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Real Time Simulation of TCSC

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Abstract

Due to deregulation, open access, and co-generation in electrical power system, there is a probability of transmission voltage sags, swells, congestion scenarios, forced outages, followed by black-outs, and many such problems. Flexible AC Transmission System (FACTS) devices are one of the solutions for such complications. TCSC is a high-performance, and cost-effective series FACTS device that has a significant practical background. Real-Time Simulator facilitates a physically large, and spatially diverse or distributed power system to be accurately simulated in laboratory, and testing of physical devices, like controllers or protection equipment in real time, with all possible conditions, like introduction of faults, over loads, loss of generation condition, for stability analysis purpose. This paper presents comparison of power flow parameter with and without Thyristor Controlled Series capacitor (TCSC), and the performance characteristic of TCSC on Real-Time Simulator OPAL-RT-OP4510. The waveforms of active power, impedance, and firing angle are taken out from simulation environment to the outside world using input/output devices, and seen on Digital Storage Oscilloscope (DSO), during the Real-Time execution. The MATLAB/SIMULINK model of power system with TCSC is developed, and made compatible with the Real-Time Simulator, and validated on multi-machine-9-bus system. Also the Load Flow Analysis (LFA) is performed for the same system without TCSC and with TCSC, using MATLAB .m-file. The results indicate improved power flow parameters of the network, and increased active power transmitted, through the line as compared to the without TCSC.

Keywords: *FACTS, TCSC, LFA, DSO, Real Time Simulator*

1. Introduction

The behavior of electrical power systems, and its complex components, can be studied by many analytical tools. Real Time Digital Simulation represents a relatively new tool that combines the continuous real time response of traditional analogue models with the flexibility and accuracy of modern computer simulation techniques. Many of the world's leading equipment manufacturers, utilities and educational institutions now rely on real time digital simulation. Persistent development in processing hardware, and innovative software solutions, have led to advancement of real time simulation technology at an affordable price, and adapting to stretch the boundaries of application in design and testing [1]. The FACTS controllers can be effectively applied, if its type, rating as well as the control, and protection circuits are well matched to the specific network parameters and the specification requirements. Hence, design verification by real-time simulation is imperative for the successful operational performance [2]. In recent years, electric utilities are functioning in a growing competitive market where environmental and economic scenarios are of major concern, while planning for expanding the transmission facilities [3]. LFA is one of the necessary tools used worldwide to compute power flow parameters of the network under steady-state conditions, subjected to certain constraints under which the system operates [4]. In this paper LFA without TCSC and with TCSC is computed and

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the improved parameters of the power system are highlighted. Also the Real-Time Simulation of multi-machine-9-bus system without and with TCSC has been carried out on Real- time Simulator OPAL-RT OP4510. The paper is structured such as Section 2 gives literature review of TCSC, Section 3 details the LFA of the system without TCSC and with TCSC, Section 4 details the significance of Real-Time Simulation and OPAL-RT OP4510 Simulator, Section 5 gives the results and the related discussion, Section VI concludes the novel research work.

2. Literature Review

Among the series controllers, TCSC, an impedance type FACTS controller, is preferred in spite of an advanced, and VSC based, Series Static Synchronous Compensator (SSSC), because it has most of the benefits of that SSSC, at a lower cost, and with less complexity of working, which may be the reason of SSSC not yet being, in commercial operation as an independent controller, worldwide, beside the TCSC installations. Power flow model of TCSC was being used for active power flow control using firing angle control and the control strategy was implemented on hardware setup of 2-bus system [5]. A new approach of modelling, Holomorphic Embedding Load-Flow Method (HELM) was developed for modelling the thyristor based FACTS devices, and for evaluating its performance in the power flow control. HELM overcomes the traditional iterative method of solving non-linear power flow equations by iterative method for load flow solutions [6]. TCSC model for transient and oscillatory stability studies and relevant information to extend the modeling detail of the TCSC for long-term stability analysis was discussed in [7]. Modelling and interfacing techniques of Static Var Compensator (SVC) and TCSC for real time simulation for maintaining the voltage at load bus, and real power flow through a typically selected line was discussed in [8]. The design of control system for changing the impedance of TCSC by controlling thyristors firing angle (α) for constant power control strategy with increased reactive power compensation of the transmission line was discussed in [9]. The execution of TCSC on Real-Time Simulator OP4510 was missing in the literature, which inspired the author to work in this area.

3. Load Flow Analysis

Traditionally LFA is computed by methods such as Gauss-Seidel method, Newton Raphson (NR) method, Decoupled method and Fast decoupled method. Among these methods, the NR method is very popular due to its fast convergence with a less number of iterations [10]. For calculating LF, the bus classification, with its specified variables, and unknown variables is detailed in [11]

3.1. Load Flow Analysis of an uncompensated System

The net active and reactive power flow injected at bus-*k*, for the network shown in Figure 1 (a), and Figure 1 (b), is given by (1) and (2).

$$P_{Gk} - P_{Lk} - \sum_{i=1}^{n} P_k^{ical} = 0 \tag{1}$$

$$Q_{Gk} - Q_{Lk} - \sum_{i=1}^{n} Q_k^{ical} = 0 \tag{2}$$

where P_{Gk}, P_{Lk} are real power generation and load, and Q_{Gk}, Q_{Lk} are reactive power

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generation and load at bus-*k* respectively, and $P_k^{i\ cal}$, $Q_k^{\ i\ cal}$. The active and reactive power exchanged between bus-*k* and bus-*i*, and is given by (3) and (4), and at bus-*m* is given by replacing the subscript *k* by *m* in (3) and (4).

$$P_k^{ical} = \sum_{i=1}^{n} V_k^{\ 2} G_{kk} + V_k V_i [G_{kk} cos(\theta_k - \theta_i) + B_{kk} sin(\theta_k - \theta_i)] \tag{3}$$

$$Q_k^{ical} = \sum_{i=1}^{n} -V_k^{\ 2} B_{kk} + V_k V_i [B_{kk} cos(\theta_k - \theta_i) - G_{kk} sin(\theta_k - \theta_i)] \tag{4}$$

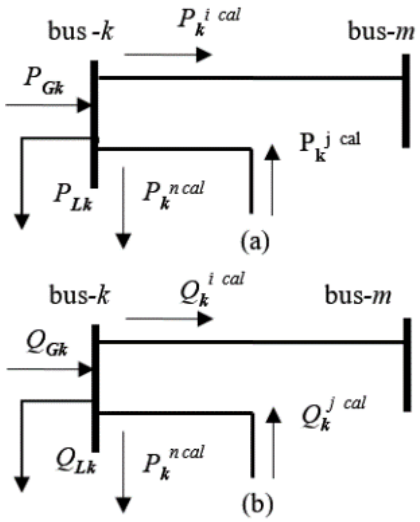

Figure 1. Power Balance at Bus-*k* (a) Active Power (b) Reactive Power

For LFA computation, the bus voltage magnitude and angle form the state variables, and the active and reactive power form the control variables.

3.2. Load Flow Analysis with TCSC

TCSC contributes substantially to the improvement of the dynamic stability of power systems. The series compensation technology uses Thyristor Controlled Reactor (TCR), very similar to the classical shunt compensation by means of an SVC [2]. It is considered to be a rapid FACTS device, providing the control for voltage amplitude, phase angle, line flow along with the increase in the active power transfer by altering the series impedance on the line [12]. When the phase of injected voltage is in quadrature with the line current, it supplies or absorbs reactive power and any other phase relationship, will alter real power as well [13]. It consists of a capacitor bank in series with the line and shunted by the TCR, as shown in Figure 2 (a) [14].

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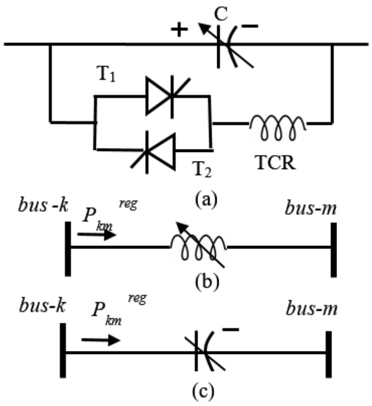

Figure 2. TCSC (a) Basic model (b) Inductive (c) Capacitive Operating mode

With the variation of the phase and magnitude of current through inductor, by controlling firing angle of thyristors, the effective impedance and, hence the voltage of TCSC is altered. The reactance of TCR is given by (5) and that of TCSC is given by (6). $X = \omega L \dfrac{\pi}{\pi - 2\alpha - sin2\alpha}$

(5)

$$X_{TCSC} = \frac{X_L(\alpha) X_C}{X_L(\alpha) - X_C} \quad (6)$$

At α = 0, TCSC operates in inductive mode, and at α = π/2, it operates in capacitive mode and at some limiting angle α, at a point, parallel resonance of capacitor and TCR will occur, when TCSC will offer infinite reactance, and within this range of $\alpha_{L\,lim} \leq \alpha \leq \alpha_{C\,lim,}$ operation of TCSC should be avoided. The TCSC reactance is calculated, so as to maintain the desired power flow across the branch. Figure 2 (b) and Figure 2 (c) show that the active power P_{km}^{reg}, to be regulated flowing from bus-*k* to bus-*m*, by the series reactance. The network equation for Figure 2 (b), and Figure 2 (c) is given by (7)

$$\begin{bmatrix} I_k \\ I_m \end{bmatrix} = \begin{bmatrix} jB_{kk} & jB_{km} \\ jB_{mk} & jB_{mm} \end{bmatrix} \begin{bmatrix} V_k \\ V_m \end{bmatrix} \quad (7)$$

For capacitive operation of TCSC

$$B_{kk} = B_{mm} = \frac{-1}{X_{TCSC}} \; ; \; B_{km} = B_{mk} = \frac{1}{X_{TCSC}}$$

The active and reactive power equations at bus-*k* are:

$$P_k = V_k V_m B_{km} sin(\theta_k - \theta_m) \quad (8)$$

$$Q_k = -V_k^2 B_{kk} - V_k V_m B_{km} cos(\theta_k - \theta_m) \quad (9)$$

The power flow equations at bus-m can be obtained by exchanging of subscripts of k with m, in (8), and (9) [15]. In NR solutions (8), (9) are linearized in Newton's power flow equations, and

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the variable reactance of the TCSC is taken as the state variable, and active power to be controlled is taken as control variable and included in Jacobian matrix [16].

4. Real-Time Simulator OPAL-RT OP4510

The offline PC-based time response of the large systems, may be slower/faster than the actual phenomenon. Hence if the models are tested in close loop with the real-time simulator, the designer gains more confidence in the design of the hardware device or software routine for controlling the power system [17]. OPAL-RT-OP4510 is a Real-Time Simulator used in this research, and has 4 cores. RT-LAB system is it's one of the features, and its architecture consists a host computer and a target computer that are connected by TCP/IP. It's a distributed real-time platform that allows users to test dynamical models built in MATLAB/Simulink environment, for Hardware in Loop (HIL) simulation, at very high accuracy, low cost, and in real time. It also has special Simulink-based modelling tools, namely, ARTEMiS and RT-Events which allow real time simulation in multi-core processors, which is required for very complex non-linear systems like power system in real time, with high precision and high stability. ARTEMiS is a power system real-time solver that provides a high degree of stability for the discrete time state-space models. It enables parallel computation of electric circuits on different CPU cores. It also enables to simulate a very large number of switches in real-time. It facilitates to gain important computational time when compared to SimPowerSystems because it makes full pre-computation of all state-space equations before the real-time loop. RT-Events block-set lead to accurate simulation because RT-Events blocks propagate zero crossing information at fixed time step, and the time stamped bridge use this information to produce compensated output voltages to the load. For executing the model on OPAL-RT, the MATLAB Simulink model is be divided into subsystems, master subsystem, console subsystem, and slave subsystem if the model is too large and complex, and the sub-systems are run in multi core/processers in parallel without affecting the dynamics of the original system. Thus in RT-LAB, computational time is reduced as the model is processed across multiple cores. The signal communication is done across the subsystems with the help of OpCom block. For connecting two subsystems ARTEMiS transmission lines/distributed parameter lines are generally used. The steps to simulate the system in RT-LAB are as follows.

- Starting compilation
- Separating RT-LAB model
- Generating C code
  - Using System Target File (TLC file) : rtlab_rtmodel.tlc
  - Using Template Make file (TMF file) : rtlab_rtmodel.tmf
- Transferring the generated C code
- Building the generated C code
- Transferring the built model
- Loading the model
- Executing model
- Reset

The host computer facilitates the edition of Simulink model, model compilation with RT-LAB, and user interface. On the target computer, the real-time model gets executed and with the input-output ports, the controlling signals can be communicated to the real-time hardware. FTP and TELNET communication is possible with the host. The Real Time Simulator does the real-

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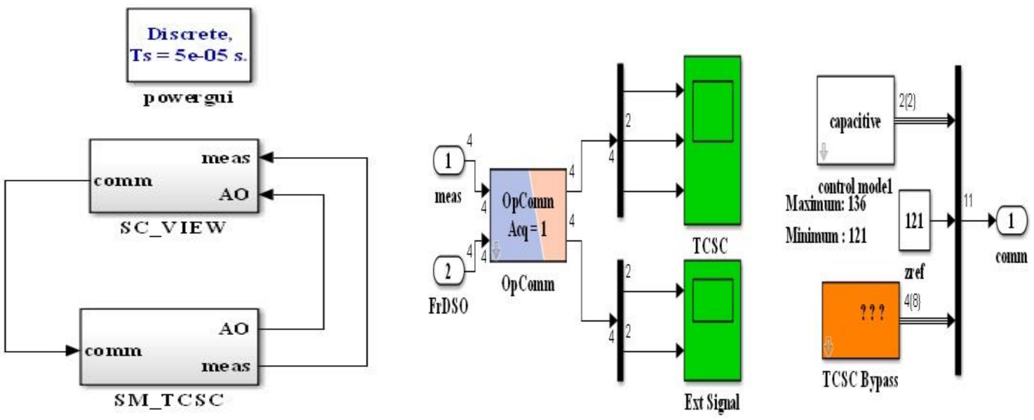
time model execution. It has REDHAT as an operating system [18]. Table 1 gives the specifications of OPAL-RT OP4510 Simulator.

Table 1. Specifications of OPAL-RT OP4510 Simulator

S.N.	Particular	Specification
1	Model OP4510	Propagation delay of digital input-output as 40ns
2	CPU	4 Cores
3	Processor	Xeon E3 3.2 GHz
4	FPGA	Kintex-7 XILINX Board
5	Hard disk	128 GB
6	6 optical link	50 Mbps
7	Analog in	16 channels
8	Analog out	16 channels
9	Digital in	32 channels
10	Digital out	32 channels
11	Encoder, decoder, input / output expansion boards and other applications	12RS422

[19]. MATLAB/Simulink model of the multi-machine-9-bus system is developed without TCSC. Then TCSC is connected in series with transmission line 7-8. Both the models are made compatible for execution on OPAL-RT OP4510 Simulator. The Top-level model with TCSC, consists two sub-systems, master subsystem, and console subsystem, as shown in Figure 3 (a). The Console Subsystem (SC_VIEW) consists control over the variation of the type of fault and location of fault, and the scopes to see the response of network, as shown in Figure 3 (b). The Master Subsystem, (SM_TCSC), consisting of Multi-machine-9-bus network, the fault subsystem, the OPAL-RT OpComm block, input/output blocks OpControl, AnalogIn, and AnalogOut, as shown in Figure 4.



(a) (b)

Figure 3. TCSC (a) Top-Level mode (b) Console Subsystem

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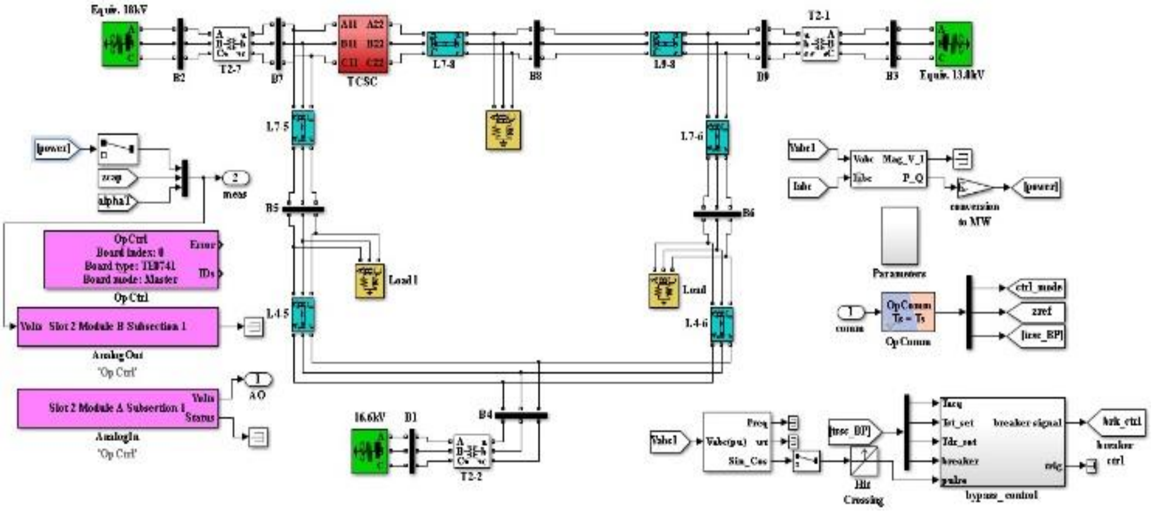

Figure 4. Master Subsystem with TCSC

5. Result and Discussion

The MATLAB .m-file is developed for LFA computation of network, with TCSC, and without TCSC. NR algorithm, embedded with the FACTS devices data, and their location, and network parameters is developed. The multi-machine-9-bus system consists of 9 lines, 3 generators connected to bus-1, bus- 2, and bus-3 through a step-up transformer, 3-loads connected to bus-5, bus-6, and bus-8 as shown in Figure 5. The per unit values of line parameters of multi-machine-9 bus system, and ratings of generator, load and transformer, are shown in Figure 5. For computing LFA, per unit values of the parameters are taken, and for developing MATLAB/Simulink model, actual values of parameters are taken.

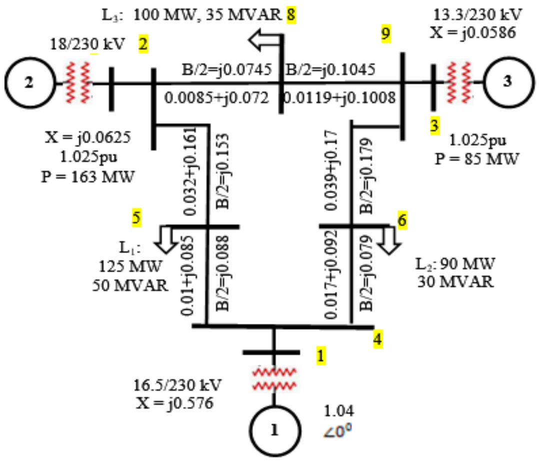

Figure 5. Multi-Machine-9 Bus System

5.1. Comparison of LFA without TCSC and with TCSC

Bus-1 is slack bus, and bus-2, and bus-3 are PV buses. The power flow parameters without TCSC and with TCSC are mentioned in Table 2.

Table 2. Power Flow Parameters without TCSC and with TCSC

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Bus	Voltage (pu) Angle (degree)		P ± j Q (P-MW, Q-MVAR)	
	Without TCSC	**With TCSC**	**Without TCSC**	**With TCSC**
1	1.04 ∠0	1.04 ∠0	71.641 +27.0459j	71.8829 +26.1235j
2	1.025 ∠9.28	1.025 ∠6.8414	163.0 +6.6537j	163.0 -3.5085j
3	1.025 ∠4.6648	1.025 ∠7.0960	85.0 -10.8597j	85.0 -8.8276j
4	1.0258 ∠-2.217	1.0263 ∠-2.223	0.0 + 0.0j	0.0 + 0.0j
5	0.9956 ∠-3.989	0.9999 ∠-4.775	-125.0 -50.0j	-125.0-50.0j
6	1.0127∠-3.6874	1.0112 ∠-2.8531	-90.0 -30.0j	-90.0 -30.0j
7	1.0258 ∠3.7197	1.0319 ∠1.3144	0.0 + 0.0j	-92.98 +13.2707j
8	1.0159 ∠0.7275	1.0128 ∠4.0822	-100.0 -35.0j	-100.0-35.0j
9	1.0324 ∠1.9667	1.0312 ∠4.3949	0.0 + 0.0j	0.0 +0.0j

For connecting TCSC, an extra bus, bus-10 is introduced, in the line connecting bus-7 and bus-8, and TCSC is connected in between bus-7, and bus-10. With the TCSC implementation, bus voltage profile has improved. Active power flows downhill from leading bus voltage angle to lagging bus voltage angle. The power transmitted through the line connecting bus-7, and bus-8, has increased by 21.75%, as compared to the system without TCSC. The total active power loss in MW, and reactive power loss in MVAR with TCSC is (4.8829-90.6538j) and without TCSC is (4.6410-92.1601j). The capacitive reactance of TCSC is -0.1275 per unit, and voltage injected in series with the line is 0.2219 per unit, at an angle of 85.80º. The active and reactive power at the load buses are as per the connected load magnitude.

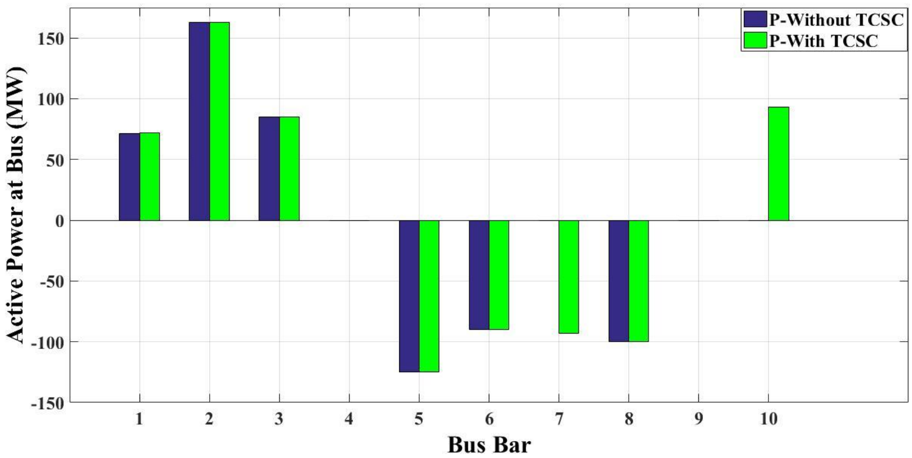

Figure 6. Comparison of Active Power at Bus without TCSC and with TCSC

The bus-10 does not exists in the system without TCSC. Hence in Figure 6, there no active power at bus-10, and also bus-7, is an interconnecting bus, hence there is no active power in the system without TCSC. But since TCSC is connected in line connecting bus-7, and bus-8, there is active power at bus-7 of 92.98 MW (outgoing). Power through transmission line connecting bus-7, and bus-8, has increased by 21.75% than the line without TCSC system.

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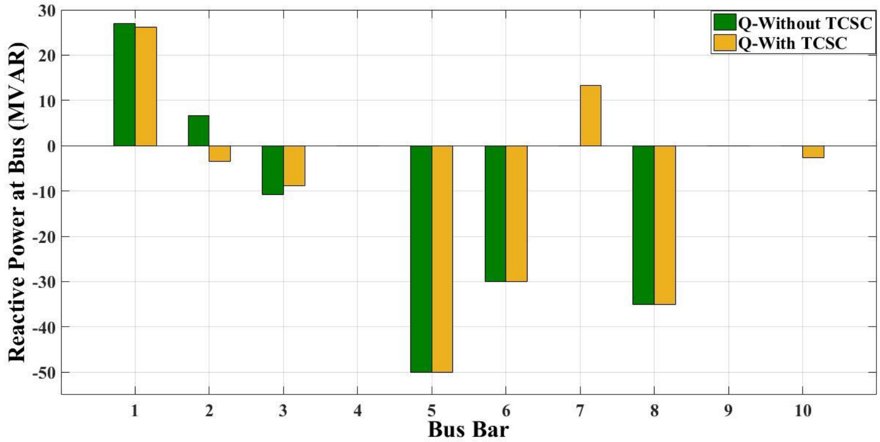

Figure 7. Comparison of Reactive Power at Bus without TCSC and with TCSC

The reactive is observed in the system with TCSC, at bus-7, due to the presence of TCSC in the system, though it is an interconnecting bus, and is zero for the system without TCSC. The reactive power generation with TCSC has reduced, as seen on bus-1, bus-2, and bus-3. This is clearly seen in Figure 7. The reduced reactive power generation also reduces over all transmission losses.

5.2 Real-Time Simulation without TCSC and with TCSC

The MATLAB/Simulink models developed for without TCSC system, and with TCSC were made compatible with the Real-Time Simulator, OPAL-RT OP4510. Figure 8 shows the waveforms of the V, I, P, and Q of the system without TCSC system. The voltage, current, active and reactive power are within the rated values during the healthy condition, but when the LLLG fault is introduced, voltage drops to a very low value (approximately zero), with sudden increase in current, and change in active and reactive power.

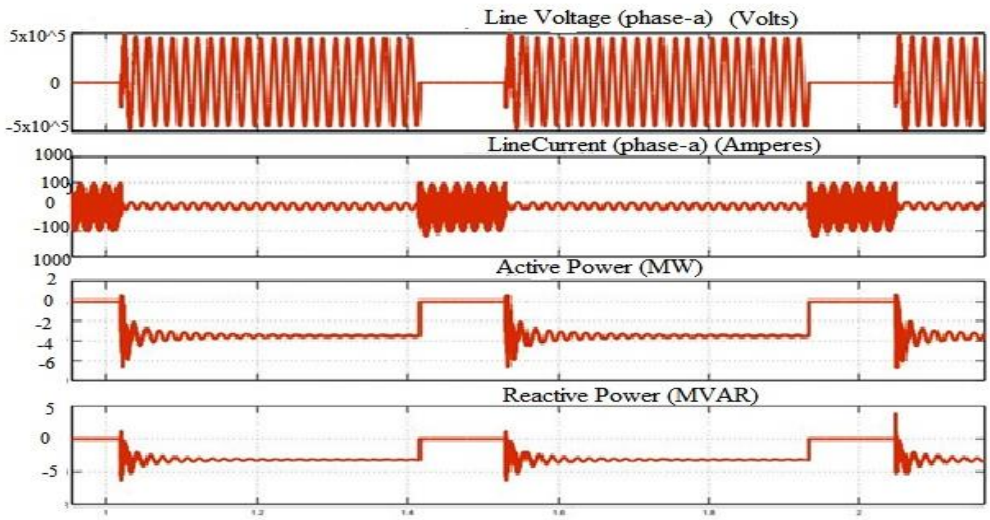

Figure 8. Line Voltage, Line Current, Active and Reactive Power of an Uncompensated System

TCSC is can be operated in capacitive or inductive mode, which can be controlled from console subsystem as shown in Figure 3, though inductive mode is rarely used in practice. TCSC

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while operating in the constant impedance mode, uses voltage and current feedback for calculating the TCSC impedance. The reference impedance indirectly determines the active power level. The impedance is lowest at 90º. Figure 9 shows active power transferred, reference and actual impedance of TCSC, and the firing angle in compensated mode with capacitive compensation of TCSC. The reference impedance is set to 128 Ω. For the first 0.5s, the TCSC is bypassed using the circuit breaker, and the power transfer is 110 MW. At 0.5s TCSC begins to regulate the impedance to 128 Ω, and this increases power transfer to 610 MW. TCSC starts with alpha at 90º, for minimum switching transient disturbance on the line. The third part of waveform corresponds to firing angle for tracking reference impedance, with variation in reference impedance and system voltage. At 2.5s a 5% change in the reference impedance is applied, and TCSC enables tracking of the reference impedance. Also at 3.3s, a 4% reduction in the source voltage is applied, followed by the voltage magnitude tracking to 1 per unit at 3.8s. Thus TCSC controller compensates for these disturbances and the TCSC impedance stays constant.

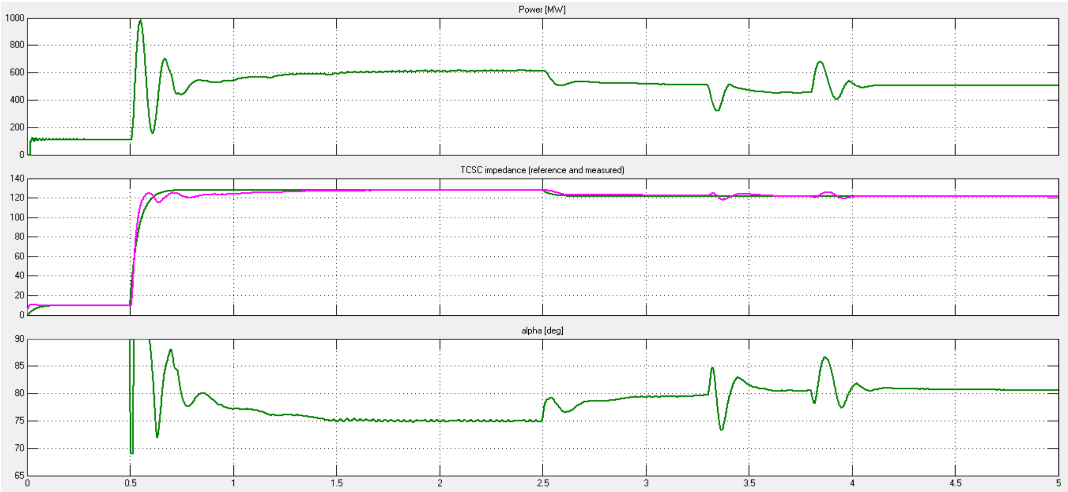

Figure 9. Active Power, Impedance, and Firing angle with TCSC

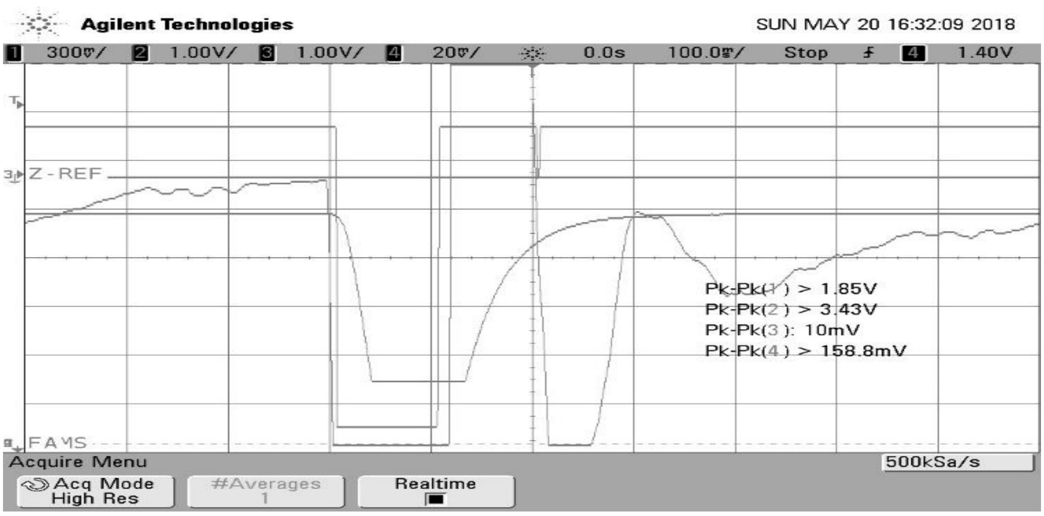

Figure 10. Active Power, Impedance, and Firing angle with TCSC on DSO

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Figure 10 shows the same signals of active power, actual and reference impedance, firing angle of TCR taken out from simulation environment to DSO. The characteristic of tracking the reference impedance, thereby controlling active power is clearly seen in the waveforms by altering firing angle control.

6. Conclusion

TCSC can boost its degree of compensation, making it very useful as a tool for improving the post-contingency status of networks, thereby adding to the dynamic stability of the network (voltage and angular) precisely. The power flow parameters with TCSC are improved, with increased active power flow capacity (nearly 1.21%) through the lines. The performance of TCSC on Real-Time Simulator OPAL RT- OP4510, shows that TCSC is capable of controlling active power efficiently, during small disturbances. Thus Real-Time Simulation has a great advantage during designing, and testing of controller before installing in the system, for its performance during various conditions, thereby gaining confidence to the power system operator, for its smooth control.

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