A Robust Algorithm for Power Flow Analysis in Power Systems Embedded with MTDC Systems and FACTS Devices

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Abstract: A novel and robust algorithm, called improved sequential method, for the power flow solution of power systems embedded with MTDC (Multi-Terminal DC) systems and FACTS (Flexible AC Transmission System) devices is proposed in this paper. General injected power models of FACTS devices and MTDC systems are developed and incorporated into the new algorithm. The proposed method exhibits good convergence characteristics and abilities to be implemented in conventional AC power flow programs. The effectiveness of the proposed algorithm is demonstrated in this paper and the results are compared with the other two conventional methods, simultaneous Newton-type algorithm and sequential method.

Keywords: Power flow, FACTS, MTDC

1. INTRODUCTION

A number of papers have been published on the power flow applied to the integrated AC-DC power system. Recently, with the development of the FACTS (Flexible AC Transmission System) technology [1-4], different kinds of algorithms have been carried out to solve the power flow with various FACTS devices [5][7]. This paper intends to present a general method to consider the MTDC (Multi-Terminal DC) systems and FACTS devices simultaneously.

With the introduction of FACTS devices and MTDC systems, there are new control variables and control equations added into the conventional power flow equations. A simultaneous method has been presented in [5] and [6] for FACTS devices and MTDC systems respectively, which uses the Newton method to solve the combined set of power flow equations and extra control equations simultaneously. The method is robust and reliable. However, if we apply this method to the power flow computation for the power system with MTDC systems and FACTS devices, it is a must to rewrite the program because the simultaneous method augments the Jacobian matrix and increases the state variables. Another algorithm, the sequential method, also is adopted in AC-MTDC or AC-FACTS power flow calculation, which solves the power flow equations and control equations iteratively. This method is simple and can use the conventional power flow program almost without changes. But because this method neglects the coupling effects between the power flow equations and control equations, the convergence may be degraded.

After comprehensively analyzing the MTDC systems and FACTS devices, we find that the MTDC systems and FACTS devices can be considered as some voltage-dependent loads with injected power models being adopted. Then conventional power flow programs can still be used to solve the AC-MTDC-FACTS power system with minor changes in Jacobian matrix to consider the impacts of these equivalent voltage-dependent loads.

This paper thus proposes a novel approach, called improved sequential method, to solve the power flow for the AC-MTDC-FACTS power system. Because this method does not neglect the coupling effects between the conventional power flow equations and control equations, it will maintain the good convergence property of Newton method. Moreover, by this method we can partition AC, MTDC and FACTS parts in the power flow calculation so that a simple sequential form can be adopted, and little modification is needed in existing AC power flow programs to include the MTDC systems and FACTS devices. Numerical tests on IEEE test systems have been done and the results show that the proposed method is efficient and valid.

2. AC-MTDC-FACTS POWER FLOW ANALYSIS

With the introduction of FACTS devices and MTDC systems, the power flow equations can be written as (1).

$$\begin{cases} F(X_{ac}, X_{dc}, X_f) = 0 \\ G_d(X_{ac}, X_{dc}) = 0 \\ G_f(X_{ac}, X_f) = 0 \end{cases} \tag{1}$$

where, $X_{ac} = [V, \theta]^T$ is a vector of original AC system state variables, X_{dc} and X_f are control variables of MTDC systems and FACTS devices, F represents power flow equations, and G_d, G_f stand for the control equations of MTDC systems and FACTS devices.

If MTDC systems and FACTS devices are introduced into AC power flow equations by injected power models, and X_{dc}, X_f can be expressed as $X_{dc} = G_d^{-1}(X_{ac})$ and $X_f = G_f^{-1}(X_{ac})$, then (1) can be written as:

$$\begin{aligned} F &= S_g - S_{ld} - S_{ac}(X_{ac}) - S_{dc}(X_{ac}, X_{dc}) - S_f(X_{ac}, X_f) \\ &= S_g - S_{ld} - S_{ac}(X_{ac}) - S_{dc}(X_{ac}, G_d^{-1}(X_{ac})) - S_f(X_{ac}, G_f^{-1}(X_{ac})) \end{aligned} \tag{1'}$$

Additional subscripts g, ld, dc and f are used to denote the quantities of the generator, load, DC system, and FACTS, respectively. From (1'), it is clearly to see the MTDC systems and FACTS devices can be considered as some voltage-dependent loads though these loads can not be expressed explicitly by AC quantities. So, how to consider the impacts of these introduced loads on the conventional AC Jacobian matrix becomes the key in AC-MTDC-FACTS power flow calculation.

To solve (1), mathematically the following Newton-Raphson iteration form is adopted:

$$-\begin{bmatrix} H_{ac} & H_{ac-dc} & H_{ac-f} \\ H_{dc-ac} & H_{dc} & 0 \\ H_{f-ac} & 0 & H_f \end{bmatrix}\begin{bmatrix} \Delta X_{ac} \\ \Delta X_{dc} \\ \Delta X_f \end{bmatrix} = \begin{bmatrix} \Delta F \\ \Delta G_d \\ \Delta G_f \end{bmatrix} \quad (2)$$

By the gaussian elimination process, the sub-blocks, H_{ac-dc} and H_{ac-f}, of Jacobian matrix are eliminated. Then,

$$-\begin{bmatrix} \widetilde{H}_{ac} & 0 & 0 \\ 0 & H_{dc} & 0 \\ 0 & 0 & H_f \end{bmatrix}\begin{bmatrix} \Delta X_{ac} \\ \Delta X_{dc} \\ \Delta X_f \end{bmatrix} = \begin{bmatrix} \Delta \widetilde{F} \\ \Delta \widetilde{G}_d \\ \Delta \widetilde{G}_f \end{bmatrix} \quad (3)$$

where, $\widetilde{H}_{ac} = H_{ac} - H_{ac-dc}H_{dc}^{-1}H_{dc-ac} - H_{ac-f}H_f^{-1}H_{f-ac}$,

$\Delta\widetilde{F} = \Delta F - H_{ac-dc}H_{dc}^{-1}\Delta G_d - H_{ac-f}H_f^{-1}\Delta G_f$,

$\Delta\widetilde{G}_d = \Delta G_d + H_{dc-ac}\Delta X_{ac}$, $\Delta\widetilde{G}_f = \Delta G_f + H_{f-ac}\Delta X_{ac}$.

Clearly the coupling effects of MTDC systems and FACTS devices have been taken into account in the modified Jacobian matrix $\widetilde{H}_{ac}$. Besides, we have

$$\begin{aligned} &\Delta F(X_{ac}, X_{dc} - H_{dc}^{-1}\Delta G_d, X_f - H_f^{-1}\Delta G_f) \\ &= \Delta F(X_{ac}, X_{dc}) - H_{ac-dc}H_{dc}^{-1}\Delta G_d - H_{ac-f}H_f^{-1}\Delta G_f = \Delta\widetilde{F} \end{aligned} \quad (4)$$

As a result, the solution procedure to equation (3) could be written as:

Step 1

$$\begin{cases} \Delta X_{dc}^{temp(k)} = -H_{dc}^{-1(k)}\Delta G_d(X_{ac}^{(k)}, X_{dc}^{(k)}) \\ X_{dc}^{temp(k+1)} = X_{dc}^{(k)} + \Delta X_{dc}^{temp(k)} \end{cases} \quad (5)$$

$$\begin{cases} \Delta X_f^{temp(k)} = -H_f^{-1(k)}\Delta G_f(X_{ac}^{(k)}, X_f^{(k)}) \\ X_f^{temp(k+1)} = X_f^{(k)} + \Delta X_f^{temp(k)} \end{cases} \quad (6)$$

Step 2

$$\begin{cases} \Delta X_{ac}^{(k)} = -\widetilde{H}_{ac}^{-1(k)}\Delta F(X_{ac}^{(k)}, X_{dc}^{temp(k+1)}, X_f^{temp(k+1)}) \\ X_{ac}^{(k+1)} = X_{ac}^{(k)} + \Delta X_{ac}^{(k)} \end{cases} \quad (7)$$

Step 3

$$\begin{cases} \Delta X_{dc}^{com(k)} = -H_{dc}^{-1(k)}H_{dc-ac}^{(k)}\Delta X_{ac}^{(k)} \\ X_{dc}^{(k+1)} = X_{dc}^{temp(k+1)} + \Delta X_{dc}^{com(k)} \end{cases} \quad (8)$$

$$\begin{cases} \Delta X_f^{com(k)} = -H_f^{-1(k)}H_{f-ac}^{(k)}\Delta X_{ac}^{(k)} \\ X_f^{(k+1)} = X_f^{temp(k+1)} + \Delta X_f^{com(k)} \end{cases} \quad (9)$$

Next we study the **step 1** of the **(k+1)th** iteration,

Step 1

$$\begin{cases} \Delta X_{dc}^{temp(k+1)} = -H_{dc}^{-1(k+1)}\Delta G_d(X_{ac}^{(k+1)}, X_{dc}^{(k+1)}) \\ X_{dc}^{temp(k+2)} = X_{dc}^{(k+1)} + \Delta X_{dc}^{temp(k+1)} \end{cases} \quad (10)$$

Here it is reasonable to assume that Jacobian matrix H_{dc} is approximately unchanged in that the values of state variables X_{dc} are little changed between **step 3** of **kth** iteration and **step 1** of **(k+1)th** iteration. So after adding $\Delta X_{dc}^{temp(k+1)}$ with $\Delta X_{dc}^{com(k)}$ we can derive [8]

$$\begin{aligned} &\Delta X_{dc}^{com(k)} + \Delta X_{dc}^{temp(k+1)} = -H_{dc}^{-1}[\Delta G_d(X_{ac}^{(k+1)}, X_{dc}^{(k+1)}) + H_{dc-ac}\Delta X_{ac}^{(k)}] \\ &= -H_{dc}^{-1}[\Delta G_d(X_{ac}^{(k+1)}, X_{dc}^{temp(k+1)} + \Delta X_{dc}^{com(k)}) + H_{dc-ac}\Delta X_{ac}^{(k)}] \\ &= -H_{dc}^{-1}[\Delta G_d(X_{ac}^{(k+1)}, X_{dc}^{temp(k+1)}) + H_{dc}\Delta X_{dc}^{com(k)} + H_{dc-ac}\Delta X_{ac}^{(k)}] \\ &= -H_{dc}^{-1}\Delta G_d(X_{ac}^{(k+1)}, X_{dc}^{temp(k+1)}) \end{aligned} \quad (11)$$

Consequently, the iteration form of (5)—(9) can be altered as follows.

Step 1

$$\begin{cases} \Delta X_{dc}^{(k)} = -H_{dc}^{-1(k)}\Delta G_d(X_{ac}^{(k)}, X_{dc}^{(k)}) \\ X_{dc}^{(k+1)} = X_{dc}^{(k)} + \Delta X_{dc}^{(k)} \end{cases} \quad (12)$$

$$\begin{cases} \Delta X_f^{(k)} = -H_f^{-1(k)}\Delta G_f(X_{ac}^{(k)}, X_f^{(k)}) \\ X_f^{(k+1)} = X_f^{(k)} + \Delta X_f^{(k)} \end{cases} \quad (13)$$

Step 2

$$\begin{cases} \Delta X_{ac}^{(k)} = -\widetilde{H}_{ac}^{-1(k)}\Delta F(X_{ac}^{(k)}, X_{dc}^{(k+1)}, X_f^{(k+1)}) \\ X_{ac}^{(k+1)} = X_{ac}^{(k)} + \Delta X_{ac}^{(k)} \end{cases} \quad (14)$$

It is noted that the solution procedure consists of two main operations:

1. Control variables of FACTS devices and MTDC systems are calculated from (12) and (13).
2. With the new values of control variables, the AC Jacobian matrix is updated. Then the state variabls are calculated through the solution (14) of power flow equations in one iteration of Newton method.

The iteration is repeated until the power mismatches in both power flow equations and control equations have converged.

A new method, improved sequential method, has been proposed to handle the AC-MTDC-FACTS power system. From the above derivation procedure, we can see that the improved sequential iteration form of (12), (13) and (14) is derived directly and exactly from the Newton-Raphson iterative form of (2). This proposed method can keep the good convergence characteristics because $\widetilde{H}_{ac}$ in (14) has considered the impacts of MTDC systems and FACTS devices on the conventional AC Jacobian matrix. Moreover, the AC power flow equations, MTDC equations and FACTS equations can be solved respectively in a simple, sequential iterative procedure. This method enables us to extend the existing AC power flow program codes easily to consider MTDC systems and established and emerging FACTS devices.

3. MTDC SYSTEM ANALYSIS

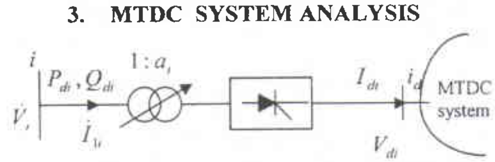


Fig 1 Equivalent representation of a converter terminal

The DC model can be defined as follows [6]:

$V_{di} = K_1 a_i V_{ti} \cos\theta_i - K_2 X_c I_{di} \cdot \xi$ (15-a)

$V_{di} = 0.995 \cdot K_1 a_i V_{ti} \cos\varphi_i$ (15-b)

$P_{di} = V_{di} I_{di}$ (15-c)

$Q_{di} = V_{di} I_{di} \tan\varphi_i \cdot \xi$ (15-d)

The various quantities of DC system involved are:

P_{di}, Q_{di} Active and reactive power transmitted from i

I_{1i} AC current drawn from bus i

ϕ_i Phase angle difference between V_i and I_{1i}

a Converter transformer tap

θ_i Converter control angle, firing angle for rectifier and extinction angle of advance for inverter

X_{ci} Commutation reactance

I_{di} DC injected current into bus i_d

V_{di} DC voltage at bus i_d

ξ 1 for rectifier, -1 for inverter

G DC network conductance matrix.

$k_1 = 3\sqrt{2}/\pi$, $k_1 = 3/\pi$, $k_3 = 0.995 \cdot k_1$.

In a MTDC system, it is assumed that the DC current leaving the termial is positive. This implies that I_{di} is negative for an inverter while positive for a rectifier. V_{di} of either inverter or rectifier is positive. Then, the MTDC network equations are obtained as $I_d = [G] \cdot V_d$. Each additional converter contributes two independent variables to the system and thus two further constraint equations must be derived from the control strategy of the system to define the operating state. Practically two control equations for each converter can be chosen from the following four control modes[9]:

1. $P_d - P_d^{sp} = 0$ and $a - a^{sp} = 0$, or $\cos\theta - \cos\theta^{sp} = 0$;
2. $I_d - I_d^{sp} = 0$ and $a - a^{sp} = 0$, or $\cos\theta - \cos\theta^{sp} = 0$;
3. $a - a^{sp} = 0$ and $\cos\theta - \cos\theta^{sp} = 0$;
4. $V_d - V_d^{sp} = 0$ and $a - a^{sp} = 0$, or $\cos\theta - \cos\theta^{sp} = 0$;

Assume that one MTDC system has four types of converters with the above four control modes in order. If the control vector is $X_{dc} = [V_{d1}, V_{d2}, V_{d3}, I_{d4}]^T$, we can obtain the reformed MTDC system network equations G_d as follows:

$$\begin{bmatrix} g_{11} & g_{12} & g_{13} & 0 \\ g_{21} & g_{22} & g_{23} & 0 \\ g_{31} & g_{32} & g_{33} & 0 \\ g_{41} & g_{42} & g_{43} & -1 \end{bmatrix} \begin{bmatrix} V_{d1} \\ V_{d2} \\ V_{d3} \\ I_{d4} \end{bmatrix} - \begin{bmatrix} I_{d1} - g_{14} \cdot V_{d4}^{sp} \\ I_{d2}^{sp} - g_{24} \cdot V_{d4}^{sp} \\ I_{d3} - g_{34} \cdot V_{d4}^{sp} \\ V_{d4}^{sp} \end{bmatrix} = 0 \tag{16}$$

where,

$$I_{d1} = P_{d1}^{sp} / V_{d1}, \; I_{d3} = \frac{K_1}{K_2 X_{c3}} a_3^{sp} \cos\theta_3^{sp} V_{t3} - \frac{1}{K_2 X_{c3}} V_{d3}.$$

In the power flow equations F of AC-MTDC system, the only modification required to the usual real and reactive power mismatch equations occurs for those equations which relate to the converter terminal AC buses. These equations with new injected power $-P_d$ and $-Q_d$ can be written as:

$$\begin{cases} P_i^{sp} - P_i(ac) - P_{di}(dc) = 0 \\ Q_i^{sp} - Q_i(ac) - Q_{di}(dc) = 0 \end{cases} \tag{17}$$

Here we can get $P_{d1} = P_{d1}^{sp}$ for the first-type converter AC buses, $P_{d2} = V_{d2} \cdot I_{d2}^{sp}$ for the second-type buses, $P_{d3} = V_{d3} \cdot (\frac{K_1}{K_2 X_{c3}} a_3^{sp} \cos\theta_3^{sp} V_{t3} - \frac{1}{K_2 X_{c3}} V_{d3})$ for the third-type buses and $P_{d4} = V_{d4}^{sp} \cdot I_{d4}$ for the forth-type buses. Q_d for the first-type,second-type and forth-type buses can be obtained as follows:

- One of the two converter control equations is the specified tap control equation, then

$$Q_{di} = I_{di} \sqrt{K_3^2 (a_i^{sp})^2 V_{ti}^2 - V_{di}^2} \cdot \xi \tag{18-a}$$

- One of the two converter control equations is the specified fire angle equation, then

$$Q_{di} = I_{di} \sqrt{K_a (V_{di} + K_2 X_{ci} I_{di})^2 - V_{di}^2} \cdot \xi$$

$$K_a = \frac{K_3^2}{K_1^2 \cos^2 \theta_i^{sp}} \tag{18-b}$$

And

$$Q_{di} = (\frac{K_1}{K_2 X_{c3}} a_3^{sp} \cos\theta_3^{sp} V_{t3} - \frac{1}{K_2 X_{c3}} V_{d3}) \sqrt{K_3^2 (a_i^{sp})^2 V_{ti}^2 - V_{di}^2} \tag{18-c}$$

for the third-type buses.

For the solution of MTDC system vector X_{dc}, the AC power flow equations F and MTDC system network equations G_d can be effectively solved by the improved sequential method introduced above..

4. FACTS DEVICES

Recently, lots of advanced FACTS devices emerged because of the rapid development of the modern power electronics technology. Mainly there are four types of FACTS devices being used to control the power flow, which are Static Synchronous Compensator (STATCOM), Thyristor Controlled Series Compensation (TCSC), Thyristor Controller Phase Shifting Transformer (TCPST), Unified Power Flow Controller (UPFC) and so on. In practice, STATCOM and Static Var compensator (SVC) are used to hold the bus voltage at specific value, so the buses connected to STATCOMs and SVCs often are considered as PV buses in power flow computation. This paper mainly discusses TCSC, TCPST and UPFC. The line with a FACTS device often is modeled as shown in Fig. 2.

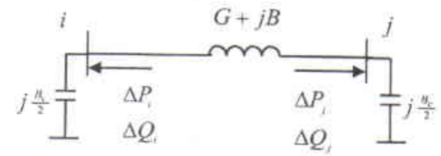


Fig. 2 Injected power model of FACTS

- TCSC

TCSC can increase or decrease the electrical length of the line by supplying positive or negative reactance to reduce or improve the line's ability to transfer power. The model presented below is simple and is to introduce a new control variable X_c with a new control objective P_{ij}^{sp} into the power flow equations. Fig. 3 can be changed into Fig. 2, which is formulated as an injected-power model. The corresponding injected power at terminal buses i and j are:

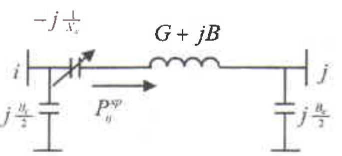


Fig. 3 Transmission line $i-j$ with TCSC

$$\begin{aligned}
\Delta P_i &= -V_i^2G'' + V_iV_jG''\cos\theta_{ij} + V_iV_jB''\sin\theta_{ij}\\
\Delta Q_i &= V_i^2B'' + V_iV_jG''\sin\theta_{ij} - V_iV_jB''\cos\theta_{ij}\\
\Delta P_j &= -V_j^2G'' + V_iV_jG''\cos\theta_{ij} - V_iV_jB''\sin\theta_{ij}\\
\Delta Q_j &= V_j^2B'' - V_iV_jG''\sin\theta_{ij} - V_iV_jB''\cos\theta_{ij}
\end{aligned} \tag{19}$$

The active power control equation G_f is

$$\Delta P_{ij} = V_i^2G' - V_iV_jG'\cos\theta_{ij} - V_iV_jB'\sin\theta_{ij} - P_{ij}^{sp} = 0 \tag{20}$$

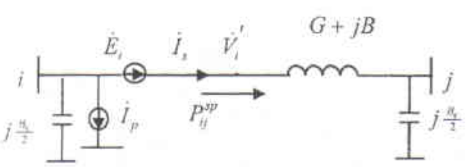
where, $Y' = G' + jB'$, $G' = \dfrac{G^2+B^2}{G^2+[(G^2+B^2)X_c - B]^2}G$,

$$B' = \frac{G^2+B^2}{G^2+[(G^2+B^2)X_c - B]^2}[B-(G^2+B^2)X_c],$$

$G'' = G' - G$, $B'' = B' - B$.

- TCPST

TCPST is capable of controlling the power flow by locally altering the voltage angle difference. Like TCSC, furtherly the model of TCPST (Fig.4) can be stated as an injected one as Fig. 2, and the injected power can be formulated as follows:



$\dot{E}_i = j\tan\phi\cdot\dot{V}_i$, $\dot{I}_p = -j\tan\phi\cdot\dot{I}_s$

Fig. 4 Schematic representation of TCPST

$$\begin{aligned}
\Delta P_i &= -V_i^2T^2G - V_iV_jT(G\sin\theta_{ij} - B\cos\theta_{ij})\\
\Delta Q_i &= V_i^2T^2B + V_iV_jT(G\cos\theta_{ij} + B\sin\theta_{ij})\\
\Delta P_j &= -V_iV_jT(G\sin\theta_{ij} + B\cos\theta_{ij})\\
\Delta Q_j &= -V_iV_jT(G\cos\theta_{ij} - B\sin\theta_{ij})
\end{aligned} \tag{21}$$

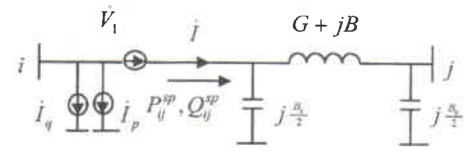
The control variable is $X_{TCPST} = [\phi]$ and control equation G_f is:

$$\Delta P_{ij} = K^2V_i^2G - KV_iV_j(G\cos(\theta_{ij}+\phi) + B\sin(\theta_{ij}+\phi)) - P_{ij}^{sp} = 0 \tag{22}$$

where, $T = \tan\phi$, $K = 1/\cos\phi$.

- UPFC

UPFC, a versatile FACTS device, has the unique capability to control simultaneously both the voltage magnitude and active and reactive power flows on a transmission corridor. Fig. 5 shows the equivalent circuit representation of a UPFC and we also can derive its injected power model as Fig. 2. Here, the equivalent injected power can be expressed as follows:



$\dot{V}_1 = K_1e^{j\phi_1}\cdot\dot{V}_i$

Fig. 5 Schematic representation of UPFC

$$\begin{aligned}
\Delta P_i &= -G[2K_1V_i^2\cos\phi_1 + K_1^2V_i^2 - K_1V_iV_j\cos(\phi_1+\theta_{ij})]\\
&\quad + BK_1V_iV_j\sin(\phi_1+\theta_{ij})\\
\Delta Q_i &= K_1V_i^2G\sin\phi_1 + K_1V_i^2B\cos\phi_1 + \frac{B_c}{2}K_1V_i^2\cos\phi_1 - V_iI_q\\
\Delta P_j &= K_1V_iV_j[G\cos(\theta_{ij}+\phi_1) - B\sin(\theta_{ij}+\phi_1)]\\
\Delta Q_j &= -K_1V_iV_j[B\cos(\theta_{ij}+\phi_1) + G\sin(\theta_{ij}+\phi_1)]
\end{aligned} \tag{23}$$

The UPFC control variables are $X_{UPFC} = [K_1, \phi_1, I_p, I_q]^T$ and control equations are:

$$\begin{aligned}
\Delta P_{ij} &= (1+K_1^2+2K_1\cos\phi_1)V_i^2G - V_iV_j(G\cos\theta_{ij} + B\sin\theta_{ij})\\
&\quad - K_1V_iV_j[G\cos(\theta_{ij}+\phi_1) + B\sin(\theta_{ij}+\phi_1)] - P_{ij}^{sp} = 0
\end{aligned} \tag{24}$$

$$\begin{aligned}
\Delta Q_{ij} &= -(1+K_1^2+2K_1\cos\phi_1)V_i^2(B+\tfrac{B_c}{2})\\
&\quad + V_iV_j(B\cos\theta_{ij} - G\sin\theta_{ij}) + K_1V_iV_j[B\cos(\theta_{ij}+\phi_1)\\
&\quad - G\sin(\theta_{ij}+\phi_1)] - Q_{ij}^{sp} = 0
\end{aligned} \tag{25}$$

For the case when the UPFC controls voltage magnitude at the AC shunt converter terminal (node i) and power flowing from node i to node j, from (24) and (25) we can see that if node i is defined as PV-type bus, there are two control variables K_1 and ϕ_1 left and needed to be computed in the iteration. Other control variables $\dot{I}_p$ and $\dot{I}_q$ can be updated after each iteration by the injected reactive power of PV-type node i and the internal active power balance equation of UPFC.

5. POWER FLOW TEST CASES

A Newton-type power flow program, based on the improved sequential method, has been extended to include the FACTS devices and MTDC systems described above. The developed program has been extensively tested on large number of power networks of different sizes with various FACTS device and MTDC systems. The test results show the proposed method is efficient with power flow solutions converging in five iterations or less. The test results of two networks are presented here:

1) IEEE 14-bus system with several FACTS devices and a DC link.
2) IEEE 30-bus system with several FACTS devices and a MTDC system.

- Test system 1

The IEEE 14-bus system is modified to include a DC link connected between nodes 4 and 5, as is shown in Fig. 6. The original line between nodes 4 and 5 is removed. A SVC is installed at the node 9 to keep the voltage at $1.06 p.u.$, and a TCSC is placed at the line 2-3 to control the real power $P_{23}^{sp} = 80MW$.

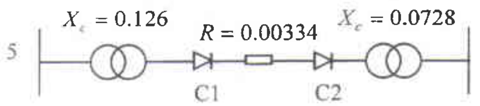


Fig. 6 A DC link in IEEE 14-bus system

Two methods, the improved sequential method and the sequential method are used to solve the system. Table 1 shows the DC link results and Fig. 7 shows the convergence trajectories of the maximum absolute, nodal power mismatches. Apparently, the improved sequential method reached convergence with the required tolerance of $10^{-7} p.u.$ faster than the sequential method.

TABLE 1. TEST RESULTS OF IEEE 14-BUS NETWORK

Conv	Control variables	$I_d(p.u.)$	$V_d(p.u.)$	$\theta(^\circ)$	$a(p.u.)$
C1	P_d^{sp}, θ^{sp}	0.4566	1.28343	8	1.030
C2	θ^{sp}, a^{sp}	-0.4566	1.28190	16	0.995
TCSC: $X_c = -0.043 p.u.$ SVC: $X_c = 4.73 MVAR$					

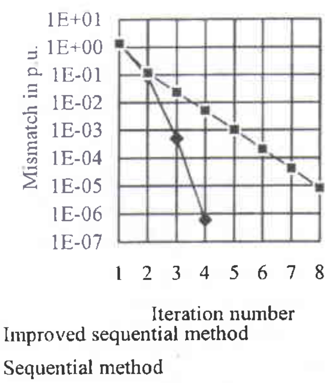


Fig. 7 Convergence trajectories of two methods for test system 1

- Test system 2

The IEEE 30-bus system with a 5-terminal DC system and various FACTS devices is tested. Table 2 reports the values of commutation reactance and DC links. Four branches are installed with FACTS devices [10]. The power flow computation with the simultaneous method (SM) and the improved sequential method (ISQ) converged in less than 6 iterations. The sequential (SQ) method required more number of iterations. The test results are shown in Table 3.

TABLE 2. MTDC SYSTEM DATA FOR TEST SYSTEM 3

	Parameter	C1	C2	C3	C4	C5
Conv	Type	Rectifier	Inverter	Inverter	Inverter	Rectifier
	Bus Number	2	4	6	28	1
	$X_c(p.u.)$	0.0474	0.0474	0.0237	0.0474	0.0602
DC network	Line $i-j$	1 – 5	2 – 3	2 – 5	4 – 5	
	$R(p.u.)$	0.0199	0.0228	0.0164	0.0173	

TABLE 3. TEST RESULTS OF 30-BUS SYSTEM

	Control variables					Iter. Num		
	C1	C2	C3	C4	C5	SM	ISQ	SQ
1	I_d^{sp}, θ^{sp}	V_d^{sp}, θ^{sp}	V_d^{sp}, θ^{sp}	V_d^{sp}, θ^{sp}	V_d^{sp}, θ^{sp}	3	3	3
2	P_d^{sp}, a^{sp}	V_d^{sp}, a^{sp}	P_d^{sp}, θ^{sp}	P_d^{sp}, θ^{sp}	V_d^{sp}, a^{sp}	4	4	6
3	P_d^{sp}, a^{sp}	V_d^{sp}, a^{sp}	V_d^{sp}, a^{sp}	P_d^{sp}, θ^{sp}	θ^{sp}, a^{sp}	4	4	8
4	θ^{sp}, a^{sp}	V_d^{sp}, a^{sp}	P_d^{sp}, θ^{sp}	V_d^{sp}, θ^{sp}	θ^{sp}, a^{sp}	5	5	10
5	θ^{sp}, a^{sp}	I_d^{sp}, a^{sp}	P_d^{sp}, a^{sp}	I_d^{sp}, a^{sp}	V_d^{sp}, θ^{sp}	5	6	10

6. CONCLUSION

This paper has presented a novel approach suitable for solving the power flow of power system embedded with FACTS devices and MTDC systems. The method is derived from the Newton-type method and is capable of solving large power networks very reliably. The algorithm retains Newton's quadratic convergence and its robustness is verified by extensive tests on several systems. Moreover, this new method can use the simple iterative form of the sequential method while maintaining the good convergence characteristics of Newton-type algorithms. In this paper, injected power models of FACTS devices and MTDC system are used in the power flow algorithm. The efficiency of the improved sequential method with these injected power models to solve power networks containing FACTS device and MTDC systems is verified. In summary, the main merit of the proposed algorithm is that it may be efficiently applied in existing AC power flow programs with extension to include the effects of FACTS devices and MTDC systems.

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