

A POWER FLOW CONTROL STRATEGY FOR FACTS DEVICES

RUSEJLA SADIKOVIC, ETH ZÜRICH, SWITZERLAND,
sadikovic@eeh.ee.ethz.ch

GÖRAN ANDERSSON, ETH ZÜRICH, SWITZERLAND,
andersson@eeh.ee.ethz.ch

PETR KORBA, ABB, SWITZERLAND, petr.korba@ch.abb.com

ABSTRACT

This paper discusses power flow control in electric power system by use of unified power flow controller (UPFC). A current injection model of the UPFC is used. The control objective is to maintain the line power flow of a controlled line at a desired value. The control objective can be achieved by linearizing the line power flow equations around the operating point. The paper introduces the criterion for validation of two proposed control methods. The UPFC and power system network model have been developed in Matlab/Simulink environment for the simulations to demonstrate the proposed methods.

KEYWORDS: Power Flow Control, Unified Power Flow Controller, Simulation.

1. INTRODUCTION

With the development of FACTS devices, it becomes possible to enhance power flow controllability considerably. To meet the load and electric market demands, new lines should be added to the system, but due to environmental reasons, the installation of electric power transmission lines must often be restricted. The need to maintain power flow between generation and loads through defined line corridors without affecting other paths or the consumers in the system will be of importance in the future. In addition to the modeling aspect, development of an appropriate method for the power flow control using FACTS devices is another important issue to consider. One approach is developed in this paper.

The UPFC current injection model [1] is used in simulations, because that model is more suitable for use in power system studies. The current injection model is obtained from modification of the UPFC power injection model [2]. To achieve the control objective, the UPFC should operate in the automatic power flow control mode keeping the active and reactive line power flow at the specified values P_{sp} and Q_{sp} . In addition, the controller has to be robust to act properly if some parameters in the transmission system are changing. This can be achieved by linearizing of the line power flow equations on the series side of the UPFC, around the operating point. The linearization results in a gain matrix, that gives the changes in the control variables. Following a closed-loop scheme, the error feedback adjustment involves adjusting the control variables in order to achieve the specified value. Two control methods are proposed, based on different representations of the control variables. They are given in polar and rectangular form, respectively. It can be seen that these two approaches give a different impact on achieving the desired power flow values. In order to evaluate the two proposed methods, a criterion considering square error area, maximum overshoot and settling time, is proposed.

2. UPFC MODEL AND CONTROL

2.1 UPFC Current Injection Model

The UPFC power injection model is derived enabling three parameters to be simultaneously controlled [2]. They are namely the shunt reactive power, Q_{conv1} , and the magnitude, r , and the angle γ , of injected series voltage \vec{V}_{se} . For a dynamic analysis, due to model requirements, current injection model is more appropriate [1]. Figure 1 shows the circuit representation of a

UPFC, where the series connected voltage source is modeled by an ideal series voltage \bar{V}_{se} which is controllable in magnitude and phase, that is $\bar{V}_{se} = r\bar{V}_i e^{j\gamma}$ where $0 \leq r \leq r_{\max}$ and $0 \leq \gamma \leq 2\pi$, and the shunt converter is modeled as an ideal shunt current source \bar{I}_{sh} . The reactance x_s in Figure 1 represents the reactance seen from the terminals of the series transformer and is equal to (in p.u. base on system voltage and base power)

$$x_s = x_k r_{\max}^2 (S_B / S_S) \quad (1)$$

where x_k denotes the series transformer reactance, r_{\max} the maximum per unit value of injected voltage magnitude, S_B the system base power, and S_S the nominal rating power of the series converter.

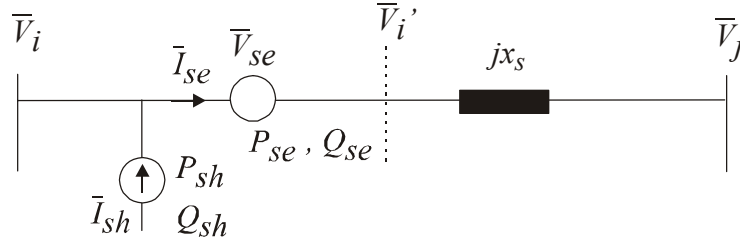


Figure 1. The UPFC electric circuit arrangement

In Figure 1,

$$\bar{I}_{sh} = \bar{I}_t + \bar{I}_q = (I_t + jI_q)e^{j\theta_i} \quad (2)$$

where \bar{I}_t is the current in phase with \bar{V}_i and \bar{I}_q is the current in quadrature with \bar{V}_i . In Figure 2 the voltage source \bar{V}_{se} is replaced by the current source $\bar{I}_{inj} = -jb_s \bar{V}_{se}$ in parallel with x_s .

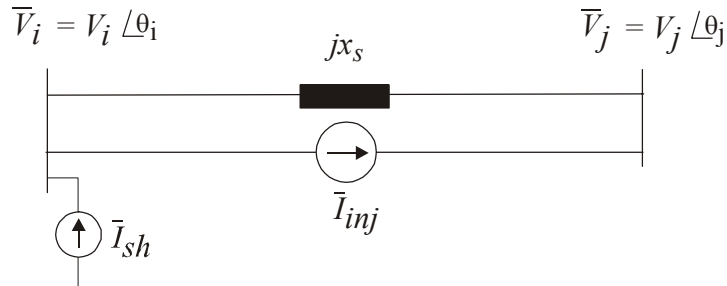


Figure 2. Transformed series voltage source

The active power supplied by the shunt current source can be calculated from

$$P_{CONV1} = \text{Re}[\bar{V}_i (-\bar{I}_{sh})^*] = -V_i I_t \quad (3)$$

Having the UPFC losses neglected,

$$P_{CONV1} = P_{CONV2} \quad (4)$$

The apparent power supplied by the series voltage source converter is calculated from

$$\bar{S}_{CONV2} = \bar{V}_{se} \bar{I}_{se}^* = r e^{j\gamma} \bar{V}_i \left(\frac{\bar{V}_i' - \bar{V}_j}{jx_s} \right)^* \quad (5)$$

Active and reactive power supplied by Converter 2 are distinguished as

$$P_{CONV2} = rb_s V_i V_j \sin(\theta_i - \theta_j + \gamma) - rb_s V_i^2 \sin \gamma \quad (6)$$

$$Q_{CONV2} = -rb_s V_i V_j \cos(\theta_i - \theta_j + \gamma) + rb_s V_i^2 \cos \gamma + r^2 b_s V_i^2 \quad (7)$$

From Eq. (3), (4) and (6) we have

$$I_t = -rb_s V_j \sin(\theta_i - \theta_j + \gamma) + rb_s V_i \sin \gamma \quad (8)$$

The shunt current source is calculated from

$$\bar{I}_{sh} = (I_t + jI_q) e^{j\theta_i} = (-rb_s V_j \sin(\theta_{ij} + \gamma) + rb_s V_i \sin \gamma + jI_q) e^{j\theta_i} \quad (9)$$

From Figure 2 the currents in Figure 3 can be defined,

$$\bar{I}_{si} = \bar{I}_{sh} - \bar{I}_{inj} \quad (10)$$

$$\bar{I}_{sj} = \bar{I}_{inj} \quad (11)$$

where

$$\bar{I}_{inj} = -jb_s \bar{V}_{se} = -jb_s r \bar{V}_i e^{j\gamma} \quad (12)$$

Inserting Eq. (9) and (12) into Eq. (10) and (11) yields

$$\bar{I}_{si} = (-rb_s V_j \sin(\theta_{ij} + \gamma) + rb_s V_i \sin \gamma + jI_q) e^{j\theta_i} + jrb_s V_i e^{j(\theta_i + \gamma)} \quad (13)$$

$$\bar{I}_{sj} = -jb_s V_i e^{j(\theta_i + \gamma)} \quad (14)$$

where I_q is an independently controlled variable, representing a shunt reactive source. Based on previous Equations, the current injection model can be presented as in Figure 3.

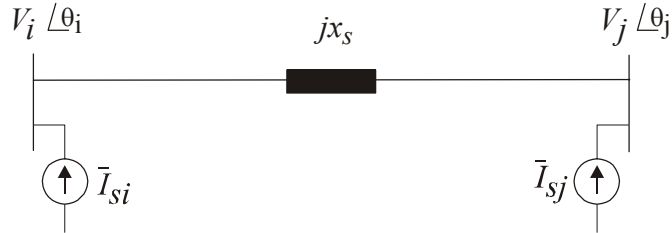


Figure 3. The UPFC current injection model

Besides the current bus injection, for the control purposes, it is very useful to have expressions for power flows from both sides of the UPFC injection model defined. At the UPFC shunt side, the active and reactive power flows are given as

$$P_{i1} = -rb_s V_i V_j \sin(\theta_{ij} + \gamma) - b_s V_i V_j \sin \theta_{ij} \quad (15)$$

$$Q_{i1} = -rb_s V_i^2 \cos \gamma + Q_{conv1} - b_s V_i^2 + b_s V_i V_j \cos \theta_{ij} \quad (16)$$

whereas at the series side they are

$$P_{j2} = rb_s V_i V_j \sin(\theta_{ij} + \gamma) + b_s V_i V_j \sin \theta_{ij} \quad (17)$$

$$Q_{i2} = rb_s V_i V_j \cos(\theta_{ij} + \gamma) - b_s V_j^2 + b_s V_i V_j \cos \theta_{ij} \quad (18)$$

2.2 Control Strategy and Results

As discussed in the previous section, the UPFC current injection model is defined by the constant series branch susceptance, b_s , which is included in the system bus admittance matrix, and the bus current injection, I_{si} and I_{sj} . If there is a control objective to be achieved, the bus current injection are modified through changes of the UPFC control parameters r, γ and I_q . In this paper, the control objective is to maintain the power of controlled line at the expected value. That means the UPFC should operate in the automatic power flow control mode keeping the active and reactive line power flow at the specified values P_{sp} and Q_{sp} .

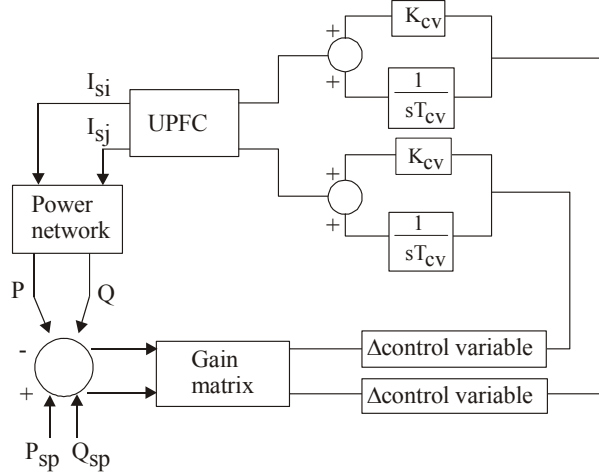


Figure 4. General form of the UPFC control system

The control objective can be achieved by linearizing the line power flow equations, Eq. (17) and (18), around the operating point. Figure 4 proposes the general form of the UPFC control system according to this approach. The linearization results with the gain matrix in Figure 4. Δr and $\Delta \gamma$ are the changes in the control variables, for the first approach, assuming that the third variable I_q is inactive. The control method is tested on the two area system, Figure 5. The UPFC is located in line 8.

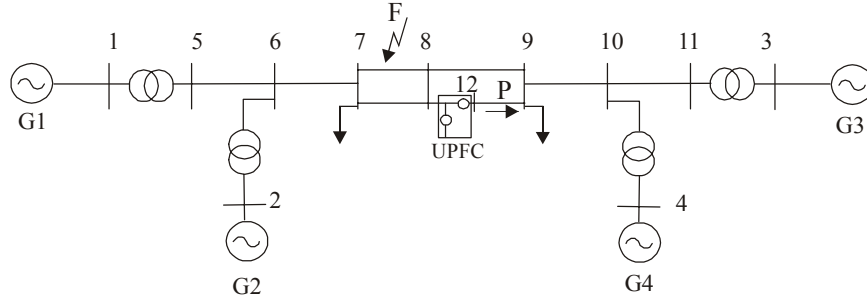


Figure 5. The two area system with UPFC located in line 8

The second control approach is based on the series voltage u_{dq} . If u_{dq} is the instantaneous voltage injected by the UPFC, the components u_d and u_q can be related to the control variables

$$u_d = r \cos(\gamma), \quad u_q = r \sin(\gamma) \quad (19)$$

and hence the current injection model is adapted to this new control variables.

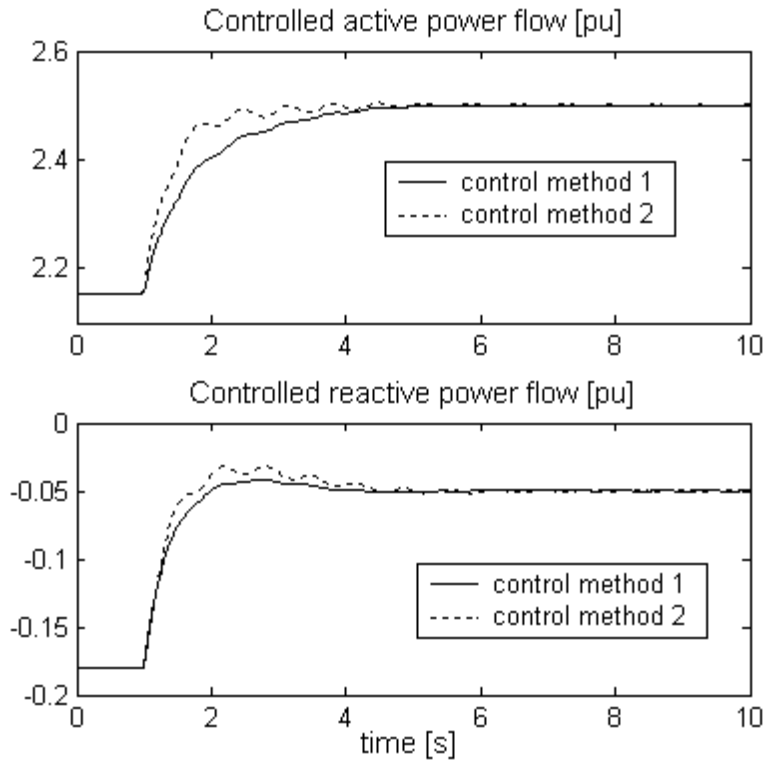


Figure 6. The first and the second methods simulation results for the active and reactive power flow

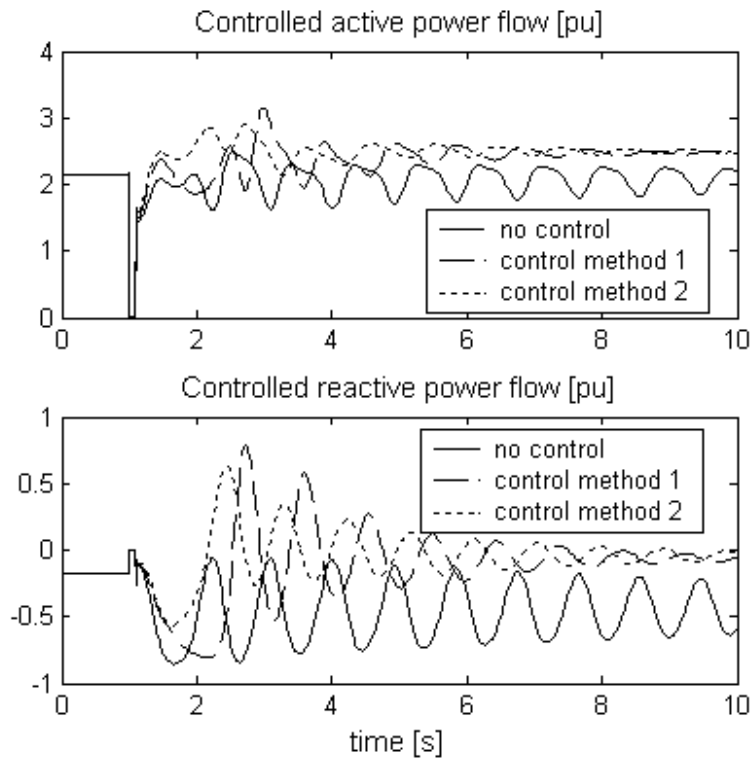


Figure 7. The first and the second methods simulation results for the active and reactive power flow with fault applied

Figure 6 shows the results of the proposed control methods. The simulation starts with actual power flow of $P_{base} = 2.1526[pu]$ and $Q_{base} = -0.1798[pu]$. At $t = 1$ s, the specified power flows change to $P_{sp} = 2.5[pu]$ and $Q_{sp} = -0.05[pu]$.

The second case study demonstrates the capabilities of the proposed control methods for the same test system but with fault occurs at point F, Figure 5. The fault is cleared after 100 ms by opening the faulted line. The control objective is the same, to maintain the power of the controlled line at the specified value. Figure 7 shows the simulated results for power flow under this fault condition, with the first and the second control approach.

In order to compare the proposed methods, the criterion considering square error area, maximum overshoot and settling time, is proposed. This criterion function is defined as:

$$J_{PQ} = J_1 + J_2 + J_3 \quad (20)$$

$$J_1 = w_1 T_s \sum \left(\frac{S_m - S_{sp}}{S_{sp}} \right)^2$$

$$J_2 = w_2 \max \left(\text{abs} \left(\frac{S_m - S_{sp}}{S_{sp}} \right) \right) \quad (21)$$

$$J_3 = w_3 i$$

where are

w_1, w_2, w_3 – weighted factors;

T_s – sampling period;

S_m – measured values;

S_{sp} – specified values;

i – settling time.

According to this criterion the first method gives better results for the power flow control, for the both cases, without and with the fault in the system. As can be seen, both controllers can effectively reach the specified values of the active and reactive line power and especially, with the fault applied, they can damp system oscillations very successfully.

3. CONCLUSIONS

In this paper two methods for power flow control are proposed. It is shown that both controllers act properly in order to achieve desired active and reactive power flows in the line, as well as to damp a power oscillations. It means that the controllers are robust and they act properly when the parameters in the transmission system are changing. The performances of the proposed UPFC controllers have been evaluated in two area system by nonlinear simulations.

4. REFERENCES

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