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Importance of TSC on Reactive Power Compensation for Power Quality Improvement

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ABSTRACT: The modern power system is a complex system consisting of a large number of different dynamic and static devices. With the increased loading of existing AC transmission systems, problems of voltage flicker and voltage stability have became important subjects in power systems. Better utilization of existing power system capacities by installing new devices such as Flexible AC Transmission Systems (FACTS) has become very important. In this paper, effects of Thyristor Switched Capacitor (TSC), which is one of shunt FACTS devices, on load voltages are investigated. The modeling and simulation of TSC are verified using the Matlab7.04® SimPowerSystems Blockset. The studied power system is a two-bus system with static and dynamic loads. The results show that significant improvement on reactive power compensation and bus voltage regulation could be achieved by using the TSC.

KEYWORDS: Flexible AC Transmission Systems, Thyristor Switched Capacitors, Compensation, Voltage Regulation, MATLAB.

I. INTRODUCTION

With the power systems growth and the increase in their complexity, many factors have become influential to the electric power generation and consumption. In recent years, voltage stability and voltage regulation have received wide attention [1], [2].

The numbers of devices and electrical machines that absorb reactive energy have been increased with either developments at technology or rising of wealth level in offices and houses. In power systems, load models are classified into two categories: static load and dynamic load models. The static load model is not dependent on time; therefore, it describes the relation of the active and reactive powers at any time with the voltage and/or frequency at the same instant of time. On the other hand, dynamic load model expresses these relations as a function of time [1]-[4].

There are many reactive compensation devices used by the utilities for voltage stability, voltage regulation etc., each of which has its own characteristics and limitations. However, the utility aims to achieve this with the most beneficial compensation device. Usually, placing adequate reactive power support at the weakest bus enhances the static-voltage stability margins. This can be done with traditional shunt capacitors or Flexible AC Transmission Systems (FACTS) controllers [5]. In recent years, thyristor controlled FACTS devices have been used for reactive power compensation. FACTS devices open up new opportunities for controlling power and enhancing the usable capacity of existing transmission lines [5]-[7].

To date, many authors have simulated Thyristor Switched Capacitor (TSC), which is one of FACTS devices, using different computer programs such as NETOMAC (Network Torsion Machine Control), MICROCAP that is a SPICE compatible software package, PSCAD (Power Systems Computer Aided Design)/EMTDC, ATP (Alternate Transient Program) and EMTP96 (Electro-magnetic Transients Program) [8]-[12]. Moreover, the TSC has been investigated at enclosure of Static VAr Compensator in many studies [8], [13]-[15]. In these studies, the load was considered either static type or dynamic type.

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In this paper, the effect of the thyristor switched capacitor to load voltages has been studied in the three phase system at different load conditions. The studied power system is a two-bus system with long transmission line model. The design and testing of TSC are verified using the MATLAB/Simulink 7.04® and Power Systems Toolbox.

II. PRINCIPLES OF THE THYRISTOR SWITCHED CAPACITOR

Thyristor Switched Capacitors are shunt compensators that can supply reactive power. The TSCs have following properties: cheaper devices achieving appropriate results in the reactive power compensation, average delay of one half a cycle and no generation of harmonics [8], [16]-[18].
The Fig. 1 illustrates an equivalent circuit of the TSC. According to Fig. 1, the TSC consists of two thyristors in anti-parallel and capacitor to be switched. Furthermore, a series inductance is considered as well as a small resistance [7]. The inductance used here is to limit inrush currents by reason of mis-firing [19].

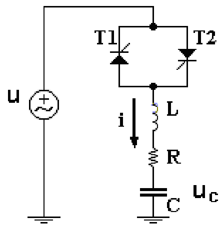

Fig. 1. Main structure of TSC

In the 3-phase applications, the basic TSC elements are connected in delta [16], [20]. The control technique of the TSC is On/Off control. The capacitor is precharged to the peak value of the source voltage for maintaining with low transients in the supply system. Control schemes of the TSC have been found detailed in [8], [16], [19], [21].

III. DESIGN AND IMPLEMENTATION

A. Modeling of TSC in MATLAB

The TSC has been modeled using the MATLAB/Simulink 7.04® and Power Systems Toolbox. A schematic diagram of a single phase TSC is in shown Fig. 2. A three phase TSC model consists of three single phase TSC's connected in delta configuration. It is in parallel connected to the load bus.

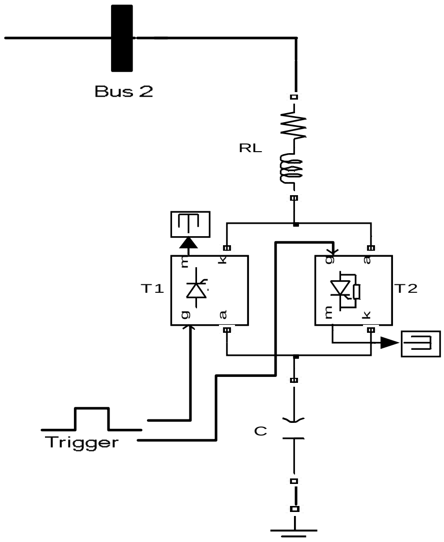

Fig. 2. A single phase TSC configuration

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A six-pulse generator has been used to fire six thyristors of the TSC. The thyristors are fired at the positive peak of the source voltage or at the zero crossing of the line current [17]. Thus the TSC behaves like a filter that reduces the harmonic distortion.

B. Modeling of Loads and Power System in MATLAB

In this study, a two-bus system with a 360 km transmission line modeled as a π-equivalent circuit is used to show the effect of the TSC on voltage regulation. Table I shows parameters of static and dynamic loads, the transmission line and the source.

TABLE I

THE LOADS AND SYSTEM PARAMETERS

Source voltage	380 kVrms (LL)
System frequency	50 Hz
Line R	6.5 Ω
Line L	145 mH
Static load P	207.52 MW
Static load Q	277.09 MVAr
Dynamic load P	300 MW
Dynamic load Q	225 MVAr

In this paper, static and dynamic loads have been separately analyzed. Fig. 3 demonstrates an equivalent circuit with a static load model. In this study, the main 380 kV link is installed between Bus 1 and Bus 2. Also this equivalent circuit, in which the static load model is replaced with the dynamic load model, is used to show the effect of the dynamic load model on the TSC.[21-23]

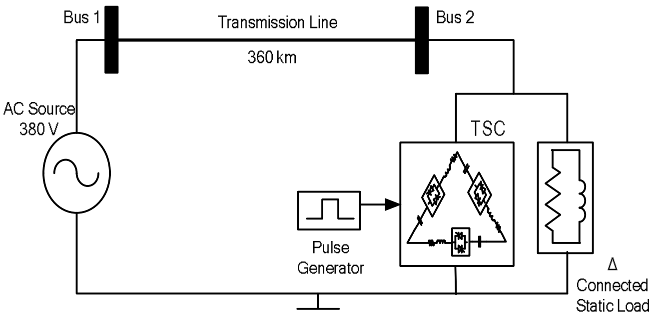

Fig. 3. Equivalent circuit with static load

The characteristic of the exponential static load model can be classified into constant power, constant current, and constant impedance load depending on the power relation to the voltage. In Matlab, the active and reactive powers absorbed by the static load are proportional to the square of the applied voltage.

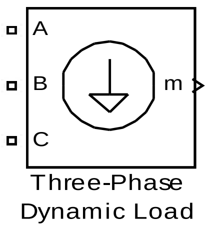

Fig. 4. Dynamic load model in MATLAB/Simulink

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The dynamic load model is given in Fig. 4 in MATLAB/Simulink. The dynamic load model in Matlab is presented below, as a set of non-linear equations, and active power and reactive powers have a non-linear dependency on the applied voltage.[24]

$$P = P_o\left(\frac{V}{V_o}\right)^{np}\left(\frac{1+T_{p1}s}{1+T_{p2}s}\right) \quad (1)$$

$$Q = Q_o\left(\frac{V}{V_o}\right)^{nq}\left(\frac{1+T_{q1}s}{1+T_{q2}s}\right) \quad (2)$$

where, V_o, P_o and Q_o are the nominal voltage, active power and reactive power of the load. T_p and T_q stand for the active and reactive load recovery time constants, n_p and n_q are the steady state active and reactive load-voltage dependences [22].

IV. Simulation Results

A. Voltage Regulation for Static Load

In this study, a two-bus system is used to show the performance of the TSC device on voltage regulation for the static load. The parameters of the system and the static load are given in Table I. A six-pulse generator is used to control of firing angle of the TSC. [25]

Firstly, the system without the thyristor switched capacitor is considered. In this case study, Table II shows obtained simulation results and gives the load voltage as rms value, (V_{LL} (kV)); the load current as rms value, (I_{load} (kA)); total active power of the load as P_{load} (MW); total reactive power of the load as Q_{load} (MVAr) and power factor as Cos φ.

TABLE II
SIMULATION RESULTS FOR THE SYSTEM WITHOUT TSC

V_{load} (kV_{LL})	**V_{L1L2}**	350.08
	V_{L2L3}	350.04
	V_{L3L1}	350.25
I_{load} (kA)	**I_{line_L1}**	0.48
	I_{line_L2}	0.48
	I_{line_L3}	0.48
P_{load} (MW)	175.78	
Q_{load} (MVAr)	235.03	
Cos φ	0.598	

It is clearly seen from in Table II that the static load absorbs active power of 175.78 MW and reactive power of 235.03 MVAr at 0.598 power factor lagging. Required active and reactive powers of the static load are far from nominal values given in Table I. Therefore the power factor would be desired to correct for improving power quality.

Fig. 5 illustrates variations of the load voltage and the source voltage. It is clearly seen that the load voltage of 350 kV, which is 0.921 pu for a base of 380 kV, is less than the source voltage for the static load model. The reactive power compensation should be definitely made for voltage regulation.

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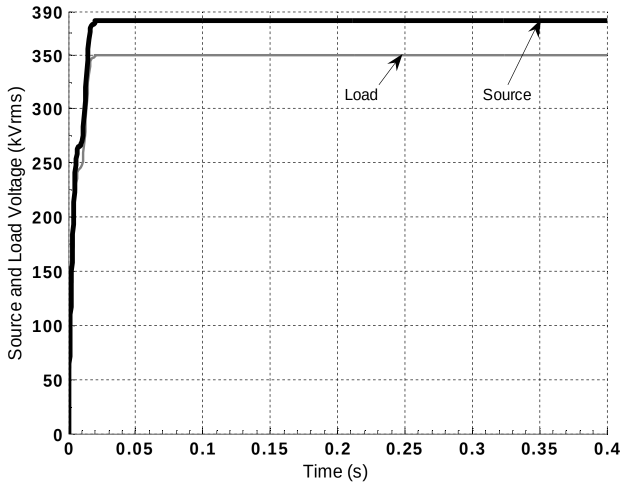

Fig. 5 Source and Load Voltage at 3 ~ System without TSC

Here, the effect of TSC will be examined for reactive power compensation. The value of the injected reactive power required to offset this voltage drop is equal to the value of reactive power of the static load. The simulation results of the test system with TSC are given in Table III. Simulations were individually made for precharged and non-precharged states of capacitors in the TSC structure. The purpose of these simulations is to show how this application can be maintained with low transients. [26-27]

TABLE III
SIMULATION RESULTS FOR THE SYSTEM WITH TSC

V_{load} (kV_{LL})	**V_{L1L2}**	378.75
	V_{L2L3}	378.75
	V_{L3L1}	378.75
I_{load} (kA)	**I_{line_L1}**	0.32
	I_{line_L2}	0.32
	I_{line_L3}	0.32
P_{load} (MW)	206.65	
Q_{load} (MVAr)	4.92	
Cos φ	0.999	

As given in Table III, the load voltage is very close to nominal value of the source. For a base of 380 kV, the load voltage is increased by using TSC from 0.921 pu to 0.996 pu. Correspondingly, measured active power of the static load is very close to nominal value of the static load and measured reactive power at Bus 2 is 4.92 MVAr. The reactive power compensation is made perfectly by using TSC. Hence power factor (Cos φ) is considerably closed to 1 and installation of TSC in the system is caused to improve power factor and voltage profile.
Figure 6-a and Fig. 6-b demonstrate the source voltage and the load voltage for TSC with non-precharged capacitor and TSC with precharged capacitor respectively.

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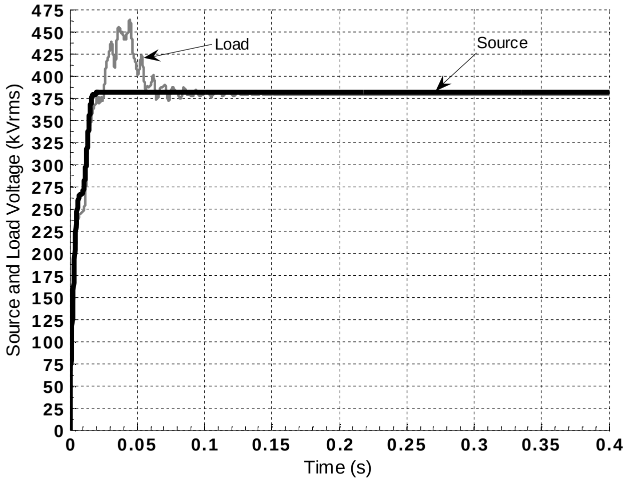

Fig. 6-a. Source and Load Voltage for the system with TSC (Capacitor is not precharged)

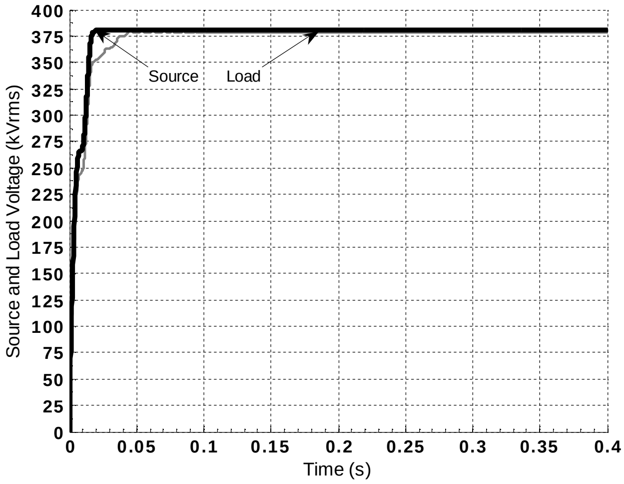

Figure 6-b. Source and Load Voltage for the system with TSC (Capacitor is precharged)

As can be seen from Fig. 6-a and Fig 6-b, TSC located at Bus 2 provides the enough reactive powers for the static load around its base value to keep the load voltage at the acceptable level. From Fig. 6-a, it is clearly seen that if the capacitor in the TSC structure is not charged before the simulation starts, TSC produces the transient component of the load voltage. On the other hand, if the capacitor is charged before the simulation starts, the transient component of the load voltage is eliminated as seen from Fig. 6-b.

Now, the waveforms of total harmonic distortion of voltage (THD_V) and total harmonic distortion of current (THD_C) are investigated. Figure 7-a shows THD_V and THD_C for non-precharged capacitor and Fig 7-b illustrates THD_V and THD_C for precharged capacitor.

Fig. 7-a and Fig. 7-b demonstrate that the system with TSC does not inject harmonic components of voltages and harmonic component of currents into the line. For precharged capacitor case, THD_V and THD_C in Fig 7-b are less than those of non-precharged capacitor case. Hence, the test system with TSC is not needed a harmonic filter and this is a great advantage of TSC.

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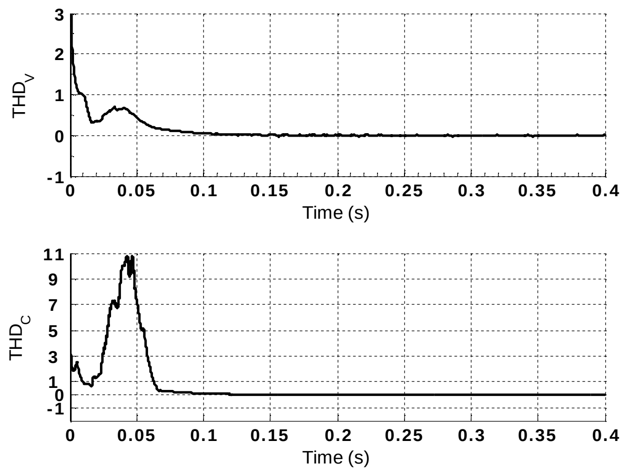

Fig. 7-a. THD_V and THD_C (Capacitor is not precharged)

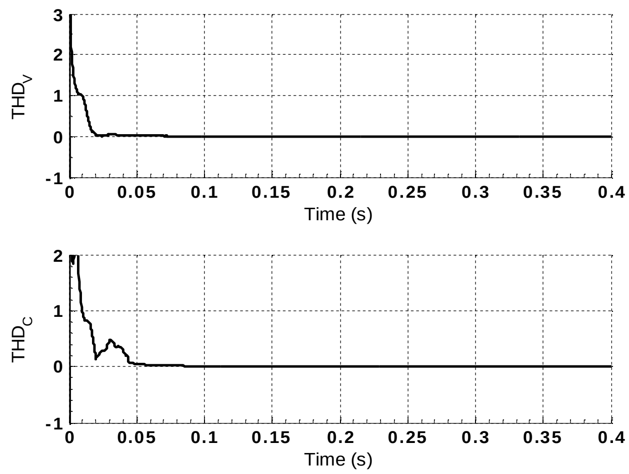

Fig. 7-b. THD_V and THD_C (Capacitor is precharged)

B. Voltage Regulation for Dynamic Load

In this case study, dynamic response of TSC on load voltage regulation is investigated for the two-bus system given in Fig. 3. The machine is connected to Bus 1 and a dynamic load is connected to Bus 2. The main 380 kV link is installed between Bus 1 and Bus 2. The six-pulse generator is used for the control of firing angles of TSC as previously used for the system with the static load.

Active and reactive powers of the dynamic load were given in Table I. Table IV gives commonly used values for the exponents of the dynamic load model [1], [2]. In this paper, load components of the constant power have been investigated for the dynamic load model which is considered as a AC motor.

TABLE IV
LOAD EXPONENTS FOR DIFFERENT LOAD TYPES

Load Component	np	nq	T_{p1}	T_{p2}	T_{q1}	T_{q2}
Constant Power	0	0	0.5	0.25	0.4	0.2
Constant Current	1	1	0.5	0.25	0.4	0.2
Constant Impedance	2	2	0.5	0.25	0.4	0.2

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TABLE V
SIMULATION RESULTS FOR THE SYSTEM WITHOUT TSC

V_{L1L2} (kV)	V_{L2L3} (kV)	V_{L3L1} (kV)	P (MW)	Q (MVAr)	Cos φ
346.75	346.75	346.73	299.99	225.00	0.799

Table V shows the obtained simulation results for the system without TSC. As given in Table V, it is clearly seen that the dynamic load absorbs active power of 299.99 MW and reactive power of 225.00 MVAr at 0.799 power factor lagging. Required active and reactive powers of the load have not been met and far from nominal values given in Table 1. Therefore, efficiency of the test system is drop dramatically and the system should be compensated for improving power factor and voltage regulation. The variation of the load voltage obtained from simulation results is given in Fig. 8.

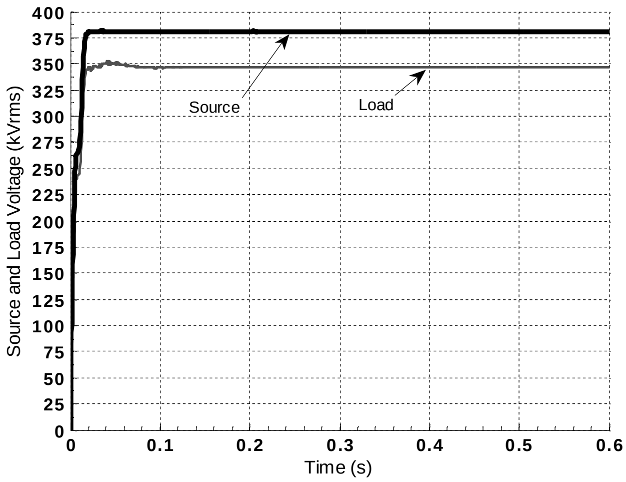

Fig. 8. Source and Load Voltage for the system without TSC

From the simulation results, it is clearly seen that the load voltage drops in the system with dynamic load. The load voltage is approximately 347 kV, which is 0.913 pu for a base of 380 kV, as illustrated in Fig. 8.
Now, TSC will be established in the test system with the dynamic load model for reactive power compensation as previously done for the system with the static load model. The simulation results of the test system with TSC are given in Table VI.
The required reactive power of the TSC was fixed at 225 MVAr capacitive that is equal to reactive power of the dynamic load. Simulations were individually made for precharged and non-precharged states of capacitors in the TSC structure.

TABLE VI
SIMULATION RESULTS FOR SYSTEM WITH TSC

V_{L1L2} (kV)	V_{L2L3} (kV)	V_{L3L1} (kV)	P (MW)	Q (MVAr)	Cos φ
376.25	376.17	376.21	300.44	4.40	0.999

As described in Table VI, the load voltage is very close to nominal value of the source. Therefore, the load voltage is increased by using TSC from 0.913 pu to 0.990 pu for a base of 380 kV and measured active power of the dynamic load is very close to nominal value of the dynamic load and measured reactive power at Bus 2 is 4.40 MVAr. Hence the power factor (Cos φ) is significantly closed to 1. The reactive power compensation is made perfectly by using TSC for the dynamic load conditions, too. So efficiency of the test system is increased and power quality is improved. In addition of these, voltage regulation is perfectly verified.

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Now, we will consider the effects of TSC with non-pre-charged capacitor and TSC with pre-charged capacitor. Figure 9-a and Fig. 9-b illustrate variations of the source voltage and the load voltage for TSC with non-pre-charged capacitor and TSC with pre-charged capacitor, respectively. When the capacitor is charged with the peak value of the source voltage, the transient components of the load voltage are considerably minimized as seen from Fig. 9-b.

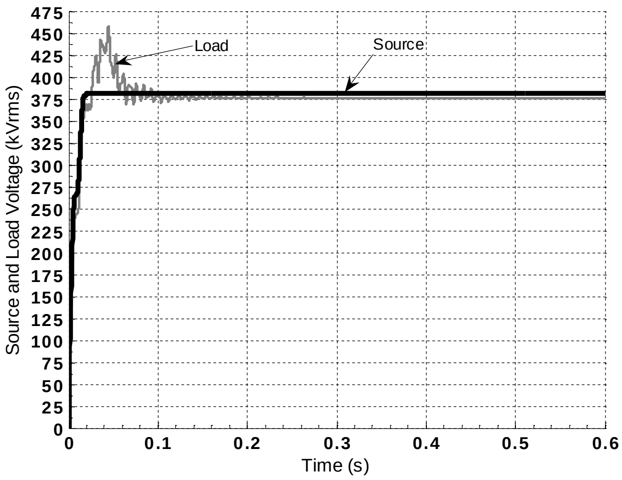

Fig. 9-a. Source and Load Voltage (Capacitor is not precharged)

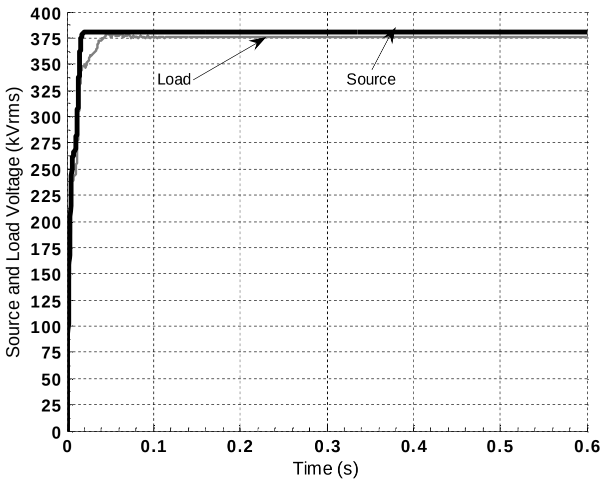

Fig. 9-b. Source and Load Voltage (Capacitor is precharged)

Finally, the waveforms of total harmonic distortion of voltage (THD_V) and total harmonic distortion of current (THD_C) are given in Fig. 10 when the capacitor is pre-charged for the test system with TSC. The obtained THD levels of the load voltage are not the cause of instability in the systems.

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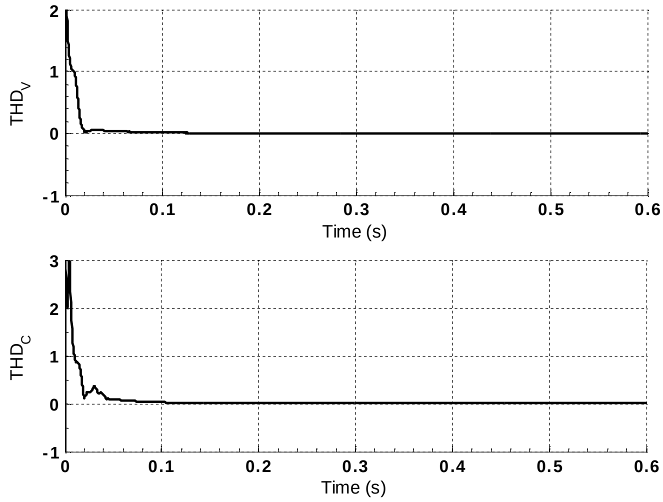

Fig. 10. THD_V and THD_C (Capacitor is precharged)

V. CONCLUSION

The voltage flicker and voltage stability have become important subjects in power systems. One of solutions of these problems is the reactive power compensation. In this paper, switching ON or OFF of a TSC bank has been proposed for the reactive power compensation and voltage regulation. This FACTS device, TSC, produces fewer harmonics and so it may preferred from operators in power systems.

In this paper, the effect of the thyristor switched capacitor on load voltages has been presented. The modelling and simulation of TSC have been verified using the Matlab7.04® SimPowerSystems Blockset. The studied power system was a two-bus system with static and dynamic loads. The simulation results demonstrated that installation of TSC in the system is caused to improve power factor and voltage profile for both static loads and dynamic loads. TSC provides to rapid control of the voltage at week points at every load level in the test system. Another result of simulations is that if capacitors are pre-charged to the peak value of the source voltage, the transient components of the load voltage are considerably minimized. Test system with TSC is not needed a harmonic filter and this is a great advantage of TSC.

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