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Modeling and Simulation of the Series Connected Matrix Converter in Newton Power Flow

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ABSTRACT

This study covers completely the modeling and simulation methods needed for a detailed study of the steady-state operation of electrical power systems containing a power electronic controller: the series connected matrix converter. The matrix converter has a link with the transmission line between two transformers. Such a compensator controls the phase-angle and magnitude of voltage node. The chief aim of this study was to show how the appropriately modified Jacobian matrixes are augmented to the conventional power flow Jacobian. Three models of matrix converter for analysis of power flow are proposed which can be employed in steady state control of one of the ensuing variables: (1) the nodal voltage; (2) the real power flowing through the line and (3) both of the nodal voltage and the active power flowing through the line. Jacobian matrixes for any feasible operation of the device are derived. MATLAB/mfile codes are used to evaluate the numerical results for 6-bus system, IEEE 14-bus, 57-bus and 118-bus systems. Numerical examples on these standard power test systems are employed to show the models' viability in Newton-Raphson power flow algorithm.

Key words: Jacobian matrix, matrix converter, Newton-Raphson power flow, steady state model

INTRODUCTION

Deregulation of power utilities and increase of demands present considerable challenges to power systems. These problems have inevitably entailed much-needed improvements in electric power systems. In their book, Hingorani and Gyugyi (2000) gave useful information relating to technologies based on power-electronics which are successfully employed in competent handling of these problems. The comparatively recent developments in power flow controllers are FACTS (flexible ac transmission systems) devices which are effectively being utilized in both transmissions and distribution systems to meet various objectives (Seifi *et al.*, 2010; Song and Johns, 1999). In comparison with traditional compensators, the intrinsic nature of power electronic switches reveals fast response time. In all installed converter-based FACTS devices such as UPFC, SSSC and STATCOM, an AC/DC/AC converter carries out the power conversion (Seifi *et al.*, 2010). In recent years a partially successful attempt has been made to replace AC/DC/AC converters with the direct AC/AC converters. Three-phase matrix converter is an available and acceptable alternative. Holmes and Lipo (1992) described its characteristics such: being able to operate within four quadrants and containing no large and unwieldy dc-link. A few studies have investigated the use of matrix converter in power system applications. Sobczyk and Sienko (2006) reported the transmission line power flow control by means of matrix converter. Dasgupta *et al.* (2007) and

Ooi and Kazerani (1998) studied a UPFC based matrix converter; however, the steady state model of matrix converter based compensator is not reported yet. This motivated the authors to develop a multi purpose steady state model for the series connected matrix converter in power flow analysis. It should be noted that this model differs from the model of a back-to-back converter. Since there is no DC link in the matrix converter topology (and therefore no constraining power equation for DC link) the steady state model of back-to-back Voltage Source Converter (VSC) which is used for light HVDC systems (Acha *et al*., 2004), is not valid for matrix converter anymore. The key and primary objective of this study was to model and properly formulate the series based matrix converter in Newton method of power flow calculation.

GENERAL PRINCIPLE OF VOLTAGE AMPLITUDE AND PHASE ANGLE CONTROL WITH MATRIX CONVERTER

A three-phase to three-phase matrix converter is delineated in Fig. 1. This converter is comprised of nine bidirectional switches. Each output may be coupled through one switch to the input phases. A three-phase matrix converter has the ability to connect two three-phase AC power systems (Fig. 1). These three-phase systems may have different voltage amplitudes, different phase angles and different frequencies. Equation 1 shows the relation between the input and the output voltages of a matrix converter:

$$[V_O(t)] = [M(t)] \times [V_t(t)] \tag{1}$$

Where:

$$[V_i(t)] = \begin{bmatrix} V_{ia} \\ V_{ib} \\ V_{ic} \end{bmatrix} = \begin{bmatrix} V_{im}\cos(\omega_i t) \\ V_{im}\cos(\omega_i t + \frac{2\pi}{3}) \\ V_{im}\cos(\omega_i t + \frac{4\pi}{3}) \end{bmatrix} \tag{2}$$

$$[V_o(t)] = \begin{bmatrix} V_{oa} \\ V_{ob} \\ V_{oc} \end{bmatrix} = \begin{bmatrix} qV_{im}\cos(\omega_o t + \psi) \\ qV_{im}\cos(\omega_o t + \frac{2\pi}{3} + \psi) \\ qV_{im}\cos(\omega_o t + \frac{4\pi}{3} + \psi) \end{bmatrix} \tag{3}$$

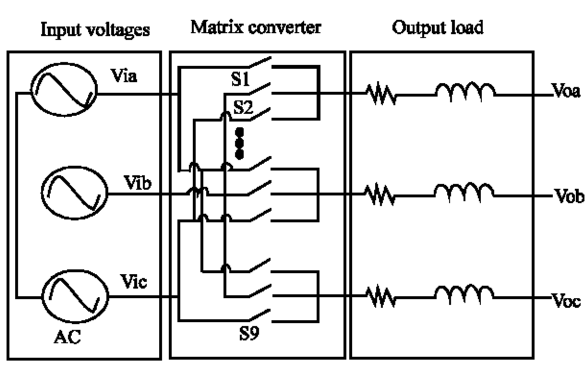

Fig. 1: Three-phase matrix converter

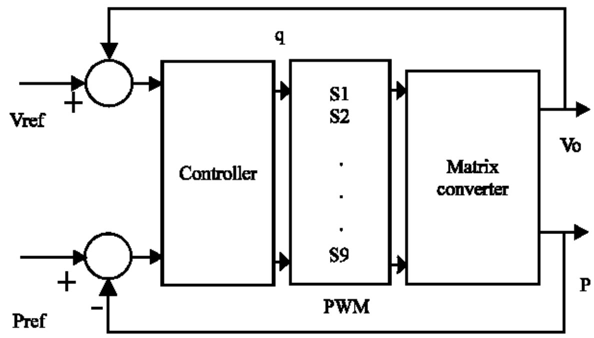

Fig. 2: Block diagram of the matrix converter control system

M (t) is noticed as the modulation matrix and is solely defined in terms of switching strategy (Casadei *et al*., 2002). Here, q is the voltage transfer ratio, V_{im} is the amplitude of input voltages and ω_i, ω_O are the angular frequencies of input and output voltages, respectively. In a power system usually ω_i, ω_O; so, the input and output frequencies of the matrix converter in steady state system studies are assumed equal.

Alesina and Venturini (1981) noted that the maximum value of q, that the converter is possible to achieve is q = 50% and again Alesina and Venturini (1989) developed a method for gaining q up to 86.6%. Normally using a step-up transformer, with a constant ratio N, adequately compensates the maximum output voltage. In order to fix the real and reactive powers to the desired values, phase angle and magnitude of output voltage must be directly controlled. These parameters are obviously related to the voltage transfer ratio and duty cycle of switching signals. Gholami and Seifi (2011) provided technical details on the matrix converter switching and control subject.

The major function of the series FACTS in steady-state compensation is to control active power flow. For the shunt FACTS controller, the chief function is to achieve the reactive compensation and bus voltage control. The matrix converter controller is able to compensate both active power flow and bus voltage. Magnitude of the matrix converter output voltage is adjusted by tuning voltage transfer ratio.

Based on Eq. 3 magnitude of the matrix converter output voltage is simply determined by q. The output voltage magnitude variable is v_O as in Fig. 2. For the voltage magnitude control a Proportional-Integral (PI) controller may be used. The magnitude of the reference v_{ref} and measured v_O values are compared and the controller regulates the q for the converter switches so that the magnitude is fixed to its reference value. In this case, the matrix converter operates like a tap changer transformer but with quick response, owing to its electronic characteristics. Furthermore, for conventional tap changer transformers, the tap ratio can not be adjusted continuously, but in matrix converter q can be changed continuously. The magnitude controller operation is given by:

$$q = K_p e + K_I \int e \qquad (4)$$

K_I and K_p express integrating and proportional controller coefficients. The error e is:

$$e = v_{ref} - v_O \qquad (5)$$

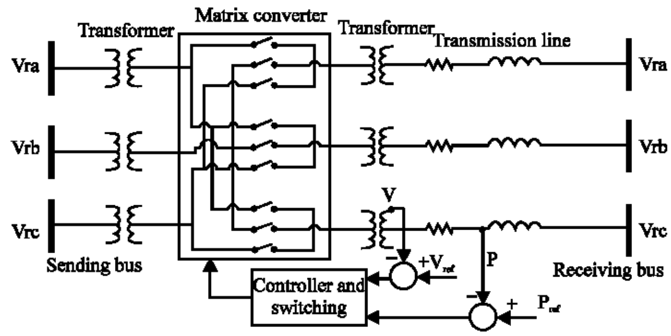

Fig. 3: A matrix converter based power system compensation interfaced between two buses

Matrix converter can also make desirable changes to the phase angle of the output voltage. Referring to Eq. 3 the phase shift is shown by Ψ. Should there is a phase angle shift between the receiving bus and sending bus, the power flows between two buses. Sobczyk and Sienko (2006) reported simulation of matrix converter as a voltage phase controller in the power system. If the phase-angle of the converter output voltage (Ψ) is controlled, active power on the transmission line is adjusted. The reference (P_{ref}) and measured value of active power (P), are compared (Fig. 2) and the controller tunes Ψ so that, the active power flow is fixed to its reference value.

The active power control is given by:

$$\Psi = K_p e + K_I \int e \quad (6)$$

And the error is:

$$e = P_{ref} - P_O \quad (7)$$

In practical operation of the matrix converter, q can be regulated to control the voltage of bus r or s and Ψ can be regulated to control the power flow of line r-s in Fig. 3.

POWER SYSTEM MODELING

In power flow calculations the voltages at all buses is determined. Eq. 8 and 9 lead to find the nodal voltages by Newton power flow method (Acha *et al*., 2004).

The real and reactive power exchange between the elements connecting to a bus in steady state operation should be brought to the expected value of zero:

$$\Delta P_s = P_S^{schedule} - P_S^{calculate} = 0 \quad (8)$$

$$\Delta Q_s = Q_S^{schedule} - Q_S^{calculate} = 0 \quad (9)$$

The load and the generation at the buses are very well known and identified as the scheduled active and reactive powers:

$$P_S^{schedule} = P_{s,generation} - P_{s,load} \quad (10)$$

$$Q_S^{schedule} = Q_{s,generation} - Q_{s,load} \tag{11}$$

The transmitted reactive ($Q_S^{schedule}$) and active ($P_S^{schedule}$) powers are the functions of power network impedances and voltages of nodes:

$$P_s = \sum_{n=1}^{N} |V_S||V_n||Y_{sn}|\cos(\delta_s \delta_n - \theta_{sn}) \tag{12}$$

$$Q_s = \sum_{n=1}^{N} |V_S||V_n||Y_{sn}|\sin(\delta_s \delta_n - \theta_{sn}) \tag{13}$$

$|V_n|<\delta_n$ is the voltage at bus n and $|Y_{sn}|<\theta_n$ is the entry of the admittance matrix. Most electric industries and academic researcher employ Newton-Raphson method because the Newton-Raphson of iterative solution gives assurance about more reliability to converge (Acha *et al.*, 2004; Zhang, 2003).

Let us assume for a set of m nonlinear equations, G(Z), where Z is the vector of m unknown state variables. The basis of Newton solution is a Taylor series expansion of G(Z) about an initial estimation $Z^{(0)}$:

$$G(Z^j) = G(Z^{(j-1)}) + J(Z^{(j-j)}) \times (Z^{(j)} - Z^{(j-1)}) + \text{waived terms} \tag{14}$$

where, J(z) is the matrix of first-order partial derivatives of G(Z) with respect to Z. The general assumption that close to the solution leads to:

$$G(Z^{(j-1)}) + J(Z^{(j-1)}) \times (Z^{(j)} - Z^{(j-1)}) = 0 \tag{15}$$

So, the solution of can be expressed as:

$$Z^{(j)} = Z^{(j-1)} - J^{-1}(Z^{(j-1)}) \times G(Z^{(j-1)}) \tag{16}$$

Or:

$$\Delta Z^{(j)} = -J^{-1}(Z^{(j-1)}) \times G(Z^{(j-1)}) \tag{17}$$

In the power flow studies Z is the unknown phase angles and magnitudes of nodal voltages. The Newton-Raphson formulation of the power flow problem is as follows:

$$\underbrace{\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix}^{(j)}}_{G(Z^{j-1})} = \underbrace{\begin{bmatrix} \frac{\partial P}{\partial \theta} & |V|\frac{\partial P}{\partial |V|} \\ \frac{\partial Q}{\partial \theta} & |V|\frac{\partial Q}{\partial |V|} \end{bmatrix}^{(j)}}_{ZJ-1\,\text{Jacobian}} \underbrace{\begin{bmatrix} \Delta \theta \\ \frac{\Delta V}{|V|} \end{bmatrix}^{(j)}}_{\Delta Z^{j-1}} \tag{18}$$

P and Q are the vectors of powers. For two buses s and r, shown in Fig. 4. The conventional Jacobian matrix is:

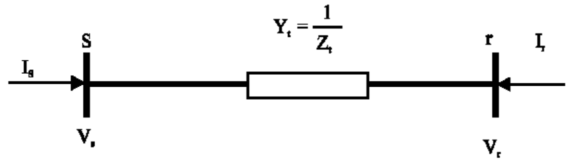

Fig. 4: Equivalent impedance in a power system without compensator

$$J = \begin{bmatrix} \frac{\partial P_s}{\partial \theta_s} & \frac{\partial P_s}{\partial \theta_r} & |V_s|\frac{\partial P_s}{\partial |V|_s} & |V_r|\frac{\partial P_s}{\partial |V|_s} \\ \frac{\partial P_r}{\partial \theta_r} & \frac{\partial P_r}{\partial \theta_r} & |V_s|\frac{\partial P_r}{\partial |V|_s} & |V_r|\frac{\partial P_s}{\partial |V|_r} \\ \frac{\partial Q_s}{\partial \theta_s} & \frac{\partial Q_s}{\partial \theta_r} & |V_s|\frac{\partial Q_s}{\partial |V|_s} & |V_r|\frac{\partial Q_s}{\partial |V|_r} \\ \frac{\partial Q_r}{\partial \theta_s} & \frac{\partial Q_r}{\partial \theta_s} & |V_s|\frac{\partial Q_r}{\partial |V|_s} & |V_r|\frac{\partial Q_r}{\partial |V|_s} \end{bmatrix} \tag{19}$$

STEADY STATE MODELING OF MATRIX CONVERTER IN NEWTON-RAPHSON ALGORITHM

Figure 5 shows the single line model of a matrix converter connected to link s-r of an N-bus power system. Three models will be discussed and elements of Jacobian matrix are derived based on the functioning modes of matrix converter. The first and the second model investigate the amplitude and phase angle change in the output voltage, respectively. The general model includes changing in the both amplitude and phase angle of the output voltage concurrently.

Amplitude control mode: Let us assume that the device only controls the magnitude of receiving bus voltages. Considering the matrix converter between two buses, the sending and receiving voltages (V_s, V_r), have the relation as Eq. 20 according to Fig. 5. T_1 and T_2 are the constant transformers ratios and q is the voltage transfer ratio of matrix converter in Eq. 3. Note that N is variable because q is variable.

If:

$$\frac{|V_s|}{|V_i|} = T_1, \frac{|V_0|}{|V_r|} = \frac{1}{T_2} \text{ and } \frac{|V_0|}{|V_i|} = q$$

Then:

$$\left|\frac{V_s}{V_r}\right| = \frac{T_1}{q \times T_2} \equiv N \tag{20}$$

Figure 6 shows the circuit model of the amplitude control mode. The matrix converter losses and two transformers are modeled as an admittance Y_T and a tap changing transformer can be a model for Eq. 20. Injection currents are found as follows:

$$\begin{bmatrix} I_s \\ I_r \end{bmatrix} = \begin{bmatrix} Y_T & -NY_T \\ -NY_T & N^2 Y_T \end{bmatrix} \begin{bmatrix} V_s \\ V_r \end{bmatrix} \tag{21}$$

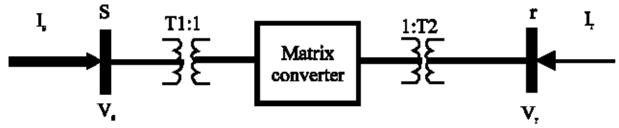

Fig. 5: Single line diagram of matrix converter interfaced between sending and receiving buses

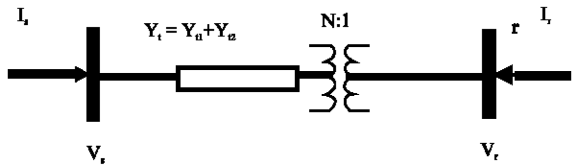

Fig. 6: Steady state model of amplitude control mode

The complex power injected at bus (r) may be expressed as: $S_r = V_r I_r^* = P_r + jQ_r$.
So, the powers injected at buses (s) and (r) are:

$$P_s = NV_sV_r\,(G_{sr}\cos(\theta_s-\theta_r)+B_{sr}\sin(\theta_s-\theta r))+V^2_s\,G_{ss} \tag{22}$$

$$Q_s = NV_sV_r\,(G_{sr}\sin(\theta_s-\theta_r)+B_{sr}\cos(\theta_s-\theta r))+V^2_s\,B_{ss} \tag{23}$$

$$P_r = NV_sV_r\,(G_{sr}\cos(\theta_r-\theta_s)+B_{sr}\sin(\theta_r-\theta_s))+N^2V_r^2\,B_{rr} \tag{24}$$

$$Q_r = NV_sV_r\,(G_{sr}\sin(\theta_r-\theta_s)-B_{sr}\cos(\theta_r-\theta_s))+N^2V_r^2\,B_{rr} \tag{25}$$

Where:

$$\begin{aligned} G_{SS}+jB_{ss} &= G_{rr}+jB_{rr} = Y_T \\ G_{Sr}+jB_{sr} &= G_{rs}+jB_{rs} = -Y_T \end{aligned} \tag{26}$$

The representation for modified Jacobian matrix is:

$$\begin{bmatrix} \Delta P_s \\ \Delta P_r \\ \Delta Q_s \\ \Delta Q_r \end{bmatrix}^{(i)} = \begin{bmatrix} \frac{\partial P_s}{\partial \theta_s} & \frac{\partial P_s}{\partial \theta_r} & |V_s|\frac{\partial P_s}{\partial |V_s|} & N\frac{\partial P_s}{\partial N} \\ \frac{\partial P_r}{\partial \theta_s} & \frac{\partial P_r}{\partial \theta_r} & |V_s|\frac{\partial P_r}{\partial |V_s|} & N\frac{\partial P_r}{\partial N} \\ \frac{\partial Q_s}{\partial \theta_s} & \frac{\partial Q_s}{\partial \theta_r} & |V_s|\frac{\partial Q_s}{\partial |V_s|} & N\frac{\partial Q_s}{\partial N} \\ \frac{\partial Q_r}{\partial \theta_s} & \frac{\partial Q_r}{\partial \theta_r} & |V_s|\frac{\partial Q_r}{\partial |V_s|} & N\frac{\partial Q_r}{\partial N} \end{bmatrix}^{(i)} \begin{bmatrix} \Delta\theta_s \\ \Delta\theta_r \\ \frac{\Delta|V|_s}{|V|_s} \\ \frac{\Delta N}{N} \end{bmatrix} \tag{27}$$

It should be noted that the new state variable N is replaced with V_r.

Phase angle control mode: Let's assume that the device only controls the phase angle of voltage. Referring to Fig. 5 the input and output voltages of matrix converter has the following relation:

$$\frac{V_O}{V_i} = q\angle\psi \tag{28}$$

Ignoring transformer's impedances:

$$\frac{V_r}{V_s} = 1\angle\psi \tag{29}$$

Injection currents in this case are as follows:

$$\begin{bmatrix} I_s \\ I_r \end{bmatrix} = \begin{bmatrix} Y_T & -Y_T\,(\cos(\psi) - j\sin(\psi)) \\ -Y_T\,(\cos(\psi) + j\sin(\psi)) & -Y_T \end{bmatrix} \begin{bmatrix} V_s \\ V_r \end{bmatrix} \tag{30}$$

The powers injected at buses (s) and (r) in this case are:

$$P_s = V_s V_r (G_{sr} \cos(\theta_s\text{-}\theta_r) + B_{sr} \sin(\theta_s\text{-}\theta_r)) + V_s^2\, G_{ss} \tag{31}$$

$$Q_s = V_s V_r (G_{sr} \sin(\theta_s\text{-}\theta_r) + B_{sr} \cos(\theta_s\text{-}\theta_r)) + V_s^2\, B_{ss} \tag{32}$$

$$P_s = V_s V_r (G_{sr} \cos(\theta_r\text{-}\theta_s) + B_{sr} \sin(\theta_r\text{-}\theta_s)) + V_r^2\, G_{rr} \tag{33}$$

$$Q_r = V_s V_r (G_{sr} \sin(\theta_r\text{-}\theta_s) + B_{sr} \cos(\theta_r\text{-}\theta_s)) + V_r^2\, B_{rr} \tag{34}$$

Where:

$$\begin{gathered} G_{ss}+jB_{ss} = G_{rr}+jB_{rr} = Y_T \\ G_{sr}+jB_{sr} = -Y_T\,(\cos(\Psi)+j\sin(\Psi)) \\ G_{rs}+jB_{rs} = -Y_T\,(\cos(\Psi)+j\sin(\Psi)) \end{gathered} \tag{35}$$

The representation for modified Jacobian matrix elements for sending (s) and receiving (r) buses is:

$$\begin{bmatrix} \Delta P_s \\ \Delta P_r \\ \Delta Q_s \\ \Delta Q_r \\ \Delta P_{sr} \end{bmatrix}^{(j)} = [j]^j \times \begin{bmatrix} \Delta\theta_s \\ \dfrac{\Delta|V_s|}{V_s} \\ \dfrac{\Delta|V_r|}{V_r} \\ \Delta\psi \end{bmatrix} \tag{36}$$

The elements of Jacobian matrix are given in Eq. 37:

$$J = \begin{bmatrix} \dfrac{\partial P_s}{\partial\theta_s} & \dfrac{\partial P_s}{\partial\theta_r} & |V_s|\dfrac{\partial P_s}{\partial|V|_s} & |V_r|\dfrac{\partial P_s}{\partial|V|_r} & \dfrac{\partial P_s}{\partial\psi} \\ \dfrac{\partial P_r}{\partial\theta_s} & \dfrac{\partial P_r}{\partial\theta_r} & |V_s|\dfrac{\partial P_r}{\partial|V|_s} & |V_r|\dfrac{\partial P_r}{\partial|V|_r} & \dfrac{\partial P_r}{\partial\psi} \\ \dfrac{\partial Q_s}{\partial\theta_s} & \dfrac{\partial Q_s}{\partial\theta_r} & |V_s|\dfrac{\partial Q_s}{\partial|V|_s} & |V_r|\dfrac{\partial Q_s}{\partial|V|_r} & \dfrac{\partial Q_s}{\partial\psi} \\ \dfrac{\partial Q_r}{\partial\theta_s} & \dfrac{\partial Q_r}{\partial\theta_r} & |V_s|\dfrac{\partial Q_r}{\partial|V|_s} & |V_r|\dfrac{\partial Q_r}{\partial|V|_r} & \dfrac{\partial Q_r}{\partial\psi} \\ \dfrac{\partial P_{sr}}{\partial\theta_s} & \dfrac{\partial P_{sr}}{\partial\theta_r} & |V_s|\dfrac{\partial P_{sr}}{\partial|V|_s} & |V_r|\dfrac{\partial P_{sr}}{\partial|V|_r} & \dfrac{\partial P_{sr}}{\partial\psi} \end{bmatrix} \tag{37}$$

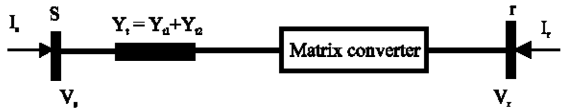

Fig. 7: Circuit model for matrix converter

Amplitude and Phase angle control mode: In this mode, the matrix converter controls both voltage amplitude and phase angle. Figure 7 shows the circuit model. The relation between the voltages is:

$$\frac{V_r}{V} = N\angle\psi \qquad (38)$$

Injection currents in this case are:

$$\begin{bmatrix} I_s \\ I_r \end{bmatrix} = \begin{bmatrix} Y_T & -NY_T(\cos(\psi) - j\sin(\psi)) \\ -NY_T(\cos(\psi) + j\sin(\psi)) & -N^2 Y_T \end{bmatrix} \begin{bmatrix} V_s \\ V_r \end{bmatrix} \qquad (39)$$

The active and reactive power equations are similar to Eq. 22-25 but G_{ss}, B_{ss}, G_{rs}, B_{rs}, G_{sr} and B_{sr} must be substituted with Eq. 35. To solve the power flow problem in a power system including matrix converter in this case, the Jacobian equation is extended as shown in Eq. 40:

$$\begin{bmatrix} \Delta P_s \\ \Delta P_r \\ \Delta Q_s \\ \Delta Q_r \\ \Delta P_{sr} \end{bmatrix}^j = [J]^j \times \begin{bmatrix} \Delta\theta_s \\ \Delta\theta_r \\ \frac{\Delta|V|_s}{V_s} \\ \frac{\Delta N}{N} \\ \Delta\psi \end{bmatrix} \qquad (40)$$

The elements of Jacobian matrix are shown in Eq. 41:

$$J = \begin{bmatrix} \frac{\partial P_s}{\partial\theta_s} & \frac{\partial P_s}{\partial\theta_r} & |V_s|\frac{\partial P_s}{\partial|V_s|} & N\frac{\partial P_s}{\partial|V_r|} & \frac{\partial P_s}{\partial\psi} \\ \frac{\partial P_r}{\partial\theta_s} & \frac{\partial P_r}{\partial\theta_r} & |V_s|\frac{\partial P_r}{\partial|V_s|} & N\frac{\partial P_r}{\partial|V_r|} & \frac{\partial P_r}{\partial\psi} \\ \frac{\partial Q_s}{\partial\theta_s} & \frac{\partial Q_s}{\partial\theta_r} & |V_s|\frac{\partial Q_s}{\partial|V_s|} & N\frac{\partial Q_s}{\partial|V_r|} & \frac{\partial Q_s}{\partial\psi} \\ \frac{\partial Q_r}{\partial\theta_s} & \frac{\partial Q_r}{\partial\theta_r} & |V_s|\frac{\partial Q_r}{\partial|V_s|} & N\frac{\partial Q_r}{\partial|V_r|} & \frac{\partial Q_r}{\partial\psi} \\ \frac{\partial P_{sr}}{\partial\theta_s} & \frac{\partial P_{sr}}{\partial\theta_r} & |V_s|\frac{\partial P_{sr}}{\partial|V_s|} & N\frac{\partial P_{sr}}{\partial|V_s|} & \frac{\partial P_{sr}}{\partial\psi} \end{bmatrix} \qquad (41)$$

NUMERICAL RESULTS

Test systems: In order to evaluate the effectiveness of matrix converter's model in multi-control functioning and Newton power flow algorithm, the following cases are carried out on the 6-bus system selected from a book by Wood and Wollenberg (1984).

Table 1: Result of Bus voltages for 6 bus system

Bus No.	Base system	Voltage (|V|, θ°) Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8	Case 9
1	1.0500<0	1.0500<0.00	1.0500<0.00	1.0500<0.00	1.0500<0.00	1.0500<0.00	1.0500<0.00	1.0500<0.00	1.0500<0.00	1.0500<0.00
2	1.0500<-3.67	1.0500<-4.17	1.0500<-3.67	1.0500<-3.43	1.0500<-3.95	1.0500<-3.77	1.0500<-3.73	1.0500<-3.88	1.0500<-3.56	1.0500<-4.12
3	1.0700<-4.27	1.0700<-4.71	1.0700<-4.21	1.0700<-4.10	1.0700<-4.57	1.0700<-2.64	1.0700<-3.35	1.0700<-4.73	1.0700<-3.97	1.0700<-5.15
4	0.9894<-4.19	1.0000<-5.36	0.9916<-4.22	0.9873<-4.11	1.0000<-5.30	0.9882<-4.24	0.9884<-4.22	0.9894<-4.26	0.9915<-4.19	0.9842<-4.37
5	0.9854<-5.27	0.9868<-5.78	1.0000<-5.51	0.9726<-5.63	0.9760<-6.08	0.9774<-5.17	0.9785<-5.18	0.9853<-4.89	1.0000<-5.82	0.9500<-4.49
6	1.0044<-5.94	1.005<-6.35	1.0076<-5.91	1.0000<-5.48	1.0000<-5.96	0.9739<-7.29	0.9763<-6.51	1.0054<-6.79	0.9874<-5.23	1.0290<-7.44

Table 2: Results of power flow on transmission lines for 6 bus system

Line No.	From bus/to bus	Power flow (P+jQ) Base sys.	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8	Case 9
1	1-2	0.28-0.15i	0.32-0.17i	0.28-0.15i	0.26-0.14i	0.30-0.16i	0.29-0.15i	0.29-0.15i	0.30-0.16i	0.27-0.15i	0.32-0.16i
2	1-4	0.43+0.20i	0.36+0.40i	0.43+0.18i	0.43+0.21i	0.36+0.44i	0.44+0.20i	0.43+0.20i	0.44+0.19i	0.43+0.19i	0.45+0.22i
3	1-5	0.35+0.11i	0.38+0.10i	0.36+0.06i	0.38+0.15i	0.40+0.13i	0.35+0.14i	0.35+0.13i	0.33+0.11i	0.37+0.05i	0.33+0.23i
4	2-3	0.02-0.12j	0.02-0.12i	0.02-0.12i	0.03-0.12i	0.03-0.12i	-0.10-0.09i	-0.04-0.10i	0.04-0.12i	0.01-0.12i	0.06-0.12i
5	2-4	0.33+0.46j	0.38+0.32i	0.32+0.44i	0.36+0.46i	0.40+0.31i	0.32+0.47i	0.32+0.47i	0.30+0.47i	0.33+0.43i	0.31+0.52i
6	2-5	0.15+0.15i	0.15+0.14i	0.17+0.37i	0.11+0.01i	0.11+0.00i	0.15+0.18i	0.15+0.17i	0.12+0.16i	0.17+0.09i	0.12+0.28i
7	2-6	0.26+0.12i	0.25+0.12i	0.25+0.10i	0.24+0.15i	0.24+0.15i	0.40+0.23i	0.34+0.24i	0.31+0.10i	0.23+0.21i	0.31-0.02i
8	3-5	0.19+0.23i	0.19+0.22i	0.18+0.17i	0.24+0.26i	0.23+0.25i	0.29+0.22i	0.24+0.23i	0.14+0.25i	0.21+0.16i	0.15+0.39i
9	3-6	0.43+0.60i	0.43+0.60i	0.43+0.57i	0.39+0.66i	0.39+0.66i	0.20+0.47i	0.30+0.46i	0.50+0.58i	0.39+0.79i	0.50+0.33i
10	4-5	0.04-0.04i	0.02-0.02i	0.03-0.07i	0.06-0.03i	0.05-0.00i	0.04-0.03i	0.04-0.03i	0.02-0.04i	0.04-0.08i	0.03+0.02i
11	5-6	0.01-0.09i	0.03-0.09i	0.02-0.05i	-0.03-0.21i	-0.03-0.20i	0.10-0.05i	0.06-0.04i	-0.10-0.04i	0.10-0.31i	-0.10+0.33i

First the Newton-Raphson algorithm is applied to the 6-bus system with no matrix converter to provide a basis for comparison. Table 1 gives the voltage magnitude and phase angle for all buses of the system. Table 2 gives the power flows through the transmission lines. Bus number 1 is slack (swing) bus and buses number 2 and 3 are generator PV bus. Voltage magnitudes at buses number 4, 5 and 6 are computed. In test cases number 1, 2, 3 and 4 our interest is in control of the voltage magnitude at these buses. It is interesting to note that line number 9 (from bus 3 to 6) has the maximum active power flowing throughout the lines. It is also interesting to note that line number 11 (from bus 5 to 6) has the minimum active power flowing throughout the lines. In test cases number 5, 6 and 7 the interest is in control of the active power flowing through these two lines.

Cases number 8 and 9 investigate the simultaneous control of voltage magnitude and active power:

- Test cases 10, 11 and 12 are carried out on the IEEE 14-bus system
- Test cases 13, 14 and 15 are carried out on the IEEE 57-bus system
- Test cases 16, 17 and 18 are carried out on the IEEE 118-bus system

Test cases 1, 2, 3 and 4

Amplitude control with matrix converter: The prototype six-bus network described in last section is modified to embody a matrix converter in series with the transmission line. The initial condition of N at Eq. 27 is set to value of N = 1. The winding impedance embraces an inductive reactance of $Y_T = 0.2$ p.u. and no resistance. In case 1 the compensator was connected to bus 1 and bus 4. The matrix converter has to maintain the voltage magnitude at bus 4 at 1 p.u. In case 2 and

3 it was connected between bus 5 and bus 6. The matrix converter is used to maintain the voltage magnitude at bus 5 and 6 at 1 p.u. In case 4 two matrix converter were connected (may not be economical) in the network like case 1 and 2. The matrix converters are used to maintain the voltage magnitude at bus 4 and 6 at 1 p.u. Convergence in cases 1, 2 and 3 is obtained in 5 iterations to a power mismatch tolerance of 10^{-12} while in case 4 it is obtained in 6 iterations. The nodal voltages are given in Table 1. The changes in the flow are given in Table 2. It should be noted that the matrix converter keeps the target value of 1 p.u. for voltage magnitudes.

Test cases 5, 6 and 7

Active power control with matrix converter: The six-bus network is modified to embody one matrix converter in series with the transmission line. The initial value of the complex tap Eq. 29 is fixed to the value $1\angle 0$. The winding impedance contains no resistance and an inductive reactance of $Y_T = 0.2$ p.u. In case 5 the matrix converter is used to maintain active power flowing from bus 5 towards bus 6 at 0.1 p.u. In case 6 the matrix converter is used to maintain active power flowing from bus 3 towards bus 6 at 0.3 p.u. In this case 7 the control objective of matrix converter is to keep the sending active power, flowing through the line number 11, equal to 0.1 p.u. same as what has occurred in case 5 but with an opposite direction of active power flow.

Convergence in cases 5, 6 and 7 is obtained in 5 iterations to a power mismatch tolerance of 10^{-12}. The matrix converter keeps its target values. The nodal voltages are given in Table 1. The power flow results are shown in Table 2. As expected, the nodal voltage magnitudes do not change compared with the base case (No matrix converter controller) presented in the first row of Table 1.

However, the voltage phase angles have changed in value to reflect the changes in the active power flow through this transmission line.

Test cases 8 and 9

Amplitude and Active power control with matrix converter: The six-bus network is modified to examine the voltage and power control capabilities of the matrix converter model. The generators are set to control voltage magnitudes at the Slack bus and the PV buses (bus 2 and 3). One matrix converter is placed at line 11 between bus 5 and bus 6. Two different power flow simulations are carried out. In case 8 the objective is to control the voltage magnitude of bus 5-1 p.u. and at the same time the sending active power flowing through line number 11, to 0.1 p.u. In case 9 the objective is to control the voltage magnitude of bus 5-0.95 p.u. and at the same time the sending active power flowing through line number 11, to -0.1 p.u. (opposite direction of active power flow in case 8). The nodal voltages are given in Table 1. The power flow results are shown in Table 2. In both cases, the matrix converter fixed its target values.

It should be noticed that matrix converter based series compensation enable us to control two parameters of power system at the same time while series compensation based on voltage source converter i.e. SSSC (Zhang, 2003) or Thyristor-based ones i.e. TCSC (Acha *et al*., 2004) enables us to control one parameter of the network. Convergence is achieved in 12 iterations in both cases. To demonstrate the prowess of the Newton-Raphson method at convergence, the convergence characteristics for some cases is given in Fig. 8.

Test cases 10, 11 and 12

Standard IEEE 14-bus system: The following cases based on the IEEE 14-bus system are carried out:

Table 3: Result of bus voltage for 14 bus system

	Voltage $\begin{pmatrix} \|V\| \\ \theta° \end{pmatrix}$			
Bus No.	Base system	Case 10	Case 11	Case 12
1	1.06000	1.06000	1.06000	1.060
2	1.0450-4.9579	1.0450-4.9593	1.0450-4.9552	1.0450-4.9559
3	1.0100-12.6398	1.0100-12.6493	1.0100-12.627	1.0100-12.631
4	1.0250-10.3524	1.0242-10.3483	1.0249-10.327	1.0242-10.316
5	1.0319-8.93890	1.0315-8.92550	1.0316-8.9543	1.0312-8.9507
6	1.0700-14.8782	1.0700-14.7689	1.0700-15.175	1.0700-15.204
7	1.0444-13.4403	1.0417-13.4980	1.0437-13.272	1.0413-13.255
8	1.0900-13.4403	1.0900-13.4980	1.0900-13.272	1.0900-13.255
9	1.0272-15.0608	1.0220-15.1579	1.0257-14.819	1.0211-14.805
10	1.0272-15.3104	1.0228-15.3699	1.0261-15.165	1.0222-15.159
11	1.0448-15.2088	1.0425-15.1818	1.0443-15.282	1.0423-15.292
12	1.0530-15.7183	1.0553-15.5880	1.0533-16.137	1.0553-16.196
13	1.0462-15.7360	1.0508-15.6351	1.0460-16.285	1.0496-16.417
14	1.0172-16.3884	1.0000-16.5250	1.0146-15.450	1.0000-15.187

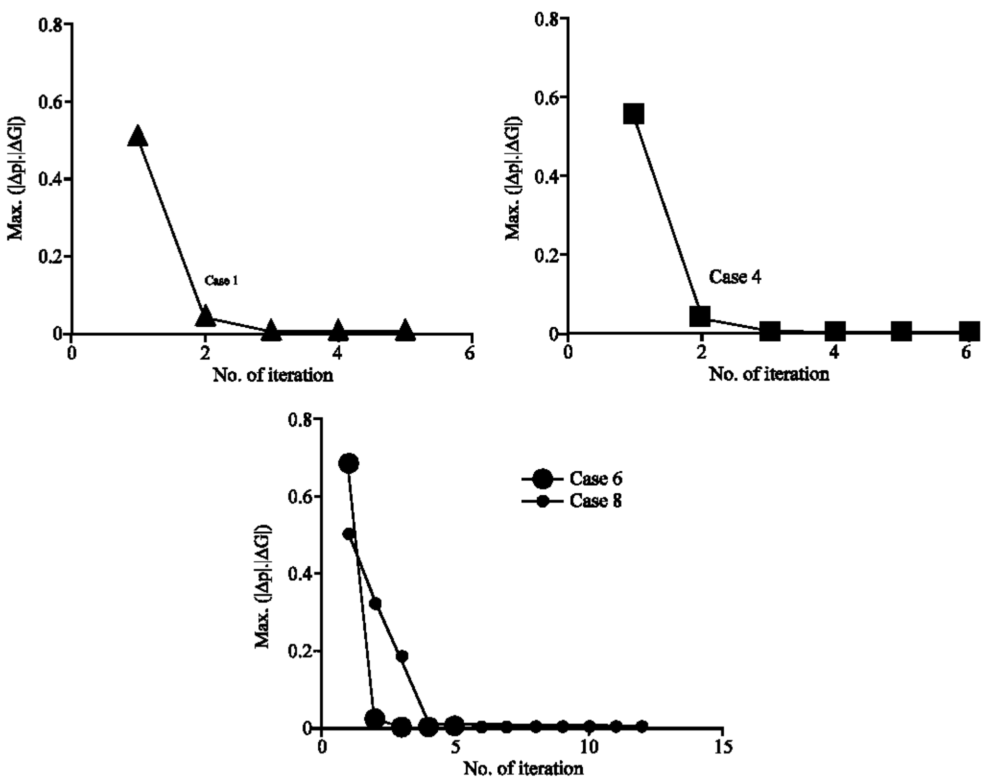

Fig. 8: Power mismatches as function of number of iterations

- The results of power flow for the base system are given in Table 3 and 4
- Case 10 is similar to the IEEE 14-bus base system except that there is a matrix converter connected in series with line 20 (line 14-13) for control of voltage magnitude at bus 14. The voltage magnitude reference is fixed to achieve |V| = 1 at bus 14

Table 4: Power flow results IEEE 14 bus system

	Power flow (P+Qj)				
Line No.	From bus-to-bus	Base system	Case 10	Case 11	Case 12
1	1-2	1.56+0.20i	1.56+0.20i	1.56+0.20i	1.56+0.20i
2	1-5	0.76+0.01i	0.76+0.01i	0.76+0.018i	0.76+0.01i
3	2-3	0.72-0.03i	0.72-0.03i	0.72-0.03i	0.72-0.03i
4	2-4	0.55+0.05i	0.55+0.05i	0.55+0.058i	0.55+0.05i
5	2-5	0.41+0.06i	0.41+0.05i	0.41+0.06i	0.41+0.05i
6	3-4	-0.23+0.00i	0.23+0.00i	-0.23+0.00i	-0.23+0.00i
7	4-5	-0.60-0.03i	0.61-0.02i	-0.5916-0.03i	-0.58-0.02i
8	4-7	0.27+0.08i	0.28+0.07i	0.26+0.08i	0.26+0.07i
9	4-9	0.15-0.00i	0.15-0.01i	0.14-0.00i	0.14-0.01i
10	5-6	0.45+0.13i	0.44+0.13i	0.47+0.13i	0.47+0.13i
11	6-11	0.07-0.09i	0.09-0.10i	0.06-0.10i	0.06-0.11i
12	6-12	0.08-0.03i	0.07-0.02i	0.08-0.02i	0.08-0.02i
13	6-13	0.18-0.10i	0.16-0.07i	0.21-0.09i	0.21-0.06i
14	7-8	-0.00+0.27i	-0.00+0.28i	-0.00+0.27i	-0.00+0.28i
15	7-9	0.27-0.16i	0.28-0.19i	0.26-0.17i	0.26-0.19i
16	9-10	0.04+0.01i	0.03+0.02i	0.06+0.02i	0.06+0.03i
17	9-14	0.08+0.00i	0.10-0.03i	0.05-0.01i	0.05-0.05i
18	10-11	-0.04+0.07i	-0.05+0.08i	-0.02+0.08i	-0.02+0.09i
19	12-13	0.01-0.01i	0.01-0.00i	0.0256-0.01i	0.02-0.00i
20	13-14	0.06-0.05i	0.04-0.02i	0.10-0.03i	0.10-0.00i

- Case 11 is similar to case 10 except that the matrix converter is used for control of active power flow on line number 20 (line 14-13). The active power flow reference is set to $P_{refline\ 20(14\text{-}13)} = -0.1$ which is 124% of its base value
- Case 12 is similar to case 10 except that the matrix-converter not only control the voltage magnitude at bus 14-but also is used for control of active power flow on line number 20 (line 14-13). Similar to cases 10 and 11 the voltage magnitude reference is set to achieve $|V| = 1$ p.u. at bus 14 and the active power flow reference is set to $P_{refline\ 20(14\text{-}13)} = -0.1$

The detailed inspection of these results discloses a considerable amount of relative information. For example in case 10 and 12 the matrix converter achieves its voltage regulation objective at the expense of consuming reactive power. Owing to the control action of the matrix converter, there is a substantial redistribution of reactive power flows throughout the power network. In the case of controlling active power (case 11) the nodal voltage magnitudes change very little compared with the base case. However, the voltages phase angle difference between bus 13 and 14 increase in value due to the increase in active power flowing through the line. As expected, in the case 12 both active and reactive net powers (i.e., the sum of entries in column 6 of Table 4) have changed compared to the base case. There is no change in active net power of case 10 compare with the base case.

Test cases 13, 14, 15, 16, 17 and 18: Standard IEEE 57-bus and IEEE 118-bus systems: The numbers of iterations for the IEEE 57-bus and IEEE 118-bus base systems are given in the Table 5 and 6, respectively. The test cases of the IEEE 57-bus and IEEE 118-bus systems are described as:

Table 5: Test results of IEEE 57 bus system

Case	Solution to the matrix converter and control parameters	No. of iterations
Base	$\|V_{55}\|$ = 0.9675 p.u. P_{line} 80 (55-9) = -0.1890 p.u.	5
10	N = 1.055, $\|V_{55}\|$ = 1 p.u., P_{line} 80 (55-9) = -0.1926 p.u.	6
11	Ψ = -6.91, $\|V_{55}\|$ = 0.9469, P_{line} 80 (55-9) = -0.10 p.u.	6
12	N = 1.075, Ψ = 9.27, $\|V_{55}\|$ = 1 p.u., P_{line}, P_{line} 80 (55-9) = -0.10 p.u.	6

Table 6: Test results of IEEE 118 bus system

Case	Solution to the matrix converter parameters	No. of iterations
Base	|V95| = 0.9551 p.u., P_{line} 147 (94-95) = 1.4367 p.u.	6
13	N = 1.1636, $\|V_{95}\|$ = 1 p.u. P_{line} 147 (94-95) = 1.0452 p.u.	7
14	Ψ = 1.89, $\|V_{95}\|$ = 0.9515 p.u., P_{line} 147 (94-95) = 1.00 p.u.	7
15	N = 1.1633, Ψ = -0.669 $\|V_{95}\|$ = 1 p.u., P_{line} 147 (94-95) = 1.00 p.u.	7

- Cases 13: This is the 57-bus system with a matrix converter coupled with line 80 (55-9). The matrix converter is used to control the voltage magnitude at bus 55
- Cases 14: This is like case 13 except that the matrix converter is used to control the active power flow of line 80 (55-9)
- Case 15: Case 15 and case 13 are alike except that the matrix converter in case 15 is used to control both the active power flow of line 80 (55-9) and the voltage magnitude at bus 55.

The test results of cases 13-15 are given by Table 5. The values of N and Ψ required to achieve the voltage magnitude and active power to their operating points are given as well.

- Cases 16: This is the 118-bus system with a matrix converter coupled with line 147 (94-95). The matrix converter is used to control the voltage magnitude at bus 95
- Cases 17: This is like case 16 except that the matrix converter is used to control the active power flow of line 147 (94-95)
- Case 18: This is like case 16 except that the matrix converter is used to control both the active power flow of line 147 (94-95) and the voltage magnitude at bus 95

The test results of cases 16-18 are given by Table 6. From the results of Tables 5 and 6, it can be observed that, in comparison with base cases of power flow solutions, the Newton power flow solutions with the matrix converter need more iteration.

CONCLUSION

In this study the models for the series connected Matrix converter suitable for power flow analysis in different functioning modes were proposed. The steady state models of matrix converter revealed three control options particularly: (1) the nodal voltage; (2) the real power flowing through the line and (3) both of the nodal voltage and the active power flowing through the line. Fully detailed implementation of the models in the Newton algorithm of power flow, were considered. It was demonstrated that how the new equations can be added to the conventional Jacobian in the presence of matrix converter. MATLAB software (m-file) was potentially useful in expanding the Jacobian matrixes and doing power flow calculations. Numerical results on the 6-bus system, IEEE 14-bus system, IEEE 57-bus system and IEEE 118-bus system demonstrated the effectiveness of steady state models for operation of a power system including a series connected matrix converter.

Different cases were verified and it was shown that a matrix converter can control the active power flowing through a transmission line and the voltage magnitude of a node/bus. Newton algorithm of power flow converged very fast; however, the number of iterations of the cases with the matrix converter was inconsiderably higher than the cases without that.

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