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Fundamental Frequency Model of Unified Power Flow Controller

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Abstract**—**The theory and modeling technique used to represent a Unified Power Flow Controller (UPFC) are presented in this paper. A fundamental frequency UPFC model is proposed for quasi-steady-state types of studies, such as voltage collapse and transient stability analyses. The proposed model gives an accurate representation of the fundamental frequency operation of the controller. The Electromagnetic Transient Program (EMTP) is used to validate the proposed model in a test system with a three-phase fault applied near the UPFC.

Keywords: UPFC, modeling, fundamental frequency, stability, EMTP.

I. Introduction

Today's power systems are highly complex and require careful design of new devices taking into consideration the already existing equipment, especially for transmission systems in new deregulated electricity markets. This is not an easy task considering that power engineers are severely limited by economic and environmental issues. Thus, this requires a review of traditional methods and the creation of new concepts that emphasize a more efficient use of already existing power system resources without reduction in system stability and security. In the late 1980s, the Electric Power Research Institute (EPRI) introduced a new approach to solve the problem of designing and operating power systems; the proposed concept is known as Flexible AC Transmission Systems (FACTS) [1]. The two main objectives of FACTS are to increase the transmission capacity of ac lines and control power flow over designated transmission routes.

The improvements in the field of power electronics have had major impact on the development of the concept itself. A new generation of FACTS controllers has emerged with improvements to Gate Turn-Off (GTO) thyristors ratings (4500 V to 6000 V, 4000 A to 6000A). These controllers are based on voltage-source inverters and include devices such as Static Synchronous Compensator (STATCOM), Static Synchronous Series Compensator (SSSC), and Unified Power Flow Controller (UPFC) [2]. The STATCOM is mainly used to regulate voltage in transmission systems, but can also be used to improve the dynamic stability of a system [3]. The SSSC, on the other hand, can be compared to some extent to a Thyristor Controlled Series Capacitor (TCSC), as it permits a change in the impedance of the transmission line through a voltage source in series with the line [4].

A UPFC is a device which can control transmission line impedance, voltage and phase angle. It is recognized as the most sophisticated power flow controller currently, and probably the most expensive one. This controller offers substantial advantages for the static and dynamic operation of power system, but it brings with it major challenges in power electronics and power system design, as demonstrated by the collaborative effort between the American Electric Power (AEP), the Westinghouse Electric Corporation, and EPRI to install the first UPFC in the USA [5, 6].

Emerging FACTS technologies should be supported by analytical tools to allow power engineers to determine the full potential of these controllers. Digital simulations have become increasingly reliable in assessing both steady-state and dynamic performance of power systems by means of general purpose simulation programs, providing cost effective and feasible ways to model the system. To represent the power system in a realistic manner, the simulation program has to be equipped with reliable models of all power system components. As the need for flexible and fast power flow controllers, such as the UPFC, is expected to grow in the future, there is a corresponding need for reliable and realistic models of these controllers.

UPFC models have been investigated by several authors [7]. In [8], the UPFC model consists of a controllable voltage source added in series with the transmission line, plus two current sources added in shunt to balance the power flow through the UPFC. The UPFC model given in [9] is made up of two ideal synchronous voltage sources; one is inserted in series with the line, while the other one is shunt-connected to the line. In [10], the steady-state model of the UPFC in a popular power system analysis software package is described. External macro programming capabilities of this software are used to model the UPFC using a coupled-source model, as series voltage sources are generally not available in commercial power system software.

The current paper proposes a fundamental frequency model of the UPFC based on the ideas presented in [11], where the authors propose a model for the STATCOM. Thus, the proposed model consists of two controlled voltage sources, one connected in series and another in shunt, to simulate the voltage-source inverters; controls are fully represented without any approximations.

In Section II the basic operating principles of the UPFC are described, and a basic model of this controller is discussed. Section III explains the development of the fundamental frequency model for the UPFC, whereas Section IV presents the results of using this model on a test system to simulate a three phase fault near the UPFC in the EMTP. Finally, Section V summarizes the main ideas presented in this paper and discusses future research directions.

II. UPFC EMTP Model

The basic structure and operation of the UPFC is well known and is briefly reviewed in this section. The interested reader is referred to [12] for a more detailed treatment of this subject.

A. *Basic Operation*

The basic components of the UPFC are two voltage-source inverters with semiconductor devices having turn-off capability (typically GTOs), sharing a common dc ca-

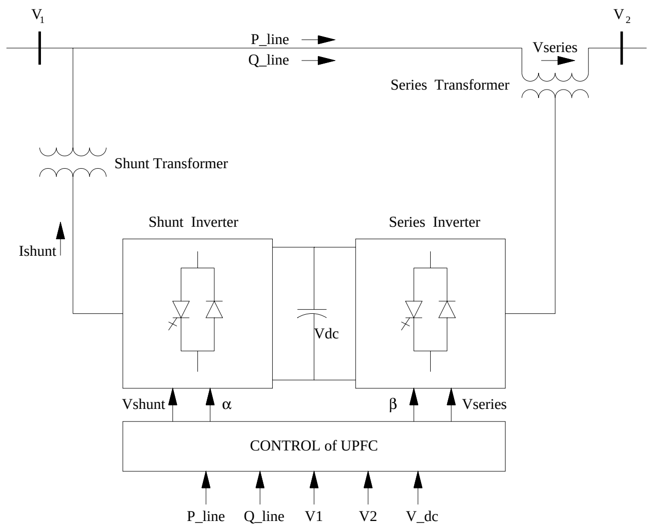

Fig. 1. UPFC functional model.

pacitor, and connected to the system through coupling transformers. One voltage-source inverter is connected in parallel to the transmission system via a shunt, step-down transformer, while the other is connected in series through a series transformer. A basic UPFC scheme is shown in Fig. 1.

The branches can work independently of each other by separating the dc side, i.e., by supplying each branch with its own dc capacitor. In that case, the shunt-connected branch becomes a STATCOM that generates/absorbs reactive power to regulate the voltage magnitude at the ac terminal. The series branch corresponds then to a SSSC that generates/absorbs reactive power to regulate the current flow, and hence the power, of the transmission line. If these two devices are merged together through a common dc capacitor, real power can be exchanged at the ac terminals; the UPFC behaves then as an ideal ac to ac power converter in which the real power can flow freely in either direction between the controller terminals. This basically results in a controllable phase shift between the terminal voltages v_1 and v_2, as the two voltage-source inverters can interchange power. It should be noted that the real power is typically negotiated by the action of the series-connected branch, whereas the shunt-connected branch is primarily used to feed real power from the ac system to the common dc link. The reactive power is generated or absorbed locally and independently from the real power by each branch and, therefore, it does not flow through the UPFC.

From this basic operational description, it can be concluded that the UPFC has the ability to:

1. control terminal voltage by locally generating or absorbing reactive power;
2. control power flows on the transmission line, both steady-state and dynamic, by regulating the real power flow through the controller (series capacitive/inductive compensation and also phase shifting regulation);
3. allow secure loading of transmission lines to their full thermal capability where desirable.

From the control point of view, it is important to distinguish between the two basic types of voltage-source inverters that can be used in the UPFC [13]. One type is based on a phase control scheme, involving multi-connected out-of-phase six-pulse inverters. The other type of inverters operate based on Pulse With Modulation (PWM) switching techniques, where active and reactive components of the variables can be independently controlled provided that the dc voltage is kept sufficiently high. In the only UPFC installation project so far [6], phase control is used in an eight six-pulse inverter scheme. PWM is considered uneconomical at present for transmission applications, due to the large switching losses of GTOs; however, in the near future, when developments in high power, low switching loss, semiconductor devices are exploited, this control technique would become more competitive. Many research groups, e.g. [14], use PWM controls in their UPFC studies due to simplicity and control advantages.

B. Basic Model

A three-phase, PWM controlled, voltage-source inverter is typically made of six controlled switches (GTO valves) and six antiparallel uncontrolled switches (diodes). The controlled switches are switched on and off at high frequencies to synthesize the set of three-phase fundamental frequency voltage waveforms on the inverter output terminals. There is typically a need for some passive filters on the output terminals of the inverter to reduce the harmonic content of the output voltage waveforms. Hence, these voltage-source inverters with harmonic filtering can be modeled sufficiently accurately in balanced conditions as voltage sources operating at fundamental frequency. Based on this idea, the UPFC is modeled here as a device made up of two fundamental frequency voltage sources; one of the sources is connected in parallel with the ac system via a step-down transformer to represent the parallel branch of the UPFC, while the other is connected in series with the transmission line via a series inserted transformer to model the series branch.

The UPFC fundamental frequency model proposed here is simulated in the EMTP to test it and illustrate its response to sudden changes in the power system, and thus validate the model by comparing these results to the expected behavior of the controller. EMTP controllable voltage sources (type 60), where the amplitude and phase angle of the source are calculated within TACS (Transient Analysis of Control Systems), are used. The one-line diagram of the UPFC fundamental frequency model as it is modeled within the EMTP is illustrated in Fig. 2. Observe that the UPFC transformers are included in the model and represented as lossless, saturation free transformers. The resistance R_{loss} and capacitance C, shown in Fig. 2, represent the UPFC losses and the dc capacitor, respectively; these are not physically included in the model itself but represented in a basic equation derived in Section III The voltages v_1 and v_2 represent the instantaneous voltages at the shunt and series terminals of the UPFC, respectively, and are used as references for the corresponding controlled voltage sources, i.e., the angles α and β are defined with respect to v_1 and $v_{dif} = v_1 - v_2$, respectively.

The UPFC control system is modeled in TACS using a decoupled watt-var control algorithm, based on d-q axis decomposition [13]. The main objective of the UPFC is to control the power flows in the transmission line by controlling the amplitude and phase angle of the series voltage source. The shunt-connected voltage source controls the voltage on the ac bus, and supplies the real power demanded by the series voltage source by changing its amplitude and phase angle. As explained in [15], the control

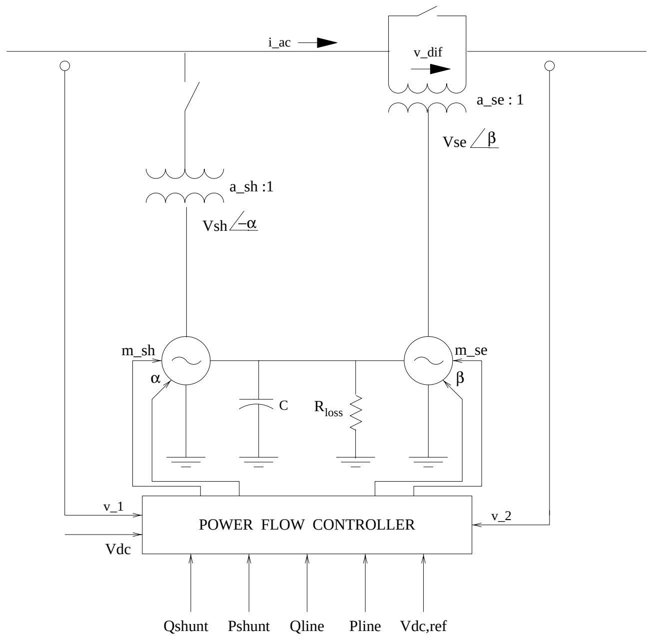

Fig. 2. The fundamental frequency model of the UPFC.

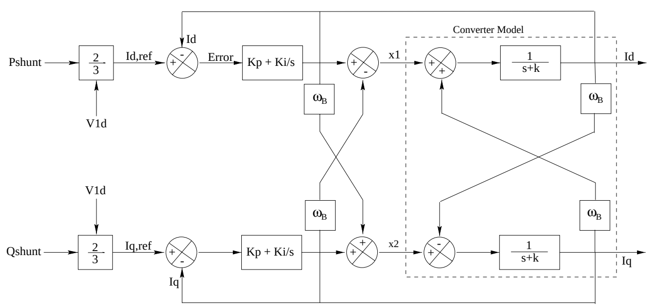

Fig. 3. Control block diagram of the UPFC's shunt branch.

scheme shown in Fig. 3 can be used to control either the parallel or the series branch of the UPFC, with slight modifications. The set-points of the shunt branch control block are the parallel branch powers P_{shunt} and Q_{shunt}, whereas the set-points of the series branch control block are the desired line powers P_{line} and Q_{line}. It should be noted that P_{shunt} is actually calculated, since the active power demand of the parallel branch is determined by the series branch controls and dc circuit. The values $I_{d,ref}$ and $I_{q,ref}$ are the reference values of the active and reactive current, respectively; K_p and K_i are the gains of the PI controllers.

The output variables x_1 and x_2 of the PI controllers are used to calculate the d- and q-axis components of the shunt converter output voltage v_{sh_d} and v_{sh_q}, the amplitude modulation index m_{sh} and the phase angles α using the following equations:

$$\begin{aligned} v_{sh_d} &= \frac{V_1}{a_{sh}} - \frac{X_{sh}}{Z_B}\frac{V_B}{\omega_B}x_1 \\ v_{sh_q} &= -\frac{X_{sh}}{Z_B}\frac{V_B}{\omega_B}x_2 \\ m_{sh} &= \frac{2\sqrt{2}\sqrt{v_{sh_d}^2 + v_{sh_q}^2}}{V_{dc}} \\ \alpha &= \tan^{-1}\left(\frac{v_{sh_q}}{v_{sh_d}}\right) \end{aligned}$$

Similar equations are used for the series converter. In these equations, V_1 represent the UPFC sending-end voltage magnitude and v_{sh} is the parallel inverter output voltage, assuming that the sending-end bus is where the parallel branch is connected and the receiving-end bus is where the series branch is connected; X_{sh} is the transformer leakage reactance; V_B and Z_B represent the base voltage and impedance, respectively; and ω_B is the synchronous angular speed. For the series branch, V_1 is replaced by V_{dif}, representing the voltage magnitude of the difference between the sending-end and receiving-end voltages of the UPFC ($v_{dif} = v_1 - v_2$), and v_{sh} is replaced by v_{se}, which is the output voltage of the series inverter.

The d-q transformations of the shunt voltage variables are computed using the following equations:

$$\begin{bmatrix} v_{1_{ds}} \\ v_{1_{qs}} \\ 0 \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \\ 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \end{bmatrix}\begin{bmatrix} v_{1_a} \\ v_{1_b} \\ v_{1_c} \end{bmatrix}$$

$$\theta = \tan^{-1}\left(\frac{v_{1_{qs}}}{v_{1_{ds}}}\right)$$

$$\begin{bmatrix} v_{1_d} \\ v_{1_q} \\ 0 \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \cos\theta & \cos(\theta - 2\pi/3) & \cos(\theta + 2\pi/3) \\ -\sin\theta & -\sin(\theta - 2\pi/3) & -\sin(\theta + 2\pi/3) \\ 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \end{bmatrix}\begin{bmatrix} v_{1_a} \\ v_{1_b} \\ v_{1_c} \end{bmatrix}$$

For a positive sequence, balanced system, $v_{1_d} = V_1$, and $v_{sh_q} = 0$. Similar equations are used for all d-q transformations of voltages and currents for both series and shunt branches.

In the equations above, α is the phase shift of the sinusoidal shunt branch voltage source v_{sh} with respect to the UPFC sending-end terminal voltage v_1, whereas β is the phase shift of the sinusoidal series branch voltage source with respect to the difference of the sending-end and receiving-end voltages $v_{dif} = v_1 - v_2$.

III. Fundamental Frequency Model

In order to develop a fundamental frequency, balanced model of the UPFC, a power balance technique, somewhat similar to the one proposed in [13, 16] and used in [11] to develop a STATCOM model, is used here.

The instantaneous power flowing into the shunt inverter from the ac bus, neglecting transformer losses and assuming fundamental frequency and balanced conditions, can be represented by

$$p_{sh} = 3\ \frac{a_{sh} V_{sh} V_1}{X_{sh}} \sin\alpha \tag{1}$$

where V_1 is the rms voltage of the sinusoidal receiving-end bus voltage v_1; X_{sh} is the shunt transformer equivalent reactance; a_{sh} is the transformer voltage ratio; and α is the phase shift between the bus phase voltage v_1 and the corresponding output voltage of the inverter v_{sh}, as discussed in the previous section, i.e.,

$$\begin{aligned} v_1 &= \sqrt{2}\, V_1 \sin(\omega t + \theta) \\ v_{sh} &= \sqrt{2}\, V_{sh} \sin(\omega t + \theta - \alpha) \end{aligned} \tag{2}$$

When $\alpha > 0^\circ$ ($p > 0$), the inverter output voltage lags the bus voltage (the capacitor charges), whereas for $\alpha < 0^\circ$ ($p < 0$), the inverter ac voltage leads the bus voltage (the capacitor discharges). V_{sh} is the rms value of the inverter output voltage v_{sh}; thus, a Fourier analysis of the actual inverter voltage, yields

$$V_{sh} = \frac{1}{2\sqrt{2}}\, m_{sh} V_{dc} \tag{3}$$

where V_{dc} is the average dc capacitor voltage, and m_{sh} is the amplitude modulation index of the shunt inverter.

For the series branch, neglecting transformer losses, the instantaneous power flowing into the series inverter under fundamental frequency, balanced conditions is represented by

$$p_{se} = 3\ a_{se} I_{ac} V_{se} \cos\gamma \tag{4}$$

where a_{se} is the turns-ratio of the series transformer; I_{ac} is the rms value of the controlled ac line current i_{ac}; V_{se} is the rms magnitude of the sinusoidal inverter output voltage v_{se}; and γ is the phase shift of the inverter voltage v_{se} with respect to the line current i_{ac}, i.e.,

$$\begin{aligned} i_{ac} &= \sqrt{2}\, I_{ac} \sin(\omega t + \phi) \\ v_{se} &= \sqrt{2}\, V_{se} \sin(\omega t + \phi + \gamma) \end{aligned}$$

The rms voltage magnitude V_{se} can be shown to be equal to

$$V_{se} = \frac{1}{2\sqrt{2}}\, m_{se} V_{dc} \tag{5}$$

where V_{dc} is the average voltage on the dc capacitor, and m_{se} is the amplitude modulation index for series branch of the UPFC.

Observe that v_{se} can also be represented by

$$\begin{aligned} v_{dif} &= v_1 - v_2 = \sqrt{2}\, v_{12} \sin(\omega t + \varphi) \\ v_{se} &= \sqrt{2}\, V_{se} \sin(\omega t + \varphi + \beta) \end{aligned} \tag{6}$$

Using these definitions, equation (1) can be rewritten as

$$p_{se} = 3\ \frac{a_{se} V_{se} V_{dif}}{X_{se}} \cos\beta \tag{7}$$

since $I_{ac} = V_{dif}/X_{se}$ and $\gamma = \beta + 90^\circ$, where X_{se} is the series transformer reactance.

If the losses of the parallel and series inverter are modeled using a resistance R_{loss} connected in shunt with the dc capacitor, the UPFC power balance assuming real power flow from the shunt inverter to the series inverter is given by

$$p_{sh} = \frac{V_{dc}^2}{R_{loss}} + V_{dc}\left(C\ \frac{\mathrm{d}V_{dc}}{\mathrm{d}t}\right) + p_{se}$$

Hence, from (1), (4), (3), and (5), it follows that the V_{dc} voltage changes are defined by the nonlinear differential equation

$$\begin{aligned} \frac{\mathrm{d}V_{dc}}{\mathrm{d}t} &= \frac{k\ a_{sh}\ m_{sh}\ V_{ac}}{C\ X_{sh}} \sin\alpha \\ &\quad - \frac{k\ a_{se}\ m_{se}\ I_{ac}}{C} \cos\gamma - \frac{V_{dc}}{R_{loss}\ C} \end{aligned} \tag{8}$$

where $k = 3/(2\sqrt{2})$; or alternatively, using (7),

$$\begin{aligned} \frac{\mathrm{d}V_{dc}}{\mathrm{d}t} &= \frac{k\ a_{sh}\ m_{sh}\ V_{ac}}{C\ X_{sh}} \sin\alpha \\ &\quad - \frac{k\ a_{se}\ m_{se}\ V_{dif}}{C\ X_{se}} \sin\beta - \frac{V_{dc}}{R_{loss}\ C} \end{aligned} \tag{9}$$

With the help of a fundamental frequency voltage tracking system, the voltage-source inverters are represented in the EMTP by controllable shunt and series voltage sources based on equations (2) and (6), respectively. The amplitudes of the voltage sources are calculated using (3) and (5), and the dc capacitor voltage is computed using (8). The variables m_{sh}, m_{se}, α and β are outputs from the UPFC power control implemented in TACS, whereas the phase shift γ is computed by tracking the fundamental frequency component of the ac current.

By using the alternative V_{dc} equation (9), there is no need to track the i_{ac} current to compute γ; this is a simpler model for the type of controller used in this paper. However, for UPFCs designed to directly control the line current, equation (8) is probably a better alternative. Either equation would produce the same results for the types of simulations presented in this paper.

IV. Test Results

A generator-line-load test system introduced in [17] is modified and used here to validate the proposed fundamental frequency model of the UPFC; the test system operates at 138 kV and is shown in Fig. 4. The generator is assumed to be an ideal voltage source behind an equivalent Thevenin impedance. The transmission system is composed of transmission lines of different lengths and modeled as a distributed-parameter lines. The two parallel transmission lines in Figure 4. have identical parameters but the lower line per unit length is assumed longer; the UPFC is placed on that line to control the power flow through it. The UPFC power flow controller is designed to maintain the power flow through the line at 0.2 p.u. The load, connected to the system through an impedance representing a step-down transformer, is modeled as an RL load. The UPFC shunt transformer is Y-Y connected and rated at 100 MVA, 138 kV/15 kV, with a leakage reactance of 14.5%. The series transformer is Y-Δ connected and rated at 100 MVA, 47.81 kV/15 kV, with a leakage reactance of 6%.

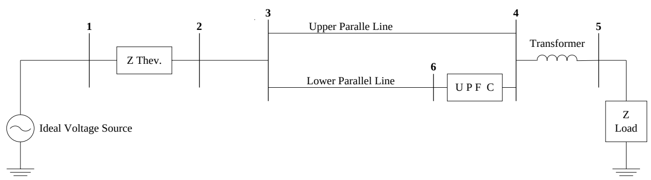

Fig. 4. 5-Bus Test system for the UPFC.

Figure 5 shows the load average power demand in one of the phases, as well as the p.u. active power flow on both parallel lines, before the UPFC is introduced in the system. A shunt capacitor bank is connected at the load bus to keep voltage at 1.0 p.u. under normal operating conditions. Observe the unequal active power sharing of these two lines due to their different impedances.

The results of introducing the UPFC at the end of the lower parallel line are shown in Fig. 6; the UPFC is placed there to control the active power flow through the line as well as to regulate the voltage at the load bus. A three phase fault is applied at load bus 5 for 0.2 s, 0.5 s into the simulation, as depicted in Fig. 6, to validate the UPFC fundamental frequency model behavior. First, observe that after the initial "cold" startup, the system reaches the desired line power flow and bus voltage conditions, and recovers quickly after the fault. These results validate the model, as the controller behaves as expected.

V. Conclusions

This paper presents description of operation and implementation of a fundamental frequency model of the UPFC. The simulation results demonstrate the validity of the proposed model, which can be used for both steady-state and transient stability studies. The model is simple and can be used in any software package that has some external programming capabilities. It should be noted that the model is completely independent of the type of control used in the UPFC; the results were obtained for a PWM-based control technique, but phase control could be also implemented without any changes to the model.

A detailed UPFC model for EMTP simulations is now being implemented to test the limitations of the proposed model.

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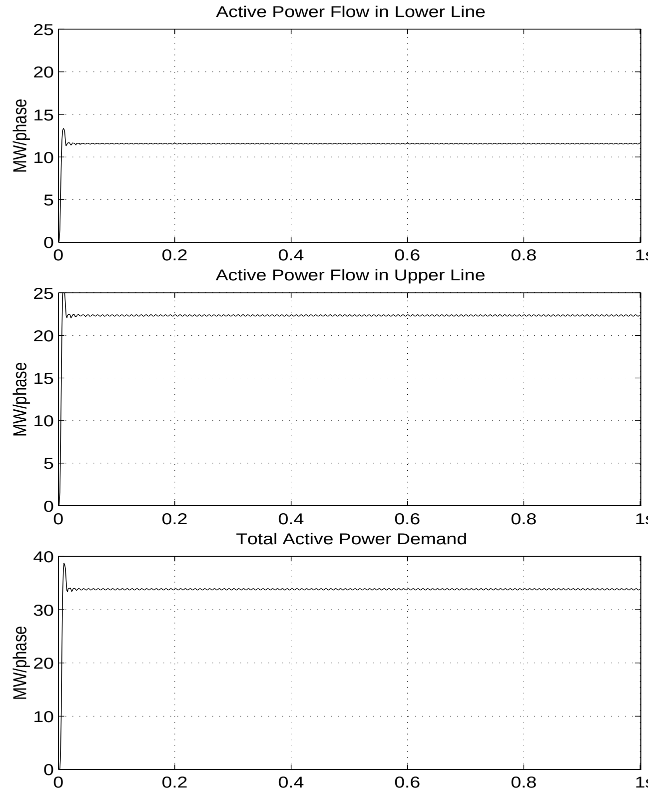

Fig. 5. Test System results without UPFC.

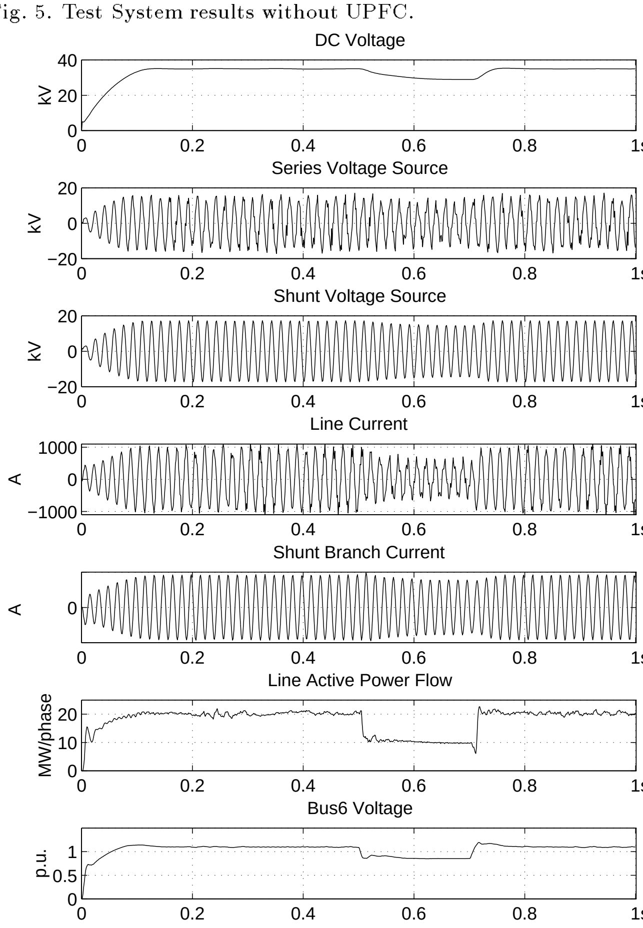

Fig. 6. Test System Results with 60-Hz UPFC model.

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