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IMPACT OF USING TCSC ON POWER SYSTEM STABILITY

[1]*Majeed Rashid Zaidan, [2]Saber Izadpanah Toos and [3]Saif Tahseen Hussain

[1]Department of Electrical Technologies, Middle Technical University, Baghdad, Iraq.
[2]Electrical Engineering Department, Sadjad University of Technology, Mashhad, Iran.
[3]Company of Electricity Transmission, Diyala, Iraq.

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***Corresponding Author**
Majeed Rashid Zaidan
Department of Electrical Technologies, Middle Technical University, Baghdad, Iraq.

ABSTRACT

Power system stability issues are generally classified into two parts, steady-state and transient. Steady-state stability is related to the ability of the power system to keep synchronism after low disturbances like gradual load change. Transient stability deals with the effects of large and sudden disturbances like fault occurrence, line outage, and sudden change in loads. The Thyristor-Controlled Series Capacitor (TCSC) is a type of series FACTS Devices that has various applications. In this paper, the impact of TCSC on power system stability under load disturbances is investigated. For the case studies, the IEEE 14-bus test system is chosen, and a TCSC is installed in the system. According to simulation results, the TCSC can improve the voltage profile and result in power system stability under load disturbances.

KEYWORDS: Series compensation, TCSC, Voltage profile, Load disturbance, Stability.

INTRODUCTION

In a transmission network, the maximum active power transmitted across a specific line is inversely proportional to the series reactance of the transmission line. In other words, if the series reactance of the line decreases, the transmission of the active power over the line increases. Series compensation (SC) or series capacitive compensation has been extensively used for transmission networks. The basic operating principle of a series compensation is connecting a capacitor in series with the transmission line. The capacitor reduces the inductive reactance of the transmission line and, as a result, increase the power transfer capability of the line. Also, series compensation can enhance network stability, improve the voltage profile, and damping power oscillations. Fig. 1 shows a single line diagram of the transmission network without and with series compensation.

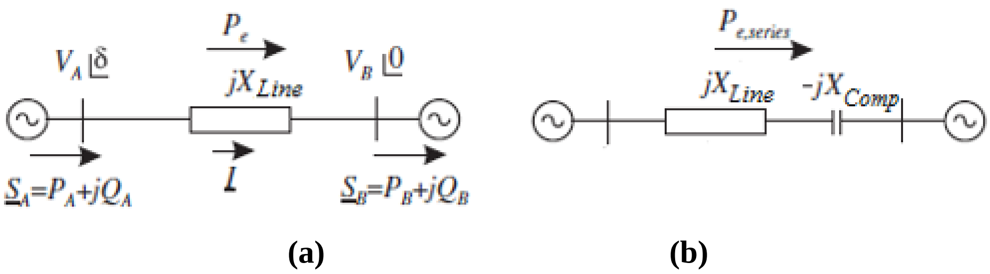

Fig. 1: A single line of the transmission network, (a) without series compensation, (b) with series compensation.[1]

Active power transfer without and with series compensation can be calculated as below.[1]

$$P_e = \frac{V_A V_B}{X_{Line}} \sin\delta \tag{1}$$

$$P_{e,series} = \frac{V_A V_B}{X_{Line} - X_{Comp}} \sin\delta \tag{2}$$

$$\frac{P_{e,series}}{P_e} = \frac{1}{1-(X_{Comp}/X_{Line})} = \frac{1}{1-K} \quad (K = \frac{X_{Comp}}{X_{Line}}) \tag{3}$$

Where:

Pe = Active power transfer without series compensation.

VA= Sending end voltage.

VB= Receiving end voltage.

δ= Phase angle between the sending end and receiving end voltages.

XLine= Line reactance.

XComp= Capacitive reactance of the series capacitor.

Pe,series = Active power transfer with series compensation.

K=Degree of compensation, economic degree of compensation is chosen within the range of $0.3 \le K \le 0.7$.

The series compensation is generally classified into two types fixed and variable series compensation. In recent years, advances in high-power semiconductor components have led to the development a new application in power systems, known as Flexible AC Transmission

Systems (FACTS). A Thyristor-Controlled Series Capacitor is a type of Thyristor-Controlled FACTS Devices used as a series compensator in a transmission network. The TCSC can change line reactance by putting a Thyristor-Controlled Capacitor (TCC) in series with the transmission line. Generally, it can increase the power transfer capability of the line and improve the power system stability.[2-4] Effects of the TCSC on power transfer capability, power system stability, power quality, protection of EHV (Extra-High Voltage) transmission lines, Available Transfer Capability (ATC), and so on are investigated in various researches.[5-13]

This paper presents a comprehensive study on the impact of the TCSC on the voltage stability under load disturbances. The rest of the paper is organized as follows; the TCSC is described in section 2. In section 3, the result of the TCSC on the steady-state stability is presented. The TCSC performance on transient stability is studied in section 4. The paper ends with a summary conclusion in the final section.

2. General Introduction of TCSC

Thyristor Controlled Series Capacitor presented as a Rapid Adjustment of Network Impedance (RANI) technique by the research team head John J. Vithayathil in 1986. The TCSC is a powerful and advantageous tool for increasing transmission capacity and improving the stability of AC transmission systems.[14,15] The main structure of the TCSC utilizes a series capacitor connected in parallel with a Thyristor-Controlled Reactor (TCR), which is shown in Fig. 2.

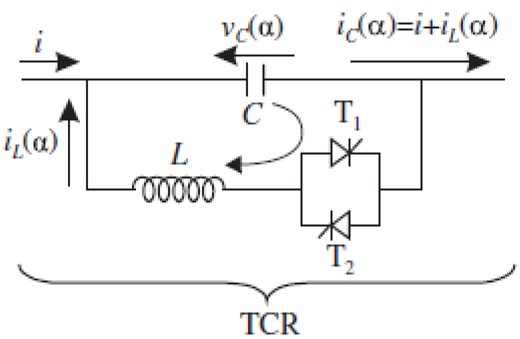

Fig. 2: The main structure of the TCSC.[1]

The TCSC inserted in the transmission line a variable capacitive reactance, X_{TCSC}. The X_{TCSC} is straightly related to the firing angle (α) of the thyristor and expressed by the following equation.[14]

$$X_{TCSC}(\alpha) = \frac{X_C X_L(\alpha)}{X_L(\alpha) - X_C} = -j\frac{1}{\omega C - \frac{1}{\omega L}} \tag{4}$$

$$X_L(\alpha) = X_L \frac{\pi}{\pi - 2\alpha - \sin\alpha} \quad (X_L \leq X_L(\alpha) \leq \infty) \tag{5}$$

Where X_C is the impedance of the capacitor, X_L is the impedance of the reactor, and $X_L(\alpha)$ is the controlled reactor impedance.

The impedance versus firing angle (α) characteristic of the TCSC is shown in Fig. 3. In the general TCSC arrangement where the impedance of the TCR reactor (X_L) is smaller than the impedance of the capacitor (X_C), the TCSC has two operating zones around the value αr of the firing angle for which the internal circuit resonance is obtained:

1. $X_{TCSC}(\alpha)$ is capacitive, for $\alpha_{C,lim} \leq \alpha \leq \pi/2$
2. $X_{TCSC}(\alpha)$ is inductive, for $0 \leq \alpha \leq \alpha_{L,lim}$

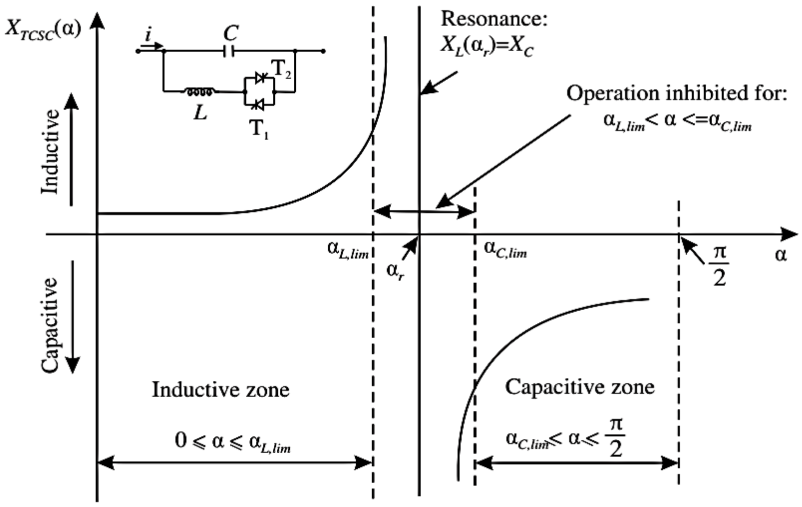

Fig. 3: The impedance (X_{TCSC}) versus firing angle (α) characteristic.[1]

3. Steady-State Stability

In sections 3 and 4, the impact of the TCSC on the IEEE 14-bus test system is analyzed using the NEPLAN version 5.5.5 software. This system consists of five synchronous machines that three of them are synchronous compensators used only for reactive power support. There are 11 loads in the system totaling 259 MW and 73.5 MVar.[16] The minimum and maximum voltage levels of all buses are considered between 90% to 110%. Also, the length of the lines is assumed 1 km.

TCSC parameters in the NEPLAN software, which will be used for simulation, are introduced in the Appendix. Also, the $\omega=\sqrt{(X_C/X_L)}$ is considered equal to 2, hence the $X_C=4 X_L$.[17]

3.1. Improving The Voltage Stability From The Point Of View Of Power Flow

Voltage stability means maintaining the permissible voltage in all buses. Due to weak systems and long lines in transmission networks, voltage stability in many power systems has become a significant challenge. The most important cause of the voltage instability and, as a result, voltage collapse is the incapability of the system to respond to the increased demand for reactive power.[18]

The increase of power system demands causes a drop in the voltage profile; hence the TCSC is employed to improve the voltage profile. In this section, the impact of the TCSC on the voltage profile is studied in two cases of low disturbances, constant loads, and variable loads. The location of the TCSC is selected according to.[19] Therefore, for the IEEE 14-bus test system, the optimal location of the TCSC for minimizing the active power losses is in line number three (from bus 2 to bus 3).

3.1.1. Constant Loads

In this case, all network loads (including active and reactive powers) are constant, i.e., total active and reactive loads are 259 MW and 73.5 MVar, respectively. The power flow results before and after installing the TCSC are shown in Table 1. As can be seen, the use of TCSC has improved the voltage profile include voltage amplitude and voltage phase angle. Also, with proper selection of X_C and X_L values, network losses can be reduced. Whether, if X_C =6 Ohm and X_L =1.5 Ohm, the active power losses will be increased.

Table 1: The power flow results before and after installing the TCSC.

	Base Case		After installing the TCSC Teta min=90° and Teta max=180° Xtot= -30%$X_{Line\ 2,3}$= -2.73 Ohm					
			Xc=4 Ohm, Xl=1 Ohm		Xc=2 Ohm Xl=0.5 Ohm		Xc=6 Ohm Xl=1.5 Ohm	
Bus Number	**V amp. (%)**	**V angle (Deg.)**	**V amp. (%)**	**V angle (Deg.)**	**V amp. (%)**	**V angle (Deg.)**	**V amp. (%)**	**V angle (Deg.)**
1	106	0	106	0	106	0	106	0
2	104.5	-5	104.5	-5.1	104.5	-5.1	104.5	-5.2
3	101	-12.7	101	-10.6	101	-11.3	101	-9.2

4	101.51	-10.3	101.55	-9.7	101.54	-9.9	101.56	-9.3
5	101.79	-8.8	101.85	-8.4	101.83	-8.5	101.87	-8.1
6	107	-14.4	107	-14	107	-14.1	107	-13.7
7	105.04	-13.3	105.08	-12.7	105.07	-12.9	105.1	-12.3
8	109	-13.3	109	-12.7	109	-12.9	109	-12.3
9	103.39	-14.8	103.43	-14.3	103.42	-14.5	103.45	-14
10	103.27	-15	103.31	-14.5	103.3	-14.7	103.33	-14.2
11	104.75	-14.9	104.78	-14.3	104.77	-14.5	104.79	-14
12	105.35	-15.3	105.35	-14.8	105.35	-15	105.35	-14.5
13	104.71	-15.3	104.72	-14.8	104.72	-15	104.73	-14.5
14	102.14	-16.1	102.17	-15.5	102.16	-15.7	102.18	-15.2
Network Losses	13.54 MW 27.23 Mvar		13.47 MW 22.16 Mvar		13.42 MW 23.95 Mvar		13.84 MW 18.9 Mvar	
			Firing angle (α)=180° X_{TCSC}= -4 Ohm K= X_{TCSC}/ X_{Line}=42.4%		α = 150.8° X_{TCSC}= -2.73 Ohm K=30%		α = 180° X_{TCSC}= -6 Ohm K=63.6%	

3.1.2. Variable Loads

In this case, three loads are variables, and other loads are considered constant. So the connected loads to buses 3, 9, and 12 for 24 hours are assumed according to Fig. 4.

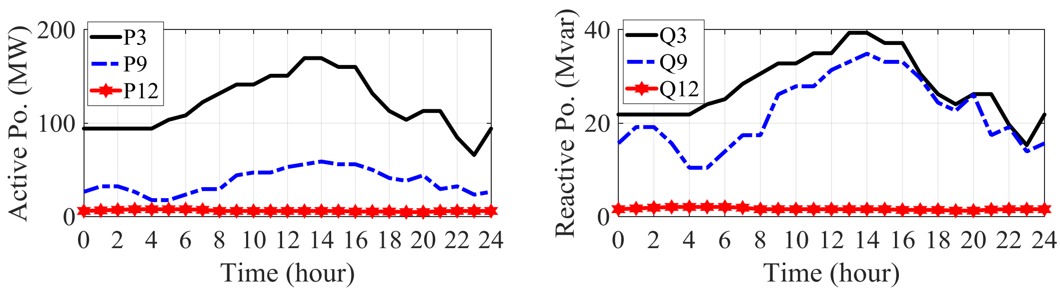

Fig. 4: Connected variable loads to buses 3, 9, and 12.

Before installing the TCSC, the voltage profile is shown in Fig. 5. A bus with having a synchronous machine (generator or compensator) is not plotted. As can be observed, due to the increase in network loads, the voltage level in all buses has decreased. Also, the voltage level for buses 9, 10, and 14 at 14:00 is placed under the minimum voltage level, i.e., 90%.

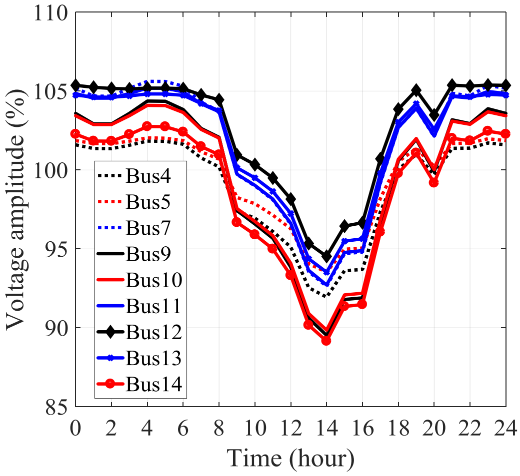

Fig. 5: The voltage profile before installing the TCSC.

The TCSC is installed in line number three (from bus 2 to bus 3), and the parameters are set. According to Fig. 6, after installing the TCSC, the voltage level for all buses is improved so that the voltage levels are higher than the minimum voltage level, i.e., 90%.

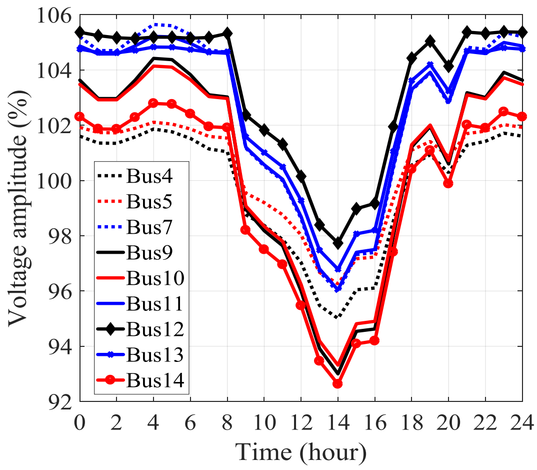

Fig. 6: The voltage profile after installing the TCSC (Teta min=90° and Teta max=180°, Xtot= -60% $X_{Line\ 2,3}$= -5.66 Ohm, Xc=4 Ohm, Xl=1 Ohm).

The voltage profile for buses 4, 12, and 14 before and after installing the TCSC is compared in Table 2. The results show that in addition to enhancing the voltage amplitude, the TCSC has a useful role in improving the voltage phase angle, and improving the stability of the system under gradual load disturbances will be realized.

Table 2. Comparing the voltage profile for buses 4, 12, and 14 before and after installing the TCSC.

		Time (hour)				
		10	**12**	**14**	**16**	**18**
Bus 4	**W/O TCSC**	96.95∠-13.3	95.12∠-14.1	91.94∠-15.5	93.96∠-14.8	100∠-11.6
	With TCSC	98.16∠-11.9	96.7∠-12.6	94.41∠-13.6	95.65∠-13	100.6∠-10.6
Bus 12	**W/O TCSC**	100.3∠-19.4	98.15∠-20.7	94.53∠-22.8	96.66∠-21.5	103.9∠-17.1
	With TCSC	101.6∠-18.1	99.76∠-19.2	97.07∠-20.9	98.66∠-19.9	104.4∠-16.2
Bus 14	**W/O TCSC**	95.9∠-20.7	93.31∠-22.3	89.15∠-24.8	91.47∠-23.4	99.78∠-18.3
	With TCSC	97.22∠-19.4	95.06∠-20.7	91.91∠-22.6	93.65∠-21.5	100.4∠-17.3

The comparison of network energy losses is shown in Fig. 7. After installing the TCSC, the active and reactive energy losses are decreased.

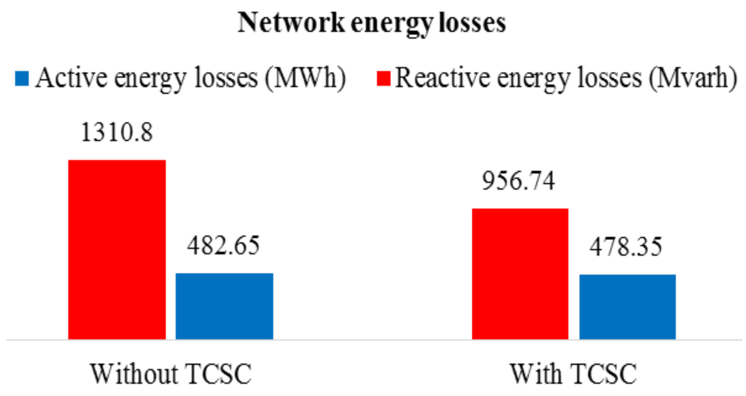

Fig. 7: Network energy losses before and after installing the TCSC.

3.2. Improving The Voltage Stability From The Point Of View Of Continuous Power Flow

The TCSC can affect the voltage stability of power systems and increase the loading parameter (λ); hence the Continuous Power Flow (CPF) is used to determine the weakest buses and the loading parameter value and investigate the impact of the TCSC on voltage stability.

Before installing the TCSC, the voltage amplitude from power flow results, and critical voltage and the loading parameter from continuous power flow are given in Table 3. According to results, buses 9, 10, 13, and 14 are weak and have a lower critical voltage.

The TCSC is placed in line number 16 (from bus 9 to bus 10), parameters are set, and the CPF run. After that, the TCSC is relocated to line number 20 (from bus 13 to bus 14), parameters are set, and the CPF run. The complete results of power flow and CPF are shown before and after installing the TCSC in Table 3.

In general, the results show that the TCSC can increase the loading parameter and critical voltage. As a result, voltage stability will be improved. When TCSC is placed in line number 20, its effectiveness is high because the loading parameter and the voltage stability are enhanced compared to when TCSC is installed in line number 16, although active power losses will be increased.

Table 3: Power flow and CPF results before and after installing the TCSC, Teta min=90°, and Teta max=180°.

	W/O TCSC		TCSC in line #16 Xtot= -30% $X_{Line\ 9,10}$= -0.05 Ohm Xc=0.12 Ohm, Xl=0.03 Ohm		TCSC in line #20 Xtot= -30% $X_{Line\ 13,14}$= -0.2 Ohm Xc=0.6 Ohm, Xl=0.15 Ohm	
Bus No.	**V amp. (%)**	**CRIT. V (%)**	**V amp. (%)**	**CRIT. V (%)**	**V amp. (%)**	**CRIT. V (%)**
1	106	106	106	106	106	106
2	104.5	104.5	104.5	104.5	104.5	104.5
3	101	101	101	101	101	101
4	101.51	76	101.51	76.6	101.56	76.84
5	101.79	78.7	101.8	79.3	101.81	79.38
6	107	107	107	107	107	107
7	105.04	70.2	105.05	71.1	105.19	71.73
8	109	109	109	109	109	109
9	103.39	64.2	103.41	**65.25**	103.59	**65.95**
10	103.27	63	103.27	**64.5**	103.44	**64.7**
11	104.75	65.5	104.76	66.9	104.85	66.95
12	105.35	65.4	105.35	66.6	105.29	66.56
13	104.71	63.7	104.71	**64.9**	104.52	**64.74**
14	102.14	57.9	102.15	**59.1**	102.82	**60.49**
	Network Losses	**λ (p.u.)**	**Network Losses**	**λ (p.u.)**	**Network Losses**	**λ (p.u.)**
	13.54 MW 27.23 Mvar	2.407	13.54 MW 27.21 Mvar	**2.416**	**13.6 MW** 27.07 Mvar	**2.867**

The P-V curves for bus 14 are shown in Fig. 8. The P-V curves describe bus voltages to load in a specified area. The advantage of the P-V curves is that it provides evidence of closeness to voltage collapse throughout a range of load levels. As can be seen, the TCSC enables improvement of the critical voltage. As a result, it can prevent voltage collapse during load increasing.

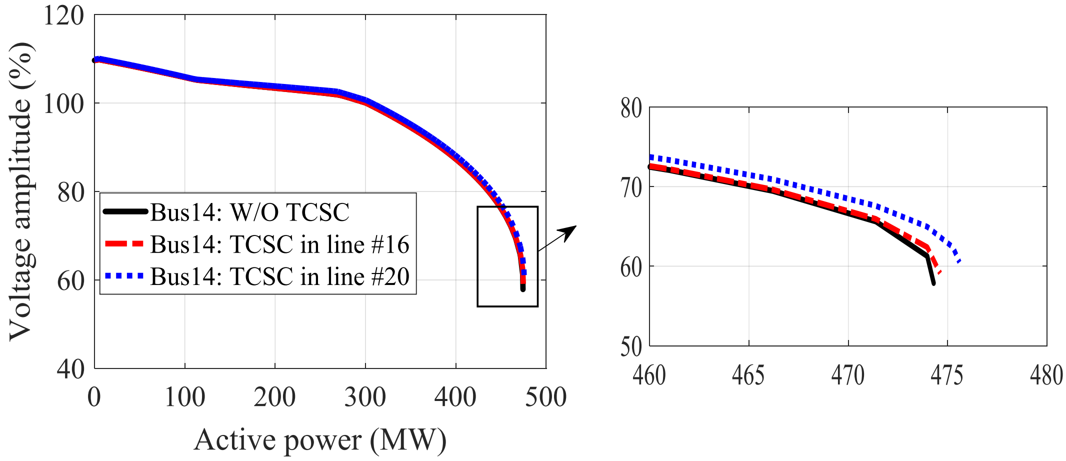

Fig. 8: The P-V curves for bus 14 before and after installing the TCSC.

4. Improving the transient stability

Transient stability is a significant problem in power systems. Transient stability can be described as the ability of a power system to maintain its synchronism under large and transient disturbances.[20] This section discusses the impact of the TCSC on the transient stability of a power system. To perform a transient stability simulation, dynamic data of the synchronous machines have to set in the software as inputs. Dynamic data is set based on.[21] Of course, minor changes must be considered, including:

- The rated power for all synchronous machines= 100 MVA.
- The rated voltage for buses 1, 2, and 3= 69 kV.
- The rated voltage for bus 6= 13.8 kV.
- The rated voltage for bus 8= 18 kV.

The variation in load consumption causes load disturbance. For load disturbance, adding an initial in active and reactive power for the static load of bus 9 is considered. According to Fig. 9, the disturbance is occurred at t=2 s and lasts for 5 s.

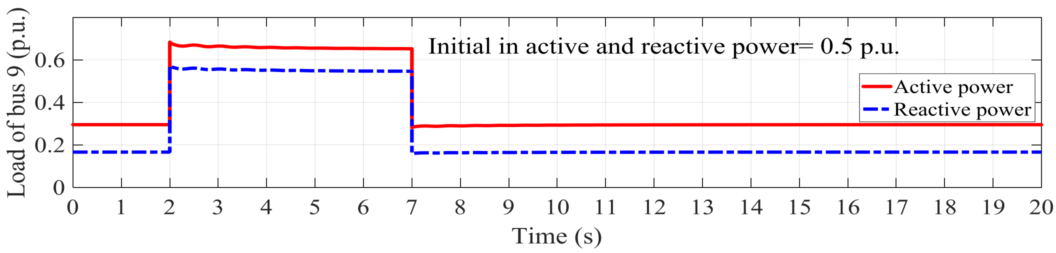

Fig. 9: Load disturbance in bus 9 at t=2 s to t=7 s.

The voltage profile of buses 9 and 14 under load disturbance is shown in Fig. 10. The TCSC is installed in line number 20 (from bus 13 to bus 14) and parameters are set as, Teta min=90°, Teta max=180°, Xtot= -30%XLine 13,14= -0.2 Ohm, Xc=0.2 Ohm, and Xl=0.05 Ohm. Simulation results show the TCSC can leading to improve transient stability under load disturbance.

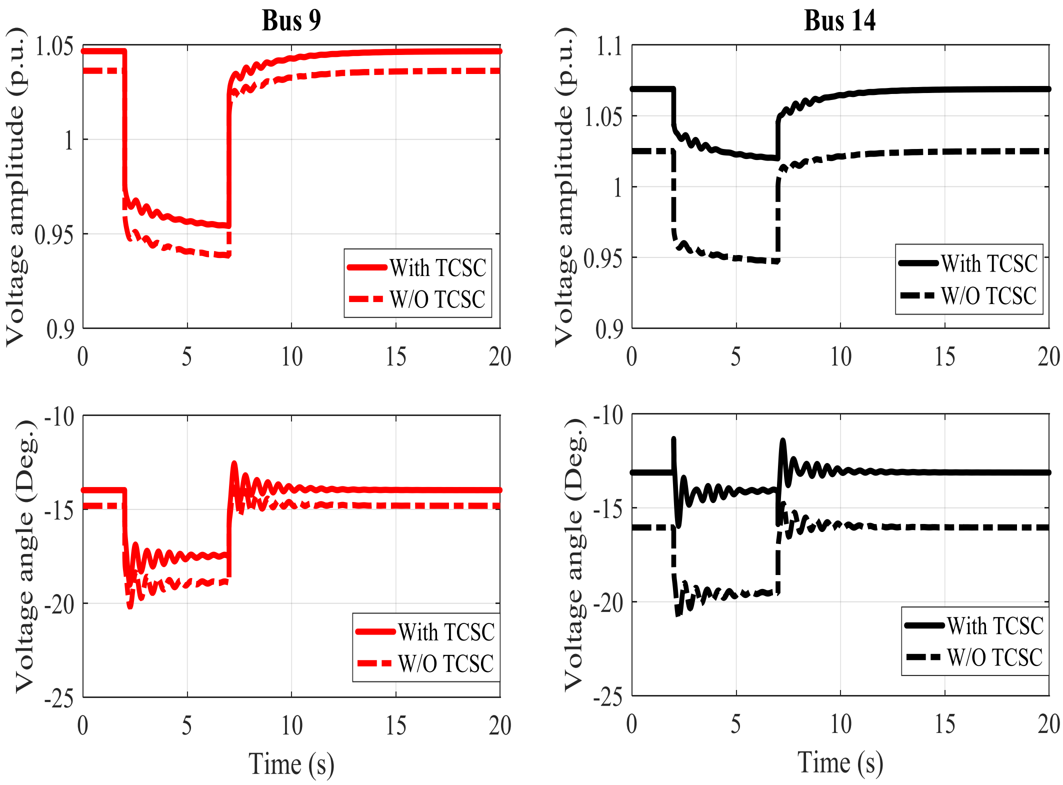

Fig. 10: The voltage profile under load disturbance, X_{TCSC}= -0.35 Ohm and K= 52.8%.

APPENDIX

Table 4: The parameters of the TCSC in the NEPLAN software.[24]

Parameter	Description
Xc	The reactance of the capacitor (Ohm)
Xl	The reactance of the inductor (Ohm)
Teta Limits	Limits on total reactance of the TCSC or the Thyristor firing angle.
Teta min/ Teta max	Minimum/Maximum value of thyristor firing angle (degree). The (Teta min, Teta max) range should not contain resonance values. If: firing angle limitation=180°, $X_{TCSC}= Xc$ firing angle limitation=90°, $X_{TCSC}= Xl$
Xtot	Control value for total TCSC reactance control (Ohm). A negative sign means capacitive reactance.

5. CONCLUSION

This paper provides the impact of the TCSC on voltage stability on steady-state and transient. TCSC is a series compensating FACTS device employed to improve power transfer capability, power system stability, and power quality. Performed simulations on the IEEE 14-bus test system show the TCSC can improve voltage stability under load disturbance.

In other words, the TCSC plays an essential role in simultaneously improving the voltage amplitude and voltage phase angle and causes maintain the stability of the power system when the demand increases, either gradually or suddenly. Also, with the precise selection of the TCSC parameters, the network losses can be reduced.

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