International Journal of Robotics and Control Systems
Vol. 4, No. 1, 2024, pp. 1-32
ISSN 2775-2658
http://pubs2.ascee.org/index.php/ijrcs

Enhancing the Performance of Power System under Abnormal Conditions Using Three Different FACTS Devices

Ibram Y. Fawzy [a,1], Mahmoud A. Mossa [a,2,*], Ahmed M. Elsawy [a,3], Ahmed A. Zaki Diab [a,4]

[a] Electrical Engineering Department, Faculty of Engineering, Minia University, Minia 61111, Egypt
[1] ibramyehia@yahoo.com; [2] mahmoud_a_mossa@mu.edu.eg; [3] ahmed.elsawy@mu.edu.eg; [4] a.diab@mu.edu.eg
* Corresponding Author

ARTICLE INFO

Article history
Received October 04, 2023
Revised November 27, 2023
Accepted January 02, 2024

Keywords
Power System;
Flexible Alternating Current Transmission System (FACTS);
Static Synchronous Compensator (STATCOM);
Static Synchronous Series Compensator (SSSC);
Unified Power Flow Controller (UPFC);
Faults Types

ABSTRACT

In this paper, a comparison between Flexible Alternating Current Transmission System (FACTS) devices including Static Synchronous Compensator (STATCOM), Static Synchronous Series Compensator (SSSC) and Unified Power Flow Controller (UPFC) for providing a better adaptation to changing operating conditions and improving the usage of current systems. The power system using FACTS devices is presented under different conditions such as single phase fault and three phase fault. A digital simulation using Matlab/Simulink software package is carried out to demonstrate the better performance including the voltage and the current of the presented system using FACTS that located between buses B1 and B2 under different faults types. The results obtained investigate that the presented system gives better response with FACTS as compared to not using them under abnormal conditions besides, the UPFC gives better performance of power system under several faults as compared to STATCOM or SSSC as It can absorb reactive power in a manner which significantly reduced the fault current. It is demonstrated that UPFC can reduce the peak fault current at bus B1 to 63.85% of its value without using FACTS devices under line to ground fault and 79.18% under three line to ground fault whereas STATCOM and SSSC reduce it to (75.21, 94.35%) and (75.40, 94.68%), respectively.

1. Introduction

The power system is getting more multifaceted day by day owing to increase in electric power demand and the construction of new generating plants and transmission lines. Consequently, the power system is forced to provide electric power close to their thermal limits [1]. A system that generates and transfers electric power through a grid of electrical components to the customers is known as power system. The power system control can be thought of as maintaining a balance between power generation and load demand [2]. The technologies used in power systems are continuously advancing so as the power system. The continuously evolving power system earn a more ideal and beneficial procedure with regard to generation, transmission and distribution system [1]. Flexible Alternating Current Transmission Systems also known as FACTS technology is announced by Electric Power Research Institute (EPRI) in the last period of 1980s [3] to progress the system stability, flow of power and to develop the reliability. Power System Stabilizers (PSS) have played a spirited part in controlling and damping out fluctuations in power system [1]. Enhanced utilization of the existing power system is provided through the application of FACTS devices which are operative and capable of increasing the power transmission capacity of transmission lines helping power systems to operate within comfortable stability margins [4][5]. FACTS devices are used in transmission system for controlling and utilizing the flexibility and system performance. To accomplish all, the addition of FACTS devices required in plant to control the main parameters like voltage, impedance and phase angle, that is affecting AC power transmission. The power transmission lines could be capable of supporting power transfer with comfortable and stable manner using FACTS devices [4][5]. FACTS are considered the best solutions for enhancement electrical network's power quality, reliability and efficiency [6].

The FACTS controllers are based on thyristor devices with only gate turn on ability and no gate turn off ability [7]. They can be divided into three categories according to their connection: shunt connected controllers such as Static Synchronous Compensator (STATCOM), series connected controllers such as Static Synchronous Series Compensator (SSSC) and combined series and shunt connected controllers such as Unified Power Flow Controller (UPFC) [8]. UPFC is a device designed to provide rapid acting reactive power compensation on the transmission networks. It can be used for controlling active and reactive power flows in the transmission lines. It employs solid state devices that offer purposeful flexibility, mostly not attainable by conventional thyristor controlled systems. It is a combination of STATCOM and SSSC which are coupled through DC voltage link [9].

Fault current is referred to the instantaneous rise in current created by a short circuit or other fault in the power network. Short circuits regularly happen between the lines together or the lines and the ground in the three-phase transmission power system. Through a short-circuit fault, the current can increase by up to 10 times the load currents. This will harmfully influence the power grid's reliability and efficiency. Transmission system and distribution network have regularly implemented FACTS devices in order to improve and regulate reliability of power system [10]-[12].

The reviews of some literatures related to this paper are given as below;

D. Murali, M. Rajaram, and N. Reka (2010) presented dynamic performance of two zone power system with and without UPFC. In this approach the UPFC is compared with other FACTS devices. Several types of FACTS controllers and their performance characteristics have been described [13]. R. Somalwar and M. Khemariya (2012) presented FACTS devices for solving instability problems. . The FACTS controller can also be used for power flow control and stability enhancement control. The use of FACTS controller is investigated to improve the transient stability of the system [14]. S. T. FADHIL, M. HAMAD, A. O. Arslan, and A. M. VURAL (2020) introduced the FACTS devices working principles and control functions in addition to the simulation results of the system with applying faults [15].

M. P. Donsion, J. Guemes, and J. Rodriguez (2007) studied FACTS devices for power quality improvement. In this study impedance, current and voltage are improved using FACTS devices to improve power system performance [16]. S. Panda (2010) introduced modeling and simulation of SSSC multi-machine system to improve power system stability. In this approach the SSSC controller is operative in damping a range of disturbance conditions in the power system [17]. S. Akter, A. Saha, and P. Das (2012) presented modeling and simulation of some FACTS devices such as STATCOM, SSSC and UPFC for power system stability improvement and enhancement of power transfer capability [18].

T. U. Okeke and R. G. Zaher (2013) discussed essentially the importance of FACTS devices in the networks and their technologies which are the earliest technology used-Static VAR Compensator (SVC), and the most recent technology used-UPFC [19]. M. D. STOCHITOIU and I. UTU (2020) presented the performance comparison of different FACTS devices as todays electricity demand increases with the development of transmission networks. It creates an environment of competition and bargaining power due to open market power and regulation [20]. S. Mirsaeidi, S. Devkota, X. Wang, D. Tzelepis, G. Abbas, A. Alshahir, et al (2022) introduced a comprehensive review of existing proposals to improve power system efficiency by adopting FACTS devices [21]. S. Khanchi and V.

K. Garg (2013) presented a comprehensive review on UPFC which is one of FACTS devices . The vital features of UPFC controller and simulation model are illustrated. UPFC controllers allow transmission lines to deliver power close to their thermal ratings [22].

K. Gupta and Y. Pahariya (2017) studied the relationship between SVC, STATCOM and UPFC performance in order to improve the transient stability of power systems [23]. M. Rohit and N. K. Sharma (2022) described the benefits of using FACTS devices to improve the performance of power systems. Different FACTS controllers have been discussed [24]. H. Joshi and S. Sahay (2017) presented modeling, controlling of UPFC and studying its influence on the electrical power system. The simulation results show the improvement of UPFC performance by controlling the power system voltage. The UPFC can control the flow of active and reactive power in the transmission system [25].

M. R. Wara and A. Rahim (2020) presented a survey of the evolution of STATCOM technology and its applications in the power industry. This study covers the ability of STATCOM to interact with energy storage-based solutions and is included to illustrate future directions for this device [26]. A. Raj and D. Vishwakarma (2023) presented the application of SSSC to control the power flow between two ends of the transmission line to maintain the phase angle, voltage magnitude and line impedance. A series-compensated SSSC device that controls the transmission line power flow by changing the effective reactance of the system is studied [27]. A. Udaratin, K. Loginov, A. Nemirovskiy, N. Rozhentsova, and E. Gracheva (2020) considered installation of FACTS devices in a 500 kV line of substation. Three FACTS devices in emergency mode are modelled: STATCOM, SSSC, and UPFC [28].

B. Musa and M. Mustapha (2015) described the approach of STATCOM, in which the device is modelled and used for providing controllable bus voltage and reactive power compensation [29]. A. Singh and A. U. Ahmad (2015) presented comparison of active and reactive power for STATCOM, SSSC and UPFC at different distances of transmission line using Matlab/Simulink [9]. M. Eslami, H. Shareef, A. Mohamed, and M. Khajehzadeh (2012) presented a comprehensive analysis of research and developments in power system stability improvement using FACTS controllers. Several technical publications related to FACTS devices are highlighted and the performance of various FACTS controllers is compared [30]. A. S. Shelke and A. A. Bhole (2021) presented a brief description of different FACTS devices like STATCOM, SVC, SSSC, and UPFC [31]. A. A. Nimje, C. K. Panigrahi, and A. K. Mohanty (2011) introduced the achievement of the required active and reactive power flow in a transmission line and increase the power carrying capacity of the transmission using SSSC [32]. R. K. Bindal (2014) presented various types of FACTS devices like STATCOM, SSSC and UPFC and their benefits for power system transmission [8].

The main contribution of the present paper is the focus on different FACTS devices, their comparative studies and benefits to the power system under abnormal conditions. The major drawback is the need to study another faults cases at some positions in the power system using FACTS devices.

The purpose of this paper is to provide an overview of three different FACTS devices including STATCOM, SSSC and UPFC for improving power system performance. The presented system is studied under single phase fault and three phase fault using Matlab/Simulink software package. The obtained results investigated that the power system performance can be enhanced precisely with FACTS devices and the UPFC gives the better performance as compared to other FACTS types.

2. Overview of FACTS Devices

2.1. Static Synchronous Compensator (STATCOM)

STATCOM is a shunt attached reactive power compensation controller. The progresses in power electronics, especially the GTO thyristor, allowed implementation of such technology as a reasonable alternative to conventional SVC. A schematic arrangement of STATCOM is displayed in Fig. 1.

Vol. 4, No. 1, 2024, pp. 1-32

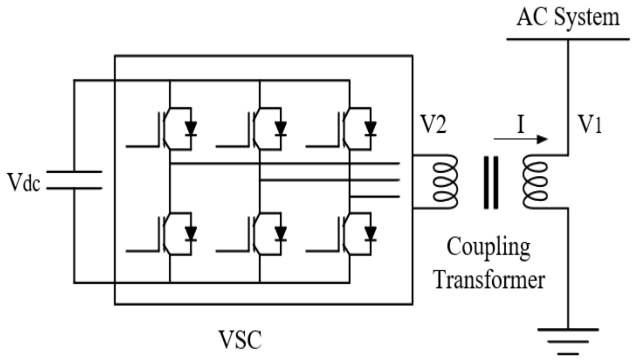


Fig. 1. Basic configuration of STATCOM

The active power (P) and reactive power (Q) of the transmission line are shown as follows:

$$P = \frac{V1 \times V2}{X} sin\, \delta \tag{1}$$

$$Q = \frac{V1^2}{X} - \frac{V1 \times V2}{X} cos\, \delta \tag{2}$$

where $V1$ and $V2$ are the inverter output voltage and the system bus voltage respectively and X is the reactance of the line from the inverter to the system bus [31].

The relations between the AC voltage of the system and the voltage at the STATCOM AC side terminals provide the reactive power flow control. If the STATCOM terminals voltage is greater than the system voltage, STATCOM will behave as a capacitor and the reactive power will be injected from the STATCOM to the system. When the STATCOM voltage is less than the AC voltage, STATCOM will perform as an inductor and the reactive power flow will be reversed. Both voltages will be the same and no power exchange will be there between the STATCOM and the system at normal operating conditions. Fig. 2 displays the STATCOM voltage and current characteristics. Numerous studies substantiated that STATCOM is able to improve power system dynamics and system stability for applications of renewable energy [33].

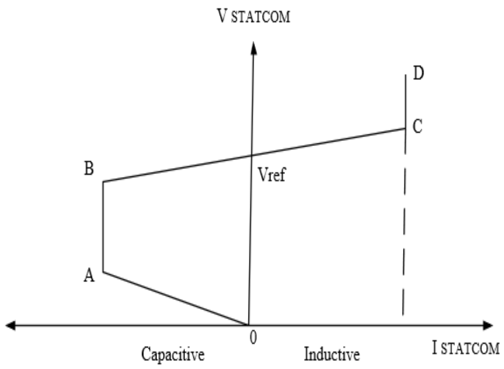


Fig. 2. STATCOM V-I characteristics

2.2. Static Synchronous Series Compensator (SSSC)

SSSC is a series connected FACTS device which can supply inductive or capacitive voltage independent of the current of transmission line up to the rated current limits. Also, SSSC is capable of exchanging both active and reactive power with the AC system, basically by controlling the injected voltage angular position [33]. The basic arrangement of SSSC is displayed in Fig. 3. It consists of a voltage source converter attached to a dc voltage source and coupled with the AC system through a series transformer.

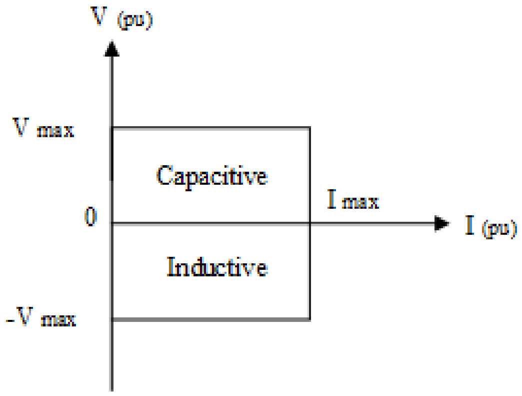


Fig. 3. Basic configuration of SSSC

The active power (P) and reactive power (Q) of the transmission line are shown as follows:

$$P = \frac{V1\,V2}{Xl} sin(\delta 1 - \delta 2) = \frac{V^2}{X} sin\,\delta \tag{3}$$

$$Q = \frac{V1\,V2}{Xl}(1 - cos(\delta 1 - \delta 2)) = \frac{V1\,V2}{X}(1 - cos\,\delta) \tag{4}$$

where $V1$ and $V2$ are the voltage values at the two ends, $\delta 1$ and $\delta 2$ are the phase angles of the voltage sources $V1$ and $V2$ respectively and X is the combined reactance of the transmission line and the SSSC.

In order to simplify these relations, it is taken V as the magnitude of the voltage and δ as the magnitude of the phase difference.

Fig. 4 displays the SSSC voltage and current characteristics during voltage control operation. During the voltage control mode the SSSC maintains the inductive or capacitive compensating voltage through the change in the line current from zero to I_{max}. SSSC has been involved in numerous studies to investigate its applications for stability enhancement [33].

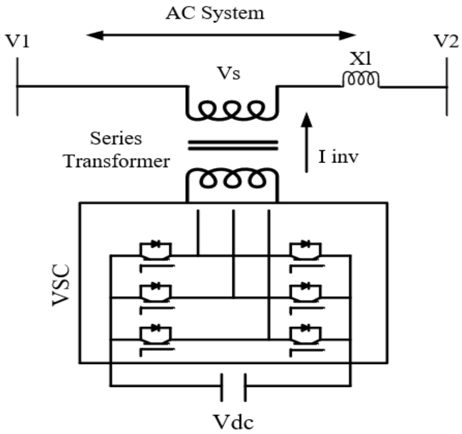


Fig. 4. SSSC V-I characteristics

2.3. Unified Power Flow Controller (UPFC)

UPFC is a compound power electronic device which was advanced in order to control and enhance the power flow in power transmission systems. The UPFC as a multipurpose device is accomplished to control all the parameters affecting the transmission lines power flow, containing voltage, impedance and phase angle. As displayed in Fig. 5 a UPFC is mostly a blend of STATCOM and SSSC coupled throughout a common dc link. The UPFC application to power systems has been broadly considered by the power manufacturing owing to its many benefits, that comprise smooth control of both system active and reactive power at the point of common coupling (PCC) and its quick and independent performance [33].

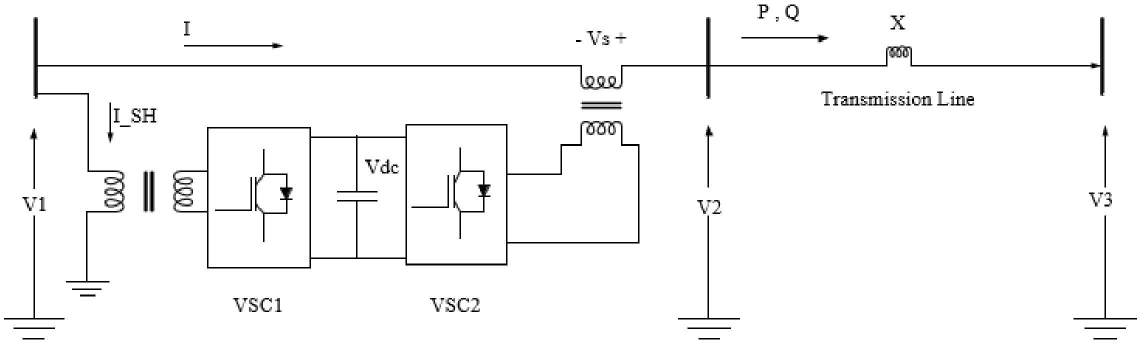


Fig. 5. Basic configuration of UPFC

UPFC is the most functional and FACTS equipment which has developed for the power flow control and optimization in power transmission system. It has the combining types of both series and shunt converters founded FACTS devices and is accomplished of appreciating voltage regulation, series compensation and phase angle regulation simultaneously. Consequently, the UPFC is able to independently control the active power and reactive power on the compensated transmission lines [34]-[37].

Through the FACTS devices, the UPFC is the most adaptable and effective [38]-[40]. The opportunity of installing a UPFC on a 500kV transmission system exploring the application of the UPFC for active and reactive power flow control. The result displayed that the attainable response of the control is very fast, nearly instantaneous, and thus the UPFC is operative in handling dynamic system response [39][40].

The active power (P) and reactive power (Q) of the transmission line are shown as follows:

$$P = \frac{V2 \times V3}{X} sin\,\delta \tag{5}$$

$$Q = \frac{V2^2}{X} - \frac{V2 \times V3}{X} cos\,\delta \tag{6}$$

where $V2$ and $V3$ are the voltages at the buses 2, 3 [41].

A fault in a power system is the unintended conducting path (short circuit) or impasse of current (open circuit). The short-circuit fault is naturally the most common and is typically inferred when majority use the term fault. A fault happens when one energized electrical component associates another at a different voltage. This permits the impedance between the two components to fall to near zero letting current to flow along an undesired pathway from the one initially projected. The short-circuit fault current could be guidelines of magnitude greater than the normal functional current. The current from such an occasion can comprise marvelous critical energy, that can harm electrical apparatus and pose security concerns for both utility and non-utility employees [42].

3. System under Study

A detailed model of a 48-Pulse, GTO-based unified power flow controller (500 kV, 100 MVA) is shown in Fig. 6. A UPFC is used to control the power flow in a 500 kV transmission system. The UPFC located at the left end of the 75-km line L2, between the 500 kV buses B1 and B2, is used to control the active and reactive powers flowing through bus B2 while controlling voltage at bus B1. It consists of two 100-MVA, three-level, 48-pulse GTO-based converters, one connected in shunt at bus B1 and one connected in series between buses B1 and B2. The shunt and series converters can exchange power through a DC bus. The series converter can inject a maximum of 10% of nominal line-to-ground voltage (28.87 kV) in series with line L2.

This pair of converters can be operated in three modes:

- UPFC mode, when the shunt and series converters are interconnected through the DC bus. When the disconnect switches between the DC buses of the shunt and series converter are opened, two additional modes are available:
- Shunt converter operating as STATCOM controlling voltage at bus B1.
- Series converter operating as SSSC controlling injected voltage, while keeping injected voltage in quadrature with current.

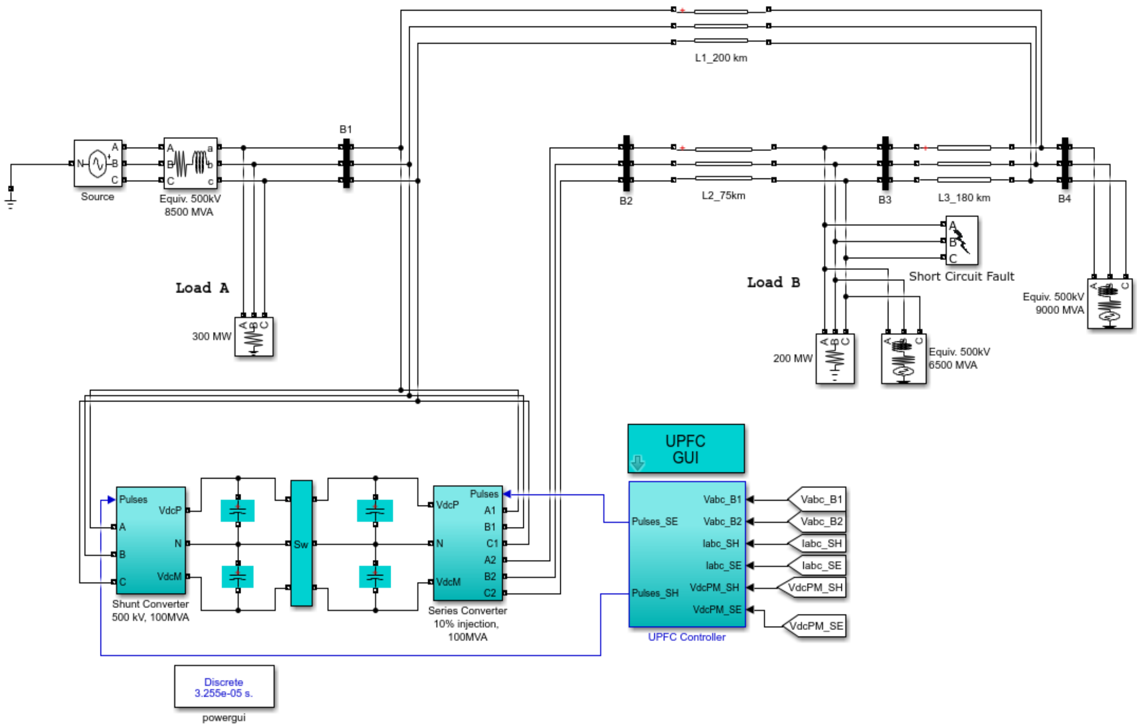


Fig. 6. The proposed model in Matlab/Simulink

When the two converters are operated in UPFC mode, the shunt converter operates as a STATCOM. It controls the bus B1 voltage by controlling the absorbed or generated reactive power while also allowing active power transfer to the series converter through the DC bus. The reactive power variation is obtained by varying the DC bus voltage. The four three-level shunt converters operate at a constant conduction angle (Sigma= 180-7.5 = 172.5 degrees), thus generating a quasi-sinusoidal 48-step voltage waveform. When operating in UPFC mode, the magnitude of the series injected voltage is varied by varying the Sigma conduction angle, therefore generating higher harmonic contents than the shunt converter.

The natural power flow through bus B2 when zero voltage is generated by the series converter (zero voltage on converter side of the four converter transformers) is P=+870 MW and Q=-70 Mvar. In UPFC mode, both the magnitude and phase angle and the series injected voltage can be varied, thus allowing control of P and Q. The UPFC controllable region is obtained by keeping the injected voltage to its maximum value (0.1 per unit (pu)) and varying its phase angle from zero to 360 degrees. Table 1 indicates data parameters of FACTS devices in the model under study.

Table 1. The data of FACTS devices used in this paper

STATCOM	STATCOM (Qref)	T1	0.3
		T2	0.5
		Q1	+0.8
		Q2	-0.8
	STATCOM Vref (pu)	Initial	1
		Final	1.005
		Step Time	0.3*100
SSSC	SSSC voltage injection (pu)	Initial	0.0
		Final	0.08
		Step Time	0.3
UPFC	UPFC Pref (pu)	Initial	+8.7
		Final	+10
		Step Time	0.25
	UPFC Qref (pu)	Initial	-0.6
		Final	+0.7
		Step Time	0.5

The performance of power system with FACTS devices is presented and checked under different faults. The possible cases for investigation are listed below:

- The power system under single line to ground fault and three phases to ground fault was inserted at load B without using FACTS devices.
- The power system under single line to ground fault and three phases to ground fault was inserted at load B with using STACTOM.
- The power system under single line to ground fault and three phases to ground fault was inserted at load B with using SSSC.
- The power system under single line to ground fault and three phases to ground fault was inserted at load B with using UPFC.

4. Simulation Results

The simulation procedure is prepared using MATLAB/Simulink software package. In this simulation, a short circuit fault with different faults types is injected at t = 0.5 sec. The fault was inserted at load B and, the grid parameters are measured in each case. In this arrangement, the fault current with different FACTS devices was also observed. It is possible to use different FACTS devices in order to reduce the fault current. Different FACTS devices and their effects are discussed below.

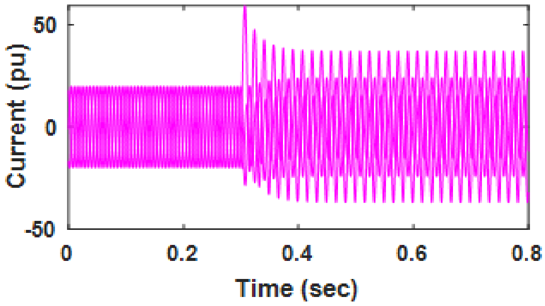
4.1. The Power System under Abnormal Conditions without Using FACTS Devices

4.1.1. Single Line to Ground Fault

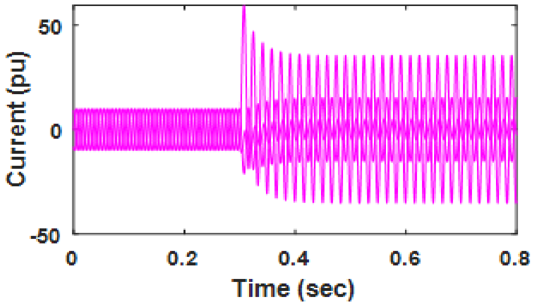
The power system performance without FACTS devices under single line to ground fault inserted at load B is illustrated in Fig. 7 and Fig. 8. They show that the fault current at buses 1, 2, 3, and 4 is highly increased, while, buses voltages are slightly decreases at faulty period. The fault current increased and reaches to the maximum value (59.42 pu) at bus 1 (B1) whereas the peak fault current at buses B2, B3, and B4, respectively would be (59.29, 17.88, 25.26 pu).

4.1.2. Three Line to Ground Fault

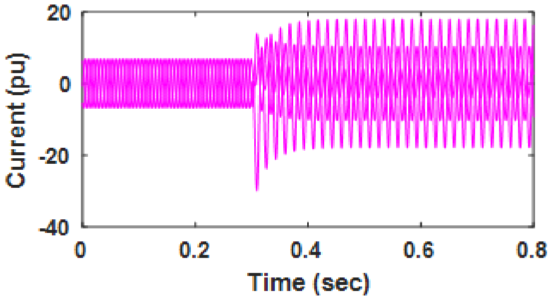
The power system performance without FACTS devices under three line to ground fault inserted at load B is displayed in Fig. 9 and Fig. 10. They show that the fault current at buses 1, 2, 3, and 4 is highly increased, while, buses voltages except if bus 3 is slightly decreased at faulty period. The fault current increased and reaches to the maximum value (84.85 pu) at bus 2 (B2) whereas the peak fault current at buses B1, B3, and B4, respectively would be (79.83, 41.15, 48.05 pu).



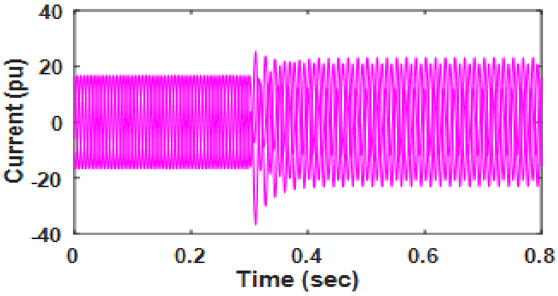
(a) The current wave shape of B1 in p.u



(b) The current wave shape of B2 in p.u

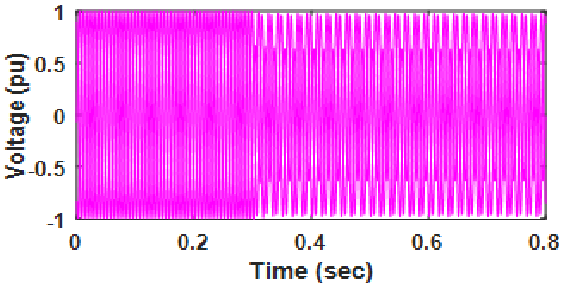


(c) The current wave shape of B3 in p.u

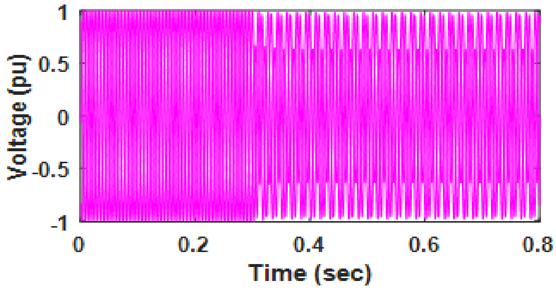


(d) The current wave shape of B4 in p.u

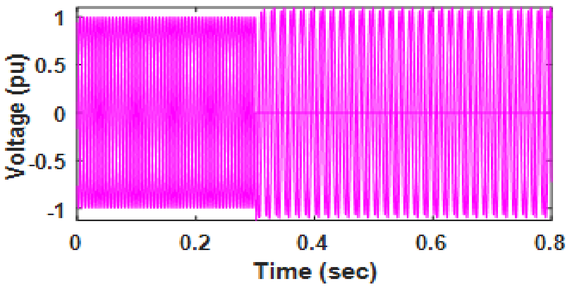
Fig. 7. The current wave shapes of B1, B2, B3 and B4 in pu without FACTS devices for single line to ground fault in load B inserted at t = 0.3 sec



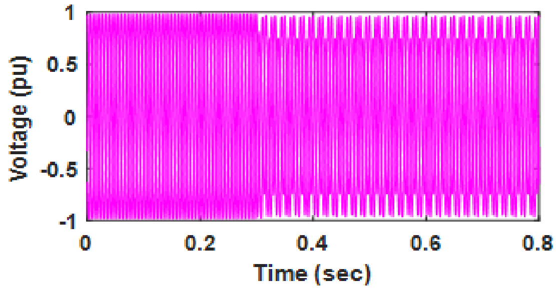
(a) The voltage wave shape of B1 in p.u



(b) The voltage wave shape of B2 in p.u

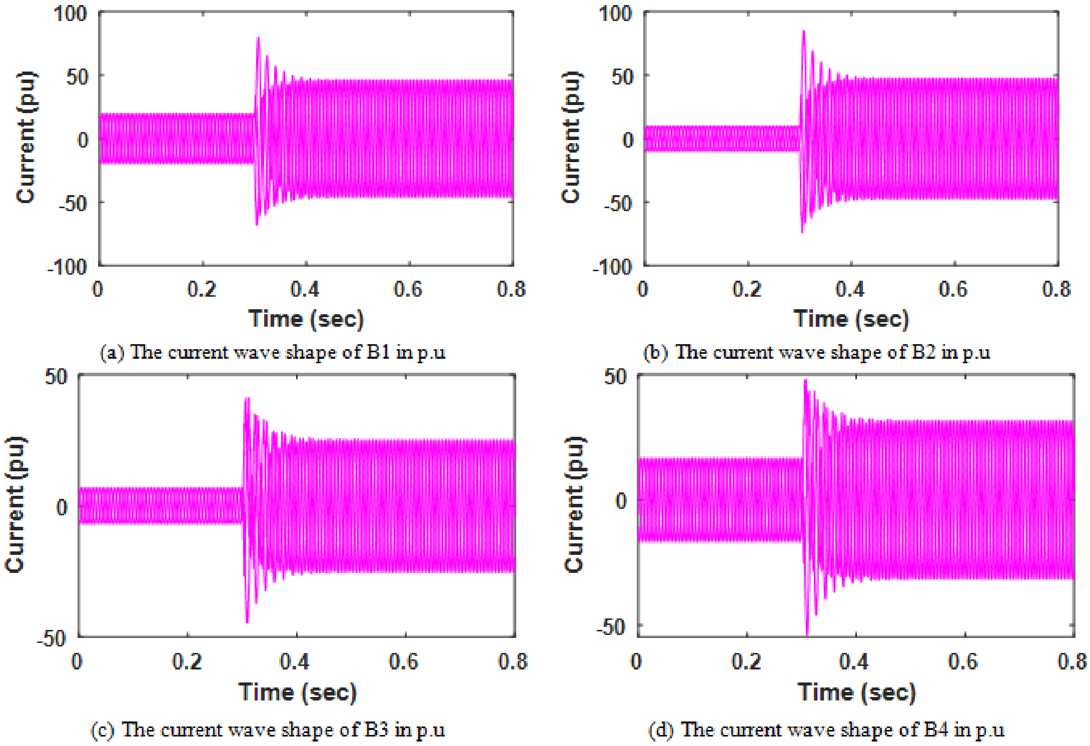


(c) The voltage wave shape of B3 in p.u



(d) The voltage wave shape of B4 in p.u

Fig. 8. The voltage wave shapes of B1, B2, B3 and B4 in pu without FACTS devices for single line to ground fault in load B inserted at t = 0.3 sec



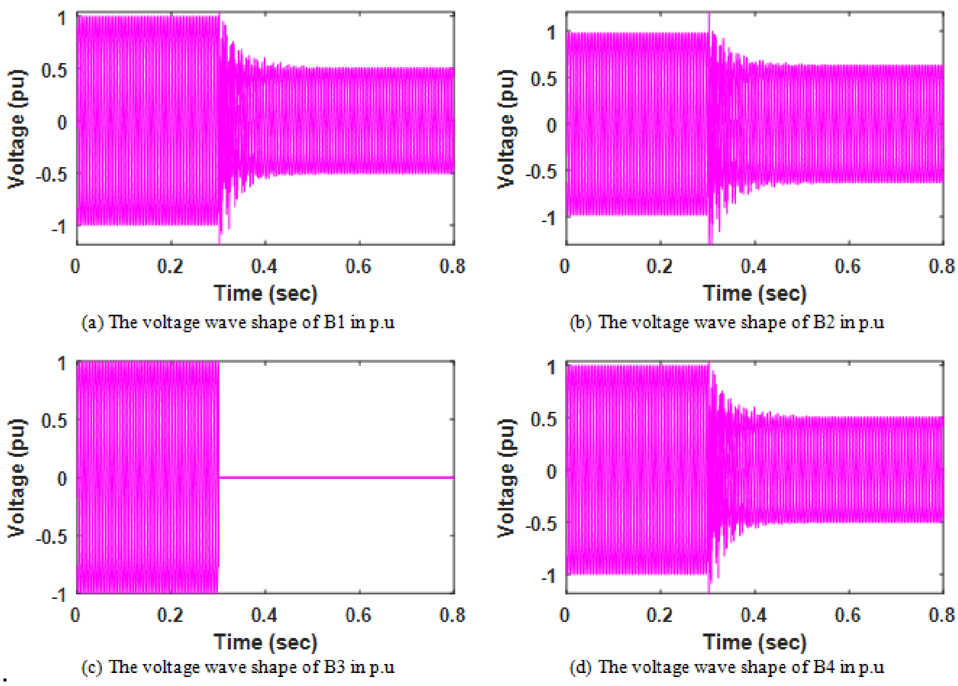
(a) The current wave shape of B1 in p.u

(b) The current wave shape of B2 in p.u

(c) The current wave shape of B3 in p.u

(d) The current wave shape of B4 in p.u

Fig. 9. The current wave shapes of B1, B2, B3 and B4 in pu without FACTS devices for three line to ground fault in load B inserted at t = 0.3 sec



(a) The voltage wave shape of B1 in p.u

(b) The voltage wave shape of B2 in p.u

(c) The voltage wave shape of B3 in p.u

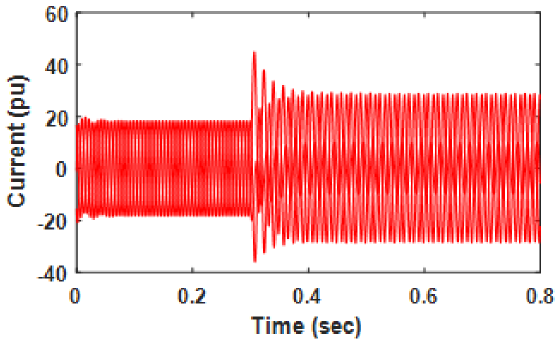
(d) The voltage wave shape of B4 in p.u

Fig. 10. The voltage wave shapes of B1, B2, B3 and B4 in pu without FACTS devices for three line to ground fault in load B inserted at t = 0.3 sec

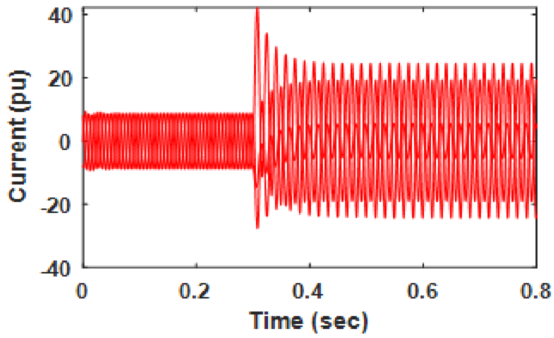
4.2. The Power System under Abnormal Conditions with Using STATCOM

4.2.1. Single Line to Ground Fault

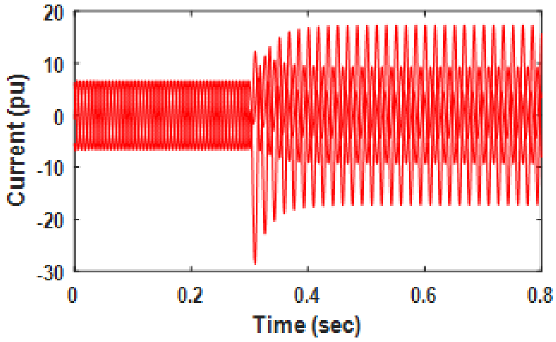
The power system performance with using STATCOM under single line to ground fault inserted at load B is illustrated in Fig. 11 and Fig. 12. They show that the fault current at buses 1, 2, 3, and 4 is highly increased, while, buses voltages are slightly decreases at faulty period. The fault current increased and reaches to the maximum value (44.69 pu) at bus 1 (B1) whereas the peak fault current at buses B2, B3, and B4, respectively would be (42.17, 17.2, 23.69 pu).



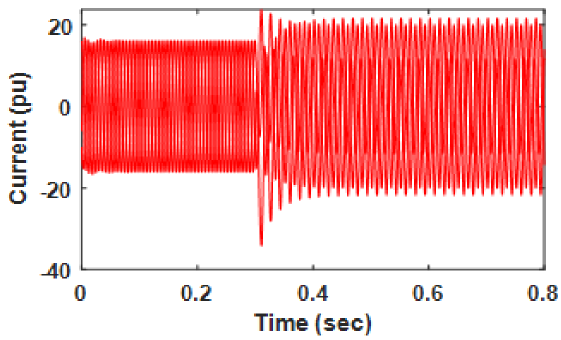
(a) The current wave shape of B1 in p.u



(b) The current wave shape of B2 in p.u

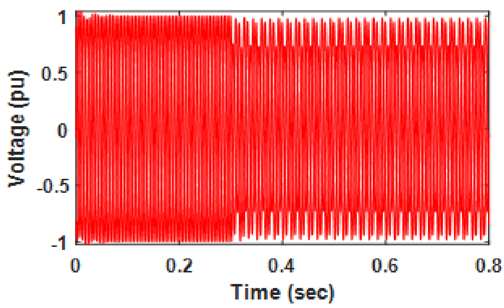


(c) The current wave shape of B3 in p.u

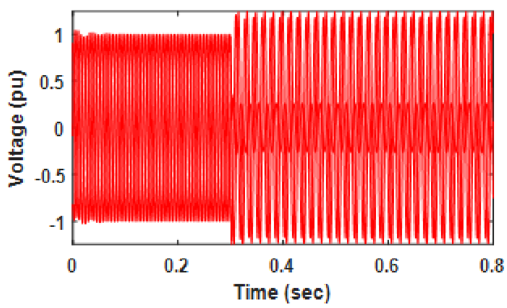


(d) The current wave shape of B4 in p.u

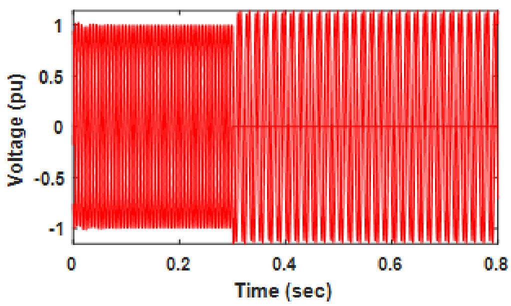
Fig. 11. The current wave shapes of B1, B2, B3 and B4 in pu using STATCOM for single line to ground fault in load B inserted at t = 0.3 sec



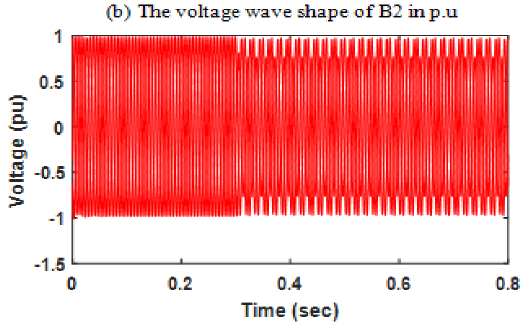
(a) The voltage wave shape of B1 in p.u



(b) The voltage wave shape of B2 in p.u



(c) The voltage wave shape of B3 in p.u



(d) The voltage wave shape of B4 in p.u

Fig. 12. The voltage wave shapes of B1, B2, B3 and B4 in pu using STATCOM for single line to ground fault in load B inserted at t = 0.3 sec

Fig. 13 to Fig. 16 show the comparison between the current wave shape of buses B1, B2, B3, and B4 in pu without FACTS and using STATCOM for single line to ground fault in load B at t = 0.3 sec. These figures demonstrated that better performance of power system under single phase fault is achieved using STATCOM as it is able to reduce fault current of the system as the peak fault current at bus B1 is decreased from 59.42 pu to 44.69 pu using STATCOM. Similarly, the fault current levels at other buses are also decreased with using STATCOM.

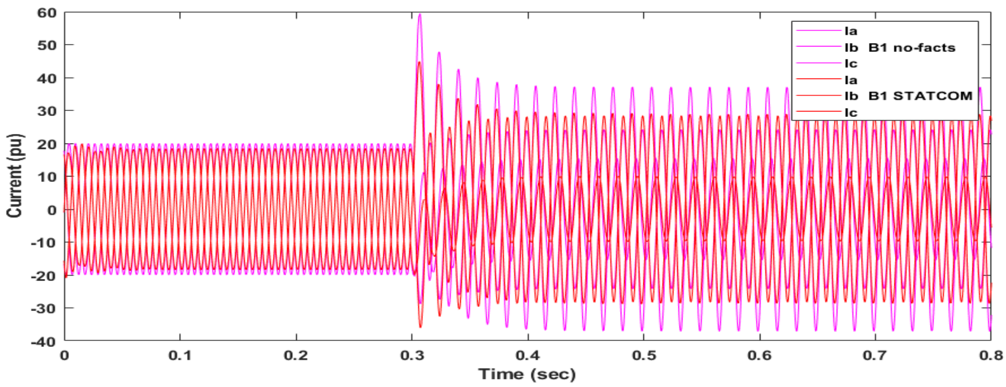


Fig. 13. Comparison between the current wave shape of B1 in pu without FACTS and using STATCOM for single line to ground fault in load B inserted at t = 0.3 sec

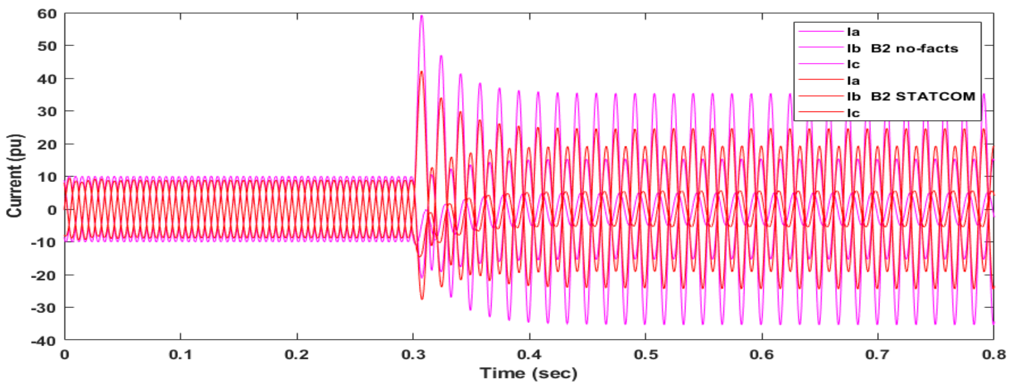


Fig. 14. Comparison between the current wave shape of B2 in pu without FACTS and using STATCOM for single line to ground fault in load B inserted at t = 0.3 sec

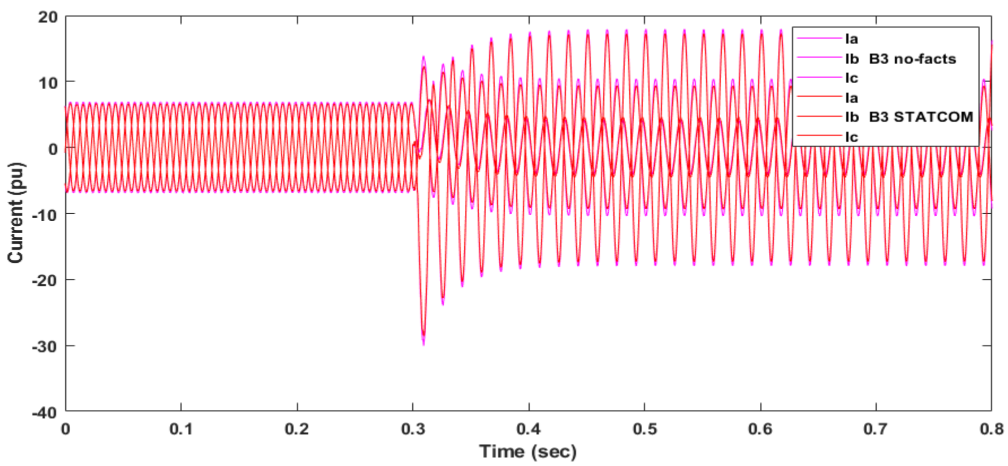


Fig. 15. Comparison between the current wave shape of B3 in pu without FACTS and using STATCOM for single line to ground fault in load B inserted at t = 0.3 sec

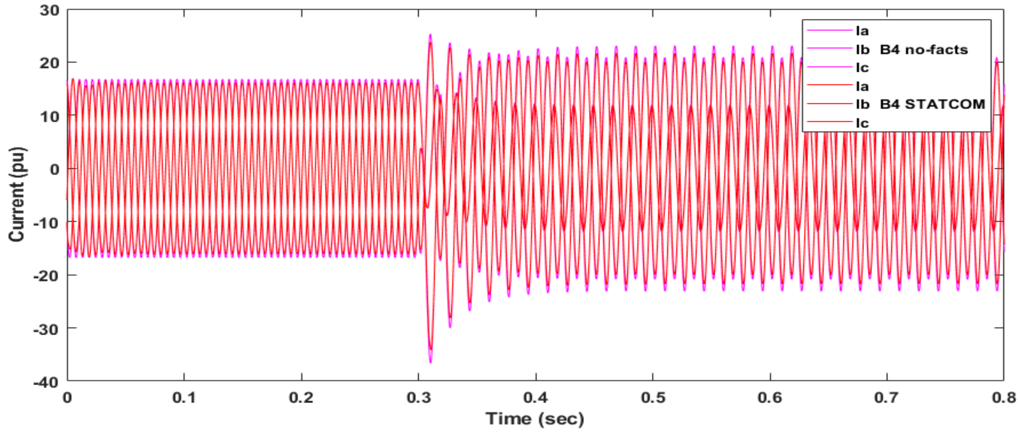


Fig. 16. Comparison between the current wave shape of B4 in pu without FACTS and using STATCOM for single line to ground fault in load B inserted at t = 0.3 sec

4.2.2. Three Line to Ground Fault

The power system performance with STATCOM under three line to ground fault inserted at load B is displayed in Fig. 17 and Fig. 18. They show that the fault current at buses 1, 2, 3, and 4 is highly increased, while, buses voltages except if bus 3 is slightly decreased at faulty period. The fault current increased and reaches to the maximum value (80.13 pu) at bus 2 (B2) whereas the peak fault current at buses B1, B3, and B4, respectively would be (75.23, 40.87, 46.01 pu).

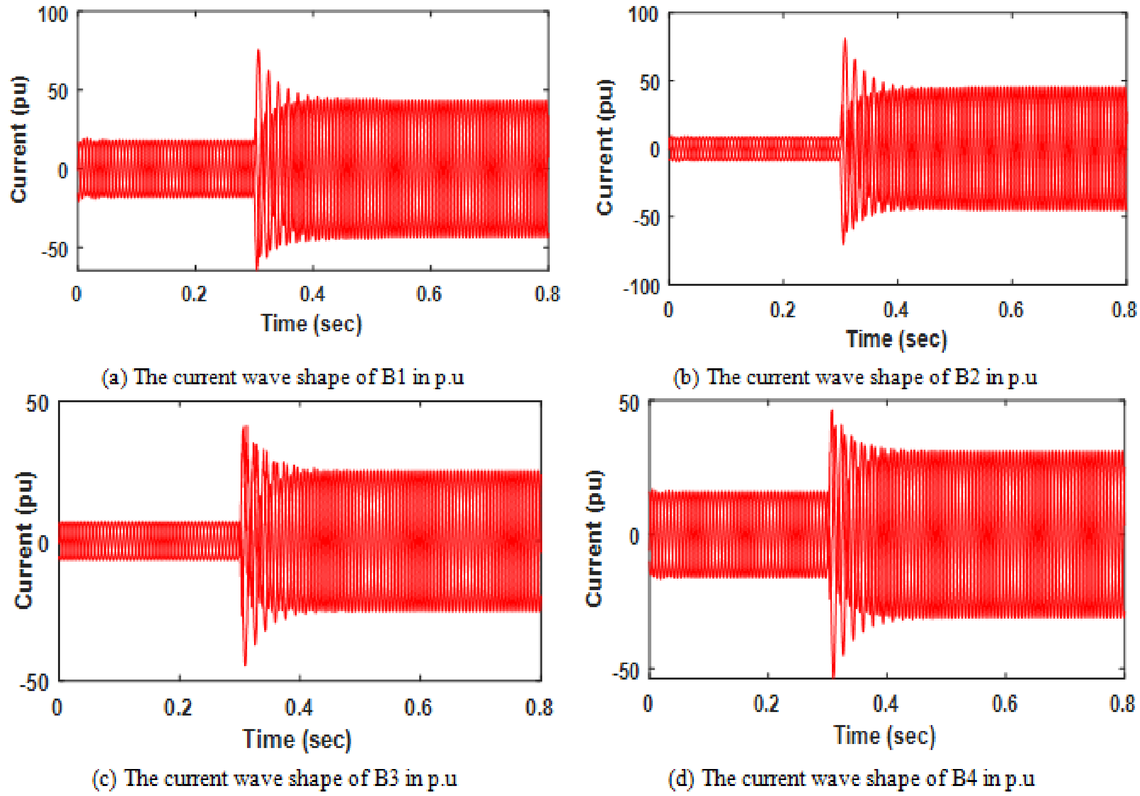
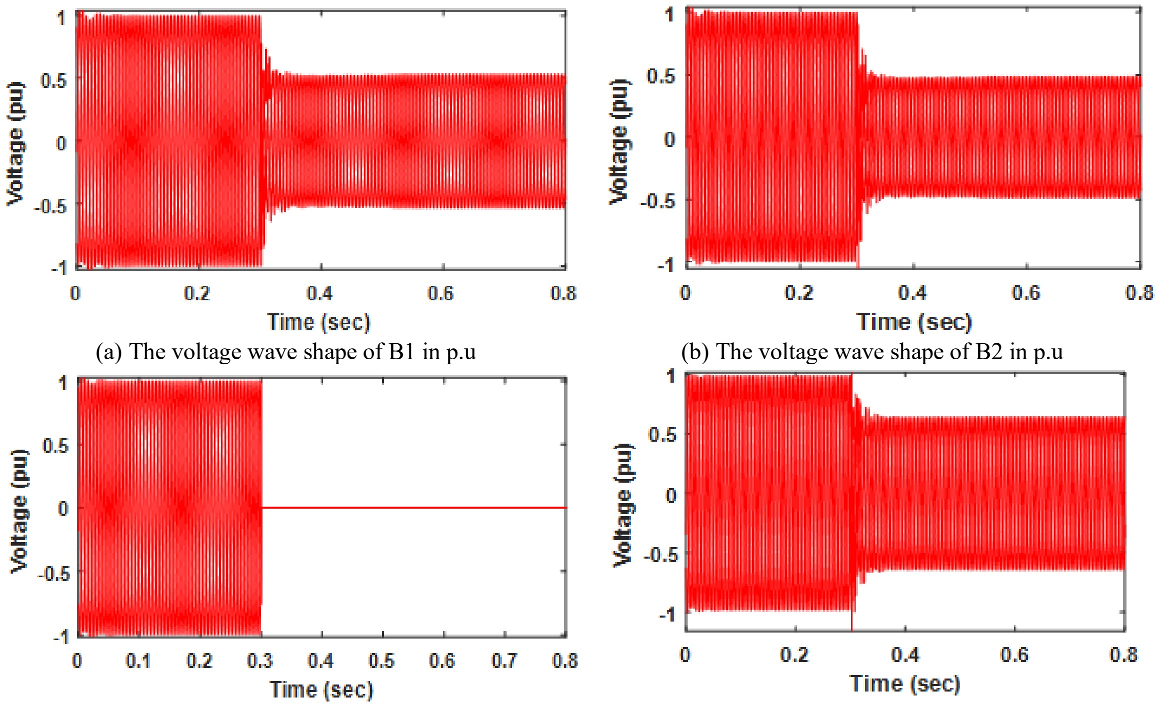


Fig. 17. The current wave shapes of B1, B2, B3 and B4 in pu using STATCOM for three line to ground fault in load B inserted at t = 0.3 sec



(a) The voltage wave shape of B1 in p.u (b) The voltage wave shape of B2 in p.u

(c) The voltage wave shape of B3 in p.u (d) The voltage wave shape of B4 in p.u

Fig. 18. The voltage wave shapes of B1, B2, B3 and B4 in pu using STATCOM for three line to ground fault in load B inserted at t = 0.3 sec

Fig. 19 to Fig. 22 display the comparison between the current wave shape of buses B1, B2, B3, and B4 in pu without FACTS and using STATCOM for three line to ground fault in load B at t = 0.3 sec. These figures revealed that STATCOM gives better performance for the power system under three phase faults as it is able to reduce fault current of the system as the peak fault current at bus B1 is decreased from 79.83 pu to 75.32 pu using STATCOM. Similarly, the fault current levels at other buses are also decreased with using STATCOM.

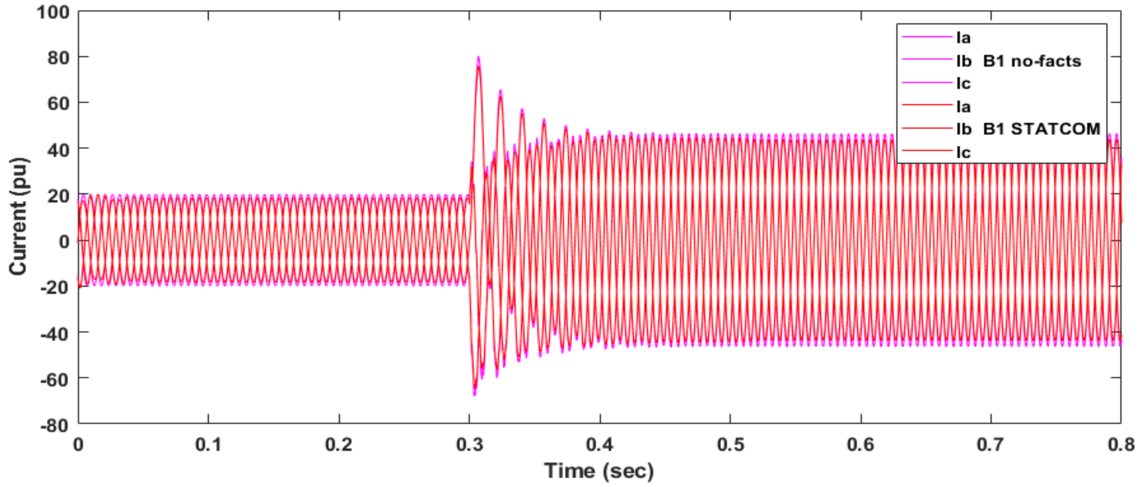


Fig. 19. Comparison between the current wave shape of B1 in pu without FACTS and using STATCOM for three line to ground fault in load B inserted at t = 0.3 sec

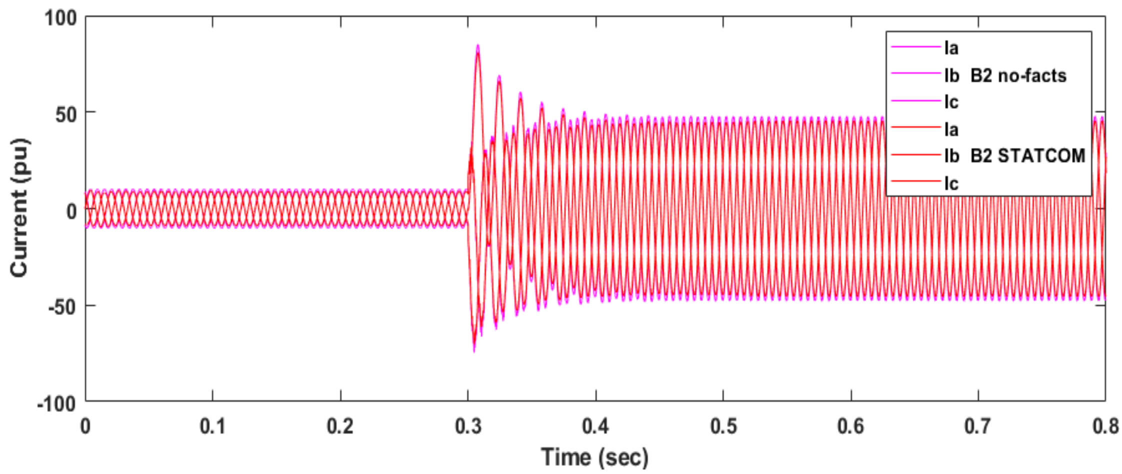


Fig. 20. Comparison between the current wave shape of B2 in pu without FACTS and using STATCOM for three line to ground fault in load B inserted at t = 0.3 sec

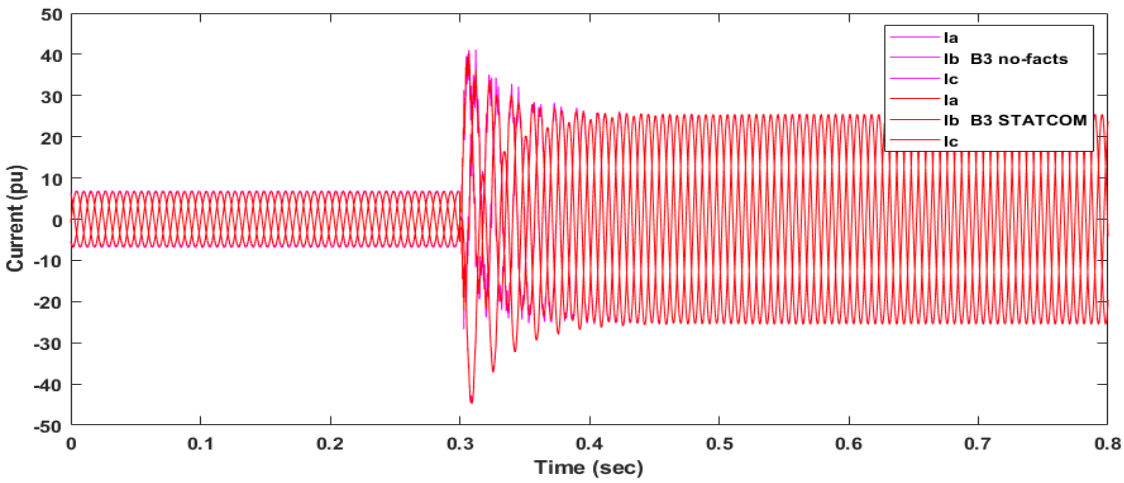


Fig. 21. Comparison between the current wave shape of B3 in pu without FACTS and using STATCOM for three line to ground fault in load B inserted at t = 0.3 sec

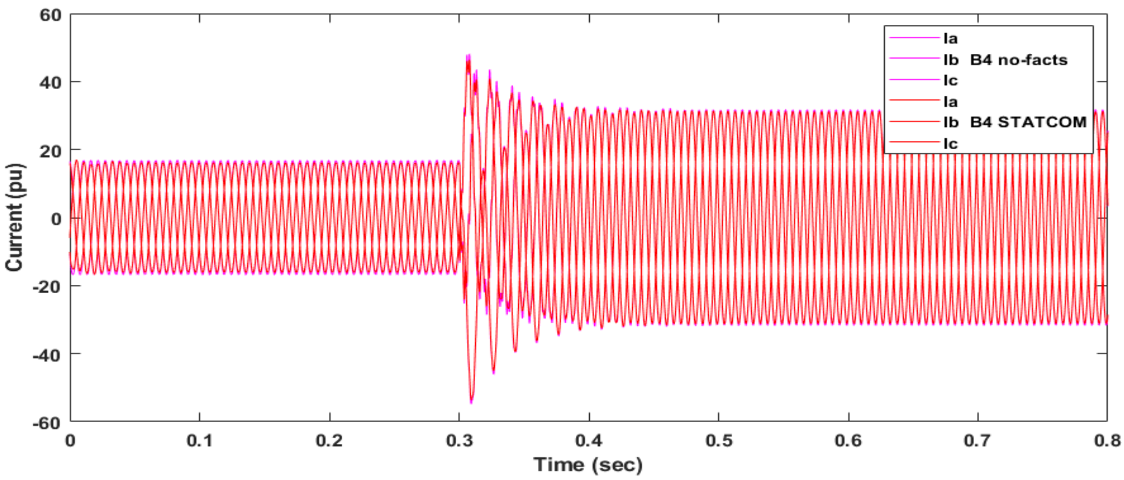
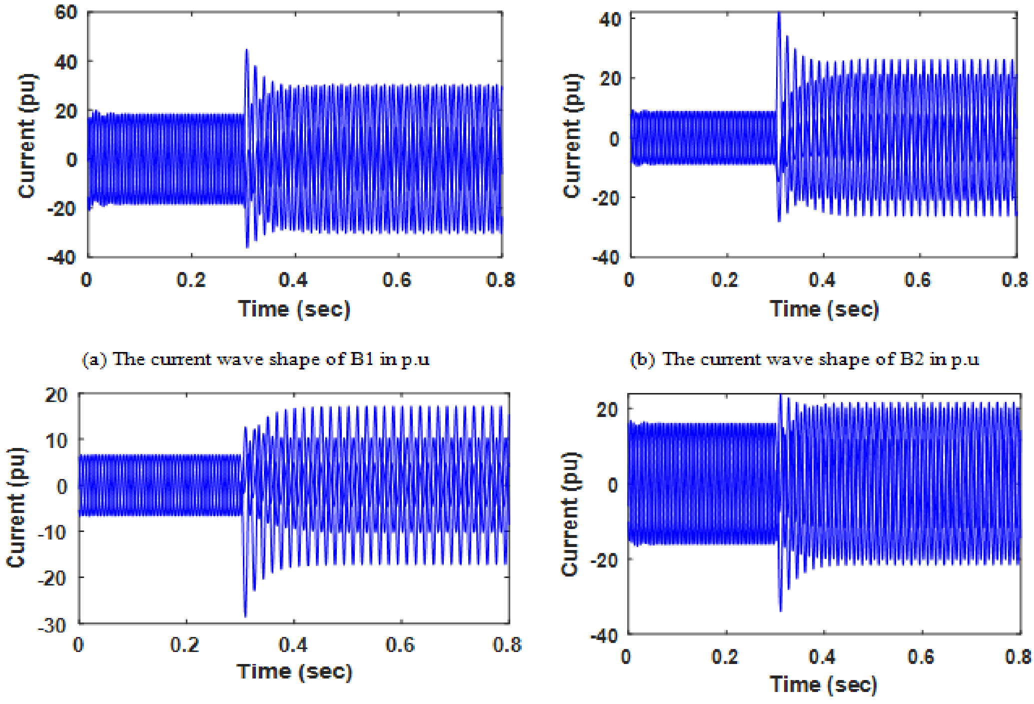


Fig. 22. Comparison between the current wave shape of B4 in pu without FACTS and using STATCOM for three line to ground fault in load B inserted at t = 0.3 sec

4.3. The Power System under Abnormal Conditions with Using SSSC

4.3.1. Single Line to Ground Fault

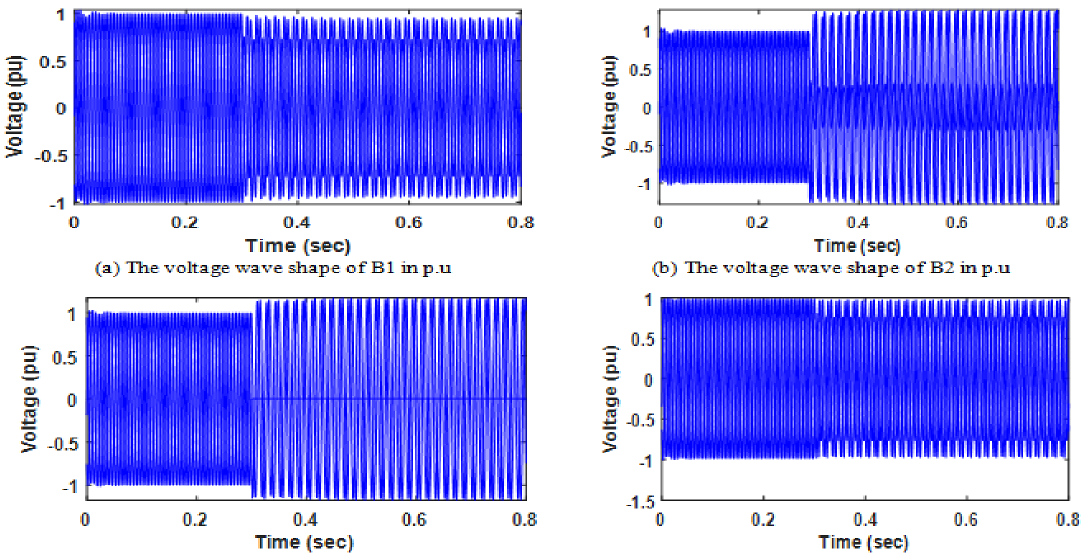
The power system performance with SSSC under single line to ground fault inserted at load B is illustrated in Fig. 23 and Fig. 24. They show that the fault current at buses 1, 2, 3, and 4 is highly increased, while, buses voltages are slightly decreases at faulty period. The fault current increased and reaches to the maximum value (44.96 pu) at bus 1 (B1) whereas the peak fault current at buses B2, B3 and B4, respectively would be (42.17, 17.15, 23.8 pu).



(a) The current wave shape of B1 in p.u (b) The current wave shape of B2 in p.u

(c) The current wave shape of B3 in p.u (d) The current wave shape of B4 in p.u

Fig. 23. The current wave shapes of B1, B2, B3 and B4 in pu using SSSC for single line to ground fault in load B inserted at t = 0.3 sec



(a) The voltage wave shape of B1 in p.u (b) The voltage wave shape of B2 in p.u

(c) The voltage wave shape of B3 in p.u (d) The voltage wave shape of B4 in p.u

Fig. 24. The voltage wave shapes of B1, B2, B3 and B4 in pu using SSSC for single line to ground fault in load B inserted at t = 0.3 sec

Fig. 25 to Fig. 28 display the comparison between the current wave shape of buses B1, B2, B3, and B4 in pu without FACTS and using SSSC for single line to ground fault in load B at t = 0.3 sec. These figures revealed that SSSC gives better performance for the power system under single phase faults as it is able to reduce fault current of the system as the peak fault current at bus B1 is decreased from 59.42 pu to 44.8 pu using SSSC. Similarly, the fault current levels at other buses are also decreased with using SSSC.

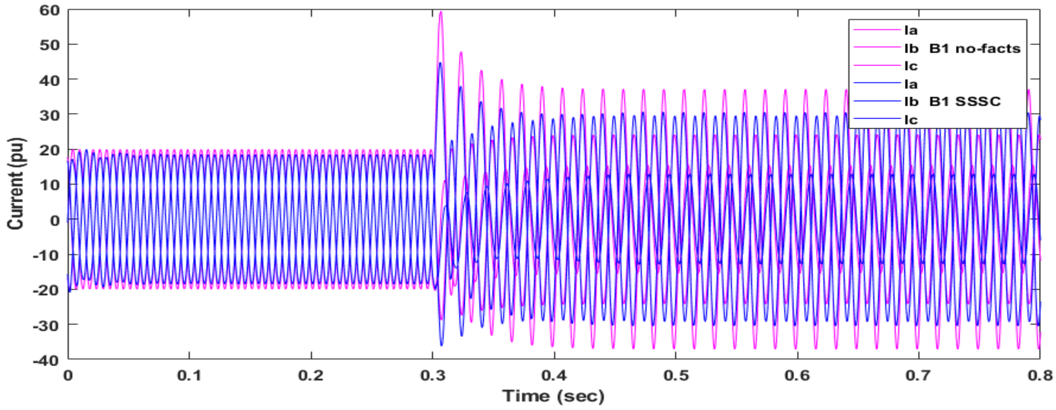


Fig. 25. Comparison between the current wave shape of B1 in pu without FACTS and using SSSC for single line to ground fault in load B inserted at t = 0.3 sec

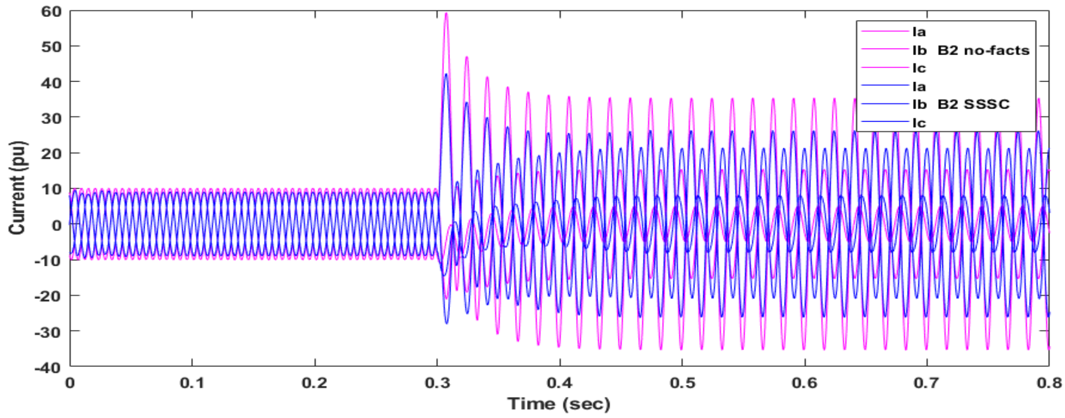


Fig. 26. Comparison between the current wave shape of B2 in pu without FACTS and using SSSC for single line to ground fault in load B inserted at t = 0.3 sec

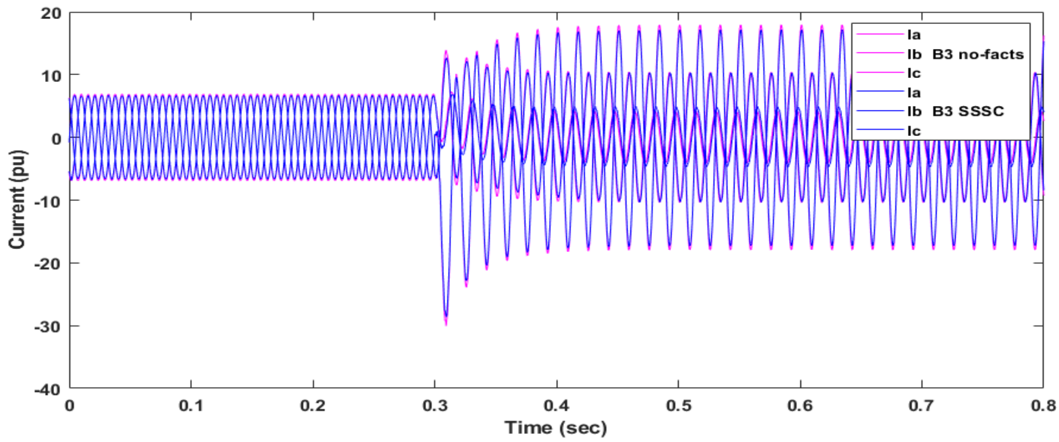


Fig. 27. Comparison between the current wave shape of B3 in pu without FACTS and using SSSC for single line to ground fault in load B inserted at t = 0.3 sec

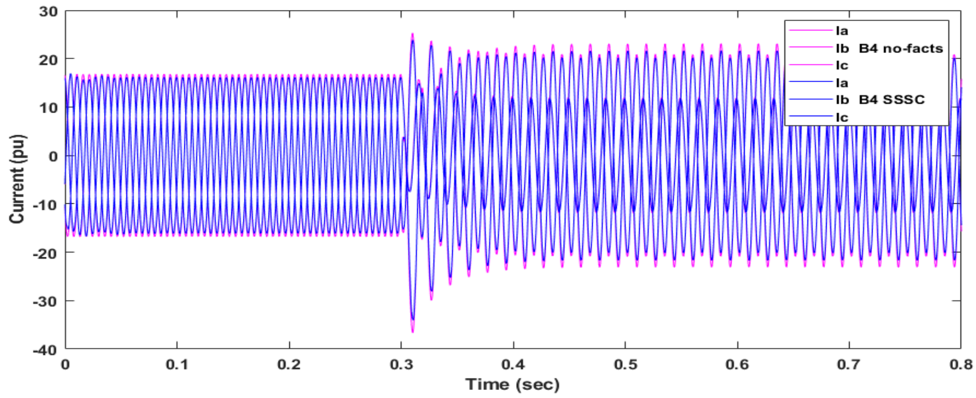


Fig. 28. Comparison between the current wave shape of B4 in pu without FACTS and using SSSC for single line to ground fault in load B inserted at t = 0.3 sec

4.3.2. Three Line to Ground Fault

The power system performance with SSSC under three line to ground fault inserted at load B is displayed in Fig. 29 and Fig. 30. They show that the fault current at buses 1, 2, 3, and 4 is highly increased, while, buses voltages except if bus 3 is slightly decreased at faulty period. The fault current increased and reaches to the maximum value (80.67 pu) at bus 2 (B2) whereas the peak fault current at buses B1, B3 and B4, respectively would be (75.58, 40.05, 46.21 pu).

Fig. 31 to Fig. 34 display the comparison between the current wave shape of buses B1, B2, B3, and B4 in pu without FACTS and using SSSC for three line to ground fault in load B at t = 0.3 sec. These figures illustrated that SSSC gives better performance for the power system under three phase faults as it is able to reduce fault current of the system as the peak fault current at bus B1 is decreased from 79.83 pu to 75.58 pu using SSSC. Similarly, the fault current levels at other buses are also decreased with using SSSC.

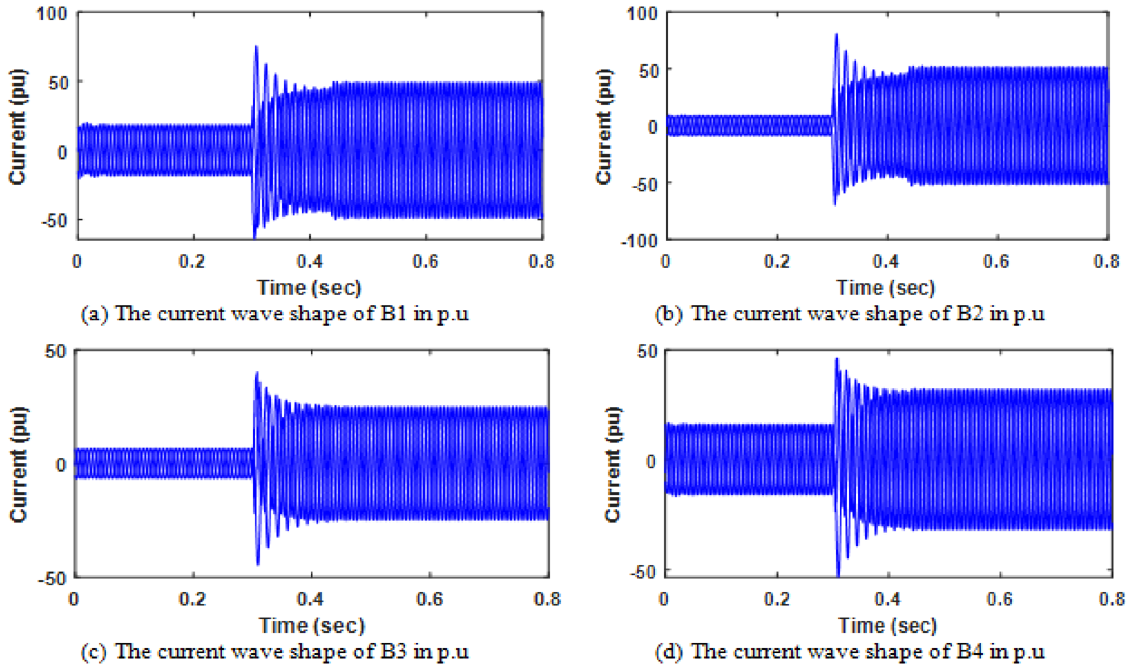


Fig. 29. The current wave shapes of B1, B2, B3 and B4 in pu using SSSC for three line to ground fault in load B inserted at t = 0.3 sec

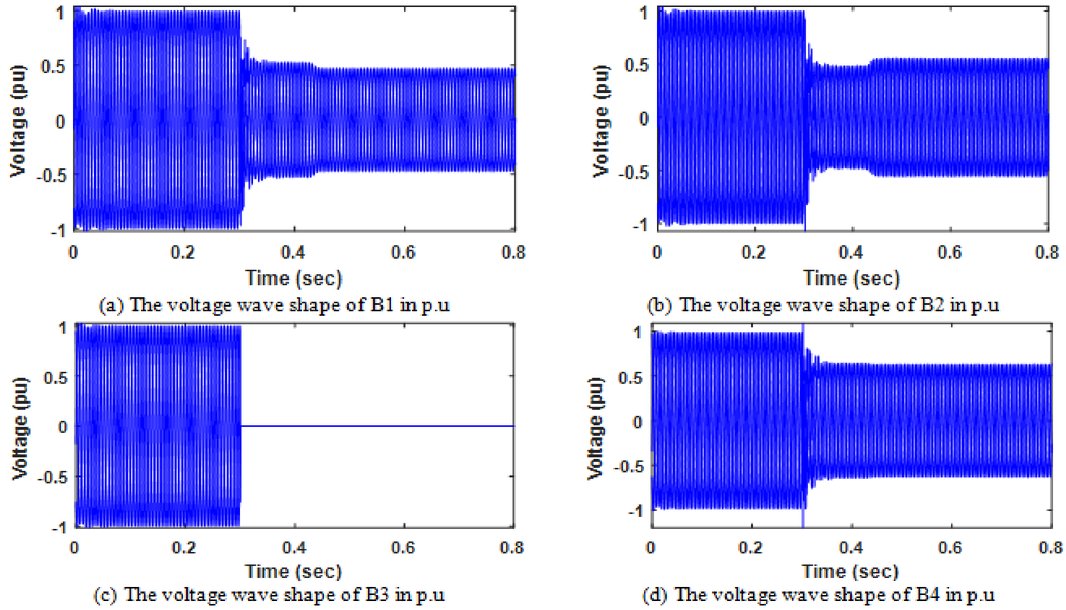


Fig. 30. The voltage wave shapes of B1, B2, B3 and B4 in pu using SSSC for three line to ground fault in load B inserted at t = 0.3 sec

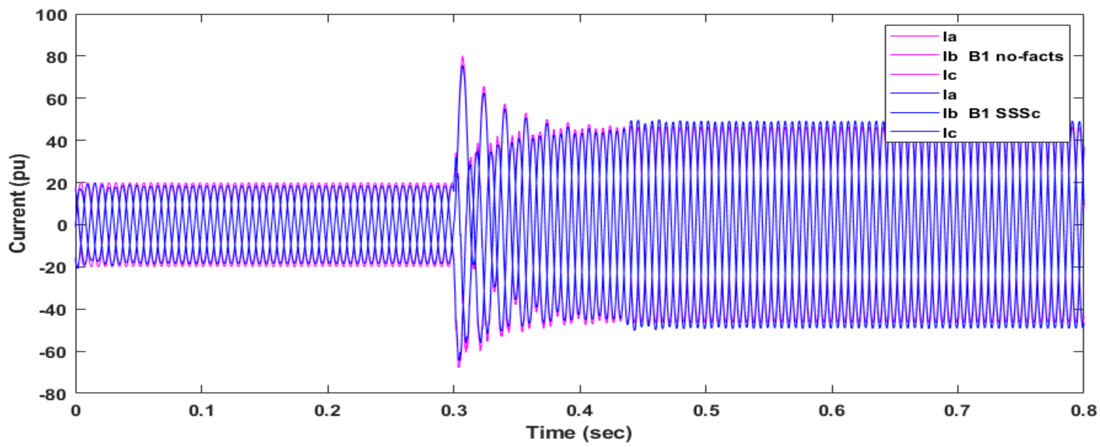


Fig. 31. Comparison between the current wave shape of B1 in pu without FACTS and using SSSC for three line to ground fault in load B inserted at t = 0.3 sec

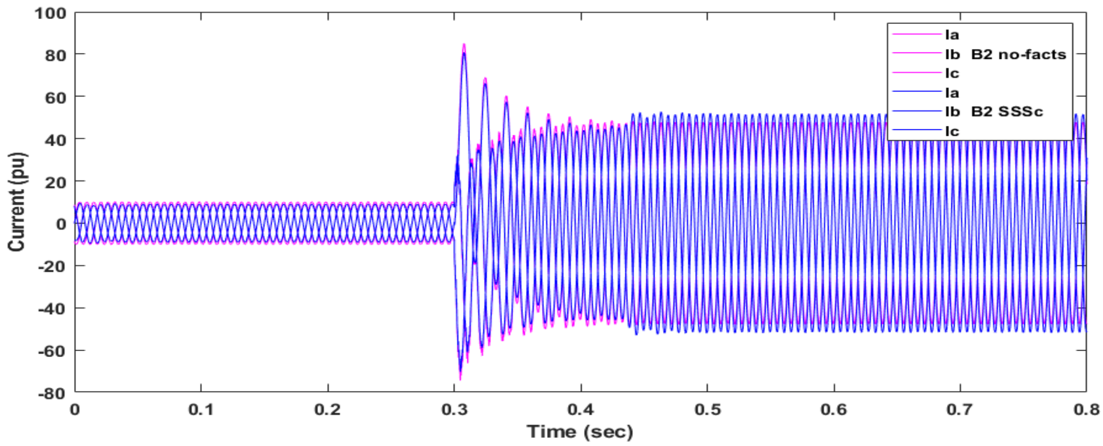


Fig. 32. Comparison between the current wave shape of B2 in pu without FACTS and using SSSC for three line to ground fault in load B inserted at t = 0.3 sec

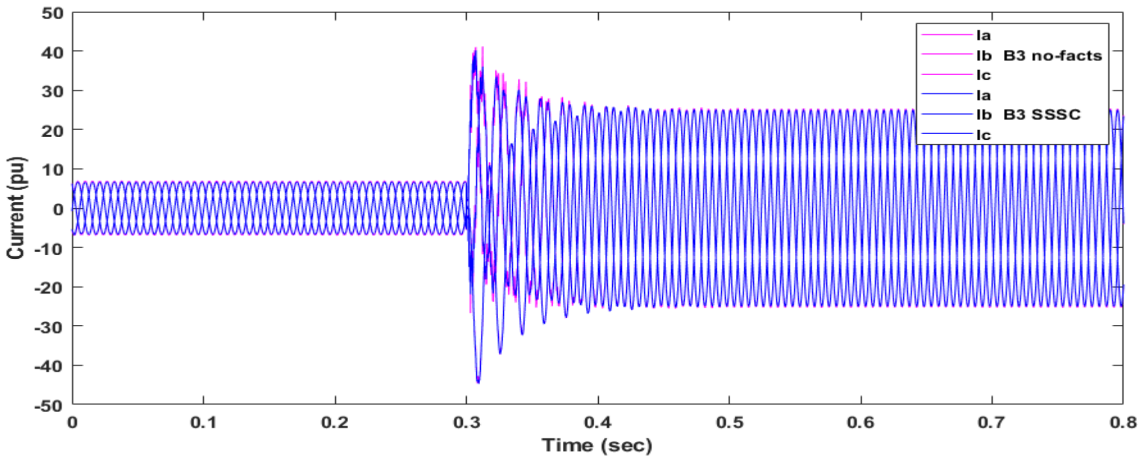


Fig. 33. Comparison between the current wave shape of B3 in pu without FACTS and using SSSC for three line to ground fault in load B inserted at t = 0.3 sec

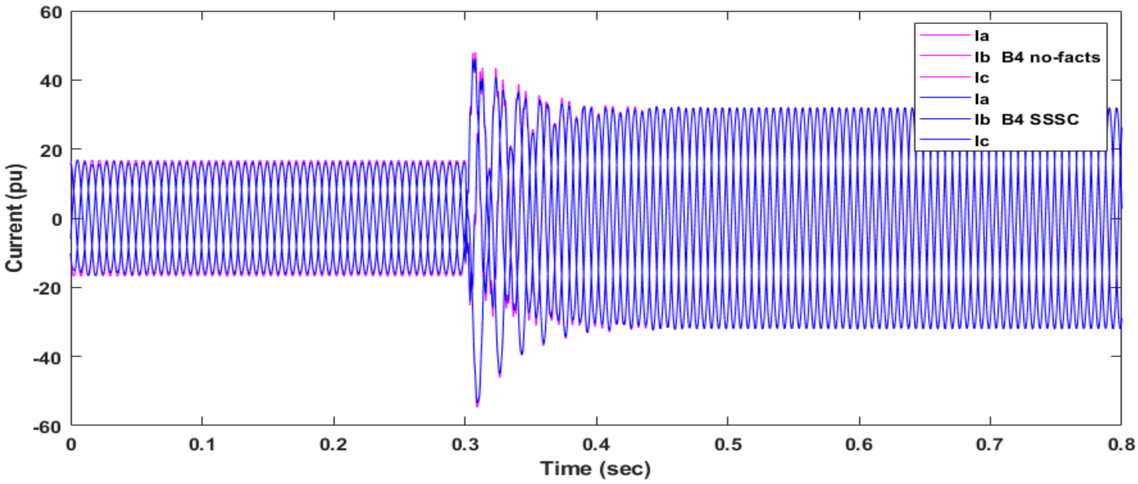


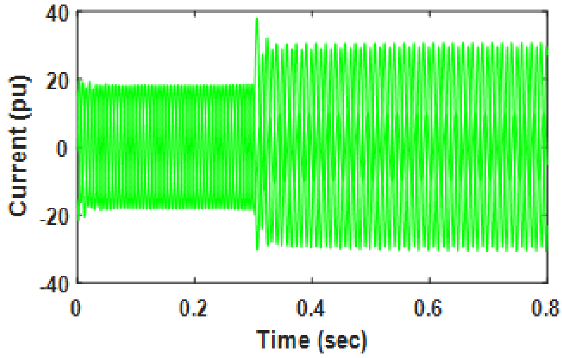
Fig. 34. Comparison between the current wave shape of B4 in pu without FACTS and using SSSC for three line to ground fault in load B inserted at t = 0.3 sec

4.4. The Power System under Abnormal Conditions with Using UPFC

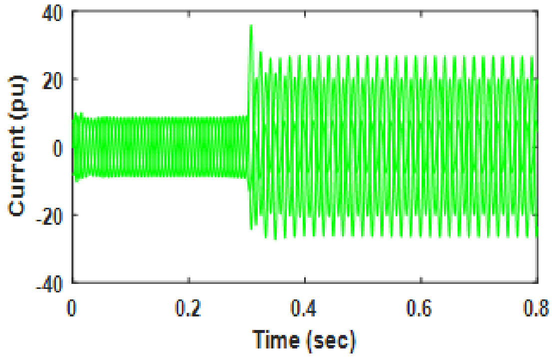
4.4.1. Single Line to Ground Fault

The power system performance with UPFC under single line to ground fault inserted at load B is illustrated in Fig. 35 and Fig. 36. They show that the fault current at buses 1, 2, 3, and 4 is highly increased, while, buses voltages are slightly decreases at faulty period. The fault current increased and reaches to the maximum value (37.49 pu) at bus 1 (B1) whereas the peak fault current at buses B2, B3 and B4, respectively would be (35.89, 17.42, 23.69 pu). Moreover, The bus voltage (B1) is increased from (0.63 pu) without FACTS devices to (0.74 pu) using UPFC.

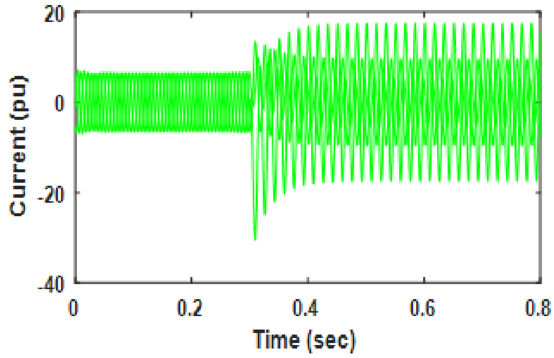
Fig. 37 to Fig. 40 display the comparison between the current wave shape of buses B1, B2, B3, and B4 in pu without FACTS and using UPFC for three line to ground fault in load B at t = 0.3 sec. These figures illustrated that UPFC gives better performance for the power system under three phase faults as it is able to reduce fault current of the system as the peak fault current at bus B1 is decreased from 59.42 pu to 37.94 pu using UPFC. Similarly, the fault current levels at other buses are also decreased with using UPFC.



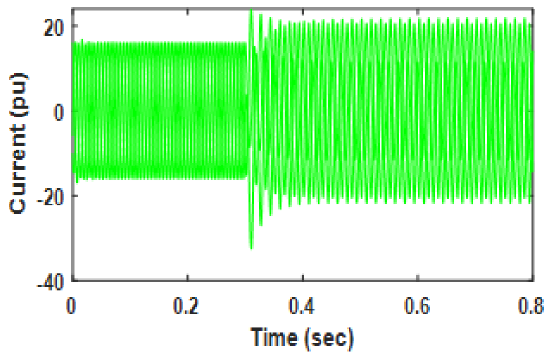
(a) The current wave shape of B1 in p.u



(b) The current wave shape of B2 in p.u

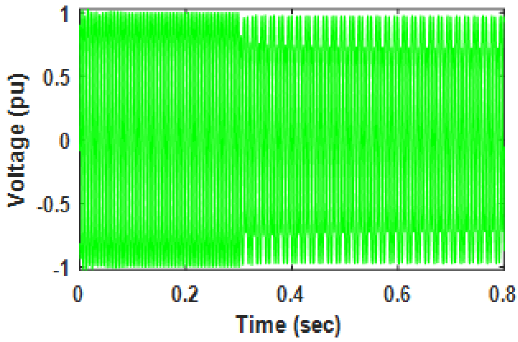


(c) The current wave shape of B3 in p.u

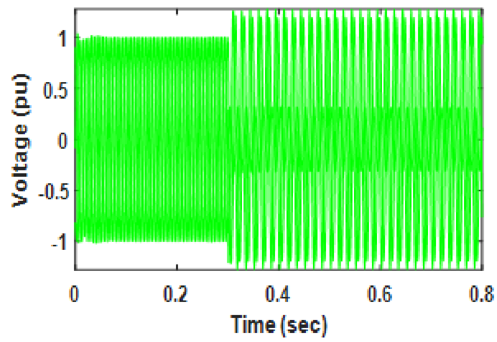


(d) The current wave shape of B4 in p.u

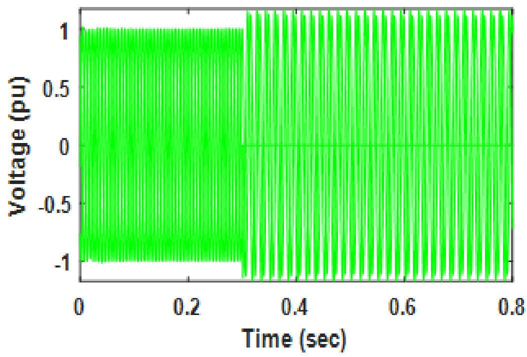
Fig. 35. The current wave shapes of B1, B2, B3 and B4 in pu using UPFC for single line to ground fault in load B inserted at t = 0.3 sec



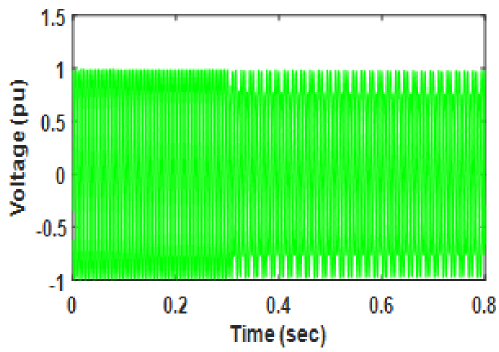
(a) The voltage wave shape of B1 in p.u



(b) The voltage wave shape of B2 in p.u



(c) The voltage wave shape of B3 in p.u



(d) The voltage wave shape of B4 in p.u

Fig. 36. The voltage wave shapes of B1, B2, B3 and B4 in pu using UPFC for single line to ground fault in load B inserted at t = 0.3 sec

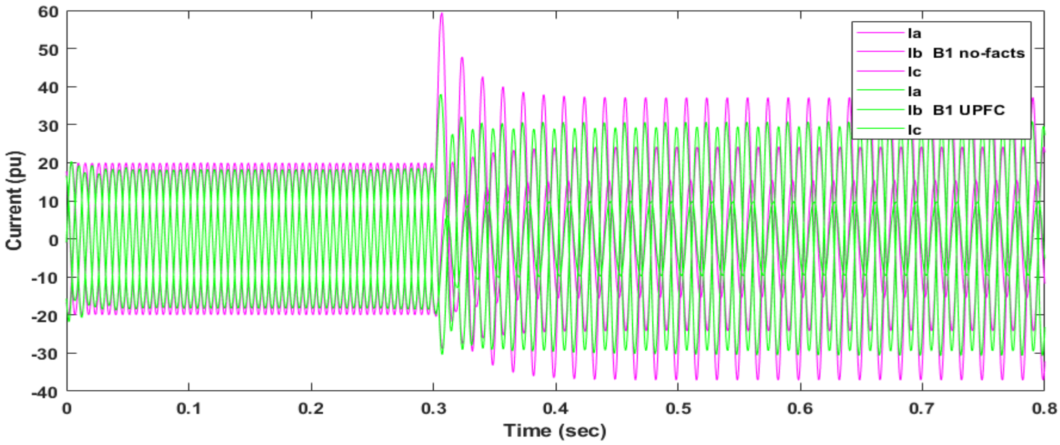


Fig. 37. Comparison between the current wave shape of B1 in pu without FACTS and using UPFC for single line to ground fault in load B inserted at t = 0.3 sec

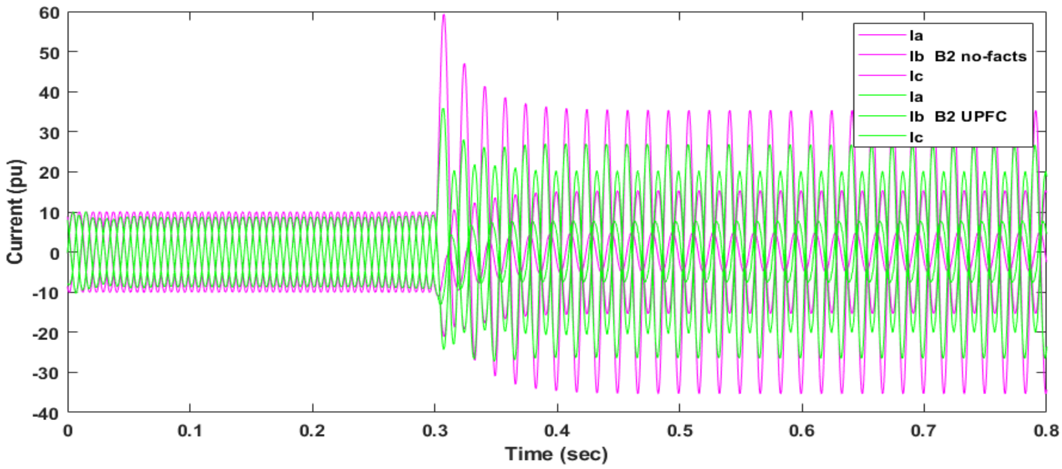


Fig. 38. Comparison between the current wave shape of B2 in pu without FACTS and using UPFC for single line to ground fault in load B inserted at t = 0.3 sec

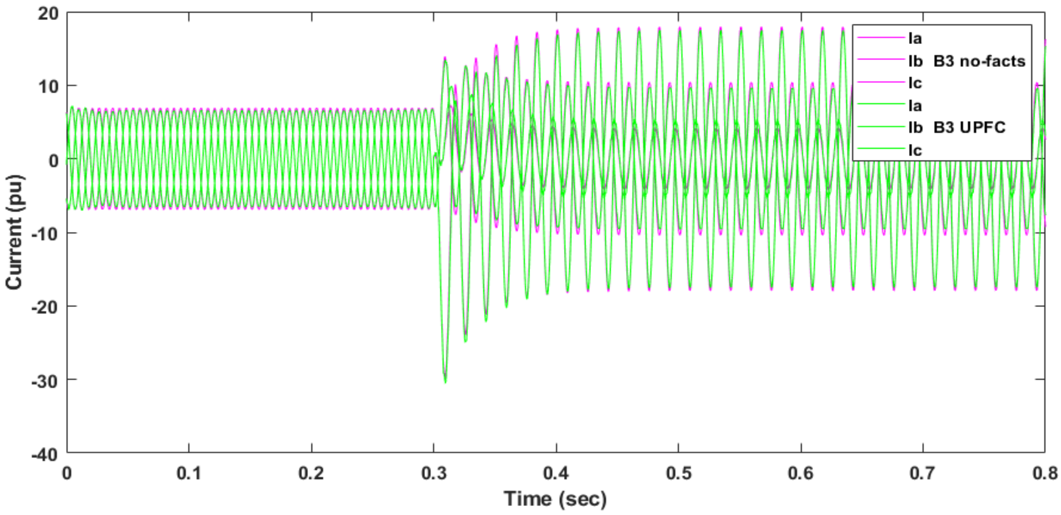


Fig. 39. Comparison between the current wave shape of B3 in pu without FACTS and using UPFC for single line to ground fault in load B inserted at t = 0.3 sec

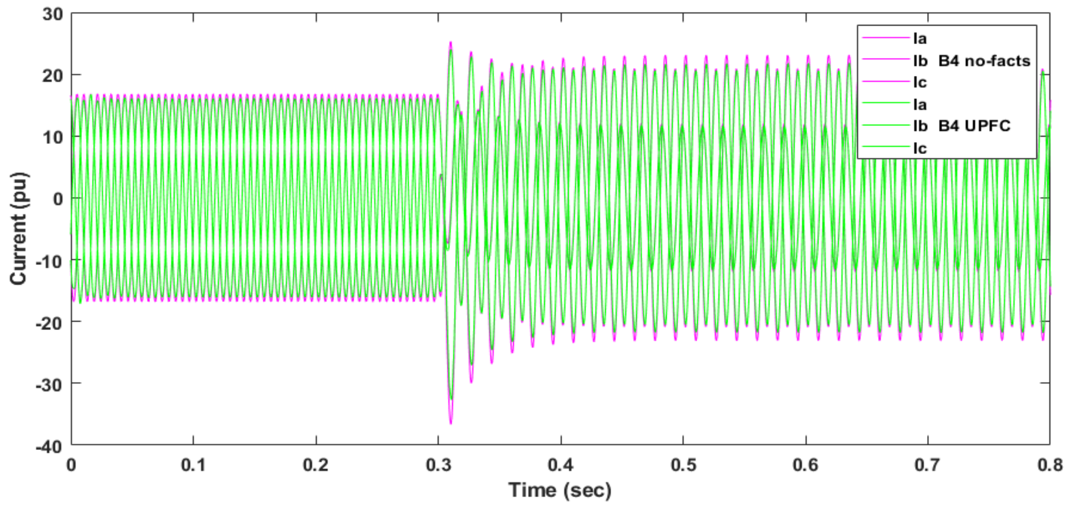


Fig. 40. Comparison between the current wave shape of B4 in pu without FACTS and using UPFC for single line to ground fault in load B inserted at t = 0.3 sec

4.4.2. Three Line to Ground Fault

The power system performance with UPFC under three line to ground fault inserted at load B is displayed in Fig. 41 and Fig. 42. They show that the fault current at buses 1, 2, 3, and 4 is highly increased, while, buses voltages except if bus 3 is slightly decreased at faulty period. The fault current increased and reaches to the maximum value (71.63 pu) at bus 2 (B2) whereas the peak fault current at buses B1, B3 and B4, respectively would be (63.21, 41.31, 43.5 pu).

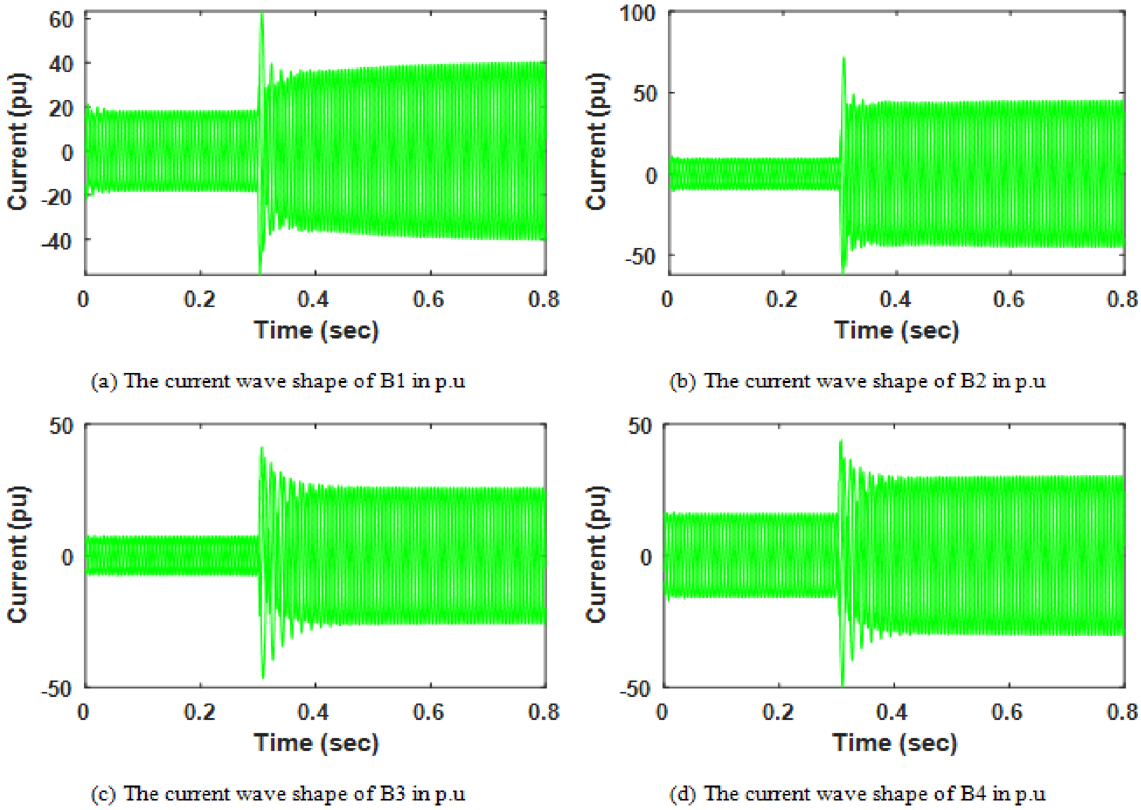


Fig. 41. The current wave shapes of B1, B2, B3 and B4 in pu using UPFC for three line to ground fault in load B inserted at t = 0.3 sec

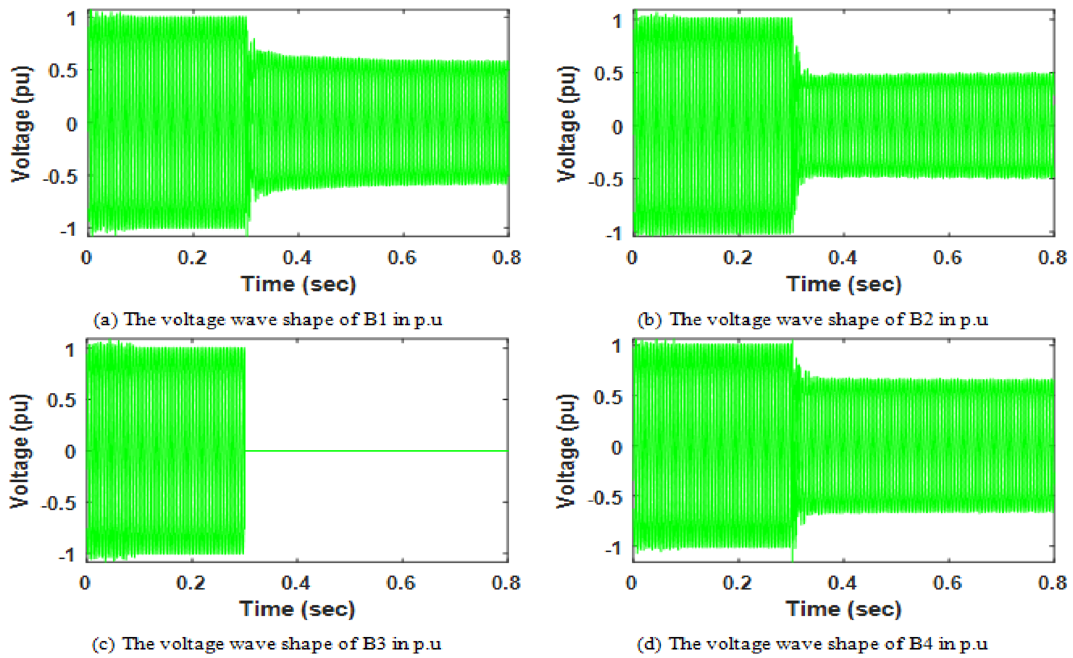


Fig. 42. The voltage wave shapes of B1, B2, B3 and B4 in pu using UPFC for three line to ground fault in load B inserted at t = 0.3 sec

Fig. 43 to Fig. 46 display the comparison between the current wave shape of buses B1, B2, B3, and B4 in pu without FACTS and using UPFC for three line to ground fault in load B at t = 0.3 sec. These figures demonstrated that UPFC gives better performance for the power system under three phase faults as it is able to reduce fault current of the system as the peak fault current at bus B1 is decreased from 79.83 pu to 63.21 pu using UPFC. Similarly, the fault current levels at other buses are also decreased with using UPFC. Furthermore, the bus voltage (B1) is increased from (0.50 pu) without FACTS devices to (0.60 pu) using UPFC.

Fig. 47 to Fig. 50 display the comparison between the current wave shape of buses B1, B2, B3, and B4 in pu without FACTS, with STATCOM, with SSSC and with UPFC for single line to ground fault in load B inserted at t = 0.3 sec. These figures demonstrated that STATCOM gives better performance for the power system under three phase faults than SSSC and UPFC gives the best performance for reducing the fault current.

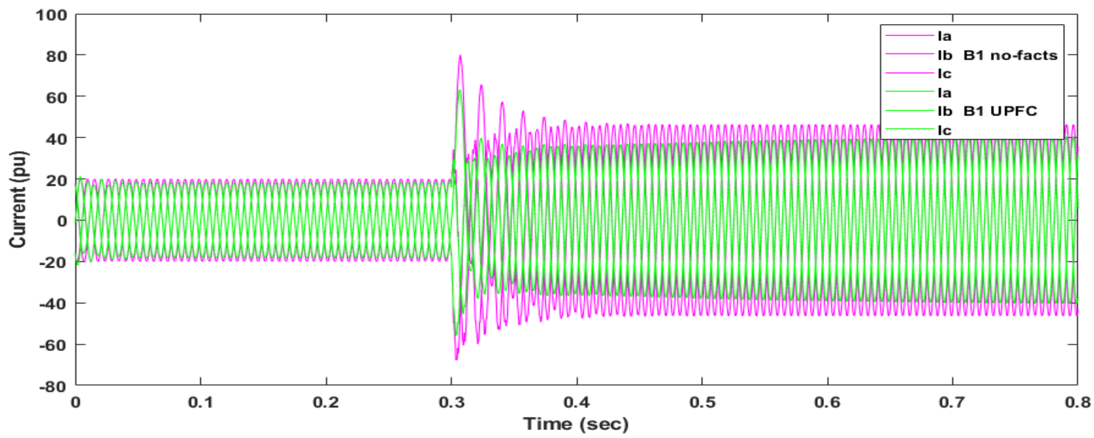


Fig. 43. Comparison between the current wave shape of B1 in pu without FACTS and using UPFC for three line to ground fault in load B inserted at t = 0.3 sec

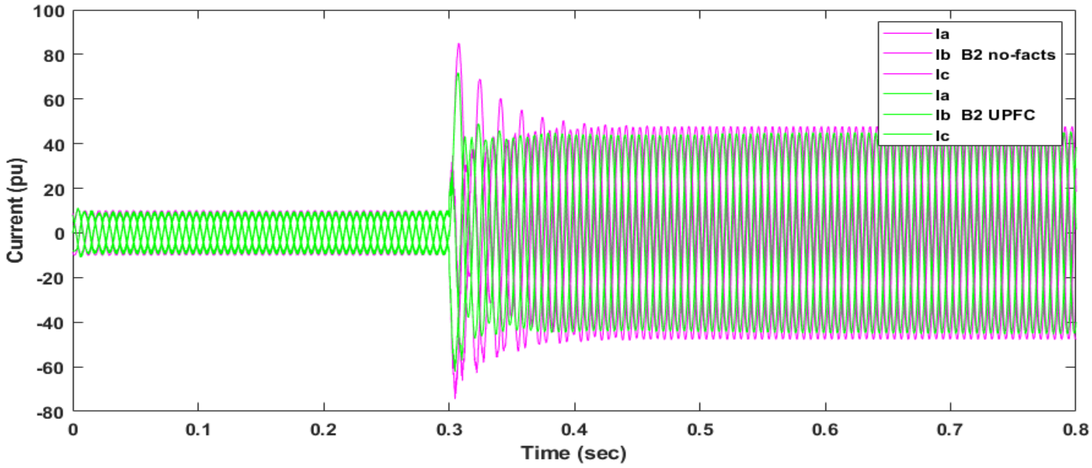


Fig. 44. Comparison between the current wave shape of B2 in pu without FACTS and using UPFC for three line to ground fault in load B inserted at t = 0.3 sec

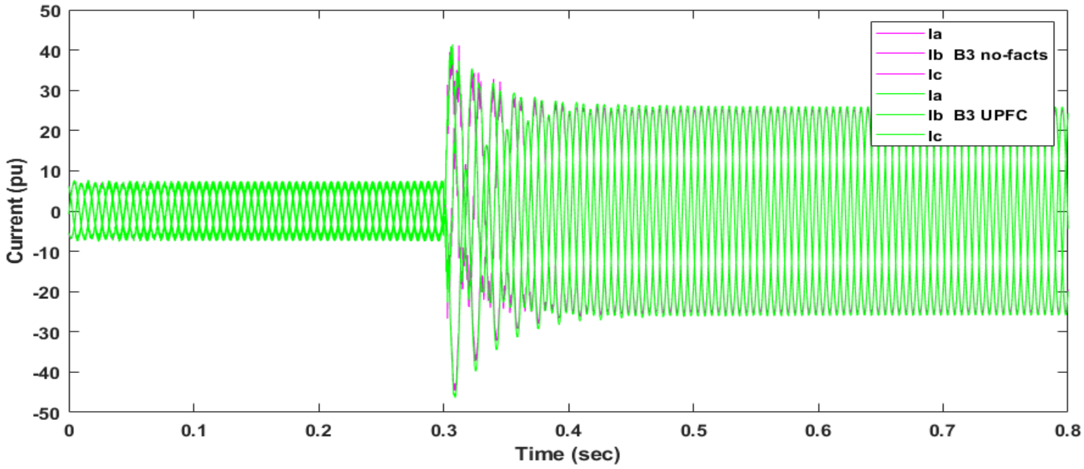


Fig. 45. Comparison between the current wave shape of B3 in pu without FACTS and using UPFC for three line to ground fault in load B inserted at t = 0.3 sec

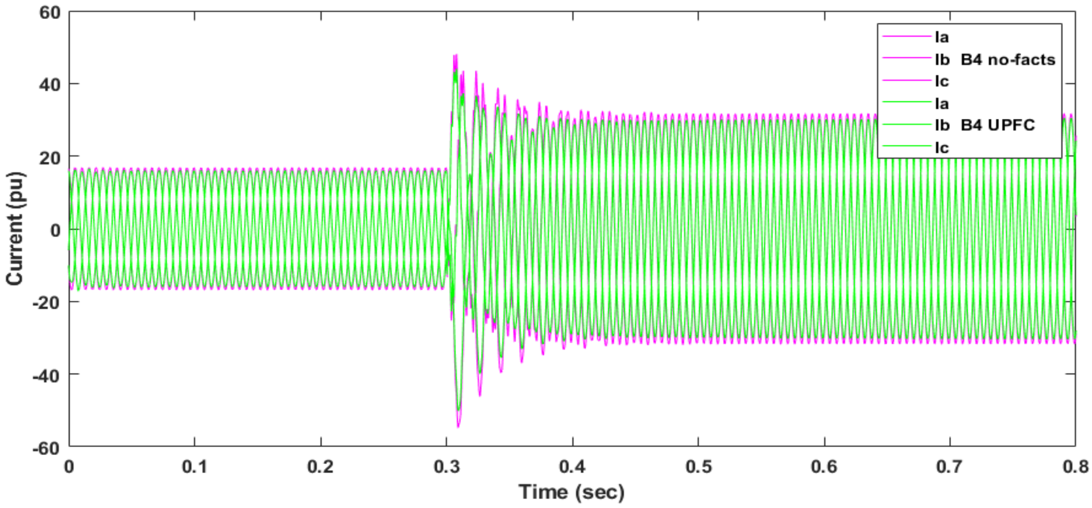


Fig. 46. Comparison between the current wave shape of B4 in pu without FACTS and using UPFC for three line to ground fault in load B inserted at t = 0.3 sec

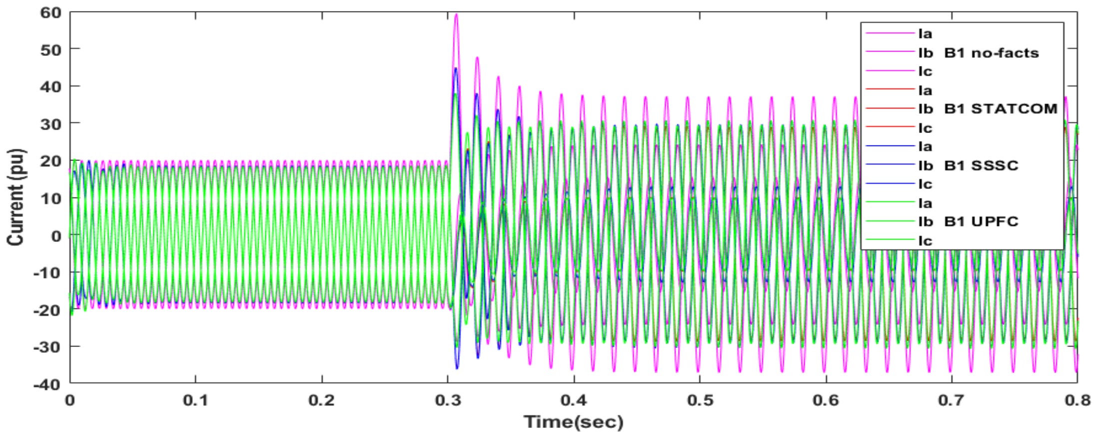


Fig. 47. Comparison between the current wave shape of B1 in pu without FACTS, with STATCOM, with SSSC and with UPFC for single line to ground fault in load B inserted at t = 0.3 sec

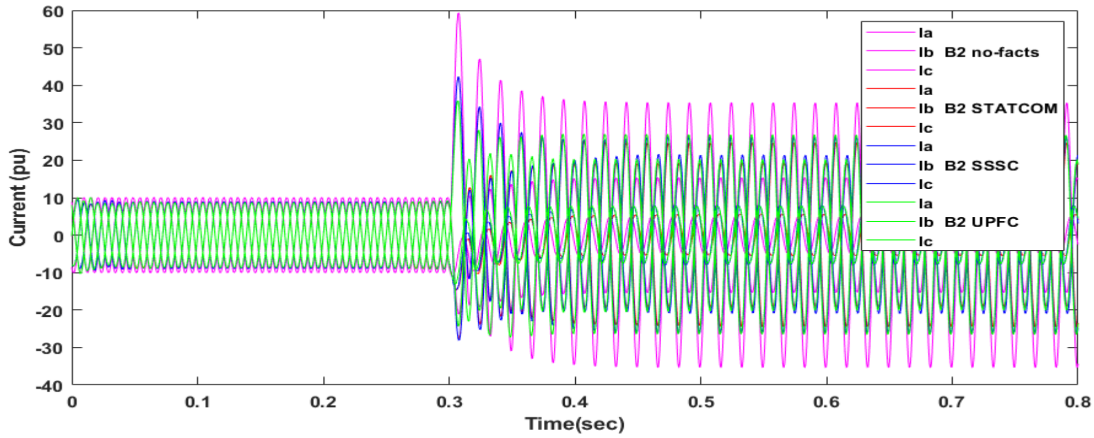


Fig. 48. Comparison between the current wave shape of B2 in pu without FACTS, with STATCOM, with SSSC and with UPFC for single line to ground fault in load B inserted at t = 0.3 sec

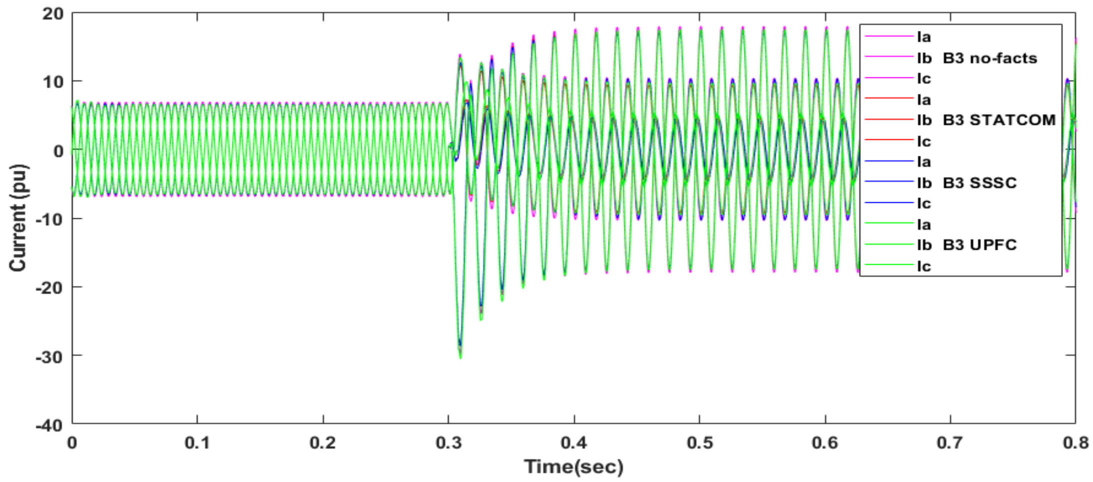


Fig. 49. Comparison between the current wave shape of B3 in pu without FACTS, with STATCOM, with SSSC and with UPFC for single line to ground fault in load B inserted at t = 0.3 sec

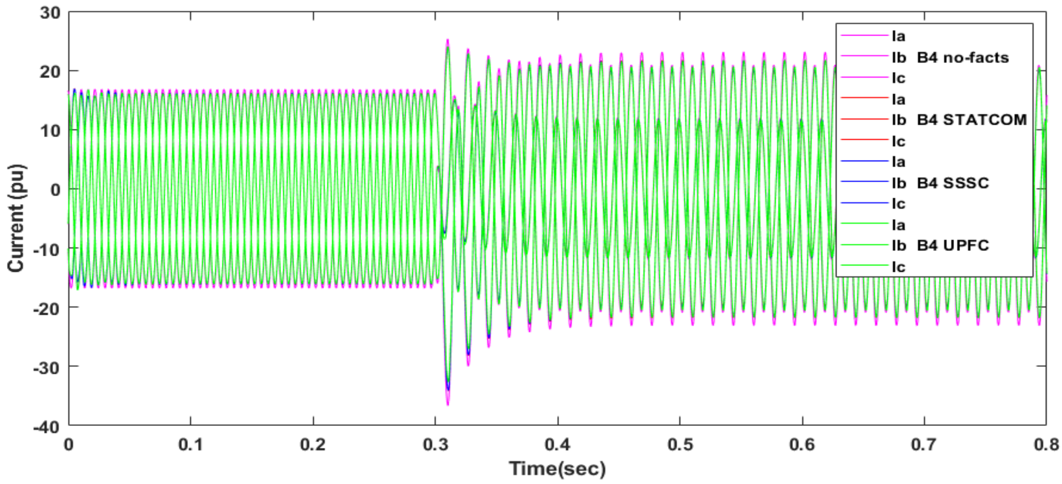


Fig. 50. Comparison between the current wave shape of B4 in pu without FACTS, with STATCOM, with SSSC and with UPFC for single line to ground fault in load B inserted at t = 0.3 sec

Fig. 51 to Fig. 54 display the comparison between the current wave shape of buses B1, B2, B3, and B4 in pu without FACTS, with STATCOM, with SSSC and with UPFC for three line to ground fault in load B inserted at t = 0.3 sec. These figures verified that STATCOM gives better performance for the power system under three phase faults than SSSC and UPFC gives the best performance for reducing the fault current.

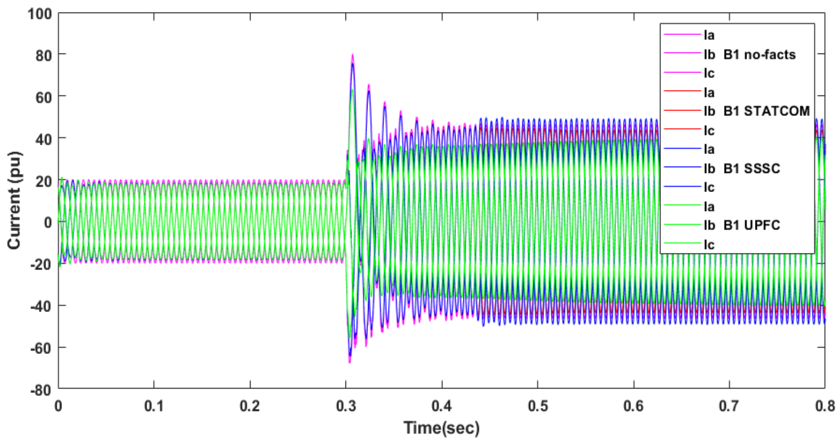


Fig. 51. Comparison between the current wave shape of B1 in pu without FACTS, with STATCOM, with SSSC and with UPFC for three line to ground fault in load B inserted at t = 0.3 sec

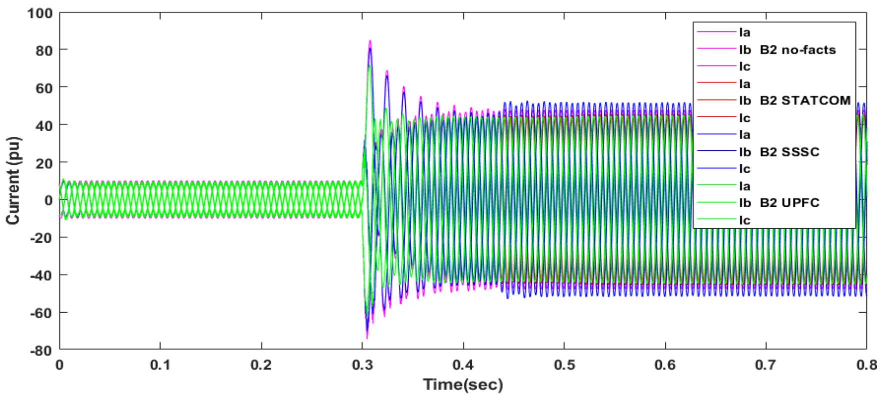


Fig. 52. Comparison between the current wave shape of B2 in pu without FACTS, with STATCOM, with SSSC and with UPFC for three line to ground fault in load B inserted at t = 0.3 sec

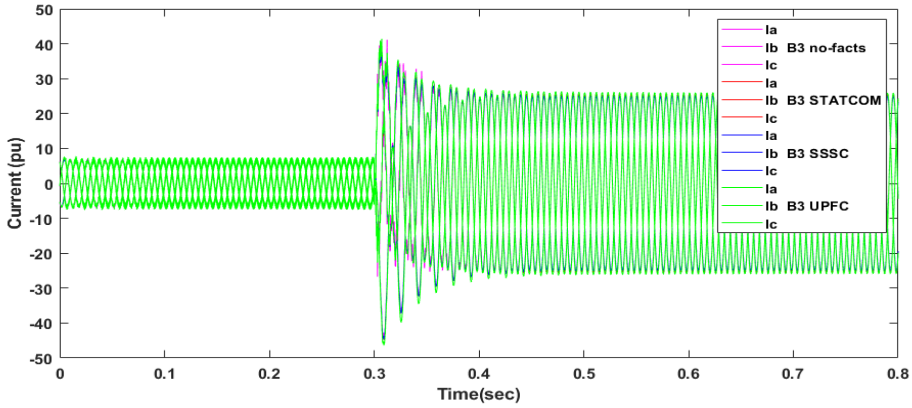


Fig. 53. Comparison between the current wave shape of B3 in pu without FACTS, with STATCOM, with SSSC and with UPFC for three line to ground fault in load B inserted at t = 0.3 sec

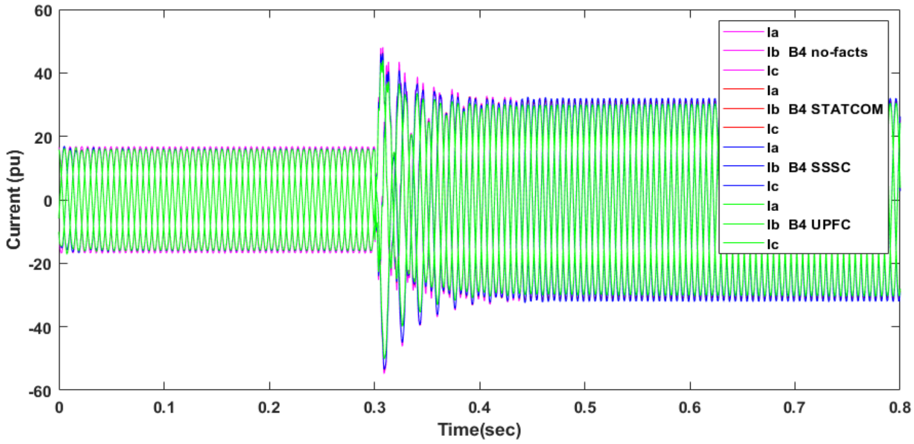


Fig. 54. Comparison between the current wave shape of B4 in pu without FACTS, with STATCOM, with SSSC and with UPFC for three line to ground fault in load B inserted at t = 0.3 sec

UPFC and STATCOM can absorb the reactive power from the presented system in a way which significantly reduces the fault currents and UPFC can gives better response than STATCOM [10]. Table 2 shows the effect of FACTS devices in peak fault current for different faults. It is noted that the peak fault current is reduced with FACTS devices and the UPFC gives the best results as compared to other ones. As the FACTS devices in this study are located between buses B1 and B2 and with comparing the peak fault current at bus B1 with and without using these devices under different faults. It is observed that FACTS devices can precisely reduce the peak fault current of bus B1 besides; UPFC gives the better results than STATCOM or SSSC. The peak fault current is reduced to (63.85, 79.18 %), respectively by using UPFC under line to ground fault and three line to ground fault whereas it is reduced to (75.21, 94.35%) by using STATCOM and (75.40, 94.68%) by using SSSC.

Table 2. Effect of FACTS devices in peak fault current for different faults

Fault Type	Bus ID	Without FACTS	With STATCOM		With SSSC		With UPFC	
		Maximum Current (pu)	Maximum Current (pu)	Percentage reduction (%)	Maximum Current (pu)	Percentage reduction (%)	Maximum Current (pu)	Percentage reduction (%)
Line to ground fault	B1	59.42	44.69	75.21	44.8	75.40	37.94	63.85
	B2	59.29	42.17	71.12	42.17	71.12	35.89	60.53
	B3	17.88	17.2	96.20	17.15	95.92	17.42	97.43
	B4	25.26	23.69	93.78	23.8	94.22	23.69	93.78
Three line to ground fault	B1	79.83	75.32	94.35	75.58	94.68	63.21	79.18
	B2	84.85	80.13	94.43	80.67	95.07	71.63	84.42
	B3	41.15	40.87	99.32	40.05	97.33	41.31	100.39
	B4	48.05	46.01	95.75	46.21	96.17	43.5	90.53

5. Conclusion and Further Work

Simulation results of the power system with three different FACTS devices are carried out under different faults types for enhancing system ability and performance using Matlab/Simulink software package. The three main aspects of the proposed system are STATCOM, SSSC and UPFC. These three aspects are interconnected and performing well. UPFC are linked with STATCOM & SSSC and these are interlinked with the transmission lines with different distances. This paper shows that these numerous FACTS devices have been assessed as fault current limiters which are capable of decreasing fault current besides improving voltage. The FACTS devices are presented and compared together in order to give better performance of power system under unbalanced conditions. The results demonstrated that the FACTS devices could improve the power system, while STATCOM gives better performance than SSSC and UPFC gives the best performance as compared to other FACTS types. The results demonstrated that UPFC which is located between buses B1 and B2 can decrease the peak fault current at bus B1 to (63.85, 79.18 %), respectively under line to ground fault and three line to ground fault though STATCOM and SSSC decrease it to (75.21, 94.35%) and (75.40, 94.68%), respectively. Additionally, The bus voltage (B1) is increased from (0.63, 0.50 pu), respectively under line to ground fault and three phase fault without FACTS devices to (0.74, 0.60 pu) using UPFC. For the future works, it is required to study the system with FACTS devices under additional types of abnormal conditions at different positions of this system.

Author Contribution: All authors contributed equally to the main contributor to this paper. All authors read and approved the final paper.

Funding: This research received no external funding.

Acknowledgment: The authors would like to thank the managers and the members of the "International Journal of Robotics and Control Systems (IJRCS)" for their precious remarks and suggestions.

Conflicts of Interest: The authors declare no conflict of interest.

References

[1] T. P. Kumar and A. Jeevanandham, "Analysis of transient stability using UPFC for symmetrical faults," in *2017 International Conference on Advances in Electrical Technology for Green Energy (ICAETGT)*, pp. 131-134, 2017, https://doi.org/10.1109/ICAETGT.2017.8341465.

[2] A. S. Mohammed, T. H. Sikiru, I. Bello, A. T. Salawudeen, and U. A. Dodo, "Modified Fractional Order PID Controller for Load Frequency Control of Four Area Thermal Power System," *International Journal of Robotics and Control Systems*, vol. 3, 2023, https://doi.org/10.31763/ijrcs.v3i2.957.

[3] A. Das, S. Dawn, and S. Gope, "A review on optimal placement of FACTS devices," *International Journal of Computational Intelligence & IoT*, vol. 2, no. 3, 2019, https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3358367#paper-citations-widget.

[4] J. J. Paserba, "How FACTS controllers-benefit AC transmission systems," *2003 IEEE PES Transmission and Distribution Conference and Exposition*, vol. 3, pp. 949-956, 2003, https://doi.org/10.1109/TDC.2003.1335066.

[5] V. Candrakar, M. Missal, V. Rajderkar, and S. Durve. *Flexible Alternating Current Transmission System (FACTS) for cost effective and reliable transmission of electrical energy*. National Power engineering conference (NPEC-07), 2007.

[6] Y. Esmail and G. M. Dousoky, "Power Quality Improvement in Smart Distribution Grid Using Low-Cost Two-level Inverter DVR," *Journal of Advanced Engineering Trends*, vol. 42, pp. 111-120, 2022, https://doi.org/10.21608/jaet.2021.67681.1098.

[7] S. Verma, "Comparative study of different facts devices," *International Journal of Engineering Research & Technology (IJERT)*, vol. 3, no. 6, 2014, https://www.ijert.org/comparative-study-of-different-facts-devices.

[8] R. K. Bindal, "A Review of Benefits of FACTS Devices in Power system," *International Journal of Engineering and Advanced Technology (IJEAT)*, vol. 3, no. 4, pp. 105-108, 2014, https://www.ijeat.org/portfolio-item/d2903043414/.

[9] A. Singh and A. U. Ahmad, "Control Reactive Power Flow with UPFC Connected Using Different Distance Transmission Line," in *International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering*, vol. 4, no. 9, 2015, http://www.ijareeie.com/upload/2015/september/34_4_Control.pdf.

[10] I. M. Mehedi *et al*., "Reducing fault current by using FACTS devices to improve electrical power flow," *Mathematical Problems in Engineering*, vol. 2021, pp. 1-9, 2021, https://doi.org/10.1155/2021/8116816.

[11] K. R. Padiyar. *FACTS controllers in power transmission and distribution*. New Age International (P) Limited, 2007.

[12] T. Yazawa *et al*., "Design and test results of 6.6 kV high-Tc superconducting fault current limiter," *IEEE transactions on applied superconductivity*, vol. 11, pp. 2511-2514, 2001, https://doi.org/10.1109/77.920376.

[13] D. Murali, M. Rajaram, and N. Reka, "Comparison of FACTS devices for power system stability enhancement," *International Journal of Computer Applications*, vol. 8, pp. 30-35, 2010, https://doi.org/10.5120/1198-1701.

[14] B. B. Adetokun, C. M. Muriithi, and J. O. Ojo, "Voltage stability assessment and enhancement of power grid with increasing wind energy penetration," *International Journal of Electrical Power & Energy Systems*, vol. 120, 105988, 2020, https://doi.org/10.1016/j.ijepes.2020.105988.

[15] S. T. Fadhil, M. Hamad, A. O. Arslan, and A. M. Vural, "Comparison of Dynamic Performances of Statcom, SSSC, IPFC and UPFC On Inter-Area Oscillation Damping," *The International Journal of Energy and Engineering Sciences*, vol. 5, no. 2, pp. 62-79, 2020, https://dergipark.org.tr/en/pub/ijees/issue/56352/755448.

[16] M. P. Donsion, J. Guemes, and J. Rodriguez, "Power Quality. Benefits of Utilizing FACTS Devices in Electrical Power Systems," in *2007 7th International Symposium on Electromagnetic Compatibility and Electromagnetic Ecology*, pp. 26-29, 2007, https://doi.org/10.1109/EMCECO.2007.4371637.

[17] S. Panda, "Modelling, simulation and optimal tuning of SSSC-based controller in a multi-machine power system," *World Journal of Modelling and simulation*, vol. 6, no. 2, pp. 110-121, 2010, http://www.wjms.org.uk/wjmsvol06no02paper03.pdf.

[18] S. Akter, A. Saha, and P. Das, "Modelling, simulation and comparison of various FACTS devices in power system," *International Journal of Engineering Research and Technology*, vol. 1, pp. 1-13, 2012, https://www.ijert.org/modelling-simulation-and-comparison-of-various-facts-devices-in-power-system.

[19] T. U. Okeke and R. G. Zaher, "Flexible AC transmission systems (FACTS)," in *2013 international conference on new concepts in smart cities: fostering public and private alliances (SmartMILE)*, pp. 1-4, 2013, https://doi.org/10.1109/SmartMILE.2013.6708208.

[20] M. D. Stochitoiu and I. Utu, "A Brief Review of Approach the Role of Facts Devices," *Annals of the University of Petrosani Electrical Engineering*, vol. 21, 2020, https://www.upet.ro/annals/electrical/doc/2020/L17%20Stochitoiu%20Daniela.pdf.

[21] S. Mirsaeidi *et al*., "A review on optimization objectives for power system operation improvement using FACTS devices," *Energies*, vol. 16, no. 1, p. 161, 2022, https://doi.org/10.3390/en16010161.

[22] S. Khanchi and V. K. Garg, "Unified Power Flow Controller (FACTS Device): A Review," *system*, vol. 3, no. 4, pp. 1430-1435, 2013, https://www.ijera.com/papers/Vol3_issue4/HS3414301435.pdf.

[23] K. Gupta and Y. Pahariya, "Simulation Analysis of FACTs Devices for Transient Stability Improvement in Multi Machine System," *Simulation*, vol. 3, no. 1, 2017, https://www.academia.edu/31142699.

[24] M. Rohit and N. K. Sharma, "Improvement of Transmission Line Voltage Using Facts," *International Journal of Current Science (IJCSPUB)*, vol. 12, no. 3, 2022, https://www.ijcspub.org/papers/IJCSP22C1179.pdf.

[25] H. Joshi and S. Sahay, "Performance Analysis of Different Types of Facts Controllers in a Transmission Line," *International Journal on Emerging Technologies*, vol. 8, no. 1, pp. 243-249, 2017, https://www.researchtrend.net/ijet/pdf/60-F-744.pdf.

[26] M. R. Wara and A. Rahim, " STATCOM in Power Systems: A Review," *International Journal of Power Electronics Controllers and Converters (IJPECC)*, vol. 6, no. 2, 2020, https://ecc.journalspub.info/index.php?journal=JPECC&page=article&op=view&path%5B%5D=1426.

[27] A. Raj and D. Vishwakarma, "Simulation and Analysis of Static Synchronous Series Compensator for Power Flow Control in Power System: Review," *International Journal of Progressive Research in Engineering Management and Science (IJPREMS)*, vol. 3, no. 4, pp. 68-73, 2023, https://www.ijprems.com/uploadedfiles/paper//issue_4_april_2023/30829/final/fin_ijprems1680765959.pdf.

[28] A. Udaratin, K. Loginov, A. Nemirovskiy, N. Rozhentsova, and E. Gracheva, "Modelling of emergency modes with FACTS devices installed," in *E3S Web of Conferences*, vol. 178, p. 01052, 2020, https://doi.org/10.1051/e3sconf/202017801052.

[29] B. Musa and M. Mustapha, "Modelling and simulation of STATCOM for reactive power and voltage control," *Journal of Multidisciplinary Engineering Science and Technology (JMEST)*, vol. 2, no. 2, 2015, https://www.jmest.org/wp-content/uploads/JMESTN42350466.pdf.

[30] M. Eslami, H. Shareef, A. Mohamed, and M. Khajehzadeh, "A survey on flexible AC transmission systems (FACTS)," *Przegląd Elektrotechniczny*, vol. 1, 2012, http://pe.org.pl/abstract_pl.php?nid=5443&lang=1.

[31] A. S. Shelke and A. A. Bhole, "A Review on Different FACTS Devices used in Electrical Power System," *International Journal of Engineering Research & Technology (IJERT)*, vol. 10, no. 4, pp. 309-312, 2021, https://www.ijert.org/a-review-on-different-facts-devices-used-in-electrical-power-system.

[32] A. A. Nimje, C. K. Panigrahi, and A. K. Mohanty, "Enhanced power transfer capability by using SSSC," *Journal of Mechanical Engineering Research*, vol. 3, no. 2, pp. 48-56, 2011, https://academicjournals.org/journal/JMER/article-abstract/40858194983.

[33] S. Bhowmick. *Flexible AC Transmission Systems (FACTS): Newton Power-Flow Modeling of Voltage-Sourced Converter-Based Controllers*. CRC Press, 2018, https://doi.org/10.1201/9781315222431.

[34] S. Bandopadhyay and A. Roy, "Digital Simulation of 48 Pulse GTO Based Statcom and Reactive Power Compensation," *Int. J. Recent Innov. Trends Comput. Commun*, vol. 2, no. 4, pp. 824-827, 2014, https://www.ijritcc.org/index.php/ijritcc/article/view/3068.

[35] D. Soto and T. C. Green, "A comparison of high-power converter topologies for the implementation of FACTS controllers," *IEEE Transactions on Industrial Electronics*, vol. 49, pp. 1072-1080, 2002, https://doi.org/10.1109/TIE.2002.803217.

[36] C. Dinakaran, "Simulation of 48 Pulse GTO Based STATCOM, SSSC & UPFC Controller," *International Journal of Modern Science and Technology*, vol. 2, no. 1, pp. 31-40, 2017, http://www.ijmst.co/vol.-2.-issue-1---jan-2017---paper-6.html.

[37] H. Wang, "A unified model for the analysis of FACTS devices in damping power system oscillations. III. Unified power flow controller," *IEEE Transactions on Power Delivery*, vol. 15, pp. 978-983, 2000, https://doi.org/10.1109/61.871362.

[38] M. S. Rawat and S. Vadhera, "Comparison of FACTS devices for transient stability enhancement of multi machine power system," in *2016 International Conference on Microelectronics, Computing and Communications (MicroCom)*, pp. 1-5, 2016, https://doi.org/10.1109/MicroCom.2016.7522419.

[39] S. E. Mubeen, R. Nema, and G. Agnihotri, "Power flow control with UPFC in power transmission system," *International Journal of Electrical and Computer Engineering*, vol. 2, no. 11, pp. 2507-2511, 2008, https://publications.waset.org/7733/pdf.

[40] B. O. Anyaka, J. F. Manirakiza, L. U. Omeje, and M. C. Odo, "Voltage profile improvement of a disturbed electric power system using UPFC compensation," *Int. Journal of Recent Technology and Engineering*, vol. 8, pp. 1888-1893, 2020, https://doi.org/10.35940/ijrte.E6254.018520.

Vol. 4, No. 1, 2024, pp. 1-32

[41] V. Gupta, "Study and effects of UPFC and its control system for power flow control and voltage injection in a power system," *International journal of engineering science and technology*, vol. 2, no. 7, pp. 2558-2566, 2010, https://www.ijest.info/abstract.php?file=10-02-07-13.

[42] K. Deepak, G. S. Ilango, C. Nagamani, and K. S. Swarup, "Performance of UPFC on system behavior under fault conditions," in *2005 Annual IEEE India Conference-Indicon*, pp. 505-509, 2005, https://doi.org/10.1109/INDCON.2005.1590222.