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Steady State Analysis of a UPFC as Voltage Regulator for Optimal Position in the Transmission Line

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تحليل مرحلة الاستقرار للمتحكم في توحيد سريان الطاقة الكهربائية (UPFC) كمنظم للجهد من أجل موقع مثالي على خط نقل القوى

السيد علي الموسوي و محمد رضا قادر

خلاصة : في خلال السنة الحالية من الواضح أن تنصيب المتحكم في توحيد سريان الطاقة الكهربائية (UPFC) يلعب دوراً مهماً في قاعدة التأثير غير الخطي لسلوكية استقرار النظام . ولهذا السبب فإن عرض معدل النبض (PWM) معتمداً على (UPFC) كمنظم للجهد الكهربائي يمكن نمذجته وتحليله من أجل استنتاج الموقع المثالي على خط نقل القوى الكهربائية من خلال الدراسة التي تمت في هذه الورقة، فقد تم توضيح موقع (UPFC) الذي يلعب دوراً ذا مغزى في التأثير غير الخطي. كما أنه تم استعراض النتائج المستقاة من الحاسوب بأن توزيع الطاقة الكهربائية المؤثرة (Active Power) و الطاقة الكهربائية الحيثية (Reactive Power) الساريتان يمكن التحكم بهما بتغير معامل التعديل للجهاز.

ABSTRACT: it has recently been illustrated that the Unified Power Flow Controller (UPFC) installation location plays an important role in effecting nonlinearly in the UPFC steady state performance of the system. A Pulse Width Modulation (PWM) based on UPFC as a voltage regulator is modeled and analyzed to investigate the optimal position in the transmission line. From the study made in this paper, it is shown that the location of UPFC plays a significant part in effecting nonlinearly. It is also found from the simulation results that the distribution of the active and reactive power flows can be controlled by varying the modulation index of the device.

KEYWORDS: FACTS, UPFC, Voltage Regulator , Active and Reactive Power.

1. Introduction

The concept of a unified power flow controller (UPFC) has been proposed recently(Gyugyi, 1992; Gyugyi and Hingorani 1990; Gyugyi *et al*., 1995). The UPFC has the potential to become one of the most important Flexible AC Transmission Systems (FACTS) since it can provide various types of compensation, i.e., voltage regulator, phase shifting regulator, impedance compensation and reactive compensation.

Practically, the UPFC is implemented by using two similar solid-state phase voltage source inverters (shunt compensation block and series compensation block) which are connected through a common DC link capacitor as shown in Figure 1 (Gyugyi *et al.,* 1995) and each inverter is coupled with a transformer.

In the last few years, a number of landmark publications have appeared in the literature, which described the basic operation of the UPFC (Gyugyi, 1992; Gyugyi and Hingorani, 1990; and Gyugyi *et al*., 1995).

Gyugyi (1994) has proposed the concept of the UPFC to control independently both the real power and the reactive power flows at the sending and receiving ends of the transmission line. He also compared the performance and equipment of the UPFC to the more conventional, but related, power flow controllers such as the Thyristor controller Series Capacitor and the Thyristor controller Phase Angle Regulator. He claimed that, due to the capability and performance of the UPFC in controlling the power flow in transmission lines, this device becomes the most important FACTS device. Furthermore, it has been presented in reference (Fuerte-Esquivel and Acha 1997) that the UPFC can control active and reactive power and voltage magnitude simultaneously. This showed that caution has to be exercised with the UPFC model since it has been assumed that the shunt converter is operating at unity power factor.

This paper deals with the mathematical modeling and analysis of a Pulse-Width-Modulation (PWM) based UPFC operating as voltage regulator implemented on a single machine connected to infinite bus through parallel transmission lines. The steady-state performance simulation results of the system are presented for different value of the modulation index. In addition, the optimum position of the UPFC device is investigated.

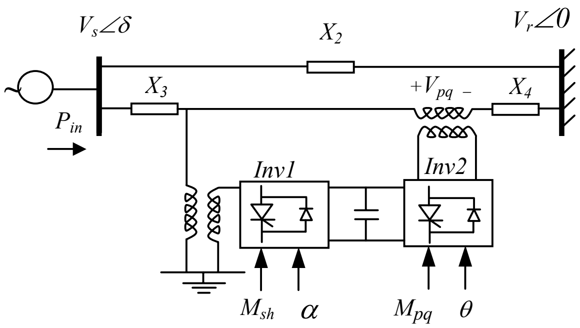

Figure 1. UPFC Controller.

2. Mathematical model

The study system on which the UPFC device is implemented is shown as a single line diagram in Figure 2. A synchronous machine feeds an active power P_1 and reactive power Q_1 to an infinite bus-bar via a parallel transmission lines. V_s is the sending end voltage with δ load angle, V_r is the receiving end voltage, and X_2, X_3, X_4 are the transmission lines impedance. V_{pq} is the series injected voltage of inverter (2). I_{pq} is the transmission line current passing through the series compensation block of the UPFC. V_{sh} is the shunt input voltage of inverter (1) and X_{sh} is the leakage reactance of the shunt transformer, which is assumed to be purely inductive for simplicity.

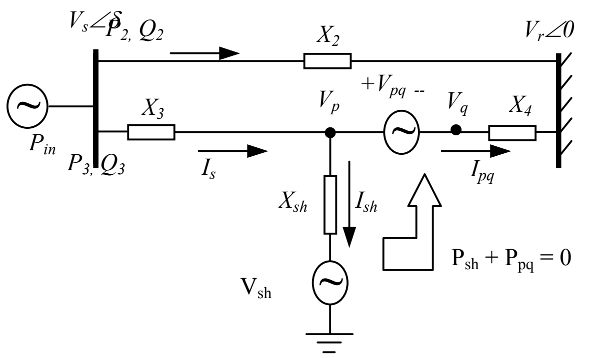

Figure 2. Single Line Diagram of the Study System.

In order to operate the UPFC systems as a voltage regulator, the voltage V_{pq} should be injected to the transmission line in phase with the transmission line voltage V_p. This can be seen in the vector diagram shown in Figure 3.

$$V_p = |V_{pq}| \angle \beta \tag{1}$$

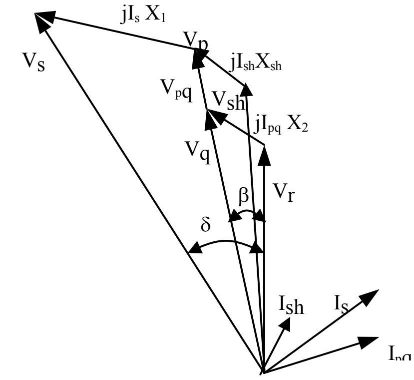

Figure 3. Vector Diagram of Figure 2.

If the UPFC is an operating base on the PWM method, the magnitude of V_{pq} can be calculated as (Mohan, *et al.* 1998),

$$|V_{pq}| = 0.35 M_{pq} Vdc \tag{2}$$

where M_{pq} is the modulation index of the inverter (2) and it is varying from 10% to 100%. On the other hand, the voltage magnitude of the input voltage V_{sh} of the inverter (1) is:

$$|V_{sh}| = 0.35 M_{sh} Vdc \tag{3}$$

where M_{sh} is the modulation index of the inverter (2) and its value is assumed to be constant (M_{sh} = 100%). Therefore, from equation (2) and (3), we can confirm that;

$$|V_{pq}| = M_{pq} |V_{sh}| \tag{4}$$

In general,

$$V_{sh} = |V_{sh}| \angle -\alpha \tag{5}$$

where α is the angle with respect to the transmission line voltage V_p as shown in Figure 3. This angle will determine the amount of the power demand to the inverter (2) from inverter (1).

From the vector diagram of Figure 3 it can be seen that;

$$V_p = |V_{sh}| \angle (\beta - \alpha) + jX_{sh}(I_s - I_{pq}) \tag{6}$$

Equating the real and imaginary parts of equation (6) leads to;

$$\begin{aligned} |V_p| \cos(\beta)[1 + \frac{X_{sh}}{X_3} + \frac{X_{sh}}{X_4}] &= |V_{sh}| \cos(\beta - \alpha) + \frac{X_{sh}|V_s|}{X_3} \cos(\delta) \\ &+ \frac{X_{sh}|V_{pq}|}{X_4} \cos(\beta) + \frac{X_{sh}|V_r|}{X_4} \end{aligned} \tag{7}$$

$$|V_p| \sin(\beta)[1 + \frac{X_{sh}}{X_3} + \frac{X_{sh}}{X_4}] = |V_{sh}| \sin(\beta - \alpha) + \frac{X_{sh}|V_s|}{X_3} \sin(\delta) - \frac{X_{sh}|V_{pq}|}{X_4} \sin(\beta) \tag{8}$$

Hence, the active and reactive power at the shunt compensation block is calculated as

$$P_{sh} = \frac{|V_{sh}||V_p|}{X_{sh}}\sin(\alpha), \; Q_{sh} = \frac{|V_{sh}||V_p|}{X_{sh}}\cos(\alpha) - \frac{|V_{sh}|^2}{X_{sh}} \quad (9),(10)$$

The active and reactive power of the series compensation block is determined as

$$P_{pq} = -\frac{|V_{pq}||V_r|}{X_4}\cos(\beta + 90) \quad (11)$$

$$Q_{pq} = \frac{|V_{pq}||V_p|}{X_4} - \frac{|V_{pq}|^2}{X_4} - \frac{|V_{pq}||V_r|}{X_4}\sin(\beta + 90) \quad (12)$$

For the sake of simplicity, it is assumed that the active power consumed by this FACTS device is zero. Therefore, from (9) and (11)

$$P_{pq} + P_{sh} = 0 \quad (13)$$

Hence, the input power (P_1) can be determined as

$$P_1 = \frac{|V_s||V_r|}{X_2}\sin(\delta) + \frac{|V_s||V_p|}{X_3}\sin(\delta - \beta) \quad (14)$$

Therefore; if $P_1, |V_s|, |V_r|,$ and $|V_{sh}|$ are given (known), then equations (4), (7), (8), (13) and (14) can be solved. Accordingly, the UPFC can be operated as a voltage regulator with different operation points by varying the modulation index M_{pq} from 10% to 100%. In addition, if X_3 is varied with respect to X_4, then an investigation for locating the optimum position of the FACTS device along the transmission line is also possible.

3. Simulation results

The system in Figure 1 has been modeled and simulated by using the Matlab package program. An active power (P_1) supplied to the grid by the synchronous machine selected to be 40 MW, the terminal sending end voltage V_s = 66.9 kV and the receiving end voltage V_r = 65.4 kV. The two parallel transmission lines are assumed to be identical and each having a series reactance of (X=20 Ω). Hence the power injected by the generator will be equally divided on the two transmission lines before installing the FACTS device (i.e. $P_2 = P_3$ = 20 MW). On the other hand, V_{sh} is selected to be 20% of the terminal line voltage V_p before the installation of the FACTS device.

The steady-state performance results have been tested by varying the series modulation index M_{pq} from 10% to 100%. In addition, the effect of the installation location of the FACTS device has been investigated.

Figure 4 shows that at each position the terminal line voltage (V_p) can be controlled by varying the modulation index M_{pq}. However it can be seen that, the V_p is more sensitive to the variation of the modulation index M_{pq} as the installation of the FACTS device is more close to the receiving terminal bus. In addition, minimum value of V_p can be obtained when the device is installed at position around mid point of the transmission line.

Figures 5 and 6 show that, at each position, the distribution of the active power flow in both lines can be controlled by varying the modulation index *Mpq*. However, it can be seen that, in some positions the power flows in both lines are more sensitive to the variation of the modulation index *Mpq*.

Figure 7 shows that the reactive power flow (Q_3) through the transmission line on which the FACTS device is installed, is highly sensitive to the change of the modulation index M_{pq}, whereas the reactive power flow of the other line (Q_2) is slightly sensitive to the change of the modulation index M_{pq} as shown in Figure 8. Furthermore, Figure 7 shows that the reactive power (Q_3) is decreasing as the position is increasing and this is because both angles β and δ are also decreasing as the percentage position is increasing as shown in Figures 9 and 10.

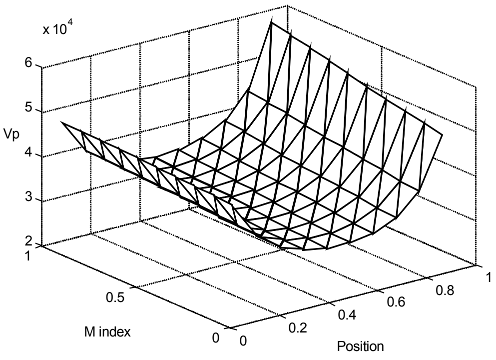

Figure 4. Terminal voltage V_p for various various Modulations index.

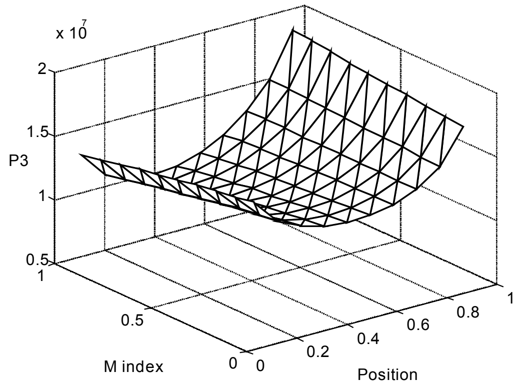

Figure 5. Active power Flow P2 for Modulation index.

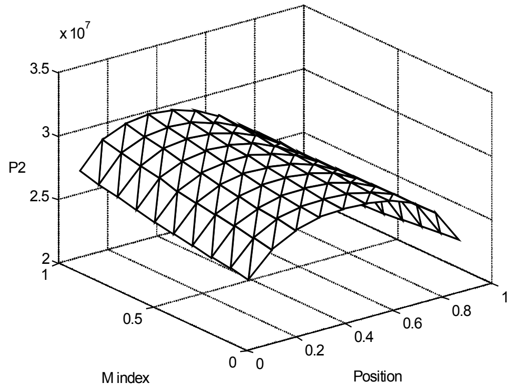

Figure 6. Active Power Flow P2 for various. for various Modulations index.

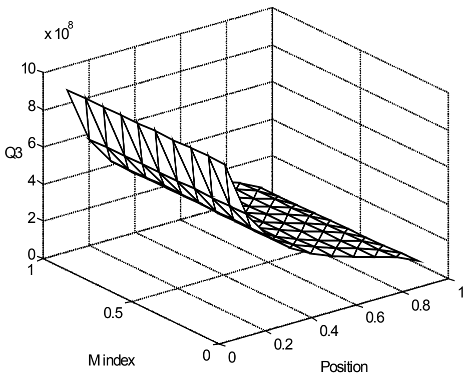

Figure 7. Reactive power Flow Q3 Modulation index.

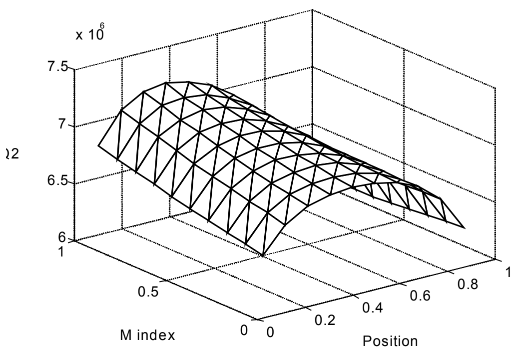

Figure 8. Reactive power flow Q2 for various various Modulation index.

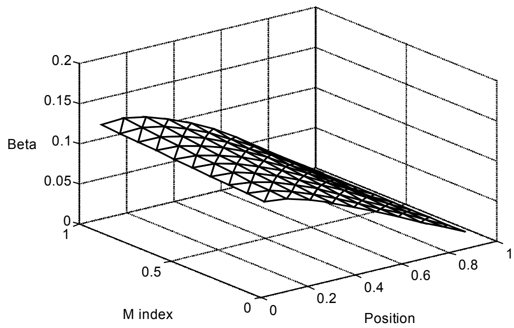

Figure 9. Variation of angle (β) for Modulation index.

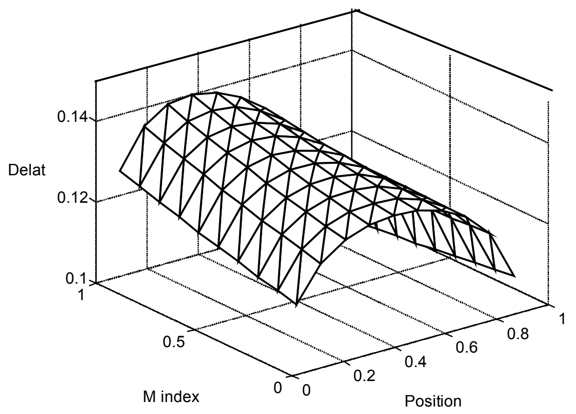

Figure 10. Load angle (δ) for various Modulation index.

6. Conclusions

The UPFC has been modeled as a voltage regulator. The system with parallel transmission lines has been simulated using a Matlab program package. In this case a PWM scheme has been used to control the operation of the series compensation block of the UPFC. It has been shown that by varying the modulation index (M_{pq}), the active power flow distribution in the parallel transmission lines can be controlled. In addition, the effect of the installation location of such FACTS device has been discussed. Furthermore, the simulation results have shown that the reactive power flow is highly sensitive to the variation of the modulation index (*Mpq*) on the line connected to the device, while it is much less sensitive to the variation of *Mpq* on the other line.

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