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Power Flow Modelling for Power Systems with Dynamic Flow Controller

Roya Ahmadi Ahangar[1*], **Abdolreza Sheykholeslami**[1] and **Hamidreza Ghaffari**[2]

[1]Department of Electrical Engineering, Noushirvani Industrial University, Babol, Iran.
[2]Sharif University of Technology, Iran.

[*]Corresponding author: roya_ahmadi_h@yahoo.com (Roya Ahmadi Ahangar), Tel: +989113116187

Abstract: This paper presents a new method for power flow calculation of power systems in presence of Dynamic Flow Controller (DFC) which is a new member of FACTS controllers. The focus of the paper is to explore how to systematically extend and modify Newton-Raphson power flow method to include DFC. A new steady state model of DFC is introduced for the implementation of the device in the conventional Newton-Raphson power flow. The impact of DFC on power flow is accommodated by adding new entries and modifying some existing ones in the linearised Jacobian equations of the same system without DFC. A case study on a power system located in northern of Iran shows the effectiveness of proposed method.

Keywords: Dynamic flow controller, Newton-Raphson, power flow.

1. INTRODUCTION

Application of Flexible AC Transmission Systems (FACTS) controllers has been considered as a satisfied solution especially in regions that it is becoming very difficult to construct a new transmission line in order to avoid a power transmission limit of the existing lines, particularly under heavily loaded system conditions [1]. A new member of FACTS controllers is considered in this paper. The controller, Dynamic Flow Controller (DFC) is a hybrid compensator that provides series and/or shunt compensation. In comparison with Unified Power Flow Controller (UPFC) [2], DFC has some salient features like cost effectiveness, simplicity, maturity and ruggedness of the technologies of its subsystems, potentially lower losses and thus higher efficiency, which makes it alternative to the UPFC [3].

Structurally, a DFC unit is composed of a mechanically-switched phase shifting transformer (PST), a mechanically switched shunt capacitor (MSC), and multi-module, thyristor-switched series capacitor (TSSC) and inductors (TSSR) [4-6]. Since parameters of DFC change in discrete steps, results of power flow algorithm may not exactly match these discrete points. In order to avoid complexity and reaching a general view, the effect of this mismatch has been neglected in this paper.

Most researchers and industries use Newton-Raphson method of iterative solution [7], and the technique is used in this paper. While traditional power flow program do not include FACTS controllers, papers have been published dealing with power flow problem considering FACTS controllers [8-13]. Undoubtedly, an important part of power system study is power flow, thus for power flow control of a system in presence of DFC, it is very important to include this new FACTS controller in power flow equations.

The objective of the present paper is to develop a power flow model for a power system with DFC. In this method the conventional power flow calculation is systematically extended to include this controller. The modelling approach presented in this paper is tested on a 9-bus system and implemented using MATLAB software package.

2. PRINCIPLES OF OPERATION OF DFC

As mentioned before, DFC consists of three main parts. Figure 1 shows a schematic diagram of DFC which is connected between buses i and j in a transmission system. Vp is the series injected voltage and V_E is the parallel injected voltage of the PST. Based on DFC steady state model [2] a Single-phase equivalent model of the DFC is shown in Figure 2 . Details for reducing the single phase PST of Figure 2 from that of Figure 1, under balance conditions are given in [3]. Extraction of per-phase representation of the TSSC, TSSR and MSC is given in [11].

In Figure 2 $k_L.X_L$ and $k_C.Xc$ represents the reactive and capacitive modules (ohmic losses are ignored). k is the PST voltage ratio which is between -1 and 1, XE, XB, XP and Rv are PST internal parameters. Thus, the line between busses i and j it can be written as

$$Xij=kL.XL+k2.XE+XB+XLINE-kcXc \quad (1)$$
$$Zij=Rij+jXij \quad (2)$$
$$Ys=Yij=1/Zij=Gs+jBs \quad (3)$$

Since the ideal transformers of the PST do not exchange any power with the system:

$$Ip+Iv=-jkIij \quad (4)$$

and Iij is calculated in [2]:

$$\text{Iij} = \frac{(1+jk\;\;)}{j.Xij}\text{Vi} + \frac{\text{Vj}}{j.Xij} \quad (5)$$

At bus i

$$\text{Ii= Ip+Iv+Iij} \quad (6)$$

Substituting for Ip+Iv from (4) and Iij from (5) in (6) deduced:

$$\text{Ii= (1+k2) YijVi-(1-jk) YijVj} \quad (7)$$

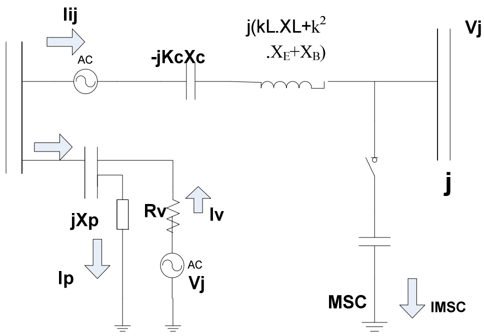

Figure 1.schematic diagram of DFC

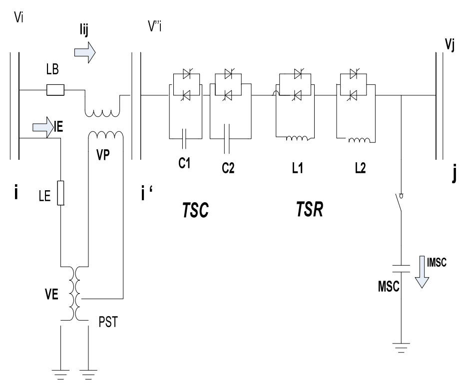

Figure2. Single-line equivalent model of DFC

3. POWER FLOW CALCULATION IN PRESENCE OF DFC

The block diagram given in Figure 3 shows a symbolic representation of a power system that includes several generators, loads and a DFC. The power flow equations for a power system's generic bus (bus i) without DFC is:

$$\text{Pi= } \sum |\text{Vi}||\text{ Vj}||\text{Yij}|\cos(\delta\text{i-}\delta\text{j-}\theta\text{ij}) \quad (8)$$

$$\text{Qi= } \sum |\text{Vi}||\text{ Vj}||\text{Yij}|\sin(\delta\text{i- }\delta\text{j-}\theta\text{ij}) \quad (9)$$

where represents the voltage of Bus i and represents elements of Y-matrix. Equations (1) and (2) are iteratively solved using linearised Jacobian equation, shown in Equation (10).

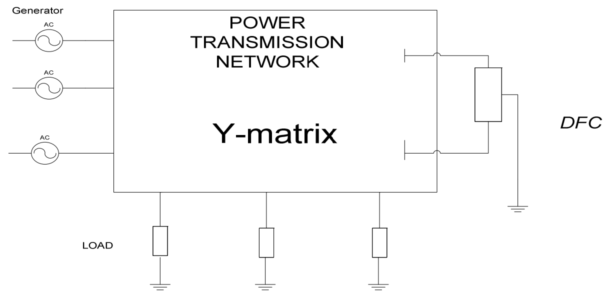

Figure 3. Symbolic representation of a power system

where the sub Jacobian matrices are defined as $J_1=\partial P/\partial\delta$, $J_2=\partial P/\partial|V|$, $J_3=\partial Q/\partial\delta$, $J_4=\partial Q/\partial|V|$.

$$\begin{bmatrix} J_1 & J_2 \\ J_3 & J_4 \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta|V| \end{bmatrix} = \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} \quad (10)$$

DFC can actively adjust its internal parameters for controlling active and reactive power flow and regulating the voltage. That means based on power flow solution, parameters P, Q, V, δ at buses which the DFC is located are determined. Thus, the internal control parameters of the DFC can be calculated as follows:

$$\text{Si=Vi Ii*} \quad (11)$$

Substituting for Ii from (7) in (11) we deduce

$$\text{Si} = -\frac{(1+k^2)}{j.Xij}|Vi|^2 + \frac{(1+jk)}{j.Xij}\text{Vi. Vj}^\circ \quad (12)$$

$$\text{Sj} = -\frac{(1-jk)}{j.Xij}\text{Vi. Vj}^\circ + \frac{(XMSC-Xij)}{j.Xij.XMSC} \quad (13)$$

As mentioned, power flow is analyzed based on the preset values of power and voltage magnitude that the DFC is expected to impose. However, since the DFC works in discrete steps, a set of solutions may not exactly match the actual values of DFC parameters. The consequence mismatch may have effects on analyzing iterations, convergence or even speed of calculations, but not in the results of power flow. This problem could be faced with several ways. In this paper we assume that step magnitudes are close enough together, thus if the calculated values of internal parameters correspond to a point located between two steps by rounding up the parameters to those of the closest step values the probable mismatch error can be neglected.

For including the DFC in power flow equations, its circuit model must be changed. In this way it is much easier to write DFC equations in the format of power flow equations. This new model which is extracted from Figure 2 is illustrated in Figure 4:

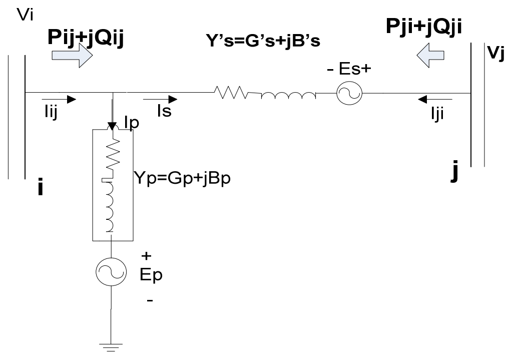

Figure 4. New circuit model of DFC

As it shown in Figure 4, circuit model of DFC is converted to a new model, which only consists of one series and one parallel branch. It is clear that the admittance of MSC is included in Ys (Figure 2) results in Y's (Figure 4).

Parallel branches of PST in Figure 2 can be converted to their Thevenin equivalent. The Thevenin parameters and parallel branches can be replaced with an admittance of Yp and a voltage source of Ep as it shown in Figure 4. The power flow equations for all busses of the system with DFC in place are the same as those of the system without DFC, except for buses i and j which are shown as follow:

$$P_i=P_{ij}+\sum |V_i||V_x||Y_{ix}|\cos(\delta_i-\delta_x-\theta_{ix}) \quad (14)$$

$$Q_i=Q_{ij}+\sum|V_i||V_x||Y_{ix}|\sin(\delta_i-\delta_x-\theta_{ix}) \quad (15)$$

$$P_j=P_{ji}+\sum |V_j||V_x||Y_{jx}|\cos(\delta_j-\delta_x-\theta_{jx}) \quad (16)$$

$$Q_j=Q_{ji}+\sum|V_j| V_x||Y_{jx}|\sin(\delta_j-\delta_x-\theta_{jx}) \quad (17)$$

The summation terms in the above equations represents the same equations for the system without DFC. The equations for Pij and Qij are found to be:

$$P_{ij}=(G_p+G_s)|V_i|2-|V_i||E_P||Y_P|\cos(\delta_i-\delta_p-\theta_p)+ |V_i||E_s||Y_s|\cos(\delta_i-\delta_s-\theta_s)-|V_i||V_j||Y_s|\cos(\delta_i-\delta_j-\theta_p) \quad (18)$$

$$Q_{ij}=-(B_p+B_s)|V_i|2-|V_i||E_P||Y_P|\sin(\delta_i-\delta_p-\theta_p)+ |V_i||E_s||Y_s|\sin(\delta_i-\delta_s-\theta_s) -|V_i||V_j||Y_s|\sin(\delta_i-\delta_j-\theta_p) \quad (19)$$

The presence of the voltage sources EP and ES introduces four new variables (|EP|, δp, |Es|, δs) to the power flow problem. However |Vi| is now known. Thus three additional equations are needed to solve the power flow problem. Two of these equations are found by equating Pij and Qij to their pre-specified target values. Third equation is found by using the fact that the ideal transformers of the PST of DFC do not exchange any real and reactive power with the system. So it can be written:

$$PPST=\mathrm{Real}\,[V_p.I_{ij}^*]-\mathrm{Real}\,[V_E.I_E^*]=0 \quad (20)$$

Thus for implementation of DFC in the conventional Newton-Raphson power flow algorithm these four equations must be taken in consideration.

To solve the power flow problem with DFC in place, Jacobian equation is extended and modified as shown in (21) to accommodate the added equations (18 to 20) and the modified ones (14 to 17). As it shown in (21) Three rows and three columns are added to the original Jacobian matrix (gray colour filled in), the added elements are mentioned in these rows and columns. The elements of original Jacobian matrix which need to be modified are written in grey cells. Algorithm illustrated in Figure 5 shows proposed method mentioned in this study.

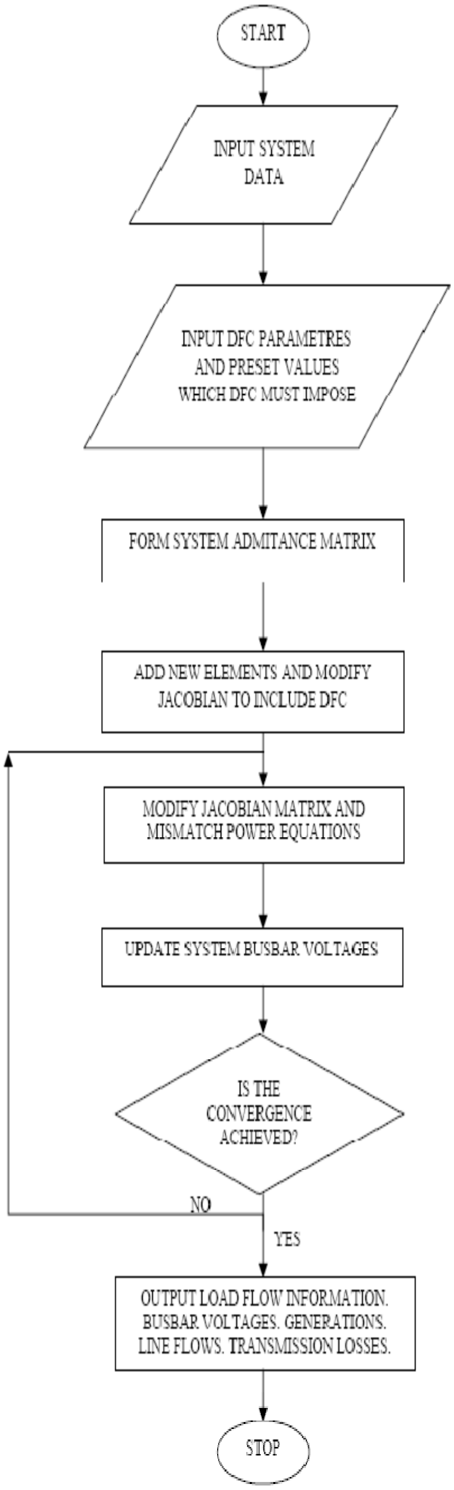

Figure 5. Proposed Algorithm for Including DFC in Newton-Raphson Power Flow

4.CASE STUDY

In order to investigate the feasibility of the proposed method, DFC embedded in power flow studies on the 230-400 KV network of a power system which is located in the northern part of Iran. It is predicted that the system will experience unacceptable under-voltage due to increase in load demand. A proposed solution to the problem is to connect bus-7 and 8 through a set of transformers. The power flow shown in Figure 6 is based on the presence of hypothetical transformers. The drawback of proposed connection is that it reduces the loading of the 230 KV line between bus-5 and bus-7 from 382 MW to 36 MW and it reduces the loading of the 230 KV lines and results in their permanent and uncontrolled under-utilization.

Installation of a DFC in path between bus-5 and 7 is investigated, to increase the 230 KV line power transfer from 36 MW to about 400 MW while maintaining the voltage at both buses 5 and 7. The proposed DFC composed of a 115 MWA PST, which can introduce up to -15° phase shift, a three module TSSC with reactance of 4, 8 and 12Ω and a MSC system (2×25 MVAr).

Figure 7 shows the receiving-end between the busses which the DFC is in service (MSC is disconnected).The phase shifter of the DFC can increase real power transfer from 70 MW to 275 MW through 18 steps. The series capacitor modules can be controlled to increase real power transfer up to 440 MW by seven steps. These modules can be switched in/out at any tap position. Figure 8 is illustrated including this and impacts of the MSC. In Figure 8 discrete points cover all operating steps of the PST (18 steps), the TSC(7 steps), and the MSC (3 steps) of the DFC unit, i.e. 3 discrete operating points. Figure 8 shows that the DFC can maintain active power transfer up to 450 MW, and reactive power up to 40 MVAr. Operating point of DFC can change between these points based on scheduled active and reactive power transfer. Here the scheduled power transfer which the DFC must maintain is 400 MW and 53 MVAr. Therefore, based on these values and equations (12) and (13) the DFC can regulate its internal parameters. By controlling reactive power transfers the DFC can although improve voltage profile. The bus voltages (both magnitude and angles) with and without DFC are shown in Table 1. Figure 9 shows the convergence characteristics for iterative solution in this case. These results are obtained by implementing proposed method using MATLAB package software. Results indicate that after installing the DFC, objective of increasing active power between bus-5 and 7 to 400MW is achieved. Besides, the acceptable voltage profile shows that new algorithm can effectively handle presence of DFC and modification process did not destroy the original algorithm.

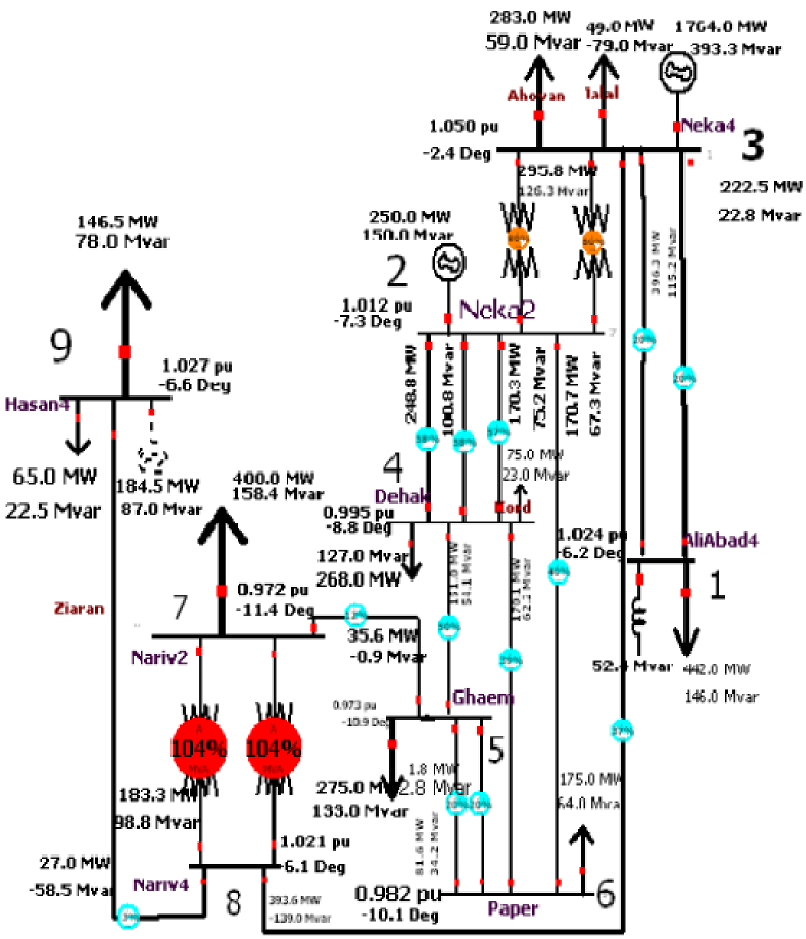

Figure 6. 230-400KV power system

$$\begin{bmatrix} P_i/\ \delta_i & P_i/\ \delta_j & P_i/\ E_p & P_i/\ |V_j| & P_i/\ \delta_p & P_i/\ \delta_s & P_i/\ |E_s| \\ P_j/\ \delta_i & {}_j/\ \delta_j & & P_j/\ |V_j| & & P_j/\ \delta_s & P_j/\ |E_s| \\ Q_i/\ \delta_i & Q_i/\ \delta_j & Q_i/\ E_p & Q_i/\ |V_j| & Q_i/\ \delta_p & Q_i/\ \delta_s & Q_i/\ |E_s| \\ Q_j/\ \delta_i & Q_j/\ \delta_j & & Q_j/\ |V_j| & & Q_j/\ \delta_s & Q_j/\ |E_s| \\ P_{PST}/\ \delta_i & P_{PST}/\ \delta_j & P_{PST}/\ E_p & P_{PST}/\ |V_j| & P_{PST}/\ \delta_p & P_{PST}/\ \delta_s & P_{PST}/\ |E_s| \\ P_{ij}/\ \delta_i & P_{ij}/\ \delta_j & P_{ij}/\ E_p & P_{ij}/\ |V_j| & P_{ij}/\ \delta_p & P_{ij}/\ \delta_s & P_{ij}/\ |E_s| \\ Q_{ij}/\ \delta_i & Q_{ij}/\ \delta_j & Q_{ij}/\ E_p & Q_{ij}/\ |V_j| & Q_{ij}/\ \delta_p & Q_{ij}/\ \delta_s & Q_{ij}/\ |E_s| \end{bmatrix} \times \begin{bmatrix} \Delta\delta \\ \\ \Delta E_p \\ \Delta|V| \\ \Delta\delta_p \\ \Delta\delta_s \\ \Delta|E_s| \end{bmatrix} = \begin{bmatrix} \Delta P \\ \\ \Delta \\ \\ \Delta P_S \\ \Delta P_{ij} \\ \Delta Q_{ij} \end{bmatrix} \quad (21)$$

Table 1: Power flow results for test system

Bus	1	2	3	4	5	6	7	8	9
Voltage without DFC	1.03	1.02	1.05	1.04	0.98	0.99	0.978	1.02	1.03
Angle without DFC	-3.45	-4.75	0	-5.95	-8	-7.3	-7.6	-3.6	-4
Voltage with DFC	1.02	1.02	1.05	0.997	0.97	0.99	0.972	1.02	1.03
Angle with DFC	-3.8	-5	0	-7	-12	-8	1	0.2	-0.2

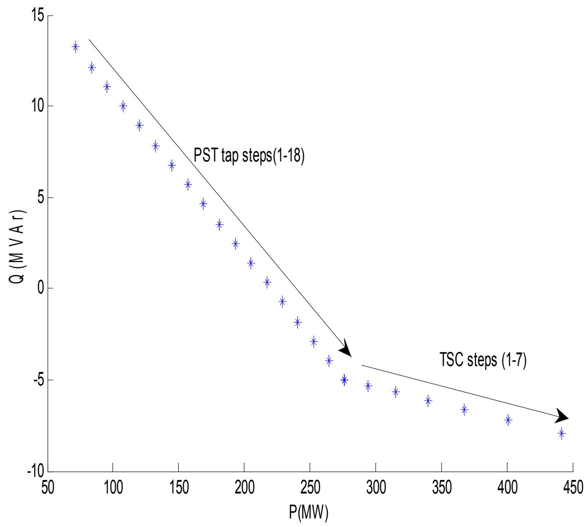

Figure 7. Impact of DFC on the receiving-end power

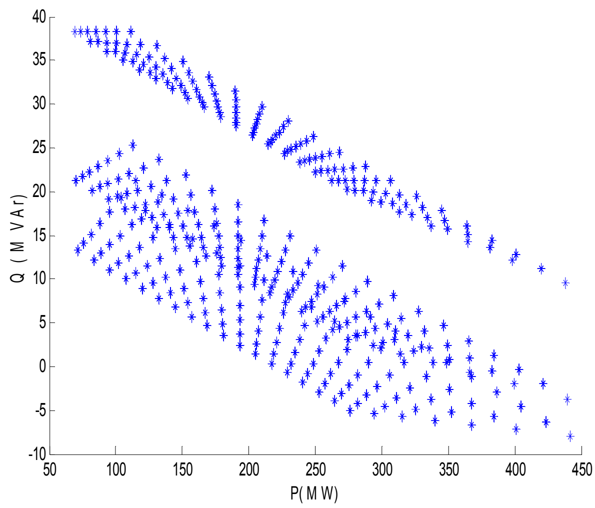

Figure 8. The receiving end P-Q area covering all operating points of the DFC

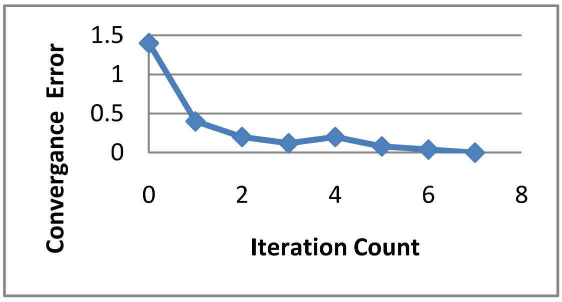

Figure 9. The convergence characteristics for the system with DFC

5. CONCLUSION

In this study an improved steady-state mathematical model for implementation of a new member of FACTS controllers has been presented. DFC has been developed in the conventional Newton-Raphson power flow algorithm. Besides, this paper demonstrates how the conventional power flow solution could be systematically modified and extended to include DFC. Impact of DFC on power flow can be accommodated by introducing a new suitable model for DFC and making changes in the linearised Jacobian equation of the original system. An existing power flow program that uses Newton-Raphson method of solution can be easily modified to include DFC using methods introduced in this paper. The results on the 230-400 KV power system located in Northern of Iran, show the effectiveness of proposed method. With DFC, power flow between buses is increased between 36 MW to 400 MW. The results also show the robust convergence of the proposed method.

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