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Optimal control of the UPFC for the stability of electrical networks

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ABSTRACT

The unified power flow controller (UPFC) is a crucial element in contemporary power systems, specifically engineered to augment the manageability and adaptability of power transmission in electrical networks. UPFC provides instantaneous modifications to voltage magnitude, phase angle, and line impedance by using sophisticated power electronics and control algorithms. This research examines the function of the unified power flow controller (UPFC) in enhancing the power quality of electrical networks. The UPFC's capacity to dynamically regulate and optimize power flow assists in minimizing voltage fluctuations, decreasing transmission line losses, and improving system stability. In addition, UPFC effectively addresses problems such as voltage sags, swells, and flickers, hence enhancing the resilience and dependability of the power supply. This research highlights the importance of unified power flow control (UPFC) technology in improving system performance and power quality of electrical networks via a thorough examination of its applications. This article presents research on the performance of the unified power flow controller (UPFC) device in a network, specifically focusing on the use of PID and FO-PID controllers for regulating active and passive power.

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1. INTRODUCTION

Advances in electrical and electronic engineering have significantly increased the reliance on electrical energy in modern life. This increased demand creates fluctuations in the power system network, preventing it from operating in a single stable mode. Today, a key objective for electrical engineers is to deliver high-quality power while minimizing transmission losses [1]-[3]. The development of flexible AC transmission system (FACTS) devices, spurred by rapid advancements in power electronics and microelectronics since the late 1980s, has been instrumental in enhancing power system stability. These devices provide fast, dynamic control and enable better system management, leading to improved overall performance.

Among various FACTS devices, the unified power flow controller (UPFC) is one of the most widely adopted [4]-[6]. Due to its versatility, UPFC has been applied in diverse research objectives. Numerous studies have explored the optimal placement of UPFC in power networks, utilizing optimization techniques such as particle swarm optimization (PSO), FVSI, the CPF method, and PSAT software to boost voltage stability, increase transfer capability, and reduce power losses [7]-[10]. In [11], three FACTS devices-static VAR compensator (SVC), STATCOM, and UPFC-were analyzed and optimized to enhance the protection of wind farms. A novel relay system was developed, demonstrating that UPFC outperforms static synchronous compensator (STATCOM) and SVC by combining the advantages of both devices.

UPFC was implemented for power flow control, with results showing that it improved both instantaneous and fluctuation stability [12], [13]. Despite its advantages, designing a UPFC controller remains complex due to its multivariable nature. Various control strategies have been proposed to address these challenges. For instance, PSO optimization was applied to improve PI controller gains, yielding better results than a standalone PI controller [14], [15]. Similarly, PSO was used to determine optimal PI gains and ideal UPFC placement, achieving enhanced system performance and loss reduction [16].

Recently, a sliding mode controller (SMC) was applied to the UPFC system in [17]. Comparative simulations indicated that SMC outperformed traditional PI control, particularly in durability and the independent regulation of active and reactive power. This article aims to evaluate the fractional order PID (FOPID) control strategy for UPFC and compare it with the PID strategy, aiming to determine which approach optimally regulates active and reactive power.

2. UNIFIED POWER FLOW CONTROLLER

The unified power flow controller (UPFC) consists of two main voltage sources: one connected in parallel and the other in series. The parallel component, known as static synchronous compensator (STATCOM), is connected to a series component, the static synchronous series compensator (SSSC), through a common DC link. This configuration enables the UPFC (Figure 1) to combine the functionalities of both STATCOM and SSSC [18]. The UPFC's primary function is to inject an adjustable AC voltage both in magnitude and phase into the transmission line via a series transformer. This transformer plays a crucial role by either supplying or absorbing the real power required by the series transformer at the shared DC link. The figures below depict the electrical model of the UPFC, illustrating how it integrates these components to control power flow effectively [19].

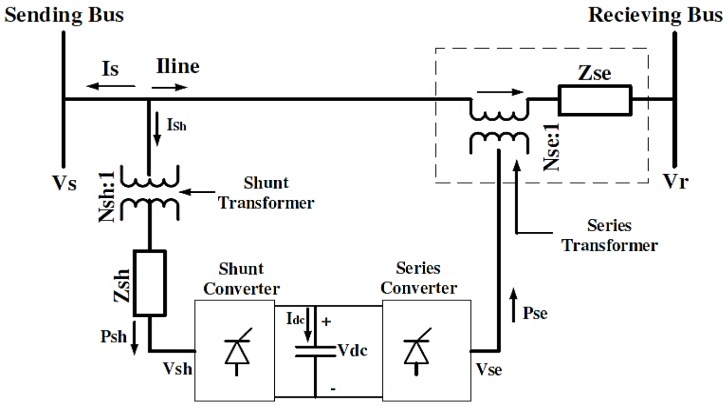


Figure 1. The fundamental scheme of UPFC

3. MODELING OF THE UPFC

Figure 2 shows modeling the unified power flow controller (UPFC) involves developing a mathematical and control framework to simulate its effects on power flow, voltage control, and system stability in a power network. The UPFC is a complex FACTS device that consists of two interconnected converters a shunt and a series converter linked by a common DC circuit. The UPFC's model incorporates these elements using differential equations and power flow equations to represent dynamic behavior under different operating conditions. This model is crucial for simulating how the UPFC can enhance system stability, reduce power losses, and respond effectively to network disturbances [20].

3.1. Serial model and associated equations

To model the series physical system in Figure 2 we apply Kirchhoff's second law. We then obtain the equation in the abc frame of refer to the following form:

$$\frac{d}{dt}\begin{bmatrix} I_{sa} \\ I_{sb} \\ I_{sc} \end{bmatrix} = \begin{bmatrix} \frac{-r}{L} & 0 & 0 \\ 0 & \frac{-r}{L} & 0 \\ 0 & 0 & \frac{-r}{L} \end{bmatrix}\begin{bmatrix} I_{sa} \\ I_{sb} \\ I_{sc} \end{bmatrix} + \begin{bmatrix} \frac{1}{L} & 0 & 0 \\ 0 & \frac{1}{L} & 0 \\ 0 & 0 & \frac{1}{L} \end{bmatrix}\begin{bmatrix} V_{sa} & -V_{ca} & -V_{ra} \\ V_{sb} & -V_{cb} & -V_{rb} \\ V_{sc} & -V_{cc} & -V_{rc} \end{bmatrix} \quad (1)$$

Applying Park's transformation to the system (1) allows us to write:

$$\frac{d}{dt}\begin{bmatrix} I_{sd} \\ I_{sq} \end{bmatrix} = \begin{bmatrix} \frac{-r}{L} & +w \\ -w & \frac{-r}{L} \end{bmatrix}\begin{bmatrix} I_{sd} \\ I_{sq} \end{bmatrix} + \begin{bmatrix} \frac{1}{L} & 0 \\ 0 & \frac{1}{L} \end{bmatrix}\begin{bmatrix} V_{sd} & -V_{cd} & -V_{rd} \\ V_{sq} & -V_{cq} & -V_{rq} \end{bmatrix} \quad (2)$$

3.2. Shunt model et and associated equations

To model the physical system of the shunt circuit in Figure 2 we apply Kirchhoff's second law. The equation in the abc frame of reference takes the (3).

$$\frac{d}{dt}\begin{bmatrix} I_{pa} \\ I_{pb} \\ I_{pc} \end{bmatrix} = \begin{bmatrix} \frac{-r_p}{L_p} & 0 & 0 \\ 0 & \frac{-r_p}{L_p} & 0 \\ 0 & 0 & \frac{-r_p}{L_p} \end{bmatrix}\begin{bmatrix} I_{pa} \\ I_{pb} \\ I_{pc} \end{bmatrix} + \begin{bmatrix} \frac{1}{L_p} & 0 & 0 \\ 0 & \frac{1}{L_p} & 0 \\ 0 & 0 & \frac{1}{L_p} \end{bmatrix}\begin{bmatrix} V_{pa} & -V_{ca} & -V_{ra} \\ V_{pb} & -V_{cb} & -V_{rb} \\ V_{pc} & -V_{cc} & -V_{rc} \end{bmatrix} \quad (3)$$

To convert a balanced system to a synchronous d-q-o frame, use Park's transformation. The matrix form (3) is as (4).

$$\frac{d}{dt}\begin{bmatrix} I_{pd} \\ I_{pq} \end{bmatrix} = \begin{bmatrix} \frac{-r_p}{L_p} & +w \\ -w & \frac{-r_p}{L_p} \end{bmatrix}\begin{bmatrix} I_{pd} \\ I_{pq} \end{bmatrix} + \begin{bmatrix} \frac{1}{L_p} & 0 \\ 0 & \frac{1}{L_p} \end{bmatrix}\begin{bmatrix} V_{pd} & -V_{cd} & -V_{rd} \\ V_{pq} & -V_{cq} & -V_{rq} \end{bmatrix} \quad (4)$$

3.3. The modeling of the UPFC keeps branching

To maintain a constant capacitor voltage, the net real power exchanged between both converters via the DC link must be zero, as dictated by the power balance equation governing the UPFC's input and output. The equation describing the behavior of the DC voltage VdcV_{dc}Vdc across the capacitor is as (5).

$$\frac{dV_{dc}}{dt} = \frac{1}{CVd_c}(P_e - P_{ep}) \quad (5)$$

With:

$$P_e = v_{ca}i_{sa} + v_{cb}i_{sb} + v_{cc}i_{sc}$$
$$P_{pe} = v_{pa}i_{pa} + v_{pb}i_{pb} + v_{pc}i_{pc}$$

with: P_e: Active power absorbed by the AC system; Pep: Active power injection using the shunt inverter AC method. The (6) explains the DC voltage V_dc behavior across a capacitor after Park transformation.

$$\frac{dV_{dc}}{dt} = \frac{2}{2CVd_c}(v_{pd}I_{pd} + v_{pq}I_{pq} - v_{cd}I_{rd} - v_{cq}I_{rq}) \quad (6)$$

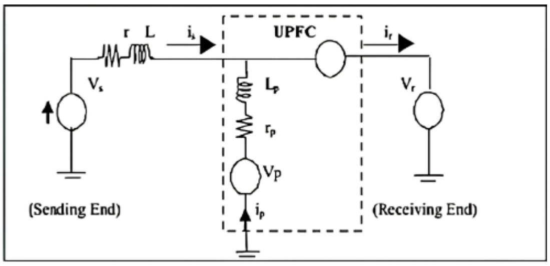


Figure 2. The physical representation of a UPFC converter connected to the network

4. THE DESIGN OF CONTROLLERS

4.1. UPFC controller based on PID controller

Figure 3 depicts the total system setup under PID management. As seen below, the observed active and reactive power are compared to reference values to generate P and Q errors. Two PID regulators employ the P and Q errors to compute the Vq and Vd voltage components that the VSC will generate. (Vq in quadrature with V1 regulates active power, whereas Vd in phase with V1 controls reactive power) [21].

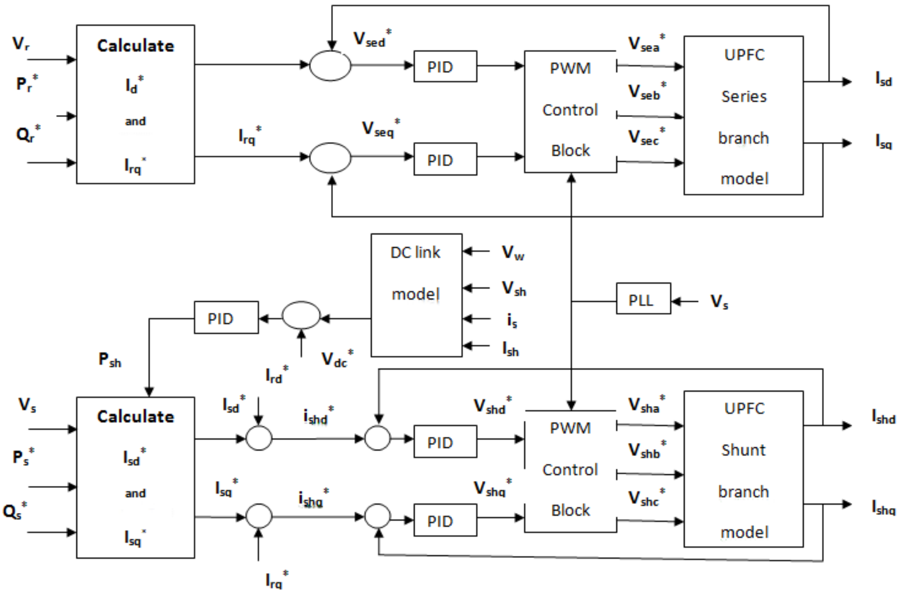


Figure 3. General design of UPFC system with PID control

4.2. UPFC with FOPID controller

The fractional order PID (FOPID) controller has emerged as a more flexible and efficient alternative to the traditional PID controller in controlling the unified power flow controller (UPFC) within power systems. Unlike the conventional PID controller, which relies on fixed-order parameters for proportional, integral, and derivative actions, the FOPID controller introduces fractional (non-integer) orders for these terms. This additional degree of freedom allows for more nuanced and precise tuning, making it particularly effective in complex and dynamic systems like the UPFC. Figure 4 shows the total system setup with FOPID control.

Here's a closer look at why the FOPID controller enhances UPFC performance:

- Increased tuning flexibility
- Enhanced robustness
- Improved stability and damping
- Superior response time
- Optimized control of active and reactive power

These benefits translate into more efficient, stable, and adaptable control of power flow, ultimately improving the overall performance and reliability of the power system

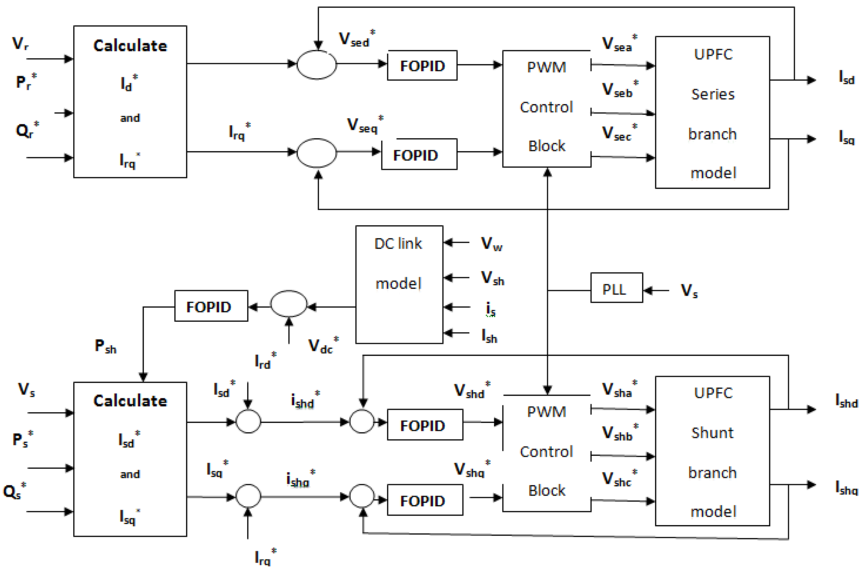


Figure 4. General design of the UPFC system with FOPID control

5. UPFC OPERATING PRINCIPLE

The series inverter injects a voltage at the same frequency as that of the network of which amplitude and phase are adjustable. This amplitude and phase adjustment makes it possible to obtain three operating modes of the serial part:

- Voltage control: the injected voltage is in phase with that on the source side.
- Line impedance control: The current line and the injected voltage are in quadrature. This mode allows you to alter the line's impedance in the same way as a compensator series does.
- Phase control: the injected voltage's amplitude and phase are calculated to produce the same voltage module before and after the UPFC.

The primary goal of these three operating modes is to regulate the active and reactive power that flows through the line. Furthermore, the UPFC may combine several compensations and move from one operating mode to another. The shunt part can be used to compensate for the reactive power to maintain the plan voltage and possibly provide active power in the network by the serial part [22], [23].

6. FRACTIONAL-ORDER PID (FOPID)

Fractional integer-order FO-PID controllers are a variant of integer-order PID controllers. The following is the basic Fractional FOPID controller:

$$C(s) = K_p + K_i S^{-x} + K_d S^{y} \tag{7}$$

K_p, K_i, and K_d: Represent the gains of the proportional, fractional integrator, and fractional differentiators respectively. x and y: Represent fractional integration and differentiation orders. The correct-order PID controller is obtained if x = y = 1, Likewise, different combinations of x and y give PI, PD, FOPI, and FOPD controllers [24], [25]

7. RESULTS AND DISCUSSION

The objective of this study is to examine the control of active and reactive power exchange within an electrical interconnection line using a UPFC. Specifically, we analyze a UPFC connected to a high-capacity THT interconnection line with a transport capability of 1000 MVA. The configuration of the network under investigation is illustrated in Figure 5. This setup provides a suitable environment to evaluate the UPFC's effectiveness in managing power flow and enhancing stability in high-capacity transmission networks. The PID controller and FOPID. The parameters controller are presented in Table 1.

Table 1. The parameters of the PID controller and FOPID controller

Parameters	K_P	K_i	K_d	λ	µ
Parameter of PID controller	4000	4500	1000	/	/
Parameter of FOPID controller	4000	4500	1000	0.3	0.25

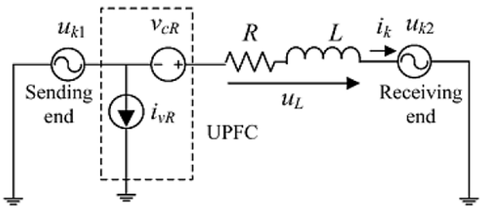
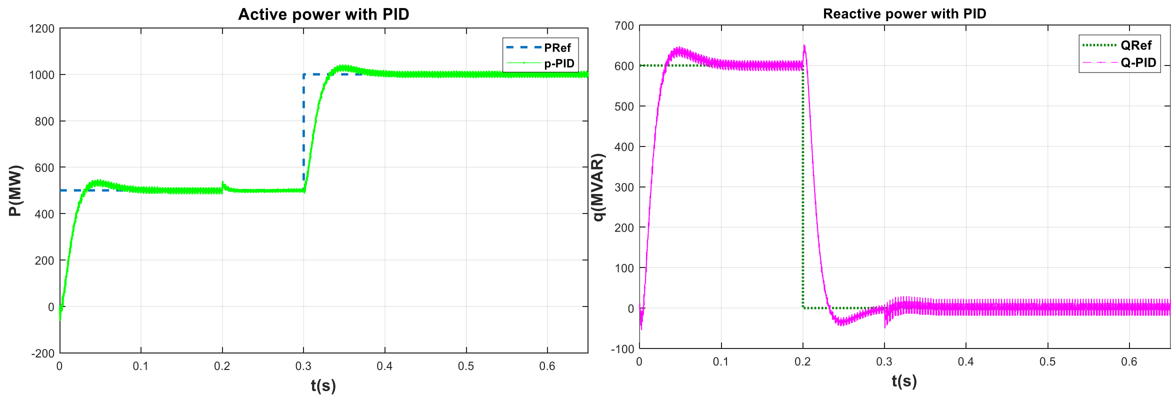


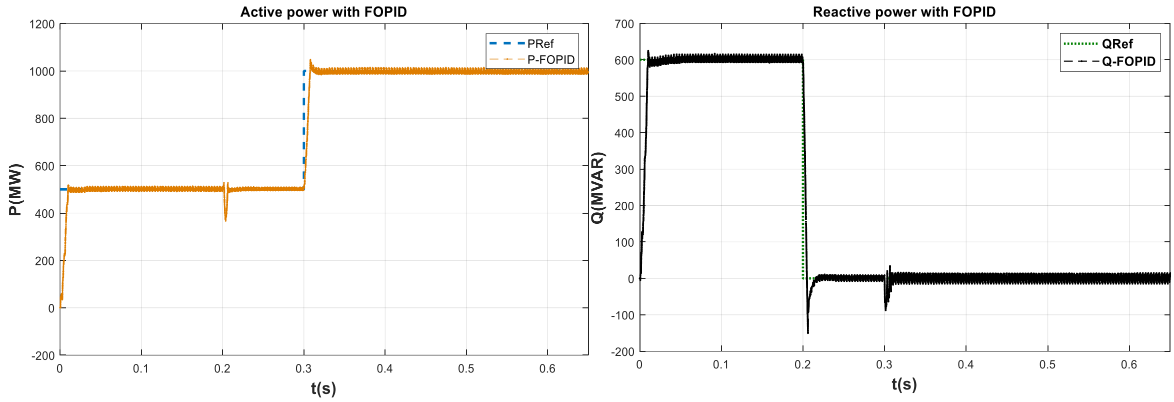
Figure 5. Equivalent circuit of a transmission system with UPFC

All results for the PID and FOPID are presented in the Figures 6-8. The results presented Figures 6-8 demonstrate that the FOPID controller provides a clear advantage over the PID controller in managing power flow through the transmission line. The FOPID controller achieves smoother response curves, better set-point tracking, and improved stability, resulting in more precise and consistent power flow control. As summarized in Table 2, the FOPID controller exhibits significantly enhanced dynamic performance compared to the PID controller, with faster rise and settling times, indicating a quicker and more stable response to changes in load and system conditions. This superior performance makes the FOPID controller highly effective for UPFC applications where precision and responsiveness are critical.



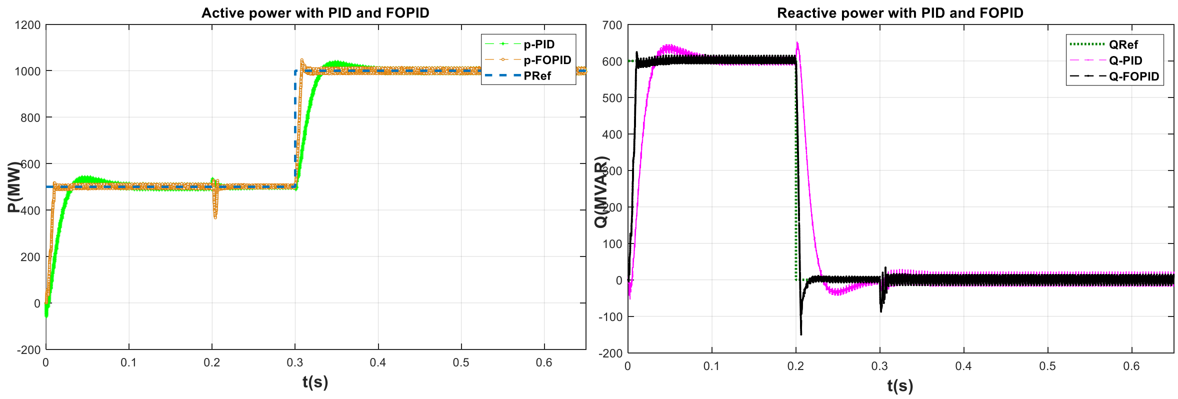
(a) (b)

Figure 6. PID regulator with (a) active power and (b) reactive power



(a) (b)

Figure 7. FOPID regulator with (a) active power and (b) reactive power



(a) (b)

Figure 8. PID and FOPID regulator with (a) active power and (b) reactive power

Table 2. Comparison of methods

Parameter	Active power with PID	Active power with FOPID	Reactive power with PID	Reactive power with FOPID
RiseTime	0.3145	0.3031	0.0050	8.1085e-04
SettlingTime	0.3782	0.3115	0.6499	0.6496
SettlingMin	898.4733	900.1147	-49.7324	-150.0071
SettlingMax	1.0399e+03	1.0471e+03	651.4553	624.3497
Overshoot	3.9913	4.7905	2.8921e+03	4.2947e+03
Undershoot	5.9667	7.0921e-28	247.3368	1.0559e+03
Peak	1.0399e+03	1.0471e+03	651.4553	624.3497

8. CONCLUSION

In conclusion, a comparison of two control strategies the classic proportional-integral-derivative (PID) and the fractional-order PID (FOPID) shows that the FOPID control strategy works better for system response and overall performance than the classic PID. The fractional-order technique increases flexibility and adaptability, allowing for more accurate control parameter adjustment to meet the system's dynamic features. The FOPID controller outperforms the standard PID controller in terms of stability, overshoot, and settling time.This study shows that fractional order control works well to get better results in the power system that was looked at. It also gives us useful information for making control strategies work better in similar situations. The FOPID controller outperforms the typical PID controller in terms of peak overshoot and settling time when the parameter reference values vary. The results obtained showed that the proposed UPFC based on FOPID has enhanced the power flow capacity and reduced its loss, which allows it to respond better to system changes and leads to increased stability, which reduces the occurrence of disturbances and failures in electrical networks. Hence, improving the performance control units lead to increased efficiency of power systems, which reduces losses and improves resource utilization. It can also reduce maintenance and repair costs, and increase the life of equipment. In the future and as a continuation of this work, methods for artificial intelligence and performance analysis may be introduced. Implementation of UPFC unified power flow controller using ANN and FLC algorithms.

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