The Impedance and Firing-Angle Model Based Control of TCSC using N-R and AD Techniques

Pradeep Singh, Dr. Ramesh Kumar Pachar, Abhishek Jain, Mahesh Garg

***Abstract*— This paper 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. A novel technique which uses AD to realize firing-angle model based control of TCSC is proposed.**

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*—TSCS, N-R, AD, Firing Angle.**

I. INTRODUCTION

Many interconnected power system networks require stability promote to operate at desired power transfer levels. TCSC can provide such assistance for stability [1], [5], [11].

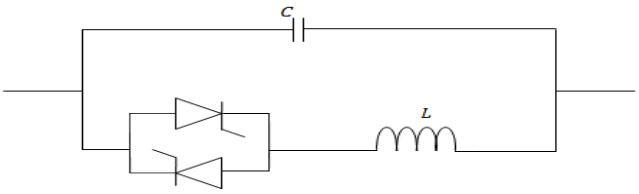

Fig. 1. Equivalent circuit of TCSC

The continuous variation in transmission line impedance is achieved by using TCSC and thereby maintaining the active power-flow in the transmission line at a specified level. TCSC consist of a capacitor in parallel with a thyristor-controlled reactor (TCR) as shown in figure 1.

II. FIRING-ANGLE POWER-FLOW MODEL OF TCSC

The impedance power-flow model uses the concept of an equivalent series reactance to represent the TCSC. Once the value of reactance is determined using Newton's method then the associated firing-angle α_{TCSC} can be calculated. Of course, this makes engineering sense only in cases, when all the modules making up the TCSC have identical design characteristics and are made to operate at equal firing-angles. If this is the case, the computation of the firing-angle is carried out. However, such calculation involves an iterative solution since the TCSC reactance and firing-angle are non-linearly related. One way to avoid the additional iterative process is to use the alternative TCSC power-flow model presented in this section. The fundamental frequency equivalent reactance $X_{TCSC(1)}$ of the TCSC module is given as

$$X_{TCSC(1)} = -X_c + C_1\{2(\pi-\alpha)+\sin 2(\pi-\alpha)\} - C_2\cos^2(\pi-\alpha)\begin{Bmatrix}\varpi\tan\varpi(\pi-\alpha)\\ -\tan(\pi-\alpha)\end{Bmatrix} \quad (1)$$

Where

$$C_1 = \frac{X_C+X_{LC}}{\pi}$$

$$C_2 = \frac{4X_{LC}^2}{\pi X_L}$$

$$X_{LC} = \frac{X_C X_L}{X_C - X_L}$$

$$\varpi = \left(\frac{X_C}{X_L}\right)^{\frac{1}{2}}$$

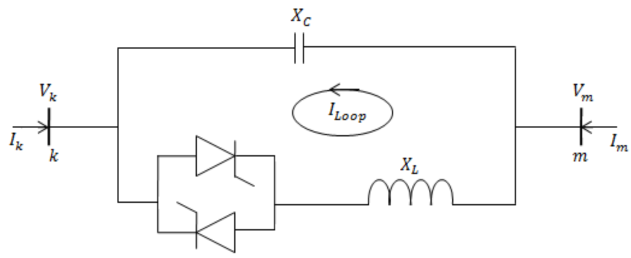

Fig. 2. Thyristor-controlled series compensator module

The transfer admittance matrix of the variable series compensator is shown in figure 2 and is given by

$$\begin{bmatrix} I_k \\ I_m \end{bmatrix} = \begin{bmatrix} jB_{kk} & jB_{km} \\ jB_{mk} & jB_{mm} \end{bmatrix}\begin{bmatrix} V_k \\ V_m \end{bmatrix} \quad (2)$$

For inductive operation, we have

$$\left.\begin{aligned} B_{kk} &= B_{mm} = \frac{-1}{X_{TCSC}} \\ B_{km} &= B_{mk} = \frac{1}{X_{TCSC}} \end{aligned}\right\} \quad (3)$$

and for capacitive operation the signs are reversed. The active and reactive power equations at the bus k are

$$P_k = V_k V_m B_{km(f1)} \sin(\delta_k - \delta_m) \quad (4)$$

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$$Q_k = -V_k^2 B_{kk\,(f1)} - V_k V_m B_{km\,(f1)} \cos(\delta_k - \delta_m) \quad (5)$$

Where $B_{kk\,(1)} = -B_{km\,(1)} = B_{TCSC\,(1)}$ (6)

For the power equations at bus m, the subscripts k and $m$are exchanged in equation (4) and equation (5). For the case when the TCSC controls active power flowing from bus k to the bus m at a specified value, the set of linearized power-flow equations is

$$\begin{bmatrix} \Delta P_k \\ \Delta P_m \\ \Delta Q_k \\ \Delta Q_m \\ \Delta P_{km}^{\alpha TCSC} \end{bmatrix} = \begin{bmatrix} \frac{\partial P_k}{\partial \delta_k} & \frac{\partial P_k}{\partial \delta_m} & \frac{\partial P_k}{\partial V_k} V_k & \frac{\partial P_k}{\partial V_m} V_m & \frac{\partial P_k}{\partial \alpha} \\ \frac{\partial P_m}{\partial \delta_k} & \frac{\partial P_m}{\partial \delta_m} & \frac{\partial P_m}{\partial V_k} V_k & \frac{\partial P_m}{\partial V_m} V_m & \frac{\partial P_m}{\partial \alpha} \\ \frac{\partial Q_k}{\partial \delta_k} & \frac{\partial Q_k}{\partial \delta_m} & \frac{\partial Q_k}{\partial V_k} V_k & \frac{\partial Q_k}{\partial V_m} V_m & \frac{\partial Q_k}{\partial \alpha} \\ \frac{\partial Q_m}{\partial \delta_k} & \frac{\partial Q_m}{\partial \delta_m} & \frac{\partial Q_m}{\partial V_k} V_k & \frac{\partial Q_m}{\partial V_m} V_m & \frac{\partial Q_m}{\partial \alpha} \\ \frac{\partial P_{km}^{\alpha TCSC}}{\partial \delta_k} & \frac{\partial P_{km}^{\alpha TCSC}}{\partial \delta_m} & \frac{\partial P_{km}^{\alpha TCSC}}{\partial V_k} V_k & \frac{\partial P_{km}^{\alpha TCSC}}{\partial V_m} V_m & \frac{\partial P_{km}^{\alpha TCSC}}{\partial \alpha_{TCSC}} \end{bmatrix} \begin{bmatrix} \Delta \delta_k \\ \Delta \delta_m \\ \frac{\Delta V_k}{V_k} \\ \frac{\Delta V_m}{V_m} \\ \Delta \alpha_{TCSC} \end{bmatrix} \quad (7)$$

Where

$\Delta P_{km}^{\alpha_{TCSC}} = P_{km}^{reg} - P_{km}^{\alpha_{TCSC},cal}$: is the active power-flow mismatch for the TCSC module and

$\Delta \alpha_{TCSC} = \alpha_{TCSC}^{(i+1)} - \alpha_{TCSC}^{(i)}$: is the incremental change in the TCSC firing-angle at the i^{th} iteration and

$P_{km}^{\alpha_{TCSC},cal}$: is the calculated power as given by equation (4).

III. AUTOMATIC-DIFFERENTIATION

In the world of engineering and science, differentiations often play a vital role in system analysis and modelling. Differentiation is one of the fundamental problems in numerical mathematics. 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 [12].The traditional methods of obtaining derivatives are: hand coded derivatives, finite divided differences and symbolic differentiation.

In power system analysis, derivatives are hand-coded in a higher level language. But when the function expression is complicated then the hand-coding can be cumbersome and is also subjected to error. 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 [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.Automatic differentiation is a chain rule based computational technique by which the value of a function and its derivatives without any truncation errors with respect to input variables of functions defined by a high level language computer program can be calculated. This process, which replaces the need for explicit derivative expression is based on two evaluations: function evaluation and derivative evaluation. Some nomenclature adopted for variables used by AD modes is given below:

n : is the number of independent variables

m : is the index of last intermediate variables

$x_1, x_2, \dots \dots, x_n$: are the independent variables

$x_{n+1}, \dots \dots, x_m$: are the intermediate variables

$\nabla x_{n+1}, \dots \dots, \nabla x_m$: are the gradients of intermediate variables

A. *Function Evaluation*

Given a function $f(x_1, x_2, \dots \dots, x_n)$, the value of the function is computed by introducing intermediate variables for each elementary mathematical operation such as addition, subtraction and each elementary function such as exponential and trigonometric expression. The last intermediate variable serves as the value of the function. It is noted that an intermediate variable can depend on the original independent variable and/or previously defined intermediate variables.

Consider the following function:

$$F = (x_1, x_2) = x_1{}^2 + x_1 \cos(x_2)$$

The function F has two independent variables ($n = 2$). The intermediate variables are defined in such a way that the last intermediate variable becomes the function value. Here 4 intermediate variables are introduced with $m = 6$. To calculate the function value, we must use 4 intermediate variables as shown in Table 1.The corresponding program can be visualized as a computational graph as shown in figure 3. At each node a corresponding independent or intermediate variable can be found.

TABLE1, INTERMEDIATE VARIABLES AND ELEMENTARY FUNCTIONS

Intermediate variable	Elementary function
$x_3 = x_1{}^2$	$x_3 = f_3(x_1)$
$x_4 = \cos(x_2)$	$x_4 = f_4(x_2)$
$x_5 = x_1 x_4$	$x_5 = f_5(x_1, x_4)$

$x_6 = x_3 + x_5$	$x_6 = f_6(x_3, x_5)$
$F = x_6$	

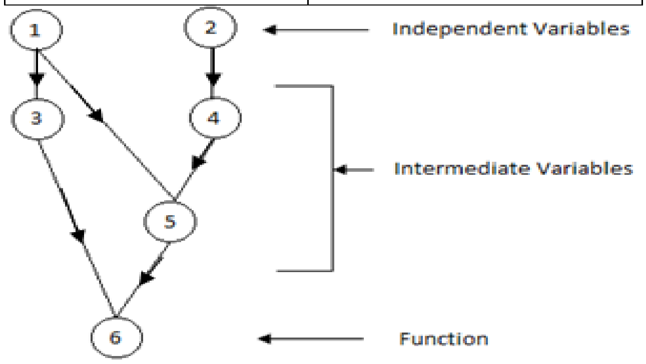

Fig. 3. Computational graph (a variable is associated with a node)

B. *Derivative Evaluation*

The process of computing derivatives is achieved using either of the following modes:

(a) Forward mode
(b) Reverse mode

The idea behind these modes is to use the chain rule fundamentals to propagate the derivatives in the forward or reverse direction. Actually, each mode of AD combines the function and derivatives evaluation in its algorithm.In the forward mode, each intermediate variable has a gradient vector ∇x_i , $i = n+1, \dots\dots, m$ with respect to the independent variables$x_1, x_2, \dots\dots, x_n$. Each assignment of an intermediate variable is augmented by its gradient calculation. It is noted that the gradient computation through the forward mode increases proportionally with the number of independent variables. The forward mode is more efficient when derivatives with respect to a few parameters are desired.

For computing the desired derivatives using the AD forward mode firstly, the gradients are initialized as follows:

$$\nabla x_1 = \begin{bmatrix} 1 \\ 0 \end{bmatrix} \quad , \quad \nabla x_2 = \begin{bmatrix} 0 \\ 1 \end{bmatrix}$$

Now, the intermediate variables and their gradients are computed as below:

$$\nabla x_3 = \frac{\partial f_3}{\partial x_1} \nabla x_1 + \frac{\partial f_3}{\partial x_2} \nabla x_2$$

$$\nabla x_3 = 2x_1 \begin{bmatrix} 1 \\ 0 \end{bmatrix} + 0$$

$$\nabla x_3 = \begin{bmatrix} 2x_1 \\ 0 \end{bmatrix}$$

Now

$$\nabla x_4 = \frac{\partial f_4}{\partial x_1} \nabla x_1 + \frac{\partial f_4}{\partial x_2} \nabla x_2$$

$$\nabla x_4 = 0 - \sin(x_2) \begin{bmatrix} 0 \\ 1 \end{bmatrix}$$

$$\nabla x_4 = \begin{bmatrix} 0 \\ -\sin(x_2) \end{bmatrix}$$

$$\nabla x_5 = \frac{\partial f_5}{\partial x_1} \nabla x_1 + \frac{\partial f_5}{\partial x_2} \nabla x_2$$

$$\nabla x_5 = x_4 \begin{bmatrix} 1 \\ 0 \end{bmatrix} + x_1 \nabla x_4 \begin{bmatrix} 0 \\ 1 \end{bmatrix}$$

$$\nabla x_5 = \begin{bmatrix} x_4 \\ -x_1 \sin(x_2) \end{bmatrix}$$

Similarly

$$\nabla x_6 = \frac{\partial f_6}{\partial x_1} \nabla x_1 + \frac{\partial f_6}{\partial x_2} \nabla x_2$$

$$\nabla x_6 = \left[\frac{\partial x_3}{\partial x_1} + \frac{\partial x_5}{\partial x_1}\right] \nabla x_1 + \left[\frac{\partial x_3}{\partial x_2} + \frac{\partial x_5}{\partial x_2}\right] \nabla x_2$$

$$\nabla x_6 = \left[\frac{\partial x_3}{\partial x_1} \nabla x_1 + \frac{\partial x_3}{\partial x_2} \nabla x_2\right] + \left[\frac{\partial x_5}{\partial x_2} \nabla x_2 + \frac{\partial x_5}{\partial x_1} \nabla x_1\right]$$

$$\nabla x_6 = \nabla x_3 + \nabla x_5$$

$$\nabla x_6 = \begin{bmatrix} 2x_1 \\ 0 \end{bmatrix} + \begin{bmatrix} x_4 \\ -x_1 \sin(x_2) \end{bmatrix}$$

$$\nabla x_6 = \begin{bmatrix} 2x_1 + x_4 \\ -x_1 \sin(x_2) \end{bmatrix}$$

The desired gradient vector is $g$is given by

$$g = \begin{bmatrix} 2x_1 + x_4 \\ -x_1 \sin(x_2) \end{bmatrix}$$

The manner in which derivative codes are generated, AD will not generally follow the exact sequential operations, as illustrated in the preceding example. Automatic differentiation techniques rely on complier operations to generate derivatives. The complier is written in a higher language such as C and is equipped with powerful tools for derivatives taking capabilities. As the complier interprets the code submitted for differentiation, it allocates all intermediate variables and generates derivatives codes based on the programmed mode. It is important to realize those AD programmed compliers are efficient and produce code that can be instantly processed by the scientist. The output of AD will be the function value and the derivatives with respect to the independent variables. Overall AD packages are based on the forward mode, reverse mode or both. The derivatives produced are in the form of gradients and matrices, which is convenience for power system analysis.

C. *Essential Qualities of Derivative Method*

The basic requirements of derivative method are as follows:

(a) Reliability: A derivative method must be reliable in terms of the correctness and numerical accuracy of the derivative results.

(b) Computational cost: The computational cost should be minimum and is affected by the amount of runtime and memory required by the derivative code.

(c) Development time: The time taken by the derivative method to design, implement and verify the derivative code should be minimum.

D. Chain Rule

Assume a function $f(s) = f(g(t))$ where t is the independent variable and variable s is an intermediate variable that derives from the elementary function g. By applying the chain rule derivatives of f are calculated as follows:

$$\left(\frac{\partial f(g(t))}{\partial t}\Big| t = to\right) = \left(\frac{\partial f(s)}{\partial s}\Big| t = to\right)\left(\frac{\partial g(t)}{\partial t}\Big| t = to\right)$$

IV. RESULTS AND DISCUSSIONS

In this research work two different cases (i) Without TCSC (ii) With TCSC are considered for the study purpose and MATLAB software is used for analysis purpose.

***Case 1:Without TCSC*:** The voltage profile and corresponding angles of an IEEE 5 bus test system without TCSC are shown in figures 4 to 7 using N-R and AD techniques.

TABLE 2, VOLTAGE AND ANGLE PROFILE FOR A IEEE 5 BUS TEST SYSTEM WITHOUT TCSC

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	-2.0565	-2.0565
3	0.9940	0.9940	-4.7405	-4.7405
4	0.9712	0.9912	-5.0636	-5.0636
5	0.9773	0.9773	-5.8402	-5.8402

The power-flow results for various lines are given in Table 3. From Tables 2 and 3 and from figures 4 to 7, it is clear that both the technique give the same results for the voltages, corresponding angles and power-flows for all buses.

TABLE 3 REAL AND REACTIVE POWER-FLOW IN VARIOUS LINES WITHOUT TCSC FOR A IEEE 5 BUS TEST SYSTEM

Line Number	Real Power-Flow Without TCSC (pu)		Reactive Power-Flow Without TCSC (pu)	
	N-R	AD	N-R	AD
1-2	0.8920	0.8920	0.7403	0.7403
1-3	0.4185	0.4185	0.1388	0.1388
2-3	0.2445	0.2445	-0.0623	-0.0623
2-4	0.2769	0.2769	-0.0560	-0.0560
2-5	0.5458	0.5458	0.0101	0.0101
3-4	0.1948	0.1948	0.0189	0.0189
4-5	0.0666	0.0666	0.0112	0.0112

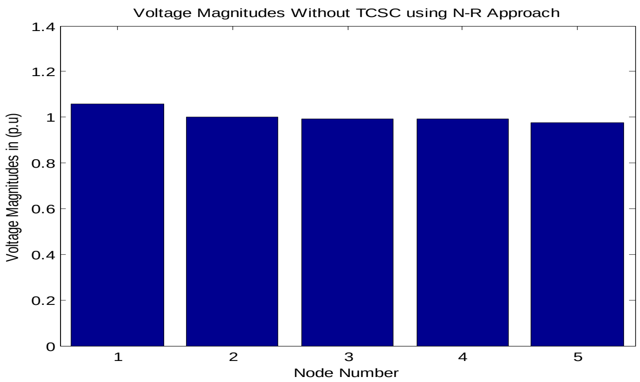

Fig. 4. Voltage magnitude profile of IEEE 5 bus test system without TCSC using N-R approach

TABLE 4 TCSC PARAMETERS FOR VARIABLE-REACTANCE MODEL

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

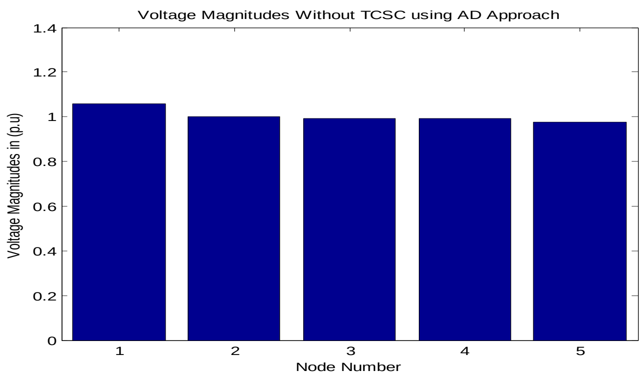

Fig. 5. Voltage magnitude profile of IEEE 5 bus test system without TCSC using AD approach

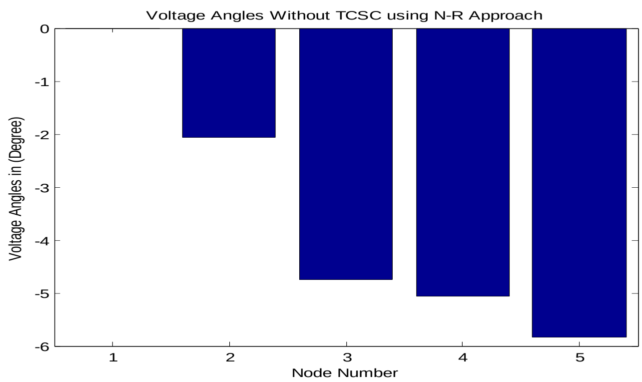

Fig. 6. Angle profile of IEEE 5 bus test system without TCSC using N-R approach

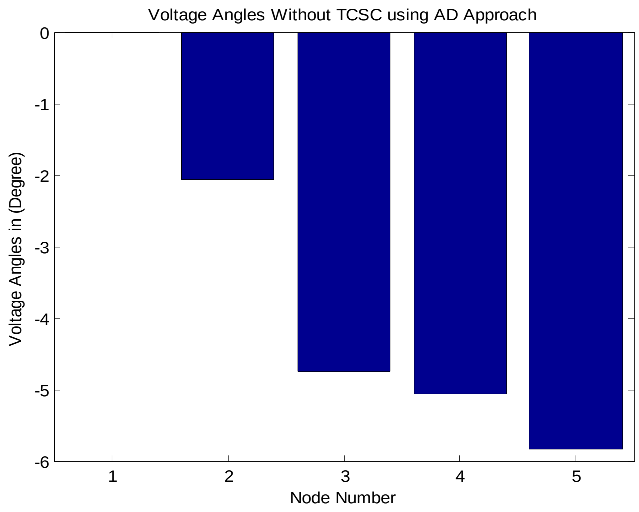

Fig. 7. Angle profile of IEEE 5 bus test system without TCSC using AD approach

Case 2: With TCSC(a) Impednce Model of TCSC: The same IEEE 5 bus test system is used to enumerate the TCSC behaviour 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. The TCSC parameters used in calculations are given in Table 4.

TABLE 5 VOLTAGE AND ANGLE PROFILE FOR A IEEE 5 BUS TEST SYSTEM WITH VARIABLE-IMPEDANCE MODEL BASED CONTROL OF TCSC IN LINE 3-4

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

The voltage and corresponding angle profiles of an IEEE 5 bus test system with TCSC in line 3–4 is shown in figures 8 to 11 using N-R and AD techniques. The power-flow results are shown in Table 5. The TCSC upholds the target value of 21MW between the line it is connected. From Tables 4 and 5 and figures 8 to 11, it is clear that the both methods give the same result for the voltages, corresponding angles and power-flows for all buses.

TABLE 6 REAL AND REACTIVE POWER-FLOW IN VARIOUS LINES WITH VARIABLE-IMPEDANCE MODEL BASED CONTROL OF TCSC FOR A IEEE 5 BUS TEST SYSTEM

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

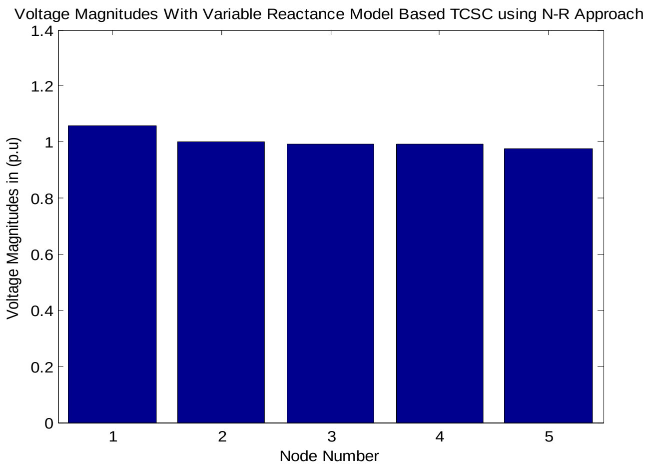

Fig. 8. Voltage magnitude profile of IEEE 5 bus test system with variable-reactance model based TCSC placed in line 3-4 using N-R approach

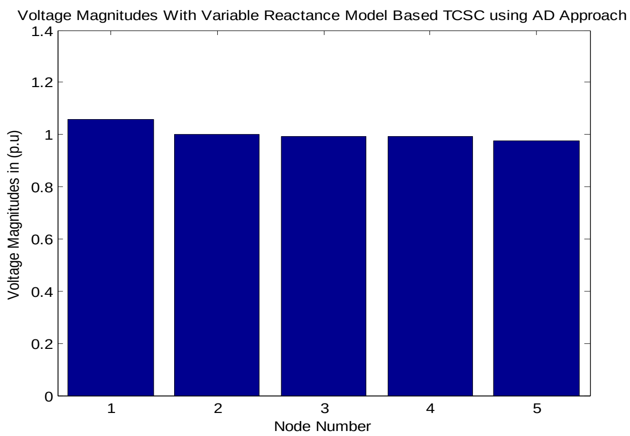

Fig. 9. Voltage magnitude profile of IEEE 5 bus test system with variable-reactance model based TCSC placed in line 3-4 using AD approach

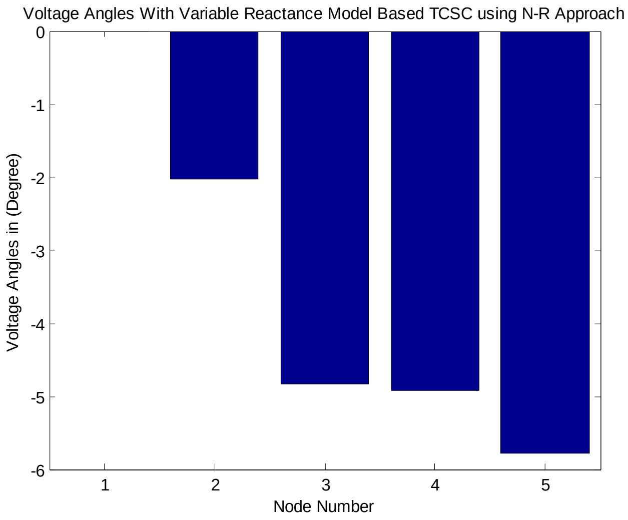

Fig. 10. Angle profile of IEEE 5 bus test system with variable-reactance model based TCSC placed in line 3-4 using N-R approach

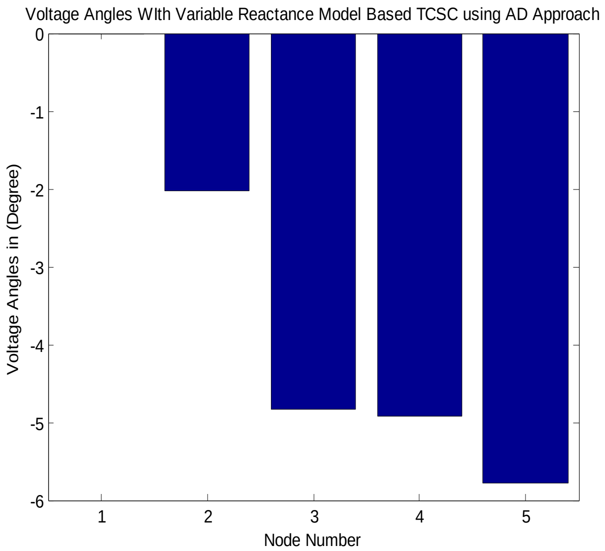

Fig. 11. Angle profile of IEEE 5 bus test system with variable-reactance model based TCSC placed in line 3-4 using AD approach

(b)Firing-Angle Model of TCSC

In this research work the firing-angle model based control of TCSC using N-R and AD techniques is also examined. The parameters of TCSC which are used in load-flow analysis for firing-angle model control are given in Table 7. 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 8. These observations are also shown with the help of figures 12 to 15. The power-flow results are given in Table 8. It is noted that the TCSC upholds the target value of 21MW for line 3-4, at which it is connected.

TABLE 7 TCSC PARAMETERS FOR FIRING-ANGLE MODEL

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

The TCSC equivalent reactance, which is calculated using the variable reactance and firing-angle models, agrees with each other. Also from Tables 8 and 9 and figures 12 to 15, it is clear that both the method gives same results for the voltages, corresponding angles and power-flows associated with all buses.

TABLE 8 VOLTAGE AND ANGLE PROFILE FOR A IEEE 5 BUS TEST SYSTEM WITH FIRING-ANGLE MODEL BASED CONTROL OF TCSC (WITH TCSC IN LINE 3-4)

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

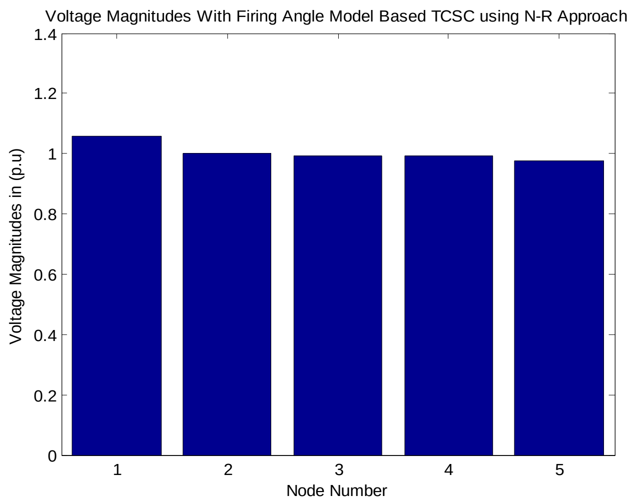

Fig. 12. Voltage magnitude profile of IEEE 5 bus test system with firing-angle model based control (TCSC placed in line 3-4) using N-R approach

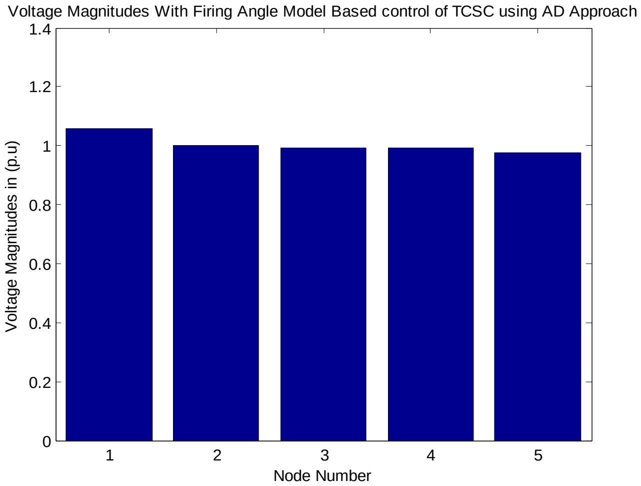

Fig. 13. Voltage magnitude profile of IEEE 5 bus test system with firing-angle model based control (TCSC placed in line 3-4) using AD approach

TABLE 9REAL 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)

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

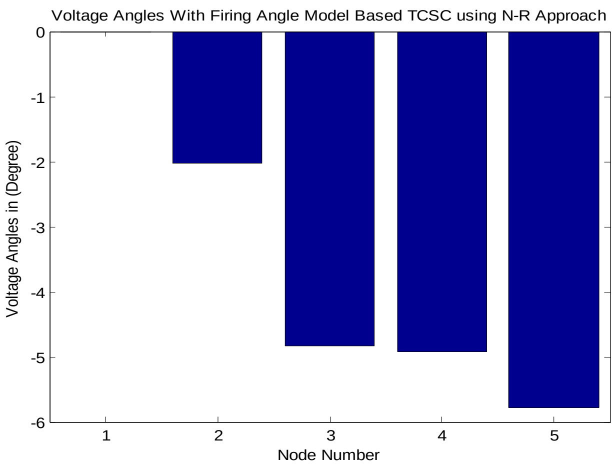

Fig. 14. Angle profile of IEEE 5 bus test system with firing-angle model based control (TCSC placed in line 3-4) using N-R approach

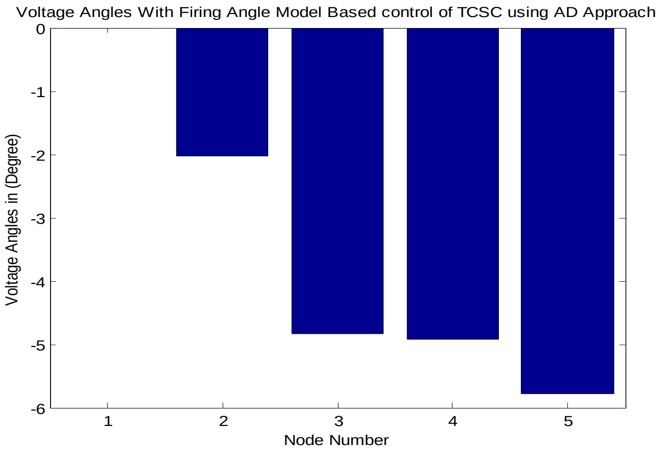

Fig. 15. Angle profile of IEEE 5 bus test system with firing-angle model based control (TCSC placed in line 3-4) using AD approach

V. CONCLUSION

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 and firing-angle model based control of TCSC 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 very much similar (almost identical). It is also noted that as compared to N-R approach, the implementation of the impedance model based control of TCSC using AD technique is much easier.

The firing-angle model based control of TCSC is developed and is implemented using both, the N-R and AD techniques. The results obtained by application of these techniques during firing-angle model based control are found to be very much similar. It is noted that as compared to N-R approach, the implementation of the firing-angle based control of TCSC using AD technique is much easier. It is also noted that the firing-angle calculation of TCSC using firing-angle model based control is much easier as compared to impedance model based control.

VI. FUTURE SCOPE

Suggested areas for future research work are as follows:

- Suitability of AD technique in controlling FACTS devices other than TCSC can be investigated.
- The use of AD technique in identification of optimal location of TCSC or other FACTS devices can be studied.
- Comparison of convergence timings with AD vs. other approaches for load-flow analysis/ TCSC control can be analyzed.

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