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Power Flow and Transient Stability Enhancement using Thyristor Controlled Series Compensation

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ABSTRACT

TL (Transmission Line) congestion is a key factor that affects the power system operational cost. In addition of renewable generation in National Grid of Pakistan, transmission line congestion are frequent. Consequently, the network in this particular region faces severe congestion and dynamic stability problems. It has been planned that renewable plants shaved to curtail some available generation to minimize this inevitable congestion. However, one of the cost-efficient solutions to this problem is series compensation of lines using TCSC (Thyristor Controlled Series Compensation). It significantly increases the transfer capability of existing power transmission and enhances the dynamic stability of system at a lower cost, and has shorter installation time as compared to the construction of new TLs. This paper deals with the dynamic modeling of a TCSC in the NTDC (National Transmission and Dispatch Company) network with its applications to alleviate congestion during fault conditions. This study has been carried out using simulation software PSS/E (Power System Simulator for Engineers) which does not have a predefined dynamic model for TCSC, this leads to the necessity of creating a user defined model. The model of TCSC has been programmed in FORTRAN and compiled along with existing dynamic models of network components. The results indicate that power flow and dynamic stability of network is enhanced.

Key Words: Transmission Lines Congestion, Renewable Energy, Thyristor Controlled Series Compensation, Power System Simulator for Engineers, National Transmission and Dispatch Company, Dynamic Simulations, FORTRAN.

1. INTRODUCTION

The primary transmission network of Pakistan rests at its two ends, the mountainous region in the North boasts hydropower plants while the Southern side caters a significant amount of thermal and renewable generating units. Faisalabad and Lahore are load center of Pakistan's system which are coupled by 500 kV TLs, under NTDC. During summers, the hydropower plants operate at their maximum level, consequently, electrical power flows from the North towards the South. On the contrary, in winter season, water supply to hydropower plants is considerably reduced, and thermal generation in the South becomes a major supplier of electrical power. Hence, the overall power flows from the South towards the North. The existing

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network in the South is energized almost exclusively by thermal power plants. However, in near future, NTDC has planned to utilize the wind power potential of the South and to install wind power plants with a combined capacity of 2410 MW, in the region. This poses a challenge to the capacity of 500 kV transmission network as the flow through that region increases drastically. Studies conclude that the previously planned 500 kV transmission network is not sufficient for the power evacuation from both, thermal and renewable plants. The network in this particular region faces severe congestion and dynamic stability problems. Resultantly, the condition has compelled NTDC to consider reinforcements, including the addition of new grid stations and transmission lines. However, transmission lines are expensive and take a long time to construct. Thus, as a remedial solution, FACTS devices are proposed [1-2] but a much more feasible alternative is the series compensation of TLs using TCSC [3]. The distinctive quality of the TCSC concept is the use of particularly simple circuit topology. As part of TCSC, a parallel combination of capacitor and inductor with thyristor valve is installed in series [4-5]. This establishes TCSC as the most efficient member of the FACTS family [6].

In this paper, we have attempted to make a case for the installation of TCSC near the Matiari region, more specifically, on the proposed 500 kV TL from Thar Energy Power Plant to Matiari Grid Station. It significantly increases the transfer capacity of existing power TLs at low cost, and improves the reliability of the system [7-8].

2. BASIC MECHANISIM OF TCSC

TCSC is used to control the reactance of the transmission lines. Therefore, it is installed in series of TL as it is shown in Fig. 1. In this way, it enhanced the power flow and transient stability of the system. The practicality of this concept is illustrated by the following discussion.

2.1 Angular Stability Improvement

Series compensation of TLs provides the improved angular stability of the system and reduces the reactance between the lines. The increased transfer capability is estimated by the given Equation (1) [10].

$$P = \frac{V_1 V_2}{X_L - X_C}\sin\varphi \tag{1}$$

Where P is power, V_1 is sending end voltages, V_2 is receiving end voltages, X_L is line reactance, X_C is series capacitor reactance, and φ is angle between sending and receiving ends.

It shows that power transfer capability of the TL is improved by reducing the active reactance X_L of TLs [8]. Additionally, as the Equation (1) introduces the X_C factor in the line, angular separation is decreased up to some extent. It increases the angular stability without affecting the transmission capacity [4].

2.2 Voltage Stability Improvement

The voltage of a TLs is directly related to the flow of active power (P) as well as reactive power (Q) as in Equation (2):

$$V = f(P,Q) \tag{2}$$

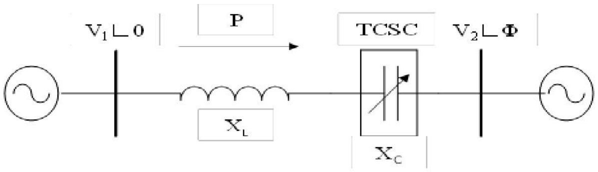


FIG. 1. SERIES COMPENSATED TRANSMISSION LINES [9]

The capacitor supply reactive power in series with the line and balance the reactive power, consequential in system voltage stability [5]. Additionally, the contribution of reactive power is instantaneous and self-regulatory in nature, inclination of reactive power is existed when the load is increased and vice versa. Therefore, it improves voltage stability in a truly dynamic fashion [10].

2.3 Degree of Compensation

The degree of series compensation is measured from ratio of capacitive reactance and inductive reactance as in Equation (3):

$$K = X_C/X_L \tag{3}$$

In TLs, the range of compensation is usually preferred $0 \leq K \leq 1$ [4-5]. Substituting the value of X_C in Equation (1):

From Equation (4), it is clearly shown that the degree of compensation due to TCSC is increased and thus, the power capability of lines is enhanced.

$$P = \frac{V_1 V_2}{X_L (1-K)} \sin\varphi \tag{4}$$

2.4 Summary and Usefulness of Series Compensation

Series compensation of TLs provides numerous beneficial effects in the network:

- The capability of TLs is increased
- The stability of the system is enhanced.
- TLs losses are reduced.

3. DYNAMIC MODELLING OF TCSC

The dynamic modelling of TCSC is discussed in this section.

3.1 TCSC Model Description

Thyristor controlled model is used to control the reactance of a TLs. In this way, it provides reactive power compensation in power systems. TCSC supports the network in two ways:

(1) It regulates the reactive compensation of TLs.

(2) It offers various modes to operate.

These characteristics are beneficial in the network where the changing of load is usually unpredictable [5]. The elementary structure of TCSC is shown in Fig. 2.

TCSC comprises of a series capacitor with a parallel combination of thyristor controlled reactor. It operates in different modes by triggering the thyristor, some modes are:

3.1.1 Block Mode

In block mode, TCSC offers the non-conducting state in non-triggered state of thyristor valve. It opens the inductive branch and causes of flow of line through the capacitor.

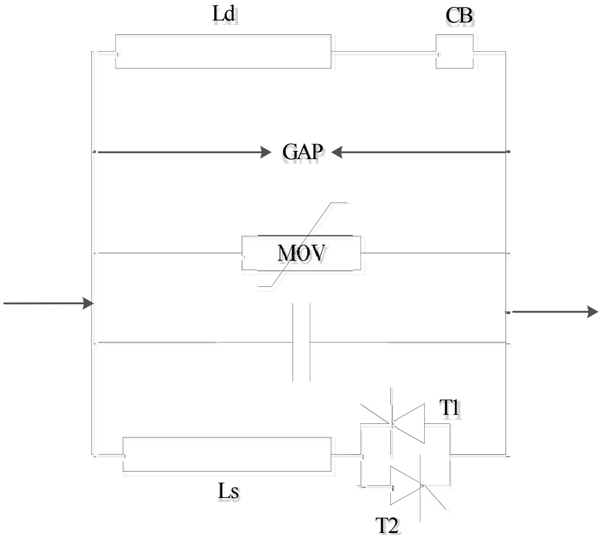


FIG. 2. TCSC BASIC STRUCTURE [11]

3.1.2 Bypass Mode

In bypass mode, TCSC offers the conducting state in triggered state of thyristor valve. It operates as a capacitor parallel with inductor and offers steady state voltage.

3.1.3 Capacitive Boost Mode

In capacitive boost mode, TCSC offers the triggered state before the capacitive voltage reaches to zero. It allows the discharge current to pass through the inductor, adds with line current and flows from the capacitor. It increases the capacitive voltage, in this way the capacitance of TCSC is enlarged without inserting a large capacitor within its structure.

3.1.4 Inductive Boost Mode

In inductive boost mode, TCSC offers the larger current in the thyristor as compared to the line current. It is caused of distortion in capacitive voltage waveform so, it is not desirable in steady state operations.

3.1.5 Harmonic Mode

In harmonic mode, the harmonics are emerged in the TCSC because it is modelled as current source. Although, the capacitor in TCSC provides low impedance and less leakage of current. In this way, lowest harmonics are observed.

3.1.6 Boost Control

In boost control, the trigger of thyristor is controlled to obtain the desired boost level in the system.

3.1.7 Open Loop Boost Control

In open loop boost control, it has response time of hundred mili-seconds and provides protection from the over-voltages in the system.

3.2 Feedback Boost Control

In feedback boost control, it provides the signal to regulator and trigger to thyristor. In this way, it speeds up the control system such as power and amplitude of current in the line.

3.3 Boost Control based on Instantaneous Capacitor Voltage and Line Current

In this boost control, an inner control loop is used based on the instantaneous capacitive voltage and line current in which both quantities are taken as input and determine the thyristor triggering instant. It is used to control the charge through the thyristor and timing of capacitor voltage zero crossing which is equivalent to timing of thyristor current peak [5].

Since TCSC facilitates different reactive compensation by means of different modes of operation depending on network requirements, it confines the line currents in occurrence of fault. Another immense advantage of TCSC is the damping of sub-synchronous resonance which leads to oscillations. These oscillations are dampen by adjusting control parameters of TCSC. Thus enhance the power transfer capability over long distances [12]. In [13], the built in model of TCSC is presented in Fig. 3.

The description of constants, used in control diagram, are given in Table 1.

In this way, the structure and functioning of TCSC model are clearly descripted.

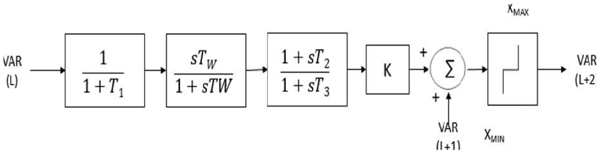


FIG. 3. CONTROL SYSTEM BLOCK DIAGRAM OF TCSC (CRANI) [13]

4. DYNAMIC MODELLING OF TCSC IN PSS/E

The dynamic modelling of TCSC in PSS/E is deliberated in this section.

4.1 TCSC Modelling in PSS/E

The simulations have been carried out in SIEMENS PTI software PSS/E, and it is the tool used by Power Planners International Private Limited, Lahore, Pakistan.

PSS/E does not have a predefined dynamic model for TCSC, making it necessary to create a user defined model. Basically, there are two methods to model TCSC in PSS/E.

First approach is to create a user defined model in FORTRAN. The source code is compiled with existing dynamic model of TCSC.

Second approach is to create API (Application Programming Interface) routines in Python. It regulates the program during dynamic simulations [14].

The first approach has been utilized in this paper due to its higher flexibility. This approach is user friendly for the implementation of user defined dynamic models in PSS/E.

TABLE 1. CONSTANTS OF TCSC (CRANI) [13]

Constants	Description
T1	Time Constant (s)
T2	
T3	
TW	
XMAX	Maximum Reactance (pu)
XMIN	Minimum Reactance (pu)
K	Gain
L	Input Signal
L+1	Initial Output
L+2	Desired Reactance

4.2 PSS/E Library Subroutines Introduction

The dynamic simulations structure is handled by activities DYRE, RSTR, STRT, RUN, and ALTR. These subroutines contain logic for parametric values, resolve the system and display the results. They do not include logic relating to the algebraic and differential equations of any equipment of power system.

For the addition of user written models, it is necessary to insert special FORTRAN logic into CONEC or CONET. The user may insert any meaningful FORTRAN statements into these subroutines before compiling them and linking them in PSS/E [14]. The linkage of the library subroutines into PSS/E is accomplished by four subroutines called TBLCNC, TBLCNT, CONEC and CONET which have certain responsibilities as outlined below. TBLCNC, TBLCNT are supplied by PSS/E and are never seen by user.

- Subroutines TBLCNC and CONEC are responsible for equipment models involving state variables and differential equations. TBLCNC is responsible for machine and their control system and CONEC is responsible for all other models.
- Subroutines TBLCNT and CONET are responsible for equipment models in which there is a purely algebraic relationship between the voltage at a bus and current drawn by the load. The principal equipment modelled in CONET is shunt load device such as reactor, relay or meter.
- The dynamic simulation structure accompanied by CONEC and CONET, is shown in Fig. 4.

4.3 Dynamic Simulation Setup for TCSC

There are four major steps involved in the creation of a user defined dynamic simulation model in PSS/E.

Step-1: Developing the Skeleton: For the dynamic setup, it is necessary to have the three following files in PSS/E, describing the system. Firstly, a properly converged load flow case. Secondly, a converted case and finally, a dynamic raw data file. Assign the names to CONEC and CONET files by opening converted case and dynamic raw data file in PSS/E, and save the Snap file [15]. This is the basic skeleton for user defined modeling.

Step-2: Apply the FLOW2 Model: FLOW2 is a built-in function of PSS/E to measure branch flow. This function in PSS/E is called by CALL FLOW2 command [15]. This function is written in the CONET subroutine with FORTRAN statements before compiling and linking them into PSS/E. The test case modeling, which includes the CONET subroutine with FLOW2, is show in Fig. 5.

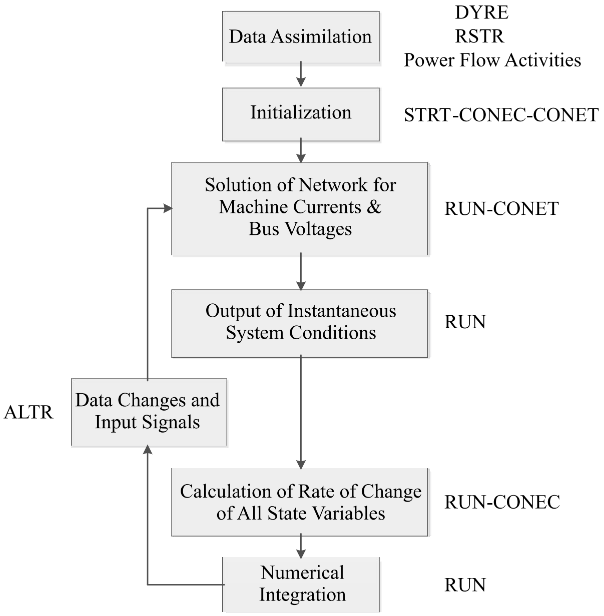
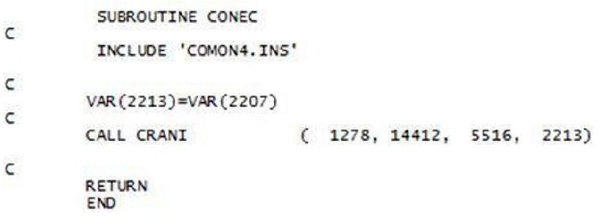


FIG. 4. DYNAMIC SIMULATION STRUCTURE INCLUDING CONEC AND CONET [15]

Step-3: Apply the CRANI Model: CRANI is a predefined model in PSS/E of a series reactor of line. This function in PSS/E is called by the CALL CRANI command [16]. It is written in CONEC subroutine with FORTRAN statements before compiling and linking them into PSS/E. The test case modeling, which includes the following CONEC subroutine with CRANI, is shown in **Fig. 6.**

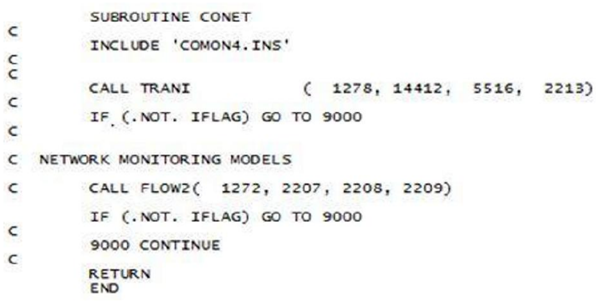
Step-4: Compile and Create USRDLL: The Auxiliary Program, USRDLL, is created, then the CONEC and CONET files are compiled and finally linked through USRDLL [17]. After successful linking, TCSC model is ready for dynamic simulations.

Consequently, first of all develop the basic skeleton for simulation setup, by assigning the names to the required files in PSS/E. In the next step, the predefined model of TCSC is called in CONEC and CONET files, using FORTRAN. Then, these files are compiled and linked to PSS/E. Thus, the TCSC model is used in the network through PSS/E, for simulation purposes.



```
         SUBROUTINE CONEC
C        INCLUDE 'COMON4.INS'
C
        VAR(2213)=VAR(2207)
C
        CALL CRANI          (  1278, 14412,  5516,  2213)
C
        RETURN
        END
```

FIG. 5. FLOW2 MODEL



```
        SUBROUTINE CONET
C       INCLUDE 'COMON4.INS'
C
C
        CALL TRANI          (  1278, 14412,  5516,  2213)
C       IF (.NOT. IFLAG) GO TO 9000
C
C  NETWORK MONITORING MODELS
C       CALL FLOW2(  1272, 2207, 2208, 2209)
        IF (.NOT. IFLAG) GO TO 9000
C       9000 CONTINUE
C
        RETURN
        END
```

FIG. 6. CRANI MODEL

5. COMPUTATIONAL RESULTS

5.1 Test Case Scenario Description

The network of National Grid of Pakistan is modeled in PSS/E tool considering all parameters of the system. This network has large integration of renewable energy sources such as 784 MW of wind energy and 400 MW of solar energy. These renewable energy sources are also modelled, to see the impact of these energy sources in the network which are shown in Figs. 7-8.

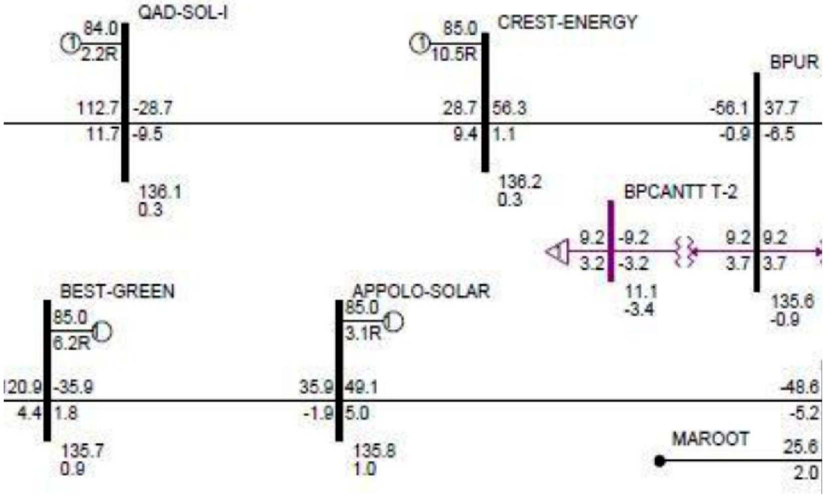


FIG. 7. SOLAR POWER PLANTS

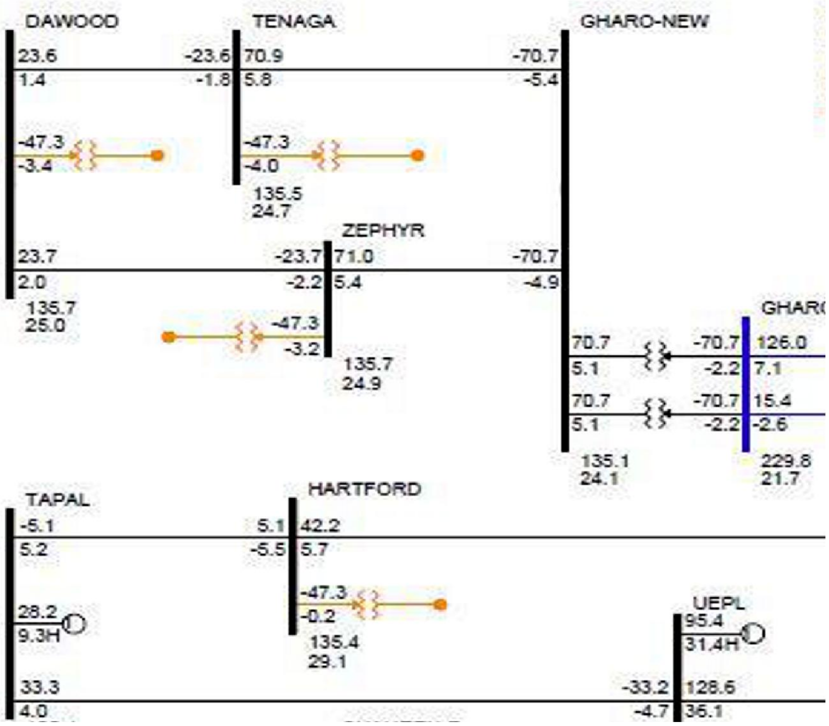


FIG. 8. WIND POWER PLANTS

This above generation integration as well as load demand and disturbed stability profiles made the congestion issues in the system. The stability analysis is analyzed using PSS/E tool and identified the most critical regions in the network. So, after the critical observations, NTDC South is selected as a test case in this paper. The lines of this region are over loaded which are clearly viewed in PSS/E tool, as shown in Fig. 9.

In case of contingency, when the line is tripped due to fault or switching from SECL CFPP to Matiari then the lines are more heavily loaded and does not maintain their stable state as shown in red color, as shown in Fig. 10.

5.2 Without TCSC in NTDC Network

The simulation of the network was run for one cycle earlier to the introduction of fault. This ensures the steady state of the system. Then the fault is introduced for five cycles to check the system stability for that period and cleared the fault. Post-fault recovery was monitored for nine

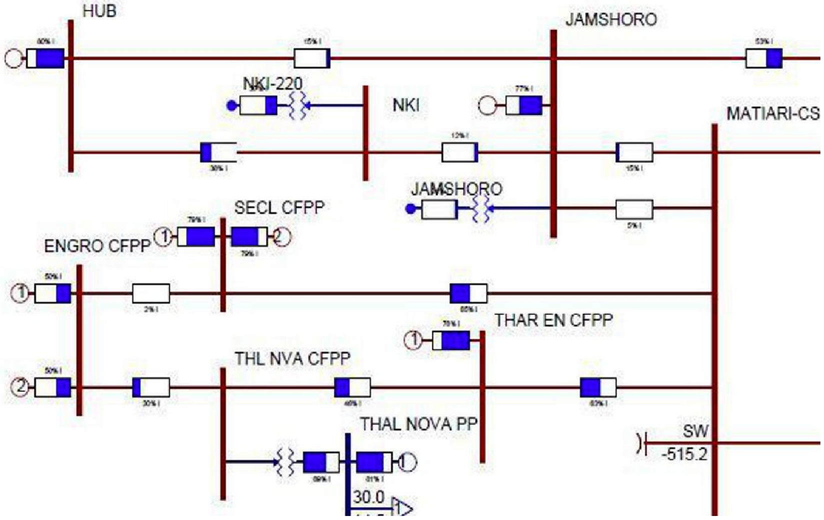


FIG. 9. LOADING OF TRANSMISSION LINES

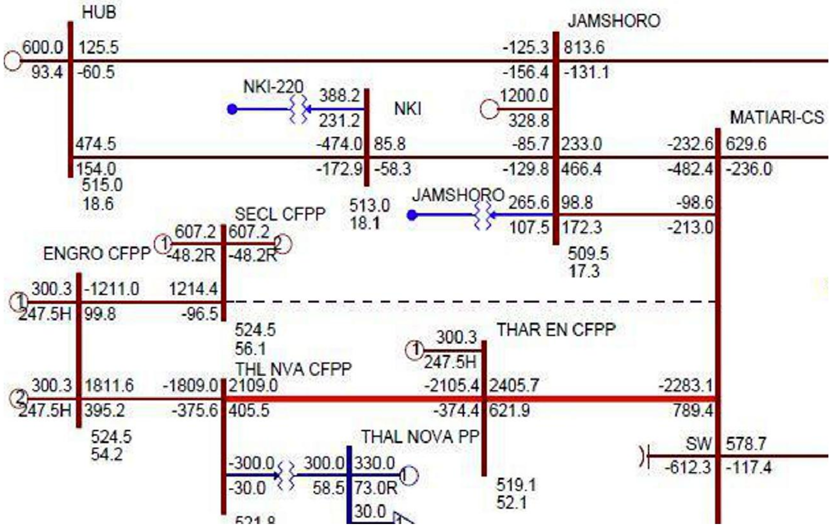


FIG. 10. NTDC NETWORK NEAR MATIARI

cycles. In most cases, the severe transient will be existed even after the fault clearance.

The test case was studied dynamically for the worst-case scenarios with following steps:

- 3-Phase fault, which is more severe in magnitude as compared to a 1-Phase fault, introduced at Matiari 500 kV bus
- Fault cleared after a time period of 100 ms, i.e. 5 cycles of a 50 Hz wave
- A 500 kV single circuit from Matiari Grid Station to SECL CFPP tripped

The following quantities were plotted in PSS/E:

(1) Bus bar voltages near the faulted bus such as Thal Nova, Thal Nova CFPP, Engro CFPP, Matiari, Jamshoro and Dadu bus bars are shown in red, green, blue, pink, black and dark red colors respectively.

(2) System frequency of Thal Nova CFPP during and after fault conditions are shown in red color.

(3) Line power flows (MW/MVAR) through Thar Energy to Matiari 500 kV circuit are shown in red and green colors respectively.

(4) Rotor angles near the faulted transmission line such as Thal Nova PP, Engro PP, Hub, Port Qasim CFPP and Jamshoro are shown in red, green, blue, pink and black colors respectively relative to the rotor angle of Guddu-New.

5.3 Plotted Result and their Description without TCSC

The bus bar voltages, frequency, rotor angle of generator and line flows of congestion area are plotted in this section.

5.3.1 Bus Bar Voltages

At the time of fault, the voltages of bus bars suddenly collapse and does not maintain their steady state value even after the fault clearance due to unbalancing of reactive power in the system shown in Fig. 11(a).

5.3.2 System Frequency

The system frequency does not recover after fault clearance due to no restoration of system generation and load in the system is shown in Fig. 11(b).

5.3.3 Line Flows MW/MVAR

At the time of fault, active power loss is ensued while reactive power reaches its peak and do not stabilize is shown in Fig. 11(c).

5.3.4 Rotor Angles

Fig. 11(d) indicate that the rotor angles do not get back to their normal state after fault application. Rotor angles of the machines also fall out of step due to no synchronism between electromagnetic and mechanical torques in the system. Thus, the system becomes unstable, failing to dampen the post fault oscillations.

5.4 Transient Stability and Voltage Improvement with TCSC

Congestion includes MW loading and MVAR loading. The traditional solution to MW loading is the installation of a new circuit while the solution to MVAR loading is usually installation of capacitors. However, these are not feasible or reliable solutions due to either high cost (in case of stringing new circuits) or due to nonexistent support during fault conditions (in case of adding capacitors).

In test case, the transient stability analysis showed that the system does not converge without compensation and the system becomes unstable [4-5]. Thus for the power evacuation of newly commissioned thermal generation near Matiari, we have proposed TCSC in the line from Thar Energy to Matiari. It is installed with given technical data to regulate the performance of TCSC during the transient situations in the system (Table 2).

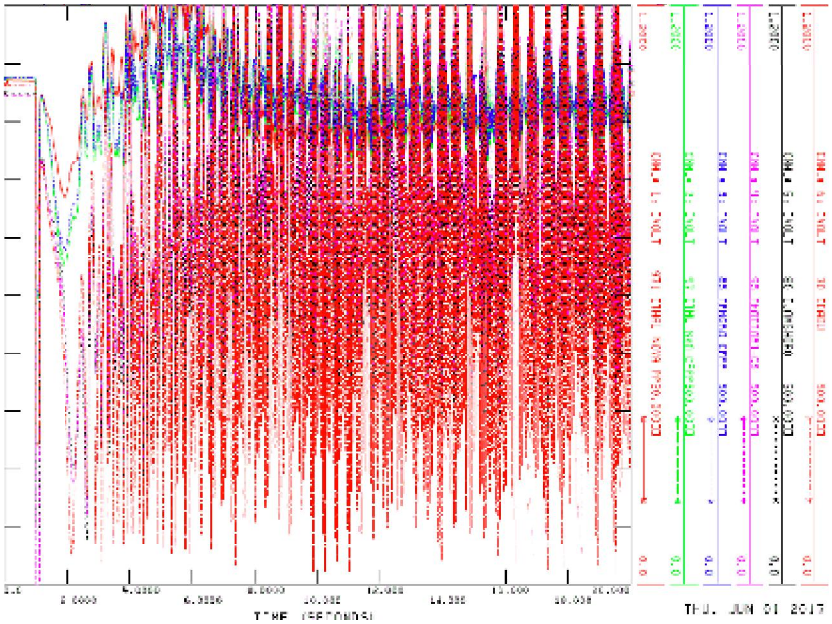


FIG. 11(a). BUS BARS VOLTAGE

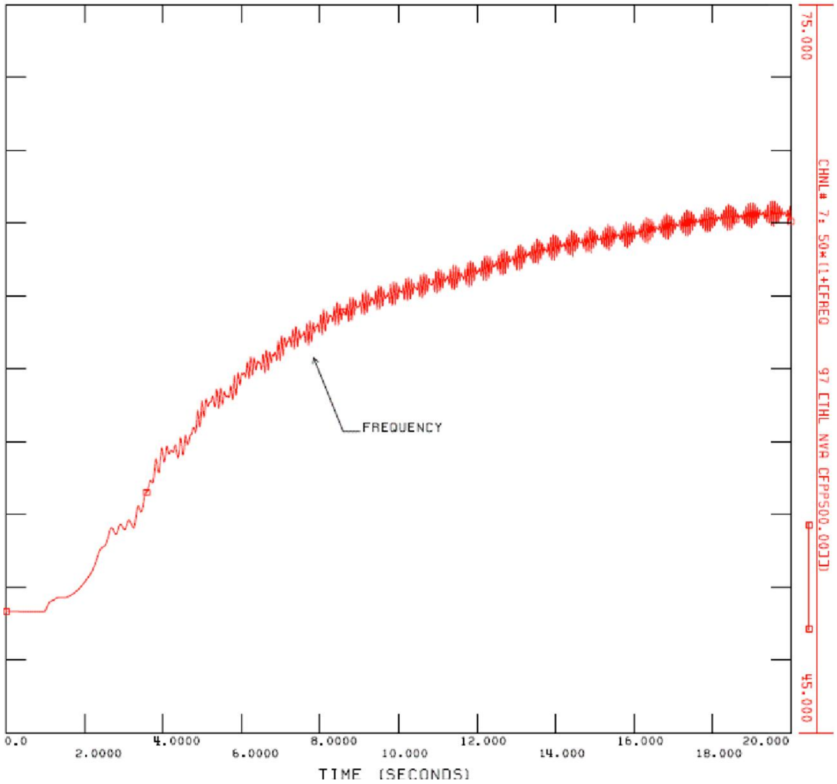


FIG. 11(b). SYSTEM FREQUENCY

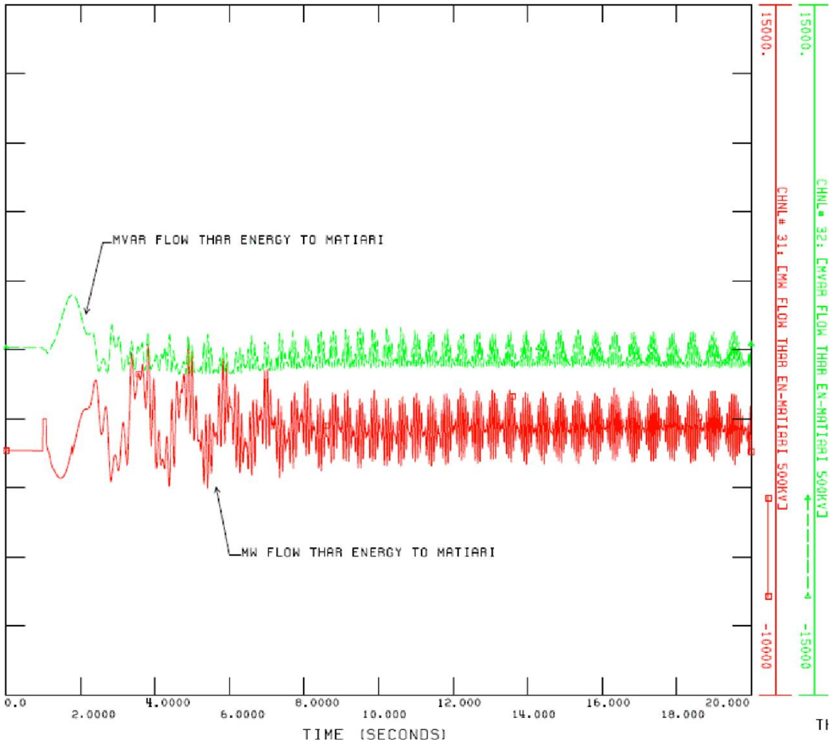


FIG. 11(c). MW AND MVAR FLOWS

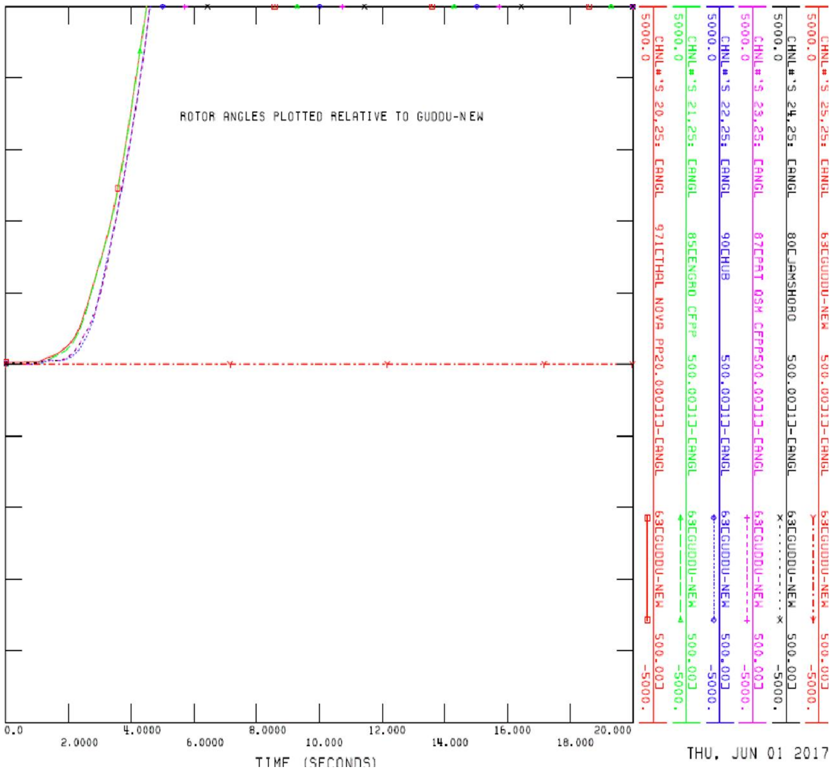


FIG. 11(d). ROTOR ANGLES

With the installation of TCSC, the over loaded lines having rating 2109 MW goes to 869 MW and being relaxed up to 58%. In this way, we could get maximum generation with minimum congestion in the network. TCSC is a dynamic device that provides critical support in steady state as well as transient conditions. It offers a more economical option as compared to the installation of extra lines (Fig. 12).

5.5 Plotted Results and their Description using TCSC

The bus bar voltages, frequency, rotor angle of generator and line flows of congestion area with the installation of TCSC are plotted in this section.

TABLE 2. TCSC TECHNICAL DATA IN TEST SYSTEM

Parameter	Value
Nominal System Voltage	500 kV
Rated Line Current	2101 A
Overload Line Current	2692 A
Physical Capacitive Reactance	40 ?
Rated Capacitive Reactive Power	70 MVAR
Compensation	5-10%

5.5.1 BUS BAR Voltages Using TCSC

The voltages of all bus bars near the faulted bus recover soon after fault clearance with the help of TCSC, it provides reactive power balancing in the network is shown in Fig. 13(a).

5.5.2 System Frequency using TCSC

The result showed that frequency recovers soon after the fault clearance due to restoration of system generation and loadviewed in Fig. 13(b).

5.5.3 Line Flows MW/MVAR using TCSC

We plotted the flows of MW and MVAR and it can be seen that transients in the MW and MVAR flows on the intact 500 kV circuit between Thar Energy and Matiari Grid Station settle down quickly and acquire new steady state levels shown in Fig. 13(c).

5.5.4 Rotor Angles

The Fig. 13(d) indicate that the rotor angles assume to a new stable state soon after fault clearance. The system is

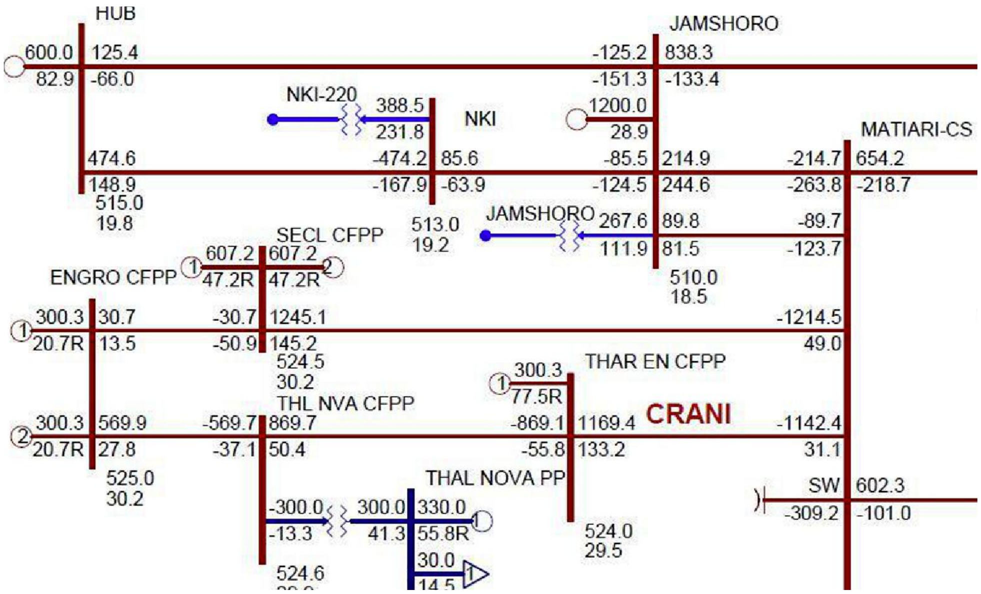


FIG. 12. NTDC SOUTH NETWORK WITH TCSC

now stable and strong enough to dampen post fault oscillations, with the induction of TCSC, it provides synchronism between electromagnetic and mechanical torques in the system.

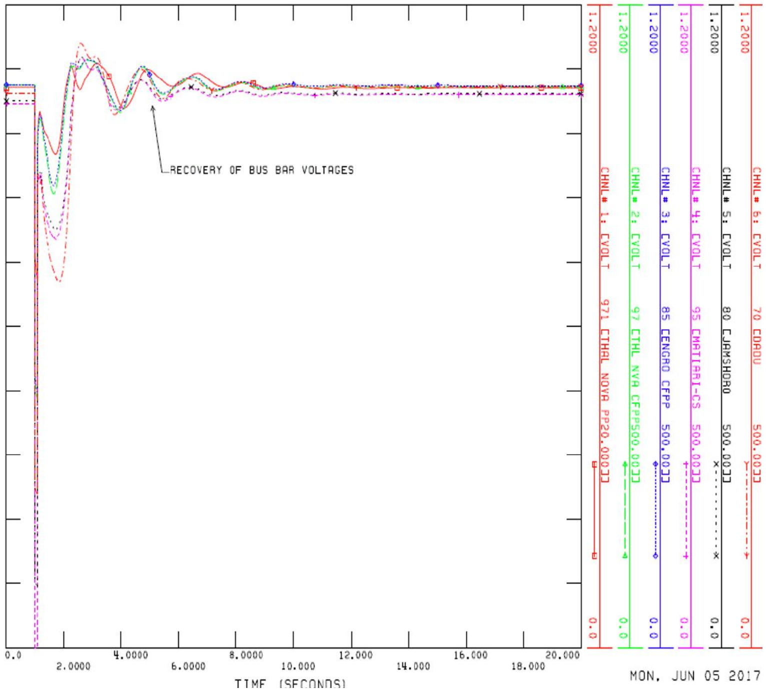


FIG. 13(a). RECOVERY OF BUS BARS VOLTAGES WITH TCSC

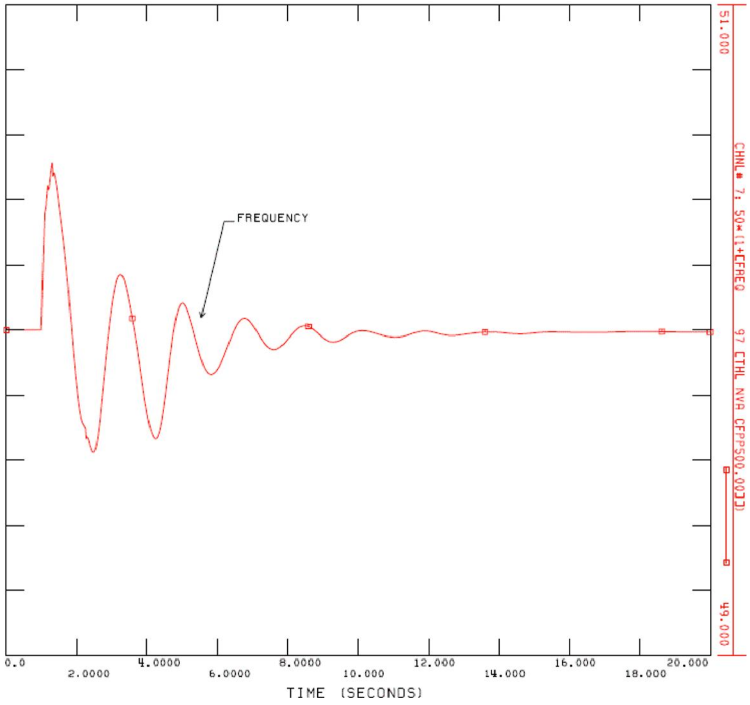


FIG. 13(b). RECOVERY OF SYSTEM FREQUENCY WITH TCSC

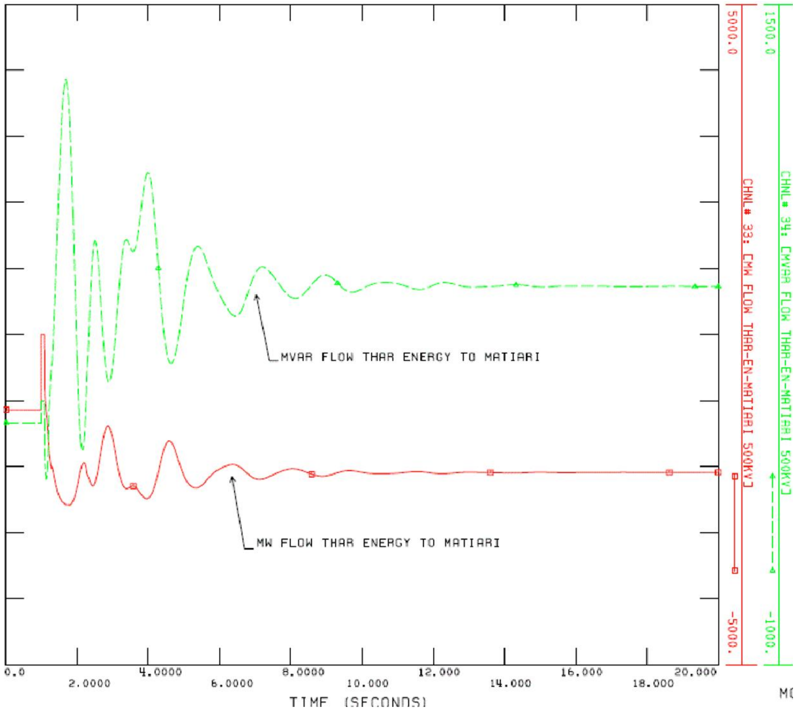


FIG. 13(c). RECOVERY OF MW AND MVAR FLOWS WITH TCSC

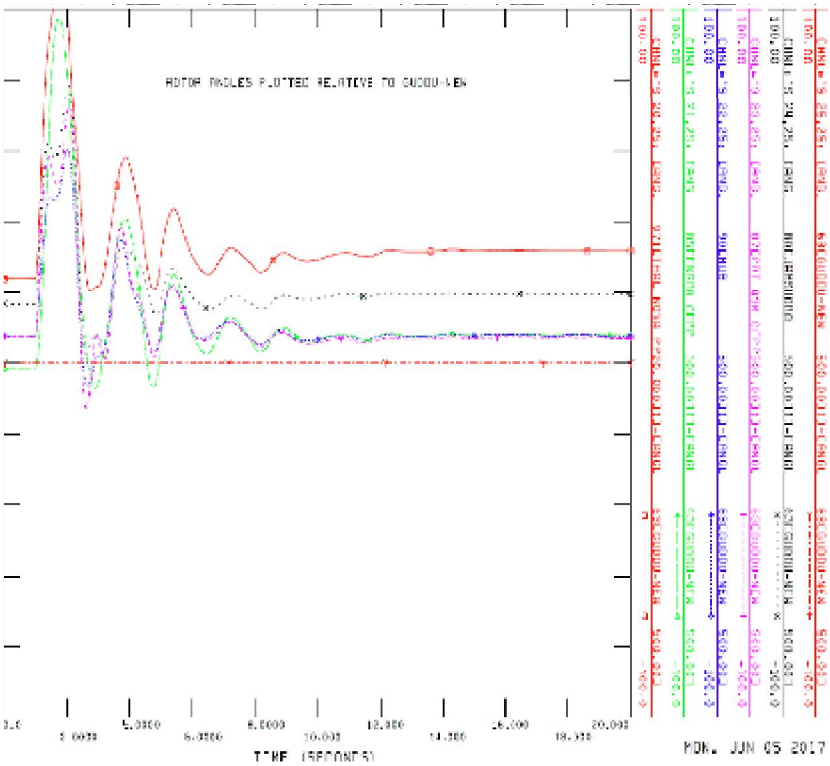


FIG. 13(d). RECOVERY OF ROTOR ANGLES RELATIVE TO GUDDU-NEW WITH TCSC

5.5.5 Desired Reactance of TCSC

As TCSC has been installed on the line between Thar energy and Matiari, we can now monitor the effective reactance contributed by it. The reactance supplied by TCSC during fault was also plotted is shown in Fig. 13(e).

6. RESULTS AND DISCUSSION

The issues of congestion become more frequent due to disturbed voltage profile, generation integration and load demand. These issues are generally observed in NTDC South network after the critical study of Pakistan National Grid in PSS/E tool. In PSS/E tool, the simulations are performed which showed that without the insertion of TCSC, voltage, frequency, load flows and angle profiles are disturbed due to unbalanced reactive power, sub-synchronous reactance and loss of synchronism.

As a remedial solution to these disturbed profiles is to insert the TCSC between Thar Energy to Matiari region. In this way, the reactance of the lines reduced and causes of reactive power balancing, restoration between generation and load with less losses, load balancing and synchronism between electromagnetic and mechanical torque. Thus, the voltage, frequency, load flows and angle profiles are maintained and in this way, the capability of TLs is increased. The dynamic and transient stability of the system is enhanced and losses are reduced in the network.

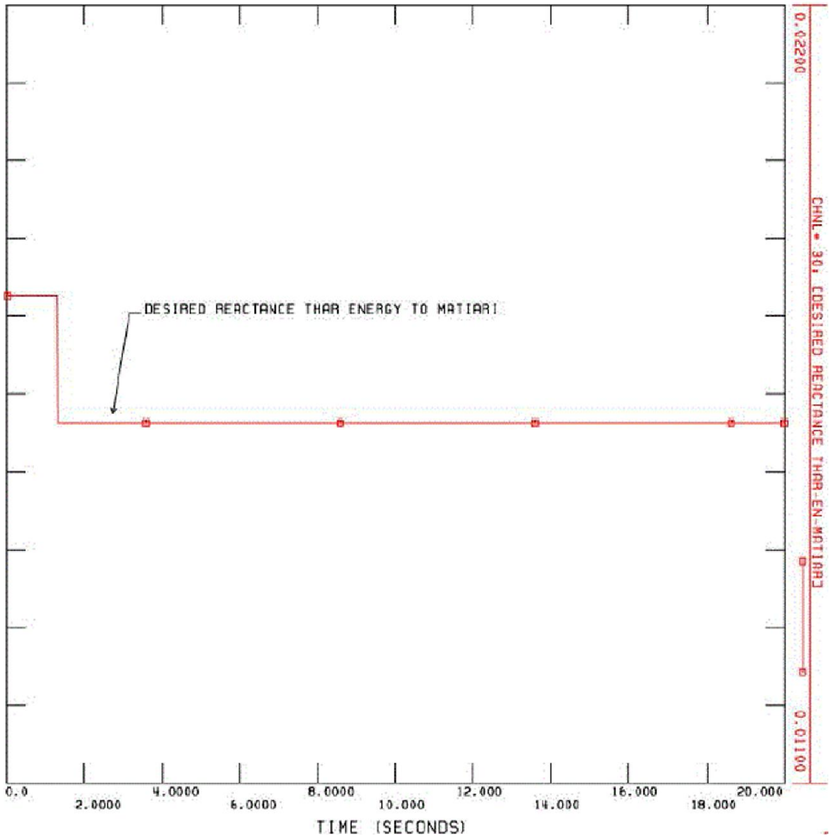


FIG. 13(e). REACTANCE SUPPLIED BY TCSC

7. CONCLUSION

In this paper, the power flow and dynamic stability enhancement using TCSC is presented. The power oscillations of the system are also examined. For an analysis, the critical region of NTDC South network of Pakistan National Grid is selected for the installation of TCSC at optimal position. The model of TCSC is programmed in FORTRAN and compiled with PSS/E. The simulation results indicated that the system is not stable without line compensation. Therefore, line compensation has been applied using TCSC to support the system. The plotted results show that the voltage, frequency, and power flows of the circuit settled within the rated capacities and enhanced the transfer capability of lines. Significantly, the dynamic stability analysis shows that the reliability of existing National Grid is enhanced with the series compensation using TCSC. It improves the transient stability by reducing the reactance of lines and also increases the power flow capacity of TLs. In this way, it provides the reactive power support to the system.In future, the IGBT controlled devices will be used in practical applications in high voltage power networks.

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