Steady State Analysis of Power Transmission Using Unified Power Flow Controller

M.W. Mustafa, A. A. Mohd Zin, A.F. Abdul Kadir
Faculty of Electrical Engineering,
Universiti Teknologi Malaysia,
Malaysia

ABSTRACT

This paper presents the application of UPFC in steady-state analysis and demonstrates the capabilities of UPFC in controlling real and reactive power flow within any electrical network. The PWM based UPFC model is implemented in Single Machine Infinite Bus system and 22-bus IEEE test system. To demonstrate the performance of PWM based UPFC model in power system, both power system networks have been simulated using PSCAD/EMTDC. From the simulation results, it has been shown that the UPFC controller is capable of controlling independently real and reactive power flow through the transmission line. It has also been shown that UPFC can be used for voltage support.

Keywords: FACTS, PSCAD/EMTDC, PWM, Steady-state analysis, UPFC.

1.0 INTRODUCTION

Nowadays the growth of power systems will rely more on increasing capability of already existing transmissions systems, rather then on building new transmission lines and power stations, for economical and environmental reasons. Due to deregulation electricity markets, the need for new power flow controllers capable of increasing transmission capability and controlling power flows through predefined corridors will certainly increase. Ideally, these new controllers should be able to control voltage level and flow of real and reactive power on transmission lines to allow for their secure loading, to full thermal capability in some cases, with no reduction of system stability and security margin [1].

Flexible AC Transmission System (FACTS) which was introduced by Hingorani is applied to the transmission system to increase controllability and to optimise the utilization of existing power system capabilities by replacing mechanical controllers with reliable and high-speed power electronic devices [1],[2].

One of the many types of FACTS devices is the Unified Power Flow Controller (UPFC). The UPFC combines two voltage-sourced converters to control the voltage at a transmission substation and at the same time control the real and reactive power flow on a transmission line. With its unique capability to control real and reactive power flow simultaneously on a transmission line as well as to regulate voltage at the bus where it is connected, this device creates a tremendous quality impact on power system stability. These features become even more significant knowing that the UPFC can allow loading of the transmission lines close to their thermal limits, forcing the power to flow through the desired paths [2].

Reference [3] introduces a steady-state UPFC model based on a single, ideal, and series voltage source. It also describes the basic concepts of the generalized real and reactive power controller. Reference [4] proposed a comprehensive development procedures and final forms of UPFC for steady state, transient stability and eigenvalue studies. The method of power flow calculation considering FACTS is developed in [5] from a view of general approach of nonlinear system. The paper in [6] presents the details of extensive computer simulations of a Sinusoidal Pulse Width Modulation (SPWM) based UPFC using EMTP program. This paper studies SPWM based UPFC working on a simplified power system. Reference [7] also study the PWM based UPFC but with a series compensation block.

The objective of this paper is to represent UPFC in steady-state analysis and to demonstrate the capabilities of UPFC in controlling real and reactive power flow within any electrical network. The PWM based UPFC model is implemented in Single Machine Infinite Bus system and 22-bus IEEE test system. To demonstrate the performance of PWM based UPFC model in power system, both power system networks have been simulated using PSCAD/EMTDC. From the simulation results, it has been shown that the UPFC controller is capable of controlling independently real and reactive power flow through the transmission line. It has also been shown that UPFC can be used for voltage support.

2.0 BASIC OPERATION OF UPFC

The UPFC consists of two switching converters, which in the implementations considered are voltage sourced converters (VSC) using gate turn-off (GTO) thyristors valves, as depicted in Figure 1. These converters labelled as "Converter 1" and "Converter 2" in the figure, are operated from the common dc link provided by a dc storage capacitor. This arrangement functions as an ideal ac to ac power converter in which the real power can freely flow either direction between the ac terminals of the two converters and each converter can independently

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generate or absorb reactive power at its own ac output terminal [3].

Converter 2 provides the main function of the UPFC by injecting an ac voltage V_{pq} with controllable magnitude is between $0 \leq V_{pq} \leq V_{pqmax}$ and phase angle ρ is between $0 \leq \rho \leq 360°$, at the power frequency, in series with line via an insertion transformer. This injected voltage can be considered essentially as a synchronous as voltage source [3]. The transmission line current flows through this voltage source resulting in real and reactive power exchange between it and the ac system. The real power exchanged at the ac terminal is converted by the converter into dc power, which appears at the dc link as positive or negative real power demand. The reactive power exchanged at the ac terminal is generated internally by the converter.

The basic function of the Converter 1 is to supply or absorb the real power via a shunt-connected transformer. Converter 1 also can generate or absorb controllable reactive power, if it is desired, and thereby it can provide independent shunt reactive compensation for the line. It is important to note that whereas there is a closed "direct" path for the real power negotiated by an action of series voltage injection through Converter 1 and 2 back to the line, the corresponding reactive power exchanged is supplied or absorbed locally by Converter 2 and therefore it does not flow through the line. Thus, Converter 1 can be operated at a unity power factor or to be controlled to have a reactive power exchange with the line independently of the reactive power exchanged by Converter 2. This means that there is no continuous reactive power flow through the UPFC [2],[3].

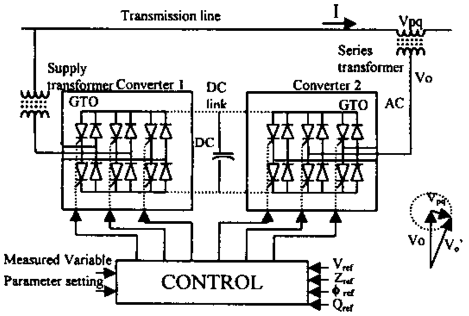

Figure 1: Unified Power Flow Controller.

3.0 PWM SWITCHING METHOD

Converter switching methods for UPFC are multi-pulse method and PWM method. Though multi-phase method uses many transformers and produces low-order harmonics, this method has been widely used because switching frequency and switching loss is relatively low. But future development of power electronic devices may solve these problems. Then PWM method will take advantage of multi-pulse method. Therefore, this paper uses PWM method for UPFC converter switching. PWM switching method produces the switching pulses of GTO thyristor by comparing reference signal, V_{ref} with the triangular wave V_{tri}. Figure 2 shows PWM switching method. If reference signal is larger than carrier signal, switch is ON. If not, switch is OFF. Amplitude modulation index, m_r and frequency modulation index, m_f is defined as follows [8]:

$$m_r = \frac{V_{mref}}{V_{mtri}} = V_{mref} \qquad (1)$$

$$m_f = \frac{f_{ref}}{f_{tri}} \qquad (2)$$

where;

V_{mref} is amplitude of reference signal
V_{mtri} is amplitude of carrier signal
f_{ref} is frequency of the reference signal
f_{tri} is frequency of carrier signal

The fundamental component of the converter output voltage, V_{out} is as follows [8]

$$V_{out} = m_r V_{dc} \sin(2\pi f_{ref} t - \theta_r) \qquad (3)$$

where;

V_{dc} is dc voltage

Therefore converter output voltage can be controlled by controlling amplitude modulation index m_r and phase shift angle, θ_r.

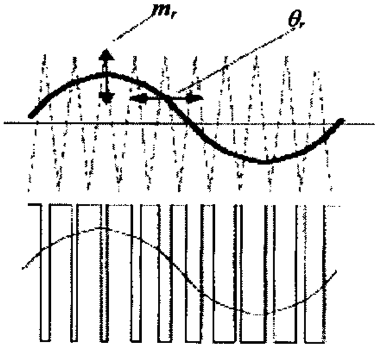

Figure 2: PWM switching method

4.0 UPFC CONTROLLERS

Because PWM is used, there are two modes of control, which can be independently applied at each converter. The modes of control used in this model are as follows:

1. Ac voltage control at the sending end is achieved by adjusting the magnitude of the voltage at the ac side of the shunt converter. The dc voltage is controlled by adjusting the phase angle of the ac side voltage of the shunt converter.
2. Quadrature voltage control is achieved by adjusting the magnitude and phase of the ac voltage out of the series converter.

Shunt converter operates in automatic voltage control mode. Shunt converter controller consists of real power control part and reactive power control part. Real power control part supplies the real power that converter 2 requires and compensates the losses of the converter 1, so that dc link capacitor voltage remains constant. Real power flow part compares dc link capacitor voltage with the reference input and the difference is controlled by PI controller. Finally, this part produces the angle of PWM output signal, α. Reactive power control part supplies reactive power to power system to control the shunt connected bus voltage, V_s. This part produces the modulation index of PWM output signal, m_{sh}.

$$i^*_{shq} = \left(V^*_s - V_s\right)\left(K_{p1} + \frac{K_{i1}}{s}\right) \qquad (4)$$

$$e^*_d = \left(i^*_{shq} - i_{shq}\right)\left(K_{p2} + \frac{K_{i2}}{s}\right) + i_{shd}\omega \qquad (5)$$

$$i^*_{shd} = \left(V^*_{dc} - V_{dc}\right)\left(K_{p3} + \frac{K_{i3}}{s}\right) \qquad (6)$$

$$e^*_q = \left(i^*_{shd} - i_{shd}\right)\left(K_{p4} + \frac{K_{i4}}{s}\right) - i_{shq}\omega \qquad (7)$$

$$m_{sh} = i^*_{shq} \qquad (8)$$

$$\alpha = i^*_{shd} \qquad (9)$$

where;

i^*_{shd} and i^*_{shq} are the reference values of the real and reactive current

e^*_d and e^*_q are the reference values of the real and reactive voltage

K_p is the gain in the proportional part

K_i is the gain in the integral part of an individual controller

i_{shd} and i_{shq} are the values of the real and reactive current

Using the α and m_{sh}, the shunt PWM output signal, V_{sh} is obtained. This signal is compared with triangular wave, so that the gating pulses of GTO thyristor are produced [8].

$$V_{sh} = m_{sh} \cos\,(2\pi ft - \alpha) \qquad (10)$$

Series converter operates in automatic power flow control mode. A simplified control system block diagram for series controller of UPFC is shown in Figure 4. The output series compensation voltage $V_{pq} = V_{pq}\angle\theta_{pq}$ can be decomposed as V_p and V_q. V_p has strong impacts on real power flow, and V_q has significant effects on reactive power flow.

$$V_p = (P_{ref} - P)\left(K_{p5} + \frac{K_{i5}}{s}\right) \qquad (11)$$

$$V_q = \left(Q_{ref} - Q\right)\left(K_{p6} + \frac{K_{i6}}{s}\right) \qquad (12)$$

where;

P_{ref} and Q_{ref} are the reference of the real and reactive power

P and Q are the real and reactive power at transmission line

Real power control part compares the real power with reference input and the difference is controlled by PI controller. For reactive power control part also compares the reactive power with reference input and the difference is controlled by PI controller. Then, V_p and V_q is converting to desire series modulation index, m_{se} and angle, β through a smooth block for PWM control of converter 2.

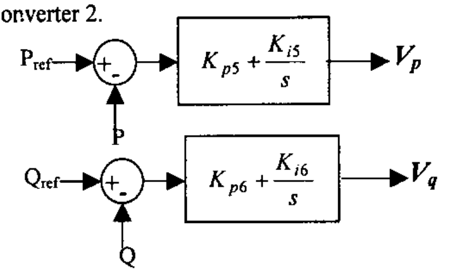

Figure 4: Series controller of UPFC

$$m_{se} = \sqrt{V_p^2 + V_q^2} \qquad (13)$$

$$\beta = \tan^{-1}\left(\frac{V_p}{V_q}\right) \qquad (14)$$

Using the β and m_{se}, the series PWM output signal, V_{se} is obtained. This signal is compared with triangular wave, so that the gating pulses of GTO thyristor are produced [8].

$$V_{se} = m_{se} \cos\,(2\pi ft - \beta) \qquad (15)$$

5.0 ANALYSIS OF SIMULATION RESULTS

Case studies are conducted to evaluate the performance of the UPFC described in the above section using a single machine infinite bus (SMIB) and the 22-bus IEEE test system. A SMIB test system introduced in [7] is modified and used here to validate the model of UPFC; the test system operates at 230 kV and is shown in Figure 5. The generator is assumed to be an ideal voltage source behind equivalent Thevenin impedance. The transmission system is composed of transmission lines of different lengths and modelled as a distributed-parameter line. The UPFC shunt transformer is Y-Δ connected and rated at 100 MVA, 230 kV/ 20 kV, with the leakage reactance of 10%. The series transformer is Y-Δ connected and rated at 100 MVA, 132 kV/20 kV, with a leakage reactance of 10%.

The UPFC model selected here is made out of two six-pulse voltage source converters with a sinusoidal Pulse Width Modulation (PWM) power controller. The typical 3-phase voltage source converters contain six controlled switches (GTO valves) and six uncontrolled switches (diodes). The simulation using previous stated PWM based UPFC model is performed by

PSCAD/EMTDC simulation program. The simulation results of the SMIB system for the base case (without UPFC) and with UPFC are illustrated in Figure 6. The simulation results are also shown in Table 1.

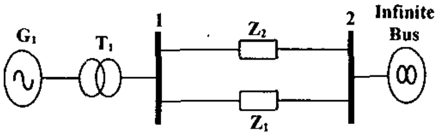

Figure 5: SMIB test system

The Voltage Source Converters de-block at 1 seconds at each end simultaneously. Only after 1 second does the system start operating. Overall, the system reaches stability after approximately 1.5 seconds. From the results obtained, there can be seen that UPFC can change the power flow of the line where it is installed and this change affects the other lines. As shown in Table 1, the power flow increases 55.34% when UPFC is install at line 1. If the power of the line 1 increases, that of line 2 decreases. This shows that UPFC does not produce real power but only redistribute real power. The mismatch between the amount of increase and that of decrease comes from change of overall system impedance changed by UPFC [8].

By the AC voltage control loop, modulation index can be controlled, where changes in modulation index will cause changes in the magnitude of AC voltage generated by shunt converter, which will eventually affect the amount of reactive power being generated or absorbed by the shunt converter. This shows that UPFC can take a role of shunt compensator, which can control the bus voltage by supplying reactive power to the system. Then, the real power is balanced when the dc voltage remains constant.

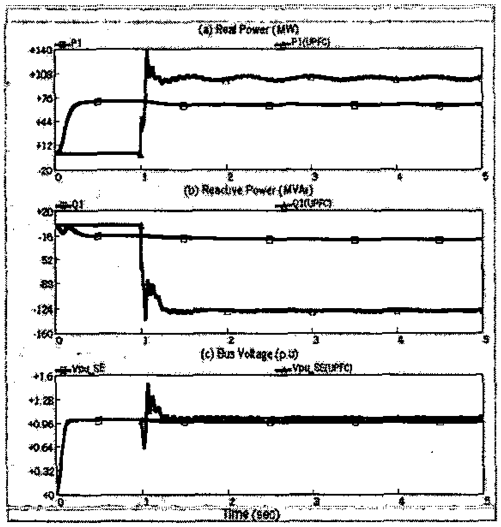

Figure 6: Comparison of simulation results of SMIB without and with UPFC in a steady state

Table 1: Power flow results with and without UPFC for SMIB system

Parameter	Without UPFC	With UPFC
P_1 (MW)	65.21	101.3
P_2 (MW)	65.21	15.528
Q_1 (MVAr)	-22.74	-126.9
Q_2 (MVAr)	-22.74	0.816
Vs (p.u)	0.9659	1.016
Vr (p.u)	0.9893	0.9505

By referring to paper [7], the real and reactive power in a parallel transmission line can be controlled using the UPFC model by the series modulation index (M_α), injected angle (α), or any combination of them. Since, the UPFC series controller has both of them (m_{se} and β), as shown in equation (13) and (14), the proposed model has been validated.

The 22-bus IEEE test system as shown in Figure 7 is considered for the multimachine study. For this study, UPFC is connected in the line 17-18, at the end of the line close to bus 17. This study aim to increase the power transfer capability of between two areas. The simulation results of the 22-bus IEEE test system for the base case (without UPFC) and with UPFC are illustrated in Figure 8. The simulation results are also shown in Table 2.

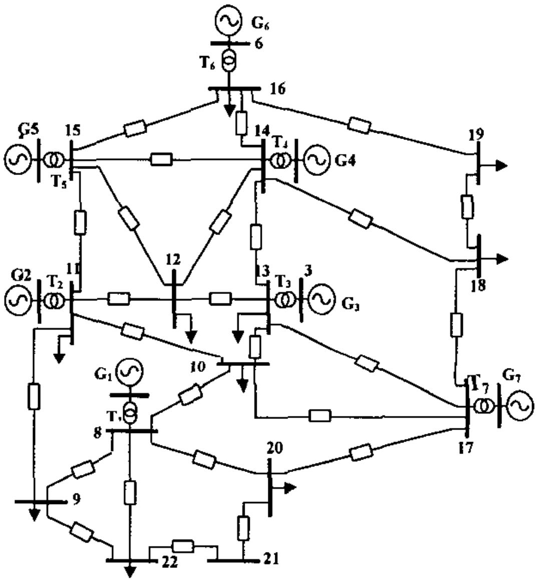

Figure 7: 22-bus IEEE test system

These result shows that by inclusion of the UPFC in the system can increase the power flow from bus 17 to bus 18 to 55.8 MW through that line and allow greater use of utility generation capacity. Beside that, this result also show that UPFC can regulate the voltage of bus 17 at its steady state value which is equal to 1.0 p.u by supplying reactive power to the power system network.

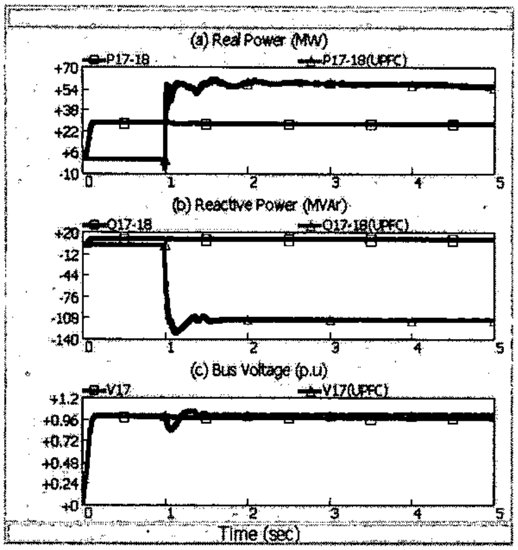

Figure 8: Comparison of simulation results of 22-bus test system without and with UPFC in a steady state

Table 2: Power flow results with and without UPFC for 22-bus test system

Parameter	Without UPFC	With UPFC
$P_{17\text{-}18}$ (MW)	27.1667	55.7917
$Q_{17\text{-}18}$ (MVAr)	9.3658	-112.77
V_{17} (p.u)	0.9669	1.001

6.0 CONCLUSIONS

This paper has presented the analysis of steady state performance of PWM based UPFC and its interaction with power system. The PWM based UPFC model is implemented in Single Machine Infinite Bus system and 22-bus IEEE test system. To demonstrate the performance of PWM based model in power system, both power system networks have been simulated using PSCAD/EMTDC. From the simulation results, it has been shown that the UPFC controller is capable to control independently the real and reactive power flow through the transmission line as well as to regulate voltage at the bus where it is connected. The results shows that UPFC does not produce real power but only redistribute real power. The mismatch between the amount of increase and that of decrease comes from change of overall system impedance changed by UPFC. The significant of UPFC is the increment of power flow of transmission line close to their thermal limit gives the power system operator much flexible to satisfy the demand that the deregulated power system will impose.

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8.0 ACKNOWLEDGMENT

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9.0 BIOGRAPHIES

Mohd. Wazir Mustafa received his B.Eng degree (1988), M.Sc (1993) and PhD (1997) from University of Strathclyde. His research interests include power system stability, Flexible AC Transmission System, wireless power and power system distribution & automation. He is currently an Associate Professor of Electrical Engineering, Faculty of Electrical Engineering, and Universiti Teknologi Malaysia. He is also a Member of Institution of Engineers, Malaysia (IEM) and a Member of IEEE.

Abdullah Asuhaimi Mohd.Zin is currently a Professor of Electrical Engineering, Faculty of Electrical Engineering, Universiti Teknologi Malaysia. He received his B.Sc. degree (1976) from Gadjah Mada University, M.Sc. degree (1981) from University of Strathclyde and PhD degree (1988) from UMIST. He authored/co-authored over 65 technical papers. His research interests include power system protection, application of neural network in power system, power system harmonics and power system distribution & automation. Dr. Mohd. Zin is also a Corporate Member of Institution of Engineers, Malaysia (IEM) and a Senior Member of IEEE.

Aida Fazliana Abdul Kadir earned the B.Sc. degree in Electrical Engineering (2000) from Universiti Teknologi Malaysia. She is presently doing research in Universiti Teknologi Malaysia.