

COMPARATIVE STUDY BETWEEN PI AND SLIDING MODE CONTROL OF A UNIFIED POWER FLOW CONTROLLER

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Abstract: *This paper presents a stability of power system by unified power flow controller (UPFC). This controller offers advantages in terms of static and dynamic operation of the power system such as the control law is synthesized using two types of controllers: proportional integral (PI), and sliding mode controller. Their respective performances are compared in terms of reference tracking, sensitivity to perturbations and robustness. We have to study the problem of controlling power in electric system by UPFC. The simulation results show the effectiveness of the proposed method especially in chattering-free behavior, response to sudden load variations and robustness. All the simulations for the above work have been carried out using MATLAB/Simulink. Various simulations have given very satisfactory results and we have successfully improved the real and reactive power flows on a transmission line as well as to regulate voltage at the bus where it is connected, the studies and illustrate the effectiveness and capability of UPFC in improving power.*

Key words: UPFC, FACTS, sliding mode control, power, PI.

1. Introduction.

In recent years, the electrical power distribution system are suffering from significant power flow quality (PQ) problems, which are characterized by low power factor, poor voltage profile, voltage stability, load unbalancing, and supply interruptions. These power quality issues have attracted attention to the researchers both in academic and industry. As a result, many power quality standards were proposed in [1]. By the reason of these power quality issues, the use of flexible AC transmission system (FACTS) controllers in power system has been of worldwide interest for increasing the power transfer capability and enhancing power system controllability and stability due to their speed and flexibility. In addition, converter based FACTS controllers are capable of independently controlling both active and reactive power flow in the power system [2].

UPFC is the member of FACTS device. It is the most versatile and powerful FACTS device [3]. The fundamental theory of UPFC is that, the phase angle affects flow of real power and the magnitude of voltage affects flow of reactive power [4], [5].

This device consists of two other FACTS devices: the Static Synchronous Series Compensator (SSSC) and the Static Synchronous Compensator (STATCOM), the SSSC injects a an almost sinusoidal voltage, of variable magnitude in series with the system voltage provides the most cost effective solution to mitigate voltage sags by improving power quality level that is required by customer and the STATCOM connected by a common DC link capacitor. It can simultaneously perform the function of transmission line real/reactive power flow control in addition to UPFC bus voltage/shunt reactive power control [6].

Though UPFC implies many advantages, but its controller design still being a matter of challenge since it is a multi-variable controller. In literature, A lot of works have been presented with diverse control diagrams of UPFC for various power system applications. Recently, the sliding mode control (SMC) method has been widely used for robust control of nonlinear systems. Several papers have been published based on SMC of UPFC [7-9]. SMC based controller for UPFC has been pro-posed in this paper. That is SMC is employed to develop the control algorithms for both shunt and series converters of UPFC.

This paper discusses the capability of UPFC on controlling independently the active and reactive power in the power transmission line and the improvement of the transient and dynamic stability of the power system by the UPFC are examined. Active and reactive powers are controlled using two types of controllers: Integral-Proportional (PI) and SMC. Their performances are compared in terms of reference tracking, sensitivity to perturbations and

robustness.

2. Unified Power Flow controller (UPFC).

2.1 Structure Of The UPFC

For many years, UPFC is considered as the most versatile of the FACTS device one that can be used to enhance steady state stability, dynamic stability and transient stability, which combines the good features of STATCOM and SSSC. Fig.1 shows the basic structure of UPFC which consists of two voltage sourced converters (VSC) and used to provide galvanic isolation and adjust the voltage levels in the supply system. It is composed of two inverters with PWM control (Pulse Width Modulation), which are operated from a DC link provided by a dc storage capacitor. One is connected in parallel and the other in series with the transmission line [10]. The detailed structure and the functionality of the UPFC can be found in [11].

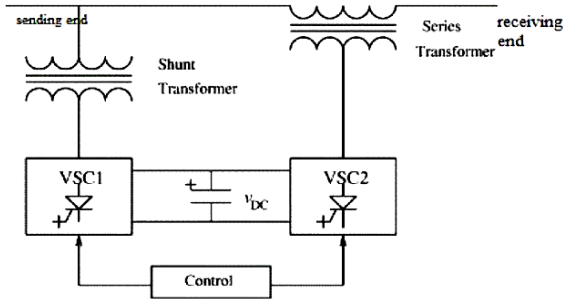


Fig.1. Basic structure of the UPFC.

2.2 The modeling of the UPFC

Figure 2 represents the simplified model circuit of the UPFC.

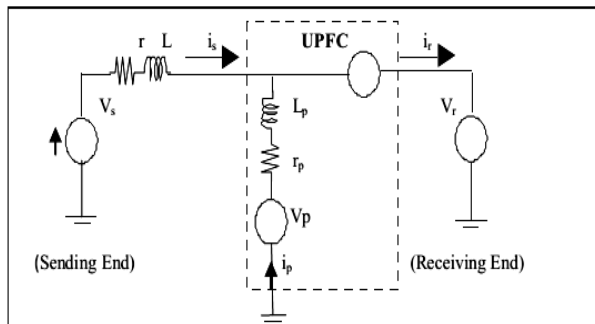


Fig.2. Equivalent circuit of the UPFC.

Applying Kirchoff law on equivalent circuit shown in Fig.2, the dynamic equations of the UPFC series branch is given in (1):

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

Using Park transformation, the equations (1) will be written as:

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

A. The modeling of the UPFC shunt branch

The complete mathematical model of the UPFC shunt is given similarly by the following matrix:

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

Since the system is assumed to be a balanced one, it can be transformed into a synchronous d-q-o frame by applying Park's transformation. The matrix form (3) is given as follows:

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

B. The modeling of the UPFC continues branch:

For the DC-side circuit, based on the power balance equation in the output and input of UPFC, The net real power exchanged by both the converters through DC side should be zero to keep the capacitor voltage constant [12]. The DC voltage V_{dc} dynamics across the capacitor is given by the following equation:

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

$$\text{With : } \begin{aligned} P_e &= v_{ca}i_{sa} + v_{cb}i_{sb} + v_{cc}i_{sc} \\ P_{ep} &= v_{pa}i_{pa} + v_{pb}i_{pb} + v_{pc}i_{pc} \end{aligned}$$

With:

P_e : active power absorbed of the AC system
 P_{ep} : active power injected by the shunt inverter AC system.

By performing Park transformation, the DC voltage V_{dc} dynamics across the capacitor can be described by the following equations.

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

3. Control strategy of the UPFC

3.1 Control of the Parallel Converter

The ordinary working principle of the parallel compensation of STATCOM is described as follows: active power control which means stabilizing the capacitor voltage of the DC side; reactive power control which means stabilizing the terminal voltage [13]. According to the system of equations (2) the control strategy of parallel compensation (STATCOM) is decoupling of the two current loops control, to reduce the interaction between the active and reactive power. The control block diagram is shown in Fig.3.

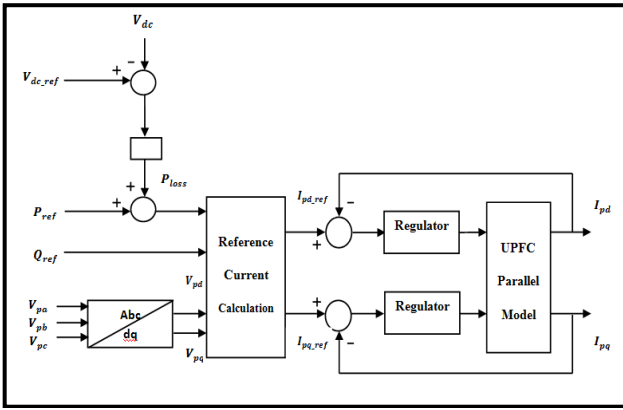


Fig.3. Control system of shunt part.

3.2 Control of the Series Converter

The SSSC regulate the active and reactive power flow on the transmission line where the UPFC is installed by injection voltage of which the amplitude and the phase both can be adjusted. The control strategy of the series compensator is decoupling of the two current loops control. The diagram of control circuits of SSSC is given in the fig.4.

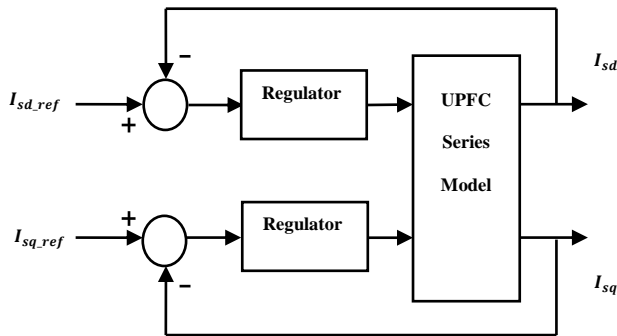


Fig.4. control system of series part.

In this section, we have chosen to compare the performances of the UPFC with two different

controllers: PI and SMC.

3.3 PI controller

This controller is simple to elaborate. Fig.5 shows the block diagram of the system implemented with this controller. The terms k_p and k_i represent respectively the proportional and integral gains.

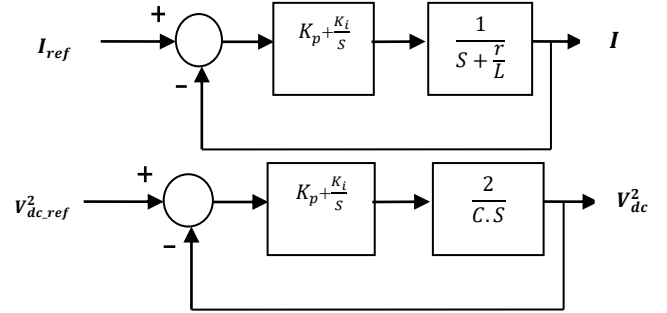


Fig.5. System with PI controller.

The regulator terms are calculated with a pole compensation method. The time response of the controlled system will be fixed at $\tau = 5ms$. This value is sufficient for our application and a lower value might involve transients with important overshoots. The calculated terms are:

Table 1

Optimal parameters of the proposed controllers.

	Controller series part	Controller shunt part	Controller continues branch
K_p	$\frac{1}{\tau}$	$\frac{1}{\tau}$	$\frac{C}{2} \cdot \omega^2$
K_i	$\left(\frac{R}{L}\right) K_p$	$\left(\frac{r_p}{L_p}\right) K_p$	$C \cdot \xi \omega$

It is important to specify that the pole compensation is not the only method to calculate a PI regulator but it is simple to elaborate with a first order transfer-function and it is sufficient in our case to compare with other regulators.

3.4 Sliding mode controller

Sliding mode control is one of the effective nonlinear robust control approaches since it provides system dynamics with an invariance property to uncertainties once the system dynamics are controlled in the sliding mode [14-16]. The main feature of Sliding mode controller (SMC) is that it only needs to drive the error to a switching surface it consists of three parts fig.6.

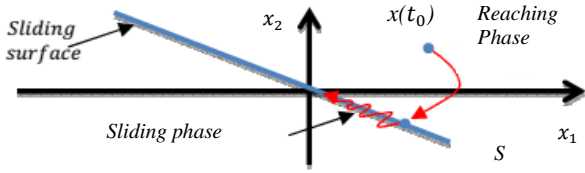


Fig.6. Phase portrait of sliding mode control

A. The switching surface choice

The design of the control system will be demonstrated for a nonlinear system presented in the canonical form [17]:

$$\begin{cases} \dot{x} = f(x, t) + B(x, t)V(x, t) \\ x \in R^n, V \in R^m, \text{ran}(B(x, t)) = m \end{cases} \quad (7)$$

Where: $f(x, t)$; $B(x, t)$ are two continuous and uncertain non-linear functions, supposed limited.

We take the general equation to determine the sliding surface, proposed by J.J. Slotine [18-19], given by:

$$S(X) = \left(\frac{d}{dt} + \lambda \right)^{n-1} e; e = x^* - x \quad (8)$$

Where: e : error on the signal to be adjusted; λ a: positive coefficient; n : system order; x^* : desired signal; x : state variable of the control signal.

B. Convergence condition

The convergence condition is defined by the Lyapunov equation [12]; it makes the surface attractive and invariant :

$$S \cdot \dot{S} < 0 \quad (9)$$

C. Control Calculation

The control algorithm is defined by the relation [15]:

$$V^{com} = V^{eq} + V^n \quad (10)$$

Here V^{com} is the control vector, V^{eq} is the equivalent control vector, V^n is the correction factor and must be calculated so that the stability conditions for the selected control are satisfied.

$$V^n = K \text{sat}(S(X)/\delta) \quad (11)$$

$$\text{sat}(S(X)/\delta) = \begin{cases} \text{sign}(S) & \text{if } |S| > \delta \\ S/\delta & \text{if } |S| < \delta \end{cases} \quad (12)$$

Here, $\text{sat}(S(X)/\delta)$ is the proposed saturation function, δ is the boundary layer thickness.

In our study, the errors between the references and measured I_d and I_q currents have been chosen as sliding mode surfaces, so we can write the following

expression:

$$\begin{cases} S_d = I_{sd.ref} - I_{sd} \\ S_q = I_{sq.ref} - I_{sq} \end{cases} \quad (13)$$

The first order derivate of (8), gives :

$$\begin{cases} \dot{S}_d = \dot{I}_{sd.ref} - \dot{I}_{sd} \\ \dot{S}_q = \dot{I}_{sq.ref} - \dot{I}_{sq} \end{cases} \quad (14)$$

Taking its derivative and replacing it in the current \dot{I}_{sd} and \dot{I}_{sq} expression (2) we get:

$$\begin{aligned} \dot{S}_d &= \dot{I}_{sd.ref} - \omega I_{sq} + \frac{r}{L} I_{sd} - \frac{1}{L} (v_{sd} - v_{cd} - v_{rd}) \\ \dot{S}_q &= \dot{I}_{sq.ref} + \omega I_{sd} + \frac{r}{L} I_{sq} - \frac{1}{L} (v_{sq} - v_{cq} - v_{rq}) \end{aligned} \quad (15)$$

Replacing the expression of v_{cd} and v_{cq} in (10) by their expressions given in (15), one obtains

$$\begin{cases} \dot{S}_d = \dot{I}_{sd.ref} - \omega I_{sq} + \frac{r}{L} I_{sd} - \frac{1}{L} (v_{sd} - (v_{cd}^n + v_{cd}^{eq}) - v_{rd}) \\ \dot{S}_q = \dot{I}_{sq.ref} + \omega I_{sd} + \frac{r}{L} I_{sq} - \frac{1}{L} (v_{sq} - (v_{cq}^n + v_{cq}^{eq}) - v_{rq}) \end{cases} \quad (16)$$

I_{qr} will be the component of the control vector used to constraint the system to converge to $S=0$. The control vector v^{eq} is obtain by imposing $\dot{S} = 0$ so the equivalent control components are given by the following relation :

$$\begin{cases} v_{cd}^{eq} = -L \dot{I}_{sd.ref} + L \omega I_{sq} - r I_{sd} + v_{sd} - v_{rd} \\ v_{cq}^{eq} = -L \dot{I}_{sq.ref} - L \omega I_{sd} - r I_{sq} + v_{sq} - v_{rq} \end{cases} \quad (17)$$

Using the same procedures as for part shunt we get the following expression:

$$\begin{cases} v_{cd}^{eq} = -L_p \dot{I}_{pd.ref} + L_p \omega I_{pq} - r_p I_{pd} + v_{pd} - v_{rd} \\ v_{cq}^{eq} = -L_p \dot{I}_{pq.ref} - L_p \omega I_{pd} - r_p I_{pq} + v_{pq} - v_{rq} \end{cases} \quad (18)$$

To obtain good performances, dynamic an commutation around the surface, the control vector is imposed as follows [17]:

$$v = v^{eq} + K \cdot \text{sign}(S) \quad (19)$$

The sliding mode will exist only if the following condition is met:

$$S \cdot \dot{S} < 0 \quad (20)$$

4. Simulation results and discussion

In this section, simulations are realized with a UPFC coupled to a 220V/50Hz grid. The system parameters are given next in appendix. The whole system is simulated using the Matlab/Simulink software.

In the objective to evaluate the performances of the controllers, three categories of tests have been

realized: pursuit test, sensitivity to introducing perturbation and robustness facing variation of the reactance XL.

4.1 Pursuit test

This test has for goal the study of the two controllers (PI and SMC) behavior in reference tracking. The simulation results are presented in fig.7. As it's shown by this figure, for the two controllers, the active and reactive power track almost perfectly their references but with an important response time for the PI controller compared to the SMC. Therefore it can be considered that this last have a very good performance for this test.

4.2 Robustness

We tested the robustness of the used controllers for a variation of the reactance XL. The results

presented in fig.8 show that reactance variation presents a clear effect on the active and reactive powers of the two used controllers and that the effect appears more significant for PI controller than that with the SMC. Thus it can be concluded that this last is robust against this parameter variation.

4.3 Sensitivity to a sub-voltage perturbation

The aim of this test is to analyze the influence of a sub-voltage perturbation (+ 50 %) in the time interval $t = 0.6s$ and $t = 0.62s$ on active and reactive powers for the two controllers. The simulation results are shown in fig.9. This figure expresses that the introducing perturbation produced a slight effect on the power curves of the two controllers. This result is attractive for UPFC applications to ensure stability and quality of the active and reactive powers when the voltage is varying.

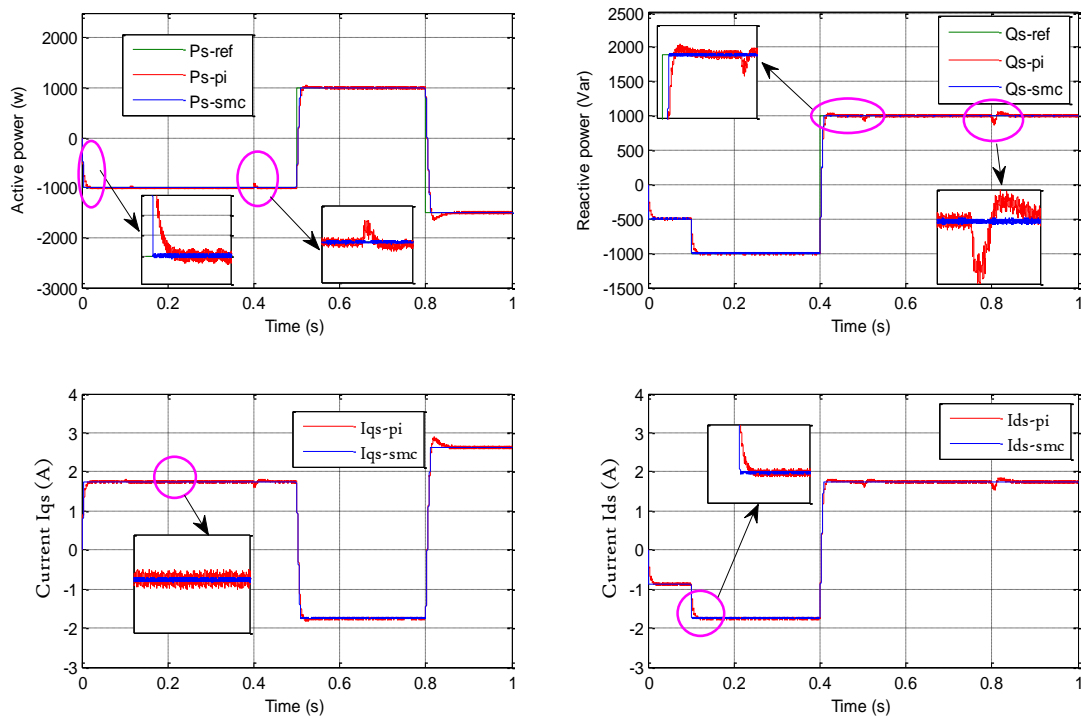


Fig.7. Reference tracking test.

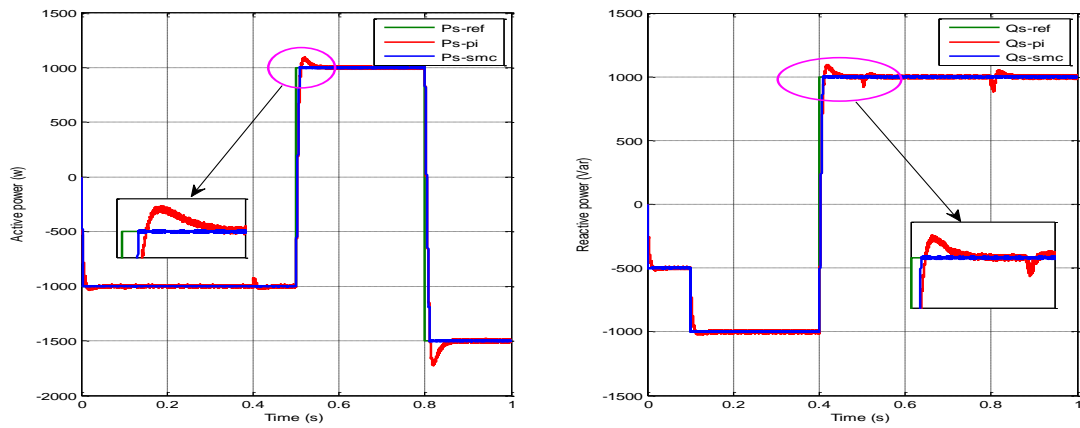


Fig.8. Sensitivity to the reactance variation (XL -30%).

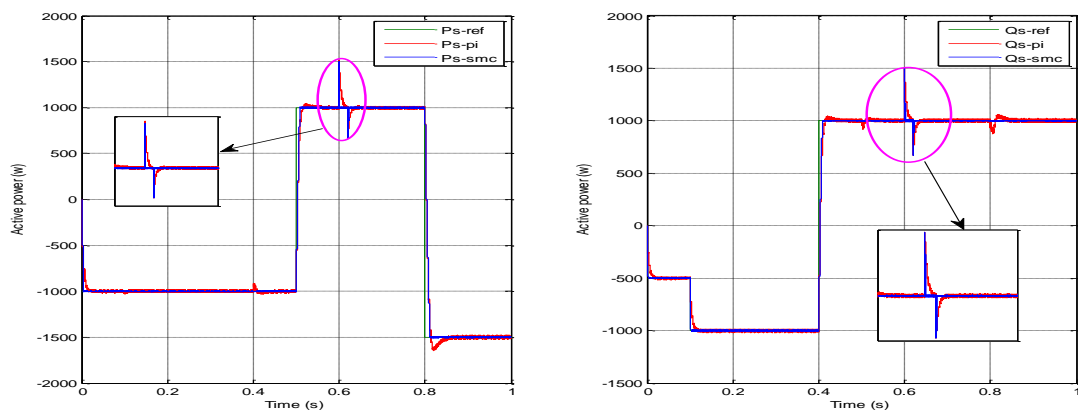


Fig.9. Sensitivity to sub-voltage perturbation (+ 50 %).

5. Conclusion

A robust control method based on variable structure technique of a UPFC has been presented in this paper. Simulation results verified the effectiveness of the control strategy that allows independent control and decoupled active and reactive power of these devices by minimizing the interaction effect between these powers. The SMC controller ensures a perfect decoupling between the two axes comparatively to the PI one where the coupling effect between them is very clear. Results comparison between conventional PI Controller and the proposed SMC based controller for UPFC indicates that the proposed SMC based controller has less settling time and less overshoot and compared with the conventional PI Controller.

Basing on all these results the UPFC device, can adjust the distribution the system power flow among the transmission line quickly and smoothly, and have no significant impact to other operating parameters of the system.

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