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Investigation Using Conventional and Automatic Differential Approach on Power Flow Models of TCSC

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Abstract – This work investigates the impact of thyristor-controlled series capacitor (TCSC) on power-flow using Newton-Raphson (N-R) and automatic differentiation (AD) techniques. The load-flow problem dealt here is to evaluate the state variables of the power network and to maintain control variables to meet operating and physical constraints. To control the power-flow using TCSC, usually impedance model based firing control is used. In this work both the impedance and the firing-angle model based control of TCSC is presented. In both types of control problems, in addition to conventional N-R method an AD based, new approach is proposed for firing-angle model based control of TCSC. The theoretical description and mathematical modeling of the TCSC device is presented in detail. The realization of the impedance and firing-angle control models of the TCSC is presented. To show the effectiveness of AD approach using both the impedance model and firing-angle model based controlling of TCSC an IEEE 5 bus test system is used for the study purpose. A comparison between impedance model and firing-angle model based control of TCSC is also presented.

Index Terms – Load Flow, Automatic Differentiation, TCSC, Firing Angle Model, IEEE 5 Bus Test System.

1. INTRODUCTION

As the power transfer grow, the power system increasingly become more complex to operate and the resulting system is less secure for riding through major outages. It may lead to large power-flows with inadequate control, excessive reactive power in various parts of the system, large dynamic swings between different parts of the system and bottlenecks and thus the full potential of transmission interconnection cannot be utilized. Available literature reveals the fact that a number of approaches are followed to improve the reliability and stability of the power system network. By controlling the voltage and reactive power, the following objective can be achieved by 1. Increase in steady-state power transfer capacity,2. Improvement of transient stability.

It has been reported in literature [1]-[3], that flexible ac transmission systems (FACTS) provide new opportunities to control the power and enhance the usable capacity of presented transmission line. FACTS controllers are able to control the power-flow through a transmission line under normal and contingency conditions[4]. Available literature clearly indicates that the reactive shunt compensation is highly effective in maintaining the desired voltage profile along the transmission line interconnecting two buses of the ac system, whereas the same is quite ineffective in controlling the actual transmitted power at a particular transmission voltage level [5]-[6]. The actual transmitted power can be controlled by controlling the series line impedance and the angle between the end voltages of line and these objectives can be achieved by series compensation[7]-[8]. For the solution of load-flow analysis using N-R method and in many other optimization problems, the knowledge of Jacobian-matrix, gradient and the hessian matrix of a given function is required. AD is an upcoming powerful technology for computing the derivatives accurately and fast [9]. The traditional methods of obtaining derivatives are: hand coded derivatives, finite divided differences and symbolic differentiation. The finite differences method is very popular in civil engineering but due to loss of accuracy and impaired reliability, this method proves to be unattractive for computing large derivative matrices. The symbolic differentiation method is widely used by scientists and mathematicians for computing derivatives. The drawback of symbolic differentiation is that they run into resource limitations and cannot handle CPU intensive processes where the dimension of matrix is large [10]-[11]. Automatic differentiation is a new method for computing the derivatives. Automatic differentiation is based on the fact that any function can be decomposed into a set of elementary operations via the introduction of sequential intermediate variables. The chain rule is applied to these elementary operations to compute the derivatives. Automatic differentiation acts on a code which is written in a general purpose programming language resulting in the simultaneous computation the value of user specified functions and the derivatives with respect to the user specified input variables. The derivative outcome can be a function gradient vector or a Jacobian-matrix. The basic requirements of derivative method are reliability, computational cost and development time [12].

2. PROBLEM FORMULATION

In this paper an attempt is made to discuss the following:

1. To enhance the performance of a transmission line, the use of a TCSC with improved control is proposed.
2. Two different control approaches which include (i) impedance model and (ii) firing-angle model based control of TCSC is implemented.
3. An algorithm for computing the load-flow using N-R and AD approach is discussed. The control of TCSC based on impedance model is realized using both N-R and AD approaches.
4. A novel technique which uses AD to realize firing-angle model based control of TCSC is proposed.

2.1. Power-Flow Models of TCSC

A basic TCSC module consists of a thyristor-controlled reactor (TCR) in parallel with a fix capacitor. An actual TCSC may comprise of one or more such modules. The TCR achieves its fundamental frequency operating state at the expenses of generating harmonic currents, which are a function of the thyristor conduction angle. Nevertheless, contrary to the SVC application where the harmonic currents generated by the TCR tend to escape towards the network, in the TCSC application the TCR harmonic currents are trapped inside the TCSC because of the low impedance of the capacitor compared with the network equivalent impedance. It should be noted that there is little incentive for operating the TCSC in inductive mode as this would increase the electrical length of the compensated transmission line, but with adverse consequences on stability margins and extra losses. For the purpose of fundamental frequency power system studies, the TCSC consist of one equivalent TCR paralleled by one equivalent capacitor as shown in figure 1. Here the surge arrestor is not included as this representation is intended for steady-state operation, but the existence of a loop current is emphasized. This equivalent circuit has an associated equivalent reactance, which is a function of the thyristor gating signals.

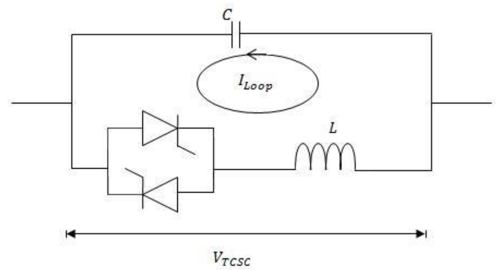

Figure 1 Equivalent Circuit of TCSC

The fundamental frequency equivalent reactance of the TCSC module as shown in figure 1 is given as

$$X_{TCSC(1)} = -X_C - C_1\{2(Л-\alpha) + \sin 2(Л-\alpha)\} + C_2\cos^2(Л-\alpha)\begin{Bmatrix}\varpi \tan \varpi(Л-\alpha) \\ -\tan(Л-\alpha)\end{Bmatrix} \text{..........................(1)}$$

Where, $C_1 = \frac{X_C+X_{LC}}{Л}$, $C_2 = \frac{-4X_{LC}^2}{ЛX_L}$), $X_{LC} = \frac{X_C X_L}{X_C - X_L}$

3. PORPOSED MODELLING

3.1. Modeling of Newton-Raphson Method in terms of AD

There are four quantities which are unknown and are associated with each bus of network. These are voltage magnitude, phase angle, real power and reactive power.

$$y = P_k^{cal} = x_1^2 G_{kk} + x_1 x_2[G_{km}\cos(x_3 - x_4) + B_{km}\sin(x_3 - x_4)] \text{ ....(2)}$$

$y = x_{16} = f_{16}(x_6, x_{15}) = x_6 + x_{15}$

$x_{15} = f_{15}(x_{13}, x_{14}) = x_{13} + x_{14}$

$x_{14} = f_{14}(x_7, x_{12}) = x_7 x_{12}$

$x_{13} = f_{13}(x_7, x_{11}) = x_7 x_{11}$

$x_{12} = f_{12}(x_{10}) = G_{km} x_{10}$

$x_{11} = f_{11}(x_9) = B_{km} x_9$

$x_{10} = f_{10}(x_8) = \cos(x_8)$

$x_9 = f_9(x_8) = \sin(x_8)$

$x_8 = f_8(x_3, x_4) = x_3 - x_4$

$x_7 = f_7(x_1, x_2) = x_1 x_2$

$x_6 = f_6(x_1) = x_1^2 G_{kk}$

$x_5 = f_5(x_1) = x_1^2$

Where $\{x_i\}$, i = 5 to 15 are the intermediate variable in which the results of the elementary function are stored. Then gradient vector is computed using above expression. The solution of power-flow problem is given by the following equation

$$\begin{bmatrix}\Delta P\\ \Delta Q\end{bmatrix} = \begin{bmatrix}\frac{\partial P}{\partial \delta} & \frac{\partial P}{\partial V}\\ \frac{\partial Q}{\partial \delta} & \frac{\partial Q}{\partial V}\end{bmatrix}\begin{bmatrix}\Delta \delta\\ \Delta V\end{bmatrix} \quad \ldots\ldots\ldots..(3)$$

The elements of jacobian-matrix can be calculated with the help of expression given by equation (2). Therefore, by solving the linear equation (3), we can get the corrected values of phase angle and the voltage magnitude.

3.2. IEEE 5 Bus Test System

An IEEE 5 bus test system is shown in figure 2. The values of the parameters associated with bus system and lines are given in Tables 1 and 2 respectively. The load-flow problem dealt here is to evaluate the network state variables and to maintain control variables so as to meet operating and physical constraints.

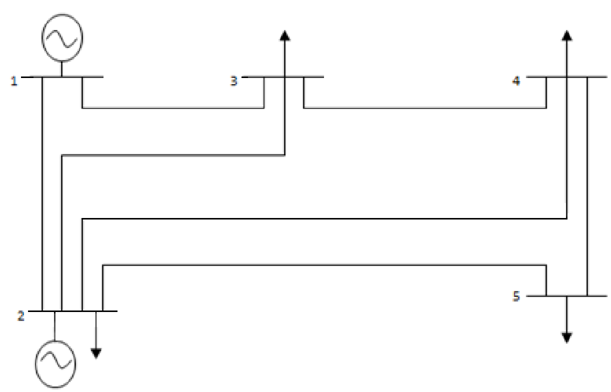

Figure 2 IEEE 5 bus test system

Analysis and Results: Two different cases (i) Without TCSC (ii) With TCSC are considered for study. MATLAB software is used for analysis purpose.

Case 1:Without TCSC: The power-flow results for various lines are given in Table 5.4. From Tables 3, it is clear that both the method give the same results for the voltages, corresponding angles and power-flows for all buses.

Case 2: With TCSC: The same IEEE 5 bus test system is used to enumerate the TCSC behavior in an interconnected network using N-R and AD approach. A new node is created to incorporate TCSC in it. The TCSC is placed between the lines 3 and 4. An extra bus, designated as bus number 6 is used to connect the TCSC. The TCSC is used to maintain an active power of 21 MW, flowing from bus 3 towards bus 4. The starting value of TCSC is set at 50% of the value of the transmission line inductive reactance.

Initial TCSC Reactance (X) (Ohm)	Lower Reactance Limit (XLo) (Ohm)	Higher Reactance Limit (XHi) (Ohm)
- 0.015	- 0.05	0.05

Table 1 TCSC Parameters for Variable-Reactance Model

Bus Number	Voltage Magnitude (pu)		Angle Profile (Degree)	
	N-R	AD	N-R	AD
1	1.0600	1.0600	0	0
2	1.0000	1.0000	-2.0346	-2.0346
3	0.9940	0.9940	-4.8278	-4.8278
4	0.9713	0.9913	-4.9235	-4.9235
5	0.9773	0.9773	-5.7789	-5.7789

Table 2 Voltage and Angle Profile for IEEE 5 Bus Test System with Variable-Impedance Model Based Control of TCSC in Line 3-4

Line Number	Real Power-Flow With Variable-Impedance Model Based control of TCSC (pu)		Reactive Power-Flow With Variable-Impedance Model Based control of TCSC (pu)	
	N-R	AD	N-R	AD
1-2	0.8858	0.8858	0.7422	0.7422
1-3	0.4246	0.4246	0.1374	0.1374
2-3	0.2541	0.2541	-0.0649	-0.0649
2-4	0.2664	0.2664	-0.0534	-0.0534
2-5	0.5406	0.5406	0.0111	0.0111
3-4	0.2100	0.2100	0.0139	0.0139
4-5	0.0717	0.0717	0.0096	0.0096

Table 3 Real and Reactive Power-Flow in Various Lines with Variable-Impedance Model Based Control of TCSC for a IEEE 5 Bus Test System

4. RESULTS AND DISCUSSIONS

4.1. TCSC Impedance Model Based Control of TCSC: An Implementation Through N-R and A-D Approach

The first application of AD to power systems is reported by Jerosolimski and Lavacher [11]. In the power-flow problem, it is important to know if there are solutions and if the solution is unique, that is, if a specific value of the state variables can be found in such way that the equalities that define the problem are satisfied. However the power-flow problem is nonlinear by nature which means that the solutions are difficult to prove mathematically. For that reason the Newton-Raphson method in its polar form, which is an iterative technique has to be used. Automatic differentiation can be utilized to calculate the jacobian and sensitivity in steady state studies as well in power-flow studies. The ordinary power-flow jacobian is calculated no more than a few times for a solution to converge. In the continuation power- flow, a locally parameterized continuation method is used in which a solution is predicted and corrected to trace a solution path. The jacobian-matrix is repeatedly updated at each solution point. The power-flow jacobian of a large system is dimensionally very large but highly sparse. In the continuation power-flow sparsity techniques are utilized to store only the nonzero elements of the argument jacobian. The automatic differentiation tool can be utilized to obtain efficient and accurate pertinent derivatives for the sparse jacobian-matrix.

In this section the firing-angle model based control of TCSC using N-R and AD techniques is discussed. IEEE 5 bus test system is used for the study. A comparison of results obtained through N-R and AD method is also presented. The analysis is carried out using MATLAB software. The IEEE 5 bus test system is used to investigate the performance of firing-angle model based control of TCSC. The details of IEEE 5 bus test system is given in Tables 2 . The parameters of TCSC which are used in load-flow analysis for firing-angle model control are given in Table 4. The controller is used to maintain the active power flowing towards 4th bus at 21 MW. The initial value of firing-angle is set at 145 degree and convergence is obtained in 10 iterations. Here a power mismatch tolerance of 1e-12 is considered. The voltage profile and corresponding angles of an IEEE 5 bus test system with TCSC in line 3–4 is estimated through N-R and AD techniques and the results are given in Table 5. These observations are also shown with the help of figures 3 to 6. The power-flow results are given in Table 5. It is noted that the TCSC upholds the target value of 21MW for line 3-4, at which it is connected.

Capacitive Reactance (X_C) (pu)	Inductive Reactance (X_L) (pu)	Initial Firing-Angle (FA) (Degree)	Minimum Value of Firing-Angle (FALo) (Degree)	Maximum Value of Firing-Angle (FAHi) (Degree)
9.375e-3	1.625e-3	145	90	180

Table 4 TCSC Parameters for Firing-Angle Model

The TCSC equivalent reactance, which is calculated using the variable reactance and firing-angle models, agrees with each other. Also from Tables 5 and 6 and figures 3 to 6, it is clear that both the method gives same results for the voltages, corresponding angles and power-flows associated with all buses.

Bus Number	Voltage Magnitude (pu)		Angle Profile (Degree)	
	N-R	AD	N-R	AD
1	1.0600	1.0600	0	0
2	1.0000	1.0000	-2.0346	-2.0346
3	0.9940	0.9940	-4.8278	-4.8278
4	0.9713	0.9913	-4.9235	-4.9235
5	0.9773	0.9773	-5.7789	-5.7789

Table 5 Voltage and Angle Profile for a IEEE 5 Bus Test System With Firing-Angle Model Based Control of TCSC (With TCSC in Line3-4)

Line Number	Real Power-Flow With Firing-Angle Model Based Control of TCSC (pu)		Reactive Power-Flow With Firing-Angle Model Based Control of TCSC (pu)	
	N-R	AD	N-R	AD
1-2	0.8858	0.8858	0.7422	0.7422
1-3	0.4246	0.4246	0.1374	0.1374
2-3	0.2541	0.2541	-0.0649	-0.0649
2-4	0.2664	0.2664	-0.0534	-0.0534
2-5	0.5406	0.5406	0.0111	0.0111
3-4	0.2100	0.2100	0.0139	0.0139
4-5	0.0717	0.0717	0.0096	0.0096

Table 6 Real and Reactive Power-Flows in Various Lines of a IEEE 5 Bus Test System with Firing-Angle Model Based Control of TCSC (with TCSC in Line 3-4)

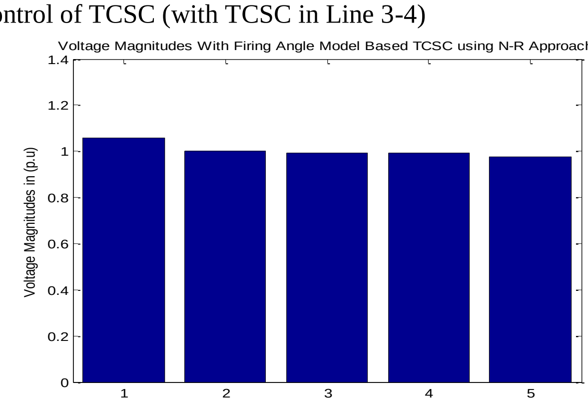

Figure 3 Voltage magnitude profile of IEEE 5 bus test system with firing-angle model based control (TCSC placed in line 3-4) using N-R approach.

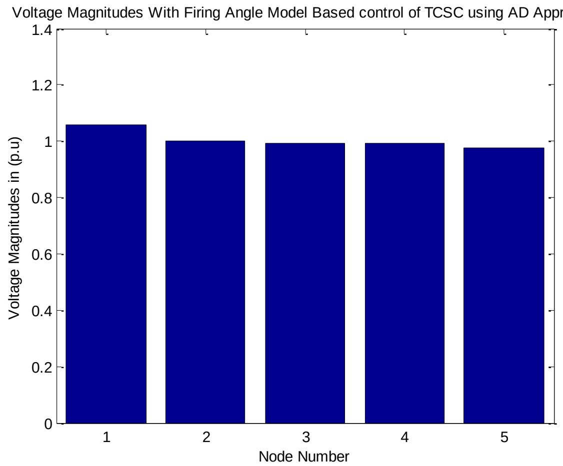

Figure 4 Voltage magnitude profile of IEEE 5 bus test system with firing-angle model based control (TCSC placed in line 3-4) using AD approach.

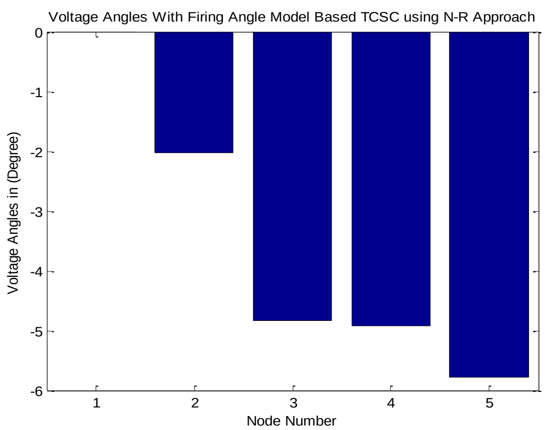

Figure 5 Angle profile of IEEE 5 bus test system with firing-angle model based control (TCSC placed in line 3-4) using N-R approach.

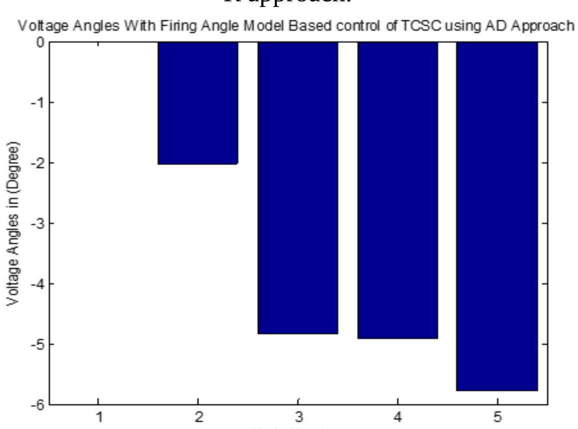

Figure 6 Angle profile of IEEE 5 bus test system with firing-angle model based control (TCSC placed in line 3-4) using AD approach.

5. CONCLUSION

Load-flow analysis is essential for continuous monitoring of the power system variables. Some commonly used load-flow techniques like Gauss-Seidal, Newton-Raphson, Decoupled load-flow and Fast Decoupled load-flow (FDLF) methods are explained. A performance comparison of these methods is also provided. In addition to this for the computation of the large derivatives matrices, automatic differentiation which is a very new and advanced tool is discussed. Due to complicacies which are method specific and also various other reasons, commonly used techniques are not very effective in calculating derivatives of large matrices.

In such cases the automatic differentiation method shows good potential and is comparatively more fast and efficient in calculating jacobian-matrix, which is a large derivative matrix. A brief discussion on the purpose of TCSC installation is included. The functioning and operational considerations are also given. The theoretical description and mathematical modeling of the TCSC device is presented in a detailed manner. The realization of the impedance and firing-angle control models of TCSC is also discussed. IEEE 5 bus test system is used to investigate the performance of power transmission line in absence as well as in presence of a TCSC device. The impedance model based control of TCSC is developed and is implemented using both, the N-R and AD techniques. It is found that during presence of TCSC the power-flows are improved as compared to the situation when there is no series compensation. The results obtained by application of N-R and AD techniques during impedance model based control are found to be very much similar (almost identical). It is noted that as compared to N-R approach, the implementation of the impedance model based control using AD technique is much easier. IEEE 5 bus test system is used to investigate the performance of power transmission line with firing-angle model based control of TCSC. The model is developed and is implemented using both, the N-R and AD techniques. It is observed that results obtained by the application of these techniques during firing-angle model based control are very much similar. It is noted that as compared to N-R approach, the implementation of the firing-angle based control using AD technique is quite easier also the firing angle calculation during firing-angle model based control is much easier as compared to impedance model based control of TCSC.

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