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Load flow analysis by Newton Raphson Method with and without UPFC

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Abstract - ***Controlling power flow in modern power systems can be made more flexible by the use of recent developments in power electronic and computing control technology. The Unified Power Flow Controller (UPFC) provides a promising means to control power flow in modern power systems. Essentially, the performance depends on proper control setting achievable through a power flow analysis program. This paper aims to present a reliable method to meet the requirements by developing a Newton-Raphson based load flow calculation program through which control setting of UPFC can be determined directly. A MATLAB program has been developed to calculate the control setting parameters of the UPFC after the load flow is converged. Case studies have been performed on IEEE 5-bus system to show that the proposed method is effective. These studies indicate that the method maintains the basic NRLF properties such as fast computational speed, high degree of accuracy and good convergence rate.***

Key Words: UPFC, FACTS, load flow, Newton-Raphson method, MATLAB.

1. INTRODUCTION

With the development of power systems, especially the opening of electric energy markets, it becomes more and more important to control the power flow along the transmission line, thus to meet the needs of power transfer. On the other hand, the fast development of electronic technology has made FACTS (Flexible A.C. Transmission Systems) a promising path for future power system needs. The UPFC is an advanced power systems device capable of providing simultaneous control of voltage magnitude and active and reactive power flows in an adaptive fashion. Owing to its instantaneous speed of response and unrivalled functionality, it is well placed to solve most issues relating to power flow control while enhancing considerably transient and dynamic stability. In this paper UPFC is treated to operate in closed loop form and the control parameters of the UPFC are derived to meet the required power flow along the line. This paper finds the control setting of UPFC i.e., the magnitude and angular position of the injected voltage, through a robust load flow calculation. The calculation involved is robust in the sense that the number of equations to be solved is more, time taking and complicated.

2. OPERATING PRINCIPLES OF UPFC

The unified power flow controller consists of two switching converters. These converters are operated from a common link provided by a dc storage capacitor (Figure1). Converter 2 provides the main function of the UPFC by injecting an ac voltage with controllable magnitude and phase angle in series with the transmission line via a series transformer. The basic function of converter 1 is to supply or absorb the real power demand by converter 2 at the common dc link. It can also generate or absorb controllable reactive power and provide independent shunt reactive compensation. The injection model is obtained by replacing the voltage for the line. Converter 2 supplies or absorbs locally required reactive power and exchanges the active power as a result of the series injection voltage.

3. Basic Principles of P and Q Control

Consider a fig 1 of simple two machine (or two bus ac inter line) system with sending end voltage Vs, receiving end voltage Vr, and line or tie impedance X, (assumed, for simplicity, inductive) the voltage of system in the form of phasor diagram of shown with transmission angle δ and Vs = Vr =V. The transmitted power P= (V2 / X) sin (δ) and the reactive power Q=Qs = Qr {Q = (V2 / X) (1-cos (δ)} supplied at the end of the line are shown plotted against angle. The reactive power Q= Qr=Qs is shown plotted against the transmitted power P corresponding to stable value of δ (0≤ δ ≤90°).The basic power system with the well known transmission characteristic is introduced for the purpose of providing a vehicle to establish the capability of the UPFC to control the transmitted real power P and reactive power demands, Qs and Qr at sending end respectively, the Transmission end of line.

The UPFC is represented by a controllable voltage source in series with the line, which as explained in the previous system, can generate or absorb reactive power that it negotiates with the line, but the real power it exchanges must be supplied to it, or absorbed from it, bye

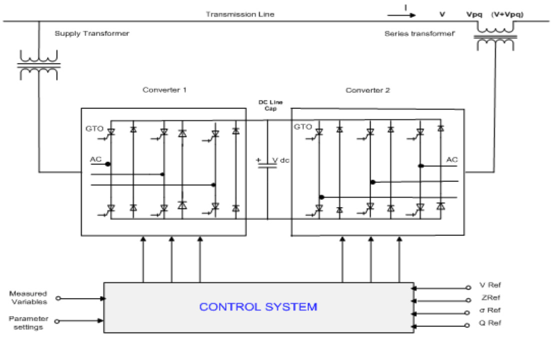

Figure1: UPFC arrangement in Transmission system

the sending end generator. The UPFC in series with the line is represented by the phasor Vpq Having magnitude V_{pq} ($0 \le V_{pq} \le V_{pq\ max}$) and angle ρ ($0 \le \rho \le 360^{\circ}$) measured from the given phase position of phasor Vs, as illustrated in the figure. The line current represented by phasor 1, flows through the series voltage source V_{pq} and generally results in both reactive and real power exchange.

3.1 Operating modes of UPFC

The UPFC have many possible operating modes. In particular, the shunt inverter is operating in a such a way to inject a controllable current Ish into the system transmission line.

The shunt inverter can be controlled in two different modes

3.1.1. VAR Controllable mode:

The reference input is an inductive or capacitive VAR request. The shunt inverter control converts the VAR reference into a corresponding shunt current request and adjusts gating of the inverter to establish the desired current. For this mode of control a feedback signal representing the dc bus voltage, Vdc is also required.

3.1.2. Automatic voltage control mode:

The shunt inverter reactive current is automatically regulated to maintain the transmission line voltage at the point of connection to a reference value. To this mode of control, voltage feedback signals are obtained from the sending end bus feeding the shunt coupling transformer. The series inverter controls the magnitude and angle of the voltage injected in series with the line to influence the power flow on the line.

The actual value of the injected voltage can be obtained in different ways.

3.1.2.1 Direct voltage injection mode:

The reference inputs are directly the magnitude and phase angle of the series voltage.

3.1.2.2 Phase angle shifter emulation mode: The reference input is phase displacement between the sending end voltage and the receiving end voltage.

3.1.2.3 Line impedance emulation mode:

The reference is an impedance value to insert in series with the line impedance.

3.1.2.4 Automatic power flow control mode:

The reference inputs are values of P and Q to maintain on the transmission line despite system changes.

4. UPFC Model For Power Flow Studies

In the following section, a model for UPFC which will be referred as UPFC injection model is derived. This model is helpful in understanding the impact of the UPFC on the power system in the steady state. Furthermore, the UPFC injection model can easily be incorporated in the steady state power flow model. Since the series voltage source converter does the main function of the UPFC, it is appropriate to discuss the modelling of a series voltage source converter first.

4.1. Series connected voltage source converter model

Suppose a series connected voltage source is located between nodes i and j in a power system. The series voltage source converter can be modelled with an ideal series voltage Vs in series with a reactance *Xs.* In Figure-2, *Vs* models an ideal voltage source and represents a fictitious voltage behind the series reactance:

The source voltage, terminal voltage at PCC and load voltage are denoted by v_s, v_t and v_L respectively. The source and load currents are denoted by i_s and i_L respectively. The voltage injected by series APF is denoted by v_{Sr}, whereas the current injected by shunt APF is denoted by i_{Sh}. Taking the load voltage, v_L, as a reference phasor and suppose the lagging power factor of the load is $Cos_{\varphi L}$ then we can write

$$\overline{V_L} = V_L \angle 0^0 \qquad 1$$

$$\overline{I_L} = I_L \angle -\emptyset_L \qquad 2$$

$$\overline{V_t} = V_L(1+K)\angle 0^0 \qquad 3$$

Where factor *k* represents the fluctuation of source voltage, defined as,

$$k = \frac{V_t - V_L}{V_L} \qquad 4$$

The voltage injected by series APF must be equal to,

$$\overline{V_{sr}} = \overline{V_L} - \overline{V_t} = -kV_L\angle 0^0 \qquad 5$$

The UPFC is assumed to be lossless and therefore, the active power demanded by the load is equal to the active power input at PCC. The UPFC provides a nearly unity power factor source current, therefore, for a given load condition the input active power at PCC can be expressed by the following equations,

$$P_t = P_L \qquad 6$$

$$V_t i_s = V_L i_s \cos \emptyset_L \qquad 7$$

$$V_L(1+k)i_s = V_L i_s \cos\emptyset_L \qquad 8$$

$$i_s = \frac{i_L}{(1+k)}\cos\emptyset_L \qquad 9$$

The above equation suggests that the source current i_S depends on the factor k, since φ_L and i_L are load characteristics and are constant for a particular type of load.

The complex power absorbed by the series APF can be expressed as,

$$\overline{S_{sr}} = \overline{V_{sr}}\, i_s \qquad 10$$

$$P_{sr} = V_{sr} i_s \sin\emptyset_s = -kV_L i_s \cos\emptyset_s \qquad 11$$

$$Q_{sr} = V_{sr} i_s \sin\emptyset_s \qquad 12$$

$\emptyset_S = 0$, since UPQC is maintaining unity power factor

$$P_{sr} = V_{sr} i_s = -kV_L i_s \qquad 13$$

$$Q_{sr} = 0 \qquad 14$$

The complex power absorbed by the shunt APF can be expressed as,

$$\overline{S_{sh}} = \overline{V_L}\,.\,i^*_{sh} \qquad 15$$

The current provided by the shunt APF, is the difference between the input source current and the load current, which includes the load harmonics current and the reactive current. Therefore, we can write;

$$\overline{I_{sh}} = \overline{I_s} - \overline{I_L} \qquad 16$$

$$\overline{I_{sh}} = \overline{I_s}\angle 0^0 - \overline{I_L}\angle - \emptyset_L \qquad 17$$

$$\overline{I_{sh}} = i_s - (i_L \cos\emptyset_L - j\, i_L \sin\emptyset_L) \qquad 18$$

$$\overline{I_{sh}} = ((i_s - (i_L\cos\emptyset_L)) + j i_L \sin\emptyset_L) \qquad 19$$

$$P_{sh} = V_L i_{sh}\cos\emptyset_{sh} = V_L(i_s - i_L\cos\emptyset_L) \qquad 20$$

$$Q_{sh} = V_L i_{sh}\sin\emptyset_{sh} = V_L i_L \sin\emptyset_L \qquad 21$$

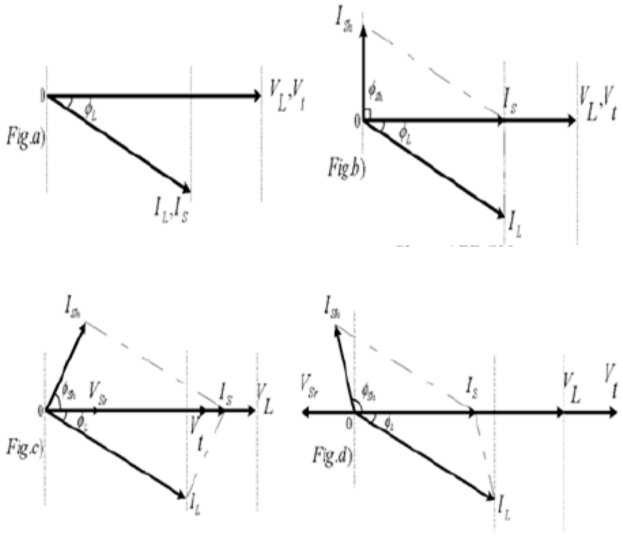

Figure2: a-d Phasor representation of all possible conditions of UPFC a)Under normal condition b) Shunt APF on c) Series APF on at condition of under voltage and d) Series APF on at condition of over voltage

Algorithm For NR Method

1. Formulate the YBUS

2. Assume initial voltages as follows:

$$v_i = v_{ispec}\llcorner 0^0 \quad \text{(at all PV buses)} \qquad 22$$

$$v_i = 1\llcorner 0^0 \quad \text{(at all PQ buses)} \qquad 23$$

3. At (r+1)st iteration, calculate Pi$^{(r+1)}$ at all the PV and PQ buses and Qi$^{(r+1)}$ at all the PQ buses, using voltages from previous iteration, Vi$^{(r)}$.

The formulae to be used are

$$p_{ical} = p_i = G_{ii}v_i^2 + \sum_{\substack{k=1\\k\neq1}}^{n} v_i v_k (G_{ik}\cos\delta_{ik} + B_{ik}\sin\delta_{ik}) \qquad 24$$

$$Q_{ical} = Q_i = -B_{ii}v_i^2 + \sum_{\substack{k=1\\k\neq1}}^{n} v_i v_k (G_{ik}\sin\delta_{ik} - B_{ik}\cos\delta_{ik}) \qquad 25$$

4. Calculate the power mismatches (power residues)

$$\Delta p_i^r = p_{ispec} - p_i^{r+1} \quad \text{(at PV and PQ buses)} \qquad 26$$

$$\Delta Q_i^r = Q_{ispec} - Q_i^{r+1} \quad \text{(at PQ buses)} \qquad 27$$

5. Calculate the Jacobian [J$^{(r)}$] using V$_i^{(r)}$ and its elements spread over H, N, M, L sub- matrices .

6.Compute

$$\begin{bmatrix}\Delta\delta^r \\ \frac{\Delta v^r}{v}\end{bmatrix} = [J^r]^{-1}\begin{bmatrix}\Delta p^r \\ \Delta Q^r\end{bmatrix} \qquad 28$$

7. Update the variables as follows:

$$\delta_i^{r+1} = \delta_i^r + \Delta\delta_i^r \qquad 29$$

$$v_i^{r+1} = \delta_i^r + \Delta\delta_i^r \qquad 30$$

8. Go to step 3 and iterate till the power mismatches are within acceptable tolerance.

5. Case Study

An IEEE 5-bus network has been used to show quantitatively, how the UPFC performs. The original network is modified to include UPFC as shown in Figure-3, which compensates the line between the buses 3 and 4. The UPFC is used to regulate the active and reactive power flowing in the line at a pre specified value. The load flow equations are modified correspondingly at bus 3 and 4. The load flow solution for the modified network is obtained by using Newton-Raphson method. Depending on the pre specified value of the active and reactive power the UPFC control setting is determined after the load flow is converged.

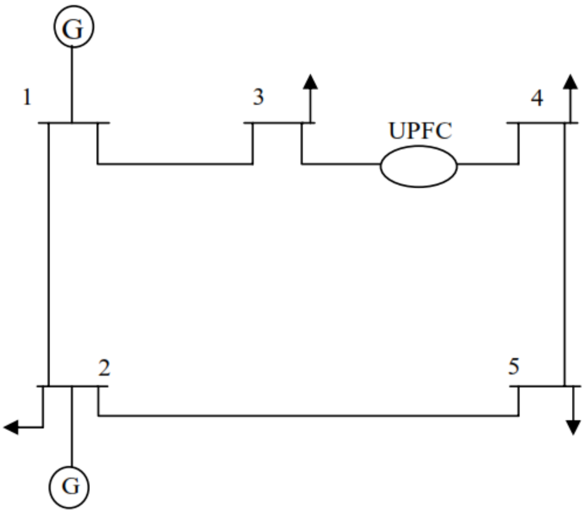

Figure3: 5 Bus system with UPFC connected between 3 and 4

The system having 5 buses in which one bus is slack bus, two buses are generating and two buses are load buses. The generation of PV buses and demand of load buses are given the following table 1 and the impedances and line charging admittances between the lines are given in table2.

Bus code p	Assumed Bus voltage	Generation		Load	
		MW	MVAR	MW	MVAR
1	1.06+j0.0	0	0	0	0
2	1.0+j0.0	40	-75	20	10
3	1.0+j0.0	0	0	45	15
4	1.0+j0.0	0	0	40	5
5	1.0+j0.0	0	0	60	10

Table 1: Data of buses in the system.

Bus code p-q	Impedance Z_{pq}	Line charging $Y_{pq}/2$
1-2	0.02+j0.06	0+j0.030
1-3	0.03+j0.24	0+j0.025
2-3	0.06+j0.18	0+j0.020
2-4	0.06+j0.18	0+j0.020
2-5	0.04+j0.12	0+j0.015
3-4	0.01+j0.03	0+j0.010
4-5	0.08+j0.24	0+j0.025

Table2: Impedances and line charging admittances between the lines in the system.

5. Results:

A MATLAB program was developed to find the control setting of UPFC when pre specified power flow is defined from bus 3 to bus 4. The results are compared and it is advantageous to keep the UPFC connected to the bus which is having low voltage profile.

Case-1: Results without UPFC

Bus code (p)	Voltage (PU)	Angle (rad)	Angle (deg)
1	1.06	0.0	0.0
2	0.992546	-0.033943	-1.944762
3	0.981424	-0.079984	-4.582736
4	0.977920	-0.085544	-4.901328
5	0.964432	-0.099612	-5.707344

Table3: Bus voltages in the system without UPFC

Case-2: Results with UPFC between buses 3 and 4

Bus code (p)	Voltage (PU)	Angle (rad)	Angle (deg)
1	1.06	0.0	0.0
2	0.998416	-0.034417	-1.971973
3	0.990050	-0.086497	-4.955889
4	0.992753	-0.081996	-4.698007
5	0.973622	-0.097996	-5.614737

Table4: Bus voltages and load angles in the system when UPFC is connected between 3 and 4

Voltage (V_T in PU)	Phase angle (Φ_T in rad)	Phase angle (Φ_T in deg)
0.0072	-1.588023	-90.98701

Table5: Controlling setting of UPFC to improve power flow between buses 3 and 4

6. Conclusion:

The Unified Power Flow Controller provides simultaneous or individual controls of basic system parameters like transmission voltage, impedance and phase angle, there by controlling the transmitted power. In this paper, a 5-bus system is considered and power flow program is run with and without UPFC. The UPFC is incorporated between buses 3 and 4 to control the transmission power to a specified value. Based on the specified transmission power, the UPFC control setting is determined for both cases. From the results it is concluded that the system performs better when the UPFC is connected to a bus which is having low voltage profile.

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