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Comparison of Fundamental Frequency Model and PWM Based Model of UPFC

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Abstract—Among all FACTS devices, the unified power flow controller (UPFC) is considered to be the most versatile device. This is due to its capability to control all the transmission system parameters (impedance, voltage magnitude, and phase angle). With the growing interest in UPFC, the attention to develop a mathematical model has increased. Several models were introduced for UPFC in literature for different type of studies in power systems. In this paper a novel comparison study between two dynamic models of UPFC with their proposed control strategies.

Keywords—FACTS, UPFC, Dynamic Modeling, PWM, Fundamental Frequency.

I. INTRODUCTION

DUE to the increasing demand on power, and with the economical and environmental constraints on building new generating plants and installing new transmission lines, interconnection of the transmission system appeared as an option in order to cover the need for power. This also meant that the system is to be operated and utilized to its limits. Since the transmission system is governed by two limits namely, electrical stability limit, and thermal limit, and by operating outside the permissible range of stability, the system security is compromised. An innovative solution to such a problem was with the introduction of flexible AC transmission system (FACTS). The idea behind FACTS was to increase controllability and optimize the existing power system capacity through the use of power electronic devices. With such devices the transmission system is to be operated near to its thermal limits without compromising the system security and reliability. Since then, the use of FACTS controllers has been popular to solve different problems faced in power systems such as power flow control, voltage support, and even oscillation damping. FACTS installations increase the system operating range, security, and reliability and also provide more functionality over mechanical devices installed in the system.

The unified power flow controller (UPFC) was introduced by Gyugyi in 1991[2]. UPFC is a voltage source converter (VSC) based FACTS device. The UPFC is composed of two voltage source converters connected back to back through a common d.c link as illustrated in Fig. 1.

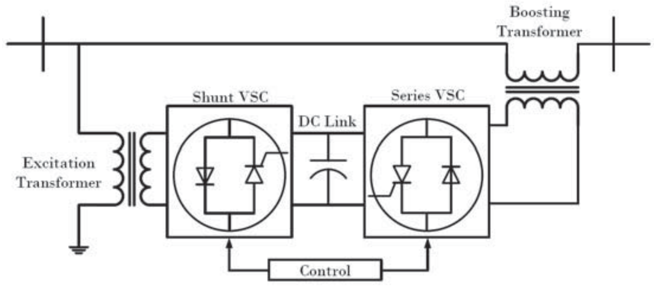

Fig. 1. Unified Power Flow Controller (UPFC) Construction

Due to its structure, UPFC is considered to be the most versatile FACTS device as it combines the functions of shunt and series connected FACTS devices. Hence, it can control all three parameters of the transmission system.

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In order to evaluate the performance of a UPFC, mathematical models for steady state and dynamic analysis are to be developed. The steady state model is mainly concerned with the incorporation of the UPFC in load flow studies, while the dynamic model is developed to investigate the behavior of UPFC during transients, the control capability, and controller design.

Several references in literature have addressed the topic of the UPFC dynamic modeling. In [5], a dynamic model for UPFC was introduced for transient and small signal stability analysis. The problem with this modeling approach was that it did not consider the DC link dynamics which could lead to implications during transients. In [6], a Newton type current injection model is used for transient stability studies. This model consists of a controllable voltage source added in series with the transmission line, plus two current sources added in shunt to balance power flow through the device. As this model has considered the power balance constraint for the UPFC, it has neglected the dynamics of the DC link also. Thus, this model is not suitable for dynamic analysis.

This paper presents two dynamic models of the UPFC that were introduced in literature in [4] and in [3].It discusses the control strategies that were proposed for these two models in literature. It highlights the major advantages and disadvantages of the two models and their respective control strategies.

II. UPFC FUNDAMENTAL FREQUENCY MODEL

A. Model Derivation

In [4], a fundamental frequency model for the UPFC was proposed. From Fig. 1, By replacing the VSCs of the UPFC with a controllable fundamental frequency voltage sources as in Fig. 2.

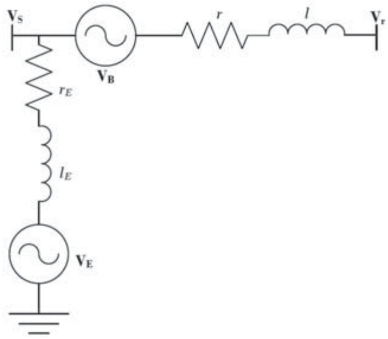


Fig. 2. UPFC Fundamental Frequency Model

where $\mathbf{V_S}$ is the sending end bus voltage and $\mathbf{V_r}$ is the receiving end bus voltage. $\mathbf{V_B}$ is the series injected voltage and $\mathbf{V_E}$ is the shunt injected voltage.

From the circuit shown in Fig. 2, the dynamics of the shunt and series converter can be deduced as:

$$\frac{di_{Eabc}}{dt} = -\frac{r_E}{l_E} i_{Eabc} + \frac{1}{l_E}\left(v_{Eabc} - v_{Sabc}\right) \tag{1}$$

$$\frac{di_{Babc}}{dt} = -\frac{r}{l} i_{Babc} + \frac{1}{l}\left(v_{Sabc} + v_{Babc} - v_{rabc}\right) \tag{2}$$

where , r and l are the losses and leakage reactances of the boosting transformer and the transmission line, r_E and l_E are the shunt converters losses and leakage reactance.

By Park's transformation for (1) and (2):

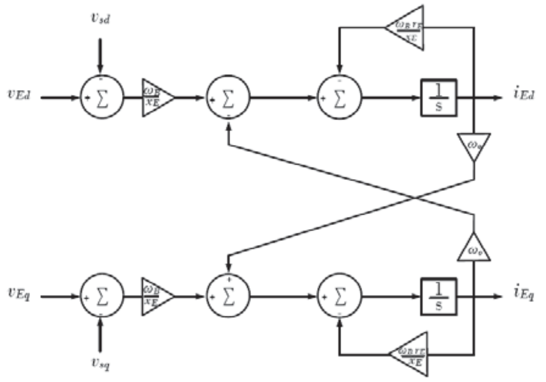
$$\frac{di_{Ed}}{dt} = -\frac{\omega_B\, r_E}{x_E}\, i_{Ed} - \omega_o\, i_{Eq} + \frac{\omega_B}{x_E}\left(v_{Ed} - v_{sd}\right) \tag{3}$$

$$\frac{di_{Eq}}{dt} = -\frac{\omega_B\, r_E}{x_E}\, i_{Eq} + \omega_o i_{Ed} + \frac{\omega_B}{x_E}\left(v_{Eq} - v_{sq}\right) \tag{4}$$

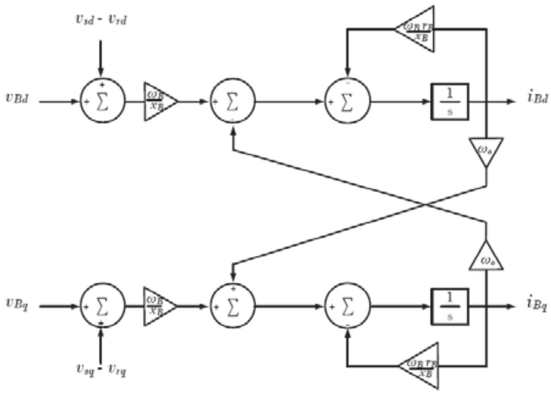
$$\frac{di_{Bd}}{dt} = -\frac{\omega_B\, r}{x}\, i_{Bd} - \omega_o\, i_{Bq} + \frac{\omega_B}{x}\left(v_{sd} + v_{Bd} - v_{rd}\right) \tag{5}$$

$$\frac{di_{Bq}}{dt} = -\frac{\omega_B\, r}{x}\, i_{Bq} + \omega_o i_{Bd} + \frac{\omega_B}{x}\left(v_{sq} + v_{Bq} - v_{rq}\right) \tag{6}$$

Fig. 3a and Fig.3b show block diagrams representation of the equations above, from which it can be seen the coupling of the system.



(a) Shunt Converter Block Diagram Representation



(b) Series Converter Block Diagram Representation

Fig. 3. UPFC Converter Block Diagram

The DC link dynamics are given as:

$$\frac{dv_{dc}}{dt} = -\frac{2}{3}\frac{\omega_B\, x_{dc}}{v_{dc}}\left(v_{Eq}\, i_{Eq} + v_{Ed}\, i_{Ed} + v_{Bq}\, i_{Bq} + v_{Bd}\, i_{Bd}\right) \tag{7}$$

B. Model Based Control Strategy

Based on the model presented earlier a control strategy for power flow control, bus voltage regulation, and DC voltage regulation is discussed here. The control strategy is intended to control both active power, reactive power, bus voltage and dc link voltage. The control strategies used were proposed in [4] and[10], and was reported also in [7], [1].

For power flow control, consider the complex power injection into the receiving bus:

$$\mathbf{S_r} = P_r + \jmath Q_r \tag{8}$$

The active and reactive received powers in dq - reference frame are found as:

$$P_r = v_{rq} i_{Bq} + v_{rd} i_{Bd} \tag{9}$$

$$Q_r = v_{rd} i_{Bq} - v_{rq} i_{Bd} \tag{10}$$

The power injection setpoint can be translated into current setpoints of the series converter as follows:

$$i_{Bq}^{*} = \frac{P_r^{*}\, v_{rq} + Q_r^{*}\, v_{rd}}{\triangle} \tag{11}$$

$$i_{Bd}^{*} = \frac{P_r^{*}\, v_{rd} - Q_r^{*}\, v_{rq}}{\triangle} \tag{12}$$

where:
P_r^{*}: desired active power setpoint
Q_r^{*}: desired reactive power setpoint
$\triangle = v_{rq}^2 + v_{rd}^2$

Similarly, for the bus voltage and dc link voltage regulation consider the complex power injection by the shunt converter:

$$\mathbf{S_E} = \mathbf{V_s}\, \mathbf{I_E^{*}} \tag{13}$$

Decomposing the voltage and current into the DQ components, this gives:

$$\begin{aligned}\mathbf{S_E} &= (v_{sq} + j\, v_{sd})\,(i_{Eq} - j\, i_{Ed}) \\ &= V_s\left[(i_{Eq}\,\cos\theta_s + i_{Ed}\,\sin\theta_s) - j\,(i_{Ed}\,\cos\theta_s - i_{Eq}\,\sin\theta_s)\right] \\ &= V_s\left[i_{psh} - j\, i_{rsh}\right]\end{aligned}$$

where

$$i_{psh} = i_{Ed}\,\cos\theta_s + i_{Eq}\,\sin\theta_s \tag{14}$$

$$i_{rsh} = i_{Ed}\,\cos\theta_s - i_{Eq}\,\sin\theta_s \tag{15}$$

i_{psh} and i_{rsh} are the real current and reactive current respectively.

Through cascade control loop as in [4], the real current i_{psh} is regulated by a PI controller by the dc voltage whereas the reactive $i_{rsh}$is regulated by a PI controller by the ac bus voltage. Thus the current setpoints for the shunt converter is obtained as:

$$i_{Ed}^{*} = i_{psh}\,\sin\theta_s + i_{rsh}\,\cos\theta_s \tag{16}$$

$$i_{Eq}^{*} = i_{psh}\,\cos\theta_s - i_{rsh}\,\sin\theta_s \tag{17}$$

Fig. 4 shows the block diagram of the proposed control strategy.

C. Model Drawbacks

This approach has considered a detailed modeling of the UPFC where the coupling transformers resistance and transients were taken into account, and this is impractical in case of large power system having multi-machines and multiple UPFCs. Moreover, the control signals that have been considered are the dq-components of the injected voltages, thus a need to convert these injected voltages to the respective modulation index and phase shift that are to be supplied to the VSCs of the UPFC. Furthermore, the control strategy proposed for the DC voltage regulation and bus voltage regulation contains a cascade control loop, which increases the number of control loops to be tuned and increase the control system complexity .

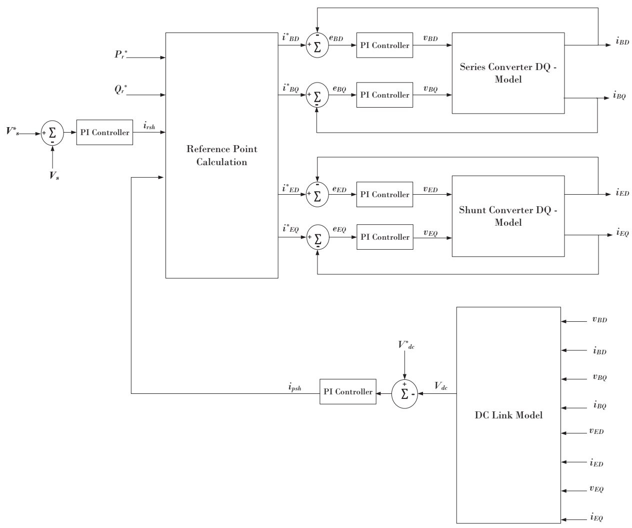


Fig. 4. Model Based Control Strategy

III. UPFC Pulse Width Modulation (PWM) Based Model

A. Model Derivation

Another modeling approach was introduced by Nabavi - Niaki and Iravani in [3]. This model is based on the three phase circuit illustrated in Fig. 5. Based on the pulse width modulation (PWM) technique used to control the converters, this modeling approach considered the injected voltages to be a pure sine wave signals by neglecting the high order frequency components introduced due to switching. Thus:

$$v_{Eabc} = \frac{m_E\, v_{dc}}{2}\cos\left(\omega t + \delta_E \pm \frac{2\pi}{3}\right) \tag{18}$$

$$v_{Babc} = \frac{m_B\, v_{dc}}{2}\cos\left(\omega t + \delta_B \pm \frac{2\pi}{3}\right) \tag{19}$$

m_E and m_B are amplitude modulation ratios, δ_E and $\delta_B$are phase angles of the voltage source converters control signal.

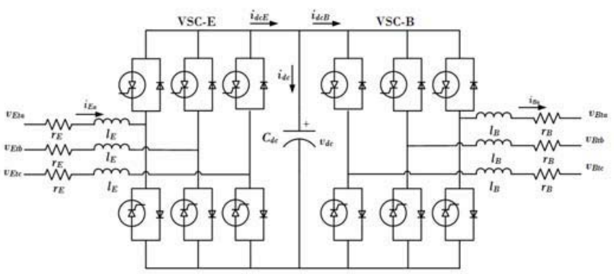


Fig. 5. UPFC Three Phase Schematic Diagram

Let (v_{Etabc}) be the three phase AC side terminal voltage of the shunt converter, and (v_{Btabc}) is the three phase AC side terminal voltage of the series converter.

The converter dynamics in the rotating reference frame is given as:

$$\begin{vmatrix} \frac{di_{Ed}}{dt} \\ \frac{di_{Eq}}{dt} \end{vmatrix} = \begin{vmatrix} -\frac{r_E}{l_E} & -\omega_o \\ \omega_o & -\frac{r_E}{l_E} \end{vmatrix} \begin{vmatrix} i_{Ed} \\ i_{Eq} \end{vmatrix} - \frac{m_E v_{dc}}{2} \begin{vmatrix} \cos\delta_E \\ \sin\delta_E \end{vmatrix} + \frac{1}{l_E} \begin{vmatrix} v_{Etd} \\ v_{Etq} \end{vmatrix} \quad (20)$$

$$\begin{vmatrix} \frac{di_{Bd}}{dt} \\ \frac{di_{Bq}}{dt} \end{vmatrix} = \begin{vmatrix} -\frac{r_B}{l_B} & -\omega_o \\ \omega_o & -\frac{r_B}{l_B} \end{vmatrix} \begin{vmatrix} i_{Bd} \\ i_{Bq} \end{vmatrix} + \frac{m_B v_{dc}}{2} \begin{vmatrix} \cos\delta_B \\ \sin\delta_B \end{vmatrix} - \frac{1}{l_B} \begin{vmatrix} v_{Btd} \\ v_{Btq} \end{vmatrix} \quad (21)$$

By neglecting the coupling transformer resistance and transients as in [9], [8] we obtain the following:

$$\begin{vmatrix} v_{Etd} \\ v_{Etq} \end{vmatrix} = \begin{vmatrix} 0 & x_E \\ -x_E & 0 \end{vmatrix} \begin{vmatrix} i_{Ed} \\ i_{Eq} \end{vmatrix} + \frac{m_E v_{dc}}{2} \begin{vmatrix} \cos\delta_E \\ \sin\delta_E \end{vmatrix} \quad (22)$$

$$\begin{vmatrix} v_{Btd} \\ v_{Btq} \end{vmatrix} = \begin{vmatrix} 0 & -x_B \\ x_B & 0 \end{vmatrix} \begin{vmatrix} i_{Bd} \\ i_{Bq} \end{vmatrix} + \frac{m_B v_{dc}}{2} \begin{vmatrix} \cos\delta_B \\ \sin\delta_B \end{vmatrix} \quad (23)$$

And the DC link dynamics is given as:

$$\frac{dv_{dc}}{dt} = \frac{3m_E}{4C_{dc}} \begin{vmatrix} \cos\delta_E & \sin\delta_E \end{vmatrix} \begin{vmatrix} i_{Ed} \\ i_{Eq} \end{vmatrix} - \frac{3m_B}{4C_{dc}} \begin{vmatrix} \cos\delta_B & \sin\delta_B \end{vmatrix} \begin{vmatrix} i_{Bd} \\ i_{Bq} \end{vmatrix} \quad (24)$$

Hence the UPFC dynamic model is represented only with dynamics of the DC link as given in (24).

B. Model Based Control Strategy

Based on this modeling approach, the control signals for the UPFC are explicitly shown as the modulation indexes and the phase angles of the injected voltages. Therefore a direct control of these variables by the outputs of the system can be done. A multiple PI controllers are used in this control strategy for active power, reactive power, bus voltage, and dc link voltage control. The selection of the output control signals for the UPFC system shown in Fig. 6 are: $U_P = \delta_B$, $U_Q = m_B$, $U_{AC} = m_E$, and $U_{DC} = \delta_E$.

C. Model Drawbacks

Although that this model and control strategy do not suffer from the shortcomings that were mentioned for the previous model, without the cascade control loop the response of the system will be slower.

IV. Conclusion

This paper discussed two dynamic models of the UPFC with two proposed control strategies. The detailed dynamic model has several shortcomings which limit its use to only power flow control in a simple system such as two bus system, where the complexity will increase as the size of the system increases. The PWM based model and its proposed control strategy is a more appropriate choice for large systems. The conclusion goes here.

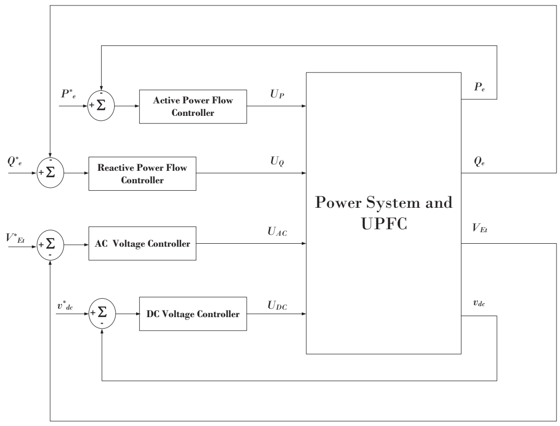


Fig. 6. PWM based control control strategy

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