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Planning of UPFC for the Power System Transient Analysis

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***Abstract*— Improvement in semiconductor technologies gave a new concept of Flexible AC Transmission system (FACTS) which brought radical changes in the power system operation, control and also for controlling power and enhancing the usable capacity of existing transmission lines by controlling both active and reactive powers. The Unified Power Flow Controller (UPFC) is devised for the real time control and dynamic compensation of ac transmission systems providing multifunctional flexibility required to solve many of problems facing the power delivery industry.**

The aim of this paper is to model UPFC and its control circuit using SIMULINK and to analyze the control circuit for effective power flow control using three different control schemes – phase angle control, cross coupling control and generalized control. After modelling UPFC, a single machine connected to a transmission line along with UPFC has been considered to study its performance. In brief, it is the study of Unified Power Flow Controller and its role in damping power oscillations and power swings to improve system performance.

I. INTRODUCTION

In recent year, right of way and cost concerns have delayed the construction of both power stations and new transmission lines, while the demand for electrical energy is continuously growing. This situation has spurred interest in providing already existing power systems with greater operating flexibility and better utilization. For this reason, as well known in recent years a new class of controllers, FACTS controllers have rapidly met with favor. The two main objectives of FACTS technology are to control power flow and increase the transmission capacity over an existing transmission corridor. The devices of this generation are based on the use of high power electronic components such as GTO and IGBT which make them respond quickly to the control inputs. So, these facts devices are able to act almost instantaneously to changes in power system.

Benefits of Facts:

The Flexible AC Transmission System (FACTS) involves the application of high power electronic controllers in AC transmission networks which enable fast and reliable control of power flows and voltages.

- Regulation of power flows in prescribed transmission routes.
- Reduces the need for construction of new transmission lines, capacitors and reactors.
- Provides greater ability to transfer power between controlled areas, so that the generation reserve margin, typically 18 percent, may be reduced to 15 percent or less. These devices help to damp the power oscillations that could damage the equipment.
- Improves the transient stability of the system.
- Controls real and reactive power flow in the line independently.

The table.1 shows the FACTS devices that are now under operation and they can be broadly classified into two classes -shunt connected controllers providing voltage control and series connected controllers providing power flow control given below:

Table.I
FACTS devices.

Name	Type	Main function	Controller
SVC (Static Var compensator)	Shunt	Voltage control	Thyristor
TCSC (Thyristor controlled Series compensation)	Series	Power flow control	Thyristor
TCPAR (Thyristor Controlled Phase angle regulator)	Series and shunt	Power flow control	Thyristor
STATCOM (Static condenser)	Shunt	Voltage control	GTO
SSSC(Static Synchronous Series compensator)	Series	Power flow control	GTO
UPFC(Unified power flow Controller)	Shunt and Series	Voltage control and Power flow control	GTO

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II. Unified Power Flow Controller (UPFC):

Introduction:

The UPFC is a device which can control simultaneously all three parameters of line power flow like line impedance, voltage and phase angle. Such device combines together the features of two FACTS devices: the Static Synchronous Compensator (STATCOM) and the Static Synchronous Series Compensator (SSSC). In practice, these two devices are two Voltage Source Inverters (VSI's) connected respectively in shunt with the transmission line through a shunt transformer and in series with the transmission line through a series transformer, connected to each other by a common dc link including a storage capacitor. The shunt inverter is used for voltage regulation at the point of connection injecting an opportune reactive power flow into the line and to balance the real power flow exchanged between the series inverter and the transmission line. The series inverter can be used to control the real and reactive line power flow inserting an opportune voltage with controllable magnitude and phase in series with the transmission line. Thereby, the UPFC can fulfill functions of reactive shunt compensation, active and reactive series compensation and phase shifting. Besides, the UPFC allows a secondary but important function such as stability control to suppress power system oscillations improving the transient stability of power system

Circuit Description of UPFC:

Figure1 shows a basic configuration of a UPFC, which is installed between the sending-end V_S and the receiving-end V_R. The UPFC consists of a combination of a series device and a shunt device, the dc terminals of which are connected to a common dc link capacitor.

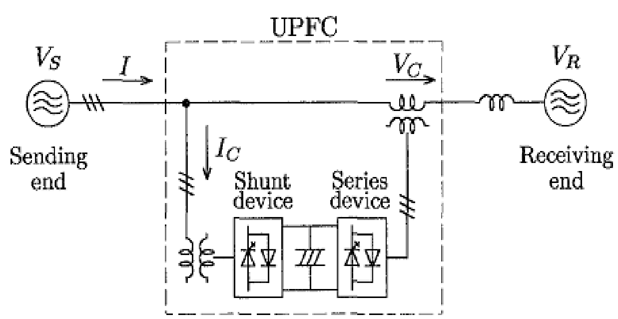

Figure 1 Basic configuration of UPFC

The series inverter is controlled to inject a symmetrical three phase voltage system, V_C of controllable magnitude and phase angle in series with the line to control active and reactive power flows on the transmission line.

So, this inverter will exchange active and reactive power with the line. The reactive power is electronically provided by the series inverter, and the active power is transmitted to the dc terminals. The shunt inverter is operated in such a way as to demand this dc terminal power (positive or negative) from the line keeping the voltage across the storage capacitor V constant. So, the net real power absorbed dc from the line by the UPFC is equal only to the losses of the two inverters and their transformers. The remaining capacity of the shunt inverter can be used to exchange reactive power with the line so to provide a voltage regulation at the connection point. The two VSIs can work independently of each other by separating the dc side. So in that case, the shunt inverter is operating as a STATCOM that generates or absorbs reactive power to regulate the voltage magnitude at the connection point. Instead, the series inverter is operating as SSSC that generates or absorbs reactive power to regulate the current flow, and hence the power flows on the transmission line.

Operating Principle of UPFC:

Figure 2 shows a single phase equivalent circuit of the UPFC, where the reactor L and the resistor R represent inductance and resistance in the transmission line, respectively. It is reasonable to remove the line resistance R from Figure 2 because $W_O L >> R$ in the overhead transmission line. Thus, the line current phasor vector, I is given by

$$\dot{I} = \frac{\dot{V}_S - \dot{V}_R + \dot{V}_C}{j\omega_0 L}$$

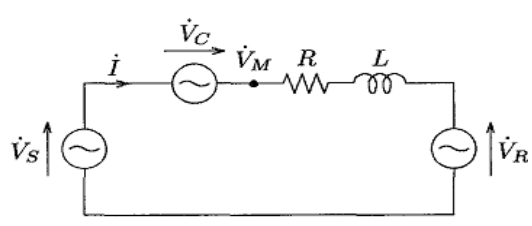

Figure 2 Single phase equivalent circuit

Conventional Control Schemes:

Phase-Angle Control: Adjusting the amplitude of the 90^0 leading or lagging output voltage makes it possible to control active power. On the d-q frame coordinates based on space vectors, the d-axis current id corresponds to active power, and so it can be controlled by the q-axis voltage V_{cq}. Therefore, the reference voltage vector $V^*_C = [V^*_{Cd}, V^*_{Cq}]$ for the series device is given by

$$\begin{bmatrix} v_{Cd}^* \\ v_{Cq}^* \end{bmatrix} = \begin{bmatrix} 0 & 0 \\ K_p & 0 \end{bmatrix} \begin{bmatrix} i_d^* - i_d \\ i_q^* - i_q \end{bmatrix} \quad \text{--- (1)}$$

Where Kp [V/A] is an active power feedback gain, and i^*_d and i^*_q are active and reactive reference currents, respectively. Then the phase angle between V_M and V_S, δ can be controlled by V_{cq} as follows: $\delta = \tan^{-1}(V_{Cq}/V_S)$

Thus, this control scheme is identical with the so-called "phase-angle control" which is one of the most basic control schemes for the UPFC.

Cross-Coupling Control: The "Cross-Coupling Control" has not only an active power feedback loop but also a reactive power feedback loop. This control scheme is characterized by controlling both the magnitude of V_M and the phase angle δ. As a result, the cross-coupling control enables us to achieve both active and reactive power control. On the d-q frame coordinates, the q-axis current i, corresponds to reactive power and so it can be controlled by V_{cd}. Therefore the reference voltage vector of the series device is given by

$$\begin{bmatrix} v_{Cd}^* \\ v_{Cq}^* \end{bmatrix} = \begin{bmatrix} 0 & -K_q \\ K_p & 0 \end{bmatrix} \begin{bmatrix} i_d^* - i_d \\ i_q^* - i_q \end{bmatrix} \quad \text{--- (2)}$$

Where K_p [V/A] is a reactive power feedback gain.

The phase-angle and cross-coupling control schemes appear to be based on space vectors. However, both control schemes may not render good dynamic performance, because their control concept comes not from space vectors but from phasor vectors. The series device injects a q-axis voltage to control the d-axis current or the active power in both control schemes. The q-axis voltage, however, induces the q-axis current to flow in transient state. Therefore, the active power flow control is accompanied by the reactive power flow control even though either control scheme provides instantaneous voltage references.

III. Generalized Control Scheme And Transient Analysis

Generalized Control Scheme:

This section proposes a "generalized control scheme." The reference voltage vector for the series device V^*_C is generalized, as follows:

$$\begin{bmatrix} v_{Cd}^* \\ v_{Cq}^* \end{bmatrix} = \begin{bmatrix} K_r & -K_q \\ K_p & K_r \end{bmatrix} \begin{bmatrix} i_d^* - i_d \\ i_q^* - i_q \end{bmatrix} \quad \text{--- (3)}$$

The scheme has two additional terms with a gain K_r. A voltage vector produced by the two terms is in phase with the current error vector i*-i. This means that the UPFC acts as a damping resistor against power swings.

Transient Analysis:

The following assumptions are made in transient analysis:

1. The sending-end voltage V_S is equal to the receiving-end voltage V_R, and they are three-phase balanced sinusoidal voltage sources.
2. The series device is assumed to be an ideal controllable voltage source. Therefore, the output voltage V_C is equal to its reference V_C*.

Invoking the first assumption yields Vs as follows:

$$\begin{bmatrix} v_{Su} \\ v_{Sv} \\ v_{Sw} \end{bmatrix} = \sqrt{\frac{2}{3}} V_S \begin{bmatrix} \cos\omega_0 t \\ \cos(\omega_0 t - 2\pi/3) \\ \cos(\omega_0 t + 2\pi/3) \end{bmatrix} \quad \text{--- (4)}$$

Where V_S is an rms voltage at the sending-end, and ω_0 is a supply angular frequency.

The equivalent circuit shown in Figure 2 provides the following equation:

$$\left(R + L\frac{d}{dt}\right) \begin{bmatrix} i_u \\ i_v \\ i_w \end{bmatrix} = \begin{bmatrix} v_{Cu} \\ v_{Cv} \\ v_{Cw} \end{bmatrix} \quad \text{--- (5)}$$

Applying the d-q transformation to (4) and (5) leads to

$$\begin{bmatrix} v_{Sd} \\ v_{Sq} \end{bmatrix} = \begin{bmatrix} V_S \\ 0 \end{bmatrix} \quad \text{--- (6)}$$

$$\begin{bmatrix} R + L\frac{d}{dt} & -\omega_0 L \\ \omega_0 L & R + L\frac{d}{dt} \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} v_{Cd} \\ v_{Cq} \end{bmatrix} \quad \text{--- (7)}$$

The instantaneous active and reactive powers, p and q are given by

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} v_{Sd} \cdot i_d + v_{Sq} \cdot i_q \\ v_{Sd} \cdot i_q - v_{Sq} \cdot i_d \end{bmatrix} = V_S \begin{bmatrix} i_d \\ i_q \end{bmatrix} \quad \text{--- (8)}$$

Substituting (3) for (7), along with invoking the second assumption, gives the following equation

$$\begin{bmatrix} R + K_r + L\frac{d}{dt} & -(\omega_0 L + K_q) \\ \omega_0 L + K_p & R + K_r + L\frac{d}{dt} \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} K_r i_d^* - K_q i_q^* \\ K_p i_d^* + K_r i_q^* \end{bmatrix}. \quad \text{--- (9)}$$

The Laplace functions for the active and reactive powers produce $I_d(s)$ and $I_q(s)$ as follows:

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$$I_d(s) = \frac{(K_r Ls + A_1)I_d^* - (K_q Ls + A_2)I_q^*}{L^2\left(s^2 + \frac{2(K_r+R)}{L}s + \omega_n^2\right)} \quad \text{--- (10)}$$

$$I_q(s) = \frac{(K_p Ls + A_3)I_d^* + (K_r Ls + A_4)I_q^*}{L^2\left(s^2 + \frac{2(K_r+R)}{L}s + \omega_n^2\right)} \quad \text{--- (11)}$$

Where $A_1 = K_p(\omega_0 L + K_q) + K_r(R + K_r),$

$$A_2 = K_q R - K_r \omega_0 L,$$
$$A_3 = K_p R - K_r \omega_0 L,$$

$$A_4 = K_q(\omega_0 L + K_p) + K_r(R + K_r),$$
$$\omega_n = \frac{\sqrt{(\omega_0 L + K_p)(\omega_0 L + K_q) + (K_r + R)^2}}{L}.$$

Here, ω_n is an un damped natural frequency. Equations (10) and (11) conclude that the UPFC exhibits a second-order system, thus causing power swings in transient states. Damping factor ς and power swings frequency ω are given as follows:

$$\zeta = \frac{K_r + R}{\sqrt{(\omega_0 L + K_p)(\omega_0 L + K_q) + (K_r + R)^2}} \quad \text{--- (12)}$$

$$\omega = \omega_n\sqrt{1 - \zeta^2}$$
$$= \frac{\sqrt{(\omega_0 L + K_p)(\omega_0 L + K_q)}}{L} \quad \text{--- (13)}$$

Equation (12) tells us that the larger the gain K_r, the closer ς is to unity. Equation (13) leads to the fact that the larger the power feedback gains K_p and K_q, the larger the power swing frequency ω. The time constant of damping of power swings, τ is given by

$$\tau = \frac{1}{\zeta\omega_n} = \frac{L}{K_r + R} \quad \text{--- (14)}$$

Where K_r acts as a damping resistor. Therefore, increasing K_r reduces the time constant and improves the transient stability. The phase-angle control and cross-coupling control schemes have no capability of damping power swings because $K_r = 0$.

D. Case Study and Results:

Introduction:

This presents the case study of a 10 KVA system using UPFC with the generalized control circuit as explained in the previous discussion along with its simulated diagram and the results.

Main Circuit:

Figure 3 show a main circuit of a system rated at 10 KVA and its circuit parameters. The main circuit of the series device consists of three single-phase H-bridge voltage-fed PWM inverters rated at 1.5 KVA. A PWM control circuit compares reference voltage V_C^* with a triangle carrier signal of f_{SW} = 1 kHz in order to generate twelve gate signals. An equivalent switching frequency is 2 kHz, which is twice as high as f_{SW} because three H-bridge PWM inverters are used. A three-phase diode rectifier is employed as the shunt device. A reactor L and a resistor R, representing the impedance of the transmission line, are inserted between V_S and V_r. In this system, V_S and V_r are connected to a common power supply V. Thus, no power flow occurs as long as the series device is not operated. The series device always delivers a small amount of active power to the transmission line, which equals the power loss dissipated in the resistor R. A three-phase PWM converter should be employed in this system because the magnitude and V_S may differ from those of V_r. While the series phase of device draws active power from the transmission line, the shunt device should regenerate the active power via the dc link capacitor to the transmission line.

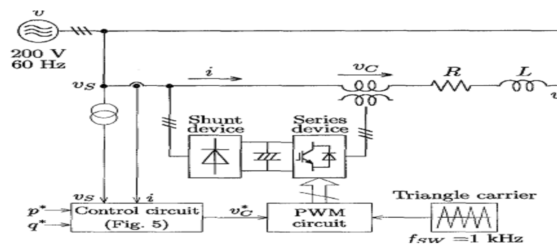

Figure 3: Main circuit of the system.

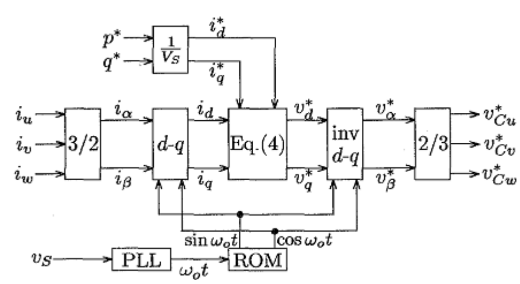

Figure 4: Control circuit

Control Circuit:

Fig.4 shows a block diagram of the control circuit. The three to two phase transformations obtains i_α and i_β from i_u, i_v and i_w.

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The d-q transformation gets i_d and i_q from i_α and i_β with the help of sin $\omega_0 t$ and cos $\omega_0 t$ taken from a read only memory (ROM).The phase information $\omega_0 t$ is generated by a phase-lock-loop (PLL) circuit. Then V_d^* and V_q^* are given by (3). The power feedback gains are set to $K_p = K_q = 0.5$ V/A in the following steps. From (12), the feedback gain K_r is obtained as

$$K_r = \frac{\zeta\sqrt{(\omega_0 L + K_p)(\omega_0 L + K_q)}}{\sqrt{1-\zeta^2}} - R \quad \text{--- (15)}$$

In order to get a damping factor of $\varsigma = 0.8$, K_r should be designed as

$$K_r = \frac{0.8\sqrt{(2\pi \times 60 \times 0.001 + 0.5)^2}}{\sqrt{1-0.8^2}} - 0.04$$
$$= 1.13 \text{ V/A}.$$

In the experimental system, therefore, gain K_r is set to 1.2 V/A.

Simulation of UPFC:

The simulated model of the main circuit of Figure 3 is shown in Figure 5 which is obtained by the interconnection of various power system equipments having the following preset block parameters are given below:

Three-phase source:

Phase to phase RMS voltage: 200 V; Frequency: 60 Hz;

Internal connection: Y_g; Source resistance: 0.8289 ohms; Source inductance: $16.53e^{-3}$H;

Transmission Line:

Resistance: 0.04ohms; Inductance: $1e^{-3}$H; Capacitance: inf;

Three-Phase Transformer:

Nominal power and frequency [P_n (VA), f_n(Hz)]: [$10e^3$,60]

$Winding_1$ (ABC) connection: Y

Winding parameters [V_1 Ph-Ph(V_{rms}), R_1(pu) , L_1(pu)]: [200,0.002,0.08]

$Winding_2$(ABC)connection:Y

Winding parameters[V_2 Ph-Ph(V_{rms}), R_2(pu) , L_2(pu)]: [20,0.002,0.08]

Shunt device:

No. of bridge arms: 3; Snubber capacitance: inf; Power electronic device: diodes;

R_{on}(ohms): $1e^{-3}$; L_{on}(H): 0; Forward voltage, V_f(v): 0

Series device:

No of bridge arms: 3; Snubber resistance (R_s (ohms):$1e^5$; T_f(s) T_t(s): [$1e^{-6}$ $2e^{-6}$];

Snubber capacitance (C_s (farads)): inf; Power electronic device: IGBT/diodes;

R_{on}(ohms):$1e^{-3}$; Forward voltage [Device V_f(V), diode V_{fd}(V)]: [0 0];

PWM Generator:

Generator model: Double 3-arm bridges (12 pulses); Carrier Frequency: 1000Hz;

3-Phase PLL:

Initial input [Phase (deg), frequency (Hz)]: [0, 60]

Regulator Gain [Kp , Ki]: [60, 1400]

The simulated model of the control circuit of Figure4 is shown in Figure 6. It consists of an embedded MATLAB function which varies from one control scheme to the other.

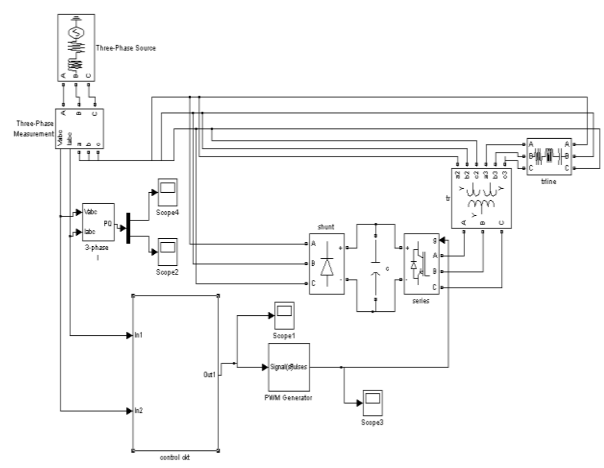

Figure 5 Simulated model of main circuit

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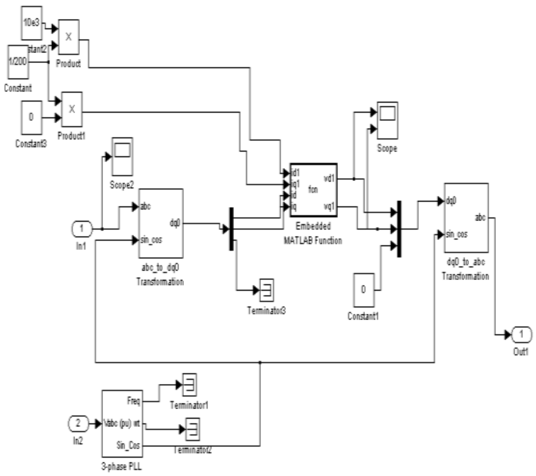


Figure 6 Simulated model of control circuit

Table II
Simulated system parameters

Controllable power rating	P	10 KW
Series device capacity (=15%)	Pinv	1.5 KVA
Peak voltage of Vc	Vcp	±17V (=15%)
Utility line to line voltage	V	200V
Utility angular frequency	ω	2π x 60 rad/sec
Line inductance	L	1.0mH (10%)
Line resistance	R	0.04Ω (1%)

Simulated Waveforms:

Figures 7 – 9 show simulated waveforms for a step change in the active power reference p*.

Phase –angle control waveforms: The embedded MATLAB function used in the control circuit of this control scheme is shown below: Function $[v_{d1}, vq1] = f_{cn}(i_{d1}, iq1, id, iq)$

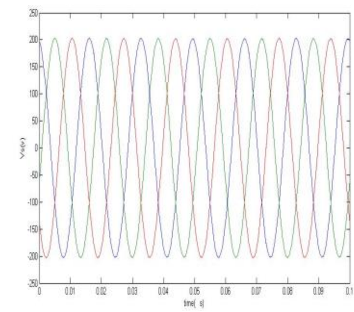
$v_{d1} = 0.0^*(i_{d1}-i_d) + 0.0^*(i_{q1}-i_q);$

$v_{q1} = 0.5^*(i_{d1}-i_d) + 0.0^*(i_{q1}-i_q);$

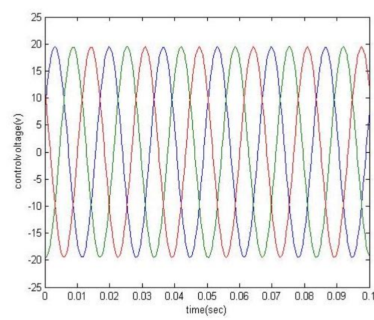
End

Figure 7 shows waveforms in the case of the phase angle control scheme. Equation (14) determines the theoretical time constant

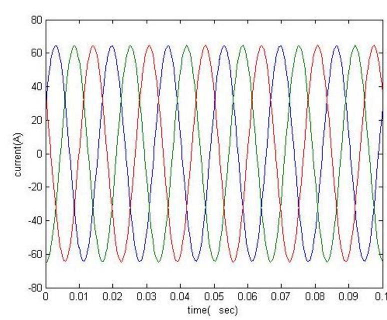
$$T = (L / (K_r+R)); \quad T=1 / (0+0.04) = 25ms$$



(a). Source Voltage



(b).Control Voltage



(c).Current

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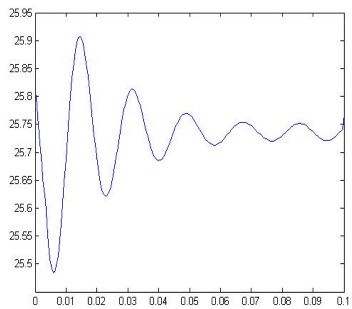
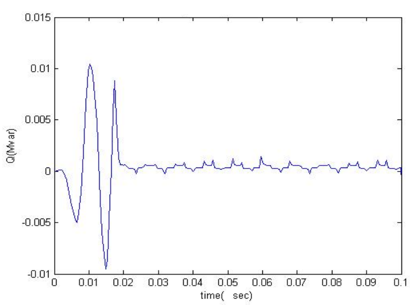


(d) Active power



(e). Reactive Power

Figure 7: Simulated waveforms when the phase-angle control scheme is applied (K_p = 0.5 V/A, p^* = 16.5 kW)

Cross-coupling Control waveforms: The embedded MATLAB function used in the control circuit of this control scheme is shown below: Function [v_{d1}, vq1] = f_{cn} (i_{d1}, iq1, id, iq)

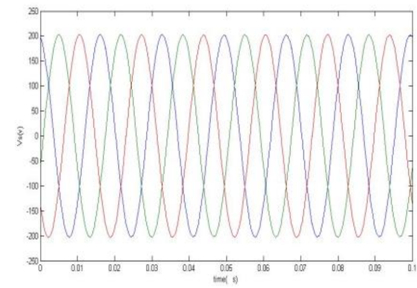
v_{d1}= $0^*(i_{d1}-i_d)$ - $0.5^*(i_{q1}-i_q)$;

v_{q1}= $0.5^*(i_{d1}-i_d)$ + $0^*(i_{q1}-i_q)$;

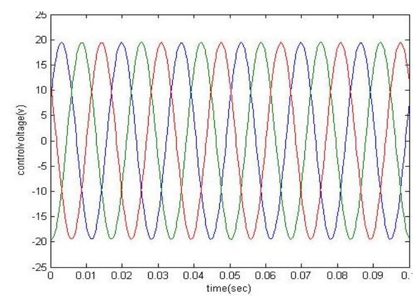
End

Figure 8 shows waveforms in the case of the cross-coupling control scheme.

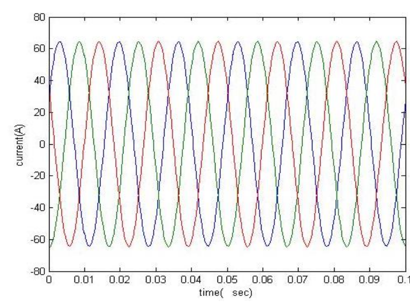
It is clear from (13) that addition of the reactive power feedback gain K increases the power swing frequency ω. Since (14) shows that the time constant τ, is independent of K_p and K_q, it takes the same time as that in Figure 7 for p and q to reach their steady-state values.



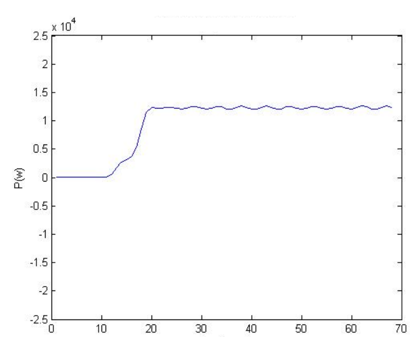
(a).Source Voltage



(b).Control Voltage



(c).Current



(d). Active Power

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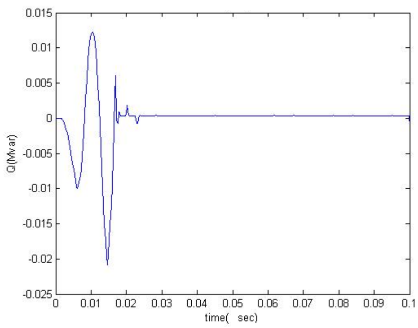


(e). Reactive Power

Figure 8: Simulated waveforms when the cross-coupling control scheme is applied. ($K_q = K_p = 0.5$ V/A, $p^* = 16.5$ KW, $q^* = 0$)

Generalized Control Scheme: The embedded MATLAB function used in the control circuit of this control scheme is shown below: Function $[v_{d1},v_{q1}] = f_{cn}(i_{d1},i_{q1},i_d,i_q)$

$v_{d1}=1.2^*(i_{d1}-i_d)-0.5^*(i_{q1}-i_q)$;

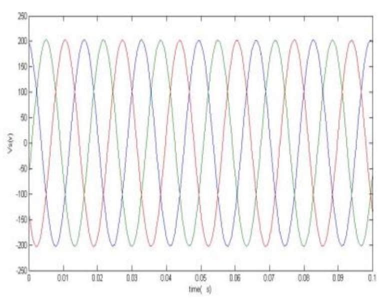
$v_{q1}=0.5^*(i_{d1}-i_d)+1.2^*(i_{q1}-i_q)$;

End

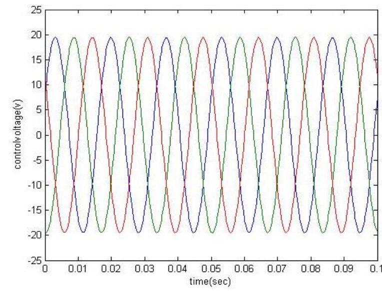
No power swing occurs in p and q. From (14), the theoretical time constant is

$T= (L / (K_r+R))$; $T=1 / (1.2+0.04) =0.81$ms

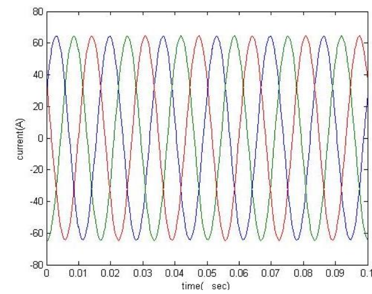
Which is superior to that of the conventional control schemes? The proposed control scheme has the capability of damping power swings and improving transient characteristics. However, significant steady-state errors exist in p and q because K_p and K_q include no integral gain.



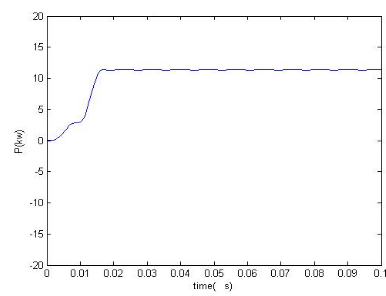
(a).Source Voltage



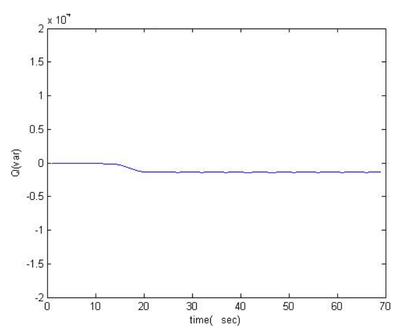
(b).Control Voltage



(c).Current



(d). Active Power



(e). Reactive Power

Figure 9: Simulated waveforms when the proposed control scheme is applied. ($K_p = K_q = 0.5$ V/A, K = 1.2 V/A, $p^* = 14.5$ KW, $q^* = 0$)

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IV. CONCLUSIONS

Conventional power feedback control schemes make the UPFC induce power swings in transient states. The time constant of damping is independent of the active and reactive power feedback gains K_p and K_q. Therefore, the conventional control schemes based on only the power feedback loops are not capable of damping of power swings. The feedback gain Kr with a physical meaning of resistor is effective in damping of power swings. The proposed control scheme achieves quick response of active and reactive power without causing power swings and producing steady state errors.

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