Improvement of transient stability of power systems by using UPFC

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Abstract. The aim of this paper is to use an Unified Power Flow Controller (UPFC) for improvement of transient stability margin. Determination of the suitable damping strategy is based on Lyapunov energy function of the power system. The injection model is used for UPFC. A complementary control strategy is proposed to calculate the series injected voltage. The simulation results by using Electromagnetic Transient Program (ATP-EMTP) show that the suggested UPFC control strategy improves transient stability of the power system.

Key words

EMTP, FACTS, Injection Model, Transient Stability, Unified Power Flow Controller.

1. Introduction

With the increased loading of long transmission lines, the problem of transient stability after a major fault can become a limiting factor for transmission power. On the other hand, in recent years, new types of FACTS devices have been investigated which may be used to increase power system operation flexibility and controllability and to enhance system stability. Noroozian [3] and Ghandhari [2] applied the injection model of UPFC for improving power system stability. In this method, the magnitude of series injected voltage is always constant and only its phase (according to the control strategy) changes. This means that the equilibrium point before and after fault will be changed. The objective of this paper is to inject series voltage with the same control strategy for the phase angle. The magnitude of this voltage is not constant and is proportional to the line active power variations.

2. UPFC operating principles

As shown in Fig. 1, UPFC consists of a parallel and series branch, each one consisting of a transformer, power electric converter with turn-off capable semiconductor devices and DC circuit.
Assume that the series voltage source ($V_b\angle\delta_b$) 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 and 2π, and its magnitude is variable between zero and a defined maximum value, $V_b$max. This implies that series voltage source must be able to exchange both active 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.

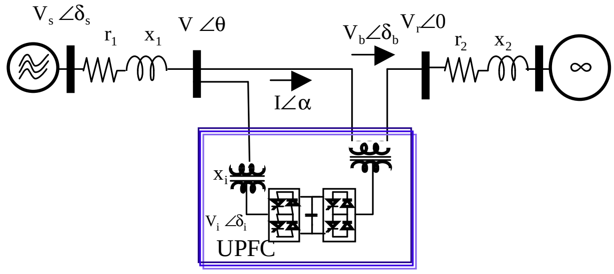


Fig. 1. UPFC Connected to the Power System

While both inverters operating together as a UPFC, the exchanged power at the terminals of each inverter can be imaginare as well as real. The component of the injected voltage, which 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. The exchanged active power, P_{inv}, and reactive power, $Q_{inv,}$ by the SSSC with the line are:

$$P_{inv} = \vec{V}_b \bullet \vec{I} = V_b \,.\, I.\cos\gamma$$
$$Q_{inv} = \vec{V}_b \times \vec{I} = V_b \,.\, I.\sin\gamma \qquad (1)$$

That: $\gamma=\delta_b-\alpha$

The real power is absorbed from or delivered to the line through the STATCOM, which injects a current at the connection point. The current injected by the STATCOM has a real or direct component, I_d, which is in phase or in opposite phase with the line voltage. This current has a reactive or quadrature component, I_q, 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 [4, 5].

Considering the values that are indicated in appendix A, one can write the equations of sending active (P_s) and reactive power (Q_s) for the studied system as follow:

$$P_s = -0.5V_b \cos\delta_b + 0.3V_i \cos\delta_i + 1.14V_b \sin\delta_b - 0.54V_i \sin\delta_i + 0.645$$

$$Q_s = 1.14V_b \cos\delta_b - 0.54V_i \cos\delta_i + 0.51V_b \sin\delta_b - 0.3V_i \sin\delta_i + 0.72 \quad (2)$$

The phase angle of sending-end voltage is taken 0.524 rad (δ_s=30°).

Figure 2 shows the impact of series voltage on the sending active and reactive power of the system in per unit. In figure 2a, the value of $|V_b|$ is considered equal to 0.16 per unit and δ_b is varied from 0° to 360°. The sending active and reactive powers are as bellow:

$$P_s(\delta_b) = 0.95 - 0.08\cos(\delta_b) + 0.183\sin(\delta_b) \quad (3)$$
$$Q_s(\delta_b) = 0.181 + 0.183\cos(\delta_b) + 0.08\sin(\delta_b)$$

In figure 2b, δ_b is considered equal to zero and $|V_b|$ is varied from 0 to 0.25 per unit. In this study, the shunt current only supplies the desired active power for DC link capacitor.

The sending active and reactive powers in this case are as bellow:

$$P_s(V_b) = 0.95 - 0.5V_b \quad (4)$$
$$Q_s(V_b) = 1.14V_b + 0.18$$

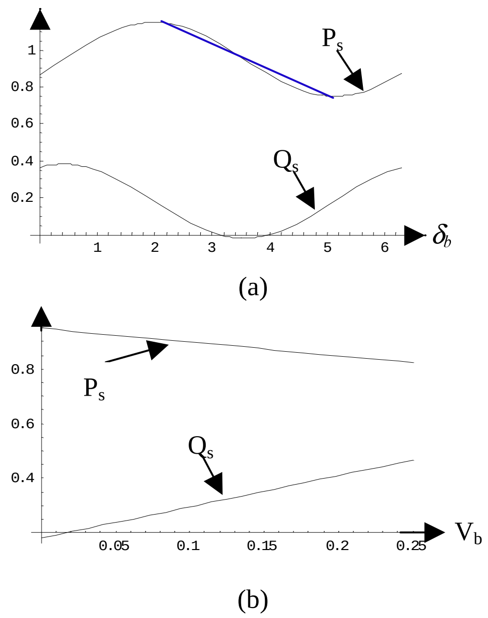


Fig. 2. P_s and Q_s versus a) δ_b b) V_b

From the above explanations it is evident that by choosing a proper control law for injected series voltage one can improve the stability of system. This control law is based on the Lyapunov energy function, which will be developed in the next sections.

3. Injection model of UPFC

Figure 3a shows the equivalent circuit diagram of a UPFC located between buses i and j. It is shown that the equivalent circuit diagram of figure 3a can be modeled as the dependent load injected at nodes i and j. This model is called injection model and the general configuration is shown in figure 3c [3].

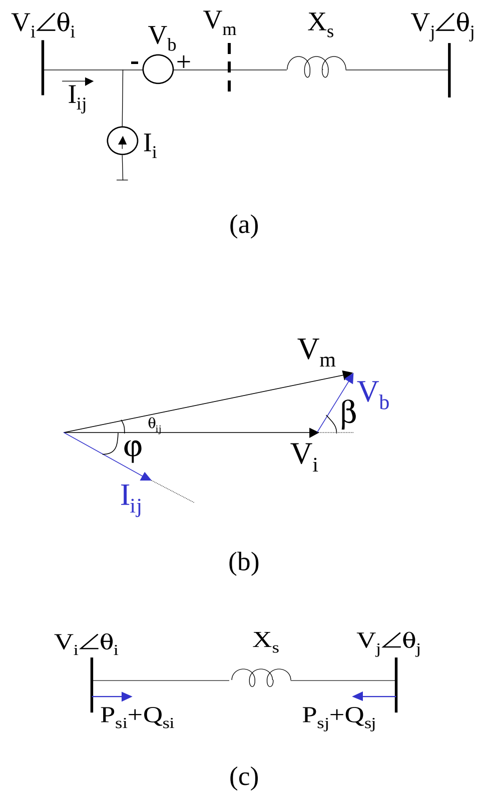


Fig.3: injection model of UPFC, a) UPFC b) Vector diagram c) Injection model

It is shown that the above active and reactive powers can be expressed as below [2,3]:

$$Q_{si} = \frac{V_b.V_i}{X_s}.\cos\beta \qquad Q_{sj} = -\frac{V_b.V_j}{X_s}.\cos(\theta_{ij} + \beta)$$
$$P_{si} = -P_{sj} = \frac{V_b.V_j}{X_s}.\sin(\theta_{ij} + \beta) \quad (5)$$

Where, X_s is the reactance of the series transformer.

4. Control strategy

The control of a UPFC can be divided into two parts, the control of the series part (SSSC) and that of shunt part (STATCOM).

A- SSSC

The SSSC can be operated in many different modes such as voltage injection, phase angle shifter emulation, line impedance emulation, automatic power flow controller, etc. In this paper the SSSC is operated in a voltage injection mode. The control strategy of series part is based on Lyapunov energy function of power system. The UPFC must be controlled in such a way that: $\nu' < 0$ where ν is the Lyapunov energy function [3].

$$\nu = \int M.\Delta\omega.d(\Delta\omega) - \int (P_{mec} - P_{max}\sin\delta).d\delta = \text{constant} \quad (6)$$

Function ν' can be expressed as (7) or approximately as (8):

$$\nu' = P_{sj}\frac{d\theta_{ij}}{dt} - [Q_{si}.\frac{d(\ln V_i)}{dt} + Q_{sj}\frac{d(\ln V_j)}{dt}] \le 0 \quad (7)$$

$$\nu' = P_{sj}.\frac{d\theta_{ij}}{dt} \le 0 \quad (8)$$

Applying (3) in (6) gives:

$$\nu' = [-\frac{V_b.V_j}{X_s}.\sin(\theta_{ij} + \beta)].\frac{d\theta_{ij}}{dt} \le 0 \quad (9)$$

For satisfying equation (9), following cases should be met:

$$\text{If } \frac{d\theta_{ij}}{dt} \ge 0 \quad \text{then} \quad V_b = V_b \max \quad \text{and} \quad \beta = \frac{\pi}{2} - \theta_{ij}$$

$$(10)$$

$$\text{If } \frac{d\theta_{ij}}{dt} < 0 \quad \text{then} \quad V_b = V_b \max \quad \text{and} \quad \beta = -\frac{\pi}{2} - \theta_{ij}$$

After clearing the fault (post fault time) if the system remains stable, so the derivation of generator active power will be decreased to zero. In this case, there is no need to apply the whole-injected series voltage ($V_b$max). By taking the following control law the magnitude of injected series voltage will be:

$$V_b = V_b \max.\frac{d(P_{GEN})}{dt} \quad (11)$$

The angle of V_b is calculated from equation (10).

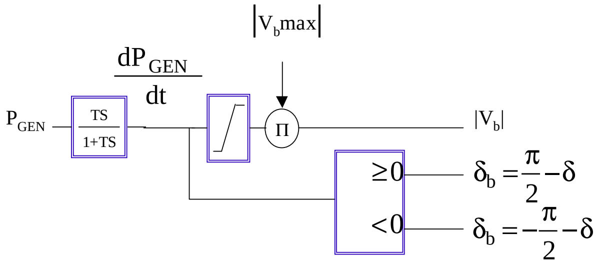


Fig.4: Control block diagram of the series part

B- STATCOM

The shunt converter has two duties: to control the voltage magnitude at the sending-end bus by locally generating (or absorbing) reactive power and to supply or absorb real power at the dc terminals as demanded by the series converter. In this paper, the voltage magnitude control is not considered. General block diagram of the shunt part control is given in figure 5.

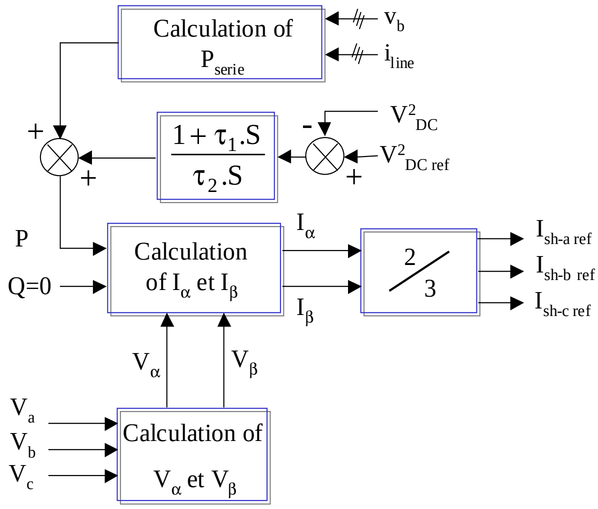


Fig.5: Control block diagram of the shunt part

5. Numerical examples

Figure 5 shows the one line diagram of a Single Machine Infinite Bus (SMIB) system, which the detailed characteristic is given in appendix A . To study the dynamic of this system, consider a 3-phase fault at the beginning of the transmission line. The duration of this short-circuit is considered to be 200 msec.

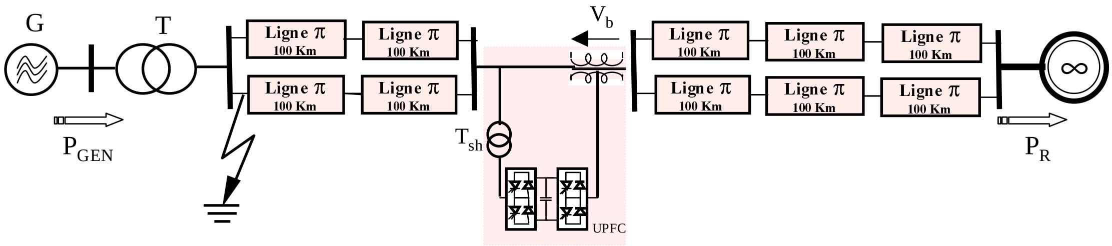


Fig.6: One line diagram of the studied system

Several cases are compared in this section.

A- Generator unstable

At first, consider that there is not any additional device like UPFC. Figure 7 shows the variation of generator active power. It is clear that after short circuit the generator will lose its synchronism and is no more stable.

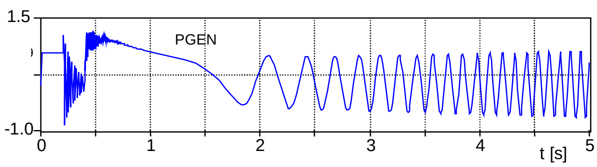
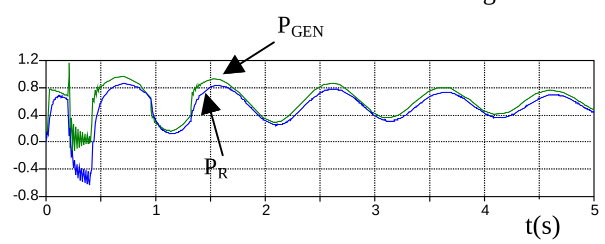


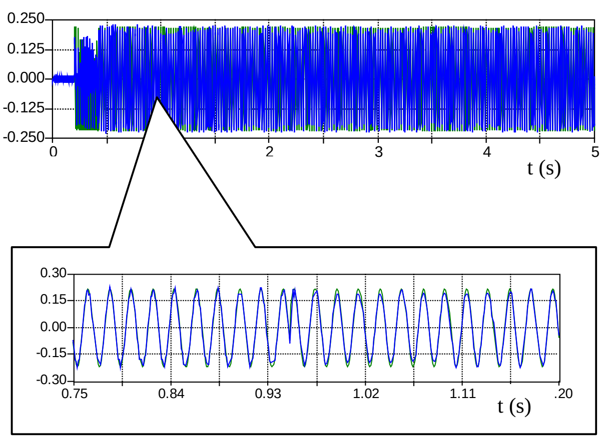
Fig.7: Generator active power (instable)

B- Generator stable (injection model)

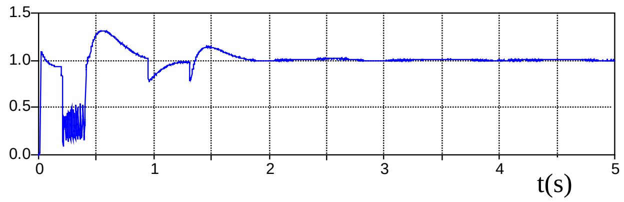
In the second case, consider the same network with UPFC. The injection model for UPFC, as proposed in [3], is used. The simulation results are shown in figure 8.



a) Sending and receiving active power



b) Series injected voltage



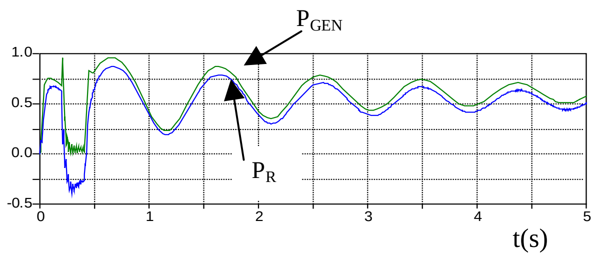
c) DC link voltage

Fig.8. Simulation results for case B

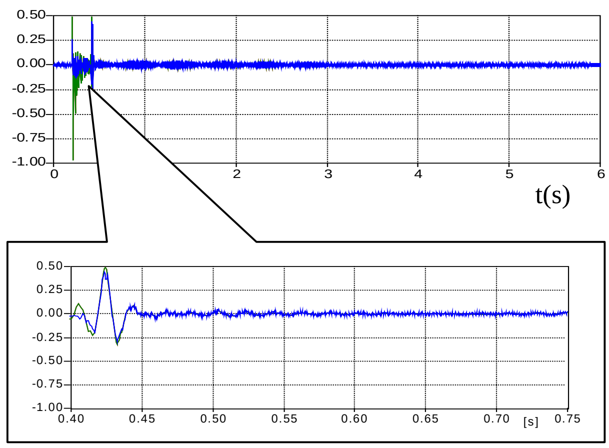
Figure 8b shows the injected series voltage of UPFC to the transmission line. According to the control strategy, only the phase angle of series voltage changes (e.g. at t=0.95 sec) and its magnitude remains constant. Therefore, the equilibrium point before and after the fault will be changed.

C- Generator stable (injection model-new control law)

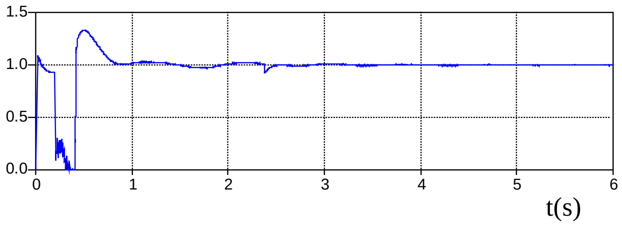
The simulation results obtained by using the improved injection model are shown in figure 9.



(a) Sending and receiving active power



(b) Series injected voltage



(c) DC link voltage

Fig.9. Simulation results for case C

Figure 9b shows that in new method, the injected series voltage after a few oscillations becomes at zero and the equilibrium point of system before and after fault remains constant.

6. Conclusion

The Lyapunov stability theory and the injection model of UPFC have been used to make a supplementary control loop in order to improve first swing transient stability. Based on injection method [3], a new control law is proposed for the first swing stability enhancement. In this method, the equilibrium point before and after the fault remains constant. The main disadvantage of this approach is in transient regime when the injected voltage can be more important than nominal. However, it does not last too much.

7. Appendix A

The electric data of the system has been considered as below:

Generator (G):

Rated voltage: 15.7 KV.
Rated Power: 1000 MVA
Synchronous reactance: 0.1 p.u.

R_a=.0024 p.u	X_d=X_q=1.89 p.u
X'_d=0.32 p.u	X''_q=0.213 p.u
X''_d=0.213 p.u	T'_{do}=1.087 sec
T''_{do}=0.135sec	$J=0.1\times10^6$ kg-m^2
T''_{qo}=0.136sec	

Transformer (T):

Voltage ratio: 15.7 / 400 KV
Rated power: 1000 MVA

Primary impedance: r_p=0.00073 Ω
l_p=0.0502 mH
Secondary impedance: r_s=0.48 Ω
l_s=32.62 mH

transmission line:

Resistance: r_{line}=3.2 Ω/100 Km
Inductance: l_{line}=103 mH/100 Km
Capacitance: c_{line}=1.1 μF/100 Km
Shunt transformer:

Voltage ratio: 20 / 400 KV

Rated power: 160 MVA
Primary impedance: r_p=0.005 Ω
l_p=0.399 mH
Secondary impedance: r_s=2 Ω
l_s=159 mH
Series transformer

Voltage ratio: 20 / 63 KV
Rated power: 160 MVA
Primary impedance: r_p=6.25 mΩ
l_p=0.239 mH
Secondary impedance: r_s=62 mΩ
l_s=2.37 mH

The base of voltage and power for per-unit calculation are:
V_{base} =15.7 Kv (at the generator output)
S_{base}=1000 MVA

Per unit values of studied network are:

x_i=0.62 p.u., x_1=0.33 p.u., x_2=0.304 p.u., r_1=0.026 p.u., r_2=0.03 p.u.,V_i=1 p.u., V_r=1 p.u., V_s=1 p.u., V_b=0.16 p.u.

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