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RESEARCH ARTICLE - ENGINEERING

Improvement of the Power System's Transient Stability Using the Unified Power Flow Controller with Fuzzy Logic Technique

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Abstract

By combining the functions of many FACTS (flexible alternative current transmission systems) devices into a single unit, the UPFC (unified power flow controller) is the most efficient FACTS device available. Two voltage converters work together to form the Unified Power Flow Controller, a flexible tool for enhancing voltage regulation, power flow management, and power system stability. Both converters rely heavily on their control methods. This article discusses the power flow mechanism in a transmission line, which is necessary for understanding the functioning of UPFC in a transmission line and using a standard PI controller with voltage references in the control circuit of both converters. This study aims to enhance the power system's dependability and stability by developing a smart support-based UPFC device. Fuzzy logic is a useful tool for controlling UPFC equipment in a variety of failure scenarios. The fuzzy logic controller contrasts power grid characteristics such as a rotor speed deviation to a reference value to create operational pulses for the voltage source converter in the UPFC system. The suggested model will be tested using MATLAB simulation. The success of the proposed model is shown by thoroughly comparing simulation results to those of previously established models. This research paper's original contribution is the creation of a smart support-based UPFC device with fuzzy logic control. By comparing power system parameters such as rotor speed deviation to a reference value and generating operational pulses for the voltage source converter in the UPFC system, this technique increases the electricity grid's dependability and stability. The effectiveness of the suggested model is proved by a comparison of simulation results obtained in a MATLAB environment with those obtained from previously developed models.

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Keywords: Transmission Line; Unified Power Flow Controller (UPFC); Flexible Alternative Current Transmission Systems (FACTS); Fuzzy Logic; Fault Conditions.

1. Introduction

Modelling, controlling, and evaluating the performance of UPFCs: A complete review of the available current transfer capacity is crucial in a deregulated power market. Using the UPFC, Kunal Gupta et al. (2015) boosted overall system flows in the power grid. This research on transitory stability is shown by running a simulation of the UPFC in a power world simulator and observing the increase in temporary steadiness. We look into the transient stability of the system as Rasheed Hameed Al-Rubaiy (2016) has described it using a variety of line and bus failures. Transient Stability Enhancement of the Power System Using a UPFC (Unified Power Flow Controller) by Noaman Khan (2017), a UPFC may be able to independently control the voltage, impedance, and phase. For grid-connected power systems, MATLAB/PSAT's power system block set can mimic the UPFC control technique. To determine how well FACTS devices function in an IEEE 9 bus power system under fault conditions, the network's UPFC's efficacy is put to the test by simulating a 3-phase failure on a variety of buses. FACTS devices are widely used in power networks to enhance their controllability and improve their power transfer capability.

This is done due to their ability to modify system parameters such as series impedance, shunt admittance, voltage magnitude/phase angle, and the current flowing through the transmission lines [1]. In addition, they are beneficial for damping the different types of oscillations in the system. The FACTS devices have evolved into different generations: capacitors and thyristor-switched reactors make up the first generation., and the second one is based on voltage source converters [2]. UPFC can be considered an extension of the second generation, which consists of FACTS devices comprising more than one VSC with some sort of energy storage device enabling them to exchange power between the converters and the transmission lines [3].

To make judgements using incomplete or unclear information, a fuzzy logic control system may be implemented Fig. 1. It's a mathematical strategy for handling difficult, vague situations. Many different kinds of control systems, from manufacturing to consumer goods to transportation, make use of fuzzy logic. It offers an adaptable and malleable approach to control that can accommodate dynamic systems and external situations.

Nomenclature & Symbols			
UPFC	Unified Power Flow Controller	P	Real Power
FACTS	Flexible Alternative Current Transmission Systems	Q	Reactive Power
VSC	Voltage Source Converter	δ	Power Angle
V_S	Sending End Voltage	G	Line Conductance
V_R	Receiving End Voltages	B	Line Susceptance
I_L	Line Current		

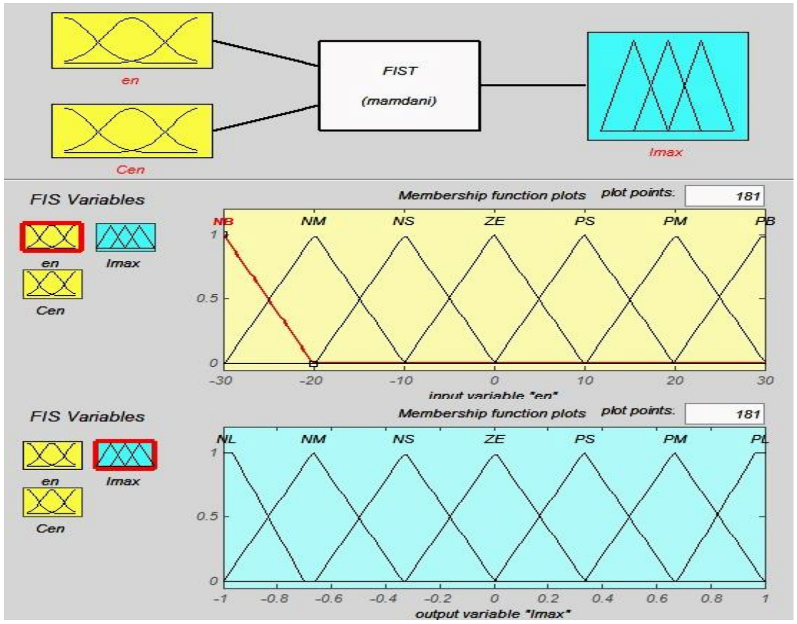


Fig. 1. Fuzzy Logic Control System [4]

2. Materials and Method

2.1. Structure of UPFC

The versatility of the UPFC comes from the fact that it comprises two converters: the series converter, which finds its connection in the transmission line through a series transformer, and the shunt converter through a shunt transformer. The schematic diagram of the UPFC is given in Fig. 2. The shunt transformer can inject a reactive current into the line in such a way that the voltage at that terminal can be kept constant [5]. When it is in operation with the series converter, its role reduces to that of supplying the losses that take place while the series converter is in operation. The DC link, which is a capacitor, has a constant voltage considering the requirements of the series converter [6].

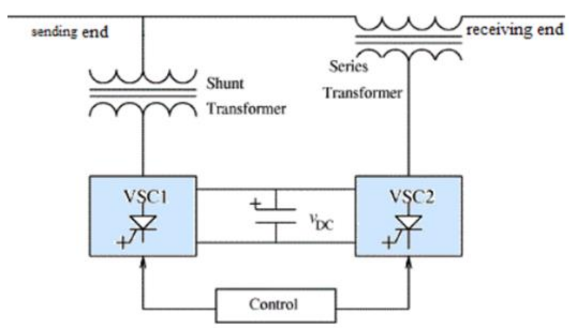


Fig. 2. Schematic diagram of UPFC[7]

2.2. Basic UPFC operations

UPFC is a FACTS device placed between two buses, namely the UPFC sending end bus and the UPFC receiving end bus, as shown in Fig. 3. The shunt converter is capable of providing shunt compensation to the system by absorbing or supplying reactive power to the bus where it is connected, but when used in UPFC, its role reduces to just providing the active power demand of the series converter, and this is performed through the common DC link capacitor [8]. The series converter, which injects a controllable voltage with appropriate amplitude and phase angle, performs the primary function of the UPFC. Through pulse width modulation (PWM), the converters' varied voltages are produced [9]. The PWM technique yields the following equations for the output voltages of the two VSCs: The magnitudes of the output voltages of the shunt and series converters are:

$$V_{SH} = \frac{m_{SH}}{2\sqrt{2}V_B} V_{dc} \quad (1)$$

$$V_{SR} = \frac{m_{SR}}{2\sqrt{2}V_B} V_{dc} \tag{2}$$

The phase angles of the output voltages are $\angle(\varphi S - \varphi SH)$ for the shunt converter and $\angle(\varphi S - \varphi SR)$ for the series converter. The series converter injects the voltage $=VSR\angle(\varphi S - \varphi SR)$, where $0 < VSR < VSRmax$ and $0 < \varphi SR < 360^{o}$. The active power required by the series converter is supplied by the shunt converter, which injects a current whose actual component is adequate. To use the shunt converter in the Automatic Voltage Regulation mode [10], the DC link capacitor between the converters allows the active power to easily flow through it. However, because the reactive power cannot pass across the DC connection, each converter must produce it locally or absorb it at the AC bus.

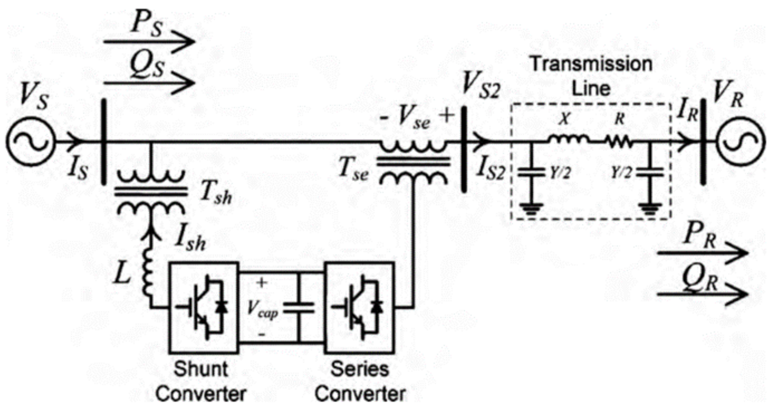


Fig. 3. Basic configuration of UPFC[11]

As the UPFC is placed on HV lines, the converters are connected through step-down transformers. When the UPFC is linked to a transmission system, it enhances the line's performance by increasing the flow of power across it and by dampening oscillations brought on by any disruption in the system. The UPFC does this by injecting a series voltage into the system where it is connected. The major purpose of the shunt-connected voltage source in UPFC is to inject active power into the network through the series-connected voltage source [9]. The reactive power delivered or absorbed by the shunt converter is independently controllable by UPFC and can be modelled as a separate, controllable shunt reactive source. Hence, QSH = 0. (QSH = shunt reactive source.) This is valid only when the losses are neglected. Hence, we can represent it by a series voltage source VC, as shown in the equivalent circuit in Fig. 4. The shunt converter has the sole responsibility of providing the real power demand for the series converter and is hence not included in this circuit [11]. The model demonstrates that, as would be predicted for a lossless UPFC, the net active power exchange of the UPFC with the power system is zero.

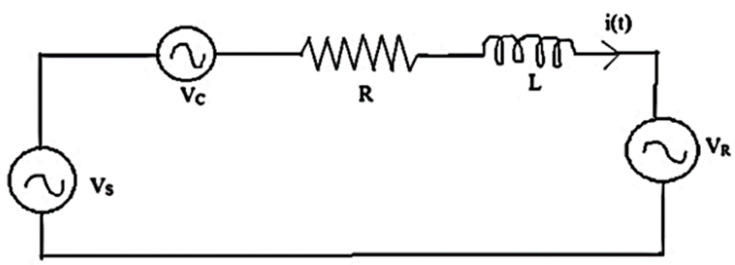


Fig. 4. UPFC's equivalent circuit[12]

2.3. Power transfer in transmission line

Here, the power flow mechanism in a transmission line is presented to comprehend how UPFC operates in a transmission line. The power flowing through a transmission line Fig. 5. Between the sending end and receiving end, buses are derived.

Let:
$V_S = V_S\angle\varphi S$ be the sending end voltage
$V_R = V_R\angle\varphi R$ receiving end voltages
I_L is the line current.t

R and X are the transmission line resistance and reactance, respectively

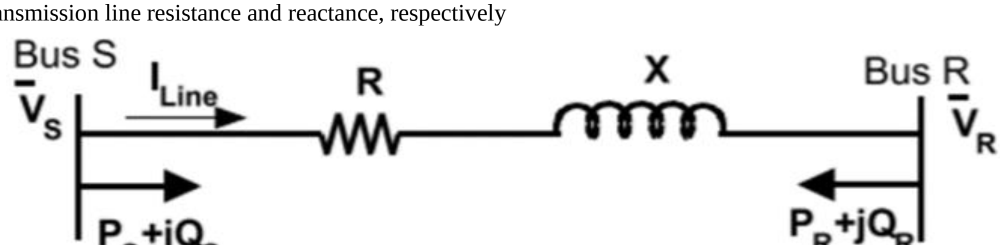


Fig. 5. Transmission line[13]

The complex power flowing in the transmission line is [11].

S_S = apparent power at the sending end
P_S = active power at the sending end
Q_S = reactive power at the sending end

$$S_S = P_S + jQ_S = \overline{V_S}\ \overline{I_L} \quad (3)$$

where

$$I_L = \frac{V_S - V_R}{R + jX} = (\overline{V}_S - \overline{V_R})\,(G - jB) \quad (4)$$

where

$G = \frac{R}{R^2 + X^2}$ Is the line conductance

$B = \frac{X}{R^2 + X^2}$ Is the line susceptance

Taking the conjugate of complex power

$$S^*{}_S = P_S - jQ_S = \bar{V}_S^*\, \bar{I}_S \quad (5)$$

$$\bar{V}_S^*\, \bar{V}_R = V_S \angle -\varphi_S\, V_R \angle\ \varphi_R\ = V_S\, V_R(\cos(\varphi_S - \varphi_R)\ - j\sin(\varphi_s - \varphi_R)) \quad (6)$$

Thus, we get the real and reactive power expressions as

$$P_S = V_S^2\, G - V_S\, V_R\, G\cos(\varphi_S - \varphi_R) + V_S V_R B\, sin(\varphi_s - \varphi_R) \quad (7)$$

$$Q_S = V_S^2 B - V_S V_R B\, cos(\varphi_S - \varphi_R) + V_S V_R G\, sin(\varphi_s - \varphi_R) \quad (8)$$

In addition, the corresponding equation at the receiving end are

$$P_R = V_R^2 G - V_S V_R G\, cos(\varphi_S - \varphi_R) + V_S V_R B\, sin(\varphi_s - \varphi_R) \quad (9)$$

$$Q_R = V_R^2 B - V_S V_R B\, cos(\varphi_S - \varphi_R) + V_S V_R G\, sin(\varphi_s - \varphi_R) \quad (10)$$

The transmission line's active and reactive power loss is determined by

$$P_{LOSS} = G(V_S^2 + V_R^2) - 2V_S V_R\cos(\varphi_S - \varphi_R) \quad (11)$$

$$Q_{LOSS} = B(V_S^2 + V_R^2) - 2V_S V_R B\cos(\varphi_S - \varphi_R) \quad (12)$$

The transmission line resistance is usually ignored in calculations compared to the reactance.
Hence, B becomes, and the power transmission equations become

$$P_S = -P_R = \frac{V_S V_R}{X}\ sin(\varphi_S - \varphi_R) = \frac{V_S V_R}{X}\sin\delta \quad (13)$$

$$Q_S = Q_R = -\frac{V_R^2}{X} + \frac{V_S V_R}{X} cos(\varphi_S - \varphi_R) = -\frac{V_R^2}{X} + \frac{V_S V_R}{X} cos\delta \quad (14)$$

where δ is called the power angle.

From Equation (13), it is possible to regulate how much power is sent over the transmission line using

- escalating the voltages at either end, also known as voltage control
- decreasing the line reactance, or compensating the series line.
- adjusting the phase angle shift control to increase the power angle

2.4. UPFC Control system

When the UPFC is incorporated into a transmission line, the power flowing in that line is modified, as derived below.

V_{SR} is the variable series voltage injected by the UPFC in the transmission line. The line current gets modified as [14]:

V_{SR}= variable series voltage
I_L= line current
V_S= voltage at sending end
V_R= voltage at reeving end
X=impedance

$$\mathrm{I_L} = \frac{\overline{\mathrm{V}}_\mathrm{S}}{\mathrm{jX}} + \frac{\overline{\mathrm{V}}_\mathrm{SR}}{\mathrm{jX}} + \frac{\overline{\mathrm{V}}_\mathrm{R}}{\mathrm{jX}} \quad (15)$$

And the power flow

$$S = \bar{V}_R \bar{I}_L^* = \bar{V}_R \left(\frac{\bar{V}_S}{jX} + \frac{\bar{V}_{SR}}{jX} + \frac{\bar{V}_R}{jX} \right)^* \quad (16)$$

The real and reactive power flows in the presence of UPFC are [15].

$$P = \frac{V_S V_R}{X} \sin\delta + \frac{V_{SR} V_R}{X} \sin(\delta - \varphi_{SR}) = P_O(\delta) + P_{UPFC} \quad (17)$$

$$Q = -\frac{V_R^2}{X} + \frac{V_S V_R}{X} \cos\delta + \frac{V_S V_R}{X} \cos(\delta - \varphi_R) = Q_O(\delta) + Q_{UPFC} \quad (18)$$

The maximum power injection is $\frac{V_{SR} V_R}{X}$. Thus, the power flows can be controlled between

$$P_O(\delta) - \frac{V_{SRmax} V_R}{X} \le P \le P_O(\delta) + \frac{V_{SRmax} V_R}{X} \text{ and } Q_O(\delta) - \frac{V_{SRmax} V_R}{X} \le P \le P_O(\delta) + \frac{V_{SRmax} V_R}{X}.$$

Equations (17) and (18) represent a circle with a radius of $\frac{V_{SRmax} V_R}{X}$ centered at

$(P_O(\delta), Q_O(\delta))$. The equation for this circle is [15].

$$\left(P_{UPFC} - P_{O(\delta)}\right)^2 + \left(Q_{UPFC} - Q_O(\delta)\right)^2 = \frac{V_{SRmax} V_R^2}{X} \quad (19)$$

As the value of δ is varied, the locus of the equation is obtained as given in Fig. 6.

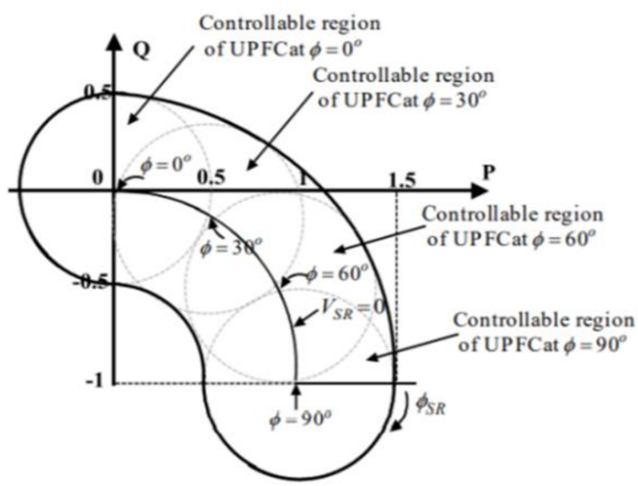


Fig. 6. Variation of Q with P as δ varies from 0 to 90°[15]

Phrases like "Variation of Q with P as varies from 0 to 90°" allude to how reactive power (Q) shifts about active power (P) when the phase angle (φ) shifts from zero to ninety degrees. It suggests that there are places where the reactive power may be controlled to various levels as the phase angle varies within this range as shown in Fig. 6.

Thus, it is clear that UPFC may independently control the power flows in a transmission network, including real and reactive powers. It can also maintain voltage regulation within limits and, along with that, improve the transient stability of the system. Hence, the control circuits for the converters play a vital role in the mode of UPFC operation [16].

2.5. Controllers for the converters

Two converters make up the UPFC, one of which is coupled by a shunt transformer and the other via a series transformer. The two converters of the UPFC necessitate the implementation of two controllers [17]. The details of the two converter controllers are given below.

2.5.1. Shunt controller

The shunt converter can operate in two modes, namely (i) voltage regulation mode, and (ii) VAR control mode.

In voltage regulation mode, the focus is on keeping the voltage within a set range independent of the reactive power input or output. In this mode, the controller makes changes to the device's reactive power output to keep the voltage at the desired level. While VAR control mode is concerned with controlling the flow of reactive power, voltage regulation mode is concerned with controlling the system's voltage.

The block diagram shown in Fig. 7 for the shunt converter includes the reactive current regulator, which functions satisfactorily for AC voltage control.

2.5.2. Series controller and optimal placement of UPFC

For the series converter shown in Fig. 8, the modes of control for operation are power flow control; series compensation control; phase angle shifter method; and manual voltage injection [19].

2.5.2.1. Power flow control

In this approach, the voltage and current of the series converter are adjusted to manage the power flow in the system. It facilitates effective control of power transfers and contributes to the optimum performance of the power grid.

2.5.2.2. Series compensation control

The series converter is used to provide series compensation to the transmission line in control mode, Series Compensation. Reactive power injection into the line aids in voltage regulation and increases system reliability. This form of regulation is often used to reduce voltage drop and improve power transmission.

2.5.2.3. Phase angle shifter method

By shifting the phase angle of the series converter's output voltage relative to the transmission line voltage, the phase angle shifter technique, may be used. This method of regulation provides operational flexibility in power transmission and voltage regulation by separating the management of active and reactive power flows.

2.5.2.4. Manual voltage injection

Using the series converter, a desired voltage may be injected into the system in this control approach through manual voltage injection. Operators may control the system's voltage levels and solve voltage-related problems by manually modifying the converter's output voltage. It allows for instantaneous and direct regulation of the power supply voltage.

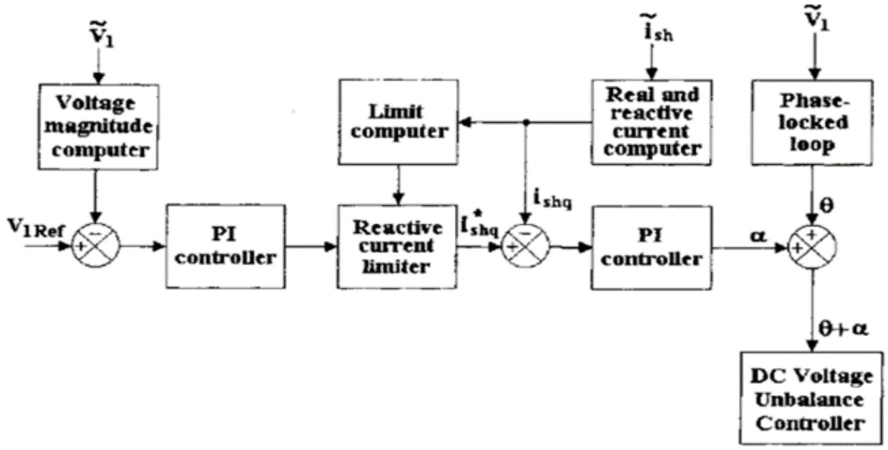


Fig. 7. Shunt controller of UPFC[18]

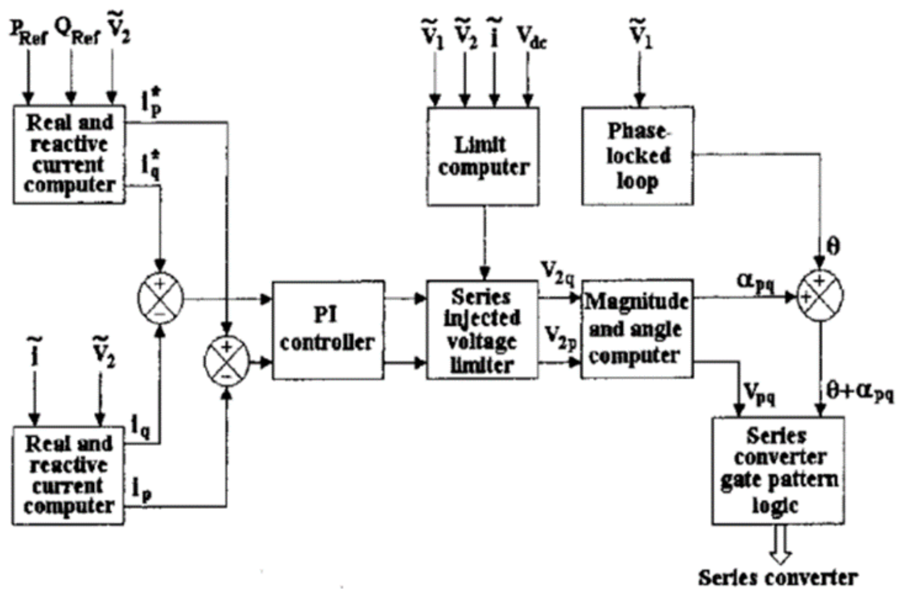


Fig. 8. Series converter controller [18]

To accomplish its control goals, the series converter controller regulates the converter's operating characteristics, such as voltage and current. The controller takes in data from several sources, such as voltage, current, and temperature readings, and uses this information to drive the series converter's operation as shown in Fig. 8. There are different methods to determine the best location for placing the UPFC in a power system. For small power networks, the location can be decided by placing the UPFC between each pair of buses, and then the power flows and voltage profiles can be compared. For power systems with a large number of buses and loads, this direct method becomes cumbersome [20]. Instead, stability index methods can be adopted. In this work, both methods are adopted to get the affirmation.

3. Results

3.1. Simulink circuit and discussion

In Fig. 9. There is a 230 kV line voltage. The characteristics of the transmission line to which the 800 MVA transformer is connected A 340-millisecond three-phase fault is delivered to the generator terminals (bus-1) Voltage drops, imbalances, and even instability have been linked to disturbances of this kind. Engineers create management strategies and preventive steps to limit the impact of these outages, maintain the reliability of systems, and restore electricity as quickly as feasible.

UPFC has helped reduce the frequency of the generator's rotor speed fluctuations. Without UPFC. The generator's rotor speed oscillations cannot be damped down, yet doing so takes just around 6 seconds to stabilize the tremors.

A three-phase fault is induced for 340 milliseconds at the generator terminals (bus-1) and then removed Fig. 10. Demonstrates the oscillations in generator 1's rotor speed caused by the absence of UPFC.

The generator rotor speed oscillations are now more effectively dampened thanks to the installation of UPFC. Without UPFC, the generator's rotor speed oscillations cannot be dampened; in contrast, with UPFC, the oscillations can be dampened in about 5 seconds. Fig. 11 shows the effect and improved damping with UPFC.

The difference between Fig. 10 and Fig. 11 These rotor angle graphs show that the system becomes unstable when the fault is applied to bus 1 for longer than 340 ms. As may be seen in Fig. 10, the rotor angle deviation steadily grows over time. Once the problem is fixed and the UPFC is reconnected, as shown in Fig. 11, the rotor angle deviations stabilize after a brief period of oscillation. This demonstrates how UPFC might be effective in enhancing transient stability.

And to use the UPFC device, which is based on a smart controller, to improve the power system's dependability and stability. Under various failure scenarios, a fuzzy logical controller should be in charge of UPFC devices. Fig. 12 shows the fuzzy logic technique.

The fuzzy logic controller generates operational pulses from the UPFC system converter by comparing power system characteristics such as rotor speed, rotor speed deviation, and output active power with the reference value. As opposed to fuzzy logic, which takes less than 5 seconds to dampen the oscillations and has fewer ripples Figure 13 shows the effect and improved damping with the fuzzy logic technique.

In the MATLAB setting, the proposed model will be simulated. The great impact of the new model is evaluated using high standards and compared to existing models.

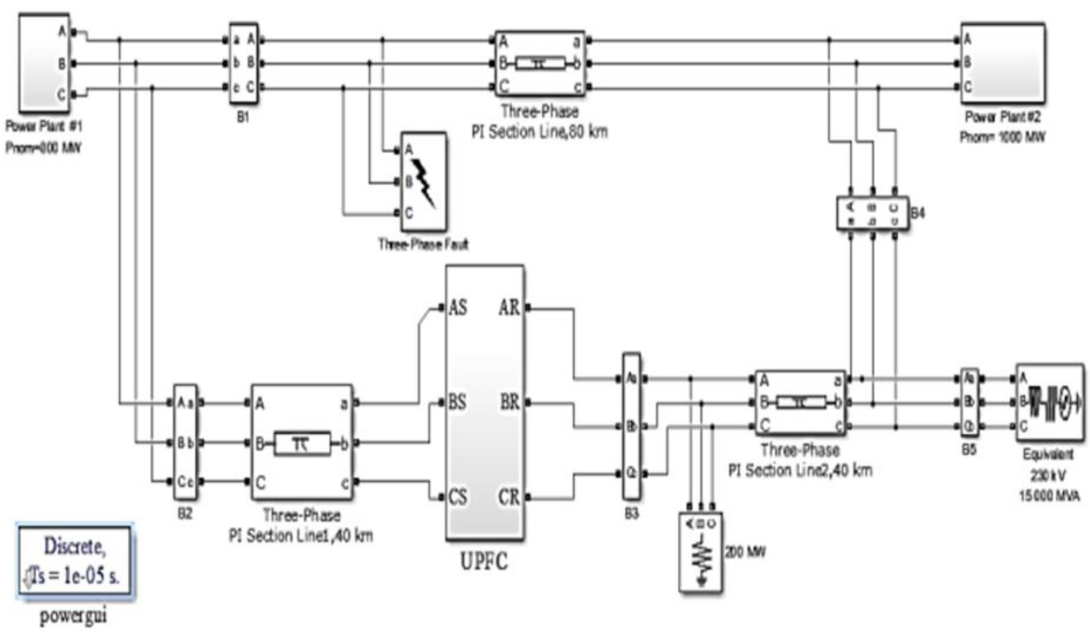
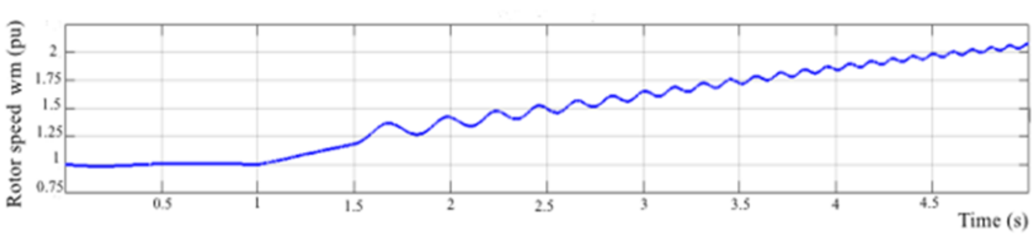


Fig. 9. Simulink circuit for the transient stability study



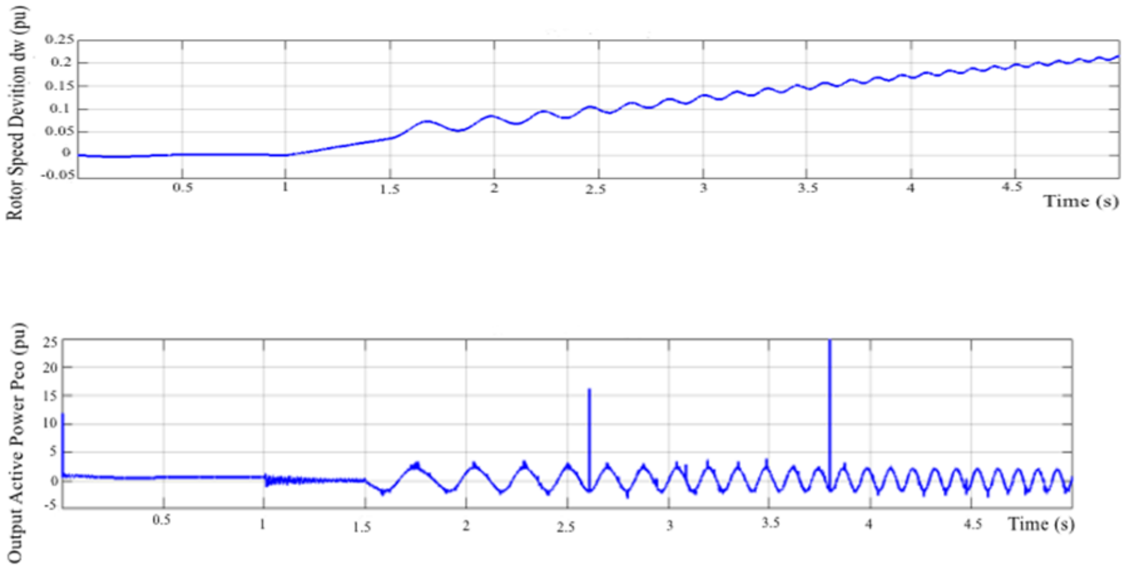


Fig. 10. Rotor speed, rotor speed deviation, and output active power without UPFC

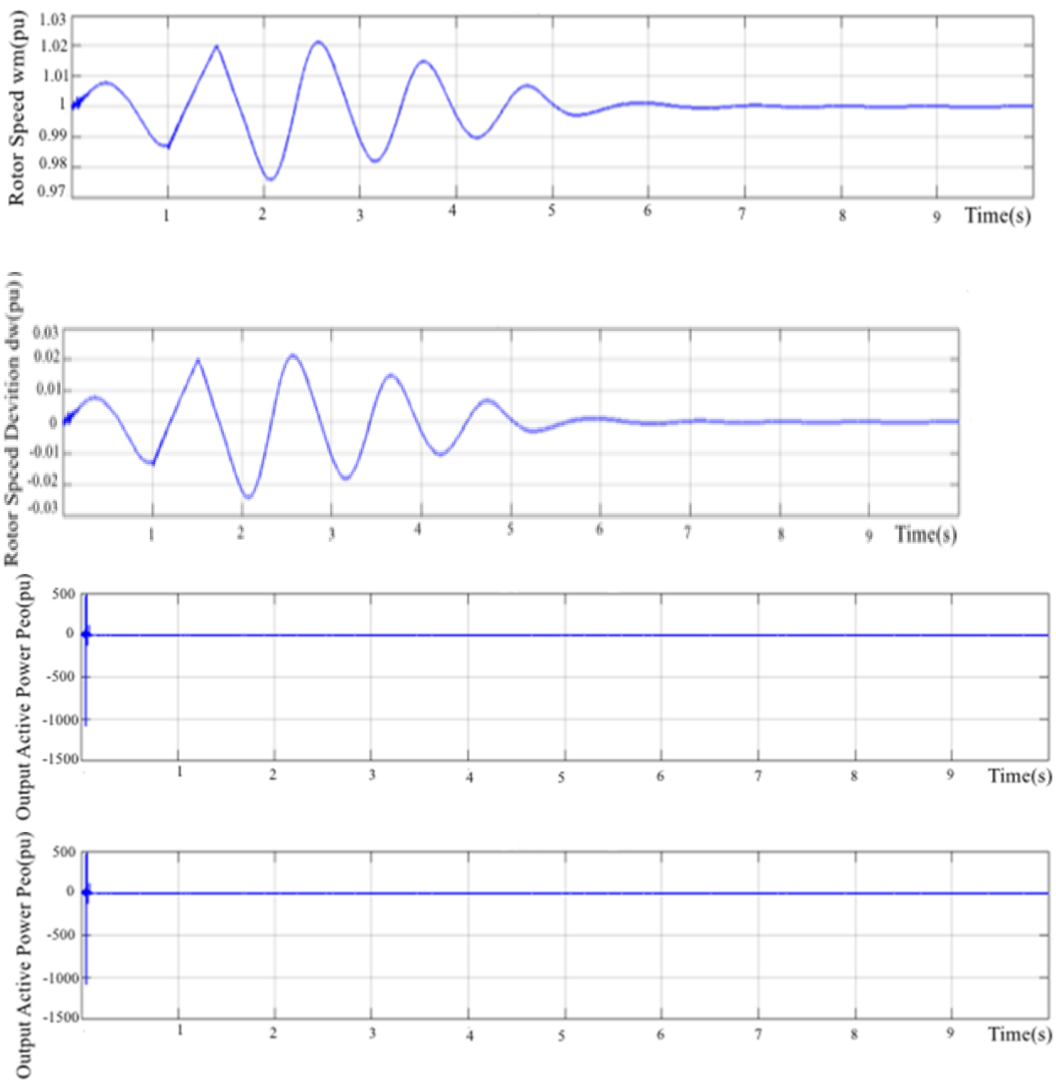


Fig. 11. Rotor speed, rotor speed deviation, and output active power with UPFC

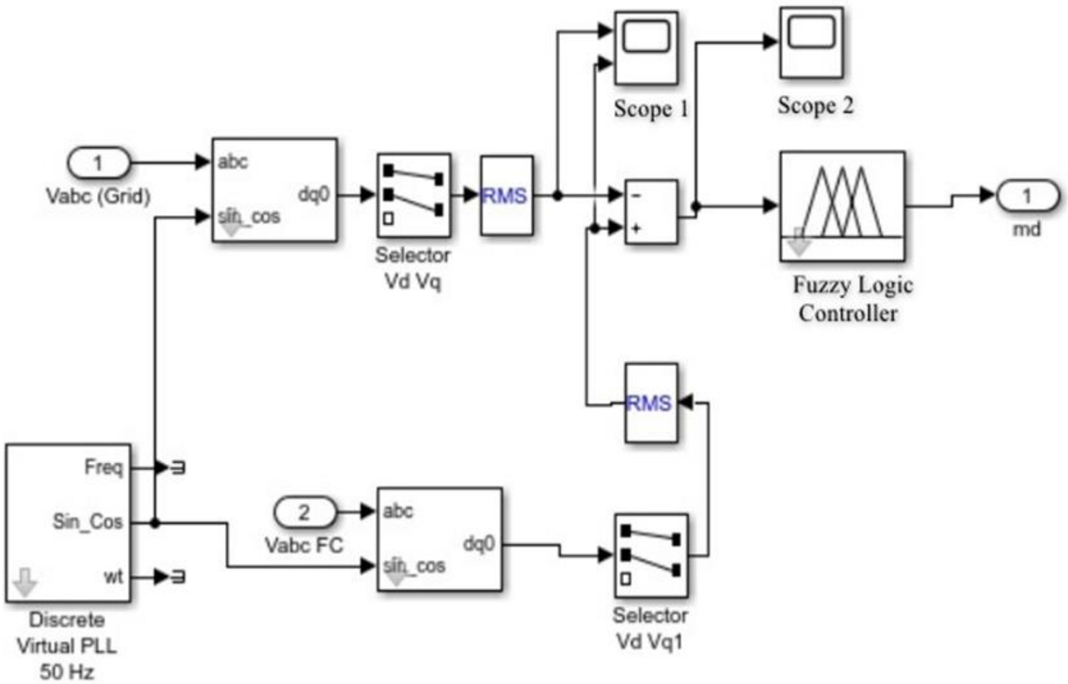


Fig. 12. Fuzzy logic technique for improving the effect of UPFC in the electrical circuit

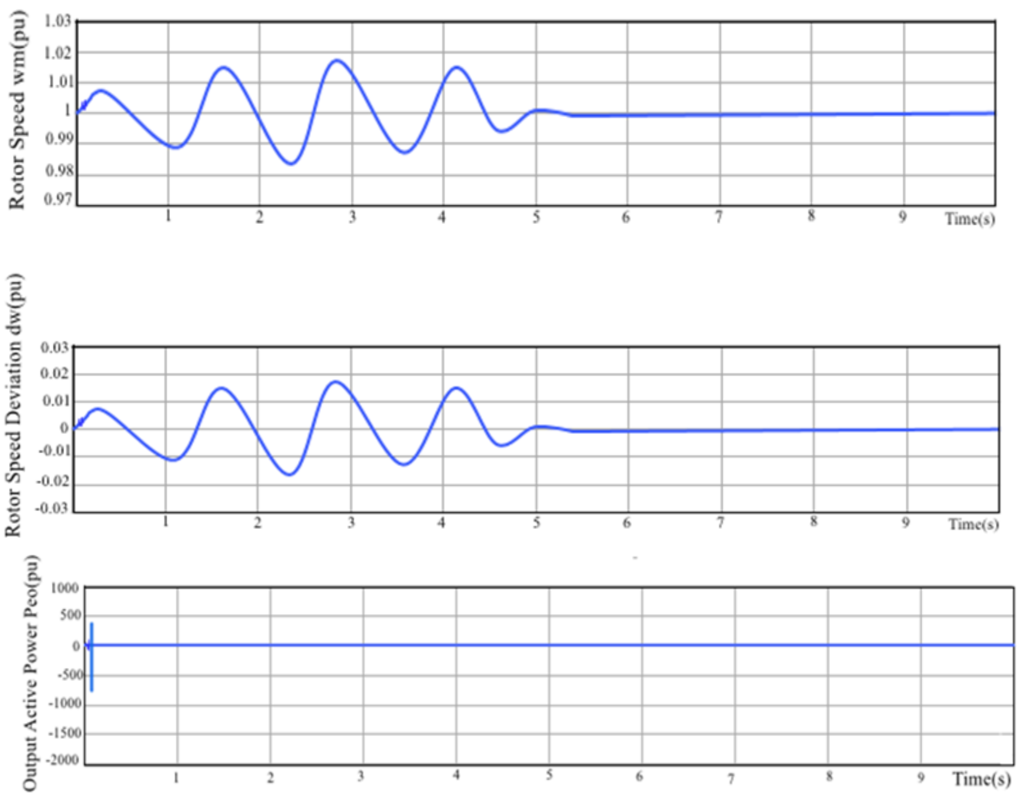


Fig. 13. Shows the impact and enhanced dampening of the fuzzy logic technique

The numerical evaluation of the simulated results As shown in Table 1.

Table 1. The numerical evaluation of the simulated results

parameters	Time to dampen oscillations after fault
rotor speed deviation without UPFC	cannot dampen the oscillations after a fault
rotor speed deviation with UPFC	dampened the oscillation at 6 s after a full
rotor speed deviation with fuzzy logic techniques to enhance the effect of UPFC.	dampened the oscillation at 5.3 s after a full

3.1.1. Membership performance

Different types of MFs, such as triangular, gaussian, trapezoidal, and sigmoid, are used in fuzzy systems, as shown in Fig. 14. The range of inputs and outputs for the fuzzy controller is represented by membership functions. The figure, for example, displays the fuzzy block and membership functions for the input and output fuzzy controllers.

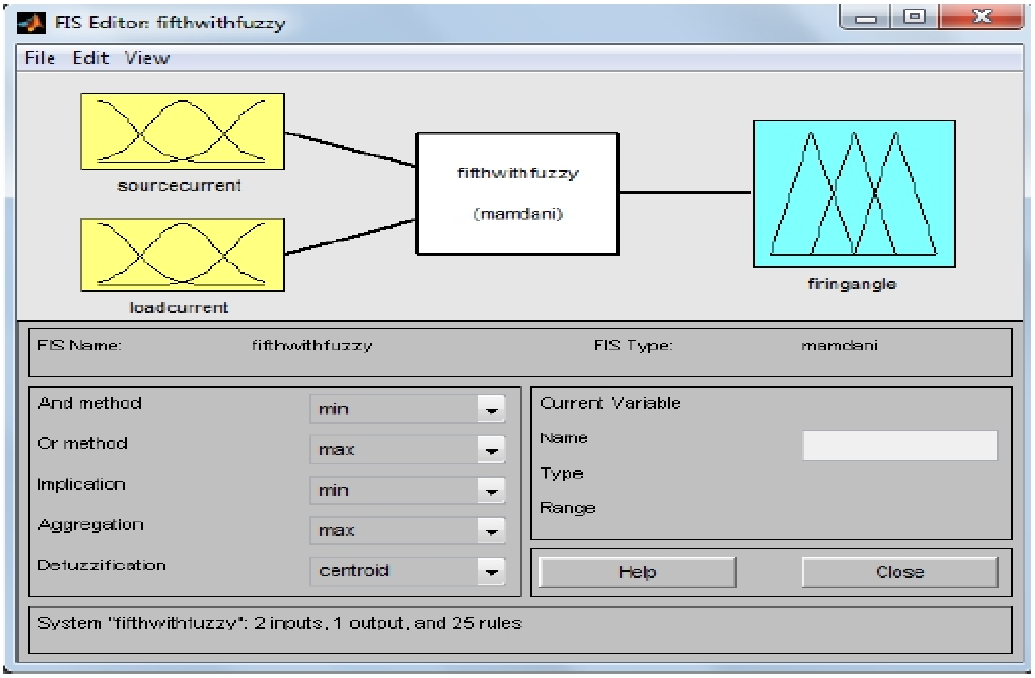


Fig. 14. System with a fuzzy interface

3.1.2. Rule-based and inference engine

Rule bases are if-then statements that connect fuzzy output and fuzzy input based on the operator's judgement to produce effective control. Table I displays a fuzzy subset of thirty rules with various membership functions.

The process of mapping an input space to an output space using fuzzy inference involves estimating each rule's firing strength depending on how closely the defined fuzzy sets match each other using the "max-min" inference technique. Mamdani's fuzzy inference approach was employed in this investigation.

3.1.3. Function of Triangular Membership

Due to the presence of a peak point, triangular membership functions that are both symmetrically and asymmetrically shaped are the easiest and most frequently utilized membership functions. In addition to being symmetric or asymmetric, trapezoidal membership functions have the shape of a truncated triangle, as shown in Figs. 15 and 16.

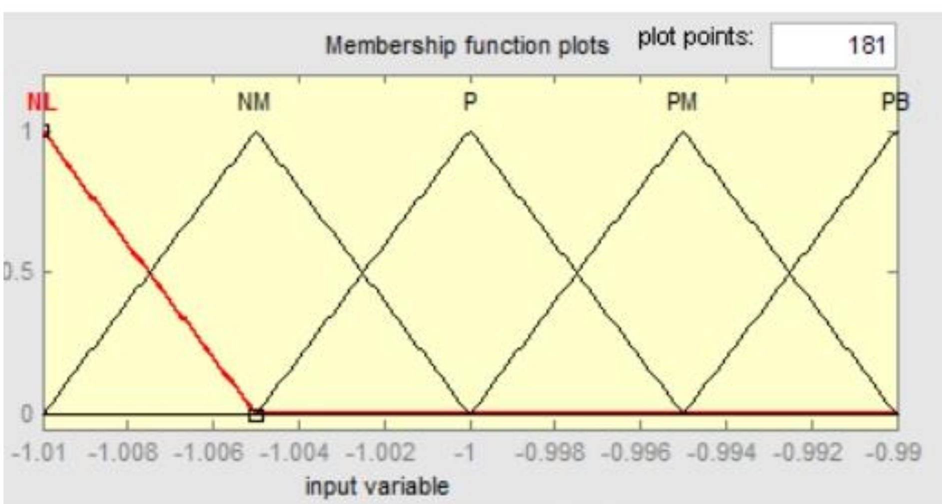


Fig. 15. Member shape input

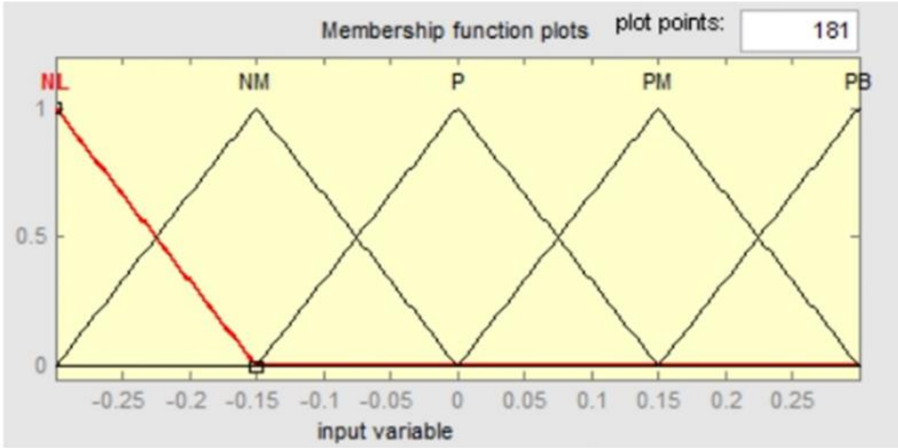


Fig. 16. Member shape output

3.1.4. Rule-based and inference engines

Rule bases are if-then statements that connect fuzzy output and fuzzy input based on the operator's judgement to produce effective control. Table I displays the fuzzy subset of thirty rules with various membership functions as in Table 2.

The process of mapping an input space to an output space using fuzzy inference involves estimating each rule's firing strength depending on how closely the defined fuzzy sets match each other using the "max-min" inference technique. Mamdani's fuzzy inference approach was employed in this investigation.

Table 2. The fuzzy membership function rule

		Input current				
		NL	NM	P	PM	PB
Load Current	NL	PB	PB	NM	NM	NL
	NM	PB	PB	NM	P	NL
	P	P	PM	NM	NM	P
	PM	NM	P	NM	NM	PM
	PB	NL	NM	NM	NL	NL

4. Conclusion

The Unified Power Flow Controller is a flexible tool for enhancing power system reliability; it has not one but two voltage converters. The two converters' control methods are crucial to how they function. The improvement in transient stability brought about by the installation of UPFC is further proven using a baseline power check and a three-phase failure on a one-bus system. The UPFC hardware should be managed by a fuzzy logic controller in the event of any number of possible malfunctions. Rotor speed deviation without UPFC cannot dampen the oscillations after a fault. rotor speed deviation with UPFC, dampened the oscillation at 6 s after a full. rotor speed deviation with fuzzy logic techniques to enhance the effect of UPFC, dampened the oscillation at 5.3 s after a full. Increasing a system's stability means making it more able to stay in balance and shrug off changes or shocks. Adjusting parameters or using feedback control are examples of control procedures used to guarantee the system's consistency in operation. Stability, reduced oscillations, and improved performance and dependability are all achieved via the use of methods such as damping control, voltage regulation, and power system stabilizers.

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