Increasing the Permissive Opening Time of Circuit Breakers by Using UPFC

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Abstract

The aim of this paper is to analyze the effect of an Unified Power Flow Controller (UPFC) in order to increase the permissive opening time of circuit breakers, keeping transient stability of power systems. Consequently the cost of these devices which are the essential factors in the cost of power systems, will be decreased.

The results of simulation performed by ATP-EMTP simulation package confirm the validity of theory on which the proposed control algorithm is based.

Keywords

ATP-EMTP, Circuit Breaker, FACTS, Local Measurement, Transient Stability, Unified Power Flow Controller.

1. INTRODUCTION

The control of an ac power system in real time is involved because power flow is a function of transmission line impedance, the magnitude of the sending and receiving end voltages, and the phase angle between these voltages. Years ago, electric power systems were relatively simple and were designed to be self-sufficient; power exportation and importation were rare. Furthermore, it was generally understood that AC transmission systems could not be controlled fast enough to handle dynamic system conditions. Transmission systems were designed with fixed or mechanically-switched series and shunt reactive compensations, together with voltage-regulating and phase shifting transformer tap-changers, to optimize line impedance, minimize voltage variation, and control power flow under steady-state or slowly changing load conditions. The dynamic system problems were usually handled by over design; transmission system were designed with generous stability margins to recover from anticipated operating contingencies caused by faults, line and generator outages, and equipment failures. All these results, in the (often considerable) under utilization of transmission systems [1].

Nowadays , energy, environment, and cost problems have delayed the construction of both generation facilities and new transmission lines, while the demand for electric power has continued to grow. This situation has necessitated a review of the traditional power system concepts and practices to achieve greater operating flexibility and better utilization of existing power systems.

Over the years, the fast development of high-power switching devices, such as Gate Turn Off thyristors (GTO_s), and Insulated Gate Bipolar Transistors ($IGBT_s$) has resulted in the possibilities to implement high-rating and fast-response FACTS (Flexible AC transmission Systems) devices. Within the framework of FACTS, and other efforts with similar objectives, the development of thyristor-controlled series compensators for line impedance control, thyristor-controlled tap-changing transformers for phase angle control, and other thyristor-controlled devices for dynamic 'brakes' and over voltage suppressors has already been started. In recent years new types of FACTS devices which may be used to increase power system operation flexibility and controllability ,to enhance system stability and to achieve better utilization of existing power systems have been investigated. The Unified Power Flow Controller (UPFC) is one of these devices and presents very attractive features [2].

This paper is organized as follows. After this introduction, the principle of operation and also the mathematical equations of an UPFC connected to a network are presented. Section 4 describes UPFC control and modeling. In section 5, the proposed control strategy for UPFC series part is introduced. Simulation results and conclusion are presented in section 6 and section 7 respectively.

2. UPFC PRINCIPLE OF OPERATION

A simplified scheme of a UPFC connected to an infinite-bus via a transmission line is shown in Fig. 1.

https://doi.org/10.24084/repqj03.256

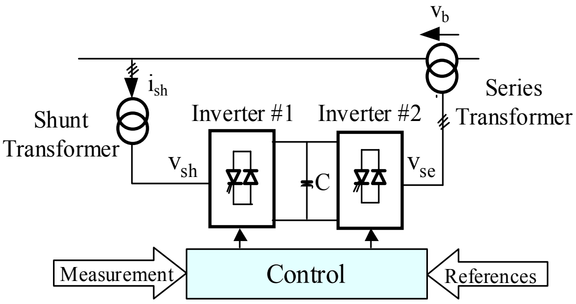

Fig. 1. UPFC installed in transmission line

UPFC is consisted of a parallel and series branch, each one containing a transformer, power electric converter with turn-off capable semiconductor devices and DC circuit. Assume that the series part known as Static Synchronous Series Compensator (SSSC) can be controlled without restrictions, that is, the phase angle of series voltage (δ_b) can be chosen independently from line current between 0 to 2π, and its magnitude is variable between zero and a defined maximum value, $V_{b\text{-}max}$. This implies that series voltage source must be able to inject both real and reactive power.

The parallel part known as STATic Synchronous COMpensator (STATCOM), injects an almost sinusoidal current of variable magnitude at the point of connection.

While operating both the inverters together as a UPFC, the exchanged power at the terminals of each inverter can be imaginary as well as real. The component of the injected voltage that is in or out of phase with the line current emulates a positive or negative resistance in series with the transmission line. The remaining component, which is in quadrature with the line current, emulates an inductive or a capacitive reactance in series with the transmission line [1,6]. The current injected by the STATCOM has a real or direct component, Id, which is in phase or in opposite phase with the line voltage. This current has also a reactive or quadrature component, Iq, which is in quadrature with the line voltage, thereby emulating an inductive or a capacitive reactance at the connection point with the transmission line.

This reactive current can independently controlled which, in turn, will regulate the line voltage [7].

3. MATHEMATICAL MODEL OF UPFC

The mathematical UPFC model was derived with the aim of being able to study the relations between the electrical transmission system and UPFC in steady state conditions. The basic scheme of this model is shown in Fig. 2.

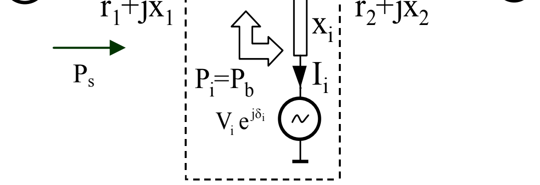

Fig. 2. Mathematical model of UPFC and transmission system

This figure represents a single line diagram of a simple transmission line with a resistance, r, an inductive reactance, x, a UPFC, a sending-end voltage source, $\overline{V}_s$, and a receiving-end voltage source, $\overline{V}_r$, respectively.

According to the Fig. 2, the currents $\bar{I}_s, \bar{I}_i$ *and* $\bar{I}_r$ are calculated by the following expressions:

$$\bar{I}_s = \frac{1}{x_{eq}^2}(V_i e^{j\delta_i}(r_2 + jx_2) + jV_r x_i - V_s e^{j\delta}(r_2 + j(x_2 + x_i)) - V_b e^{j\delta_b}(r_2 + j(x_i + x_2))$$

$$\bar{I}_i = \frac{1}{x_{eq}^2}(-V_b e^{j\delta_b}(r_2 + jx_2) - V_r(r_1 + jx_1) - e^{j\delta}V_s(r_2 + jx_2) + V_i e^{j\delta_i}(r_1 + r_2 + j(x_1 + x_2)))$$

$$\bar{I}_r = \frac{1}{x_{eq}^2}(-V_i e^{j\delta_i}(r_1 + jx_1) - jV_s e^{j\delta}x_i - jV_b e^{j\delta_b} x_i + V_r(r_1 + j(x_1 + x_i))) \tag{1}$$

Where:

$$x_{eq}^2 = x_1 x_2 + (x_1 + x_2)x_i - jr_2(x_1 + x_i) - r_1(r_2 + j(x_2 + x_i))$$

The UPFC is installed at the end of transmission line, and taken the values of a real system [9] for transmission lines and the transformers, so the active and reactive power equations are as follow:

$$P_s = \Re(\overline{V}_s e^{j\delta}\,\bar{I}_s^*) = 0.138 + 0.25\sin(\delta_b - \delta) - 0.138\cos\delta + 1.56\sin\delta + 0.02\cos(\delta_b \_ \delta)$$

$$Q_s = \Im(\overline{V}_s e^{j\delta}\,\bar{I}_s^*) = 1.56 - 1.56\cos\delta + 0.25\cos(\delta - \delta_b) + 0.02\sin(\delta - \delta_b) - 0.138\sin\delta \tag{2}$$

Considering the variation of δ_b and δ according to the following relation (3) and drawing P_s versus δ, δ_b, there will be the different possibilities of P_s, which are shown in Fig. 3.

$$0 \le \delta_b \le 2\pi$$
$$0 \le \delta \le \pi \tag{3}$$

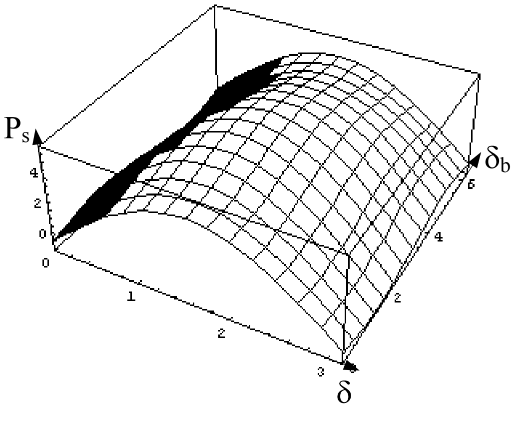

Fig. 3. Variation of Ps

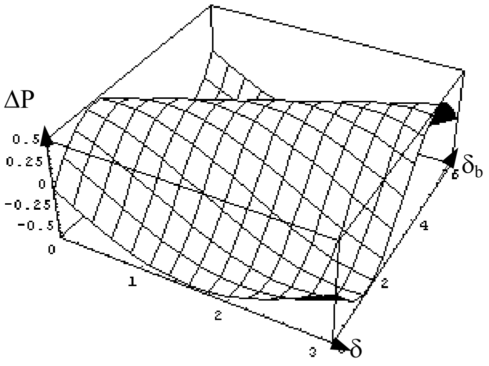

Fig. 4. Series injected voltage effect on Ps

4. UPFC CONTROL AND MODELING

Fig. 5 shows the single line diagram of a UPFC connected at the end of transmission line.

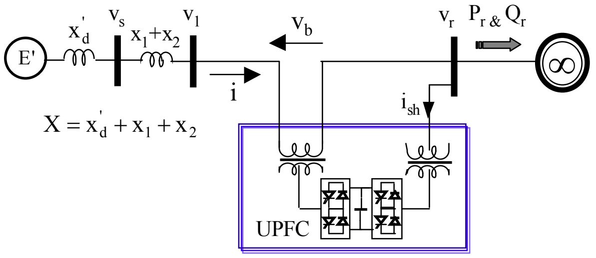

Fig. 5. Generator-infinite bus system with the UPFC

The vector diagram of an UPFC connected to a network (Fig.5) is presented in figure 6.

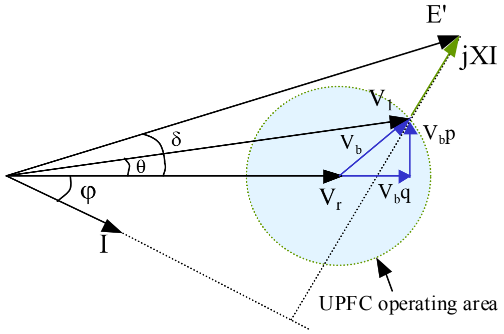

Fig. 6. Vector diagram of an UPFC connected to a network

According to the Fig. 6, V_bp and V_bq are the components of the series voltage of UPFC. They are proportional to the voltage at the point of connection of UPFC and can be written as:

$$V_bq = V_r\,\beta(t) \qquad \& \qquad V_bp = V_r\,\gamma(t) \tag{4}$$

Where β(t) and γ(t) are the control variables. Neglecting network losses, the electrical power can be expressed as:

$$P_r = \frac{E'V_1}{X}\sin(\delta-\theta) = \frac{E'V_1}{X}(\sin\delta\cos\theta - \cos\delta\sin\theta) \tag{5}$$

where X is the equivalent transient reactance which includes the transient reactance of generator, the reactance of the transformer and the transmission line.
The generator swing equation is:

$$M\frac{d^2\delta}{dt^2} = P_m - A\sin(\delta) - D\frac{d\delta}{dt} - P_{UPFC} \tag{6}$$

Where:

$$A = \frac{E'V_r}{X} \text{ and } P_{UPFC} = -A\cos(\delta)\gamma(t) + A\sin(\delta)\beta(t) \tag{7}$$

P_{UPFC} introduces additional damping to the system if it is positive and proportional to the speed deviation $\frac{d\delta}{dt}$. This can be achieved through the following control strategy:

$$\gamma(t) = -K\cos(\delta)\frac{d\delta}{dt} \qquad \& \qquad \beta(t) = K\sin(\delta)\frac{d\delta}{dt} \tag{8}$$

By replacing (8) in (7) the damping factor D_{UPFC} is represented as bellow:

$$P_{UPFC} = KA\frac{d\delta}{dt} = D_{UPFC}\frac{d\delta}{dt} \tag{9}$$

The state variables defined by equations (9) can be approximately executed by using time derivatives of the receiving active and reactive powers (P_r and Q_r).

According to Fig. 6, there are the following equations:

$$\begin{aligned} &V_r + V_bq + XI\sin(\varphi) = E'\cos(\delta) \\ &V_bp + XI\cos(\varphi) = E'\sin(\delta) \end{aligned} \tag{10}$$

Multiplying (10) by V_r, the equations (11) will be obtained:

$$\begin{aligned} P_r &= \frac{V_r E'}{X}\sin(\delta) - \frac{V_r V_bp}{X} \\ Q_r &= \frac{V_r E'}{X}\cos(\delta) - \frac{V_r V_bq}{X} - \frac{V_r^2}{X} \end{aligned} \tag{11}$$

The partial derivative of P_r is calculated as (12).

$$\begin{aligned} \frac{dP_r}{dt} &= \frac{\partial P_r}{\partial\delta}\times\frac{d\delta}{dt} + \frac{\partial P_r}{\partial V_bp}\times\frac{d(V_bp)}{dt} \\ \frac{dP_r}{dt} &= \frac{(-V_bp)E'}{KX} - \frac{V_r}{X}\times\frac{d(V_bp)}{dt} \end{aligned} \tag{12}$$

The partial derivative of Q_r is also calculated as (13).

$$\begin{aligned} \frac{dQ_r}{dt} &= \frac{\partial Q_r}{\partial\delta}\times\frac{d\delta}{dt} + \frac{\partial Q_r}{\partial V_bq}\times\frac{d(V_bq)}{dt} \\ \frac{dQ_r}{dt} &= \frac{(-V_bq)E'}{KX} - \frac{V_r}{X}\times\frac{d(V_bq)}{dt} \end{aligned} \tag{13}$$

To achieve the damping effects during the transient regime, the control strategy of injected series voltage is given in the next section based on the above discussion.

5. CONTROL STRATEGY

The reference of series injected voltage and shunt injected current are calculated and applied to the control system as described in figure 4.

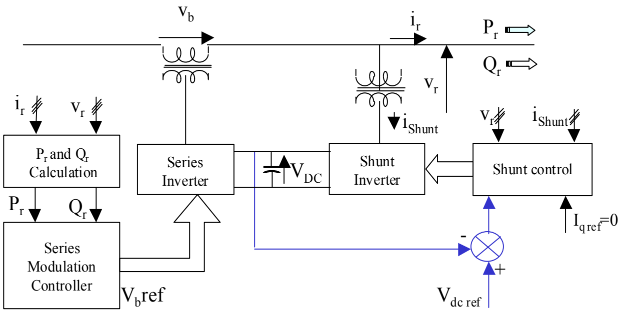

Fig. 7. Block diagram of inverter control

a) Shunt Part

The shunt converter has two duties:

1) to control the voltage magnitude at the sending-end bus by locally generating (or absorbing) reactive power
2) to supply or absorb real power at the dc terminals as demanded by the series converter [8].

In this paper, the voltage magnitude control is not considered. General block diagram of the shunt part control is given in figure 8.

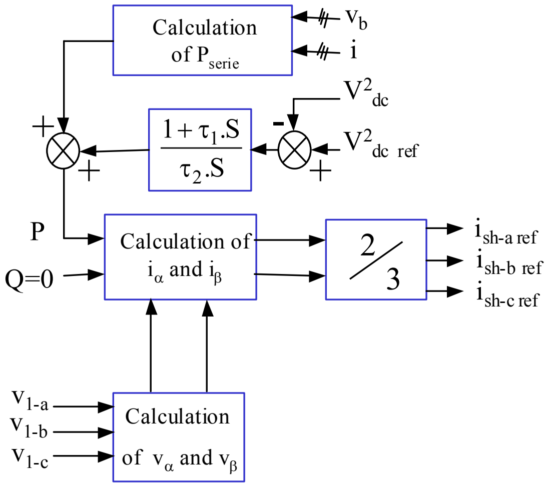

Fig. 8. Control Block Diagram of a STATCOM

b) Series Part

The SSSC can be operated in many different modes, such as voltage injection, phase angle shifter emulation, line impedance emulation, automatic power flow control, etc. In each mode of operation, the final outcome is such that the SSSC injects a voltage in series with the transmission line [10]. One can design the modulation controller for series injected voltage by using equations (10) and (11). Figure 9 shows the proposed block diagram of a modulation controller capable of producing a real differentiating element with a small time constant T. The value of K is chosen so that the injected series voltage remains at its nominal value.

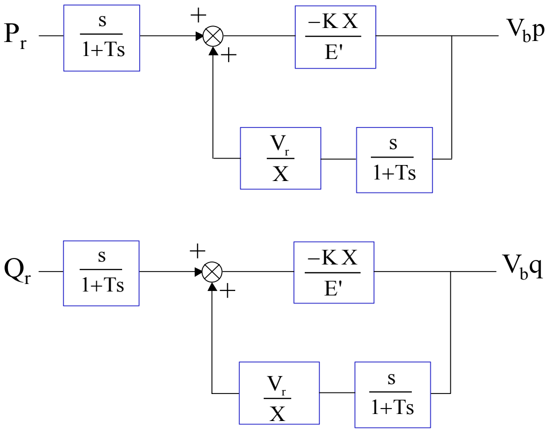

Fig. 9. Modulation controller for Vbp and Vbq

The injected series voltage is calculated as equation (14).

$$V_b\,\mathrm{ref} = \sqrt{V_b^2 p + V_b^2 q} \qquad \delta_b = Arctg\left(\frac{V_b\,p}{V_b\,q}\right) \tag{14}$$

This voltage which is applied to the control system, is presented in figure 7.

6. SIMULATION RESULTS

The results of some digital simulations are shown in figures 10-13 in per unit. The short circuit duration time in all simulations is considered between t=0.2 and 0.4 sec. In figure 10, the behavior of the test system is shown for the case of a 200 ms fault duration and without UPFC. The generator has lost its synchronism.

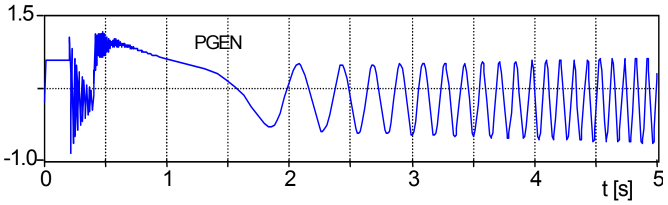

Fig. 10. Generator active power (not stable)

By using UPFC, one can increase the permissive opening time of circuit breakers and maintaining the stability of the power system.

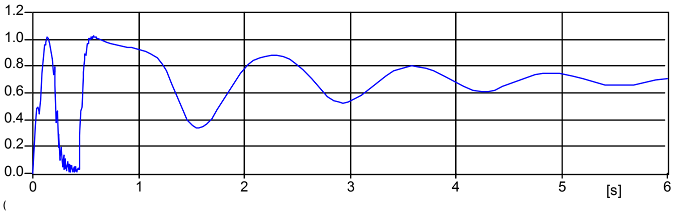

Fig. 11. Generator active power (stable)

Figure 12 shows the components of injected series voltage which was calculated by the proposed control system.

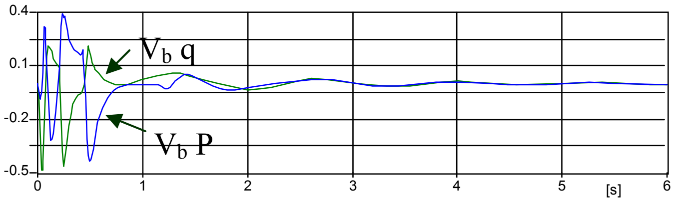

Fig. 12. Injected voltage components

Figure 13 shows the common capacitor voltage which is disturbed during the fault. It is recovered approximately 1.5 second after the fault.

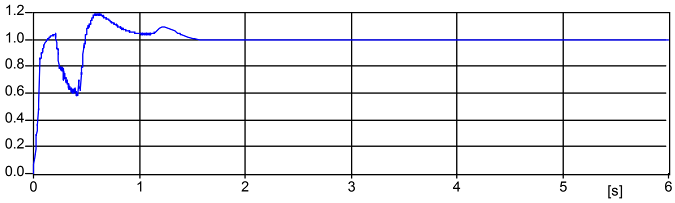

Fig. 13. DC voltage of common capacitor

7. CONCLUSION

In this paper , the influence of Flexible AC Transmission Systems (FACTS), especially Unified Power Flow Controller (UPFC) has been analyzed due to decreasing the cost of circuit breakers.

Injection series voltage of UPFC in a special network lead to increasing permissive operating time of circuit breakers, keeping transient stability of power system.

This research shows that UPFC is an effective device for decreasing the cost of circuit breakers.

A new method for determining UPFC control parameters is proposed according to the “Local Measurement”.

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9. BIOGRAPHIES

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