The Effect of FACTS Devices on Voltage Sag Following Transformers Inrush Current and Short Circuit Faults

Sajad Bagheri [1*], Amir Mohammad Khalili[1], Arash Faeghnezhad[1]

Abstract— **Power quality has a high dependence on short-term voltage changes. Voltage changes can cause damage to sensitive electronic equipment. Voltage sag is one of the short-term voltage changes that can be due to various factors, such as the inrush current of the transformers during switching in the presence of large loads or during short circuit faults. An important issue in the discussion of voltage sag is the rate of voltage recovery to a stable value. In this paper, three different compensators, Static Var Compensator (SVC), Thyristor Controlled Series Capacitor (TCSC), and Static Synchronous Series Compensator (SSSC), which are considered flexible AC transmission system (FACTS) devices, have been used to reduce the inrush current during switching of the transformers and consequently reduce the voltage sag caused by this event. Also, the efficiency of these devices has been investigated to increase the voltage recovery rate after clearing various transient faults in the network, which are the main innovations of the present study. To evaluate and validate the results, a double-fed network modeled in PSCAD software is used. The results of the simulations will show that the compensators used in this research improve the voltage sag by limiting the current and will significantly improve the rate of voltage recovery to a stable value after clearing various faults.**

Index Terms— **FACTS, Inrush Current, Power Transformer, Short circuit Faults, Voltage Sag.**

I. INTRODUCTION

Voltage is one of the factors affecting power quality in such a way that some call power quality voltage quality. Short- and long-term voltage changes reduce the quality of power delivered to the consumer. The use of devices such as variable-speed actuators and programmable logic controllers has increased in recent decades. One of the parameters affecting the power quality is the voltage sag, which is caused by the inrush current created by switching in the presence of large loads or short circuit faults. An important issue in the discussion of voltage sag is the rate of voltage recovery to a stable value, which has been investigated in this paper.

In [1], a TC limiter (TCL) comprising two diodes and two reactors in each phase has been used to reduce the inrush current for transformer energizing, motor starting, and fault event. The use of this method has led to a tangible reduction of the inrush current in the studied transformer.

In [2], power electronic converters have been used to reduce voltage sag by using a series controller connected to the voltage source converter.

The Dynamic Voltage Restorer (DVR) has been employed in series in [3] to make up for the voltage sag. This inexpensive gadget has prevented voltage fluctuations. The prior research, which was based on DVR, employed a number of techniques to lessen voltage sag. The single-phase DVR in [4], for instance, has been controlled using a special technique. It is based on a single-phase direct ac/ac converter, which limits the downstream fault currents with a straightforward topology and adjusts for various voltage disturbances. Combining DVR with supercapacitors has been the subject of more study, and it has been shown to lower voltage sag and enhance network power quality [5].

In [6], the static transfer switch operation's impact on the power quality parameters such as voltage sags, voltage harmonics, and the severity of flicker of the network in the presence of any fault has been investigated. The simulations performed in this paper show a reduction in the range of voltage changes and an improvement in power quality. The static switch in every type of fault has a higher speed than the normal switch, as well as a lower voltage sag percent.

In [7], the effect of different FACTS devices on voltage sag and harmonics has been studied. In [8], an accurate method for harmonics estimation based on an adaptive search method such as adaptive particle swarm optimization (APSO) has been investigated.

In [9, 10], D-STATCOM compensators and the addition of a voltage source converter in parallel are used to reduce the asymmetric voltage sag, and the results show the efficiency of the device used in achieving voltage stability. In another way, a controlled switching system has been used to reduce the inrush current and voltage distortion. The principles of this method are based on the use of a pre-insertion resistor circuit breaker (PIR-CB). This method ultimately leads to a reduction of the inrush current during switching in the presence of large loads [11].

In [12], a controlled switching method has been used to reduce the inrush current of three-pole, three-phase nuclear transformers. The principles of this method are based on energizing the different phases of the transformer sequentially. The results of the simulations performed in this research show a significant reduction in inrush current, taking into account various conditions such as transformer saturation. Distributed generation sources have been used in [13] to reduce the inrush

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current and subsequently reduce the voltage flux in the power network. Thus, the distributed generation sources-controlled reactive power generation method has been used to minimize the effect of induction motors at the moment of starting on the voltage.

In [14], the maximum reactive power was computed by a geometrical analysis method under voltage sags, considering current and voltage restrictions. This method was proposed for the star-connected cascaded H-bridge STATCOM under grid voltage sag, which can effectively support the grid with the maximum output reactive power. The experimental results showed that the proposed method could help to improve the output ability of 400 V/7.5 kVar STATCOM under voltage sag. In [15], detection and discrimination of inrush current and short circuit faults in transformers have been proposed. The principles of this research are based on a fuzzy system as a decision-maker that classifies the input signals to detect an internal fault in other events. The simulation results showed that the proposed technique could help improve the transformer differential protection operation.

Techniques for mitigating transformer inrush current when utilizing grid-forming inverters were suggested in [16]. Controlled energization using single-pole and three-pole CBs was examined for several configurations in [16], and their application limitations were identified. The effect of FACTS on voltage sag after transformer inrush current was not included in this study [16], which solely examined transformer energization inrush current in the presence of inverters. *A.*

In [17], an inrush current omission technique for the hybrid transformer (HT) based on an asynchronous closing technology was presented. In [17], through the rational design of the HT topology, the parallel auxiliary winding of the HT was appointed and the magnetic coupling structure was realized, which laid the magnetic circuit foundation for the inrush current control. In this paper [17], by managing the stabilization time of the skew wave and the primary voltage signal of the grid, when the core flux is stabilized, the nonsynchronous closing of the HT can efficiently reduce the inrush current.

In this paper, the reduction of the inrush current during the switching of transformers and its effect on the voltage sag in the presence of large and sensitive loads in the power network by FACTS devices have been discussed. Also, the voltage recovery rate during switching the transformers and short circuit faults have been examined in the presence of SSSC, TCSC, and SVC. In the II section, the FACTS devices used in this paper have been briefly reviewed. In the III section, the output of the simulations is analyzed to validate the results. Finally, the conclusion will be presented in the IV section.

II. STUDIED FACTS DEVICES

A. TCSC

The TCSC is a family of FACTS devices that provide uniform, fast, and continuous adjustments for the transmission line impedance. A simple schematic of this device has been presented in Fig. 1. This equipment consists of a controlled reactor with a thyristor-controlled reactor parallel to a fixed capacitor. The control elements consist of two back-to-back thyristors connected in series to the linear reactor. The TCSC reactance is controlled by the α angle. In the following equation, Xc is the capacitor reactance, X_{TCR} is the TCR reactance, and X_{TCSC} is the total compensator reactance after being connected to the studied system.

$$X_{TCSC}(\alpha) = \frac{X_C . X_{TCR}(\alpha)}{X_{TCR}(\alpha) - X_C} \quad (1)$$

Depending on the specific conditions that occur in a transmission network, this equipment operates in four operating modes: blocking mode, bypass mode, and capacitive boost mode, inductive boost mode [18]. The inductive boost mode of the TCSC increases the line inductance, and thus, it is very useful in reducing short-circuit faults, which is used in the studied system for simulating various scenarios.

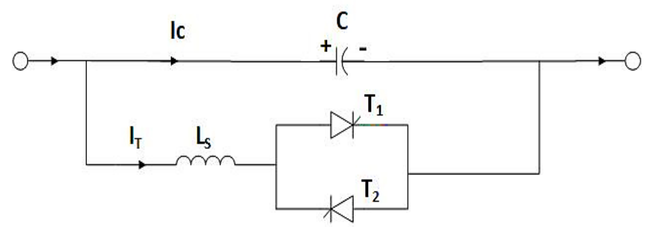

Fig. 1. Schematic of the TCSC

B. SSSC

SSSC is a static synchronous generator that works as a series compensator without an external electrical energy source, and its output voltage has a 90-degree phase difference with the line current and can be controlled independently of the line current. This equipment, like the TCSC, is used in series in the network to increase or decrease the voltage sag across the line and thus control the transmitted electrical power. By adding to the network, this device increases the power factor of the network and improves its power transfer. SSSC is also able to regulate the line voltage by generating a three-phase synchronous voltage perpendicular to the line current. By changing the impedance of this device, the current and power passing through the line can be controlled [19]. A simple schematic of the power network equipped with SSSC has been shown in Fig. 2. Also, the single-line diagram of the power system with the SSSC is obtained as shown in Fig. 3.

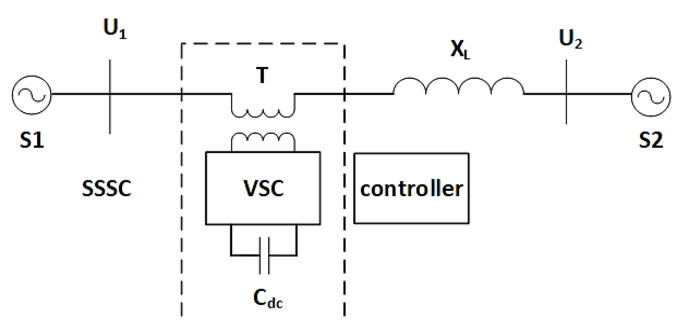

Fig. 2. Schematic of SSSC

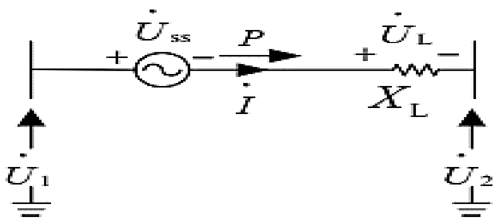

Fig. 3. Single-line diagram of the power system with SSSC

If the line current without the SSSC is I, this current after the addition of the SSSC will be as follows:

$$I_{Line} = I \pm \frac{U_{ss}}{X_L} \tag{2}$$

As can be seen from the above equation, the line current after the addition of the SSSC is more controllable, and after short-circuit currents in the system, it can be easily effective and efficient in restoring the system voltage.

C. SVC

SVC is a static electronic device that gets an inductive or capacitive reactive current from the power system and then generates or absorbs the reactive power. SVC is a continuously adjustable parallel susceptance with no moving parts, and its application is in transient and steady-state voltage stabilization, improvement of transient and dynamic stability, flicker reduction, power factor improvement, and load balancing. One of the features of this compensator is its fast response when receiving a control signal, so that the maximum delay of this device after receiving the gate signal is one cycle in single-phase systems and 1/3 cycle in three-phase systems. This reactive power source must be connected in parallel to the power network, and its output must be changed in such a way as to control certain parameters of the power system. The static concept used in this device means that this compensator, unlike synchronous compensators with moving components, has fixed components and responds faster to network changes. Also, this device has less damage and repair costs due to the lack of a moving part. All the relationships and modeling of this equipment have been presented in [20, 21]. In this paper, hybrid SVC (TSC + TCR) has been used. The single-line diagram of this system is shown in Fig. 4.

When the SVC is installed in the studied system, the effect of the SVC installed with reactance X_{svc} is seen on the performance of the whole system. The equations for calculating the capacitor compensator capacity and the transmission line reactance1-2, X_{1-2} are presented as follows:

$$C = 1 - \frac{X_L}{X_{SVC}} \tag{3}$$

$$X_{12} = \frac{X_L}{C} = \frac{X_L}{1 - \frac{X_L}{X_{SVC}}} \tag{4}$$

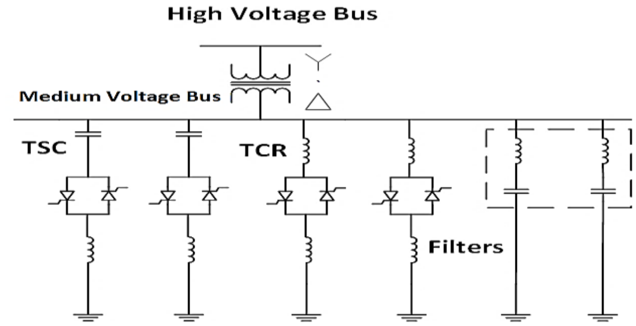

Fig. 4. schematic of SVC (TSC-TCR)

III. SIMULATION RESULTS

In this section, we first investigates the modeling procedures of SSSC, TCSC, and SVC compensators and their placement on the power network. Then, the effect of this type of device on the changes of voltage, current, and magnetic flux during the inrush current of a three-winding transformer at the moment of switching and during short circuit faults will be investigated. The single line diagram of the studied network is shown in Fig. 5. The network specifications have been presented in Table I This network includes 3-bus, double-fed supplies (100 MVA), two-winding transformers (13.8/230 kV), and a three-winding transformer (230/63/63kV) with the specifications provided in Table I. Also, the modeled power system in PSCAD software has been shown in Fig. 6. The simulations were performed in the PSCAD software.

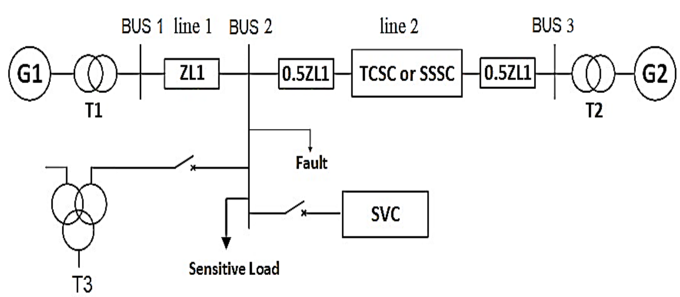

Fig. 5. Schematic diagram of the studied network

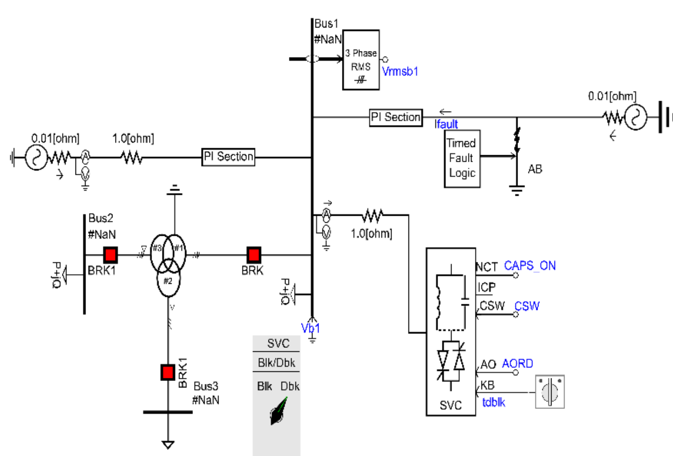

Fig. 6. Modeled power system in PSCAD software

TABLE I
Specifications of the Studied Network

Lines1,2	G1,2	T1,2	T3
100 km	S=100 MVA	S=100 MVA	S=200 MVA
R=0.028 Ω/km	f=60Hz	f=60Hz	f=60Hz
L=0.009 Ω/km	V=13.8 kV	13.8/230 kV	230/63/63kV

A. Effect of FACTS Devices on the Inrush Current

Energizing the transformers creates a current with a large amplitude called the inrush current, which returns to its normal value after a short period. The duration of the inrush current depends on the reactance and resistance of the network, which also include the magnetizing reactance of the transformer. Since the magnetic energizing of the transformer is high, the inrush current may take a long time to reach its steady-state.

The inrush current causes a temporary voltage dip due to the network impedance between the sources and the energized transformer. If the short-circuit magnitude of the transformer bus is low (or the source impedance is high), the results of the voltage dip can be significant. In the first phase, the three-winding transformer's inrush current will be investigated in the presence of sizable, delicate loads in the network and in the absence of compensating devices. The transformer energizing moment is 500 ms, and the simulation takes 3 s in total. The actions taken when TCSC, SSSC, and SVC compensators were present will all be examined in the following phase.

Fig. 7. shows the inrush current of a three-winding transformer with and without the presence of a TCSC. According to Fig. 7, the maximum amplitude of the inrush current without the presence of TCSC reaches 1.924 kA. However, in the presence of TCSC, this current reaches 1.603 kA, which shows a 16.68% improvement in the mitigation of inrush current.

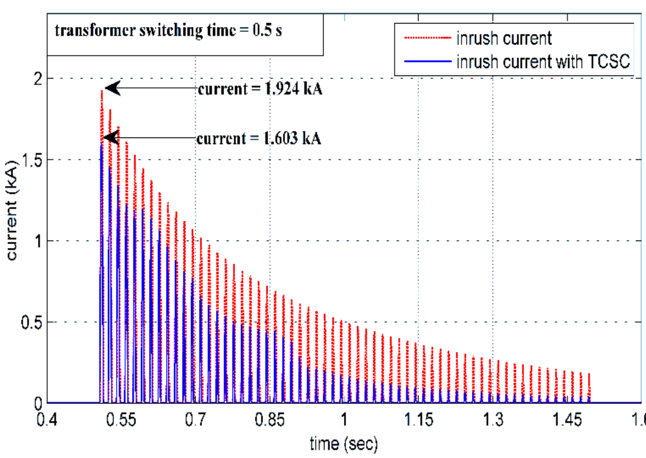

Fig. 7. Inrush current at the moment of transformer energization with and without TCSC

Fig. 8. shows the inrush current of the transformer with and without SSSC. In this case, this equipment was able to improve the peak of the inrush current by 15.8%. On the other hand, as can be deduced from Fig. 8, SSSC was able to reduce the peak value of the inrush current caused by the transformer energizing, but then failed to improve the attenuation of this current and only reduced it to its peak.

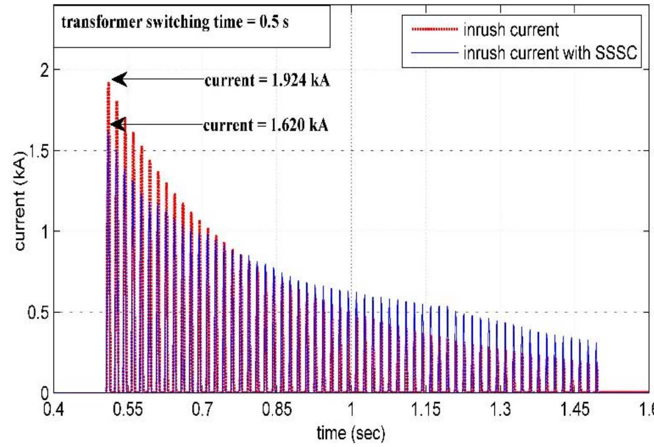

Fig. 8. Inrush current at the moment of transformer energization with and without SSSC

In the following, the effects of the SVC compensator on various events have been investigated. The inrush current with and without the presence of SVC is shown in Fig. 9. As can be seen from the simulation results, the peak of this current in the presence of SVC has reached 1.797 kA, which has created a 6.7% improvement in the inrush current while switching the transformer.

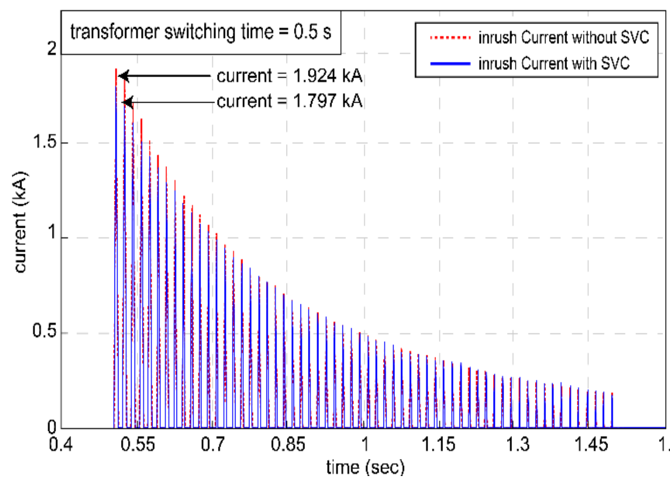

Fig. 9. Inrush current at the moment of transformer energization with and without SVC

B. Effect of FACTS Devices on the Magnetic Flux at the Moment of Transformer Energizing

This section has provided a study of the FACTS devices and their effect on the magnetic flux of the transformer winding at the switching moment. Fig. 10 shows the phase A flux of a three-winding transformer at the transformer energizing moment. According to this figure, it is proven that the presence of TCSC has reduced the peak magnetic flux from 0.765 kW to 0.725 kW. This is one of the important and effective factors in reducing the inrush current of the transformer under study. The results show that the presence of a TCSC, without change in other network parameters, was able to achieve a 5.22% improvement in the magnetic flux of the transformer.

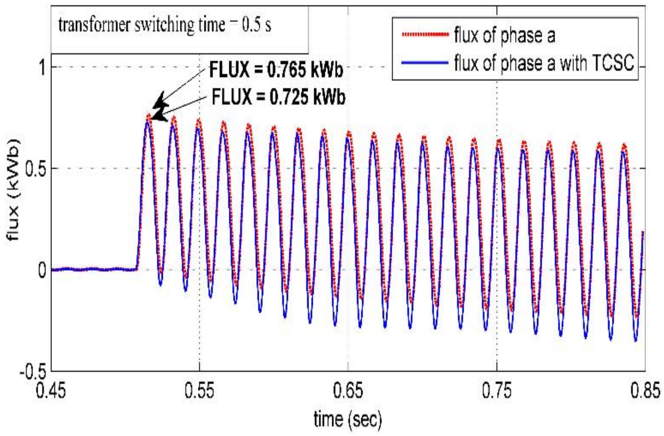

Fig. 10. Magnetic flux of transformer for phase A with and without TCSC

In the following, the phase A flux in the case of adding SSSC to the network has been investigated. According to Fig. 11. with the addition of SSSC to the network, the flux peak of phase A has decreased and its amplitude has increased from 0.765 kV to 0.727 kV, resulting in a 4.96% improvement.

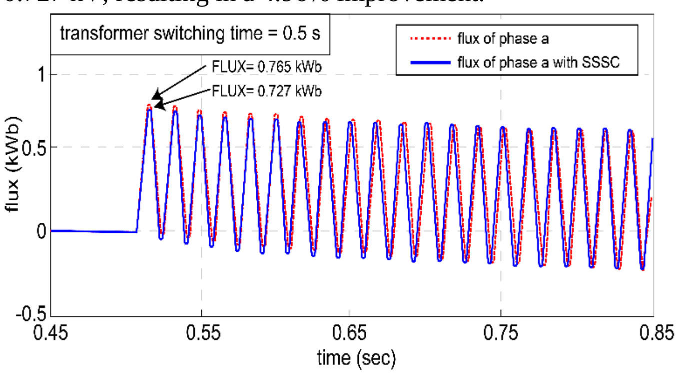

Fig. 11. Magnetic flux of transformer for phase A with and without SSSC

With the presence of SVC in the network, the magnetic flux was investigated, and its amplitude was reduced from 0.765 kW to 0.749 kW, which improved the amplitude of the magnetic flux by 2.1%, as can also be seen in Fig. 12.

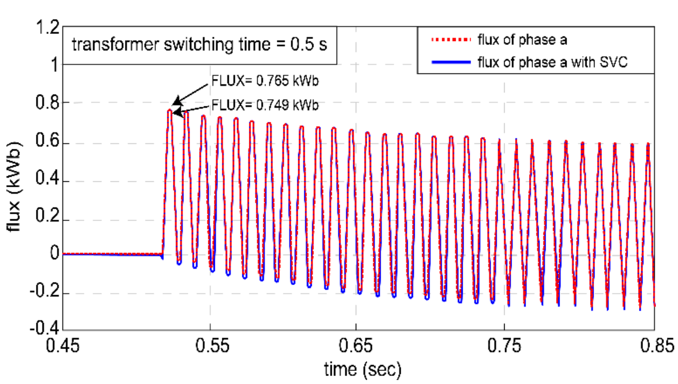

Fig. 12. Magnetic flux of transformer for phase A with and without SVC

C. The Effect of FACTS devices on Voltage Sag During Transformer Energizing

The voltage sag decreases as the inrush current dampens. Voltage sags are mainly caused by phenomena associated with high currents, which in turn cause voltage drops along the network impedance, and the magnitude of the voltage drop decreases relative to the distance from the electrical source. Voltage sag is mainly caused by phenomena that occur with high currents [2]. Common causes of voltage sag are as follows:

• Faults in distribution, over-distribution, and transmission networks. The duration of the voltage sag usually depends on the operating time of the protection equipment.

• Switching the large loads, such as power transformers and high-capacity motors.

To investigate the voltage sag during the switching of transformers and to investigate the effect of the presence or absence of compensators in the network, the three-winding transformer in the network is energized at a time of 500 ms. It should be noted that the total simulation time is 3s.

Fig. 13 shows the voltage of phases A, B, and C of Bus2 during transformer energizing at t=0.5s. In this case, line 2 is not equipped with any compensators. As a result, the voltage sag is significant and can negatively affect the sensitive loads connected to Bus2. According to the figure, this voltage has reached the value of 1 p.u. and it's steady-state in approximately 1.996s, which has taken a long time for the system to return to its steady-state (about 1.5s).

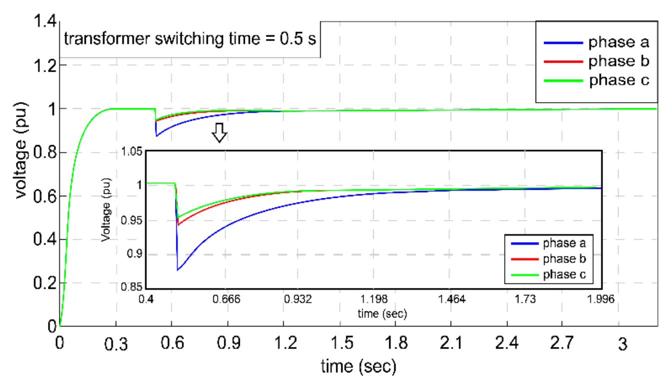

Fig. 13. Voltage of Bus2 without compensator at the moment of transformer energization

Fig. 14 shows the voltage sag when line 2 is compensated by the TCSC compensator. As it turns out, voltage recovery is much faster than that without compensation. In the first moments, the voltage has reached a steady state of 1 p.u. after two fluctuations in 0.934 s, which will show the positive effect of the TCSC compensator in the network.

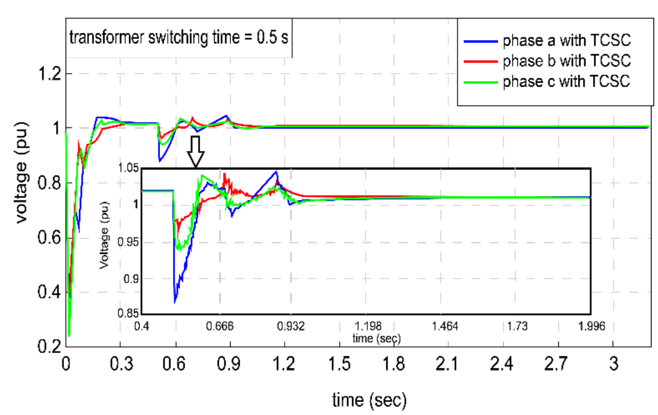

Fig. 14. Voltage of Bus2 at the moment of transformer energization with TCSC

Fig. 15 shows the voltage of Bus2 in the presence of SSSC. As it turns out, voltage recovery, as well as initial voltage fluctuations, are dramatically improved with the presence of SSSC.

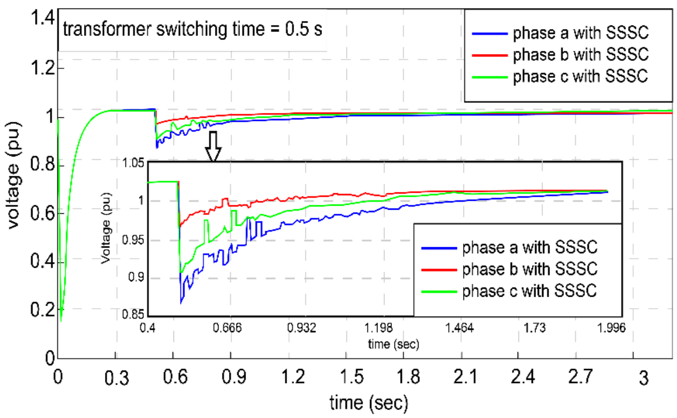

Fig. 15. Voltage of Bus2 at the moment of transformer energization with SSSC

Also, the presence of SVC at the moment of transformer energizing at t=0.5s was investigated, and the results are presented in Fig. 16. As it turns out, the voltages of three phases have reached a steady state at the moment t=1.35s and the value of 1 p.u., which indicates the optimal efficiency of the SVC compensator in the discussion of compensating for the voltage sag caused by the switching of transformers.

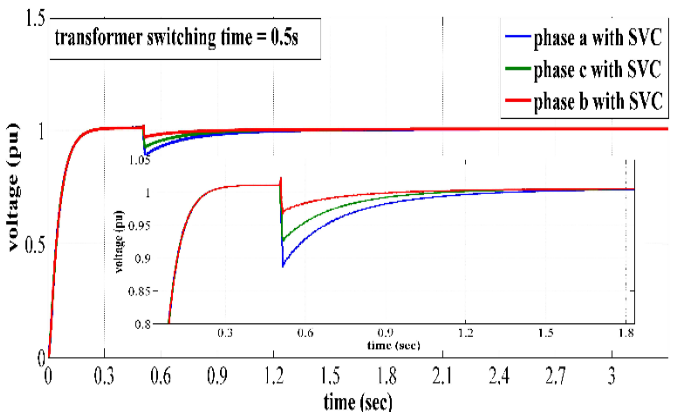

Fig. 16. Voltage of Bus 2 at the moment of transformer energization with SVC

D. Effect of FACTS Devices on Voltage Recovery Rate During Short Circuit Faults and Energizing of the Transformers

D. I. Single-Phase to Ground Fault

Fig. 17. shows the voltage characteristic of Bus2 in the presence of a single-phase to ground fault at 1.5s and during switching of the transformer at 0.5s. In this case, there is no compensator in the network. The duration of the fault is 0.2 s. At the moment of fault clearance at t=1.7 s, the voltage amplitude of phases B and C almost similarly reaches 0.98 p.u. and finally reaches a steady state at t=2.1 s. Also, the value of phase A voltage amplitude has been restored to 0.92 p.u. after a fault and then reaches its steady-state value at t=2.55 s. As it turns out, a lot of time has been spent restoring the voltage after the fault is cleared in the absence of a compensator. The above events will be investigated in the presence of various compensators. Fig. 18. shows the simulation results in the case of a single-phase ground fault in the presence of a TCSC compensator. In the presence of TCSC, the amplitude voltage of phase B at the same moment of fault clearance was able to reach the steady-state value, and the voltage amplitude of phases A and C reached the steady-state with a delay of 2.1s. The simulation results show the efficiency of the TCSC compensator in restoring the mains voltage in the case of transient short circuit faults, along with the transformers energizing.

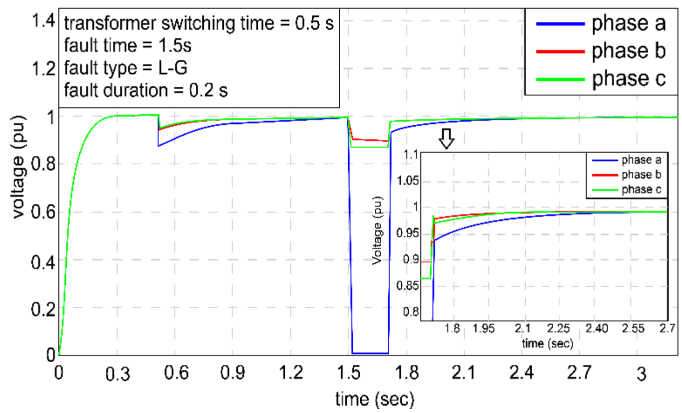

Fig. 17. Voltage of Bus2 at the moment of transformer energization and phase A to ground fault without compensator

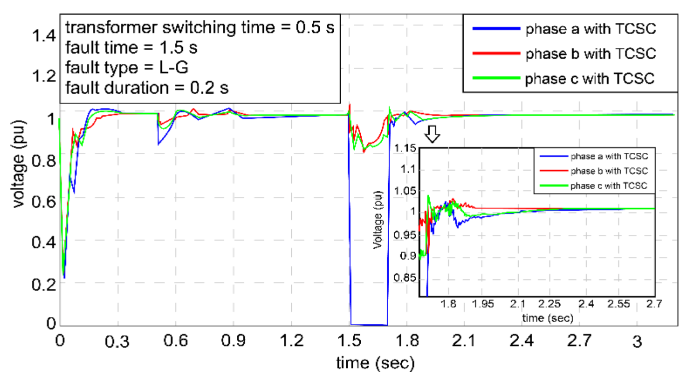

Fig. 18. Voltage of Bus2 at the moment of transformer energization and phase A to ground fault with TCSC

Fig. 19. shows the voltage of Bus2 in the presence of SSSC in single-phase to ground fault mode. As observed in the figure, in this case, the fault has affected the other two phases and reduced their voltage.

The faulty phase voltage also reached zero at the time of the fault (t=1.5s). After clearing the fault at t=1.7s, the voltage of phases B and C at t=1.75s reaches the value of 1.0 p.u., and the faulty phase voltage at t=2.1s reaches this value, which indicates that the SSSC was able to affect the system dynamics.

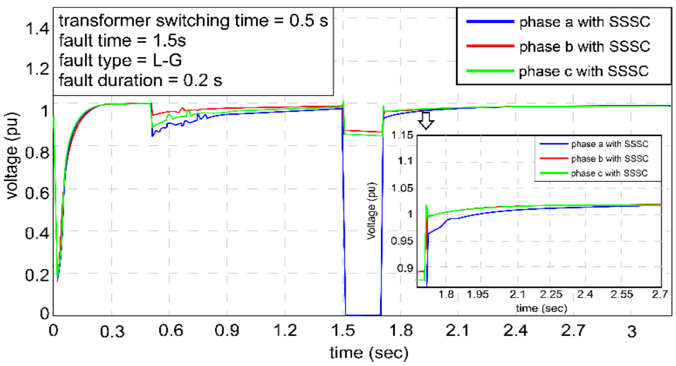

Fig. 19. Voltage of Bus2 at the moment of transformer energization and phase A to ground fault with SSSC

Fig. 20. shows the voltage of Bus2 in the presence of SVC and in the case of a single-phase ground fault and transformer energization. After clearing the fault at t=1.7s, the voltage of phases B and C at t=2.1s reaches the value of 1.0 p.u., and the voltage of the faulty phase reaches this value at t=2.35s. The simulation results show that SVC could have a desirable effect on system voltage recovery, but its effect was not as great as the presence of a TCSC compensator.

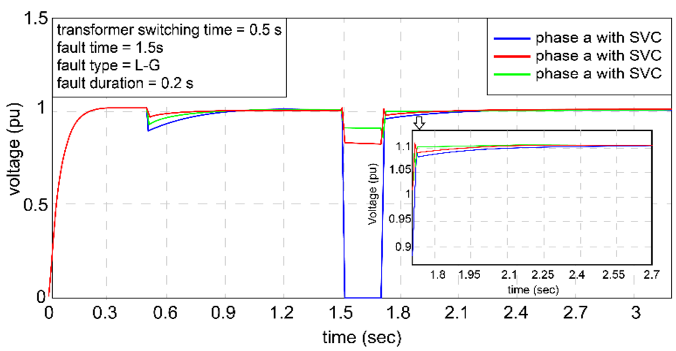

Fig. 20. Voltage of Bus2 at the moment of transformer energization and phase A to ground fault with SVC

D. II. Three Phase Fault

This section examines how compensators affect the quantity and rate of network voltage recovery in the event of a three-phase fault. Fig. 21. through 24 display the results of the simulation both with and without the compensators under investigation. The voltage of all phases at t=2.6s and after the fault is cleared approaches damping and a stable value of 1.0 p.u., as seen in Fig. 21 in the absence of the compensator. However, Fig. 22. shows that the voltage of all phases attained a stable value of 1.0 p.u. at t=1.9s after clearing the fault, following the addition of the TCSC compensator to the network. Fast charging and discharging of the capacitors in the TCSC is what causes the distortion that appears in the voltage waveform once it is installed.

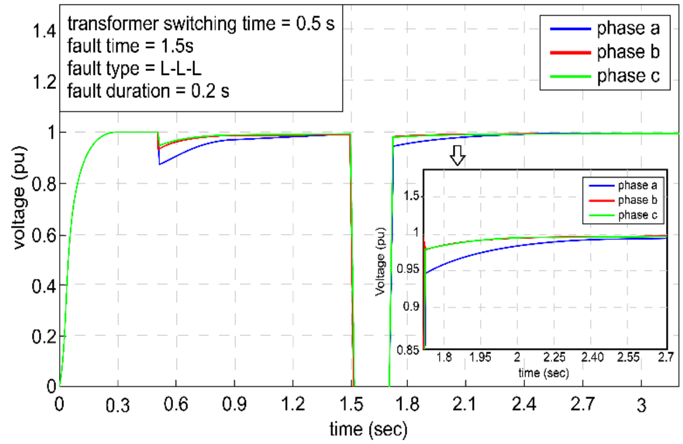

Fig. 21. Voltage of Bus2 at the moment of transformer energization and three-phase fault without compensator

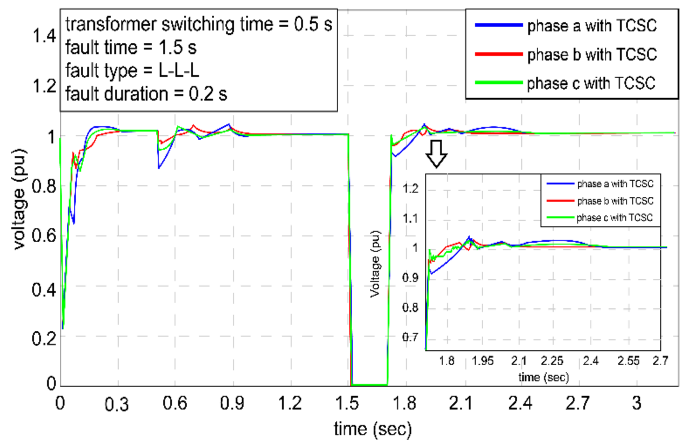

Fig. 22. Voltage of Bus2 at the moment of transformer energization and the three-phase fault with TCSC

Fig. 23. shows the voltage of Bus2 in the presence of SSSC with the three-phase fault. The voltages of all three phases at the moment t=1.7s (moment of fault clearance) have shifted to 1.0 p.u., and finally, at the time t=2s the voltage of all phases has reached its steady-state value.

Finally, Fig. 24. shows the result of the simulation of Bus2 voltage in the presence of SVC with a three-phase fault. The voltages of the three phases have finally reached the steady-state value of 1.0 p.u. at t=2.38s.

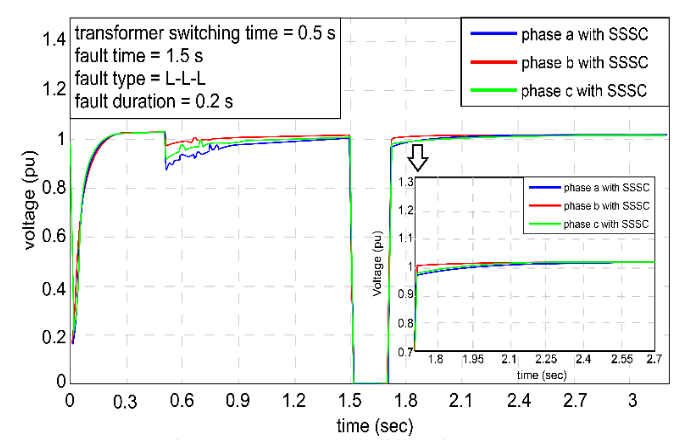

Fig. 23. Voltage of Bus2 at the moment of transformer energization and the three-phase fault with SSSC

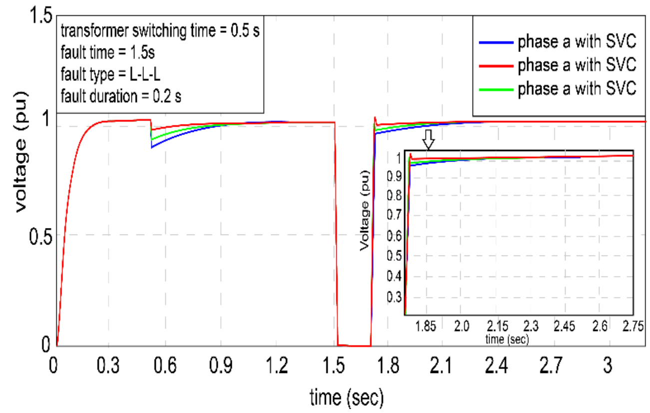

Fig. 24. Voltage of Bus2 at the moment of transformer energization and the three-phase fault with SVC

IV. CONCLUSION

An extremely high-amplitude inrush current is created in the power system when the transformers are connected to the network, but it is removed in a matter of seconds. Because of the network impedance between the sources and the activated transformer, the inrush current causes the voltage to drop. This study employed a variety of compensators, such as TCSC, SSSC, and SVC, to lower both the inrush current and the voltage sag.

The simulation results reveal that with the addition of various compensators to the network, the inrush current, magnetic flux, and voltage dynamics of the network were significantly improved, and the time to reach a stable value was reduced. During the switching of the three-winding transformer in the studied system, the peak of the inrush current without the presence of compensators reached 1.924 kA. When TCSC was added to the network, the peak inrush current reached 1.603 kA, indicating a decrease and improvement of 16.68%. Also, when SSSC and SVC are placed in the network, the inrush current is reduced to 15.8% and 6.7%, respectively.

In the study of magnetic flux, it was observed that all three compensators would be able to reduce the magnetic flux of the transformer. According to the simulation results, the presence of the TCSC compensator improved 5.22%, and SSSC and SVC improved the transformer magnetic flux in the network to 4.96% and 2.1%, respectively.

In the following, the voltage sag during the energization of the three-winding transformer was investigated in the presence of various compensators. After the TCSC was added to the network, the voltage sag improved significantly. With the addition of SSSC, the voltage reached its stable value faster, at 1.4s. However, according to the simulation results, the system voltage recovery rate was faster in the presence of TCSC than in SSSC and SVC.

Finally, voltage sag during simultaneous short circuit faults and energization of a three-winding transformer in the presence of different compensators were investigated. From the simulation results, it was observed that in the case of a single-phase to ground fault, when the network is not equipped with a compensator, the voltage will reach a stable value of 0.85s after clearing the fault. This value decreases to 0.7s when the network is equipped with SSSC, to 0.65s in the presence of SVC, and finally to 0.4s in the presence of TCSC. The use of new control systems and other types of FACTS to improve the network voltage, achieve a higher speed of voltage recovery, and also use active filters to study harmonics can be made for future works.

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