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Optimal UPFC control for electrical network stability

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Research Article

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ABSTRACT

A key component of modern power systems, the unified power flow controller (UPFC) is designed to improve the management and flexibility of power transmission in electrical networks. UPFC uses advanced power electronics and control algorithms to give immediate changes to voltage magnitude, phase angle, and line impedance. This study looks at how the unified power flow controller (UPFC) may improve electrical networks' power quality. Transmission line losses are reduced, voltage fluctuations are minimized, and system stability is enhanced by the UPFC's ability to dynamically control and optimize power flow. Additionally, UPFC successfully resolves issues including voltage sags, swells, and flickers, improving the power supply's reliability and robustness. Through a detailed analysis of its applications, this study emphasizes the significance of unified power flow control (UPFC) technology in enhancing system performance and power quality of electrical networks. The performance of the unified power flow controller (UPFC) device in a network is examined in this study, with a particular emphasis on the use of PID and FO-PID controllers for controlling active and passive power.

INTRODUCTION

Modern life is far more dependent on electrical energy due to developments in electrical and electronic engineering. The power system network cannot function in a single steady mode due to the variations caused by this increasing demand. Delivering high-quality electricity while reducing transmission losses is becoming a major goal for electrical engineers [1]–[3]. Since the late 1980s, significant developments in power electronics and microelectronics have fueled the development of flexible AC transmission system (FACTS) devices, which have proved crucial in improving power system stability. Better system administration and quick, dynamic control are made possible by these devices, which boost overall performance.

The universal power flow controller (UPFC) is one of the most popular FACTS devices [4]–[6]. UPFC has been used for a variety of research goals because of its adaptability. In order to improve voltage stability, enhance transfer capacity, and lower power losses, many studies have investigated the best location for UPFC in power networks using optimization methods such particle swarm optimization (PSO), FVSI, the CPF method, and PSAT software [7]–[10]. In order to improve wind farm protection, three FACTS devices—static VAR compensator (SVC), STATCOM, and UPFC—were examined and improved in [11]. using integrating the benefits of both devices, UPFC beats static synchronous compensator (STATCOM) and SVC, as shown using a unique relay system.

When UPFC was used for power flow management, the findings shown that it enhanced both fluctuation and instantaneous stability [12], [13]. Despite its benefits, the multivariable structure of UPFC controllers makes their design challenging. To address these issues, a number of control solutions have been put forward. For example, PSO optimization was used to increase PI controller gains, which produced better outcomes than a PI controller operating independently [14], [15]. In a similar vein, PSO was used to identify the best PI gains and UPFC location, resulting in improved system performance and decreased loss [16].

The UPFC system was recently equipped with a sliding mode controller (SMC) in [17]. SMC performed better than conventional PI control, according to comparative simulations, especially

when it came to durability and the separate management of active and reactive power. In order to ascertain which method best controls active and reactive power, this article will assess the fractional order PID (FOPID) control strategy for UPFC and compare it with the PID strategy.

UNIFIED POWER FLOW CONTROLLER

The two primary voltage sources that make up the unified power flow controller (UPFC) are coupled in series and parallel. A common DC connection connects the series component, the static synchronous series compensator (SSSC), to the parallel component, the static synchronous compensator (STATCOM). The UPFC (Figure 1) may include the features of both STATCOM and SSSC thanks to this design [18]. The main purpose of the UPFC is to use a series transformer to inject an AC voltage that can be adjusted in both amplitude and phase into the transmission line. By either providing or absorbing the actual power needed by the series transformer at the shared DC connection, this transformer performs a critical function. The UPFC's electrical model is shown in the images below, showing how it combines these elements to efficiently regulate power flow [19].

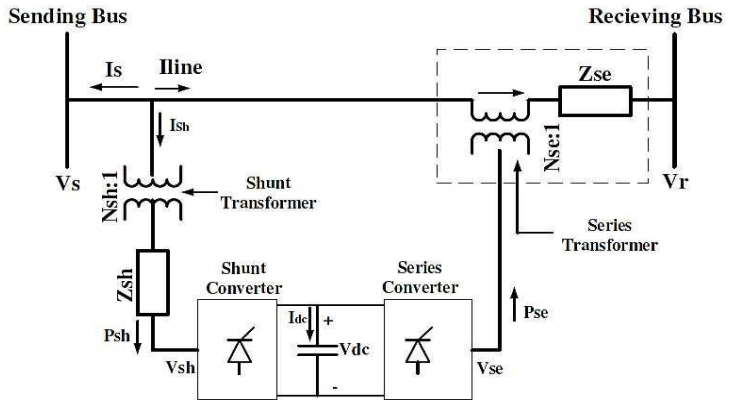


Figure 1. The fundamental scheme of UPFC

MODELING OF THE UPFC

In order to represent the impacts of the unified power flow controller (UPFC) on power flow, voltage management, and system stability in a power network, a mathematical and control framework must be developed (see Figure 2). Two interconnected converters—a shunt and a series converter—connected by a common DC circuit make up the UPFC, a sophisticated FACTS device. Differential equations and power flow equations are used in the UPFC model to depict dynamic behavior under various operating situations. In order to simulate how the UPFC may improve system stability, lower power losses, and react to network disruptions efficiently, this model is essential [20].

1.1. 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:

$$\begin{matrix} -r & & \\ F\,L & & - \\ & & \\ 0 \quad 0 & & \end{matrix}$$

I_{sa}

$\frac{1}{F_L}$

$0 \quad 0]$

$V_{sa} \; -V_{ca} \; -V_{ra}$

$d\,[I \quad -r$
$]=\mathrm{I}\,0 \quad [I \quad 1$
$]+\;0 \quad [V$
$-V$
$](\quad -$
$dt \quad sb \qquad \frac{}{L}$
$b \quad \bar{L} \quad sb \qquad]$

cb
rb
I_{sc}
$L \quad 0 \quad 0 \quad -r \quad [\quad -$
I_{sc}
I
$[0 \quad 0$
$1\,\mathrm{I}$
$]$
$V_{sc} \; -V_{cc} \; -V_{rc}$

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

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

1.2. 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).

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

I_{pc} $\begin{bmatrix} 0 & 0 & \frac{-r_p}{L_p} \end{bmatrix} I_{pc} \begin{bmatrix} 0 & 0 & \frac{1}{L_p} \end{bmatrix} V_{pc} - V_{cc} - V_{rc}$

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

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

1.3. 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).

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

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.

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

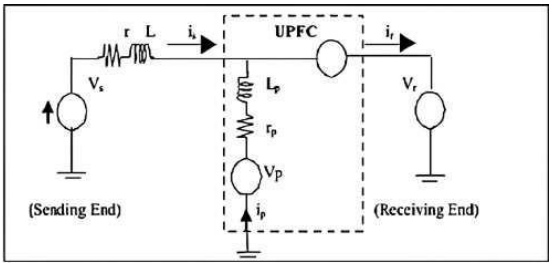


Figure 2. The physical representation of a UPFC converter connected to the network

2. THE DESIGN OF CONTROLLERS

2.1. 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].

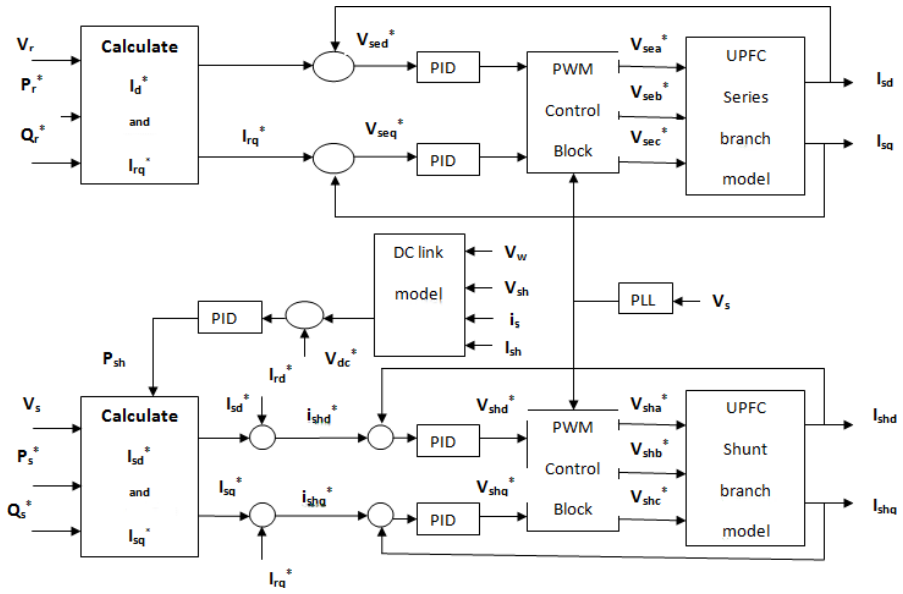


Figure 3. General design of UPFC system with PID control

2.2. UPFC with FOPID controller

When it comes to managing the unified power flow controller (UPFC) in power systems, the fractional order PID (FOPID) controller has become a more adaptable and effective substitute for the conventional PID controller. The FOPID controller provides fractional (non-integer) orders for proportional, integral, and derivative actions in contrast to the traditional PID controller, which uses fixed-order parameters for these terms. It is especially useful in intricate and dynamic systems like the UPFC because this extra degree of freedom enables more subtle and accurate adjustment. The whole system configuration with FOPID control is shown in Figure 4.

Here's a deeper look at why UPFC performance is improved with the FOPID controller:

-A greater degree of tuning flexibility

-Increased resilience

-Enhanced damping and stability
-A faster reaction time
-Optimal management of reactive and active power
These advantages result in more effective, steady, and flexible power flow regulation, which eventually enhances the power system's overall performance and dependability.

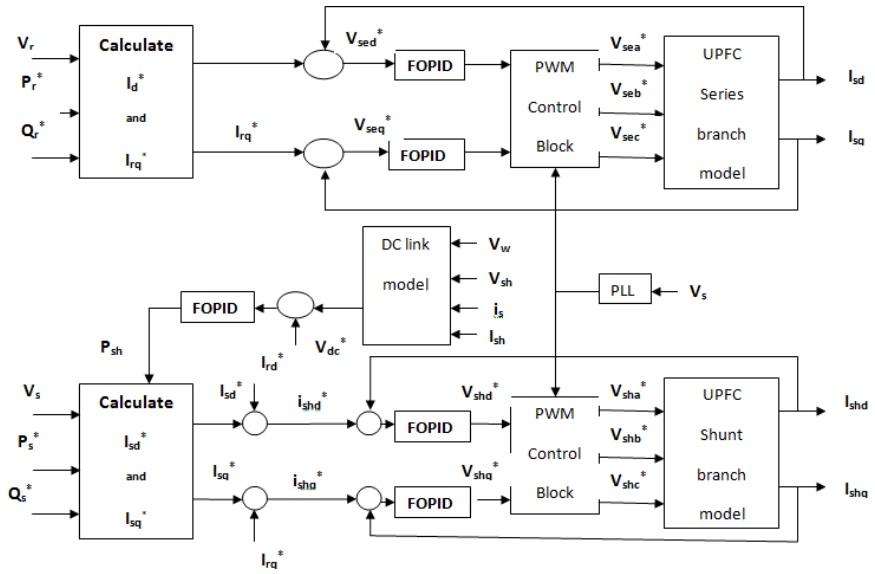


Figure 4. General design of the UPFC system with FOPID control

3. UPFC OPERATING PRINCIPLE

A voltage with adjustable amplitude and phase is injected by the series inverter at the same frequency as the network. The serial portion may operate in three different modes thanks to this amplitude and phase adjustment:

-Voltage control: the source side voltage and the injected voltage are in phase.

-Line impedance control: The injected voltage and the current line are in quadrature. Similar to a compensator series, this mode lets you change the impedance of the line.

-Phase control: To create the identical voltage module before and after the UPFC, the amplitude and phase of the injected voltage are computed.

Controlling the active and reactive power that passes through the line is the main objective of these three operating modes. Additionally, the UPFC may switch between several operating modes and incorporate multiple compensations. In order to maintain the plan voltage and potentially provide active power to the network via the serial part, the shunt part may be used to compensate for the reactive power [22], [23].

4. 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:

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

Kp, Ki, and Kd: 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]

5. RESULTS AND DISCUSSION

This research aims to investigate the use of a UPFC to manage the interchange of active and reactive power in an electrical interconnection line. In particular, we examine a UPFC that is linked to a 1000 MVA transport capacity high-throughput THT interconnection line. Figure 5 shows the configuration of the network that is being studied. This configuration offers an appropriate setting for assessing how well the UPFC controls power flow and improves stability in high-capacity transmission networks. FOPID and the PID controller. Table 1 displays the controller's parameters.

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

Parameters	KP	Ki	Kd	λ	μ
Parameter of PID controller	4000	4500	1000	/	/
Parameter of FOPID controller	4000	4500	1000	0.3	0.25

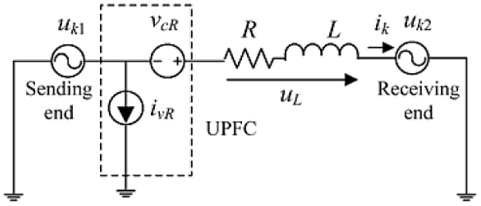
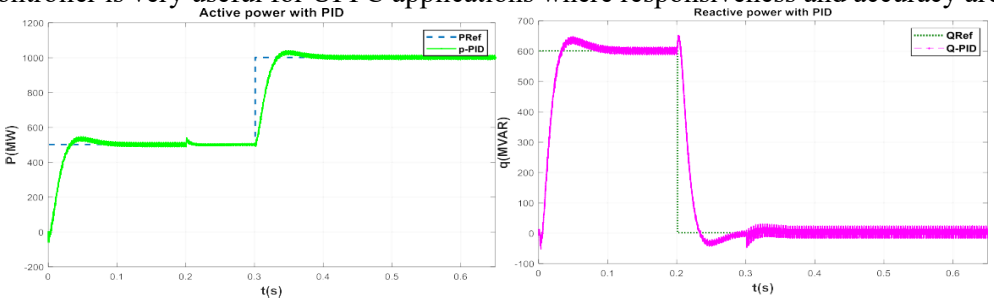


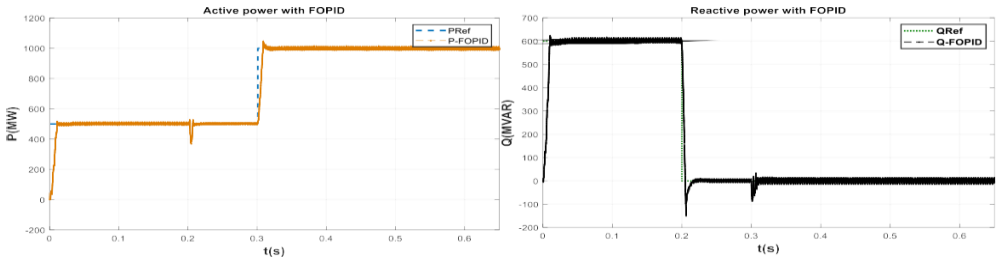
Figure 5. Equivalent circuit of a transmission system with UPFC

Figures 6-8 show all of the PID and FOPID results. The FOPID controller clearly outperforms the PID controller in controlling power flow across the transmission line, as shown by the findings shown in Figures 6-8. The FOPID controller produces more accurate and reliable power flow management by achieving smoother response curves, greater set-point tracking, and increased stability. With shorter rising and settling times than the PID controller, the FOPID controller has noticeably improved dynamic performance, as shown in Table 2, suggesting a speedier and more stable reaction to variations in load and system circumstances. Because of its exceptional performance, the FOPID controller is very useful for UPFC applications where responsiveness and accuracy are crucial.



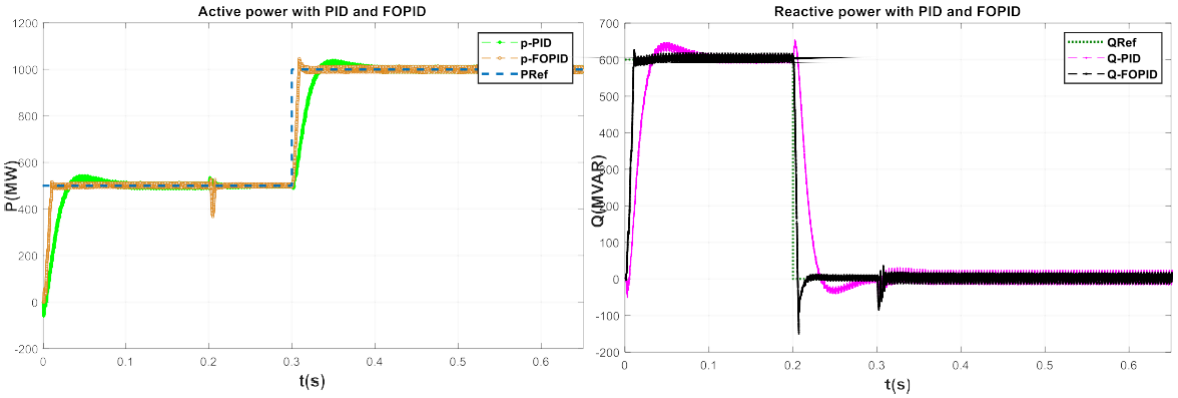
(a) (b)

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	

6. CONCLUSION

In conclusion, a comparison of two control strategies—the fractional-order PID (FOPID) and the traditional proportional-integral-derivative (PID)—shows that the FOPID control method outperforms the classic PID in terms of overall performance and system responsiveness. The fractional-order approach improves adaptability and flexibility, enabling more precise control parameter modification to satisfy the dynamic characteristics of the system. In terms of stability, overshoot, and settling time, the FOPID controller performs better than the conventional PID controller.This research demonstrates that fractional order management is effective in improving the power system under consideration. Additionally, it provides us with helpful information to improve the effectiveness of control measures in comparable circumstances. When the parameter reference values change, the FOPID controller performs better than the standard PID controller in terms of peak overshoot and settling time. The findings shown that the suggested UPFC based on FOPID has improved power flow capacity and decreased its loss, which enables it to react to system changes more effectively and increases stability, which lowers the frequency of disruptions and failures in electrical networks. Therefore, enhancing performance control units increases power systems' efficiency, which lowers losses and enhances resource utilization. It may also extend the life of equipment and save maintenance and repair expenses. Artificial intelligence and performance analysis techniques may be implemented in the future as a continuation of this effort. UPFC unified power flow controller implementation using ANN and FLC algorithms.

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