Military Technical College
Kobry El-Kobbah,
Cairo, Egypt

7th International Conference
on Electrical Engineering
ICEENG 2010

A Nonlinear Model and Steady State Analysis of A Unified Power Flow Controller

By

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Abstract:

The present paper describes the nonlinear model of unified power flow controller (UPFC) for studying the steady state and transient behavior of an electric power circuit equipped with FACTS devices. Detailed 3-dimension simulations are carried out to illustrate the control features of the UPFC and its influence to increase power transfer and improve system stability.

Keywords:

FACTS, STATCOM, SSSC, and UPFC, devices modeling, power transmission

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1. Introduction:

In recent years, power demand has increased substantially while the expansion of power generation and transmission has been severely limited due to limited resources and environmental restrictions. The continuous grow of electric demand requires building new generating units and transmission circuits.

These requirements are becoming more difficult because of economic and environmental reasons. Also, conventional devices with fixed or mechanically switchable component have low. Control speed, high wearing and require frequent.

The operation of an AC transmission system is generally constrained by limitations of one or more network parameters (such as: line impedance) and operating variables (such as voltages and currents) [1,2].

As a result, the power line is unable to direct power flow among generating stations. To increase the power transfer capability of transmission systems, to minimize the transmission losses, to support a good voltage profile and to retain system stability under large disturbances. We need modern control equipment, we call for Flexible AC Transmission Systems (FACTS) [3-7].

This paper is focused on the unified power flow controller (UPFC) which is the most of the flexible AC transmission system (FACTS) devices in power system. The steady state analysis is performed; the nonlinear mathematical models are presented in d-q frame.

Simulation studies are performed on to demonstrate the capabilities of the UPFC with different control schemes.

MODELLING OF UPFC

The operation of the UPFC from the standpoint of conventional power transmission is based on reactive shunt compensation, series compensation, and phase shifting [8-12].

The UPFC can fulfill these functions and thereby meet multiple control objectives [9,10]. The basic UPFC power flow controller functions and a simplified equivalent circuit for the parallel and series branches with neglecting the harmonics are illustrated in Fig.1.

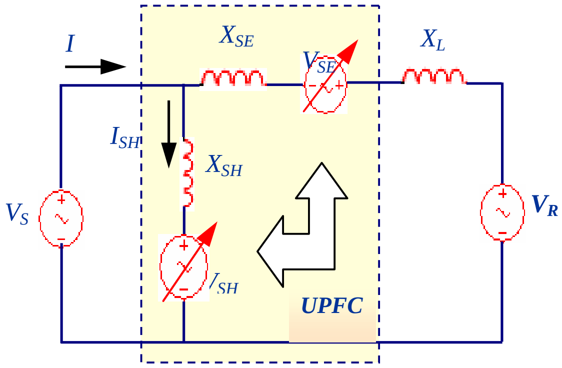

Fig. 1 UPFC schematic

The equations of shunt branch can be obtained as follows:

$$\frac{d}{dt} i'_{SH,abc} = \frac{-R'_{SH}\omega_b}{L'_{SH}} i'_{SH,abc} + \frac{\omega_b}{L'_{SH}} V'_{S,abc} - \frac{m_{SH}\omega_b}{2L'_{SH}} V'_{dc} G_{SH,abc} \qquad (1)$$

Where;

$$i'_{SH,abc} = \left[i'_{SHa}, i'_{SHb}, i'_{SHc} \right]^T$$

$$V'_{S,abc} = \left[V'_{SHa}, V'_{SHb}, V'_{SHc} \right]^T$$

$$G_{SH,abc} = \left[\cos(\delta_{SH}), \cos(\delta_{SH} - 120), \cos(\delta_{SH} + 120) \right]$$

The differentiated equations of the shunt branch in dq variable using park's transformation [5-7] are obtained

$$\frac{d}{dt} i'_{SHdq} = \frac{-R'_{SH}.\omega_b}{L'_{SH}} i'_{SHdq} - \omega . M i'_{SHdq} + \frac{\omega_b}{L'_{SH}} \mathbf{V'_{s,dq}} - \frac{m_{SH}.\omega_b}{2L'_{SH}} V'_{dc}.G_{SH,dq} \qquad (2)$$

The above equation may be written in matrix form

$$\frac{d}{dt}\begin{bmatrix} i'_{SHd} \\ i'_{SHq} \end{bmatrix} = \begin{bmatrix} \frac{-R'_{SH}\omega_b}{L'_{SH}} & \omega \\ -\omega & \frac{-R'_{SH}\omega_b}{L'_{SH}} \end{bmatrix} \begin{bmatrix} i'_{SHd} \\ i'_{SHq} \end{bmatrix} + \frac{\omega_b}{L'_{SH}} \begin{bmatrix} V'_{sd} \\ V'_{sq} \end{bmatrix} - \frac{m_{SH}\omega_b}{2L'_{SH}} V'_{dc} \begin{bmatrix} \cos\delta_{SH} \\ \sin\delta_{SH} \end{bmatrix}$$

Similarly the equations of series branch can be obtained;

$$\frac{d}{dt}\begin{bmatrix} i'_{SEd} \\ i'_{SEq} \end{bmatrix} = \begin{bmatrix} \frac{-R'_{SE}\omega_b}{L'_{SE}} & \omega \\ -\omega & \frac{-R'_{SE}\omega_b}{L'_{SE}} \end{bmatrix} \begin{bmatrix} i'_{SEd} \\ i'_{SEq} \end{bmatrix} + \frac{\omega_b}{L'_{SE}} \begin{bmatrix} V'_{Sd} - V'_{Rd} \\ V'_{Sq} - V'_{Rq} \end{bmatrix} + \frac{m_{SE}\omega_b}{2L'_{SE}} . V'_{dc} \begin{bmatrix} \cos\alpha_{SE} \\ \sin\alpha_{SE} \end{bmatrix}$$

For lossless transformer and converter, the ac power is equal to the dc power [6,7]. Then the dc currents in both shunt and series branches are obtained as follow

$$\therefore\ i'_{SH\,dc} = \frac{3}{4} m_{SH} \left[\cos\alpha_{SH} . i'_{SHd} + \sin\alpha_{SH} . i'_{SH\,q}\right]$$

Similarly $i'_{SE\,dc}$ can be obtained

$$i'_{SE\,dc} = \frac{3}{4} m_{SE} \left[\cos\alpha_{SE}\ i'_{SE\,d} + \sin\alpha_{SE}\ i'_{SE\,q}\right]$$

The differential equation of the dc voltage is:

$$\frac{dV'_{dc}}{dt} = \left(i'_{SH\,dc} + i'_{SE\,dc}\right).C'\omega_b$$

$$\frac{dV_{dc}}{dt} = \frac{3m_{SH}}{4}.C'\omega_b \left[\cos\alpha_{SH}\ \ \sin\alpha_{SH}\right] \begin{bmatrix} i'_{SHd} \\ i'_{SHq} \end{bmatrix} + \frac{3\,m_{SE}}{4}.C'\omega_b \left[\cos\ \alpha_{SE}\ \ \sin\ \alpha_{SE}\right] \begin{bmatrix} i'_{SE\ d} \\ i'_{SE\ q} \end{bmatrix}$$

The UPFC can be written in the compact form as follow:

$$\frac{d}{dt}\begin{bmatrix} i'_{SH\,d} \\ i'_{SH\,q} \\ i'_{SE\,d} \\ i'_{SE\,q} \\ V'_{dc} \end{bmatrix} = \begin{bmatrix} \frac{-R'_{SH}\omega_b}{L'_{SH}} & \omega & 0 & 0 & \frac{-m_{SH}\omega_b}{2L'_{SH}}\cos\alpha_{SH} \\ -\omega & \frac{-R'_{SH}\omega_b}{L'_{SH}} & 0 & 0 & \frac{-m_{SH}\omega_b}{2L'_{SH}}\sin\alpha_{SH} \\ 0 & 0 & \frac{-R'_{SE}\omega_b}{L'_{SE}} & \omega & \frac{m_{SE}\omega_b}{2L'_{SE}}\cos\alpha_{SE} \\ 0 & 0 & -\omega & \frac{-R'_{SE}\omega_b}{L'_{SE}} & \frac{m_{SE}\omega_b}{2L'_{SE}}\sin\alpha_{SE} \\ fm_{SH}\cos\alpha_{SH} & fm_{SH}\sin\alpha_{SH} & fm_{SE}\cos\alpha_{SE} & fm_{SE}\sin\alpha_{SE} & 0 \end{bmatrix} \begin{bmatrix} i'_{SH\,d} \\ i'_{SH\,q} \\ i'_{SE\,d} \\ i'_{SE\,q} \\ V'_{dc} \end{bmatrix} + \omega_b \begin{bmatrix} V'_{S\,d} \,/\, L'_{SH} \\ V'_{S\,q} \,/\, L'_{SH} \\ \left(V'_{S\,d} - V'_{R\,d}\right) / L'_{SE} \\ \left(V'_{S\,q} - V'_{R\,q}\right) / L'_{SE} \\ 0 \end{bmatrix}$$

Where $f = \frac{3}{4} c'.\omega_b$

Numerical Example

For achieving the steady-state analysis of the UPFC, the per-unit values for shunt, series and the dc-link parameters [6,7] are:

$R'_{SH} = 0.015$; $L'_{SH} = 0.15$, $R'_{SE} = 0.01$; $L'_{SE} = 0.1$, $c' = 0.5$, $\omega_b = 2\pi * 50$; $\omega = 2\pi * 50$ rad/sec

$V_{Sd} = 1$; $V_{Sq} = 0$, $V_{Rd} = 0.94$; $V_{Rq} = 0.34$

For a certain value of series converter modulation index m_{SE} = 0.5 and phase displacement of the series converter voltage α_{SE} = 70 degree, the 3-D steady state analysis can be achieved for the d-component of shunt current I_{SHd} with range shunt converter modulation index m_{SH} from 0 to 1 and phase displacement of the series converter voltage α_{SH} from 0 to 180 degree as shown in Fig.2.

The steady state analysis can provide dynamic behavior of the model to choose the preferable setting range of the series and shunt converter to achieve the perfect response. By changing the value of the series converter modulation index m_{SE} to 0.1 and the phase displacement of the series converter voltage α_{SE} to 40 degree the system will be unstable at certain shunt converter modulation index m_{SH} as shown in Fig.3.

Conclusion

The steady-state analysis of the UPFC was determined using the derived mathematical model or state space representation of the device.

The non-linear mathematical model based on the transformation of a three-phase system into an orthogonal synchronously rotating coordinate system.

Under steady-state conditions, all system quantities are constant values, using pulse width modulation (PWM) technique with an approximate converter output voltage and neglecting the harmonics for simplifying the analysis.

The steady state analysis also was applied in 3-dimension to illustrate the effect of the modulation ratio and phase displacement into the response of the UPFC. When the modulation index has been changed from 0.5 to 0.1 at the same phase displacement 40 degree, the system converted from stable to unstable mode.

Therefore with the steady state analysis the performance of the system for specified operating data can be investigated.

Finally, we can conclude that the analysis of the steady-state operational characteristics resulted in key findings enabling a further derivation of control algorithms and examination of the UPFC under dynamic operating conditions.

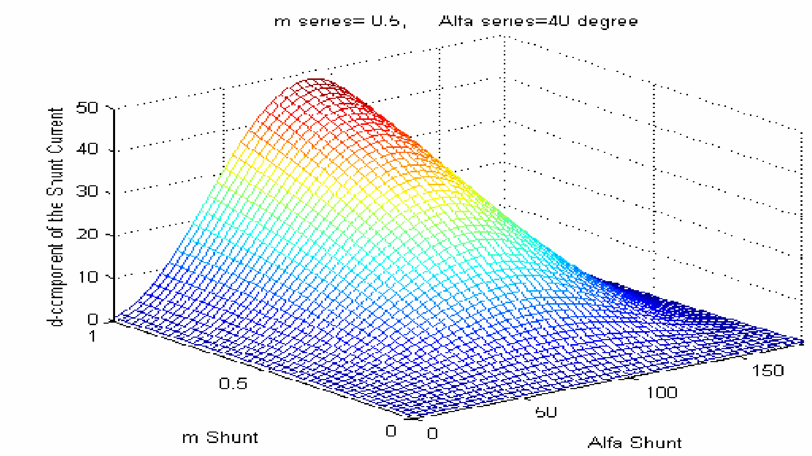

Fig. 2 3-D steady state analysis

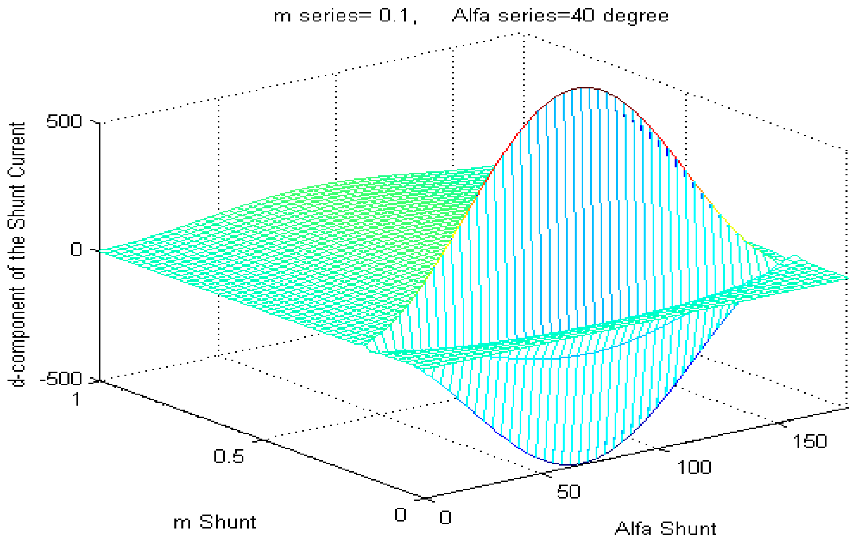

Fig. 3 3-D steady state analysis for a unstable

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