Science and Technology Publishing (SCI & TECH)
ISSN: 2632-1017
Vol. 9 Issue 3, March - 2025

Voltage Profile Enhancement And Transmission Line Loss Minimization Using Fuzzy Logic Controller (FLC)-Based Unified Power Flow Controller (UPFC)

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***Abstract*— In this work, voltage profile enhancement and transmission line power loss minimization using Fuzzy Logic Controller (FLC)-based Unified Power Flow Controller (UPFC) is presented. The work focuses on employing a Fuzzy Logic Controller (FLC)-based UPFC for addressing the problems of voltage instability and high transmission losses on the Nigerian 330 kV, 28-bus transmission system. Particle Swarm Optimization (PSO) for UPFC-based voltage stabilization and loss minimization was used to further optimize fuzzy logic controller's parameters such as membership functions, rule sets, and scaling factors. The study utilized Newton-Raphson method to conduct the power flow analysis for the baseline case without the UPFC and also for the case where the FLC-based UPFC was installed on the transmission line. Based on the simulation results, about six (6) UPFC were required to enhance the voltage profile and loss minimization. The six UPFC were installed at the following buses; New Heaven (bus13), Onitsha (bus 14), Gombe (bus 16), Jos (bus 19), Kaduna (bus 20), and Kano (bus 22). The results showed that the introduction of the six UPFC improved the voltage profile by about 2.85%, minimized the active power loss by 15.9% and minimized the reactive loss by 40.9%. In all, the results showed that the UPFC significantly improved both the voltage profile and the power loss minimization on the case study transmission line.**

Keywords — Voltage Profile, Transmission Line, Loss Minimization, Fuzzy Logic Controller (FLC), Unified Power Flow Controller (UPFC)

1. Introduction

Voltage instability and increased transmission losses are persistent challenges in modern power systems [1,2]. Traditional methods for voltage control and loss minimization, such as reactive power compensation and voltage regulators, have limitations in dynamic response and adaptability [3,4]. As transmission networks become more complex due to increasing load demand, there is a need for advanced control techniques to improve system performance. Unified Power Flow Controllers (UPFCs) have emerged as a powerful solution for voltage stability enhancement and losses minimization [5,6]. UPFCs can control active and reactive power independently, making them highly effective for flexible power flow management. However, the performance of UPFCs depends on the control strategies employed, and fuzzy logic controllers (FLCs) offer a promising approach to enhance the UPFC's response under varying operational conditions [7,8]

Also, over the years, with regards to power loss minimization and voltage profile enhancement in transmission lines, various conventional methods have been employed, including reactive power compensation, synchronous condensers, and tap-changing transformers. These methods focus on regulating reactive power to stabilize voltage levels. However, they have limitations, particularly when rapid and dynamic adjustments are needed. To address these challenges, Flexible AC Transmission Systems (FACTS) devices such as the Unified Power Flow Controller (UPFC) have been developed. UPFCs are capable of controlling both the magnitude and phase angle of voltage, allowing for more flexible and dynamic control of power flow in transmission lines [9,10]. When paired with a Fuzzy Logic Controller (FLC), the UPFC can respond quickly to changing conditions in the power system, improving voltage stability and reducing transmission losses. FLCs offer a distinct advantage due to their ability to handle uncertainty and non-linearities in system behavior, making them ideal for controlling UPFCs under varying load conditions [11,12]. Accordingly, in this work, voltage profile enhancement and transmission line power loss minimization using Fuzzy Logic Controller (FLC)-based Unified Power Flow Controller (UPFC) is presented. The work focuses on employing a Fuzzy Logic Controller (FLC)-based UPFC for addressing the problems of voltage instability and high transmission losses on the Nigerian 330 kV, 28-bus transmission system.

2. Method

2.1 The system model

This work focuses on employing a Fuzzy Logic Controller (FLC)-based UPFC for addressing the problems of voltage instability and high transmission losses on the Nigerian 330 kV, 28-bus transmission system. The objective is to improve the voltage profile across the network and minimize losses, thereby contributing to a more reliable and efficient power transmission system. The architecture for enhancing voltage profiles and minimizing losses in a transmission line through the integration of a Fuzzy Logic Controller (FLC) with a Unified Power Flow Controller (UPFC) is outlined in Figure 1. The architecture begins with the Transmission System Model, which includes the 28-bus 330 kV network and its components such as buses, transmission lines, and transformers. Data is collected and preprocessed to provide accurate input for the FLC, which employs a rule base with fuzzy sets and membership functions to interpret voltage deviations and loss conditions. The FLC generates control signals that are sent to the UPFC.

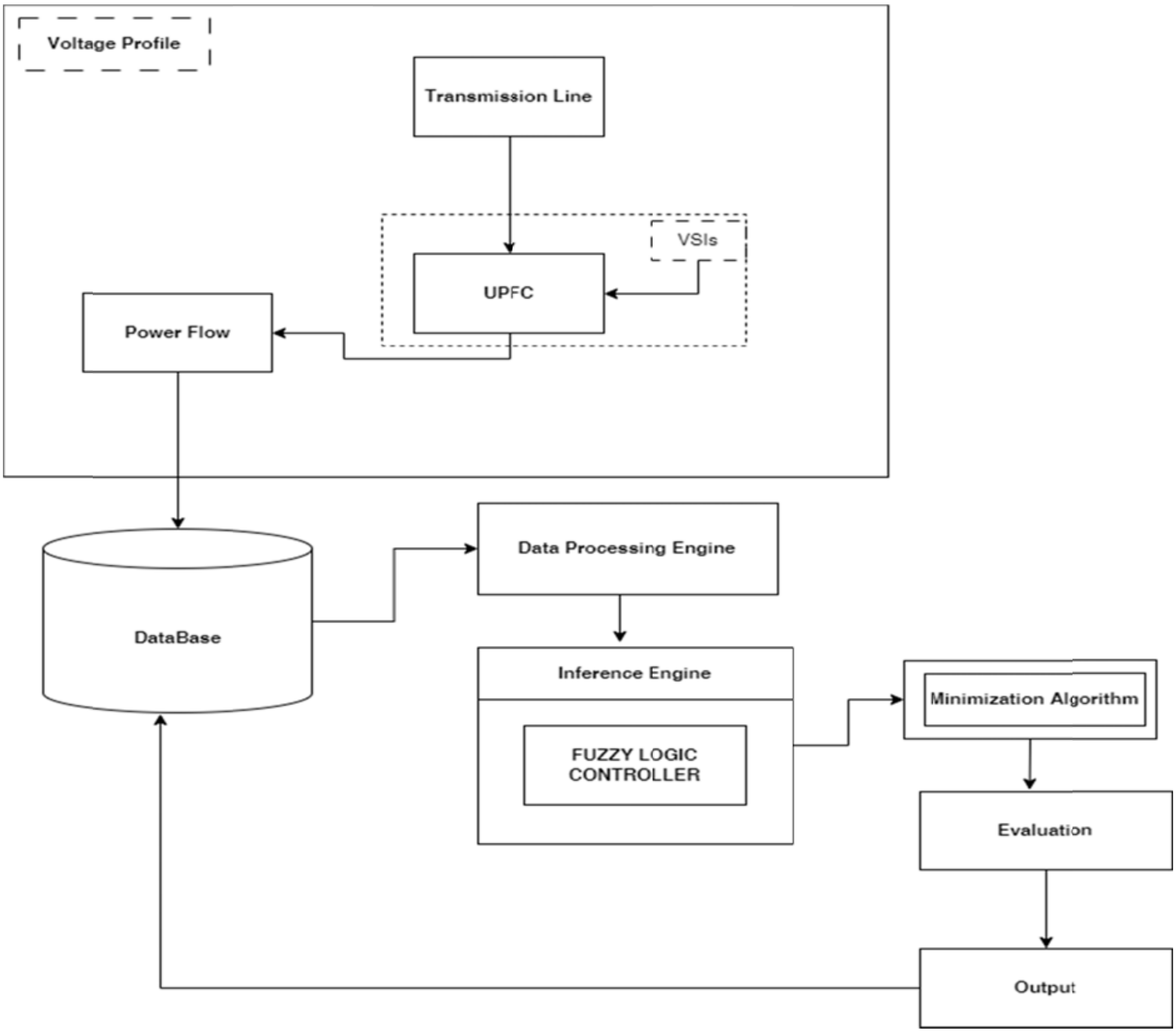

Figure 1: Architecture for Voltage Profile and Loss Minimization Using a Fuzzy Logic Controller-Based Power Flow Controller

The UPFC adjusts parameters like voltage magnitude, phase angle, and reactive power compensation to optimize the power flow in the transmission system. Particle Swarm Optimization (PSO) for UPFC-based voltage stabilization and loss minimization was used to further optimize fuzzy logic controller's parameters such as membership functions, rule sets, and scaling factors are treated as particles in a PSO framework. Each particle's position corresponds to a possible solution for tuning the fuzzy logic system. The fitness function evaluates each solution based on criteria like voltage deviation reduction and system loss minimization. PSO iteratively adjusts particle positions towards the best possible solution, improving voltage profile stability and reducing, transmission losses for efficient power delivery. This integration enhances the performance of UPFC in dynamic grid conditions. The system undergoes simulation and optimization to assess and refine performance. The implementation and monitoring phase ensures that the FLC-based UPFC operates effectively in real or simulated environments. The final results and analysis assess improvements in voltage profiles and loss reduction, and detailed reports are generated with recommendations for further optimization.

2.2 Unified Power Flow Controller (UPFC)

The UPFC is essentially made up of two voltage source inverters (VSIs) which are connected in such a way that they share one common dc storage capacitor, and also coupling transformers are used to connect these two VSIs to the power system. A shunt transformer is used to connect one of the VSI to the transmission system, while a series transformer is used to connect the other the VSI to the transmission system, as depicted in Figure 2.

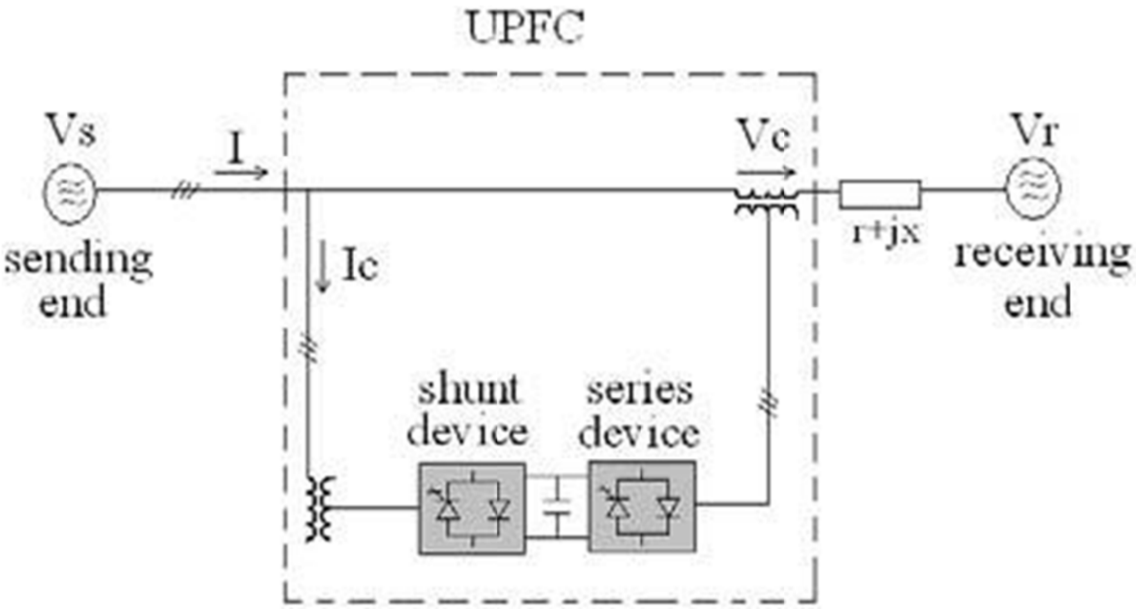

Figure 2: UPFC Link in Transmission Line

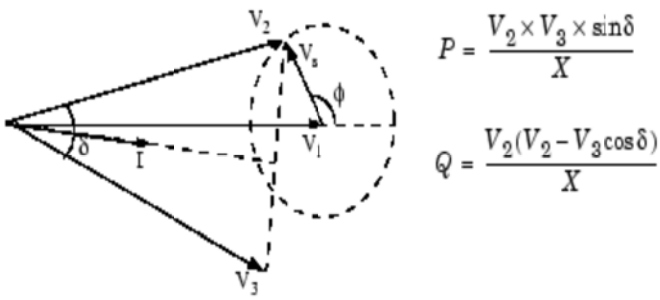

Figure 3: Phasor Diagram of Voltages and Currents

In o mmetric 3-phase voltage is injec

$$P = \frac{V_2 \times V_3 \times \sin\delta}{X} \quad (1)$$

$$Q = \frac{V_2(V_2 - V_3\cos\delta)}{X} \quad (2)$$

2.3. The Controller Circuit for the UPFC

The controller circuit of both series and shunt converters of the UPFC controller circuit are designed separately as shown in the flow chart in Figure 4.

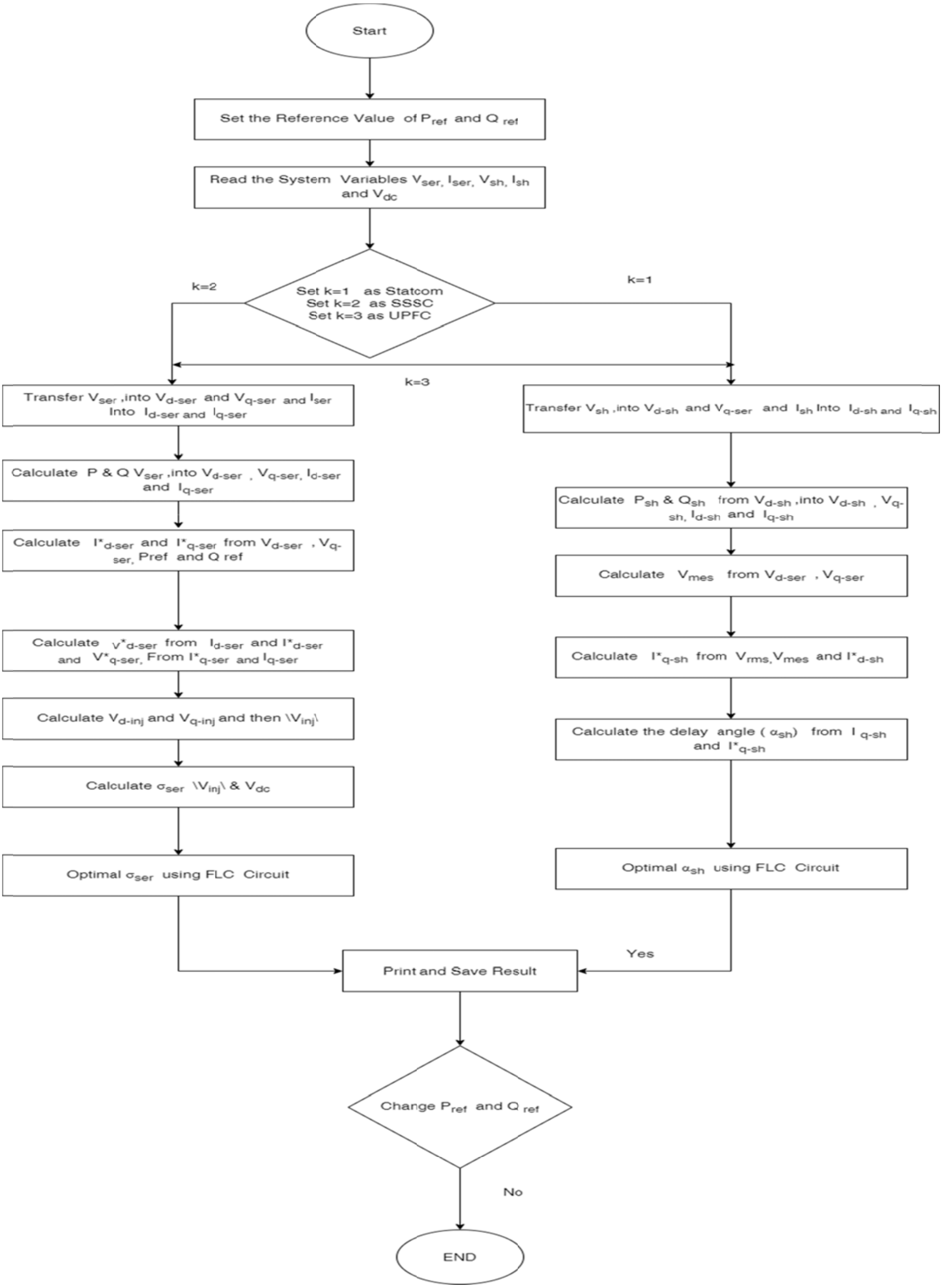

Figure 4: The flow chart of the UPFC controller circuit

2.4 The Fuzzy Logic Controller Model Development

2.4.1. Data Preprocessing For the Fuzzy Logic-based Model Development

The data preprocessing engine phase shown in Figure 3.7 is a critical stage where raw data undergoes refinement and transformation to enhance its suitability for machine learning algorithms. Following preprocessing, the Inference Engine takes charge, leveraging the structured dataset to make predictions. This sequential process ensures that the model operates with optimized and relevant information, laying the groundwork for accurate outcomes.

The data cleaning involves detecting and correcting errors or inconsistencies in the dataset used for the power flow analysis. This includes addressing missing values, handling outliers, and rectifying inaccuracies to ensure the quality of the input data. The data transformation process entails converting the original data into a format suitable for analysis. In the context of power flow control, this may involve transforming data variables or features to enhance their relevance or align them with the requirements of the fuzzy logic algorithms. Finally, the data reduction techniques, such as feature selection or extraction, was used to identify and retain the most significant variables for effective voltage profile and loss minimization, while eliminating redundant or non-essential information.

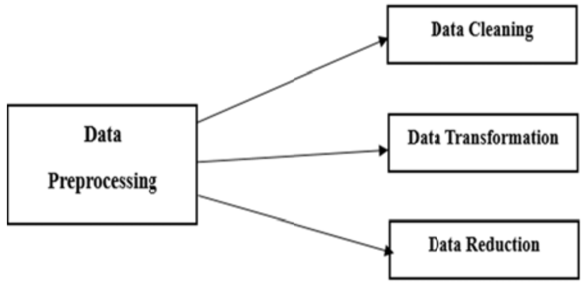

Figure 5: Preprocessing for Voltage Profile and Loss Minimization Using a Fuzzy Logic Controller-Based Power Flow Controller.

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2.4.2 The Structure of fuzzy logic control system

The fuzzy logic controller structure consists of mainly five parts, namely, knowledge base, fuzzification, inference, rule base, and defuzzification, as shown in Figure 6.

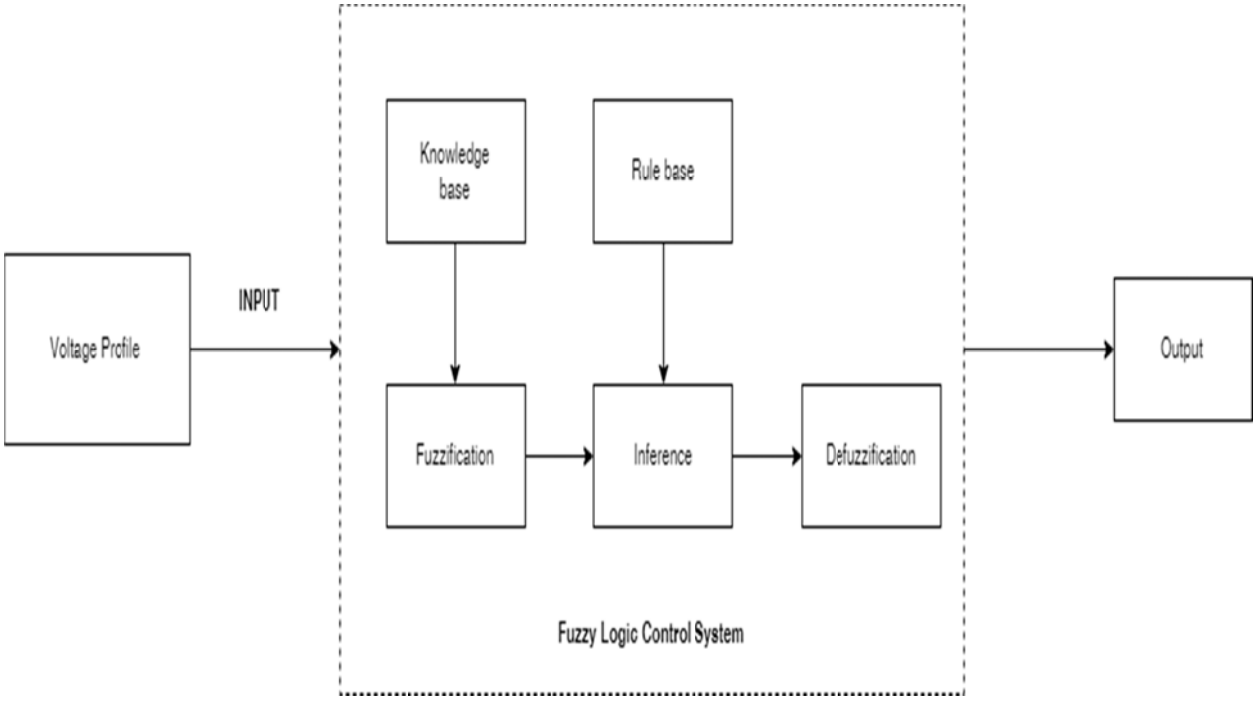


Figure 6: Structure of fuzzy logic control system

2.4.3 The Fuzzy Logic Rule Generation and the Inference Rule for Employed in the Case Study Transmission Line Parameters

A nominal voltage level of the network or a typical operating voltage is selected as the reference point; for instance, since the base voltage is 330 kV, this becomes the benchmark for converting pu values back to actual voltage. Next, the fuzzy rules are designed, specifying that the output variable (voltage) should be expressed in per-unit terms, such as low voltage (0.9 pu), nominal voltage (1.0 pu), and high voltage (1.1 pu). After processing the inputs in the fuzzy logic system, using MATLAB's Fuzzy Logic Toolbox as shown in Figure 7, the fuzzy output is normalized to ensure that the voltage result is presented in per-unit, maintaining it within a reasonable range. If it is necessary to convert the output back to an actual voltage value, this can be achieved by multiplying the per-unit result by the base voltage.

The screenshot in Figure 8 shows a set of fuzzy logic rules for determining voltage levels based on the per-unit (PU) and reactive power (PQ) values in a power system. Each rule specifies a condition involving PU and

PQ, which are categorized as "Low," "Nominal," or "High." When the conditions in a rule are met, the output voltage is set to "Low." Each rule has a weight of 1, indicating equal importance or influence in the fuzzy inference system. For example, the first rule states that if PU is "Low" and PQ is "Low," then the voltage output will be "Low." This pattern continues across all rules, where the system outputs a "Low" voltage under different combinations of PU and PQ levels. This setup indicates that the fuzzy logic system is designed to classify voltage as low across varying conditions, possibly as a conservative approach for system stability or to prioritize low-voltage outputs under different operating states. The screenshot in Figure 9 shows the visualization of the fuzzy logic inference process using specific input values for PU and PQ, both set at 0.5, which places them at the midpoint of their range.

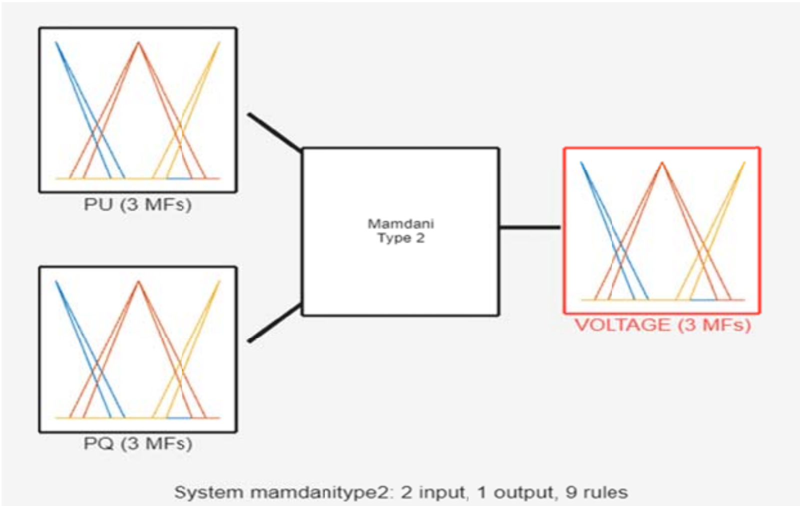
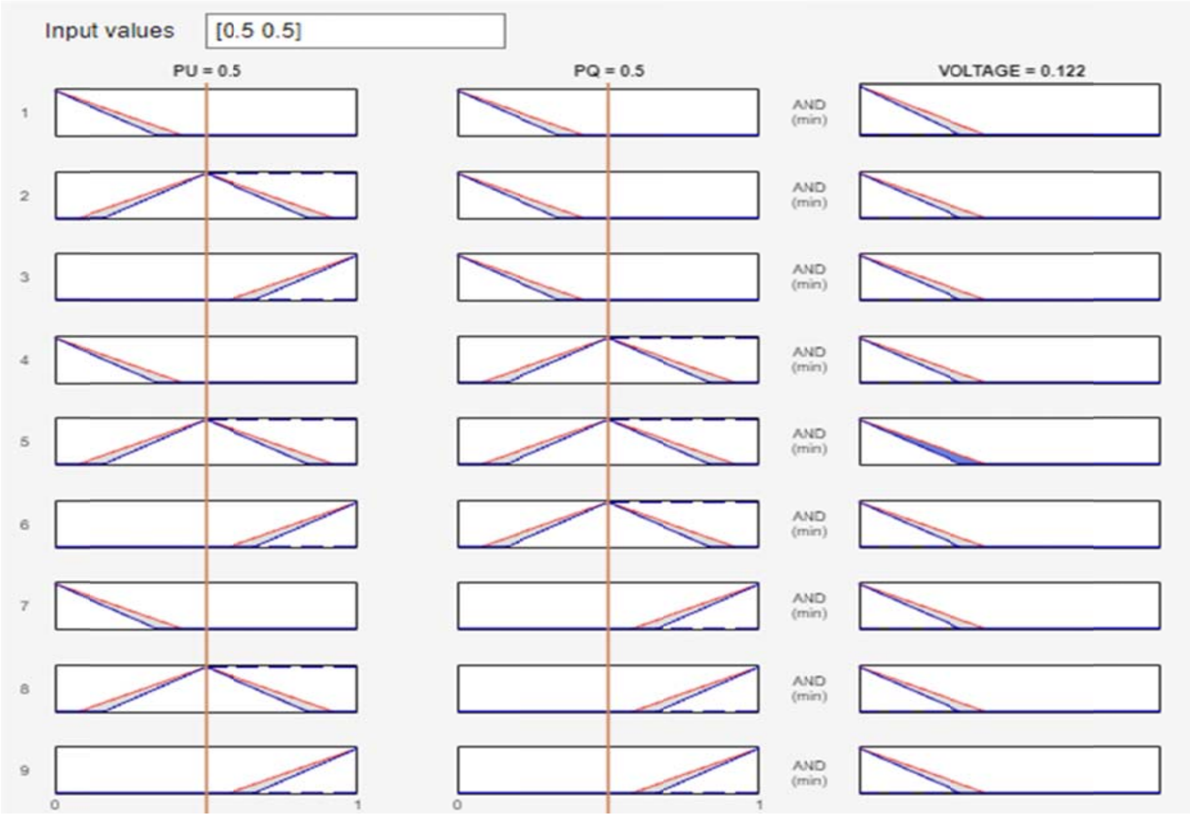


Figure 7: Interval type 2 fuzzy logic

	Rule	Weight	Name
1	If PU is LOW and PQ is Low then VOLTAGE is low	1	rule1
2	If PU is Nominal and PQ is Low then VOLTAGE is low	1	rule2
3	If PU is High and PQ is Low then VOLTAGE is low	1	rule3
4	If PU is LOW and PQ is Nominal then VOLTAGE is low	1	rule4
5	If PU is Nominal and PQ is Nominal then VOLTAGE is low	1	rule5
6	If PU is High and PQ is Nominal then VOLTAGE is low	1	rule6
7	If PU is LOW and PQ is High then VOLTAGE is low	1	rule7
8	If PU is Nominal and PQ is High then VOLTAGE is low	1	rule8
9	If PU is High and PQ is High then VOLTAGE is low	1	rule9

Figure 8: Screenshot of the Rule Generation for the Fuzzy Logic Controller



9: The screenshot showing the Inference Rule

2.5 The Power Flow Analysis Using Newton-Raphson

The procedure or sequential steps for the power flow analysis using Newton-Raphson is as follow:

Start

The process begins with the initialization of the system.

Input System Data

In this step, key system data is provided, including specified loads, generation data, and data from the FACTS controllers (such as UPFC, SVC, etc.).

i. Loads: The power demand at various points in the network.
ii. Generation: The power output of generators at various buses.
iii. FACTS Controller Data: Data about the controllers that will be used to enhance power flow and voltage regulation.

Read Voltage Specifications at Various Buses

The system then reads the voltage specifications at different buses (nodes) in the transmission network. These readings provide real-time voltage levels at strategic points in the grid.

Form the Admittance Matrix

An admittance matrix is formed, representing the electrical connections between buses in the power system. This matrix contains information about the conductance and susceptance of the lines connecting the buses, helping in the calculation of power flows.

Initialize Voltages and Angles at All System Busbars

Initial values for voltages and angles at each busbar are set. This initialization helps in starting the iterative process for load flow calculation and voltage correction.

Calculate Power Injected by Series and Shunt Elements

The power injected into the system by both series and shunt elements (such as transformers, capacitors, and inductors) is calculated.

i. Series Elements: Devices like transmission lines or transformers that can regulate the voltage along a transmission path.
ii. Shunt Elements: Devices that inject or absorb reactive power directly into the bus to control the voltage magnitude.

Calculate ΔP, ΔQ and Check If They Satisfy Tolerance Limits

Changes in active power (ΔP) and reactive power (ΔQ) are calculated to determine whether the power flows are within the tolerance limits. The system checks if these values fall within acceptable bounds for stable operation.

Are Specified Conditions Satisfied?

i. If the specified conditions for power flow and voltage regulation are satisfied, the process moves to the next step.

ii. If not, the system proceeds to update the state variables and FACTS device data, and the iterative process continues.

Update State Variables and FACTS Device Data

The system updates the state variables (voltages, angles) and the FACTS device data to improve voltage stability and power flow. This step ensures that the system adapts to any changes in load, generation, or system configuration.

Output Bus Voltages, Generation, and Power Flows

Once the conditions are satisfied, the final bus voltages, generation data, and power flows are outputted. These values reflect the optimized state of the system, ensuring efficient power distribution and voltage regulation.

The control structure of a Unified Power Flow Controller (UPFC) is shown in Figure 3.10. It is composed of two main elements: the Shunt Controller (STATCOM) and the Series Controller (SSSC). The diagram in Figure 11 shows a representation of the high-voltage power transmission network, modeled for the 330 kV, 28-bus system.

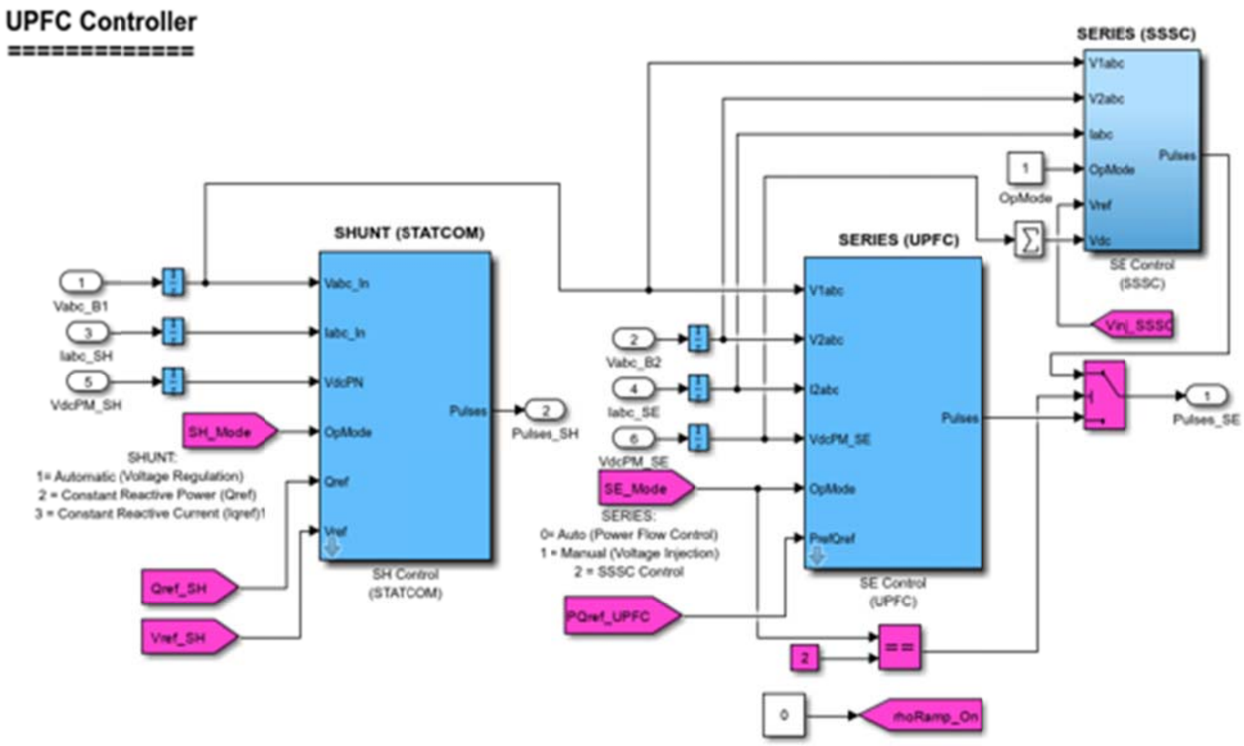


Figure 10: UPFC Controller

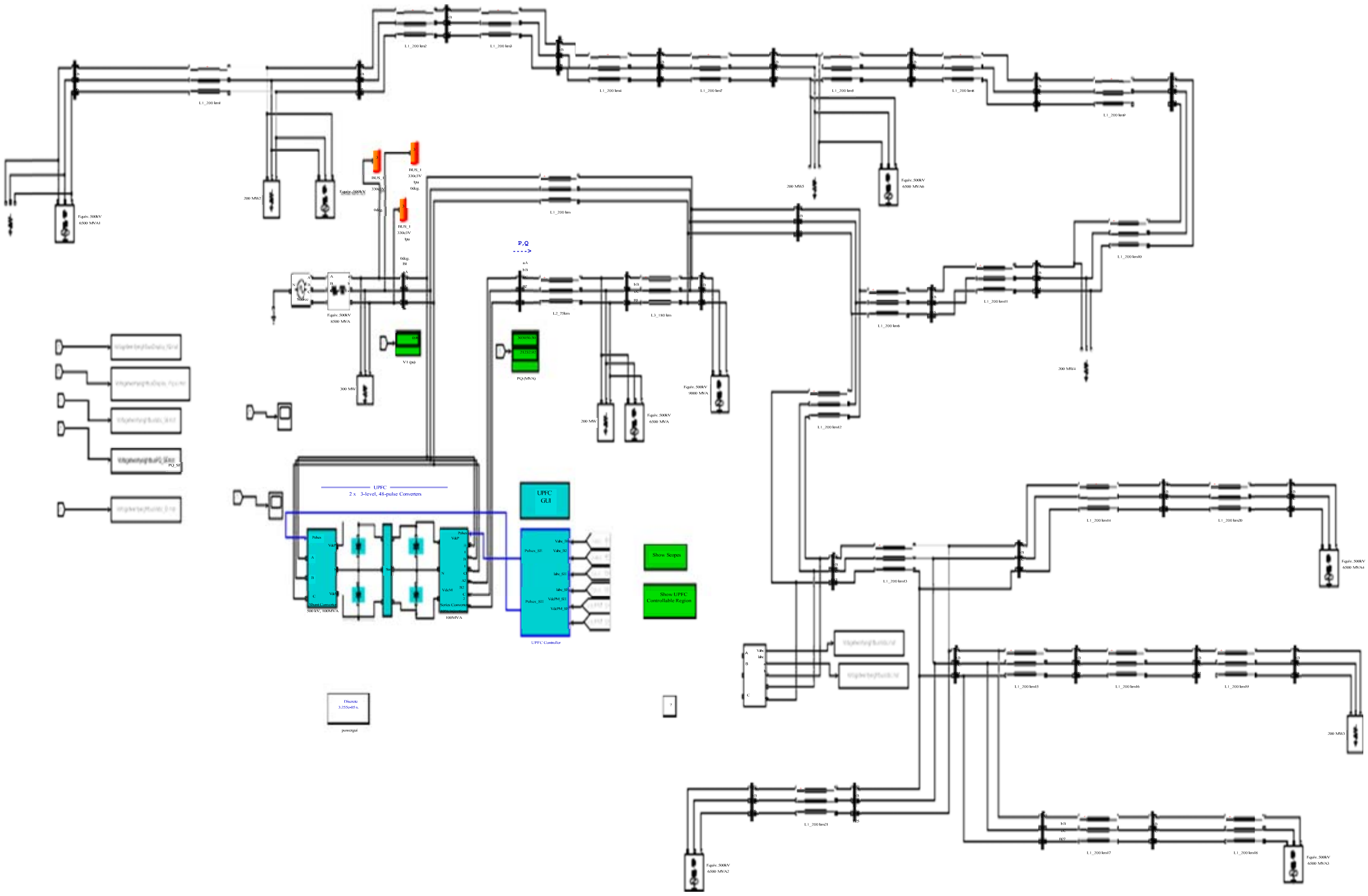


Figure 11: Circuit for Voltage profile improvement and loss minimization in a transmission line using Fuzzy logic controller based power flow controller in 28 bus

3. Results and discussion

3.1 The fuzzy logic model implementation parameter setup

The Fuzzy logic controller parameters configurations used in the implementation of the voltage profile improvement and loss minimization model are presented in Table 1 to Table 4. The parameters configurations presented in Table 1 to Table 4 were used in MATLAB for the implementation of the Fuzzy logic controller.

Table 1: Setup for Voltage Deviation V_{dev}

Membership Function	Type	Parameters
Low	Trimf	[-0.2 0 0.06]
Medium	Trimf	[0 0.06 0.12]
High	Trimf	[0.06 0.12 0.18]

Table 2: Setup for Line Loading L_{load}

Membership Function	Type	Parameters
Low	Trimf	[0 0.3 0.6]
Medium	Trimf	[0.3 0.6 1.2]
High	Trimf	[0.6 1.2 1.8]

Table 3: Setup for Reactive Power Demand Q_d

Membership Function	Type	Parameters
Low	Trimf	[0 0.0025 0.005]
Medium	Trimf	[0.0025 0.005 0.012]
High	Trimf	[0.005 0.012 0.018]

Table 4: Setup for UPFC priority $UPFC_P$

Membership Function	Type	Parameters
Low	Trimf	[0 0.1 0.5]
High	Trimf	[0.5 0.75 1.5]

3.2 Result of the power flow analysis for scenario 3 which is the case with six UPFC inserted on the network with the use of Fuzzy logic controller

The Newton-Raphson method was used for the power flow analysis. The first, power flow analysis for the baseline case where the UPFC was not installed on the network was conducted. Based on the simulation results, about six (6) UPFC were required to enhance the voltage profile and loss minimization. The six UPFC were installed at the following buses; New Heaven (bus13), Onitsha (bus 14), Gombe (bus 16), Jos (bus 19), Kaduna (bus 20), and Kano (bus 22). The results of the power flow analysis with the 6 UPFC inserted on the network with the use of Fuzzy logic controller are presented in Table 5, Table 6, Figure 12, Figure 13, Figure 14, Figure 15, Figure 16, Figure 17, Figure 18 and Figure 19. The results showed that the introduction of the six UPFC improved the voltage profile, minimized the active power loss and reactive loss in the buses in the entire power transmission network. About mean voltage profile improvement of 2.85% was obtained as shown in Figure 13. Also, mean active power loss improvement of 15.9% was obtained in scenario 3 as shown in Figure 15. Similarly, mean reactive power loss improvement of 40.9% was obtained in scenario 3 as shown in Figure 17.

Table 5: The voltage profile, the active and reactive power loss for the scenario 3 which is the case with six UPFC inserted on the network with the use of Fuzzy logic controller

Bus Number	Bus Name	Voltage Magnitude for scenario 3	Angle (degree) for scenario 3	Active Power Loss (pu) for scenario 3	Reactive Power Loss (pu) for scenario 3
1	Egbin	1.000	0.000	0.01	0.001
2	Delta IV	1.006	11.200	0.012	0.002
3	Aja	1.047	-0.100	0.01	0.001
4	Akangba	1.024	0.200	0.009	0.001
5	Ikeja West	1.030	1.500	0.01	0.003
6	Ajaokuta	1.048	5.900	0.01	0.004
7	Aladja	1.045	9.900	0.012	0.003
8	Benin	1.043	5.800	0.011	0.002
9	Ayede	1.021	1.500	0.01	0.002
10	Oshogbo	1.027	7.300	0.011	0.004
11	Afam	1.050	9.900	0.013	0.004
12	Alaoji	1.045	9.500	0.011	0.003
13	New Heaven	0.950	2.200	0.015	0.006
14	Onitsha	0.960	3.100	0.014	0.006
15	Birnin Kebbi	1.050	13.300	0.012	0.005
16	Gombe	0.950	2.900	0.015	0.007
17	Jebba Gs	1.052	12.900	0.014	0.004
18	Jebba TS	1.052	12.900	0.014	0.005
19	Jos	0.950	9.600	0.015	0.009
20	Kaduna	0.950	5.400	0.014	0.007
21	Kainji	1.054	15.900	0.013	0.008
22	Kano	0.950	1.300	0.012	0.003
23	Shiroro	1.054	7.400	0.012	0.005
24	Sapele	1.054	7.200	0.013	0.003
25	Okpai	1.030	13.700	0.012	0.003
26	Katampe	1.042	5.500	0.011	0.003
27	Delta	1.044	25.500	0.01	0.003
28	AES	1.048	2.600	0.013	0.003
		Total Loss		**0.338**	**0.110**

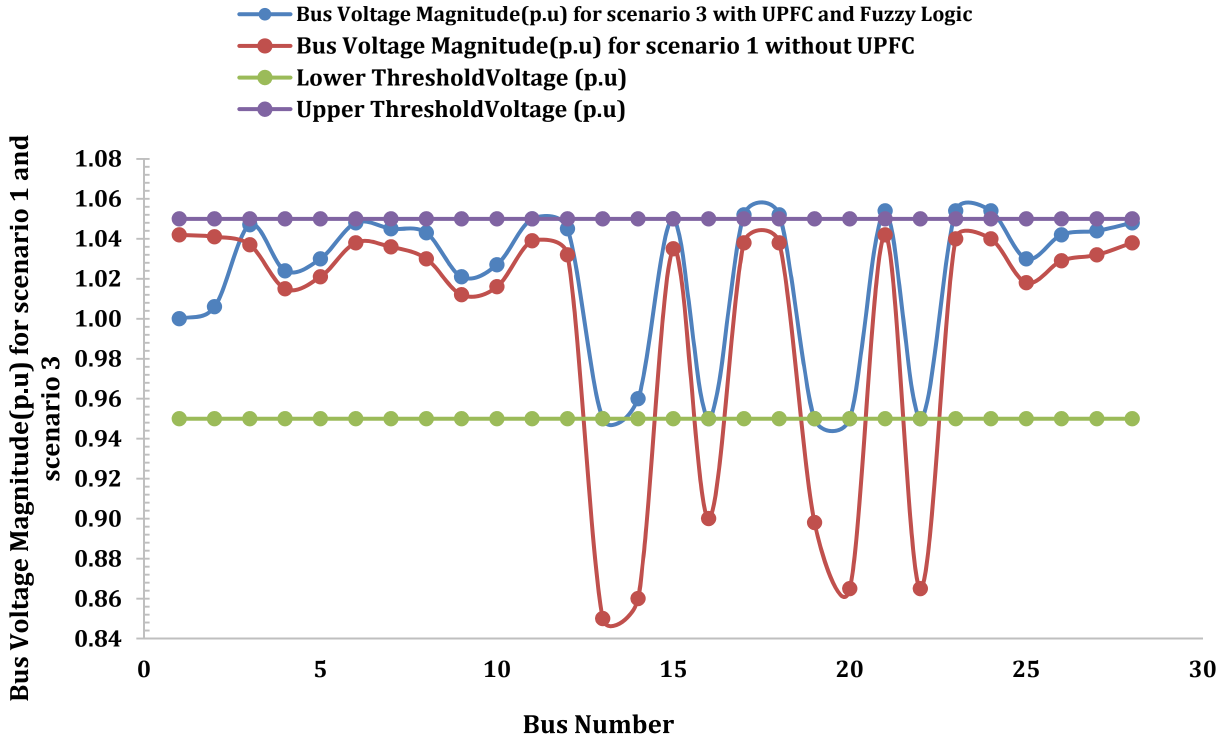


Figure 12 Comparison of Voltage Magnitude (p.u) for scenario 1 and scenario 3

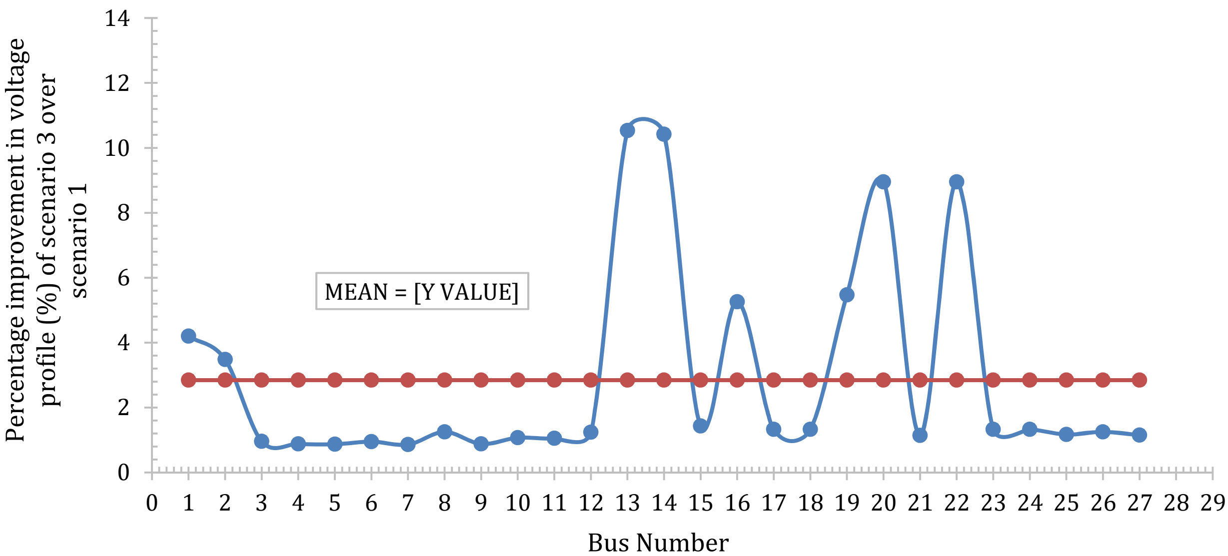


Figure 13 Percentage improvement in voltage profile (%) of scenario 3 over scenario 1

Table 6: Percentage improvement in active power and reactive power of scenario 3 over scenario 1

Bus Number	Active Power Loss (pu) with UPFC and Fuzzy Logic	Active Power Loss (Pu) for Scenario 1	Percentage improvement in active power (%) of scenario 3 over scenario 1	Reactive Power Loss (pu) with UPFC and Fuzzy Logic	Reactive Power Loss (Pu) for Scenario 1	Percentage improvement in reactive power (%) of scenario 3 over scenario 1
1	0.01	0.012	16.7	0.001	0.003	66.7
2	0.012	0.015	20.0	0.002	0.005	60.0
3	0.01	0.01	0.0	0.001	0.004	75.0
4	0.009	0.009	0.0	0.001	0.003	66.7
5	0.01	0.011	9.1	0.003	0.004	25.0
6	0.01	0.013	23.1	0.004	0.006	33.3
7	0.012	0.014	14.3	0.003	0.006	50.0
8	0.011	0.011	0.0	0.002	0.005	60.0
9	0.01	0.01	0.0	0.002	0.003	33.3
10	0.011	0.012	8.3	0.004	0.005	20.0
11	0.013	0.014	7.1	0.004	0.006	33.3
12	0.011	0.013	15.4	0.003	0.005	40.0
13	0.015	0.02	25.0	0.006	0.01	40.0
14	0.014	0.018	22.2	0.006	0.009	33.3
15	0.012	0.016	25.0	0.005	0.007	28.6
16	0.015	0.021	28.6	0.007	0.011	36.4
17	0.014	0.016	12.5	0.004	0.007	42.9
18	0.014	0.016	12.5	0.005	0.007	28.6
19	0.015	0.022	31.8	0.009	0.012	25.0
20	0.014	0.019	26.3	0.007	0.01	30.0
21	0.013	0.018	27.8	0.008	0.008	0.0
22	0.012	0.02	40.0	0.003	0.01	70.0
23	0.012	0.015	20.0	0.005	0.006	16.7
24	0.013	0.015	13.3	0.003	0.006	50.0
25	0.012	0.013	7.7	0.003	0.005	40.0
26	0.011	0.012	8.3	0.003	0.005	40.0
27	0.01	0.013	23.1	0.003	0.006	50.0
28	0.013	0.014	7.1	0.003	0.006	50.0
Mean	**0.012**	**0.015**	**15.9**	**0.004**	**0.006**	**40.9**

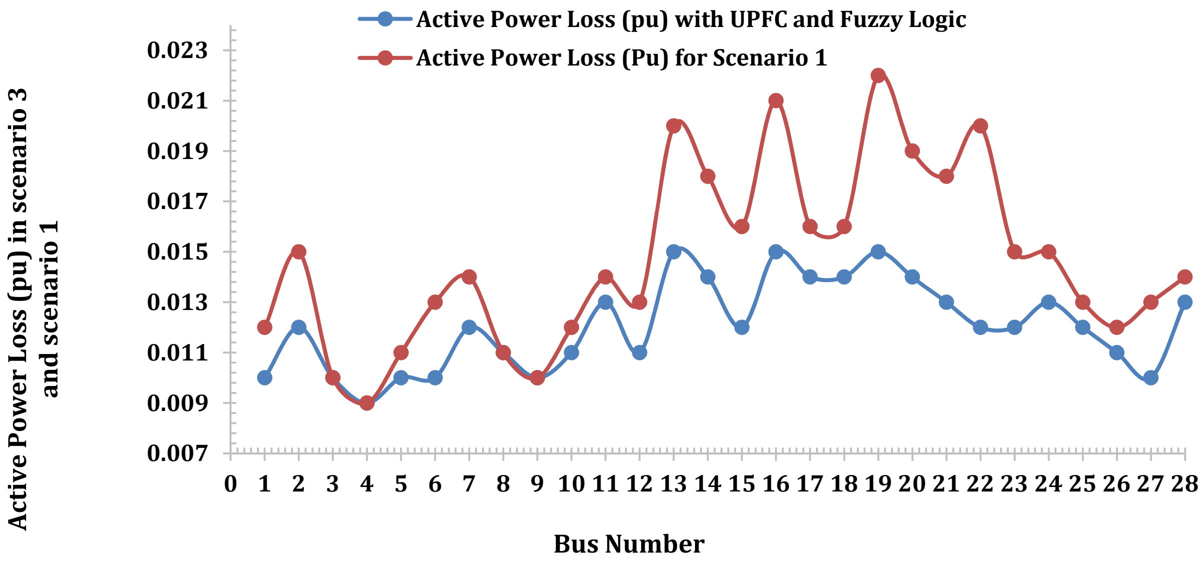


Figure 14 Comparison of the active power (%) of scenario 3 over scenario 1

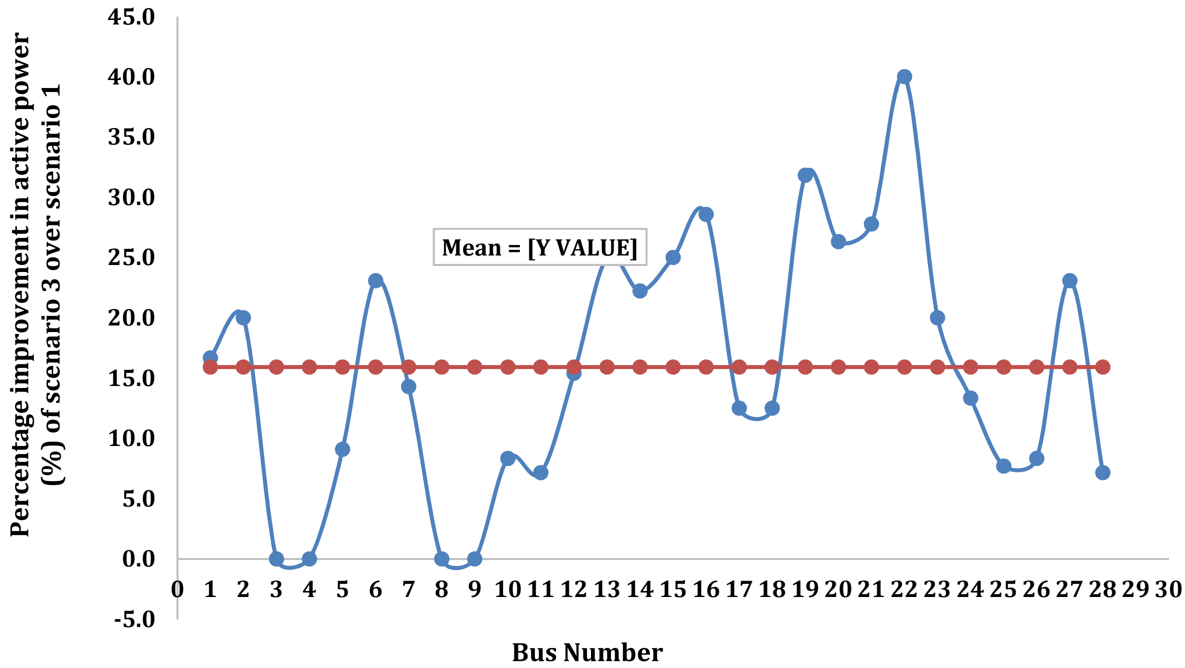


Figure 15 Percentage improvement in active power (%) of scenario 3 over scenario 1

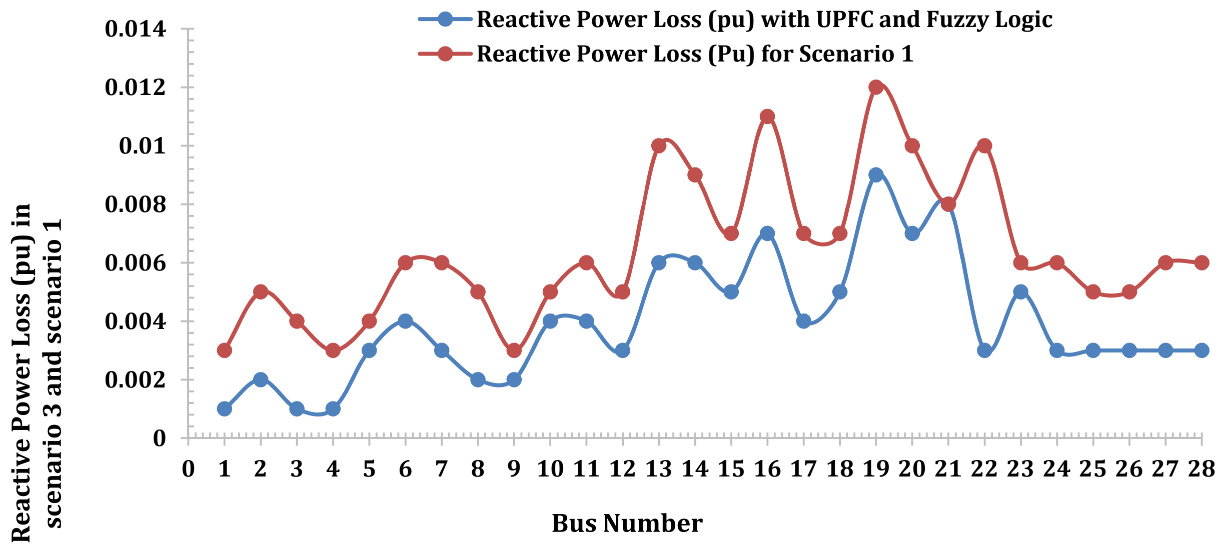


Figure 16 Comparison of the reactive power (%) of scenario 3 over scenario 1

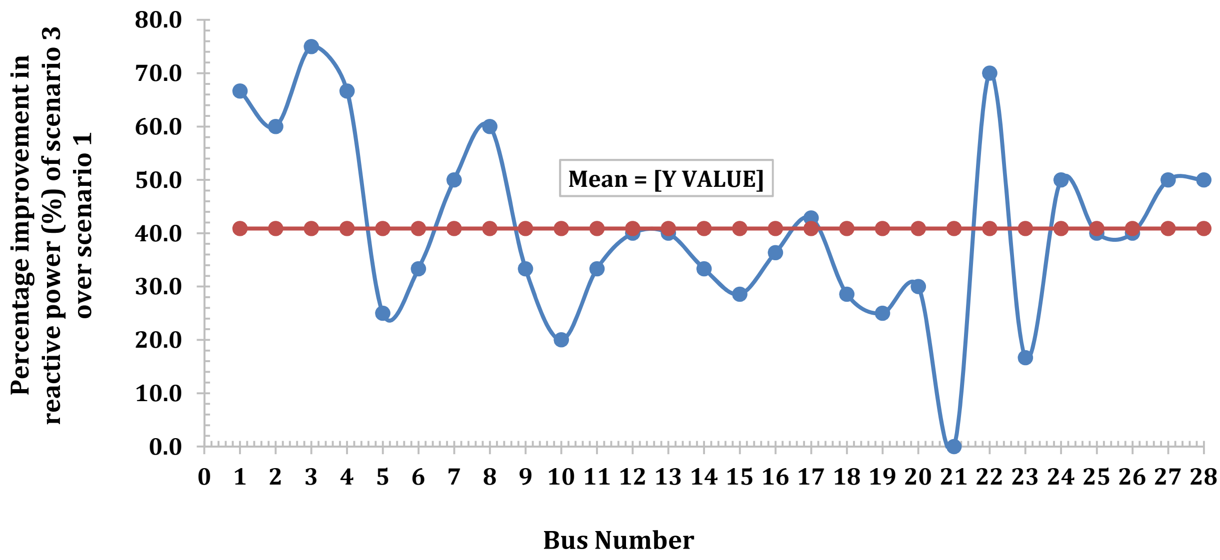


Figure 17 Percentage improvement in reactive power (%) of scenario 3 over scenario 1

In all, the use of Fuzzy logic controller to manage the placement of UPFC in the transmission line network improved the voltage profile and minimized the power loss significantly. In any case, the load or power flow analysis determines the weak buses which is used by the fuzzy logic controller to determine the appropriate location and the number of UPFC to use. As such, getting accurate results from the power flow analysis is paramount for this study.

Notably, in the work by [13] the authors identified six weak buses on the Nigerian 28-bus 330kV transmission system and the buses are: Kano, Kaduna, Jos, Gombe,Yola and Katampe. In the present research, six buses were also identified as the weak buses and they include; bus 13 (New Heaven), bus 14 (Onitsha), bus 16 (Gombe), bus 19 (Jos), bus 20 (Kaduna), and bus 22 (Kano). The two works differ on two buses. The difference can be attributed to one, the approach used in the load flow analysis. Also, the exact combination of the buses in the analysis can also be the reason for the difference.

Another work by [14] showed that there were seven weak buses on the Nigerian 28-bus 330kV transmission system. The difference in this case with the present research is due to the fact that [14] worked on 34 bus network whereas the present research worked on 28 bus network'

A third work by [15] on the the Nigerian 28-bus 330kV transmission network identified six buses as the weak buses and they included the same six buses that identified in the present work. However, the voltage profile of the buses in the two researches are slightly different. The implication of this variation is that the choice or settings of the parameters used in the load flow analysis may have significant effect on the result. Therefore, there may be need to study the impact of the load flow parameters settings on the voltage profile of the buses.

4. Conclusion

Fuzzy Logic Controller (FLC)-based Unified Power Flow Controller (UPFC) for improvement of the voltage profile and also for the minimization of the power losses in transmission power network. The study utilized Newton-Raphson method to conduct the power flow analysis for the baseline case without the UPFC and also for the case where the FLC-based UPFC was installed on the transmission line. The results of the power flow analysis in terms of voltage magnitude and the active and reactive power losses were used to evaluate the effectiveness of the UPFC in enhancing the transmission line power delivery. In all, the results showed that the UPFC significantly improved both the voltage profile and the power loss minimization on the case study transmission line.

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