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RESEARCH ARTICLE OPEN ACCESS

ANALYSIS OF REACHING LAW EFFECTIVENESS IN SLIDING MODE CONTROL OF THE UPFC

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ABSTRACT

The Unified Power Flow Controller (UPFC) represents a critical component within the Family of FACTS devices, employed to improve the stability, reliability, and controllability of electrical power systems under fluctuating load conditions. This research endeavors to assess various reaching laws within the paradigm of Sliding Mode Control (SMC) with the aim of enhancing the dynamic performance of a UPFC. Specifically, an examination and comparison of three distinct types of reaching laws—constant rate, exponential rate, and power rate—are conducted. The principal aim is to devise and implement robust control methodologies that guarantee precise tracking of reference power commands, as well as improved regulation of both active and reactive power flows within transmission lines. The proposed SMC-based controllers are incorporated into a simulated UPFC framework, with their performance being compared against that of a conventional PID controller. Simulation models have been constructed using MATLAB/Simulink, and performance metrics including overshoot, settling time, and rise time are utilized for quantitative analysis. The results demonstrate that the SMC utilizing the power rate reaching law significantly surpasses the conventional PID controller, achieving a minimal overshoot of approximately 0.5411%, a settling time of 0.1009 seconds, and a rapid rise time of 4.0720×10^{-4} seconds. These findings substantiate the efficacy of advanced reaching laws in augmenting UPFC control, thereby contributing to enhanced stability and operational efficiency within power systems.

I. INTRODUCTION

In contemporary electrical power systems, the assurance of stability and the maintenance of efficient power distribution under fluctuating load conditions and disturbances have become increasingly arduous. The escalating incorporation of renewable energy sources alongside a burgeoning demand for electricity has underscored the necessity for sophisticated and resilient control strategies to secure optimal system performance. Among the devices categorized under FACTS (Flexible AC Transmission Systems), the Unified Power Flow Controller (UPFC) is widely recognized for its capability to modulate power flow and augment voltage stability during real-time operations [1-3].

To fully harness the capabilities of the UPFC, it is imperative to implement control methodologies adept at addressing system nonlinearities and uncertainties. Sliding Mode Control (SMC) has garnered considerable attention owing to its robustness and efficacy in steering system states toward desired trajectories, even amidst parameter fluctuations and external perturbations [4-6]. A pivotal aspect influencing SMC performance is the formulation of the reaching law, which delineates the manner in which the system attains the sliding surface prior to entering the sliding mode. Recent investigations have introduced novel formulations of reaching laws aimed at enhancing convergence speed while concurrently mitigating -chattering effects [7-9]. This research centers on a comparative examination of three classifications of reaching laws—constant rate, exponential rate, and power rate—within the context of SMC applied to the UPFC. The primary objective is to assess their efficacy in regulating active and reactive power flows, improving transient performance, and sustaining system stability[10-12]. Through simulations conducted in MATLAB/Simulink and the application of metrics such as overshoot, settling time, and rise time, the study endeavors to identify the most effective reaching law for augmenting UPFC performance[13]. Ultimately, the outcomes of this investigation contribute to the progression of robust control applications within the realm of power electronics and further the overarching aim of cultivating more reliable, stable, and efficient power systems[14-16].

II. MATHEMATICAL MODEL OF THE UNIFIED POWER FLOW CONTROLLER (UPFC)

The equivalent circuit of a UPFC system isshown in Fig. 2 where the series and shuntinverters are represented by voltage sources vcand vprespectively. The transmission line ismodelled[17-20] as a series combination of resistance rand inductance L. The parameters rp and Lprepresent the shunt transformer resistance and leakage inductance respectively. The noncaused by the switching of the semiconductor devices, transformer saturation and controller linearities time delays are neglected in the equivalent circuit and it is assumed that thetransmission system is symmetrical.

III. MATERIALS AND METHODS

Write in detail the research project, including background and limitations. The selection of materials and methods, procedures and equipment must be justified so that the work can be reproduced. Modifications or new methods must be described in detail. You must clearly define the universe and specify how the sample was selected and why it is representative. Data processing represents the practical development of a theoretical basis, deriving the model equations to program the calculation algorithm, according to the need. In materials, they include the technical specifications and the quantities, the origin and, if necessary, the method for its elaboration.

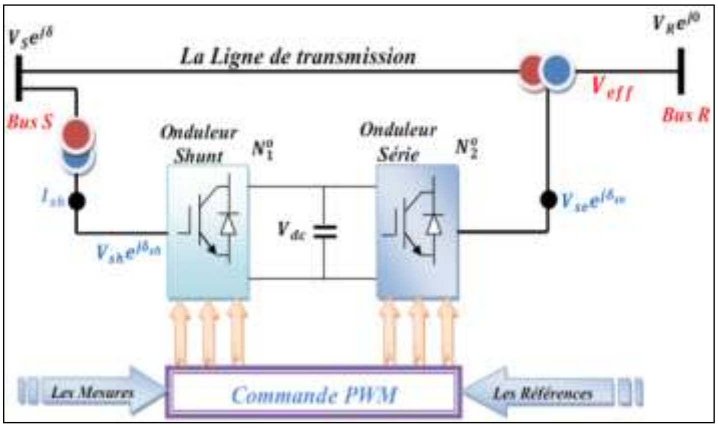


Figure 1: Basic circuit configuration of a UPFC.
Source: [1], [21].

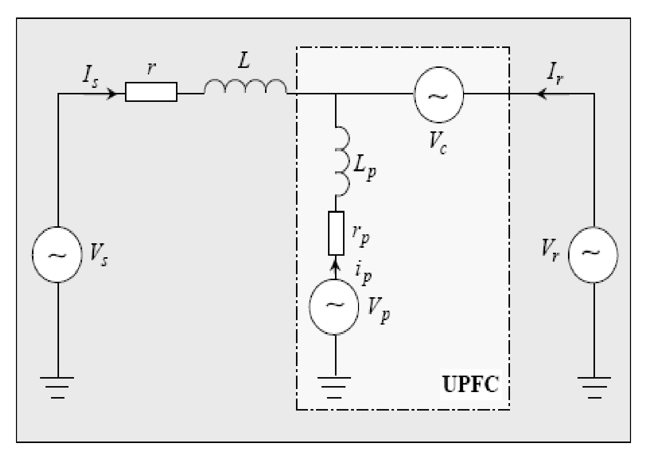


Figure 2: Equivalent circuit of UPFC system.
Source: [3].

Transmission By performing Park transformation, thecurrent through the transmission line can bedescribed by the following equations [4]

$$\frac{di_{sd}}{dt} = wi_{sq} - \frac{r_s}{l_s} i_{sd} + \frac{1}{l_s}(v_{sd} - v_{cd} - v_{rd}) \tag{1}$$

$$\frac{di_{sq}}{dt} = -wi_{sd} - \frac{r_s}{l_s} i_{sq} + \frac{1}{l_s}(v_{sq} - v_{cd} - v_{rd}) \tag{2}$$

where subscripts d and q denote the Park components of the currents and voltages. Similarly, the shunt inverter can be described by

$$\frac{di_{pd}}{dt} = wi_{pq} - \frac{r_p}{l_p} i_{pd} + \frac{1}{l_p}(v_{pd} - v_{cd} - v_{rd}) \tag{3}$$

$$\frac{di_{pq}}{dt} = -wi_{pd} - \frac{r_p}{l_p} i_{pq} + \frac{1}{l_p}(v_{pq} - v_{cd} - v_{rd}) \tag{4}$$

Using the power balance principle and neglecting the inverter losses, the dc bus voltage can be described by [5]

$$\frac{dv_{dc}}{dt} = \frac{3}{2Cv_{dc}}(v_{cd}i_{rd} + v_{cq}i_{rq} - v_{pd}i_{pd} - v_{pq}i_{pq}) \tag{5}$$

Equations (1) and (2) , (3) and (4) give a state representation of the UPFC system

$$\begin{bmatrix} i_{sd} \\ i_{sq} \end{bmatrix} = \begin{bmatrix} -r_s/l_s & w \\ -w & -r_s/l_s \end{bmatrix} \begin{bmatrix} i_{sd} \\ i_{sq} \end{bmatrix} + \begin{bmatrix} 1/l_s & 0 \\ 0 & 1/l_s \end{bmatrix} \begin{bmatrix} U_{sd} \\ U_{sq} \end{bmatrix} \tag{6}$$

$$\begin{bmatrix} i_{pd} \\ i_{pq} \end{bmatrix} = \begin{bmatrix} -r_p/l_p & w \\ -w & -r_p/l_p \end{bmatrix} \begin{bmatrix} i_{pd} \\ i_{pq} \end{bmatrix} + \begin{bmatrix} 1/l_p & 0 \\ 0 & 1/l_p \end{bmatrix} \begin{bmatrix} U_{pd} \\ U_{pq} \end{bmatrix} \tag{7}$$

Formulation of a global system

$$\dot{X} = AX + BU \tag{8}$$

$$Y = CX \tag{9}$$

Where:

$$X = [i_{sd} i_{sq} i_{pd} i_{pq}]^T$$

$$U = [U_{sd} U_{sq} U_{pd} U_{pq}]^T$$

$$A = \begin{bmatrix} -r_s/l_s & w & 0 & 0 \\ -w & -r_s/l_s & 0 & 0 \\ 0 & 0 & -r_p/l_p & w \\ 0 & 0 & -w & -r_p/l_p \end{bmatrix}$$

$$B = \begin{bmatrix} 1/l_s & 0 & 0 & 0 \\ 0 & 1/l_s & 0 & 0 \\ 0 & 0 & 1/l_p & 0 \\ 0 & 0 & 0 & 1/l_p \end{bmatrix}$$

$$C = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

IV CONTROLLER DESIGN

IV.1 PI DECOUPLING CONTROL

The principle of this control strategy is to convert the measured three phase currents and voltages into d-q values and then to calculate the current references and measured voltages as follows [22-24].

$$\mathrm{i_{sdref}} = \frac{2}{3}\frac{(\mathrm{P^*v_{sd}} - \mathrm{Q^*v_{sq}})}{\mathrm{v_{sd}^2} + \mathrm{v_{sq}^2}} \tag{10}$$

$$\mathrm{i_{sqref}} = \frac{2}{3}\frac{(\mathrm{P^{*}v_{sq}} + \mathrm{Q^{*}v_{sd}})}{\mathrm{v_{sd}^{2}} + \mathrm{v_{sq}^{2}}} \tag{11}$$

Where the * superscript defines the reference qantities. The power flow control is then realised by using properly designed controllers to force the line currents to follow their references. It is desired that the UPFC control system has a fast response with minimal interaction between the real and reactive power together with a strong damping of the resonance frequency[1]. With reference to equations (1), (2),(3) and (4) the interaction between the current loops is caused by the ωL coupling term. Decoupling is achieved by feeding back this term and subtracting [3], [23], [24]. However, perfect decoupling is difficult to achieve with a PI-D controller due to the presence of time-delays and other non linearities in the UPFC system.

IV.2 SLIDINGMODE COTROL UPFC SYSTEM BASED ON REACHING LAWS

In general , a SMC based on reaching laws included a reaching phase and a sliding phase . the reaching phase drives the system to stable manifold ,the sliding phase drives the system slide to equilibrium ,the typical reaching laws are given as follows (1):

A. Reaching laws with constant rate

$$\dot{s} = -\mathcal{E} sign(s) \;\; ,\mathcal{E}>0 \tag{12}$$

where Ɛ represents a constant rate. This law forces the switching variable to reach the switching manifold s at a constant rate Ɛ .

B. Exponential reaching law

$$\dot{s} = -\mathcal{E} sign(s) - ks \;\; ,\mathcal{E}>0 \; k>0 \tag{13}$$

Where $\dot{s} = -ks$ in the exponential reaching law ,for being to guarantee a faster convergence speed , especially when s is nearly to zero.

C. Reaching Law With Power Rate

$$\dot{s} = -k|s|^{a} sign(s), k>0 \;\; ,1>a>0 \tag{14}$$

This reaching law increases the reaching speed when the state is far away from the switching manifold ,but reduces the rate when the state is near the manifold. The result is a fast reaching and low chattering reaching mode.

IV.3 SMC CONTROLLER DESIGN BASED ON REACHING LAWS FOR THE UPFC SYSTEM

The SMC controller consists of equivalent control and switching control.

$$U_{SMC}(t) = U_{eq}(t) + U_{SW}(t) \tag{15}$$

where

$$U_{SMC} = [U_{sdSMC} U_{sqSMC} U_{pdSMC} U_{pqSMC}]^{T}$$

$$U_{eq} = [U_{sdeq} U_{sqeq} U_{pdeq} U_{pqeq}]^{T}$$

$$U_{SW} = [U_{sdSW} U_{sqSW} U_{pdSW} U_{pqSW}]^{T}$$

Now the equivalent control and switching control can be designed:

- Switching function

The sliding surface is chosen as equation (16)

$$s(t) = \left(\frac{d}{dt} + \lambda\right)^{n-1} e(t) \tag{16}$$

Since the order of the system is 1, then:

$$S(t) = e(t) \tag{17}$$.

The tracking error value is

$$e(t) = X_{ref} - X \tag{18}$$

$$X_{ref} = [i_{sdref} i_{sqref} i_{pdref} i_{pdref}]^{T}$$

where

X_{ref} is the reference current , i is the current reality

The first derivation of equation (17) we have equation (18)

$$\dot{e} = \dot{X}_{ref} - \dot{X} \tag{19}$$

Substituting equation (16) in equation (17) , we have :

$$\dot{S} = \dot{X}_{ref} - \dot{X} \tag{20}$$

Substituting equation (19) in equations (1) and (2), (3) and (4) we have:

$$\dot{S} = \dot{X}_{ref} - AX - BU \tag{21}$$

On sliding surface; S(t) = 0

Equivalent control can found;

$$U_{eq} = B^{-1}\dot{X}_{ref} - B^{-1}AX \tag{22}$$

The reaching law with constant rate as described as equation (23)

$$U_{SW} = Wsign\big(S(t)\big) \tag{23}$$

$$U_{SW} = [U_{sdsw} U_{sqsw} U_{pdsw} U_{pqsw}]^T$$

where w > 0 is selected sufficiently large . A larger value of w allows a faster the trajectory converges to the sliding surface.

The signum function is described as equation (32):

$$sign(t) = \begin{bmatrix} 1 & s(t) > 0 \\ 0 & s(t) = 0 \\ -1 & s(t) < 0 \end{bmatrix} \tag{24}$$

combine each equation among the equations (27, 28, 29, 30) with equation (31) we have the SMC

$$U_{SMC} = U_{eq} + U_{sw} \tag{25}$$

$$U_{SMC} = B^{-1}\dot{X}_{ref} - B^{-1}AX + Wsign\big(S(t)\big) \tag{26}$$

To prove the stability ,the lyapunov function can be defined by equation (27)

$$V(t) = \frac{1}{2}S^2(t) \tag{27}$$

$$\dot{V} = \dot{S}S \tag{28}$$

$$\dot{V} = S\{\dot{X}_{ref} - \dot{X}\} \tag{29}$$

$$\dot{V} = S\{\dot{X}_{ref} - (AX + BU_{SMC})\} \tag{30}$$

$$\dot{V} = S\{\dot{X}_{ref} - AX - BU_{SMC}\} \tag{31}$$

$$\dot{V} = S\{\dot{X}_{ref} - AX - B(B^{-1}\dot{X}_{ref} - B^{-1}AX + Wsign\big(S(t)\big))\} \tag{32}$$

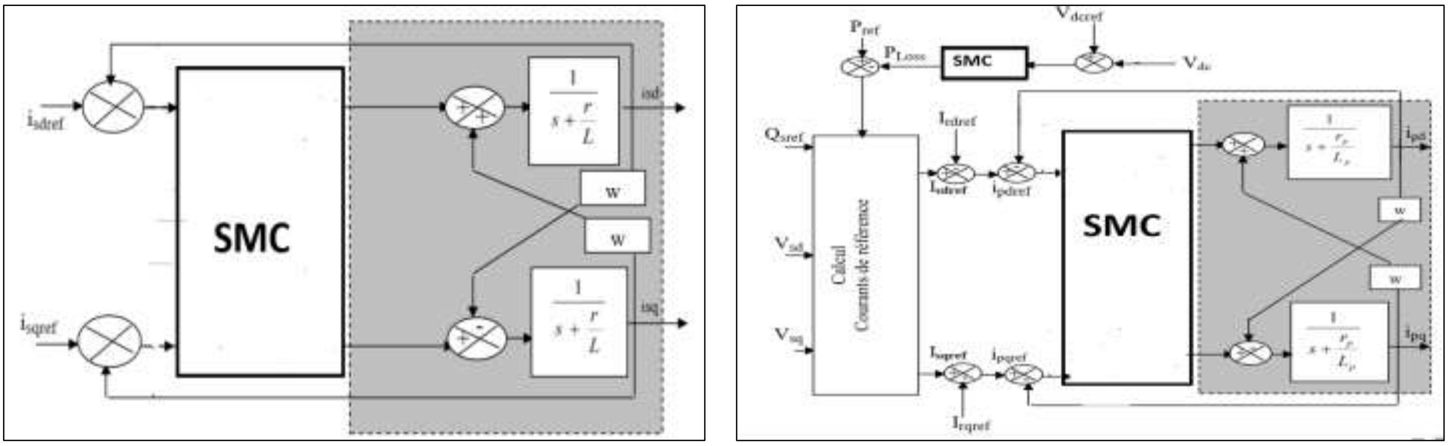
$$\dot{V} = -S\{BWsign\big(S(t)\big)\} \tag{33}$$

$$\dot{V} = -BW\left|S\right| < 0 \tag{34}$$

We can see that the sliding mode function S(t) will tend to zero exponentially with W value . Similary to above , the exponentially reahing law and the power rate reaching law are described as equations (12) and (13).

V SIMULATION AND RESULTS

The simulation is performed with MATLAB/SIMULINK software program. For each of the control systems mentioned above, simulation model is created which includes the required PWM.



A) The structure of the SMC for the UPFC (serie)

B) The structure of the SMC for the UPFC (shunt)

Figure 3: The structure of the SMC for the UPFC (serie (a) and shunt(b))

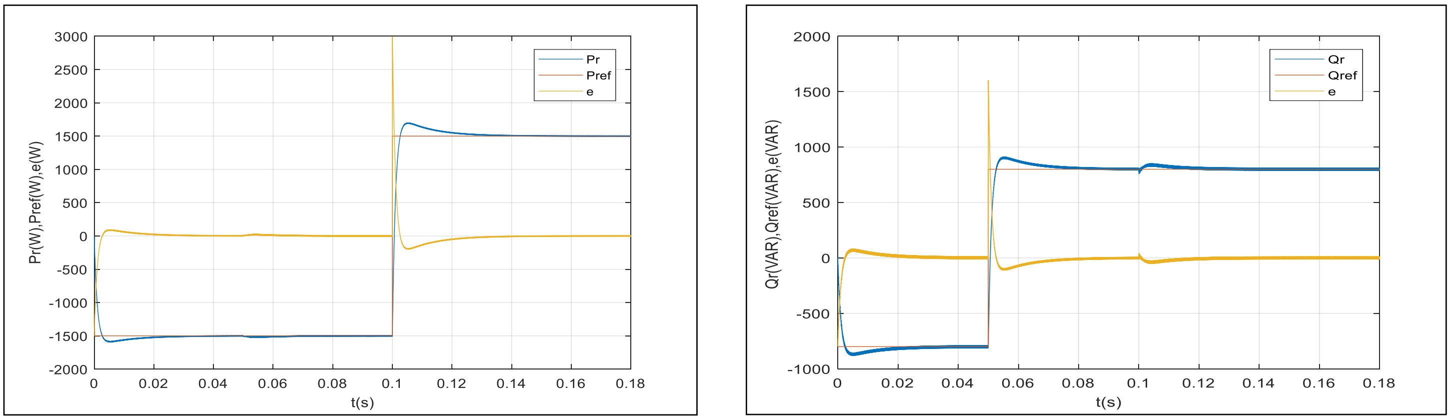
Source: Authors, (2026).

The parameters of the UPFC and SMC are shown as table 1[18].

Table 1: The parameters of the UPFC and SMC.

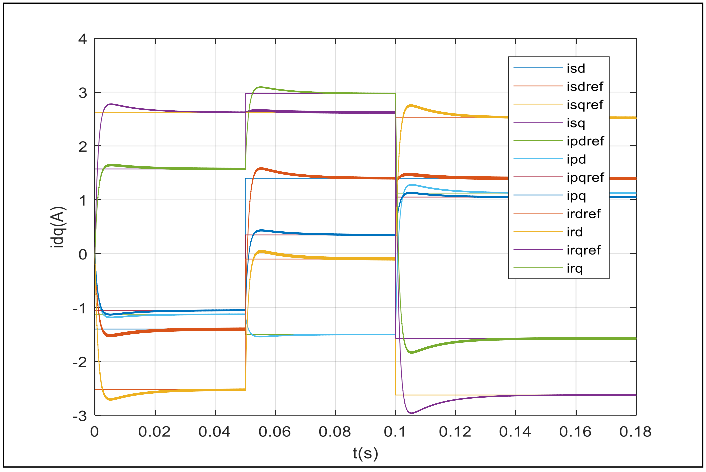
Parameters	Parametres of the UPFC			Parametres of the SMC			
	l(mH)	r_s (Ω)	r_p (Ω)	W	K	α	λ
Values	10	0.8	0.4	30	200	0.5	10

Source: [18].



a) Active power Pr, reference Prref, and corresponding error

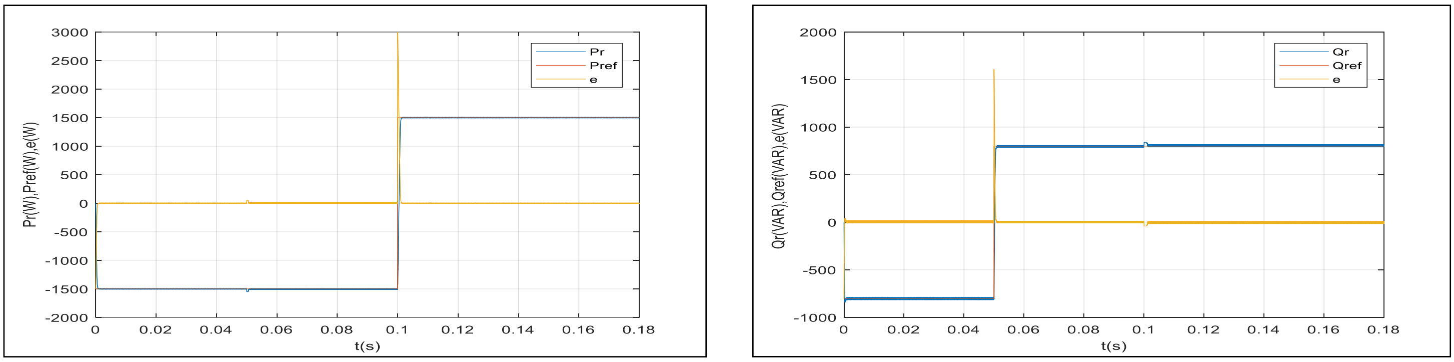
b) Reactive power Qr, reference Qrref, and corresponding error



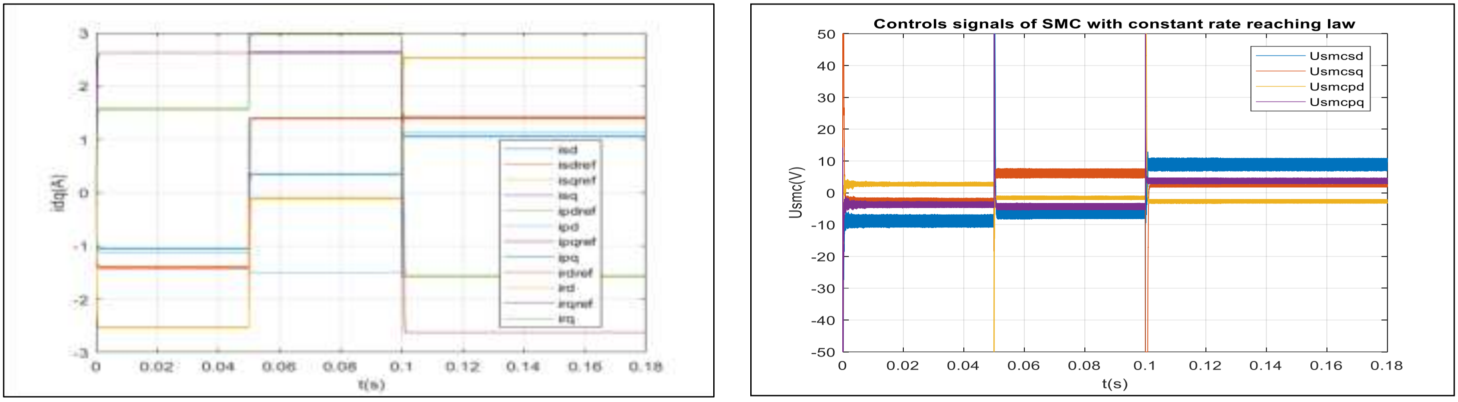
c) dq-axis currents id,iq, and their references idref,iqref

Figure 4: Simulation results of step responses with PI-decoupling in receiving end.

Source: Authors, (2026).



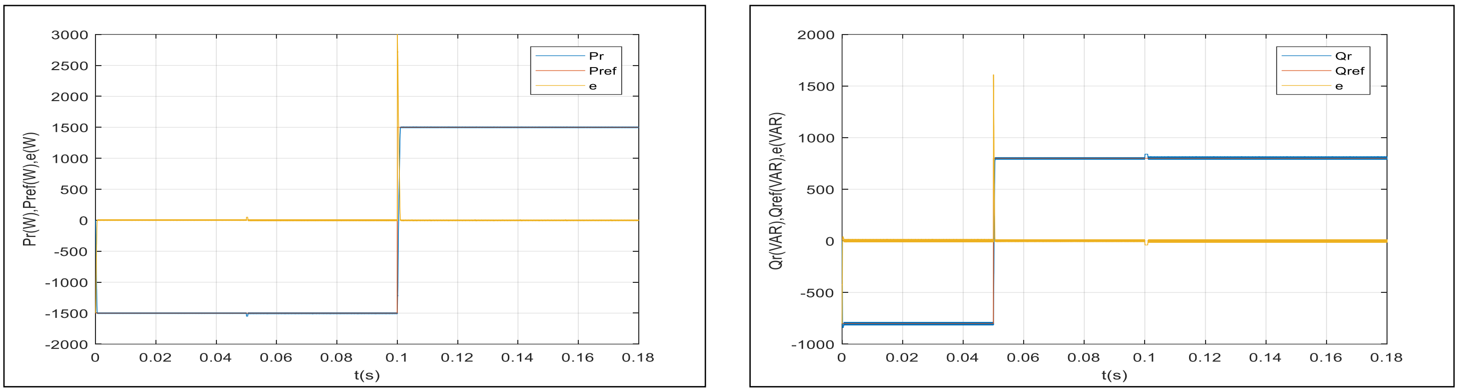
a) Active power Pr, reference Prref, and corresponding error b) Reactive power Qr, reference Qrref, and corresponding error



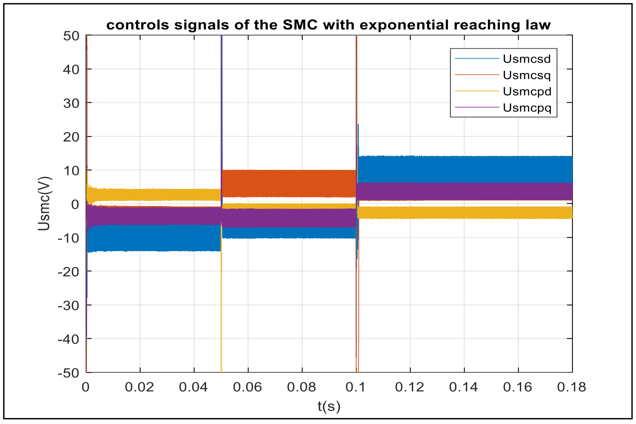
c) dq-axis currents id,iq, and their references idref,iqref d) Control signal of the SMC with constant rate reaching law

Figure 5: Simulation results of step responses with SMC based on reaching laws with constant rate.

Source: Authors, (2026).



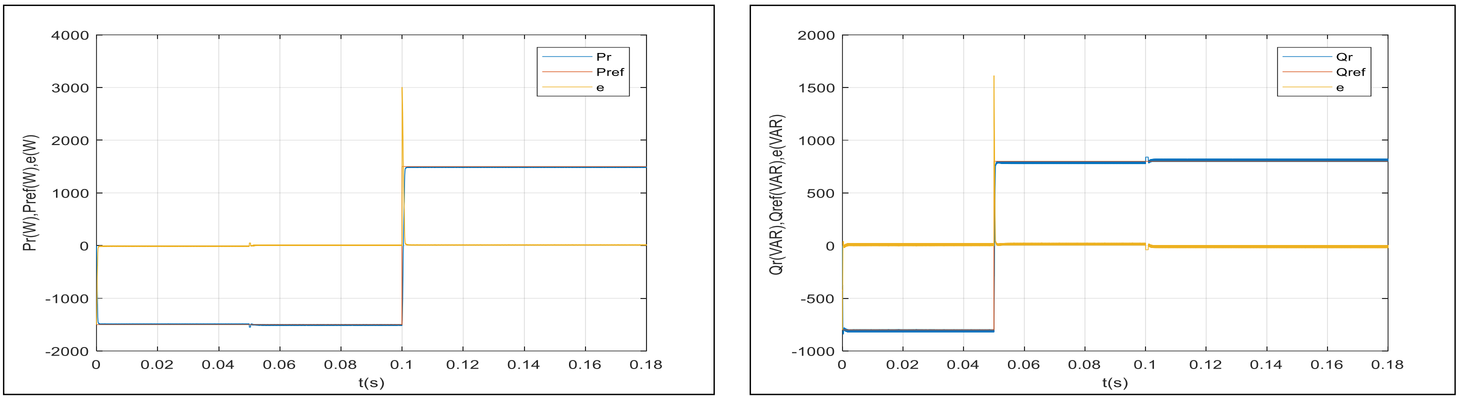
a) Active power Pr, reference Prref, and corresponding error b) Reactive power Qr, reference Qrref, and corresponding error



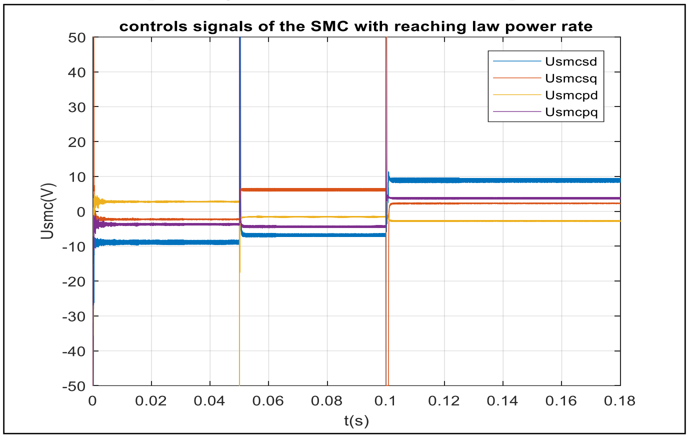
c) Control signal of the SMC with exponential reaching law

Figure 6: Simulation results of step responses with SMC based on exponential reaching law.

Source: Authors, (2026).



a) Active power Pr, reference Prref, and corresponding error b) Reactive power Qr, reference Qrref, and corresponding error



a) Control signal of the SMC with reaching law power rate

Figure 7: Simulation results of step responses with SMC based on reaching laws With Power Rate.

Source: Authors, (2026).

Table 2: Systeme Responses With The Smc Based On Different Reaching Laws.

Controller		Rise time (s)	Settling Time (s)	Overshoo t (%)
SMC	Reaching law with constant rate	reactive power		
		2.8422e-04	0.1010	4.9789
		active power		
		4.4748e-04	0.1010	0.5542
	Exponential reaching law	reactive power		
		2.1573e-04	0.1010	4.9087
		active power		
		4.4839e-04	0.1009	0.6431
	Reaching law with power rate	reactive power		
		2.4271e-04	0.1009	4.2884
		active power		
		4.0720e-04	0.1009	0.5411
PID		reactive power		
		14 e-04	0.1131	14.5714
		active power		
		14 e-04	0.1190	13.3851

Source: Authors, (2026).

VI. PERFORMANCE EVALUATION

The examination of the results indicates that the Sliding Mode Controller (SMC) for the Unified Power Flow Controller (UPFC) surpasses the conventional Proportional-Integral-Derivative (PID) controller concerning critical performance metrics for both reactive and active power responses. Analyzing the data based on the information provided yields the following insights: Reactive Power Response: The settling time for the SMC, as depicted in Figures 3b, 4b, and 5b, consistently approximates 0.1010 seconds, signifying a swift and stable convergence to the reference signal for reactive power. The overshoot values, which span from 4.2884% to 4.9789%, remain within acceptable thresholds, indicating minimal oscillatory behavior and enhanced stability. The rise times, ranging between 2.1573e-04 and 2.4271e-04 seconds, reflect a prompt response of the SMC in adapting to alterations in the reference signal. Active Power Response: The settling time for the SMC, illustrated in Figures 3a, 4a, and 5a, maintains a consistent duration of approximately 0.1010 seconds for active power, thereby demonstrating swift convergence to the reference signal.

The overshoot values for active power are markedly lower, varying from 0.5411% to 0.6431%, which suggests enhanced stability and diminished oscillations in comparison to the reactive power response. The rise times, which fall within the range of 4.0720e-4 to 4.4839e-4 seconds, indicate a rapid response of the SMC to changes in the reference signal for active power. Of the SMC is superior to that of the classical PID" is substantiated by the comparative analysis of settling time, overshoot, and rise time metrics. The SMC consistently demonstrates accelerated settling times and reduced overshoot relative to the traditional PID controller in both reactive and active power responses. Furthermore, the rise times for the SMC are either comparable to or more rapid than those associated with the PID controller, signifying an enhanced dynamic response.

VII. CONCLUSIONS

Overall Performance:

The Sliding Mode Controller (SMC), when implemented with the prescribed reaching laws, exhibits enhanced performance with respect to response velocity, system stability, and precision for both reactive and active power regulation within the framework of Unified Power Flow Controllers (UPFC). The findings presented indicate that the SMC represents a highly viable control methodology for UPFC configurations, delivering superior transient response characteristics and tracking proficiency in comparison to the Proportional-Integral-Derivative (PID) controller. In summary, the evaluation reveals that the Sliding Mode Controller confers substantial benefits over the PID controller regarding response velocity, system stability, and precision for both reactive and active power regulation in the analyzed UPFC framework.

VIII. AUTHOR’S CONTRIBUTION

Conceptualization: Mohammed Elaguab, Mohamed Boukhalfa, Abdelkrim BOUANANE, Badreddine NAAS, Benalia M'hamdi, Abdelkader Azzeddine Bengharbi, Mohamed R. Bengourina.
Methodology: Mohammed Elaguab, Mohamed Boukhalfa, Abdelkrim BOUANANE, Badreddine NAAS, Benalia M'hamdi, Abdelkader Azzeddine Bengharbi, Mohamed R. Bengourina.
Investigation: Mohammed Elaguab, Mohamed Boukhalfa, Abdelkrim BOUANANE, Badreddine NAAS, Benalia M'hamdi, Abdelkader Azzeddine Bengharbi, Mohamed R. Bengourina.
Discussion of results: Mohammed Elaguab, Mohamed Boukhalfa, Abdelkrim BOUANANE, Badreddine NAAS, Benalia M'hamdi, Abdelkader Azzeddine Bengharbi, Mohamed R. Bengourina.
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Writing – Review and Editing: Mohammed Elaguab, Mohamed Boukhalfa, Abdelkrim BOUANANE, Badreddine NAAS, Benalia M'hamdi, Abdelkader Azzeddine Bengharbi, Mohamed R. Bengourina.
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Approval of the final text: Mohammed Elaguab, Mohamed Boukhalfa, Abdelkrim BOUANANE, Badreddine NAAS, Benalia M'hamdi, Abdelkader Azzeddine Bengharbi, Mohamed R. Bengourina.

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