wind power. The sources compel power networks to operate under new conditions [37].

K. Gupta and Y. Pahariya (2017) investigated FACTS controllers effect like STATCOM on enhancing short-term stability of Electrical grids [38].

M. Eslami, H. Shareef, A. Mohamed, and M. Khajehzadeh (2012) introduced detailed study for enhancing the system stability through the FACTS controllers' usage. The discussion highlights multiple technical publications concerning FACTS devices and offers a comparison of the performance of various FACTS devices [39].

K. Pushpak, B. K. Anuradha, A. Ravi, and A. Abhishek (2016) examined how the power systems behavior equipped with wind energy can be enhanced through the use of FACTS devices like STATCOM. To assess the impact of the STATCOM device on system operations, that system has been and would continue to be tested under various disturbances, including faults and differing power operating conditions [40].

O. E. Olabode, T. O. Ajewole, D. O. Akinyele, and F. K. Ariyo (2024) examined the impact of reactive power compensation through a Distribution Static Synchronous Compensator (D-STATCOM) within a real-world distribution network. Three distinct levels of D-STATCOM integration were analyzed to evaluate their effects on improving voltage profiles, reducing active power losses, saving energy costs, determining payback

JEATSA JOURNAL
JOURNAL OF ENGINEERING ADVANCES AND TECHNOLOGIES FOR SUSTAINABLE APPLICATIONS
Volume 1, Issue 2 (April, 2025)
Print ISSN: 3062-5629 Online ISSN: 3062-5637
Open Access
https://jeats.journals.ekb.eg/

periods, and assessing procurement expenses [41].

I. Y. Fawzy, M. A. Mossa, A. M. Elsawy, and A. A. Z. Diab (2024) provided a summary of different FACTS technologies aimed at enhancing the behavior of system. The analysis was conducted with Matlab/Simulink software, focusing on both single-phase and three-phase faults. The outcomes indicated that these devices can significantly enhance the system performance, with the UPFC demonstrating superior effectiveness compared to the other FACTS types [42].

This paper presents an overview of STATCOM as one of FACTS devices with two different controllers: PI and FLC for enhancing power system stability. The offered system is analyzed under abnormal conditions at different positions within the PV/Wind energy system utilizing the Matlab/Simulink. The outcomes indicate that the behavior of that system can be significantly improved with STATCOM based on FLC, demonstrating superior performance compared to a STATCOM that employs a PI controller.

II. Overview of STATCOM and Controller

A. ***STATCOM***

Among FACTS devices, the STATCOM stands out due to its ability to improve the power system transmission capacity by enhancing voltage regulation and stability. It offers rapid and efficient reactive power compensation for voltage sustenance, while also improving the power oscillations damping and enhancing transient stability [43-47].

The STATCOM is a device used for compensating reactive power that operates in parallel. Recent adverisements in power electronic systems, particularly the introduction of GTO thyristors, have made it feasible to adopt this innovation as an effective alternative to traditional SVC systems. Fig. 1 presents a schematic representation of the STATCOM.

The system comprises a VSC, a direct current (dc) energy storage device, and a coupling transformer, all connected in parallel to the network. The VSC transforms the dc voltage from the storage device into a set of three-phase alternating current (ac) output voltages. These voltages are synchronized and connected to the ac system through the reactance of the coupling transformer. By appropriately adjusting the phase and magnitude of the output voltages from the STATCOM, effective control over active and reactive power exchanges between the STATCOM and the ac system is achieved. This configuration enables the device to either absorb or generate controllable active and reactive power [48].

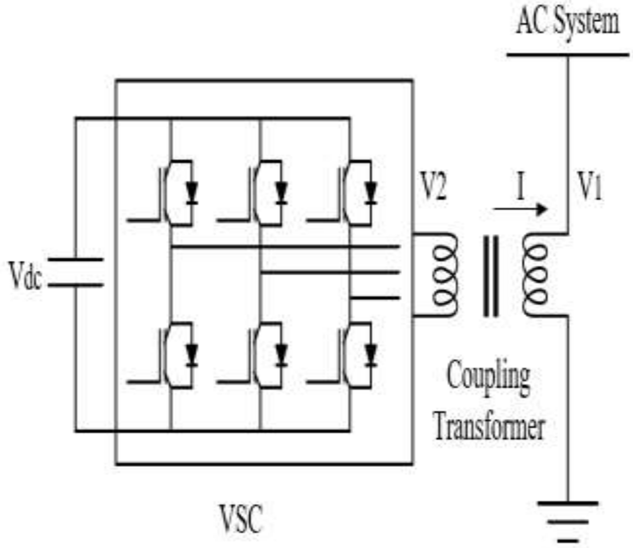


Fig. 1. Basic STATCOM Arrangement.

The transmission line active power (P) and reactive power (Q are presented below:

$$P = \frac{V1\ x\ V2}{X} sin\,\delta \qquad (1)$$

$$Q = \frac{V1^2}{X} - \frac{V1\ x\ V2}{X} cos\,\delta \qquad (2)$$

Here, V1 and V2 denote the output voltage of the inverter and the bus voltage of the system, respectively, while X represents the reactance of the line connecting the inverter to the system bus [49].

The connection between the system AC voltage and the AC voltage at the STATCOM terminals allows for effective control of reactive power flow. When the voltage at the terminals of STATCOM is higher than the voltage of the system, the device acts as a capacitor, providing reactive power to that system. In contrast, if the voltage of the STATCOM falls beneath the AC voltage, it functions like an inductor, leading to a reversal in the flow of reactive power. During standard working circumstances, the voltages are in sync, resulting in no transfer in power among the STATCOM and the network. Fig. 2 depicts the voltage and current properties of the STATCOM. Various research studies indicate that the STATCOM can significantly enhance the behavior and reliability of power systems, especially in applications involving renewable energy [50].

JEATSA JOURNAL
JOURNAL OF ENGINEERING ADVANCES AND TECHNOLOGIES FOR SUSTAINABLE APPLICATIONS
Volume 1, Issue 2 (April, 2025)
Print ISSN: 3062-5629 Online ISSN: 3062-5637
Open Access
https://jeats.journals.ekb.eg/

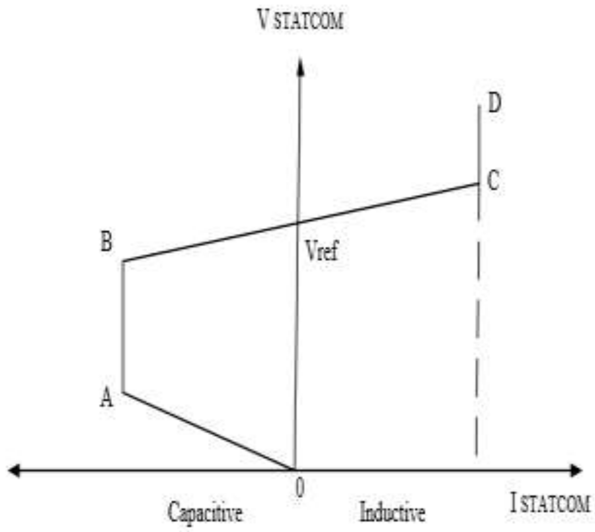


Fig. 2. STATCOM V-I attributes.

The STATCOM fundamental control illustration is shown in Fig. 3. The AC system voltage, to which the STATCOM is connected, along with the voltage across the DC link, must be kept at their specified reference values. The PWM modulator produces pulses for controlling the IGBT in the VSC [51-53].

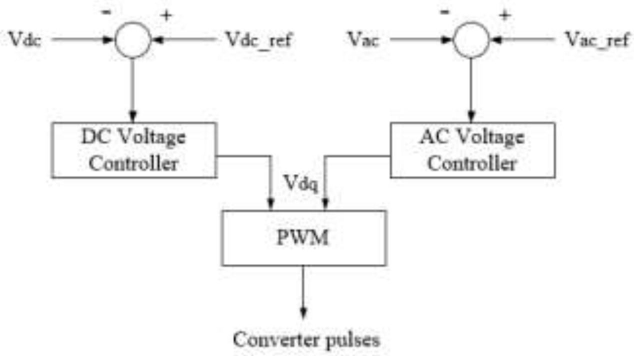


Fig. 3. Basic control diagram of STATCOM.

III. *Fuzzy Logic Control System*

The Controller Based on Fuzzy Logic (FLC). is acknowledged as the more effective and advantageous option compared to conventional controllers like PI controller. It requires less memory and is adept at handling non-linear systems [54]. The FLC is pivotal in various practical applications and provides various fuzzy reasoning systems [55]. In this research, the Mamdani-type inference mechanism is used due to its effectiveness plus compact design. The FLC system architecture is illustrated in Fig. 4, which encompasses four key components [56]: Fuzzifier, Knowledge Base, Fuzzy Inference Engine, also Defuzzifier. The fuzzy logic fundamental framework includes these four essential elements [57]:

A. Fuzzification (Fuzzifier): This step transforms numerical inputs into linguistic values, effectively mapping the input space to fuzzy sets well-defined within the discourse universe. This procedure converts input data into appropriate linguistic terms, serving as labels for the fuzzy sets.

B. Knowledge Base (Fuzzy Rule Base): This component comprises a database and a set of fuzzy rules. The database contains necessary definitions for linguistic rules and processing fuzzy data, while the rule base articulates the objectives and strategies of experts through guiding linguistic rules.

C. Decision-Making Logic (Fuzzy Inference Engine): This is the central part of that controller, capable of mimicking human judgment regarding ambiguous concepts. It infers fuzzy control functions using fuzzy implications and logical inference rules.

D. Defuzzification (Defuzzifier): This function performs scale mapping, converting output variable values into coherent universes of discourse, and produces non-fuzzy control functions from the resulting fuzzy control functions. The Mamdani Method is utilized in this study due to its computational efficiency and compactness. It features two inputs (X1 and X2) and one output (Y), where X1 represents the error, while X2 denotes the change in error within the system. The result Y is depicted as a fuzzy output [58].

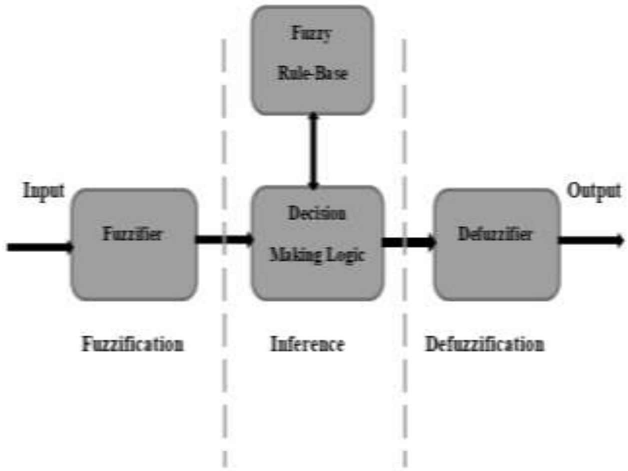
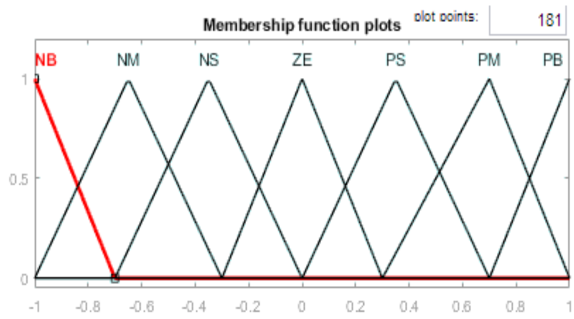


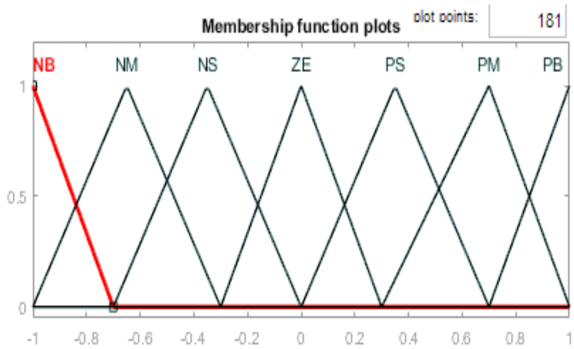
Fig. 4. The structure of FLC.

The fuzzy logic controller transforms a linguistic control approach to an automated controller system. Fuzzy rules are established either by specialists or by utilizing a knowledge database. To improve results, seven fuzzy sets or levels (membership functions) are chosen, providing a numerical representation of each fuzzy logic state [59]:

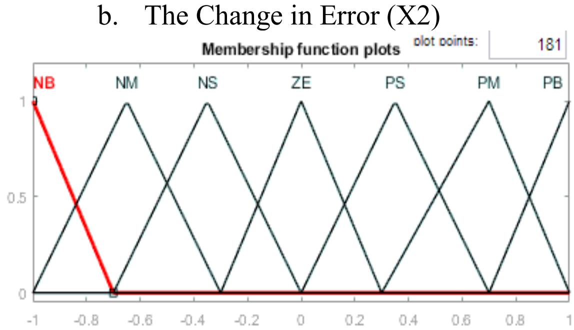
PB (positive big), PM (positive medium), PS (positive small), ZE (zero), NB (negative big), NM (negative medium), and NS (negative small), as clarified in Fig. 5.



a. The Error (X1)



b. The Change in Error (X2)



c. The result (Y)

Fig. 5. The offered FLC Membership functions.

A fuzzy inference system is a computational model that relies on the principles of fuzzy set theory. According to this theory, significant transient errors necessitate broad control through coarse input and output variables [59], whereas minor steady-state errors require more precise adjustments using hypothetical input and output parameters. The components of the rule base are formulated according to this principle, as illustrated in Table 1, where E signifies the error and ΔE indicates the change in error.

TABLE 1 THE RULESET OF FLC

E	ΔE						
	NB	NM	NS	Z	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	Z
NM	NB	NB	NB	NM	NS	Z	PS
NS	NB	NB	NM	NS	Z	PS	M
Z	NB	NM	NS	Z	PS	PM	PB
PS	NM	NS	Z	PS	PM	PB	PB
PM	NS	Z	PS	PM	PB	PB	PB
PB	Z	PS	PM	PB	PB	PB	PB

Fig. 6 illustrates the Simulink model for a STATCOM-based FLC. The voltage of the system is monitored at the point of common coupling (PCC) and evaluated against a reference value. The error signal produced, along with the variation in the error, is sent to the FLC, which then calculates the reactive reference current, denoted as Iqref. The STATCOM's reactive current, represented as Iq, is compared to Iqref, and the phase shift angle for the PWM inverter is determined by the output of the current regulator. [60]. Fig. 7 presents the flowchart of the FLC system, outlining all the steps involved in the operation of the fuzzy controller.

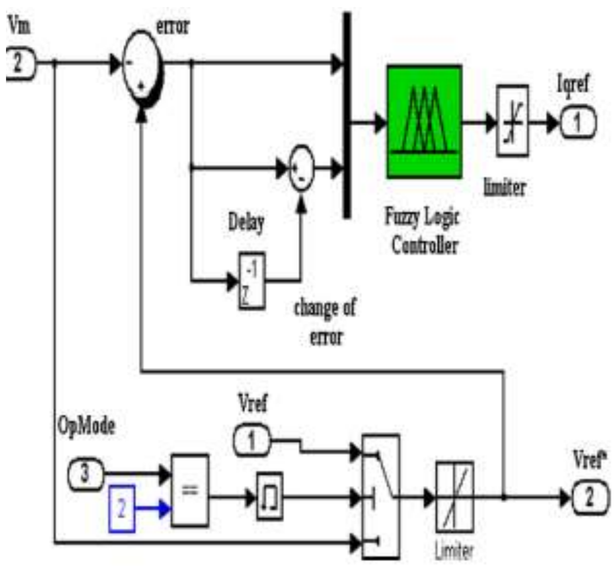


Fig. 6. Simulink model for a STATCOM-based FLC.

JEATSA JOURNAL
JOURNAL OF ENGINEERING ADVANCES AND TECHNOLOGIES FOR SUSTAINABLE APPLICATIONS
Volume 1, Issue 2 (April, 2025)
Print ISSN: 3062-5629 Online ISSN: 3062-5637
Open Access
https://jeats.journals.ekb.eg/

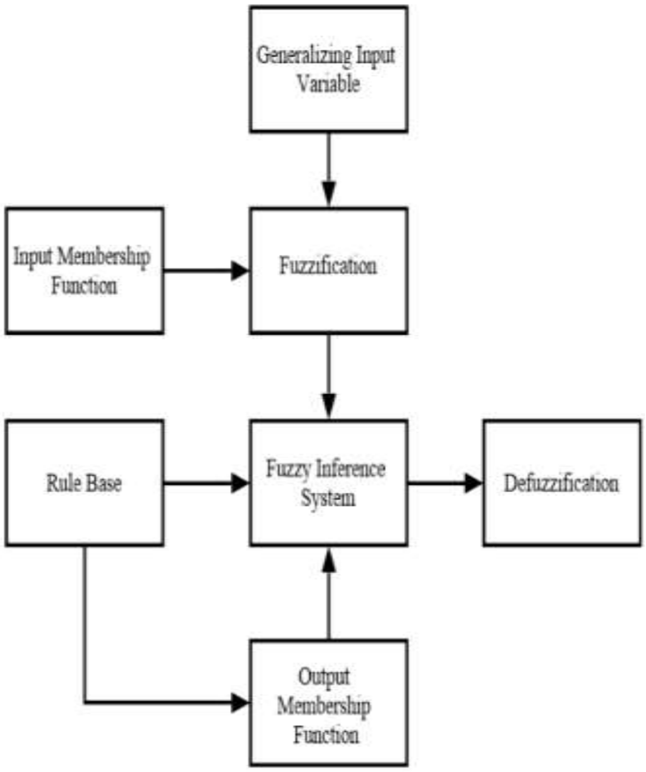


TABLE 2. THE WES PARAMETERS DESCRIPTION

Rated power	1.5 MW	[kp, ki] DC voltage regulator	[0.002 0.05]
Power factor	0.9	Friction	0.01 p.u
Line voltage	575	DC-bus voltage	1200
Stator resistance	0.00706	DC-link capacitor	0.01
	p.u		
Rotor resistance	0.005 p.u	Battery rating	900 kWh
Stator leakage inductance	0.171 p.u	System frequency	60 Hz
Rotor leakage inductance	0.156 p.u	[kp, ki] RSC regulator	[0.3 8]
[kp, ki] GSC converter	[2.5 500]	Magnetizing inductance	2.9 p.u

Fig. 7. Flowchart of fuzzy logic control system.

IV. ***System under Study***

This study conducts an examination of a modified 3-machine, 9-bus normal electric network to determine the effect of the proposed STATCOM with FLC on the system's transient behavior. In this upgraded arrangement, a wind power system has replaced a synchronous machine at bus 3, and PV energy has been added to bus 5. Fig. 8 shows the revised 9-bus system. The wind power system has an installed capacity of 90 MW, and the PV system has a rated power of 80 MW. The wind system that has replaced the traditional synchronous generator at bus 3 consists of three sets of WES. Each one contains 20 wind turbines that run in tandem, each with a nominal 1.5 MW capacity. The voltage regulator gains for the PI controller in this work are set to Kp = 0.0001 and Ki = 0.02, while the current controller gains are taken as Kp = 0.3 and Ki = 0.22. For the FLC, the voltage regulator gains are taken as Kp = 0 and Ki = 300. The parameters for the WES, along with the regulator gains, are detailed in Table 2.

JEATSA JOURNAL
JOURNAL OF ENGINEERING ADVANCES AND TECHNOLOGIES FOR SUSTAINABLE APPLICATIONS
Volume 1, Issue 2 (April, 2025)
Print ISSN: 3062-5629 Online ISSN: 3062-5637
Open Access
https://jeats.journals.ekb.eg/

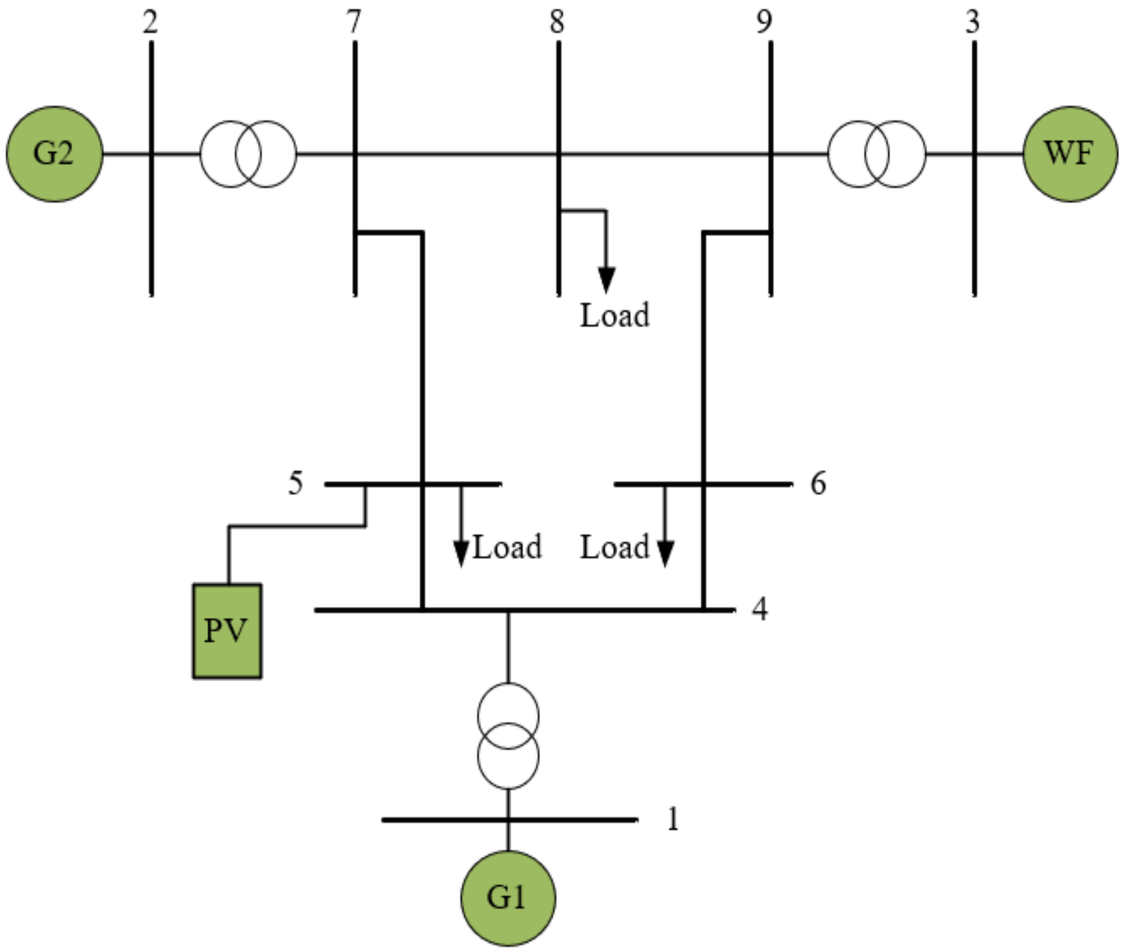


Fig. 8. Single-line representation of the modified 9-bus network being analyzed.

V. SIMULATION RESULTS

Fig. 9 illustrates the Simulink model of the electrical grid. To certify the procedure of the recommended STATCOM utilizing fuzzy controller, the electrical grid undergoes anomalous conditions caused by various fault types at different points, plus the system performance is evaluated. The system's stability can be analyzed for various fault locations as follows:

JEATSA JOURNAL
JOURNAL OF ENGINEERING ADVANCES AND TECHNOLOGIES FOR SUSTAINABLE APPLICATIONS
Volume 1, Issue 2 (April, 2025)
Print ISSN: 3062-5629 Online ISSN: 3062-5637
Open Access
https://jeats.journals.ekb.eg/

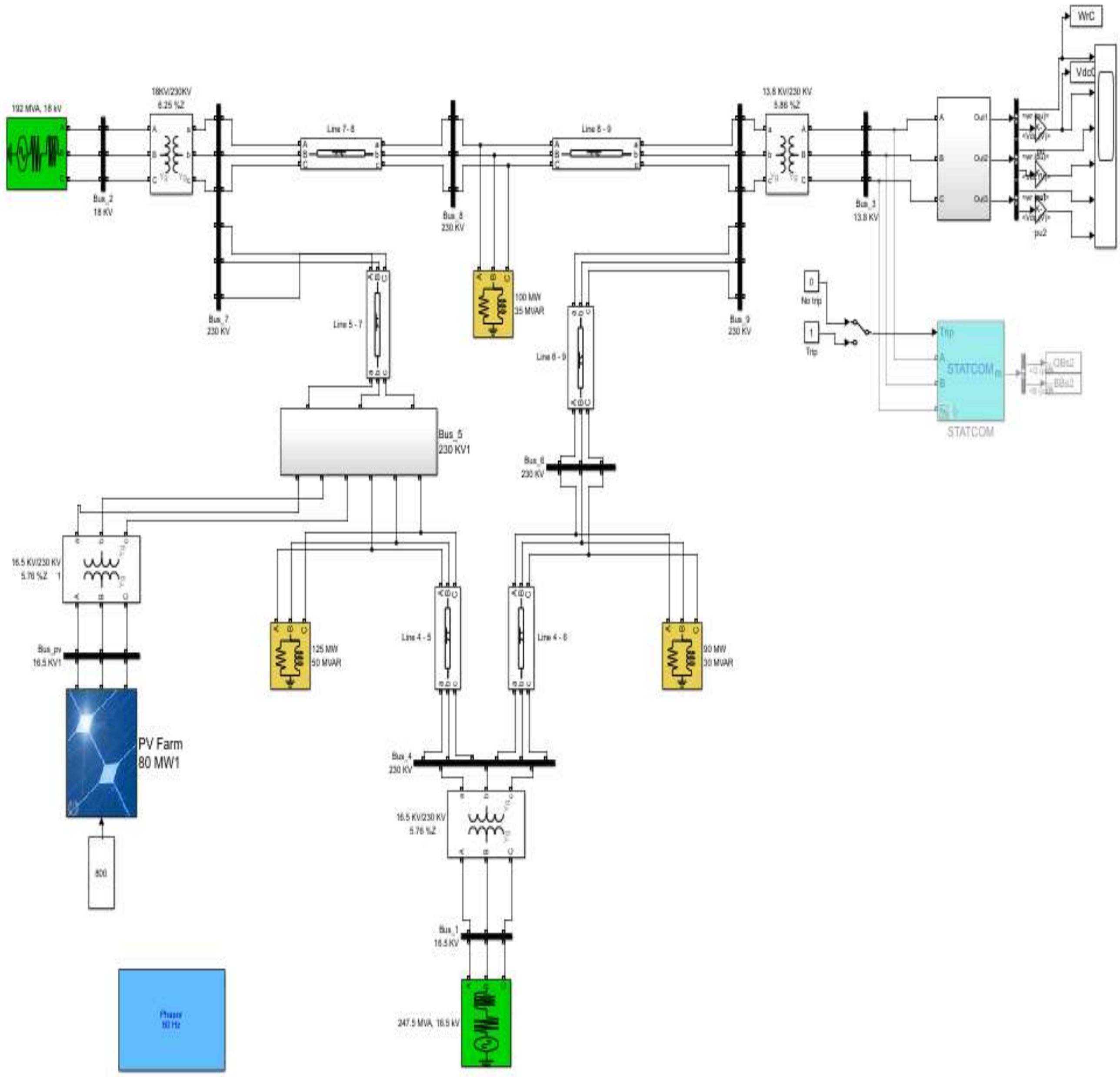


Fig. 9. The proposed model of the electrical transmission network in Matlab/Simulink.

***CASE 1**: FAULT LOCATED AT THE WIND FARM BUS (BUS-3)*

This sector presents the system's generators active response and the voltage distribution across every bus during a zero-impedance three-phase-to-ground fault occurring at PCC of the wind system connected to the electric network (bus-3). The integration of a STATCOM utilizing FLC is recommended for implementation at bus-3 throughout every case study presented in this work. In the modeling, the three-phase fault is introduced 4 seconds after the model activation plus lasts for 0.05 seconds before receiving clearance. Throughout this fault period, no protective devices will be triggered to disconnect the photovoltaic (PV) and wind power plants. Figs 10 to 12 demonstrate the power system stability with both a PI controller and the proposed STATCOM utilizing FLC. In this study, the red solid line illustrates the performance of STATCOM utilizing a FLC, whereas the dashed blue line depicts the behavior of STATCOM with a PI controller. During the fault event, the STATCOM increases its supplied reactive power to ensure that voltage levels at every bus remain within acceptable limits. The system's performance demonstrates the STATCOM's ability to mitigate oscillations, thereby enhancing system stability. Measurements of the dynamic characteristics at various buses further validate the enhanced performance enabled by the STATCOM. Additionally, Fig. 13 highlights the transient voltage behavior at various buses within the system. The integration of the STATCOM using FLC helps to stabilize the voltage distribution after the fault has been cleared, as the STATCOM effectively absorbs the reactive power generated by the accelerating generators. Overall, the obtained results indicate that the STATCOM with FLC significantly enhances the system's performance concerning oscillations and gives better response than STATCOM with PI controller under fault condition.

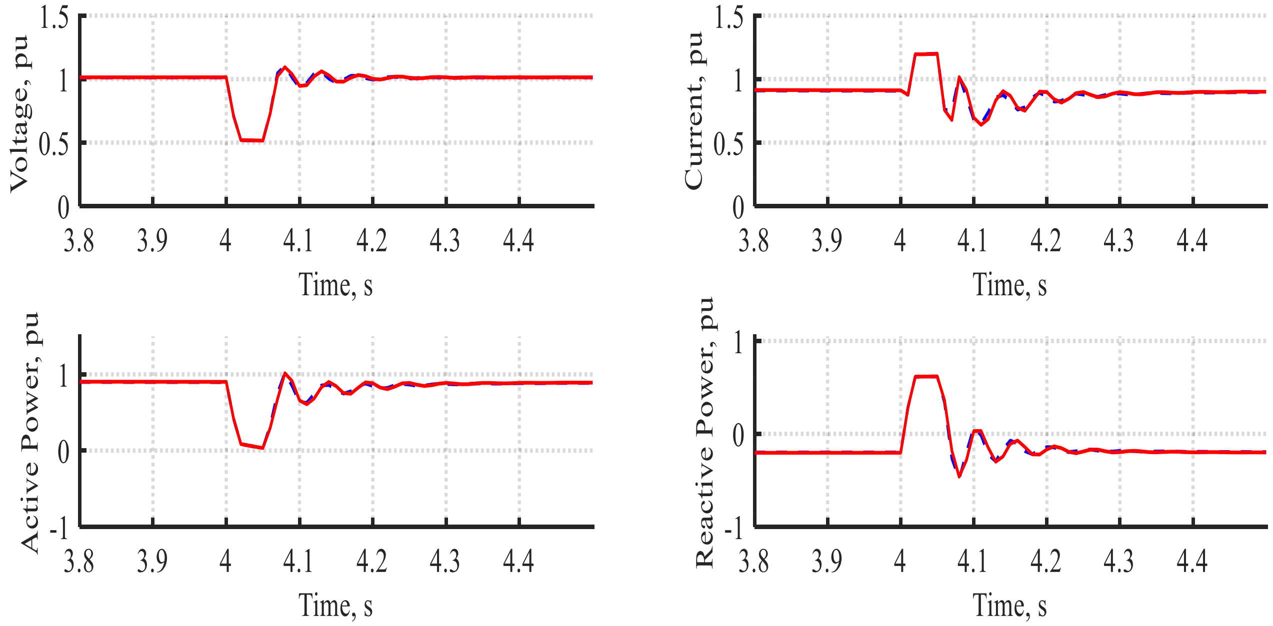


Fig. 10. Operational behavior of generator 1 based on the fault condition outlined in Case 1.

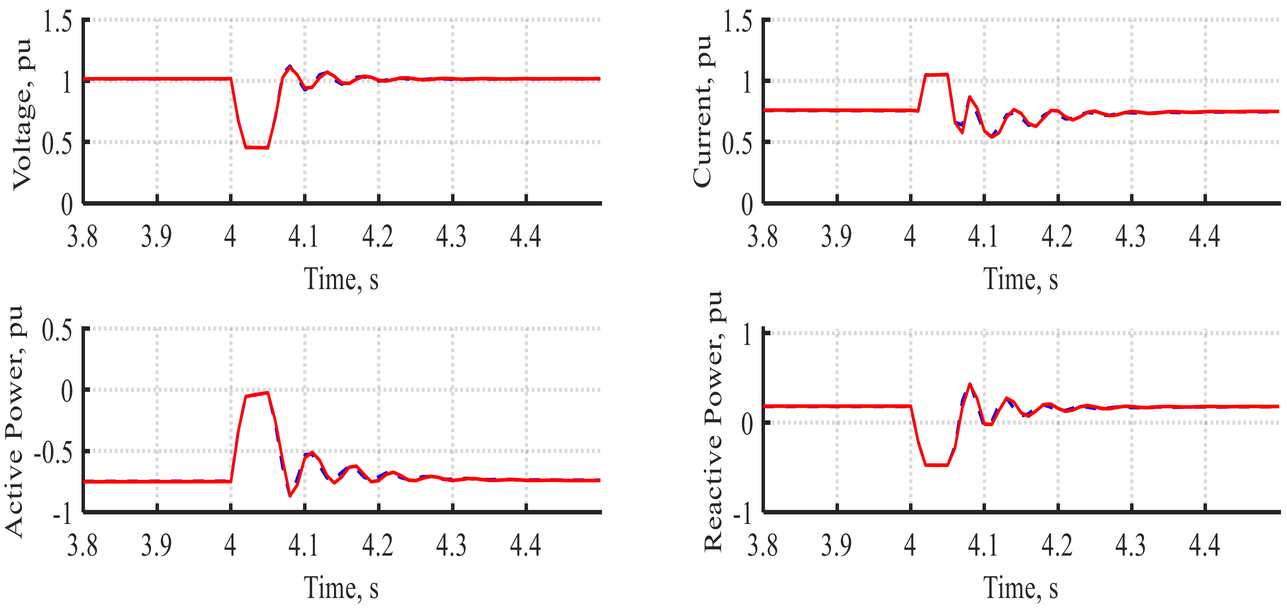


Fig. 11. Operational behavior of the WES based on the fault condition outlined in Case 1.

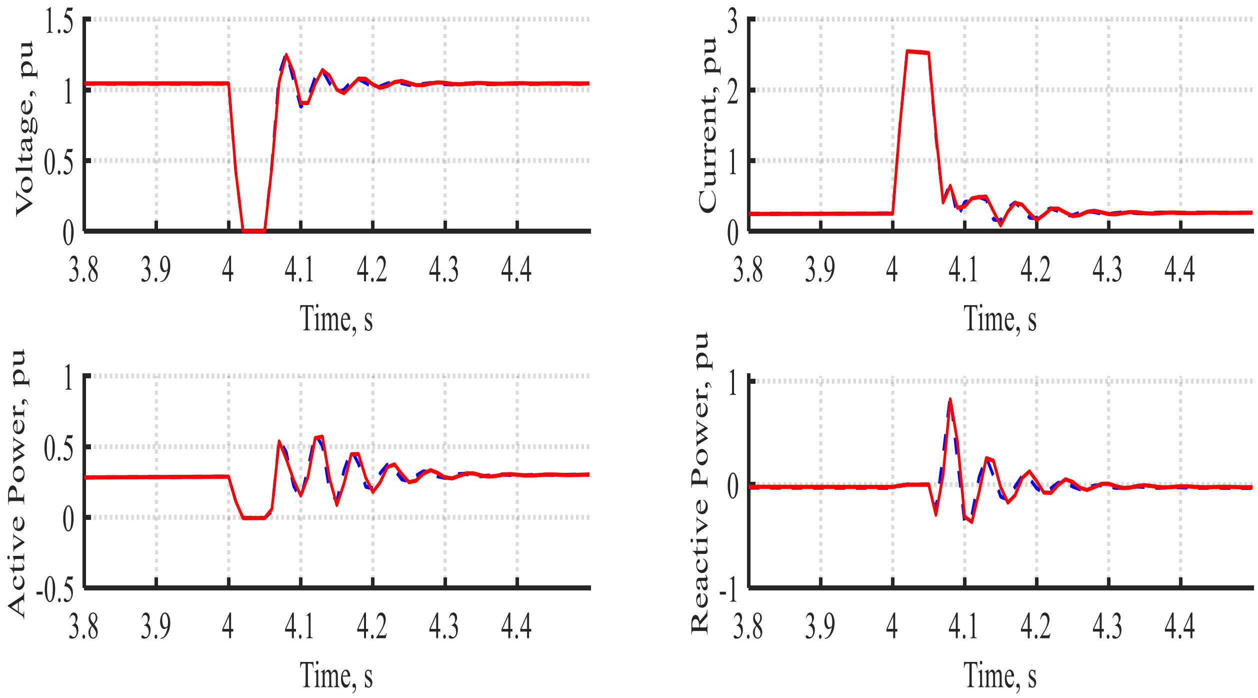


Fig. 12. Operational behavior of the PV system based on the fault condition outlined in Case 1.

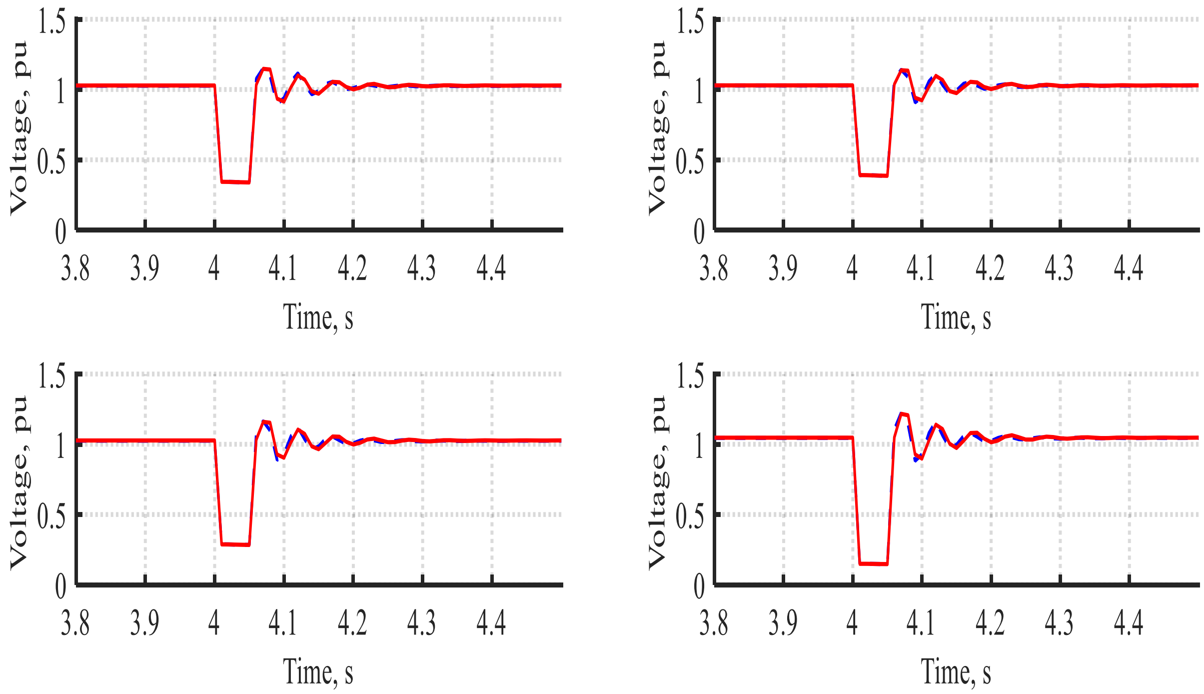


Fig. 13. Transient performance of the voltage profile at Buses B6, B7, B8 and B9 based on the fault outlined in Case 1.

JEATSA JOURNAL
JOURNAL OF ENGINEERING ADVANCES AND TECHNOLOGIES FOR SUSTAINABLE APPLICATIONS
Volume 1, Issue 2 (April, 2025)
Print ISSN: 3062-5629 Online ISSN: 3062-5637
Open Access
https://jeats.journals.ekb.eg/

***CASE 2**: FAULT LOCATED AT THE GENERATOR 1 BUS (BUS-1)*

An additional case study has been confirmed to further validate the proposed STATCOM utilizing FLC. A three-phase-to-ground fault occurred at generator 1's (bus-1) 4 seconds into the simulation, lasting for 0.05 seconds before being cleared. Figs 14 to 16 depict the system's performance during the fault condition. These results validate the efficiency of integrating the recommended STATCOM with fuzzy controller outperforms the PI controller in the power system. Furthermore, Fig. 17 highlights the transient voltage behavior at several buses within the system. The system's dynamic performance, particularly when connected to renewable energy sources during the fault, highlights significant improvements in overall system stability with reducing oscillations owing to the implementation of STATCOM utilizing FLC as compared to PI controller.

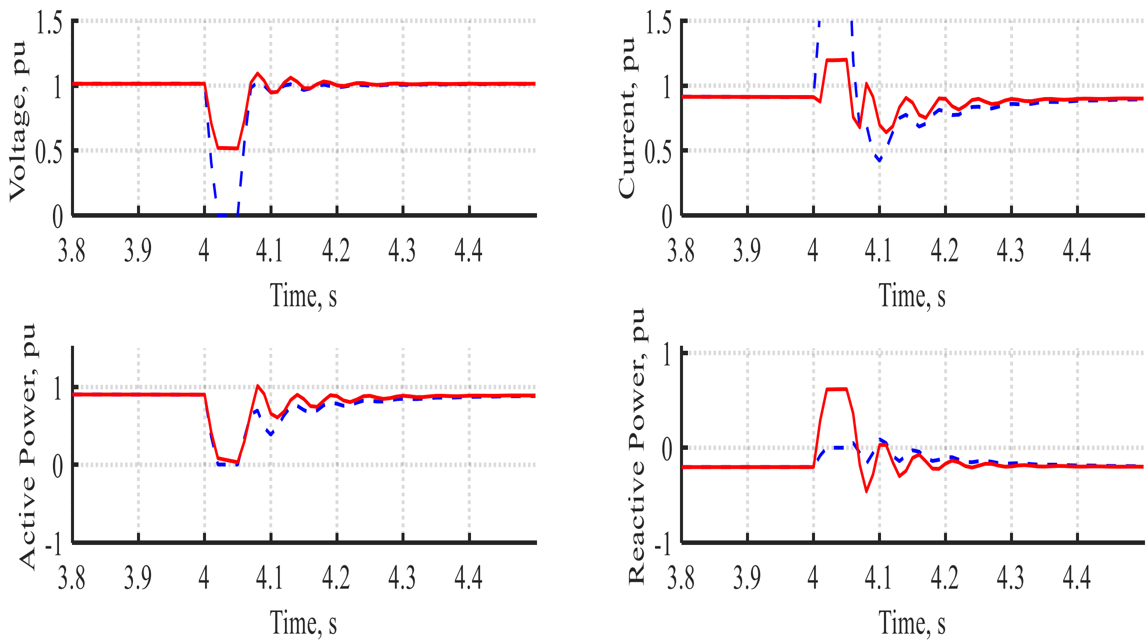


Fig. 14. Operational behavior of generator 1 based on the fault condition outlined in Case 2.

JEATSA JOURNAL
JOURNAL OF ENGINEERING ADVANCES AND TECHNOLOGIES FOR SUSTAINABLE APPLICATIONS
Volume 1, Issue 2 (April, 2025)
Print ISSN: 3062-5629 Online ISSN: 3062-5637
Open Access
https://jeats.journals.ekb.eg/

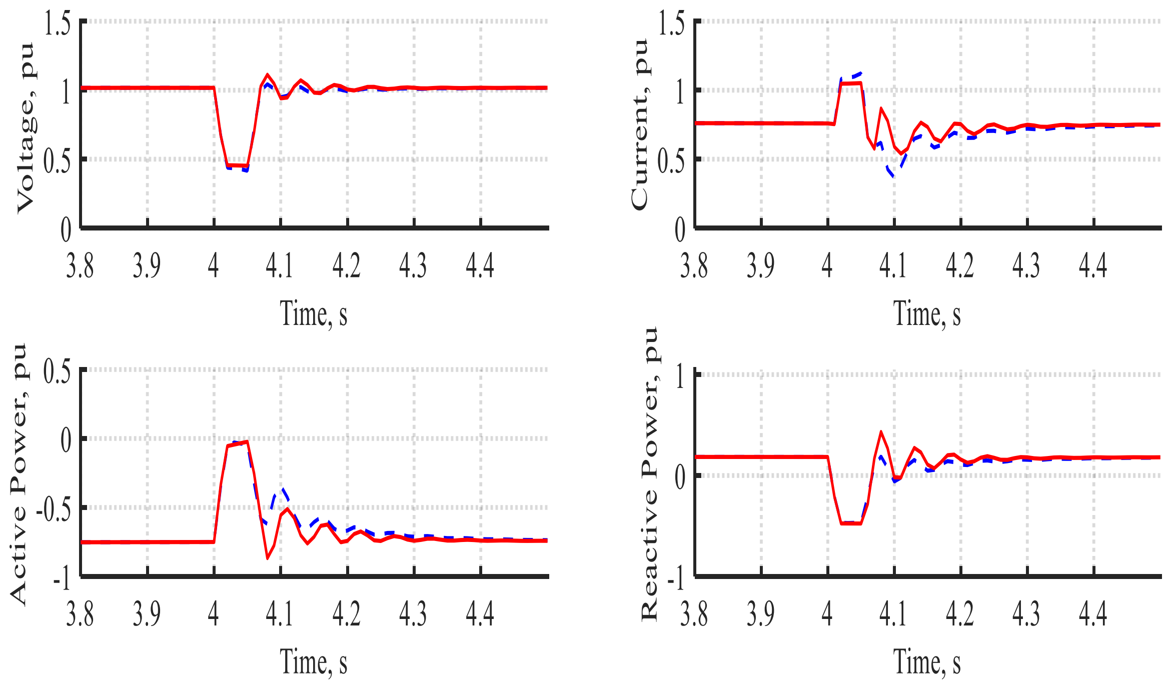
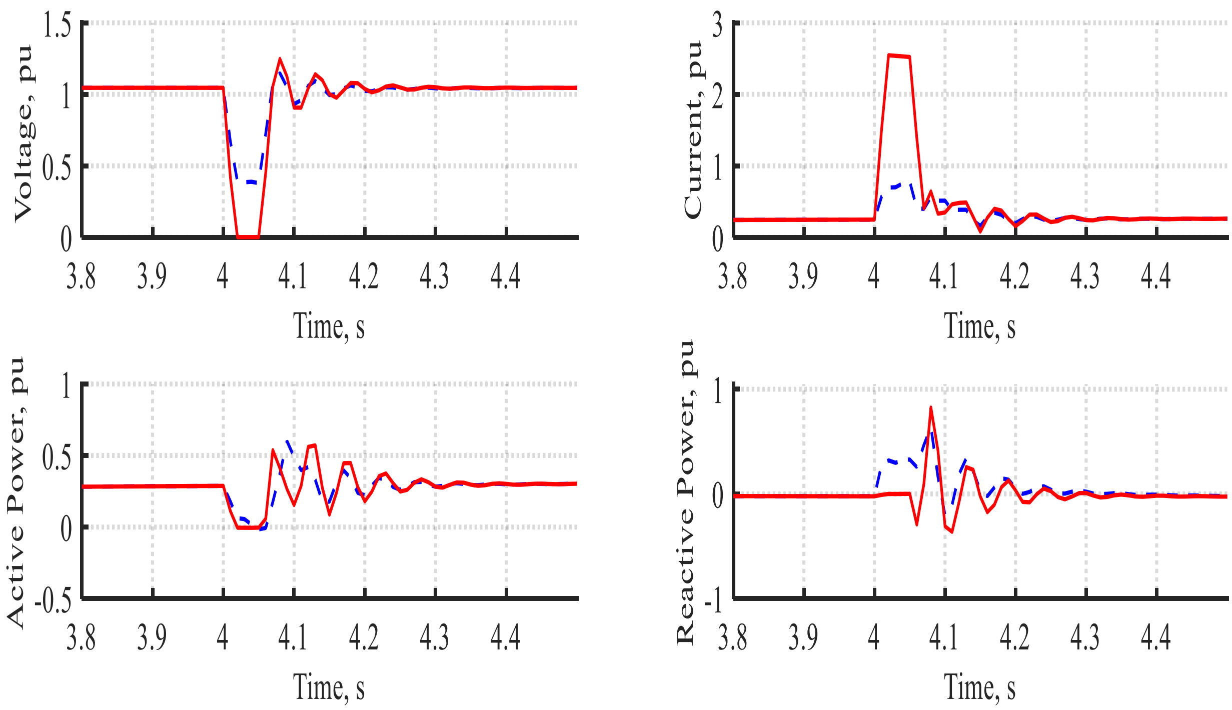


Fig. 15. Operational behavior of the WES based on the fault condition outlined in Case 2.



JEATSA JOURNAL
JOURNAL OF ENGINEERING ADVANCES AND TECHNOLOGIES FOR SUSTAINABLE APPLICATIONS
Volume 1, Issue 2 (April, 2025)
Print ISSN: 3062-5629 Online ISSN: 3062-5637
Open Access
https://jeats.journals.ekb.eg/

Fig. 16. Operational behavior of the PV system based on the fault condition outlined in Case 2.

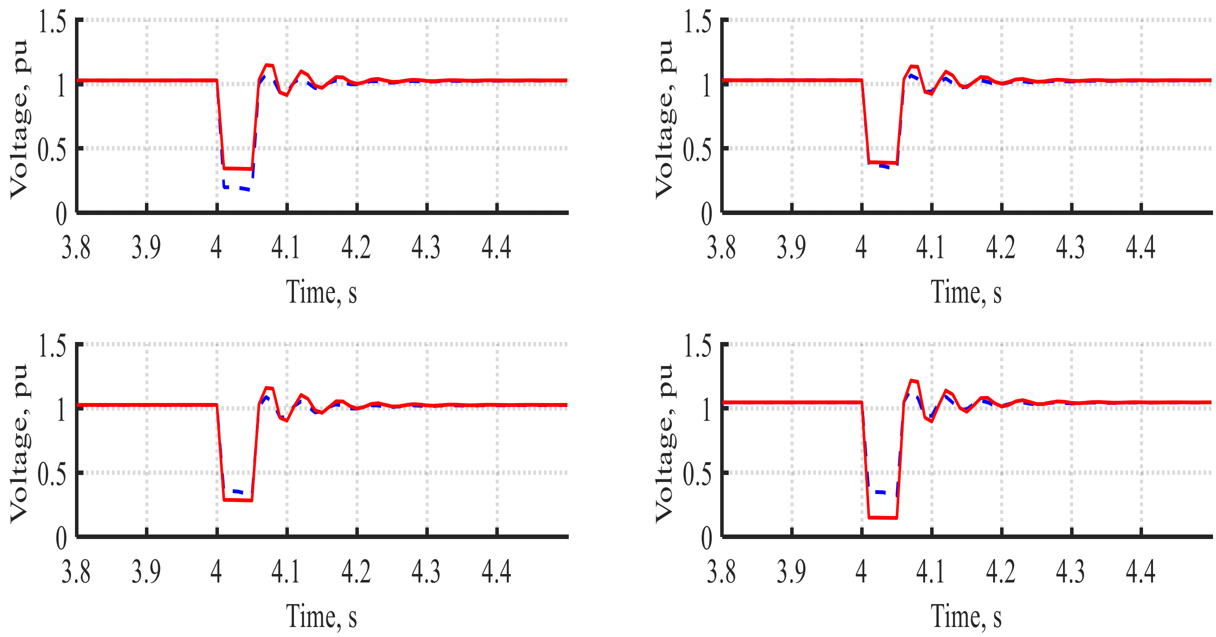


Fig. 17. Transient performance of the voltage profile at Buses B6, B7, B8 and B9 based on the fault outlined in Case 2.

***CASE 3**: THREE PHASE FAULT LOCATED AT THE PV SYSTEM TERMINALS (BUS-5)*

JEATSA JOURNAL
JOURNAL OF ENGINEERING ADVANCES AND TECHNOLOGIES FOR SUSTAINABLE APPLICATIONS
Volume 1, Issue 2 (April, 2025)
Print ISSN: 3062-5629 Online ISSN: 3062-5637
Open Access
https://jeats.journals.ekb.eg/

In order to further confirm the effectiveness of the proposed FLC for the STATCOM, a three-phase ground fault was simulated at the PV system outlets. The outcomes of this imitation are illustrated in Figs 18 to 21. The system dynamic performance across all buses using STATCOM with FLC outperforms that of the system utilizing STATCOM with PI controller. Clearly, the system behavior utilizing the PI controller is significantly deficient, exhibiting a prolonged period for stability reaching. Moreover, a significant overreach in current and voltage levels has been observed across all buses. In contrast, the implementation of the STATCOM with the proposed FLC leads to improvements regarding the system's overall performance.

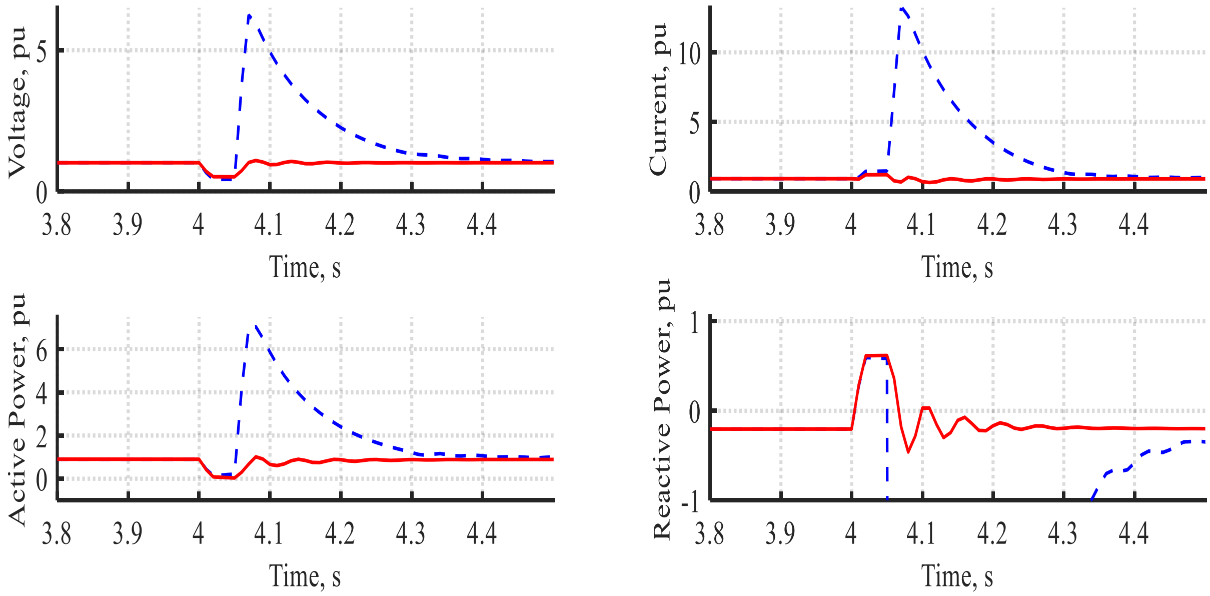


Fig. 18. Operational behavior of generator 1 based on the fault condition outlined in Case 3.

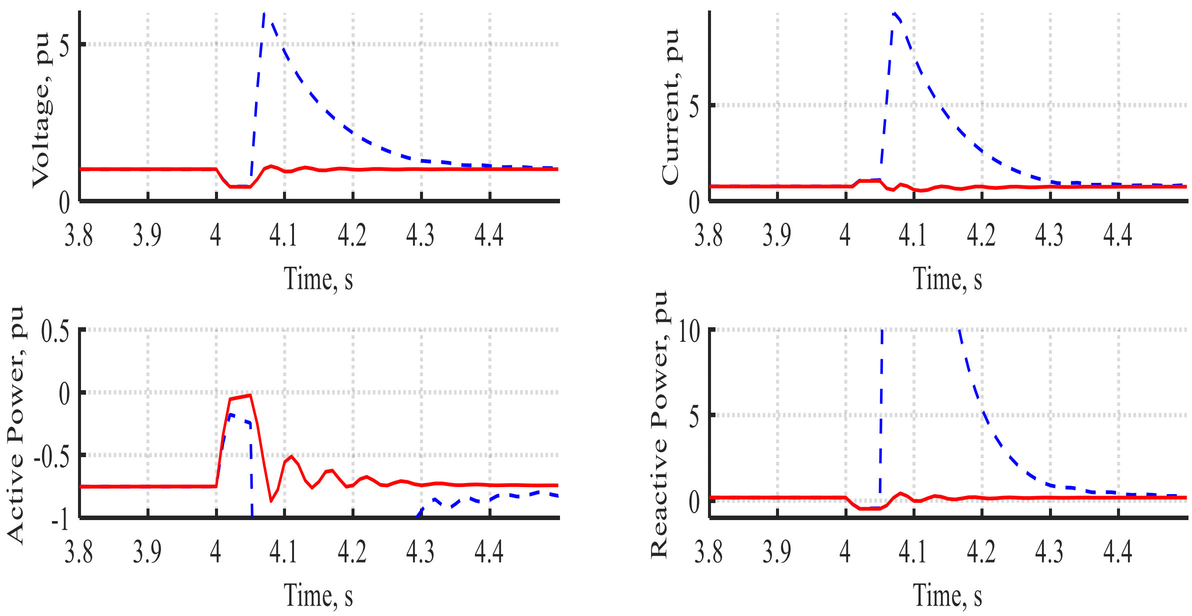


Fig. 19. Operational behavior of the WES based on the fault condition outlined in Case 3.

JEATSA JOURNAL
JOURNAL OF ENGINEERING ADVANCES AND TECHNOLOGIES FOR SUSTAINABLE APPLICATIONS
Volume 1, Issue 2 (April, 2025)
Print ISSN: 3062-5629 Online ISSN: 3062-5637
Open Access
https://jeats.journals.ekb.eg/

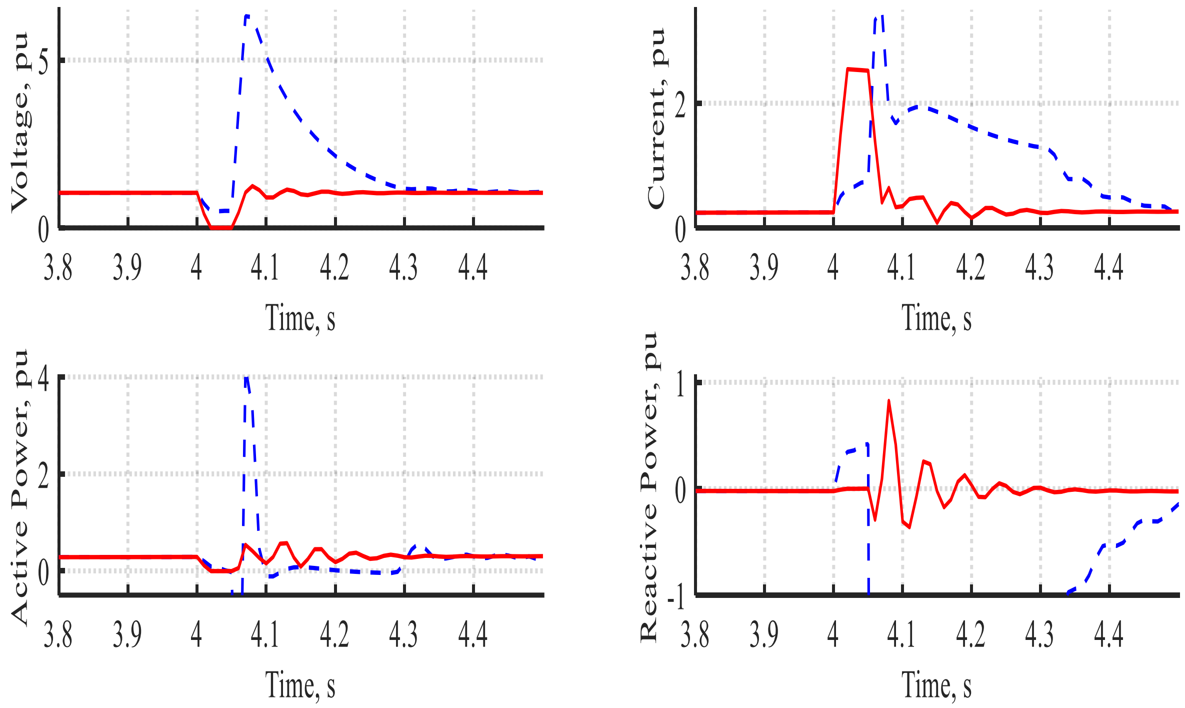


Fig. 20. Operational behavior of the PV system based on the fault condition outlined in Case 3.

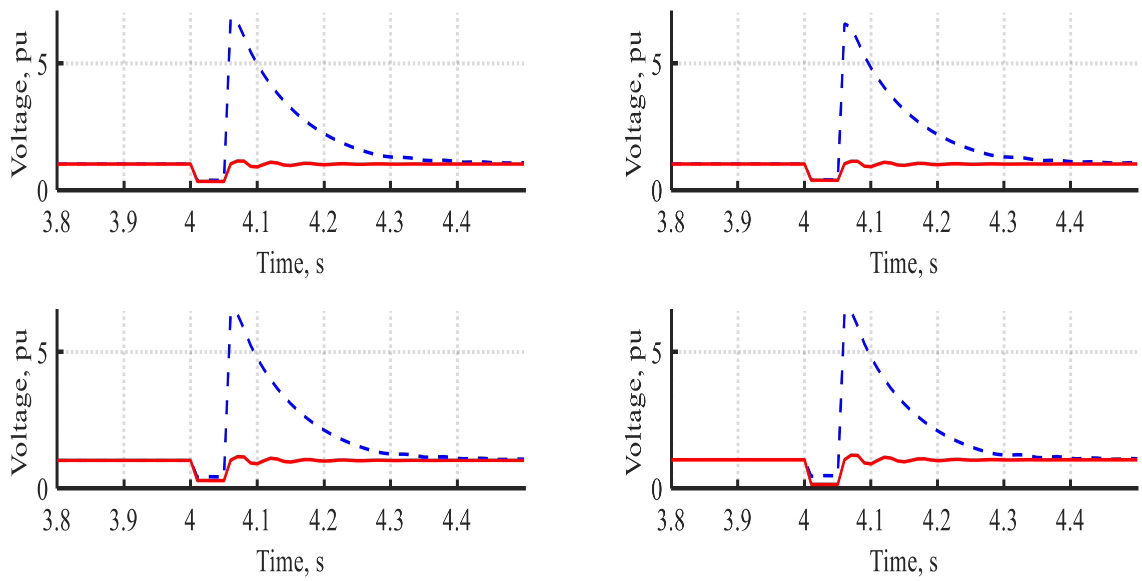


Fig. 21. Transient performance of the voltage profile at Buses B6, B7, B8 and B9 based on the fault outlined in Case 3.

JEATSA JOURNAL
JOURNAL OF ENGINEERING ADVANCES AND TECHNOLOGIES FOR SUSTAINABLE APPLICATIONS
Volume 1, Issue 2 (April, 2025)
Print ISSN: 3062-5629 Online ISSN: 3062-5637
Open Access
https://jeats.journals.ekb.eg/

***CASE 4**: SINGLE-PHASE FAULT LOCATED AT THE PV SYSTEM TERMINALS (BUS-5)*

A single-phase ground fault was simulated at the PV system outputs for additional certify of STATCOM based FLC. The results of this simulation are presented in Figs. 22 to 25. The system's dynamic performance incorporating STATCOM and FLC exceeds that of the system utilizing a STATCOM with a PI controller across all buses. In summary, the results demonstrate that the STATCOM equipped with a FLC significantly improves the system's performance in terms of oscillations and outperforms the STATCOM with a PI controller during fault condition.

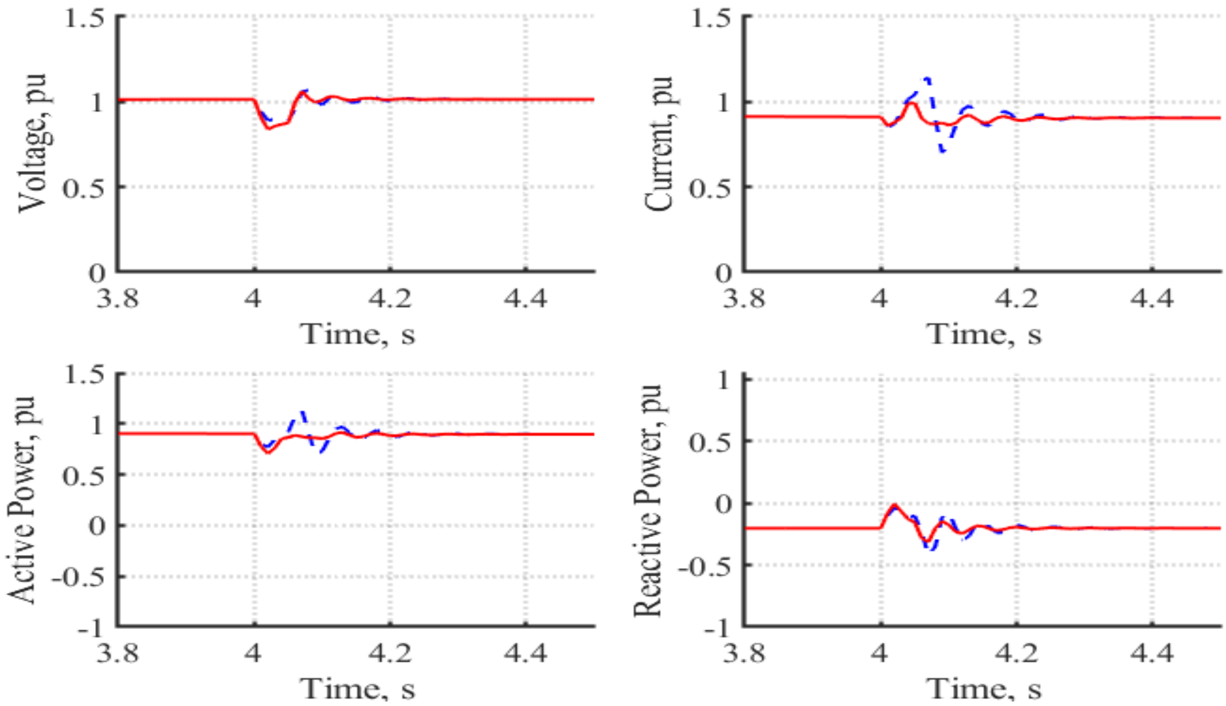


Fig. 22. Operational behavior of generator 1 based on the fault condition outlined in Case 4.

JEATSA JOURNAL
JOURNAL OF ENGINEERING ADVANCES AND TECHNOLOGIES FOR SUSTAINABLE APPLICATIONS
Volume 1, Issue 2 (April, 2025)
Print ISSN: 3062-5629 Online ISSN: 3062-5637
Open Access
https://jeats.journals.ekb.eg/

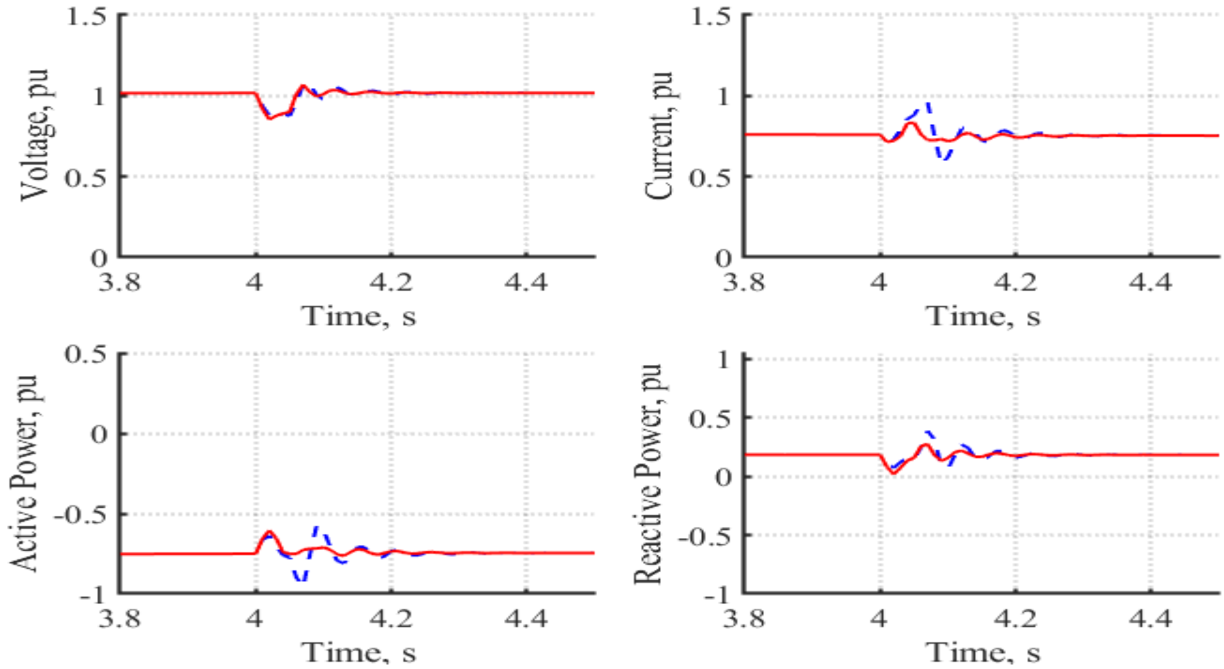


Fig. 23. Operational behavior of the WES based on the fault condition outlined in Case 4.

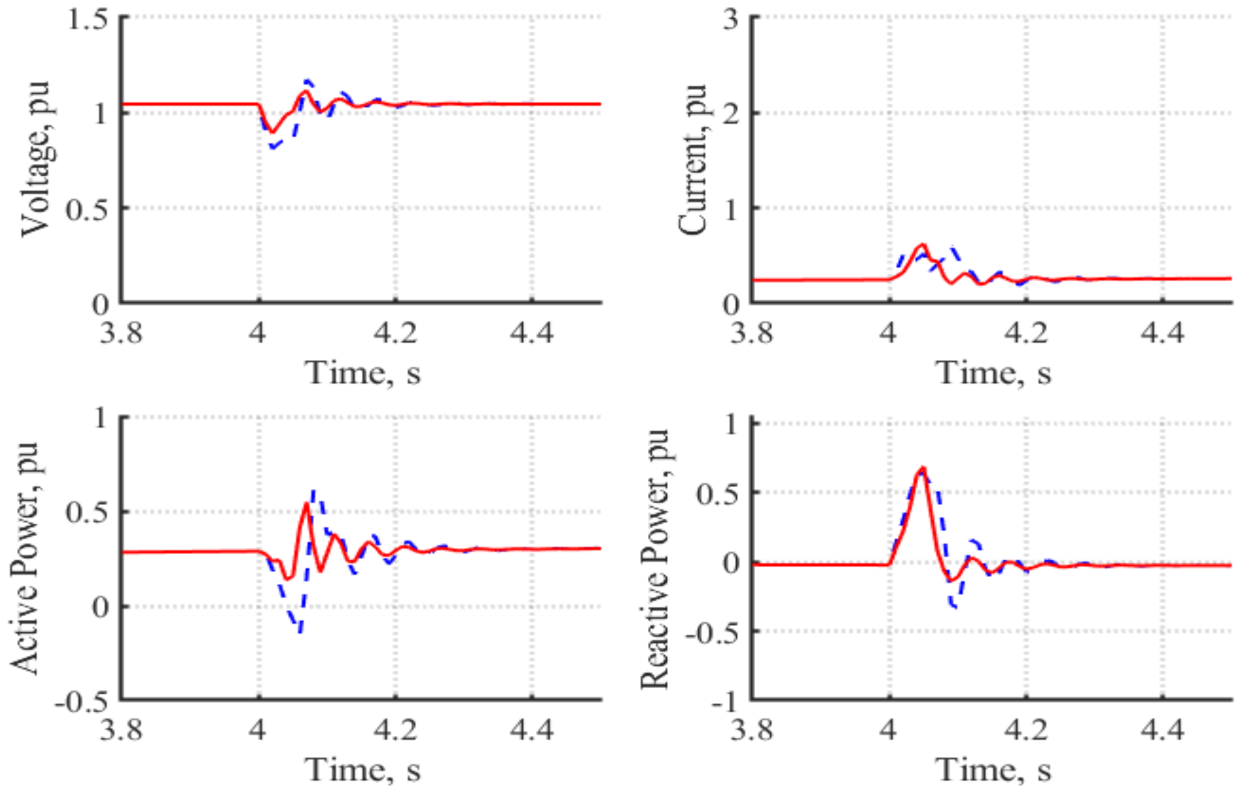


Fig. 24. Operational behavior of the PV system based on the fault condition outlined in Case 4.

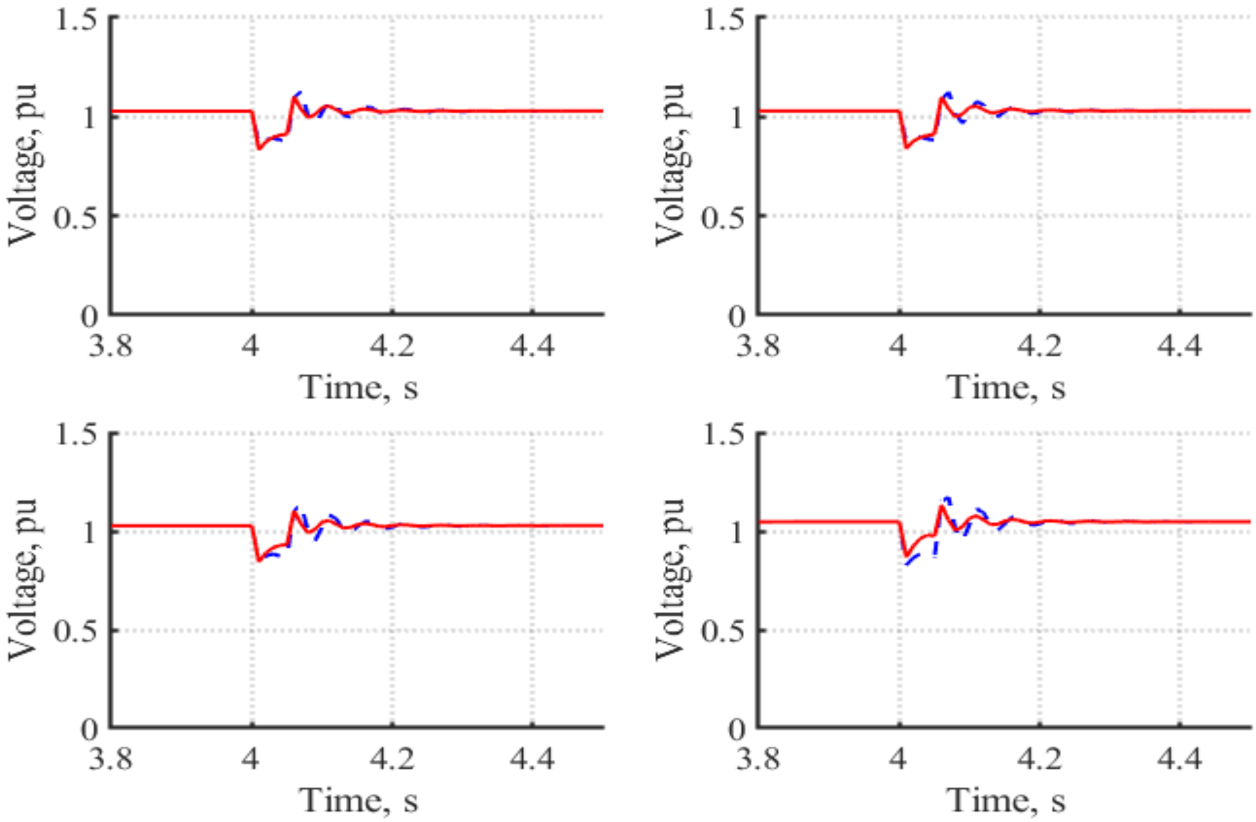


Fig. 25. Transient performance of the voltage profile at Buses B6, B7, B8 and B9 based on the fault outlined in Case 4.

VI. Conclusion and Future work

This study proposes STATCOM utilizing a fuzzy controller aimed at enhancing the system's transient behavior of an altered 9-bus IEEE normal electric network. The electric network has been restructured to incorporate RES, such as wind and PV systems. A modeling simulation for this adapted electric network, along with the recommended FLC has been created using the Matlab/Simulink environment. To evaluate the impact of the STATCOM utilizing FLC regarding the transient behavior of the system, various case studies were conducted across various locations in the electrical power system. Simulation results have obtained STATCOM with PI controller and FLC, highlighting the changes introduced by this FACTS device terms of transient stability. The system's dynamic behavior, along with the voltage profiles at all buses under study, highlighted the beneficial effect of the recommended STATCOM with FLC on enhancing the stability of the electric network. Future work will involve exploring the system's behavior with other FACTS devices under additional abnormal conditions.

VII. **References**

[1] H. Bakır, and A. A. Kulaksız, "Performance Analysis and Simulation of Solar PV-Wind Hybrid Energy System with STATCOM using Matlab/Simulink," *Nevşehir Bilim ve Teknoloji Dergisi,* vol. 7, no. 2, pp. 135-144, 2018.

[2] P. Pardhia, and A. Thakur, "Modelling and Voltage Control of the Solar Wind Hybrid Micro-Grid with STATCOM," 2023.

[3] A. Gupta, R. Saini, and M. Sharma, "Design of an optimal hybrid energy system model for remote rural area power generation." pp. 1-6.

[4] A. M. Eltamaly, K. E. Addoweesh, U. Bawah, and M. A. Mohamed, "New software for hybrid renewable energy assessment for ten locations in Saudi Arabia," *Journal of Renewable and Sustainable Energy,* vol. 5, no. 3, 2013.

[5] A. Yamany, M. A. Mohamed, and Y. Mohammed, "Optimal Sizing and Economic Evaluation of Hybrid Photovoltaic/Wind/Battery/Diesel Generation Systems for Autonomous Utilization," *Journal of Advanced Engineering Trends,* vol. 43, no. 1, pp. 47-65, 2024.

[6] Y. He, S. Guo, J. Zhou, J. Ye, J. Huang, K. Zheng, and X. Du, "Multi-objective planning-operation co-optimization of renewable energy system with hybrid energy storages," *Renewable Energy,* vol. 184, pp. 776-790, 2022.

[7] I. Y. Fawzy, Y. Mohamad, E. Shehata, and M. Abd El Sattar, "A modified perturb and observe technique for MPPt of intgrated PV system using DC-DC boost converter," *Journal of Advanced Engineering Trends,* vol. 40, no. 1, pp. 63-77, 2021.

[8] J. Kasera, "Design of grid connected photovoltaic system employing increamental conductance MPPT algotithm," *Journal of Electrical Engineering,* vol. 12, no. 4, pp. 6-6, 2012.

[9] H. Abobakr, A. Diab, Y. B. Hassan, and A. A. Khalaf, "Performance analysis of a small-scale grid-connected photovoltaic system: a real case study in Egypt," *Journal of Advanced Engineering Trends,* vol. 40, no. 1, pp. 79-96, 2021.

[10] N. Mithulananthan, A. Sode-Yome, N. Acharya, and S. Phichaisawat, "Application of FACTS controllers in Thailand power systems," *School of Environment, Resources and Development Asian Institute of Technology, Thailand*, 2005.

[11] H. M. Sultan, O. N. Kuznetsov, A. A. Z. Diab, and S. Abu-Zaid, "Enhancement of transient voltage stability of wind/PV power system using fuzzy logic based-SVC." pp. 1227-1233.

[12] V. Kleftakis, A. Rigas, A. Vassilakis, P. Kotsampopoulos, and N. Hatziargyriou, "Power-Hardware-in-the-loop simulation of a D-STATCOM equipped MV network interfaced to an actual PV inverter." pp. 1-5.

[13] J. Han, S. Khushalani-Solanki, J. Solanki, and J. Schoene, "Study of unified control of STATCOM to resolve the Power quality issues of a grid-connected three phase PV system." pp. 1-7.

[14] C. Chandarahasan, and E. S. Percis, "Optimizing resilience in large-scale integration of renewable energy sources: Exploring the role of STATCOM device," *International Journal of Power Electronics and Drive Systems (IJPEDS),* vol. 15, no. 3, pp. 1468-1477, 2024.

[15] R. SEKAR, M. ARUNACHALAM, and K. SUBRAMANIAN, "FUZZY-PROPORTIONAL INTEGRAL DERIVATIVE CONTROLLER WITH INTERACTIVE DECISION TREE," *REVUE ROUMAINE DES SCIENCES TECHNIQUES—SÉRIE ÉLECTROTECHNIQUE ET ÉNERGÉTIQUE,* vol. 69, no. 4, pp. 395-400, 2024.

[16] R. BHAVANI, N. R. Prabha, and M. Jawahar, "An ultra-capacitor integrated dynamic voltage restorer for power quality enhancement in a three-phase distribution system using an adaptive neuro-fuzzy interference system controller," *REVUE ROUMAINE DES SCIENCES TECHNIQUES—SÉRIE ÉLECTROTECHNIQUE ET ÉNERGÉTIQUE,* vol. 67, no. 4, pp. 383-388, 2022.

[17] R. Sadiq, Z. Wang, C. Chung, C. Zhou, and C. Wang, "A review of STATCOM control for stability enhancement of power systems with wind/PV penetration: Existing research and future scope," *International Transactions on Electrical Energy Systems,* vol. 31, no. 11, pp. e13079, 2021.

[18] S. Umathe, P. Daigavane, and M. Daigavane, "Improving Fault Classification Accuracy Using Wavelet Transform and Random Forest with STATCOM Integration," *EAI Endorsed Transactions on Energy Web,* vol. 12, 2025.

[19] M. Ayala-Chauvin, B. S. Kavrakov, J. Buele, and J. Varela-Aldás, "Static reactive power compensator design, based on three-phase voltage converter," *Energies,* vol. 14, no. 8, pp. 2198, 2021.

[20] S. Xu, S. Wang, G. Zuo, C. Davidson, M. M. de Oliveira, R. Memisevic, G. Pilz, B. Donmez, and B. R. Andersen, "Application examples of STATCOM," *Flexible AC Transmission Systems: FACTS*, pp. 511-584, 2020.

[21] D. Edison Raj, and Y. M. Badcha, "Power Quality Improvement using Distribution STATCOM (D-STATCOM)," 2024.

[22] V. K. Peddiny, B. Datta, and A. Banerjee, "Performance Improvement of Combined Wind Farms Using ANN-Based STATCOM and Grey Wolf Optimization-Based Tuning," *Journal of*

Operation and Automation in Power Engineering, pp. 248-254, 2025.

[23] S. Reddy, P. Prasad, and G. Srinivas, "Design of PI and fuzzy logic controllers for distribution static compensator," *International Journal of Power Electronics and Drive Systems,* vol. 9, no. 2, pp. 465, 2018.

[24] Mamdani, "Application of fuzzy logic to approximate reasoning using linguistic synthesis," *IEEE transactions on computers,* vol. 100, no. 12, pp. 1182-1191, 1977.

[25] P. C. Shill, "Fuzzy Logic Controllers: Optimization Issues on Design and Rule Base Reduction Algorithms," 2013.

[26] M. Masoumi, S. Hossani, F. Dehghani, and A. Masoumi, "The challenges and advantages of fuzzy systems applications," *A Preprint,* vol. 1, 2020.

[27] J. Yanase, and E. Triantaphyllou, "A systematic survey of computer-aided diagnosis in medicine: Past and present developments," *Expert Systems with Applications,* vol. 138, pp. 112821, 2019.

[28] J. Bhukya, and P. Singh, "Enhancing stability via coordinated control of generators, wind farms, and energy storage: Optimizing system parameters," *Journal of Energy Storage,* vol. 96, pp. 112513, 2024.

[29] R. Somalwar, and M. Khemariya, "A Review of Enhancement of Transient Stability by FACTS Devices," *International Journal of Emerging Technologies in Sciences and Engineering,* vol. 5, no. 3, pp. 72-76, 2012.

[30] I. Hamdan, A. M. Ibrahim, and O. Noureldeen, "Modified STATCOM control strategy for fault ride-through capability enhancement of grid-connected PV/wind hybrid power system during voltage sag," *SN Applied Sciences,* vol. 2, no. 3, pp. 364, 2020.

[31] D. S. Ahmed, and A. F. Marhoon, "STATCOM Controller Design for Hybrid PV-Wind of AC Microgrid," *Al-Iraqia Journal for Scientific Engineering Research,* vol. 3, no. 3, pp. 215-233, 2024.

[32] M. P. Donsion, J. Guemes, and J. Rodriguez, "Power Quality. Benefits of Utilizing FACTS Devices in Electrical Power Systems." pp. 26-29.

[33] A. M. Ibrahim, I. Hamdan, L. Nasrat, and M. A. Ismeil, "Optimal STATCOM for performance improvement of a grid-connected PV/wind hybrid energy system: case study of Gabal El Zayt Region, Egypt," *SVU-International Journal of Engineering Sciences and Applications,* vol. 3, no. 2, pp. 11-26, 2022.

[34] S. Akter, A. Saha, and P. Das, "Modelling, simulation and comparison of various FACTS devices in power system," *International Journal of Engineering Research and Technology,* vol. 1, no. 8, pp. 1-13, 2012.

[35] K. Mohd, and U. Ansari, "Use of STATCOM for Improving Dynamic Performance of Wind Farms Connected in Power Grid," *International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering,* vol. 3, no. 9, pp. 11738-11748, 2014.

[36] S. Shinde, R. Gandhi, G. S. Margarat, Y. Khairnar, H. M. Al-Jawahry, M. Landage, and K. K. Naidu, "Enhancing Power System Stability and Efficiency Using Flexible AC Transmission Systems (FACTS): A Comprehensive Analysis of Control Strategies and Applications." p. 01014.

[37] B. Bouhadouza, A. Gherbi, and H. Mellah, "Application of STATCOM to increase transient stability of wind farm," *American Journal of Electrical Power and Energy Systems*, 2013.

[38] K. Gupta, and Y. Pahariya, "Simulation Analysis of FACTs Devices for Transient Stability Improvement in Multi Machine System," *Simulation,* vol. 3, no. 01, 2017.

[39] M. Eslami, H. Shareef, A. Mohamed, and M. Khajehzadeh, "A survey on flexible AC transmission systems (FACTS)," *Organ,* vol. 1, pp. 12, 2012.

[40] K. Pushpak, B. K. Anuradha, A. Ravi, and A. Abhishek, "Improving transient stability of wind farm using FACTS devices focused on STATCOM," *Int J Eng Appl Sci Technol,* vol. 1, no. 7, pp. 163-167, 2016.

[41] O. E. Olabode, T. O. Ajewole, D. O. Akinyele, and F. K. Ariyo, "Energy Saving Analysis on Distribution Network with Incorporation of D-STATCOM Using Firefly Algorithm and Power Loss Index," *Jurnal Ilmiah Teknik Elektro Komputer dan Informatika (JITEKI),* vol. 10, no. 2, pp. 313-331, 2024.

[42] I. Y. Fawzy, M. A. Mossa, A. M. Elsawy, and A. A. Z. Diab, "Enhancing the Performance of Power System under Abnormal Conditions Using Three Different FACTS Devices," *International Journal of Robotics & Control Systems,* vol. 4, no. 1, 2024.

[43] I. Y. Fawzy, M. A. Mossa, A. M. Elsawy, I. Suwarno, and A. A. Z. Diab, "Deployment of STATCOM with Fuzzy Logic Control for Improving the Performance of Power System under Different Faults Conditions," *Journal of Robotics and Control (JRC),* vol. 5, no. 3, pp. 636-646, 2024.

[44] B. Bouhadouza, T. Bouktir, and A. Bourenane, "Transient Stability Augmentation of the Algerian South-Eastern Power System including PV Systems and STATCOM," *Engineering, Technology & Applied Science Research,* vol. 10, no. 3, pp. 5660-5667, 2020.

[45] N. E. Akpeke, C. M. Muriithi, and C. Mwaniki, “Contribution of FACTS devices to the transient stability improvement of a power system integrated with a PMSG-based wind turbine,” 2019.

[46] A. Kanchanaharuthai, V. Chankong, and K. A. Loparo, “Transient stability and voltage regulation in multimachine power systems vis-à-vis STATCOM and battery energy storage,” *IEEE Transactions on power systems,* vol. 30, no. 5, pp. 2404-2416, 2014.

[47] H. Mellah, “Application of STATCOM to Increase Transient Stability of Wind Farm,” *American Journal of Electrical Power and Energy Systems*, 2013-03-10, 2013.

[48] M. K. DEVI, G. ARCHANA, S. D. VEERAMANI, K. REVATHI, B. LIKHITHA, and S. MOHAN, “ENHANCEMENT OF POWER QUALITY DISTRIBUTION SYSTEM USING FPID IN D--STATCOM,” *International Journal of Information Technology and Computer Engineering,* vol. 12, no. 1, pp. 211-217, 2024.

[49] A. S. Shelke, and A. A. Bhole, “A Review on Different FACTS Devices used in Electrical Power System,” *International Journal of Engineering Research & Technology (IJERT)* vol. 10, pp. 15, 2021.

[50] S. Bhowmick, *Flexible AC Transmission Systems (FACTS): Newton Power-Flow Modeling of Voltage-Sourced Converter-Based Controllers*: CRC Press, 2018.

[51] S. T. Fadhıl, M. Hamad, A. O. Arslan, and A. M. Vural, “Comparison of Dynamic Performances of Statcom, SSSC, IPFC and UPFC On Inter-Area Oscillation Damping,” *The International Journal of Energy and Engineering Sciences,* vol. 5, no. 2, pp. 62-79, 2020.

[52] S. Sagar, and R. Satti, “Fuzzy Logic Control of D-STATCOM for Improving Power Quality and Dynamic Performance,” *International Journal of Innovative Technologies,* vol. 6, no. 2, pp. 0487-0490, 2018.

[53] G. Cakir, and G. Radman, "Placement and performance analysis of STATCOM and SVC for damping oscillation." pp. 1-5.

[54] K. Sundararaju, and R. Senthilkumar, “Modelling and analysis of real time power system with cascaded multilevel STATCOM using fuzzy controller,” *Journal of advances in chemistry,* vol. 12, no. 10, pp. 4408-4417, 2016.

[55] A. A. Z. Diab, T. Ebraheem, R. Aljendy, H. M. Sultan, and Z. M. Ali, “Optimal design and control of MMC STATCOM for improving power quality indicators,” *Applied Sciences,* vol. 10, no. 7, pp. 2490, 2020.

[56] S. O. Farees, M. Gayatri, and K. Sumanth, “Performance Comparison between SVC and STATCOM for Reactive Power Compensation by Using Fuzzy Logic Controller,” *IJITR,* vol. 2, pp. 991-994, 2014.

[57] I. A. Zayer, “Fuzzy logic control of crane system,” *Iraqi Journal For Mechanical And Material Engineering,* vol. 11, no. 3, 2011.

[58] A. Rajalingam, M. R. Prabhu, and K. V. Rao, “Power System Stability Enhancement Using FLC and MPC for STATCOM,” *Int. Journal of Engineering Research and Applications (IJERA),,* vol. 6, no. 1, pp. 107-113, 2016.

[59] R. Patel, and A. K. Panda, “Real time implementation of PI and fuzzy logic controller based 3-phase 4-wire interleaved buck active power filter for mitigation of harmonics with id–iq control strategy,” *International Journal of Electrical Power & Energy Systems,* vol. 59, pp. 66-78, 2014.

[60] M. Hemeida, H. Rezk, and M. M. Hamada, “A comprehensive comparison of STATCOM versus SVC-based fuzzy controller for stability improvement of wind farm connected to multi-machine power system,” *Electrical Engineering,* vol. 100, pp. 935-951, 2018.