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Voltage Stability Enhancement in Electrical Transmission Networks Using STATCOM with Two Different Controllers: Case Study in Middle Egypt Electricity Zone

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A B S T R A C T

In this paper a 25MVA Static Synchronous Compensation Device (STATCOM) that is considered an operative equipment for Flexible AC Transmission Systems (FACTS) is aimed at enhancing voltage reliability at a (66 KV, 525MVA) electrical power transmission system. The STATCOM used in this work can regulate the power system's voltage for fluctuations of ±7% from the nominal value. A model of the transmission network in Middle Egypt Electricity Zone has been developed using the Matlab/Simulink platform as well as STATCOM scheme that used to improve the stability of the system's voltage. The study assesses the electrical grid performance augmented by STATCOM connected in shunt with bus B11 at normal operation and under various faults conditions, including single-phase and three-phase faults. The STATCOM control is accomplished by employing PI controller and Fuzzy Logic Control System (FLC). The study aims to illustrate the effectiveness of FLC over PI controller for preserving the voltage profile at different conditions using STATCOM device. The findings indicate that the proposed system showcases improved voltage performance when utilizing the STATCOM device, in both normal and abnormal circumstances, compared to scenarios without it. The results show that the deviation in system voltage can reach up to 14.62% during normal operation without a STATCOM device. In comparison, a STATCOM utilizing a PI controller is able to bring this deviation down to a maximum of 5.9%. Additionally, the STATCOM incorporating a FLC surpasses the performance of the PI controller, reducing the deviation at all system buses to levels not exceeding 4.67%. Therefore the STATCOM demonstrates superior responsiveness when controlled by a FLC rather than a PI controller.

1. Introduction

Cold-formed steel members (CFS) in structures are a significant advancement in the evolution of steel structures, with these members becoming increasingly popular as primary load-carrying elements in buildings. To enhance buckling resistance, more intricate shapes are being designed, as illustrated in Figure 1.

The demand for electricity in developing nations has surged significantly due to population growth and industrialization. This increase makes it imperative to operate power plants that efficiently transfer energy to transmission and distribution lines [1-3].

The power system control is meant to maintain equilibrium among energy production and consumption [4, 5]. Technology utilized in electric power networks is constantly evolving, much like the power networks themselves. The constantly advancing power network earns a further efficient and advantageous process [5, 6].

Lately, there has been significant use of Technologies for Flexible AC Transmission Systems (FACTS) within energy applications for enhancing electrical networks' reliability and the power's quality [7-9]. The emerging designs of FACTS devices generally feature low volume, sufficient characteristic, and rapid response times. They have the ability to manage both active as well as reactive power flow instantly, maintain voltage levels within permissible ranges also increase the capacity of the transmission circuits to transmit power [10-15]. FACTS are considered the most effective means for enhancing the quality, dependability and effectiveness of electrical systems [16].

A STATCOM (Static Synchronous Compensator) is among the most promising devices in FACTS categories [11-14]. The phrase "synchronous" in relation to STATCOM context refers to its capability to either produce or absorb reactive power in accordance with the requirements for stabilizing the voltage of the power network [17]. It can continuously regulate the system's reactive power, thereby maintaining the voltage characteristics. This is a result of its working principle of using semiconductor devices instead of static capacitors or shunt reactors [12-14, 18-20].

Generally, The STATCOM is a particularly noteworthy FACTS device among others such as Static Synchronous Series

Compensation Device (SSSC), as well as Integrated Power Flow Controller (IPFC). It is notable for its ability to improve the power system's transmission capabilities through improved voltage regulation and stability. This device plays a crucial role in providing rapid and seamless reactive compensation for voltage support, as well as enhancing fluctuations in power plus transient stability [21-24].

STATCOM is typically an active device that provides near-instantaneous control of the system voltage's amplitude and phase. As a result, it has the ability to control the reactive current independently. A STATCOM could function as both a provider and a consumer for reactive power, increasing the active power transmission while maintaining voltage regulation within the system.

Also, STATCOMs are inherently connected in parallel reducing system size and rating [12]. They ensure voltage stability and regulation in the power transmission network by keeping the voltage at the specified node within the target range [4, 25]. This guarantees a dependable and effective power supply, enhancing the resilience of the energy infrastructure [26, 27].

STATCOM is widely recognized as a promising technology. It serves as an enhanced dynamic shunt compensation for distribution and transmission reactive power control [19, 28]. As a result, it is known as the next-generation of reactive power control in the electrical network system [29].

A range of reactive compensation devices encompasses STATCOMs, shunt capacitors, synchronous condensers, and saturation reactors (SRs). The STATCOM is particularly beneficial as it can compensate for reactive power in both directions and is characterized by its wide operating range, rapid response time, low energy storage requirements, and enhanced control flexibility compared to conventional compensators [30-32].

STATCOMs provide operational versatility by facilitating seamless integration with current infrastructure and accommodating a range of control strategies to improve performance under diverse operating conditions [33, 34].

stability of power systems refers to the ability of the electrical grid to sustain steady functional condition during standard circumstances also to effectively balance following any disruptions [35, 36]. Stability of voltage, in this context, indicates the voltage's capacity for reverting to its stated operational stage after experiencing an interruption [36, 37].

The proportional integral (PI controller) necessitates exact numerical model values that are difficult to generate and might not yield the desired outcomes for parameters, load fluctuations, and so on [38-41]. The employment of STATCOM's Fuzzy Logic-Based Controller (FLC) has garnered considerable devotion. The benefits of using a FLC instead of a PI controller include the fact that it does not necessitate precise values from numerical models also are capable of managing any nonlinearity even through uncertain inputs. Mamdani type FLC is most commonly utilized and produces better results for STATCOM applications than PI controllers [41, 42].

Although FLC has numerous benefits, it also has certain drawbacks or limitations. These include the intricate process of designing the rule base and the requirement for expert knowledge in fuzzy logic systems [43]. Fuzzy systems are considered intelligent systems that utilize data and reasoning to address significant problems, which necessitate substantial engineering expertise for explanation [44, 45].

A system failure may result from a short circuit, an open circuit, a natural disaster or negligent maintenance [46-48]. It could involve three-phase failures, Single-phase failures as well as two--phase failures. An increase in the current level is caused due to faults leads to a rise in the existing level and can be the reason for the black out to the full area [46, 48].

The following section presents a review of relevant literature concerning this paper:-

O. Noureldeen (2009) studied the impact of STATCOM operating conditions on the impedance readings obtained from a digital impedance-based relay throughout voltage fluctuations and fault conditions using Matlab/Simulink in 500 kV transmission line model spanning 300 km [49].

O. Noureldeen, M. Rihan, and B. Hasanin (2011) presented the STATCOM devices for maintaining the wind farm's constant speed interconnected electrical network through various faults conditions. Simulation with MATLAB/Simulink is instigated at a capacity of 9 MW wind energy facility and 120 KV system voltage grid [50].

G. El-Saady, M. A. A Wahab, M. M. Hamada, and M. Basheer (2012) investigated the improvement of the voltage stability FACTS categories specifically, SSSC as well as STATCOM device. The suggested schemes have been tested under different conditions. The findings showcased both the feasibility and effectiveness of the suggested FACTS devices [51].

Q. A. Tarbosh, Ö. Aydoğdu, N. Farah, M. H. N. Talib, A. Salh, N. Cankaya, et al. (2020) illustrated the FLC, serving as the speed regulator for drives using induction motors. A lot of research interest has been attracted because it achieves better performance than conventional controllers. The study intended to assess and evaluate the strategy, functionality, and impacts of the rule decrease in FLC drives [52].

R. Dubey, S. Dixit, and G. Agnihotri (2014) presented a comparative analysis of FACTS technologies within an unregulated electricity market, including benefits, applications and classifications [10].

Z. Yu and D. Lusan (2004) studied the present condition of the optimal arrangement of the FACTS technologies. The study proposed a model to improve the configuration of the FACTS categories in different time periods through losses taken into account. The requirements are presented as elements of the prices to align with the operational rules of the unregulated electricity market [53].

M. Rohit and N. K. Sharma (2022) demonstrated the FACTS categories' advantages for enhancing the electrical grid's efficiency using varies controls for these devices [54].

S. Rahimzadeh and M. T. Bina (2011) proposed an optimal technique series and parallel FACTS devices (SSSC and STATCOM alone) to assuage the system overcrowding. It described an index view of display values for target works to decide the optimal amount of each faithful accurate strategies in particular overview calculations [55].

I. Y. Fawzy, M. A. Mossa, A. M. Elsawy, I. Suwarno, and A. A. Z. Diab (2024) presented an overview of the STATCOM device with two controllers and studied the system under different faults types utilizing Matlab/Simulink. The findings revealed that the effectiveness of the electrical network could be precisely improved using STATCOM with FLC that gives better performance than PI controller [56].

S. O. Farees, M. Gayatri, and K. Sumanth (2014) compared the static voltage stability of STATCOM and Static VAR Compensator (SVC) with fuzzy controller utilizing Simulink for assessing the recommended controller's efficacy. The outcomes indicate that the STATCOM outperforms the traditional SVC [57].

S. Pati, K. B. Mohanty, and S. K. Kar (2018) demonstrated the efficiency of FLC relative to other controller types (e.g., PI controller) in improving load bus voltage in microgrid systems using STATCOM. The controllers' behavior was compared under various circumstances. The comparative study concluded that FLC outperforms other proposed controllers [58].

Y. Xu and F. Li (2014) illustrated different management strategies for STATCOM, featuring several implementations of PI controls. It mentions a new method utilizing adaptive PI controller that could modify the control gain through changes in operating conditions and provides ready-to-use functionality for procedure of STATCOM. Results confirm that adaptive PI control provides reliable efficiency across a diverse set of operational circumstances [59].

B. B. Adetokun and C. M. Muriithi (2021) examined the STATCOM's function to facilitate the incorporation of intermittent sustainable resources like wind and PV. It highlighted the importance of researching and developing the necessary controlling of voltage levels also reactive power to ensure the long-term viability and economic stability of future power grids [60].

K. Sundararaju and R. Senthilkumar (2014) considered the electrical system with and without STATCOM using FLC. In order to achieve better control of real-time systems, STATCOM adopted a better control scheme. With this comprehensive study, real-time technology demonstrated its possibilities for improving voltage profile and reactive power compensation [61].

S. AROCKIARAJ, B. V. MANIKANDAN, and A. BHUVANESH (2023) demonstrated STATCOM device for enhancing the bus voltage profile using PI and FLC. The effectiveness of STATCOM utilizing both controllers is simulated under different situations using Matlab/Simulink. The results validated that FLC outperforms PI controller under different load situations [62].

L. Ribeiro and D. Simonetti (2022) presented the operation of single phase STATCOM, and its performance when employing voltage or current controls within a low-voltage STATCOM system [63].

P. Kumkratug (2011) presented the system control of improving the electrical system dynamic performance with using STATCOM device. FLC is applied for system control. The results specified that the STATCOM relied on fuzzy controller could accomplish the superior system performance [64].

A. A. Z. Diab, T. Ebraheem, R. Aljendy, H. M. Sultan, and Z. M. Ali (2020) recommended a new scheme for a MMC STATCOM, a multilevel converter designed for medium to high voltage procedures. The recommended STATCOM is capable of operating seamlessly even in the event of three-phase unbalance [65].

F. Shaaban, Z. Harmoosh, and E. Alsari (2017) presented a model of power transmission network using STATCOM device considering PI controller enhanced by a FLC supervisor for the purpose of regulating system voltage. The results showed better performance using STATCOM strategy [66].

S. O. Farees, M. Gayatri, and K. Sumanth (2014) offered an examination of voltage stability for STATCOM and SVC with fuzzy controller employing Matlab/Simulink for validating the proposed controller execution. Results inspected that STATCOM contributes better performance than conventional SVC [57].

This paper presents an overview of STATCOM using two different controllers for enhancing the electric network's behavior. The proposed model is analyzed under balanced and unbalanced conditions utilizing the Matlab/Simulink program. The outcomes indicated that the effectiveness of the power network can be significantly improved using a STATCOM with a FLC, which outperforms a PI controller.

The major contribution of this study is the motivation for the STATCOM device that belongs to the FACTS devices using two different controllers for enhancing stability of the system's voltage. This study aims to offer a STATCOM's summary also its performance during standard operation and under different faults conditions. The outcomes demonstrated that the stability of voltage in the power grid could be enhanced specifically using STATCOM based on FLC which gives better performance than PI controller.

2. Research Problems and Challenges

In light of the escalating global demand for electricity, the sources of generation within electrical networks have become increasingly diverse. This surge in energy demand, combined with the expansion of generation options, has led to transmission networks operating under more complex conditions, nearing their stability limits. Consequently, these networks are facing significant challenges in maintaining safe and reliable operations, struggling to fulfill essential requirements. Various solutions can be explored, including the development of new transmission networks or enhancing the efficiency of existing ones. However, the establishment of new networks is constrained by economic and environmental factors. Likewise, efforts to improve the efficiency of current transmission systems are impeded by issues such as thermal operating limits, voltage stability requirements, generation stability thresholds, and safety regulations. So FACTS

Technologies with different controllers can be used in the current networks in order to improve its performance and voltage stability.

3. Overview of STATCOM and Controller

3.1. STATCOM

The STATCOM, a reactive power compensation controller connected to the shunt, became feasible with the advancement of power electronics, particularly the GTO thyristor. This technology emerged as a viable alternative to the conventional SVC [67]. In contrast to SVC, the STATCOM's output current can be adjusted independently of the Voltage of the AC system [68, 69]. Fig. 1 illustrates the STATCOM’s configuration layout. It is comprised of a voltage source converter (VSC), unit for storing direct current (DC), as well as a connecting transformer, all linked in parallel to the network. The VSC transforms the DC voltage into voltages of a three-phase AC output. The output voltages are synchronized also introduced into the AC system via the connecting transformer’s reactance. By precisely adjusting the output voltages' phase also amplitude from the STATCOM, the system can effectively manage exchanges of active and reactive power among the STATCOM and the system. This setup enables the equipment to either consume or produce manageable power [67].

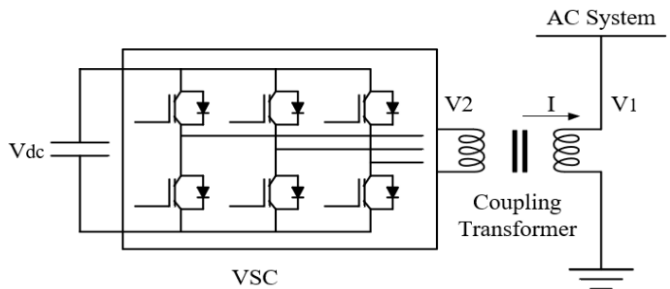


Figure 1: STATCOM's basic arrangement

The transmission lines' active and reactive power (P&Q), respectively are presented below.

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

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

Here, V1 represents the system bus voltage, V2 denotes the inverter's output voltage, while δ is the phase shift between V1 and V2 and X indicates the line reactance between the inverter and the system bus [4].

STATCOM operates by injecting reactive electricity into the grid or drawing it from the grid [5-9], which helps to stabilize voltage levels and enhance overall power quality . The reactive power flow's control results from the interaction among the system's voltage and the STATCOM’s AC voltage. When the voltage across the terminals of the STATCOM is higher than the AC voltage, STATCOM operates like a capacitor, supplying reactive power to the system. Conversely, when the STATCOM’s voltage drops below the system voltage, it acts like an inductor, reversing the reactive power direction. Within standard working circumstances, the two voltages are the same, and there is no current flow among the STATCOM and the system. Fig. 2 illustrates the current and voltage attributes of the STATCOM. A variety of research have demonstrated that the use of STATCOM can enhance dynamic performance also improve stability in alternative energy applications [76].

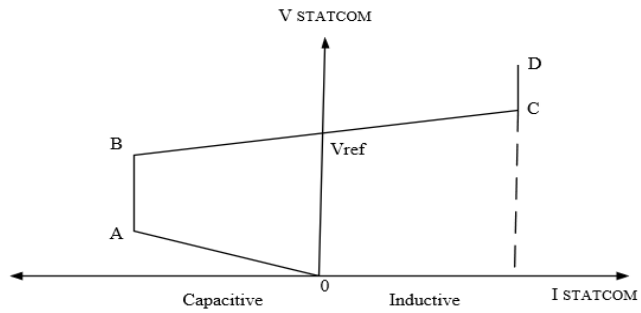


Figure 2: Voltage-Current characteristics of STATCOM

3.2. Fuzzy Logic-Based Controller

Fuzzy Logic-Based Controller (FLC) is regarded as more efficient and beneficial compared to classical controllers such as the PI controller, PID controller, and others. It requires less storage capacity and is well-suited for non-linear systems [43]. It plays a crucial role in various practical applications and offers numerous fuzzy inference mechanisms [44]. This research selects the Mamdani-type inference system due to its computational efficiency and compactness.

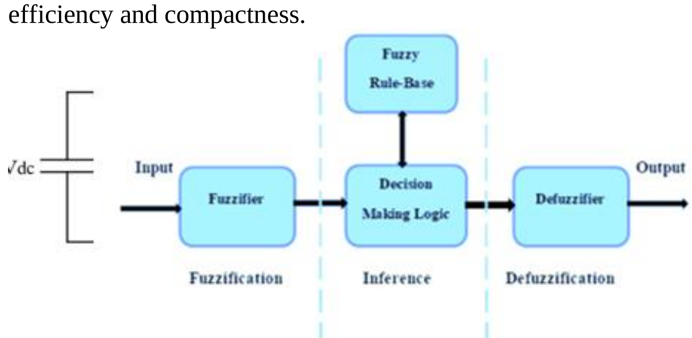


Figure 3: FLC structure

Fig. 3 illustrates the arrangement of the FLC system that involves four major components. These components [77] are Fuzzifier, Knowledge base, Decision making logic and Defuzzifier.

The fundamental structure of FLC includes four essential components [78] , that are:

- *Fuzzification (Fuzzifier)* refers to the transformation of a numerical value to a verbal representation or associating the input domain using an imprecise set explained within the range of discussion. This process involves transforming data input to appropriate language-related values may be considered as identifiers for the imprecise sets.
- *Knowledge base (FUZZY RULE BASE)* comprises an information repository along with a collection of fuzzy rules. The information repository contains explanations needed for linguistic rules and fuzzy data processing. The rule base outlines the goals and tactics of specialists through linguistic guiding rules.

- *Decision making logic (FUZZY INFERENCE ENGINE)* is the core the FLC. It can simulate human decision-making on vague concepts and infer fuzzy control functions by utilizing fuzzy implications and fuzzy logical inference rules.
- *Defuzzification (Defuzzifier)* implements the following functions: Scale mapping, that converts the result parameters' values within the coherent contexts of discussion. Defuzzifier, that produces the precise manage functions based on the derived management functions.

4. System under Study

Fig. 4 illustrates the schematic layout of electrical power transmission substations in Middle Egypt Electricity Zone under study. The Simulink representation of an electrical transmission network of a (66 KV, 525MVA) is revealed in Fig. 5. The system is combined with STATCOM using fuzzy controller. It is evaluated through different abnormal conditions. It consists of some electrical power transmission substations in Middle Egypt Electricity Zone such as substation A - 500 KV which is considered main Substation of the proposed system, substation B - 66 KV, substation C - 66KV, substation D - 66 kV, substation E – 66 KV, and substation F - 66 KV. All these 66 KV transmission substations are supplied by substation A - 500 KV transmission substations. The STATCOM of 25-MVA, 66 KV is connected in shunt at bus B11. The power system's voltage varies to (± 7 %) from the nominal value using three phase variable voltage sources according to simulation time as in Table 1.

Table 1: The Power System's Voltage

Time (sec)	(0.-0.2)	(0.2.-0.3)	(0.3.-0.4)	(0.4.-0.5
Voltage (pu)	1	1.07	0.93	1

Table 2 indicates data parameters of the System and STATCOM in the model under study. The performance of the electrical power network with STATCOM including two controller's types is offered and examined at various fault conditions.

Table 2: The Data of The System And STATCOM Used in This Paper

System	System Voltage	V(KV)	66
	Transmission Lines length (Km)	Transmission line (A – B)	2X42.4
		Transmission line (B – C)	2X10.9
		Transmission line (A – D)	2X12
		Transmission line (A – F)	2X50
	Total System loads	P (MW)	263.6
		Q (MVAR)	108.5
STATCOM	Technical Data	S (MVA)	25
		V (KV)	66
		C (μF)	16000

The potential cases for investigation are itemized underneath:
CASE 1: The electrical network at normal operation considering variable voltage source without STATCOM and utilizing a controller-based STATCOM "PI controller and FLC".
CASE 2: The electrical network with a single-phase grounding fault was initiated at load-A without STATCOM and utilizing a controller-based STATCOM "PI controller and FLC".
CASE 3: The electrical network with a three-phase grounding fault was initiated at load-A without STATCOM and utilizing a controller-based STATCOM "PI controller and FLC".

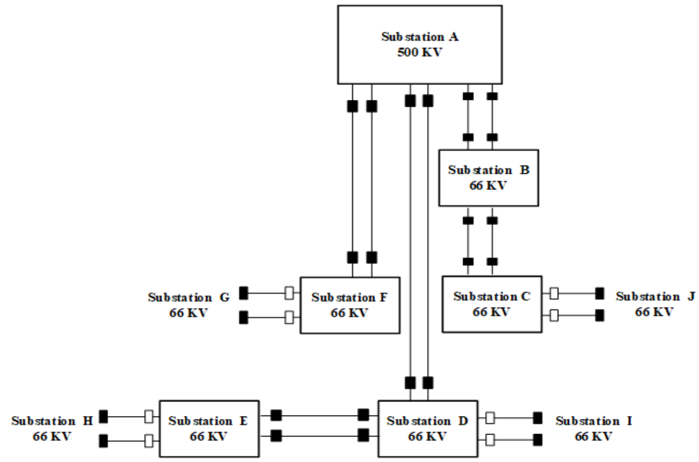


Figure 4: The block diagram of electrical power transmission stations in Middle Egypt Electricity Zone under study

5. Simulation Results

The process of simulation has been arranged utilizing MATLAB/Simulink. This process includes the power system at normal operation and under abnormal conditions. A fault caused by a short circuit featuring various types of faults in this simulation at t = (0.3-0.31) seconds. for abnormal conditions. The faults were introduced at load-A also the grid voltages were recorded within all cases. It is possible to use the STATCOM device with FLC for maintaining the system's buses voltage. Two various controllers have been implemented for enhancing the voltage levels within the power grid at normal procedure and under faults conditions.

Mamdani Method: It is implemented in this study in which is computationally effectual and more compact [79].The system comprises two inputs (X1 and X2) and a single output (Y). The error along with the change in error in the system is symbolized as (X1 & X2), respectively. The output Y is represented as fuzzy output [79].

The fuzzy logic controller transforms the linguistic management approach to the automated management approach, and the rules of fuzzy system are created whichever through an expert's input or by utilizing an information repository. Choosing the subsequent 7-fuzzy stages or categories (Membership functions) that offer a numerical description of each of the Fuzzy logic states for improved outcomes [80]: NB (Negative Big), NM (Negative Medium), NS (Negative Small), ZE (Zero), PS (Positive Small), PM (Positive Medium), PB (Positive Big) as illustrated in Fig. 6.

A fuzzy inference system is a computational model founded on the principles of fuzzy set theory. According to the theory, large transient errors require coarse control with rough input and output factors, despite minor steady-state errors require fine-tuning with fictitious input/output variables [80]. The rule base elements are determined based on this concept, as shown in table 3 where E represents error and ΔE represents the change in error. Fig. 7 shows the flowchart of FLC, encompassing all steps of fuzzy controller is described in this flowchart.

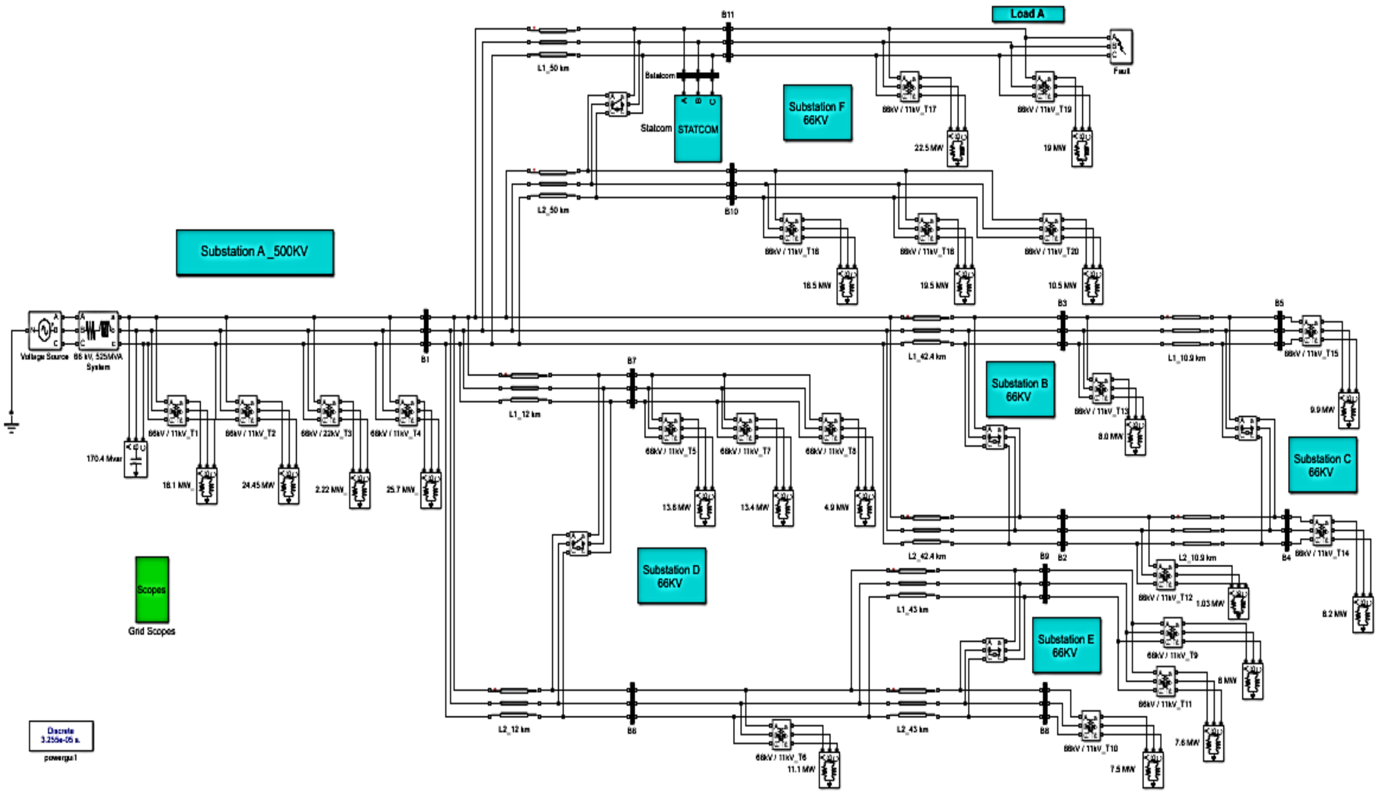
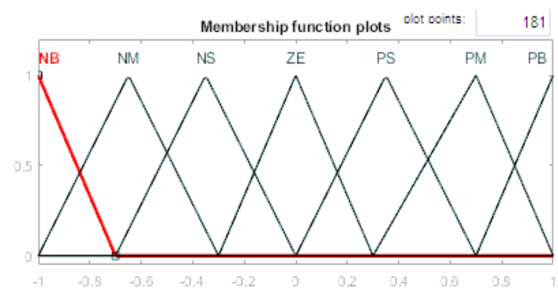
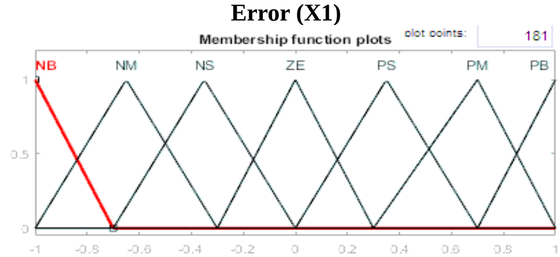


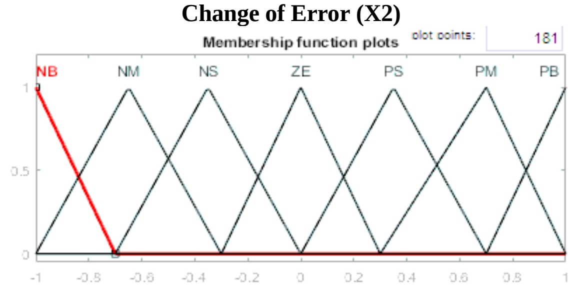
Figure 5: The proposed model of the electrical transmission network in MATLAB/Simulink



Error (X1)



Change of Error (X2)



Output (Y)

Figure 6: Membership functions for the proposed FLC

Table 3. The Ruleset of FLC

E	ΔE						
	NB	**NM**	**NS**	**Z**	**PS**	**PM**	**PB**
NB	NB	NB	NB	NB	NM	NS	Z
NM	NB	NB	NB	NM	NS	Z	PS
NS	NB	NB	NM	NS	Z	PS	PM
Z	NB	NM	NS	Z	PS	PM	PB
PS	NM	NS	Z	PS	PM	PB	PB
PM	NS	Z	PS	PM	PB	PB	PB
PB	Z	PS	PM	PB	PB	PB	PB

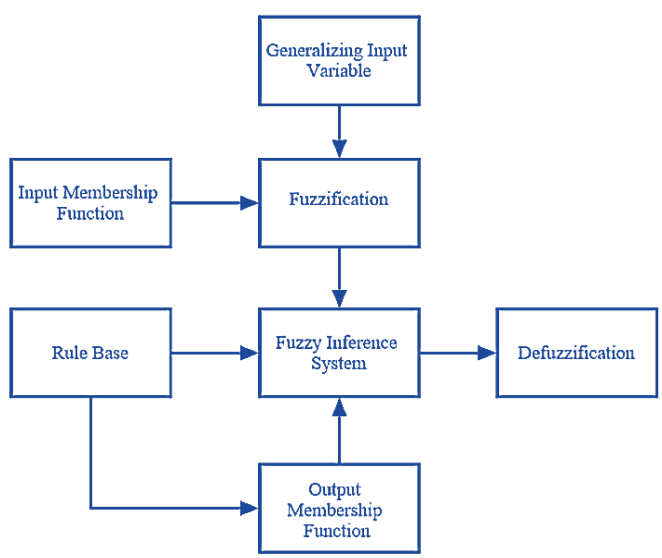


Figure 7: Flowchart of fuzzy system

CASE 1: The electrical network at normal operation considering variable voltage source without STATCOM and utilizing a controller-based STATCOM "PI controller and FLC".

Table 4 describes comparison among the recorded as well as the simulated values of voltage in the system bus B1 to bus B11. It is noted that the percentage difference between the measured and the simulated values of voltages of the system buses ranges between (0.24-1.71) percent.

Table 4. Comparison Between the Measured Voltages versus the Simulated Voltages in Pu

Bus ID	Measured voltage (pu)	Simulated voltage (pu)	Percentage difference (%)
B1	0.9697	0.9573	1.24
B2	0.9393	0.9369	0.24
B3	0.9393	0.9368	0.25
B4	0.9363	0.9278	0.85
B5	0.9363	0.9277	0.86
B6	0.9393	0.9243	1.5
B7	0.9363	0.9222	1.71
B8	0.9242	0.9093	1.49
B9	0.9242	0.9073	1.69
B10	0.8485	0.8538	-0.53
B11	0.8485	0.8581	-0.96

Fig. 8a to Fig. 18a show the voltage waveforms of bus B1 to bus B11 at normal operation without using STATCOM. These waveforms illustrate that the voltage is changed significantly according to changing the voltage source between t = 0 seconds and t = 0.5 seconds. The voltage waveforms bus B1 to bus B11 at normal operation with using STATCOM based on PI controller are shown in Fig. 8b to Fig. 18b. These Figs demonstrate that the voltage profile is improved ominously more than not using STATCOM despite changing the voltage source. Fig. 8c to Fig. 18c show the voltage waveforms of bus B1 to bus B11 at normal operation with using STATCOM based on fuzzy controller. From these waveforms, the voltage profile is improved significantly more than STATCOM based on PI controller or not using STATCOM in spite of the change in voltage source. So, the voltage stability in that system at normal operation is enhanced with using STATCOM based on FLC than PI control or not using the STATCOM devices.

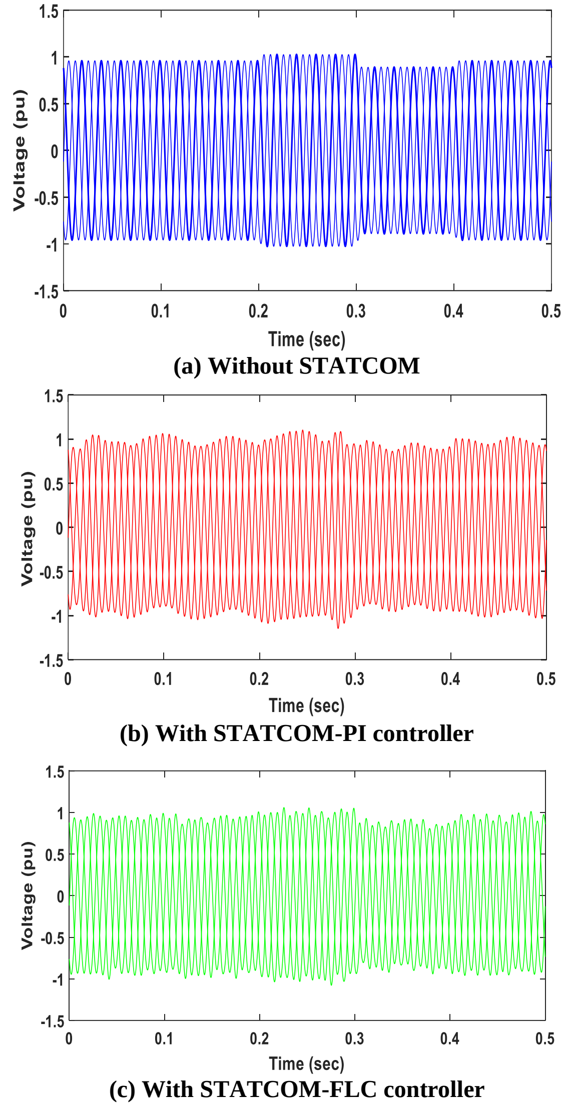
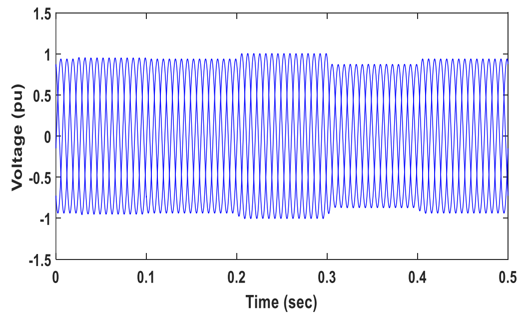
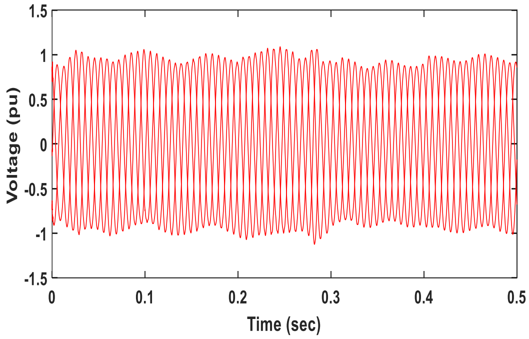


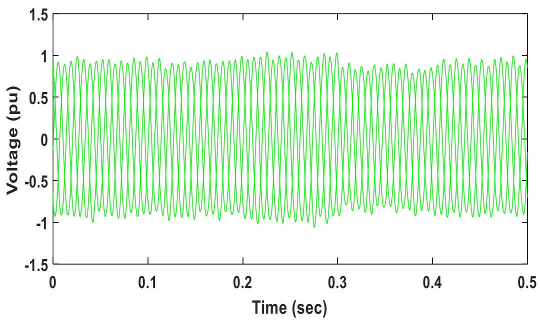
Figure 8: The patterns of voltage waves on the B1 bus without, with STATCOM-PI controller and STATCOM-FLC under standard operation



(a) Without STATCOM

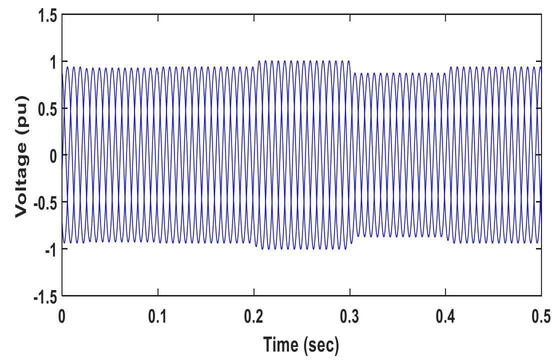


(b) With STATCOM-PI controller

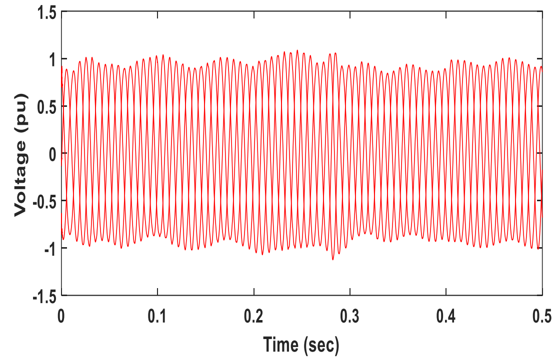


(c) With STATCOM-FLC controller

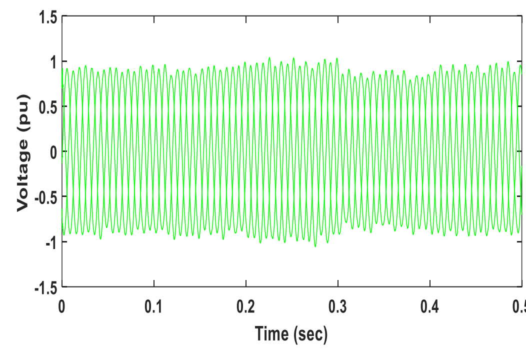
Figure 9: The patterns of voltage waves on the B2 bus without, with STATCOM-PI controller and STATCOM-FLC under standard operation



(a) Without STATCOM

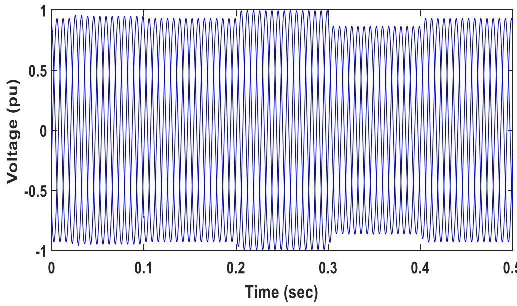


(b) With STATCOM-PI controller

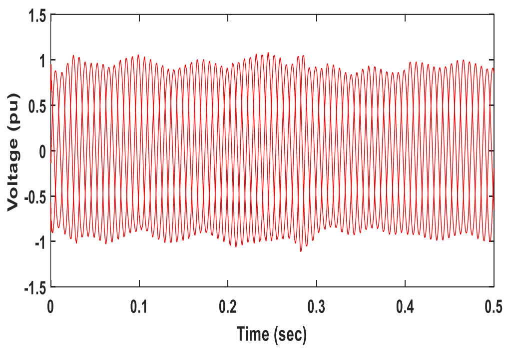


(c) With STATCOM-FLC controller

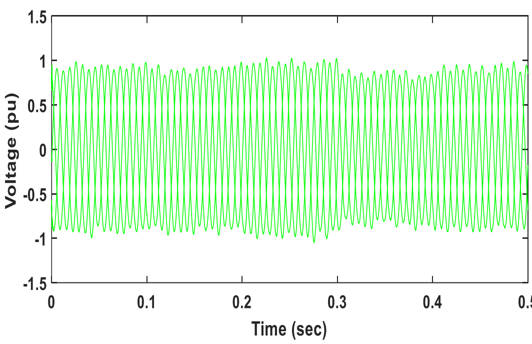
Figure 10: The patterns of voltage waves on the B3 bus without, with STATCOM-PI controller and STATCOM-FLC under standard operation



(a) Without STATCOM

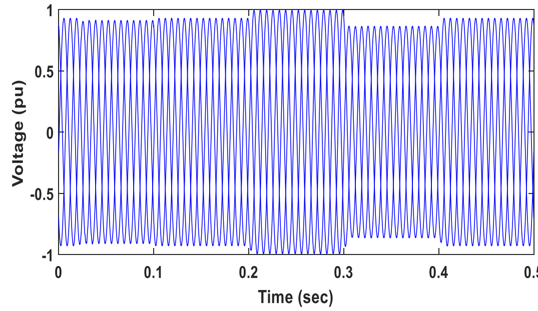


(b) With STATCOM-PI controller

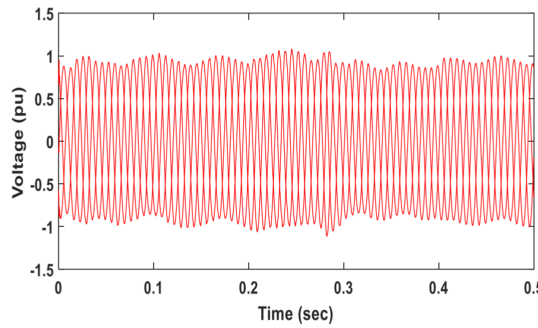


(c) With STATCOM-FLC controller

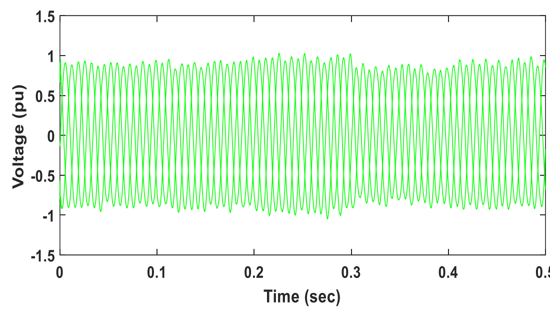
Figure 11: The patterns of voltage waves on the B4 bus without, with STATCOM-PI controller and STATCOM-FLC under standard operation



(a) Without STATCOM

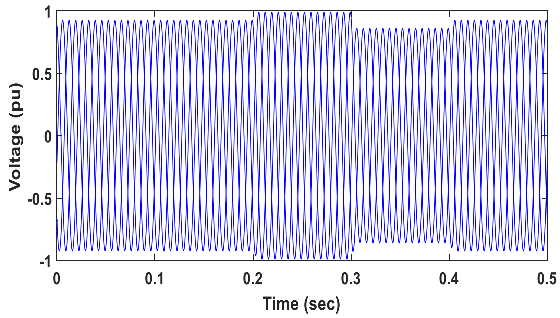


(b) With STATCOM-PI controller

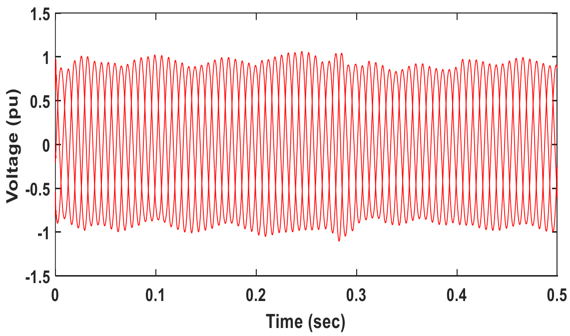


(c) With STATCOM-FLC controller

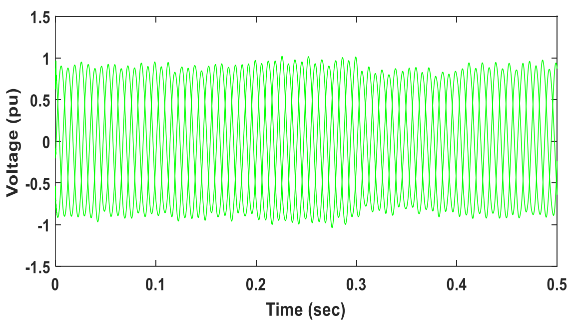
Figure 12: The patterns of voltage waves on the B5 bus without, with STATCOM-PI controller and STATCOM-FLC under standard operation



(a) Without STATCOM

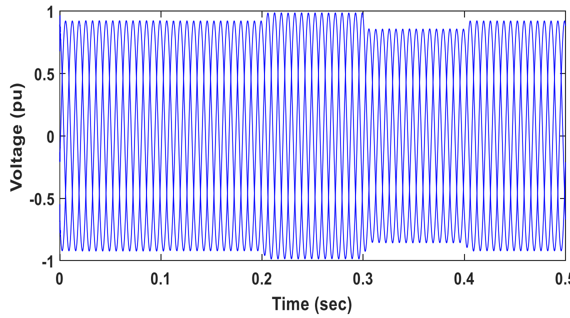


(b) With STATCOM-PI controller

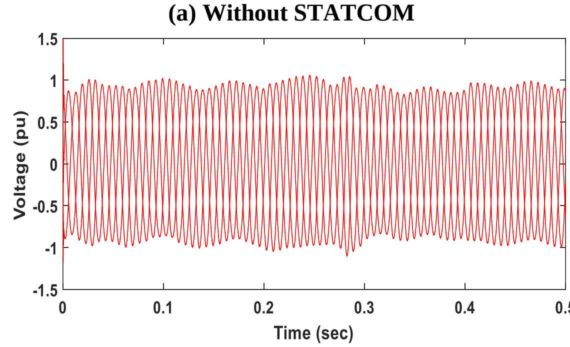


(c) With STATCOM-FLC controller

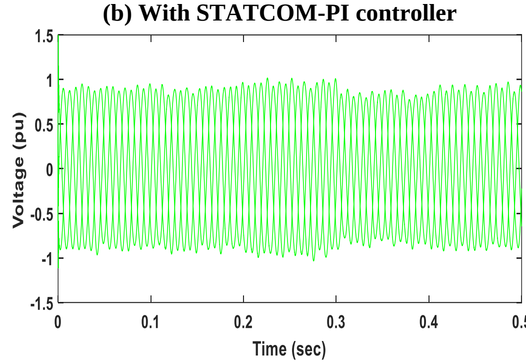
Figure 13: The patterns of voltage waves on the B6 bus without, with STATCOM-PI controller and STATCOM-FLC under standard operation



(a) Without STATCOM

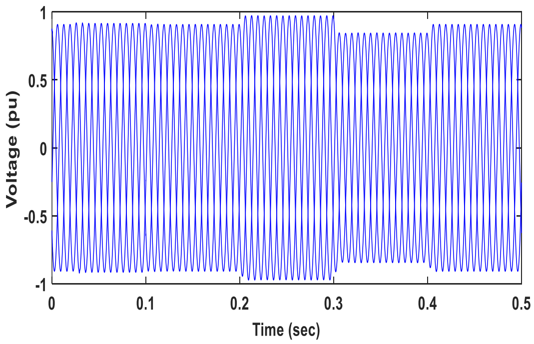


(b) With STATCOM-PI controller

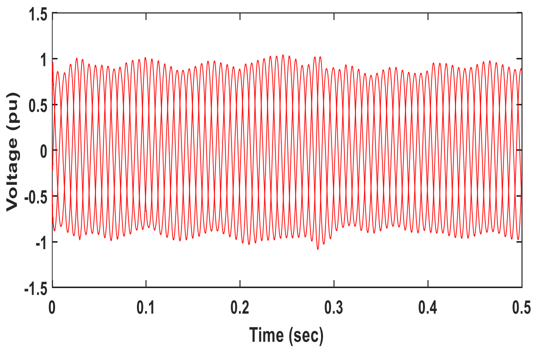


(c) With STATCOM-FLC controller

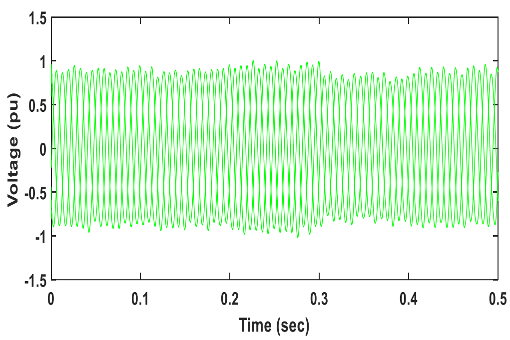
Figure 14: The patterns of voltage waves on the B7 bus without, with STATCOM-PI controller and STATCOM-FLC under standard operation



(a) Without STATCOM

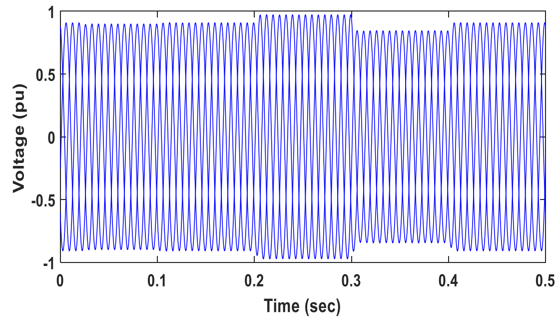


(b) With STATCOM-PI controller

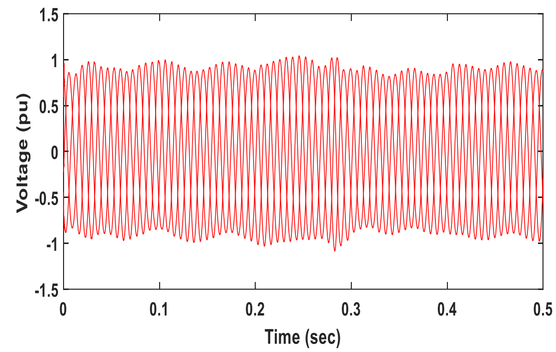


(c) With STATCOM-FLC controller

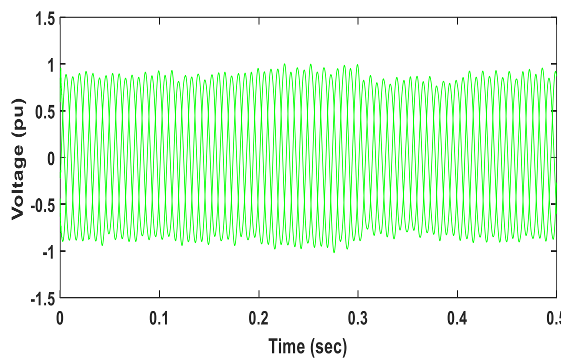
Figure 15: The patterns of voltage waves on the B8 bus without, with STATCOM-PI controller and STATCOM-FLC under standard operation



(a) Without STATCOM

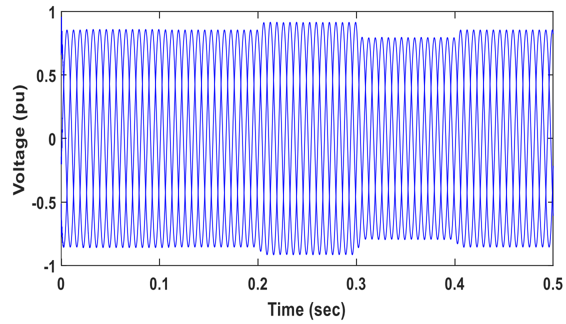


(b) With STATCOM-PI controller

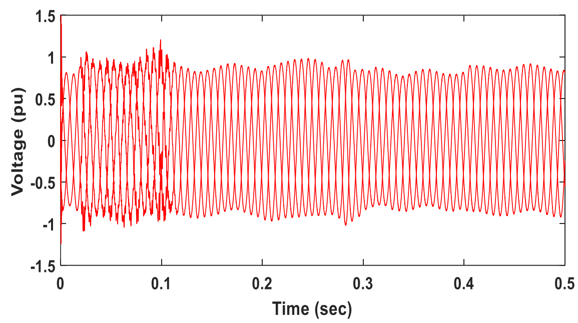


(c) With STATCOM-FLC controller

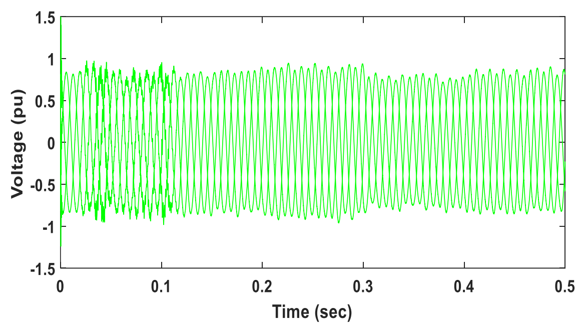
Figure 16: The patterns of voltage waves on the B9 bus without, with STATCOM-PI controller and STATCOM-FLC under standard operation



(a) Without STATCOM

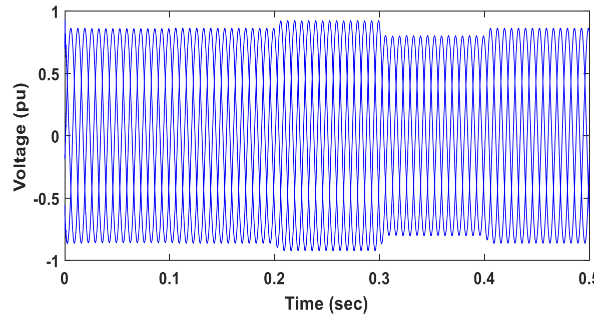


(b) With STATCOM-PI controller

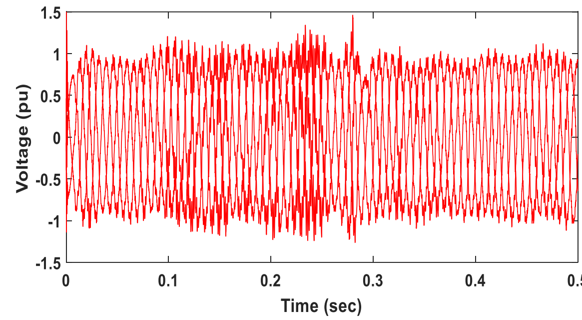


(c) With STATCOM-FLC controller

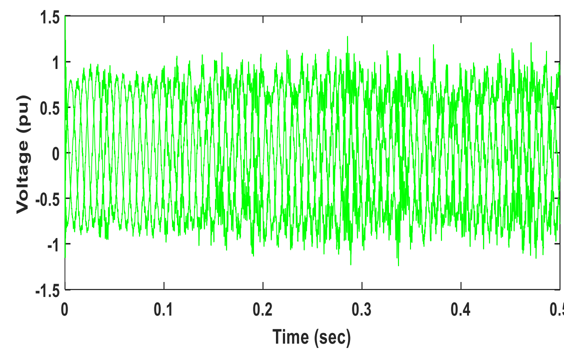
Figure 17: The patterns of voltage waves on the B10 bus without, with STATCOM-PI controller and STATCOM-FLC under standard operation



(a) Without STATCOM



(b) With STATCOM-PI controller



(c) With STATCOM-FLC controller

Fig. 18. The patterns of voltage waves on the B11 bus without, with STATCOM-PI controller and STATCOM-FLC under standard operation.

Fig. 19 to Fig. 21 show the voltage waveforms of buses B1, B5 and B11 at normal operation without using STATCOM, with STATCOM-PI controller and STATCOM-FLC. The comparisons of these wave shapes demonstrate that voltage stability in the system during normal operation is improved when employing the STATCOM with FLC compared to the use of the PI controller or operating without STATCOM devices.

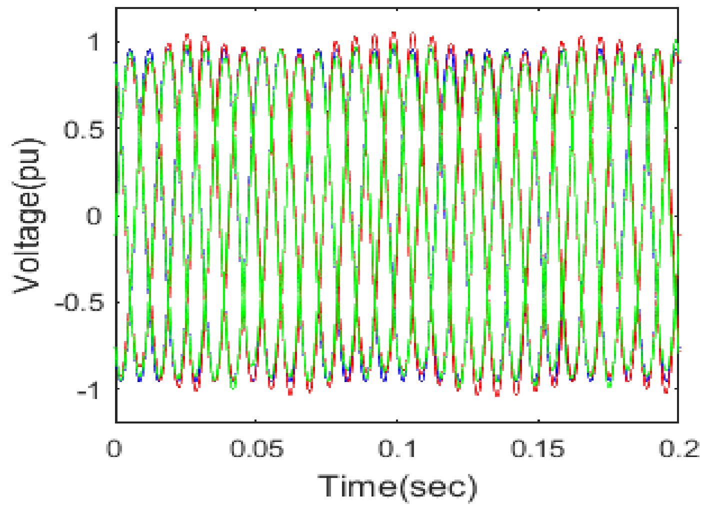


Figure 19: The pattern of voltage waves on the B1 bus without, with STATCOM-PI controller and STATCOM-FLC under standard operation

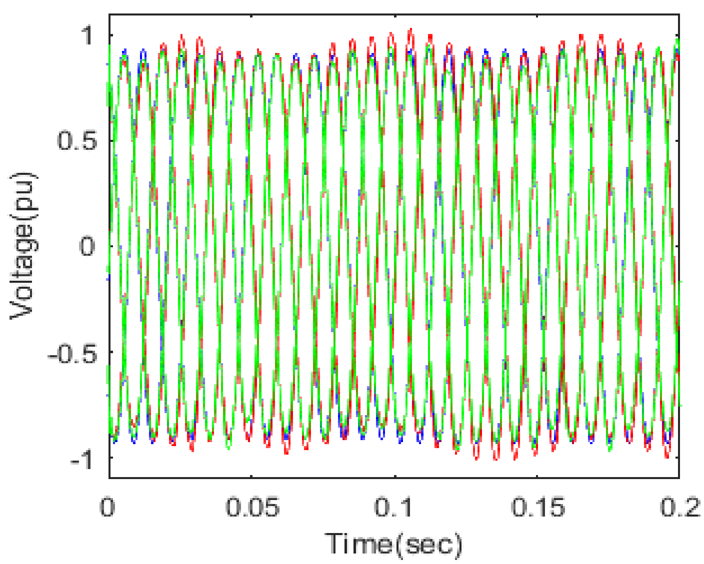


Figure 20: The pattern of voltage waves on the B5 bus without, with STATCOM-PI controller and STATCOM-FLC under standard operation

Table 5 describes the effect of STATCOM with two different controllers in system buses voltage in pu at normal operation. It is demonstrated that the percentage deviation of voltage from the expected value (1.00 pu) in the system without STATCOM device is increased and reached 14.62 % under normal operation whereas STATCOM with PI controller can reduce it to low values not exceed than 5.9 %. Furthermore, STATCOM with FLC gives better results than PI controller which the percentage deviation of voltage at all system buses is decreased to small values do not exceed than 4.67 %.

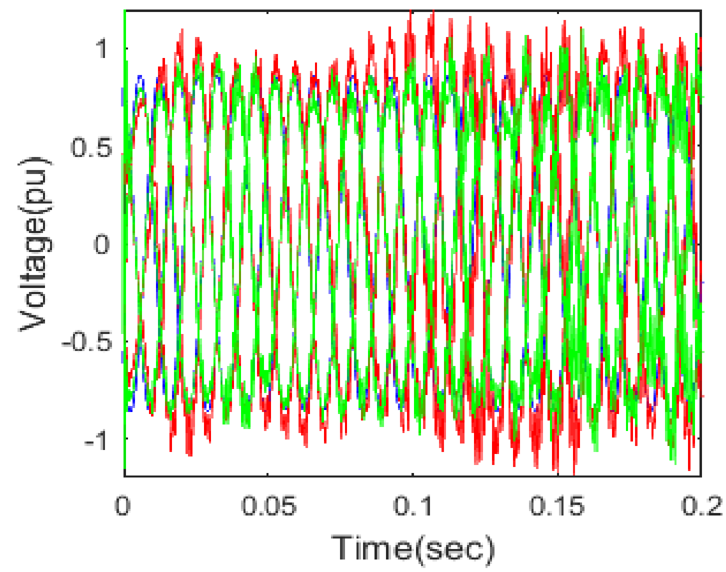


Figure 21: The pattern of voltage waves on the B11 bus without, with STATCOM-PI controller and STATCOM-FLC under standard operation

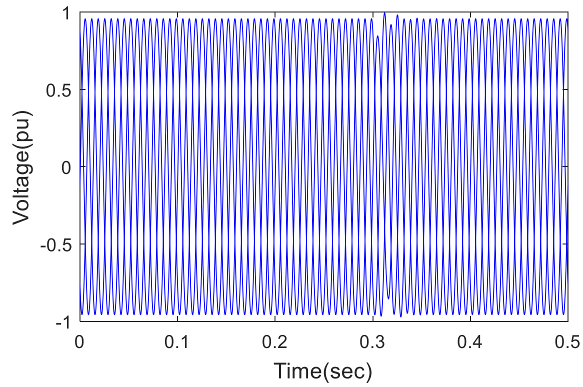
Table 5: Effect Of STATCOM with two Controllers in System Buses Voltage in Pu at Normal Operation

Bus ID	Without STATCOM		With STATCOM			
			PI Controller		Fuzzy Logic Controller	
	Voltage (pu)	Percentage Deviation (%)	Voltage (pu)	Percentage Deviation (%)	Voltage (pu)	Percentage Deviation (%)
B1	0.9573	4.27	1.046	-4.6	0.9869	1.31
B2	0.9369	6.31	1.038	-3.8	0.9887	1.13
B3	0.9368	6.32	1.039	-3.9	0.9888	1.12
B4	0.9278	7.22	1.034	-3.4	0.9851	1.49
B5	0.9277	7.23	1.031	-3.1	0.9813	1.87
B6	0.9243	7.57	1.007	-0.7	0.9697	3.03
B7	0.9222	7.78	1.008	-0.8	0.967	3.3
B8	0.9093	9.07	0.9968	0.32	0.9533	4.67
B9	0.9073	9.27	0.9967	0.33	0.9533	4.67
B10	0.8538	14.62	1.06	-6	0.9715	2.85
B11	0.8581	14.19	1.059	-5.9	0.9715	2.85

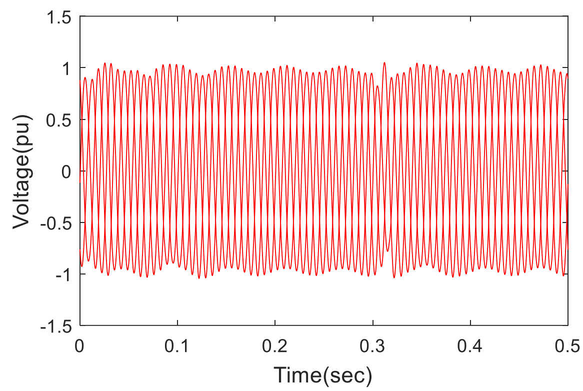
CASE 2: The electrical network with a single-phase grounding fault was initiated at load- A without STATCOM and utilizing a controller-based "PI controller and FLC".

Fig. 22a to Fig. 32a show the voltage waveforms of bus B1 to bus B11 under single-phase grounding fault was inserted at load A at t = (0.3-0.31) seconds without using STATCOM. The waveforms illustrate that the voltage is changed significantly in the period from t=0.3 sec to 0.31 sec through single-phase grounding fault at load A.

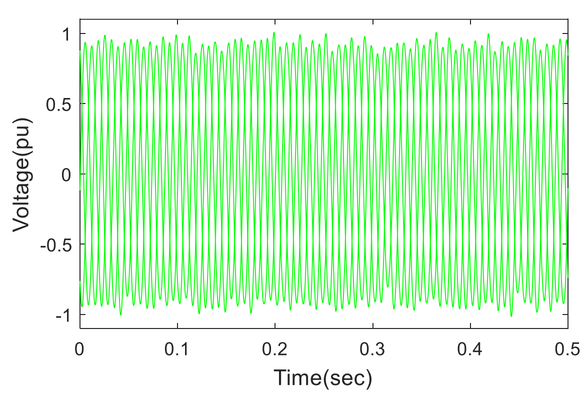
The voltage waveforms of bus B1 to bus B11 under single-phase grounding fault were inserted at load A at t = (0.3-0.31) seconds with using STATCOM based on PI controller are shown in Fig. 22b to Fig. 32b. These Figs demonstrate that the voltage profile is enhanced ominously more than not using STATCOM despite introducing single-phase grounding fault. Fig. 22c to Fig. 32c show the voltage waveforms of bus B1 to bus B11 with a single-phase grounding fault was inserted at load-A at t = (0.3-0.31) seconds with using STATCOM utilizing a fuzzy controller. From these waveforms, the voltage profile is improved significantly more than STATCOM utilizing a PI controller or not using STATCOM in spite of the change in voltage between t = 0.3 seconds and t = 0.31 seconds through fault period . So the stability of voltage in that system influenced by one-phase grounding fault is improved using STATCOM based on FLC than PI control or not using the STATCOM maneuvers.



(a) Without STATCOM

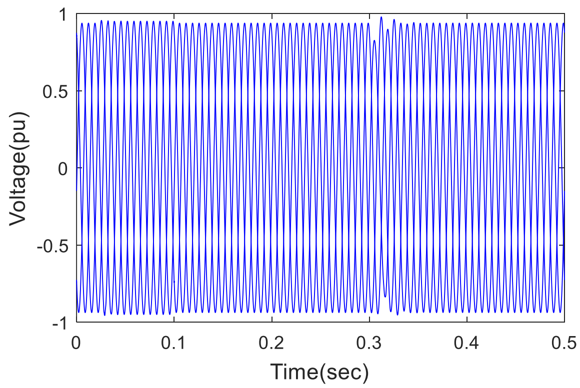


(b) With STATCOM-PI controller

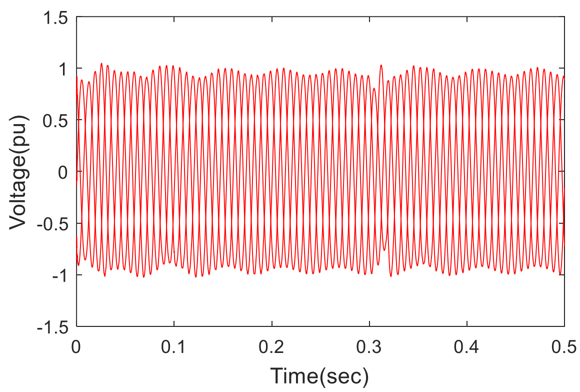


(c) With STATCOM-FLC controller

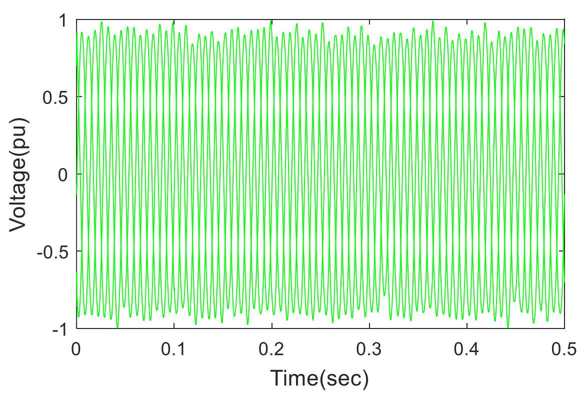
Figure 22: The patterns of voltage waves on the B1 bus without, with STATCOM-PI controller and STATCOM-FLC under single-phase grounding fault within load A introduced at t = (0.3-0.31) seconds



(a) Without STATCOM

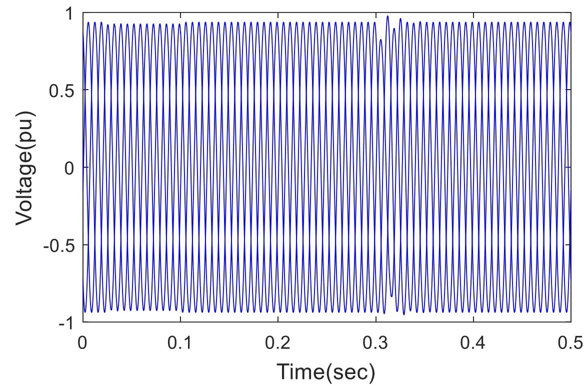


(b) With STATCOM-PI controller

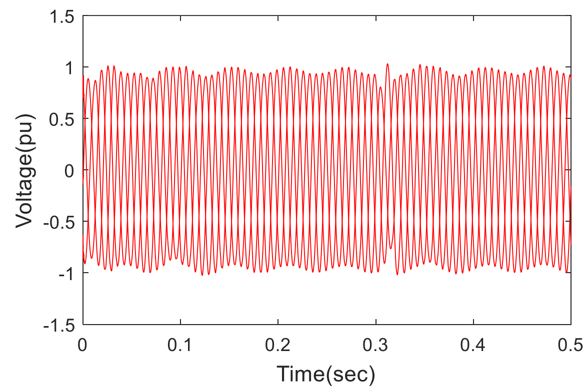


(c) With STATCOM-FLC controller

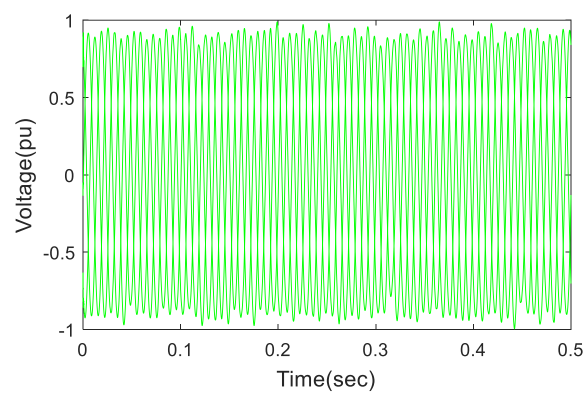
Figure 23: The patterns of voltage waves on the B2 bus without, with STATCOM-PI controller and STATCOM-FLC under single-phase grounding fault within load A introduced at t = (0.3-0.31) seconds



(a) Without STATCOM

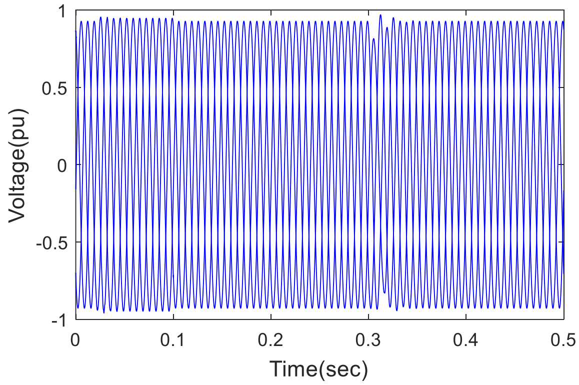


(b) With STATCOM-PI controller

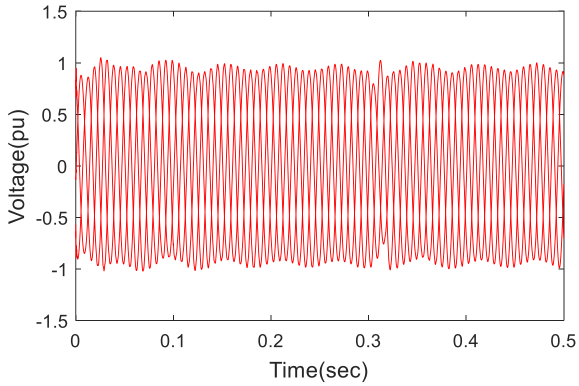


(c) With STATCOM-FLC controller

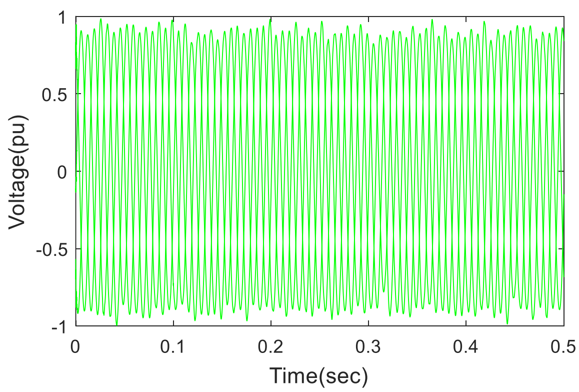
Figure 24: The patterns of voltage waves on the B3 bus without, with STATCOM-PI controller and STATCOM-FLC under single-phase grounding fault within load A introduced at t = (0.3-0.31) seconds



(a) Without STATCOM

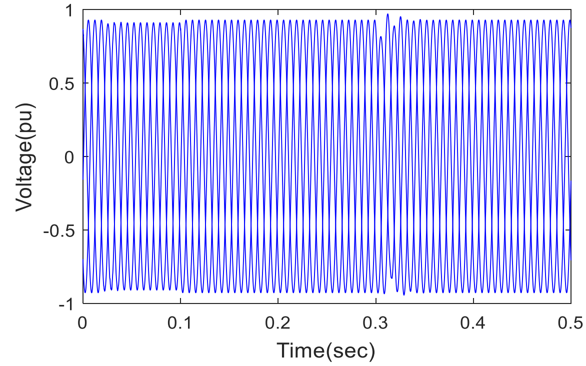


(b) With STATCOM-PI controller

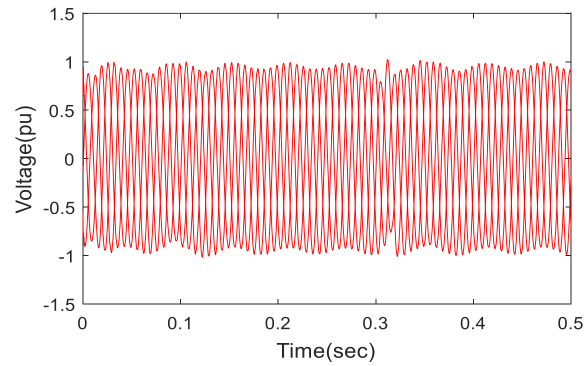


(c) With STATCOM-FLC controller

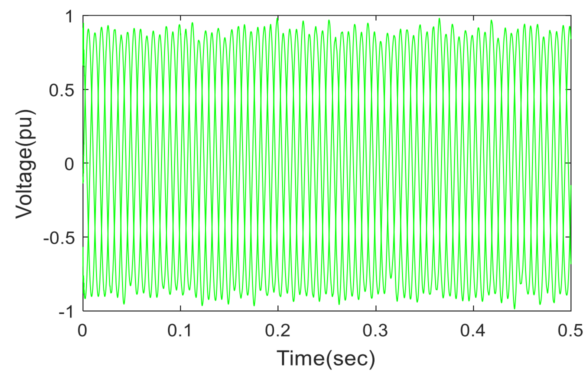
Figure 25: The patterns of voltage waves on the B4 bus without, with STATCOM-PI controller and STATCOM-FLC under single-phase grounding fault within load A introduced at t = (0.3-0.31) seconds



(a) Without STATCOM

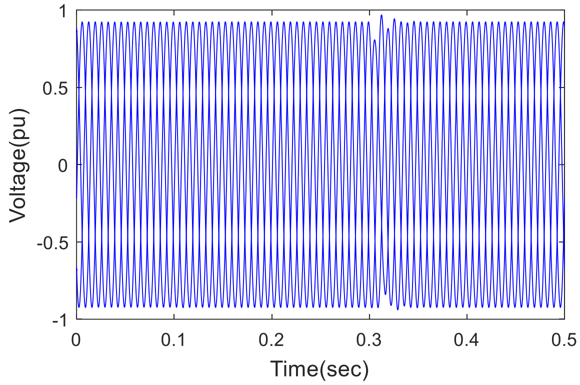


(b) With STATCOM-PI controller

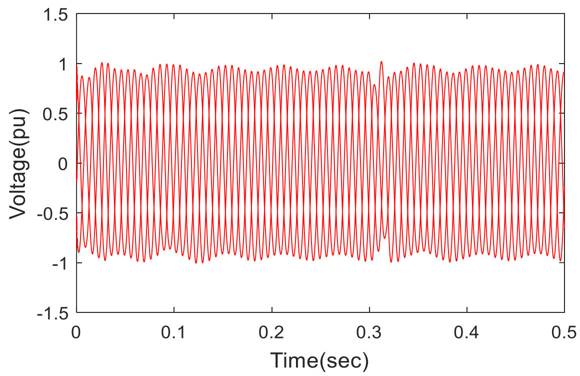


With STATCOM-FLC controller

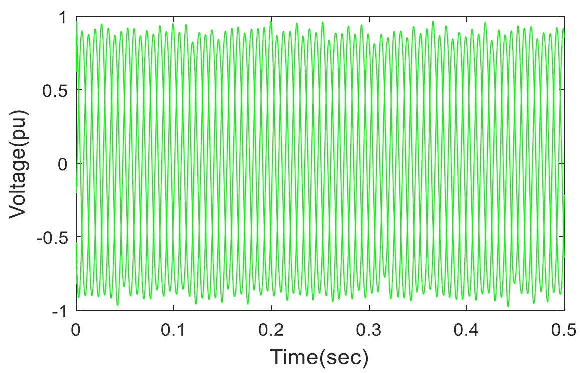
Figure 26: The patterns of voltage waves on the B5 bus without, with STATCOM-PI controller and STATCOM-FLC under single-phase grounding fault within load A introduced at t = (0.3-0.31) seconds



(a) Without STATCOM

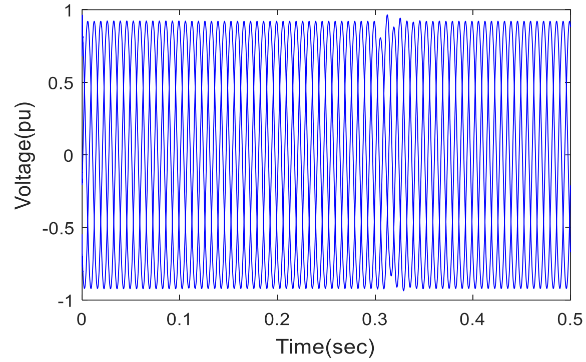


(b) With STATCOM-PI controller

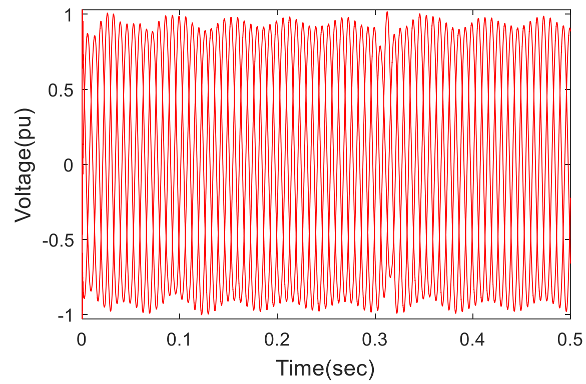


(c) With STATCOM-FLC controller

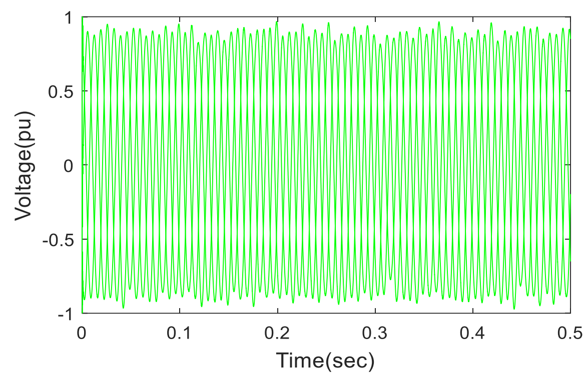
Figure 27: The patterns of voltage waves on the B6 bus without, with STATCOM-PI controller and STATCOM-FLC under single-phase grounding fault within load A introduced at t = (0.3-0.31) seconds



(a) Without STATCOM

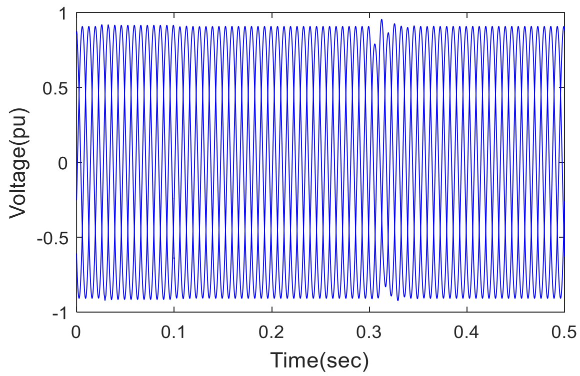


(b) With STATCOM-PI controller

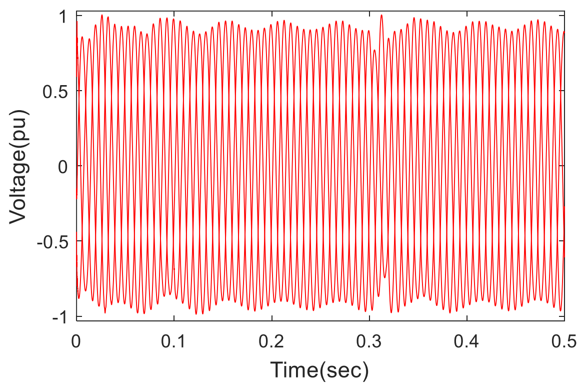


(c) With STATCOM-FLC controller

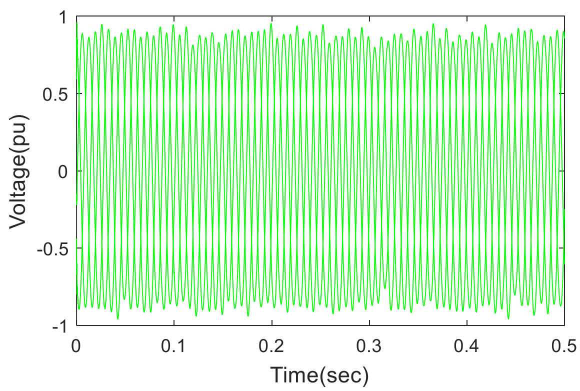
Figure 28: The patterns of voltage waves on the B7 bus without, with STATCOM-PI controller and STATCOM-FLC under single-phase grounding fault within load A introduced at t = (0.3-0.31) seconds



(a) Without STATCOM

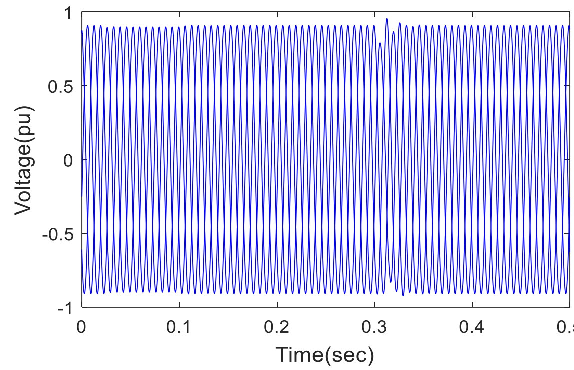


(b) With STATCOM-PI controller

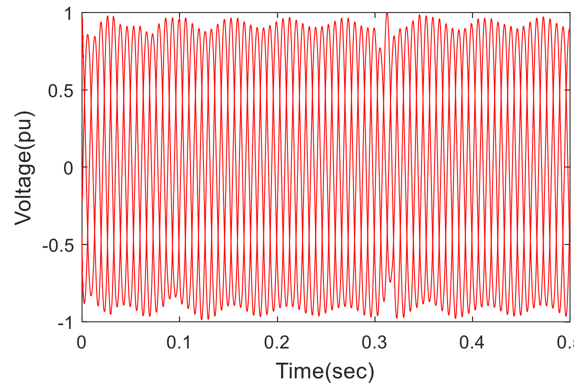


(c) With STATCOM-FLC controller

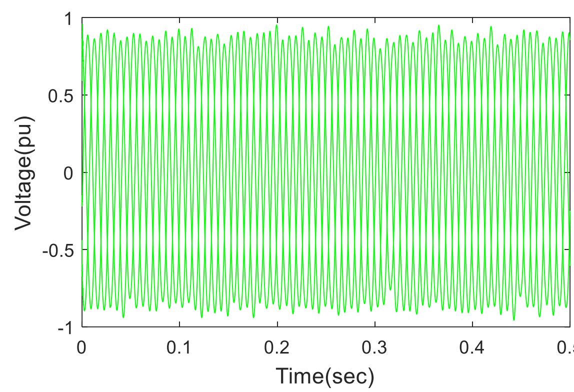
Figure 29: The patterns of voltage waves on the B8 bus without, with STATCOM-PI controller and STATCOM-FLC under single-phase grounding fault within load A introduced at t = (0.3-0.31) seconds



(a) Without STATCOM

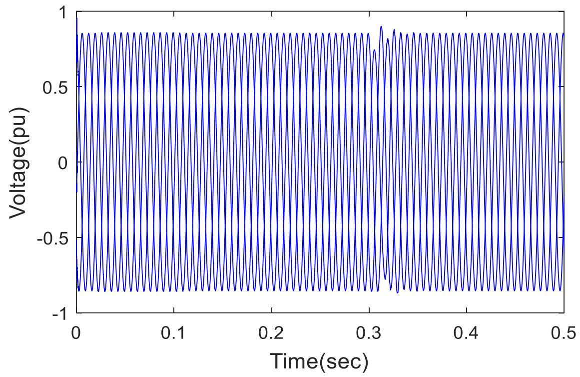


(b) With STATCOM-PI controller

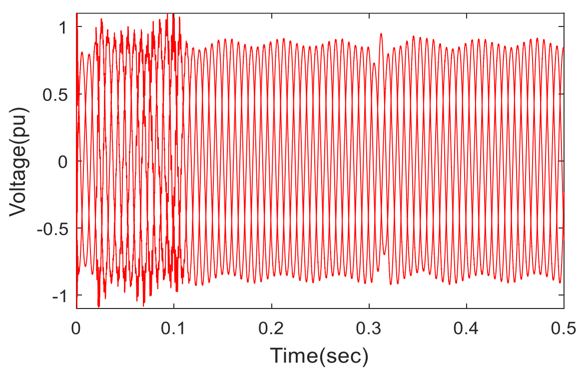


(c) With STATCOM-FLC controller

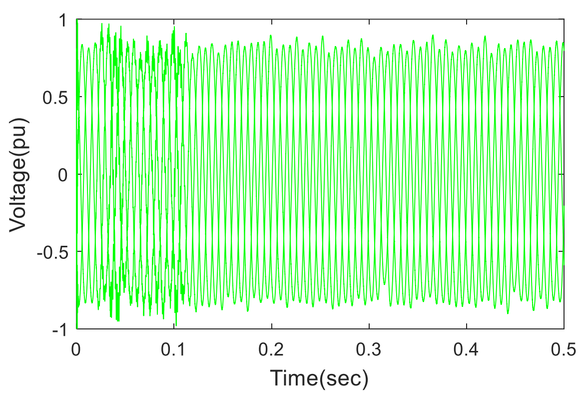
Figure 30: The patterns of voltage waves on the B9 bus without, with STATCOM-PI controller and STATCOM-FLC under single-phase grounding fault within load A introduced at t = (0.3-0.31) seconds



(a) Without STATCOM

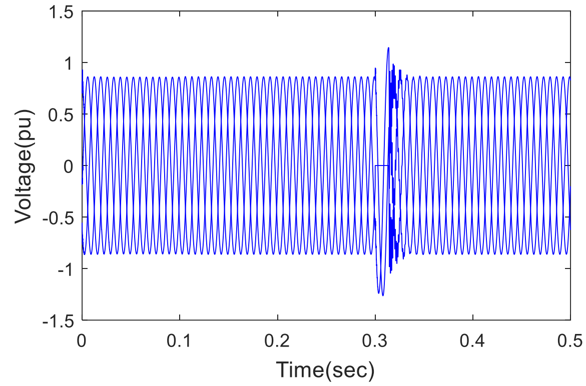


(b) With STATCOM-PI controller

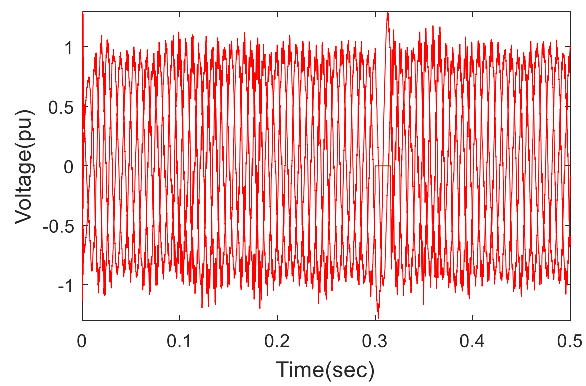


(c) With STATCOM-FLC controller

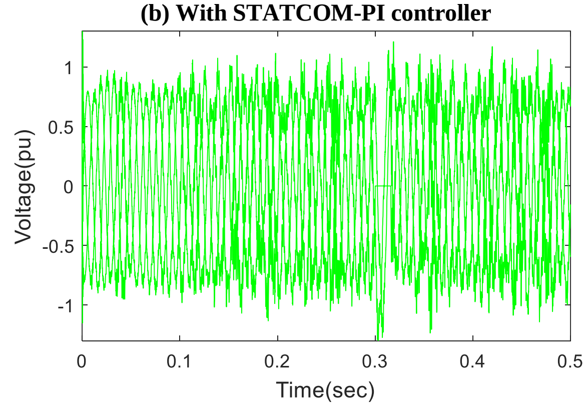
Figure 31: The patterns of voltage waves on the B10 bus without, with STATCOM-PI controller and STATCOM-FLC under single-phase grounding fault within load A introduced at t = (0.3-0.31) seconds.



(a) Without STATCOM



(b) With STATCOM-PI controller



(c) With STATCOM-FLC controller

Figure 32: The patterns of voltage waves on the B11 bus without, with STATCOM-PI controller and STATCOM-FLC under single-phase grounding fault within load A introduced at t = (0.3-0.31) seconds

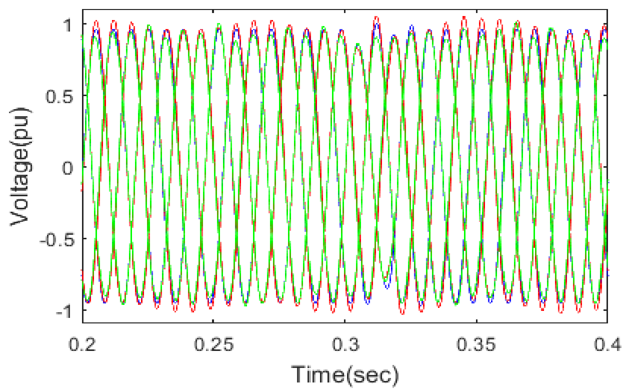


Figure 33: The pattern of voltage waves on the B1 bus without, with STATCOM-PI controller and STATCOM-FLC under single-phase grounding fault within load A introduced at t = (0.3-0.31) seconds

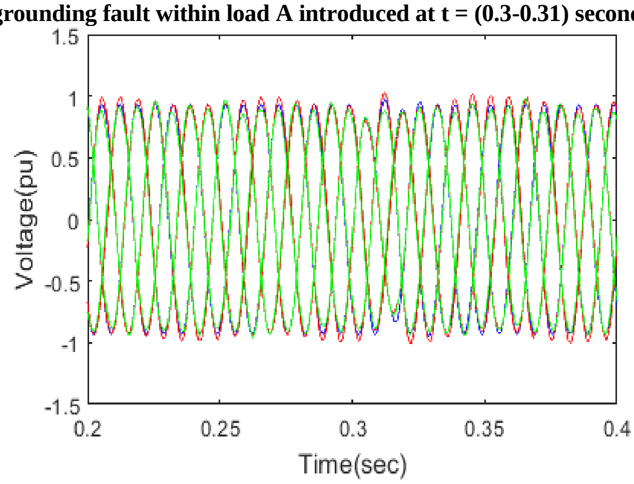


Figure 34: The pattern of voltage waves on the B5 bus without, with STATCOM-PI controller and STATCOM-FLC under single-phase grounding fault within load A introduced at t = (0.3-0.31) seconds

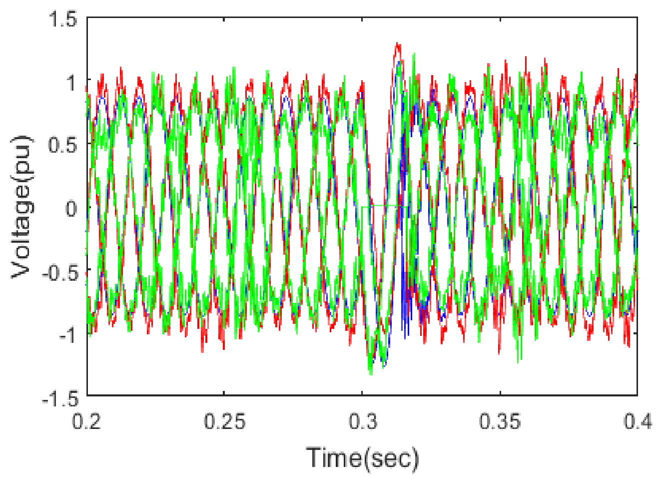
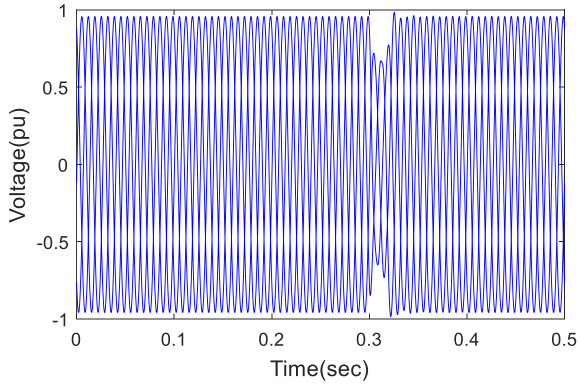


Figure 34b: The pattern of voltage waves on the B11 bus without, with STATCOM-PI controller and STATCOM-FLC under single-phase grounding fault within load A introduced at t = (0.3-0.31) seconds

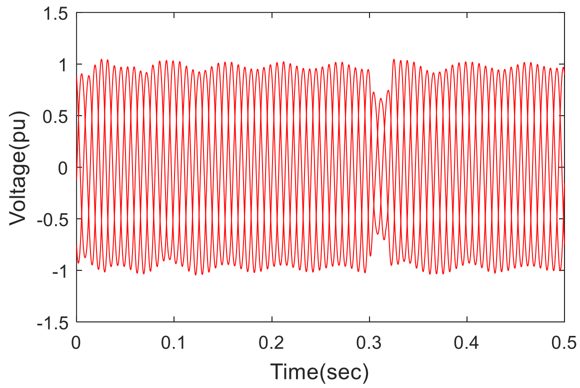
CASE 3: The electrical network with a three-phase grounding fault was initiated at load-A without STATCOM and utilizing a controller-based "PI controller and FLC".

Figs. 35a to 45a show the voltage waveforms of bus B1 to bus B11 with a three-phase grounding fault was inserted at load-A at t = (0.3-0.31) seconds without using STATCOM. The waveforms demonstrate that the voltage is varied significantly in the period from t=0.3 sec to 0.31 sec through three-phase grounding fault at load A.

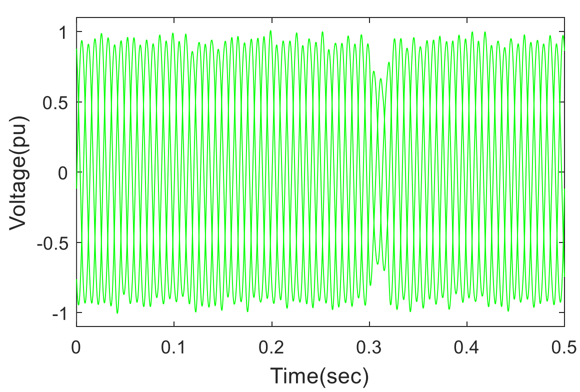
. The voltage waveforms of bus B1 to bus B11 under three-phase grounding fault was inserted at load-A at t = (0.3-0.31) seconds with using STATCOM based on PI controller are shown in Fig. 35b to Fig. 45b. These Figs demonstrate that the voltage profile is improved significantly more than not using STATCOM despite of presenting three-phase grounding fault. Fig. 35c to Fig. 45c show the voltage waveforms of bus B1 to bus B11 under three line to ground fault was inserted at load A at t = (0.3-0.31) seconds with using STATCOM utilizing a fuzzy controller. From these waveforms, the voltage profile is improved suggestively more than STATCOM based on PI controller or not using STATCOM in spite of the change in voltage between t = 0.3 seconds and t = 0.31 seconds through fault period. Therefore the voltage stability in that system under a three-line rounding fault is enhanced through the use of STATCOM utilizing a FLC than PI control or not using the STATCOM devices.



(a) Without STATCOM

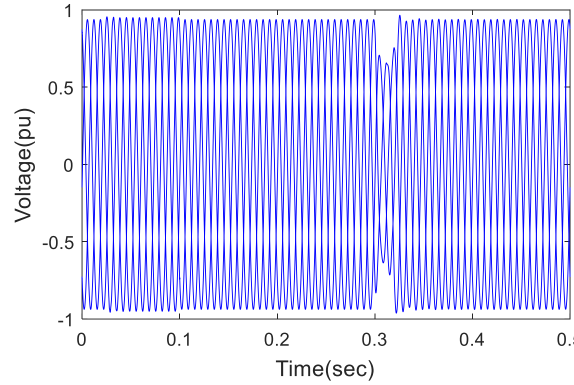


(b) With STATCOM-PI controller

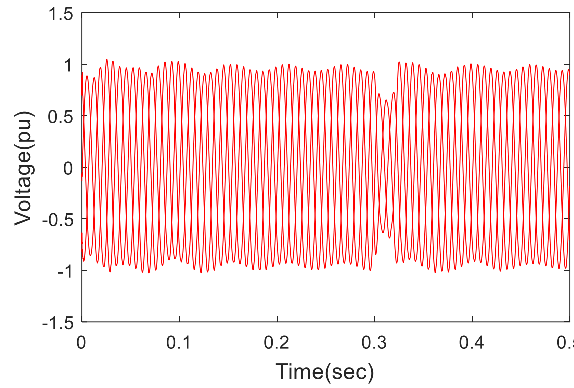


(c) With STATCOM-FLC controller

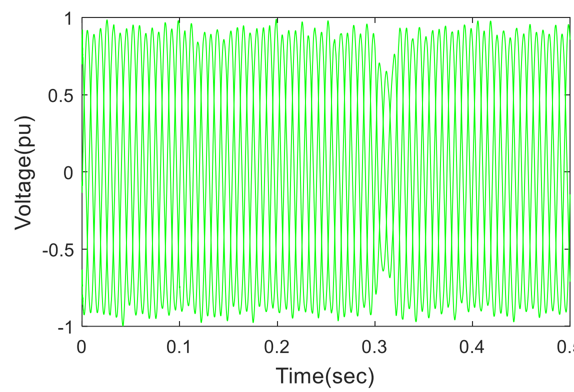
Figure 35: The patterns of voltage waves on the B1 bus without, with STATCOM-PI controller and STATCOM-FLC under three-phase to ground fault within load A introduced at t = (0.3-0.31) seconds



(a) Without STATCOM

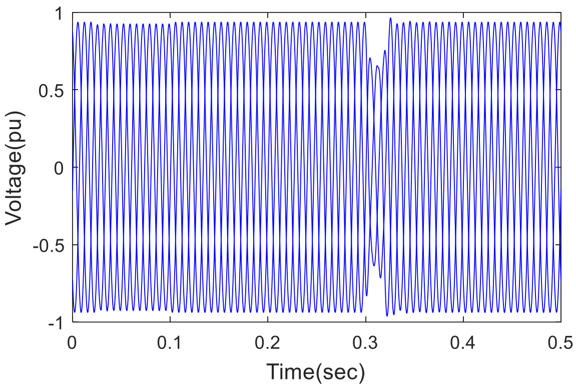


(b) With STATCOM-PI controller

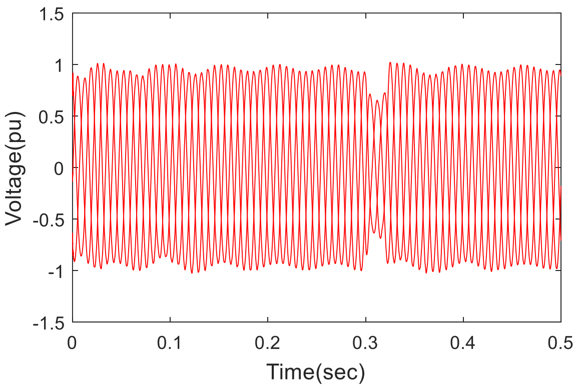


(c) With STATCOM-FLC controller

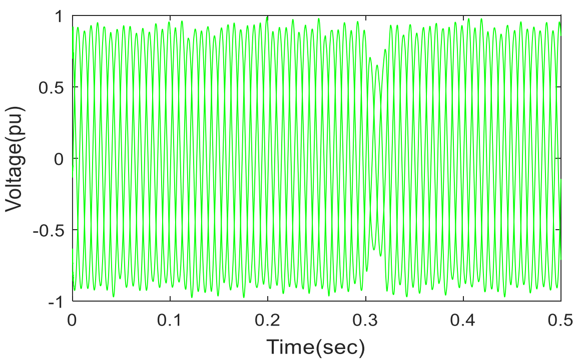
Figure 36: The patterns of voltage waves on the B2 bus without, with STATCOM-PI controller and STATCOM-FLC under three-phase to ground fault within load A introduced at t = (0.3-0.31) seconds



(a) Without STATCOM

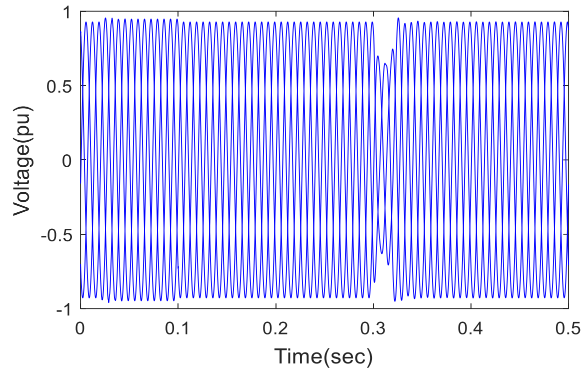


(b) With STATCOM-PI controller

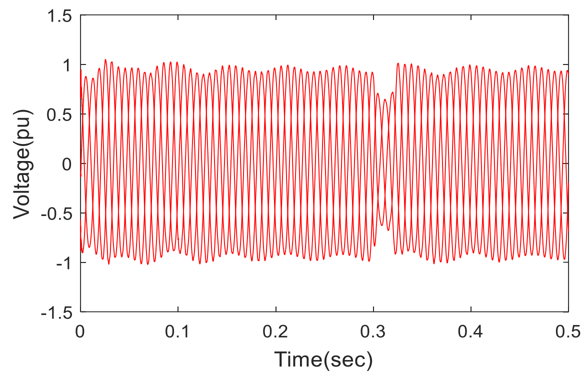


(c) With STATCOM-FLC controller

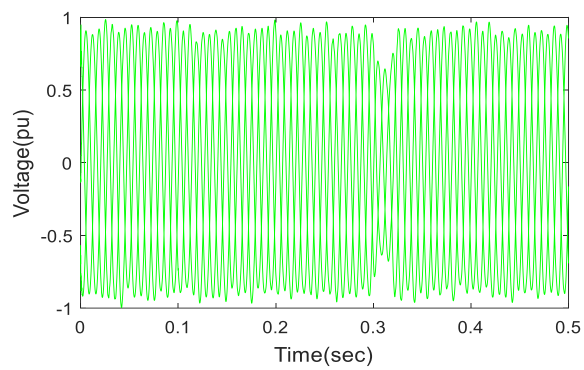
Figure 37: The patterns of voltage waves on the B3 bus without, with STATCOM-PI controller and STATCOM-FLC under three-phase to ground fault within load A introduced at t = (0.3-0.31) seconds



(a) Without STATCOM

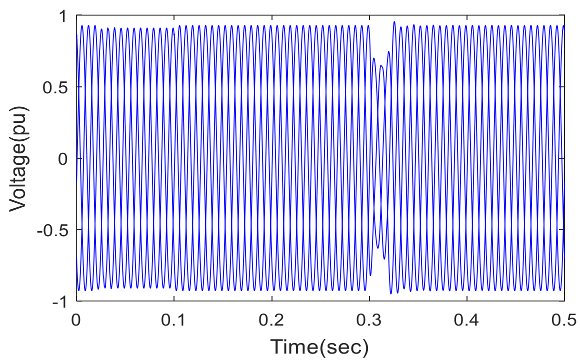


(b) With STATCOM-PI controller

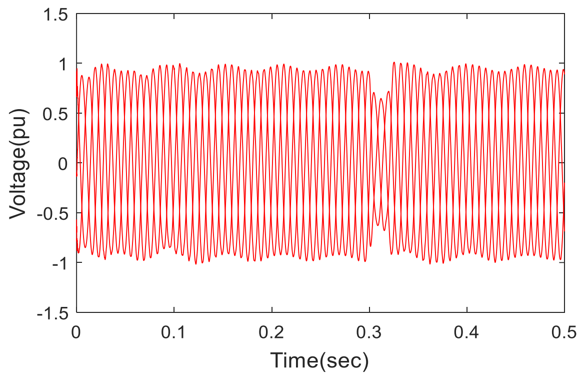


(c) With STATCOM-FLC controller

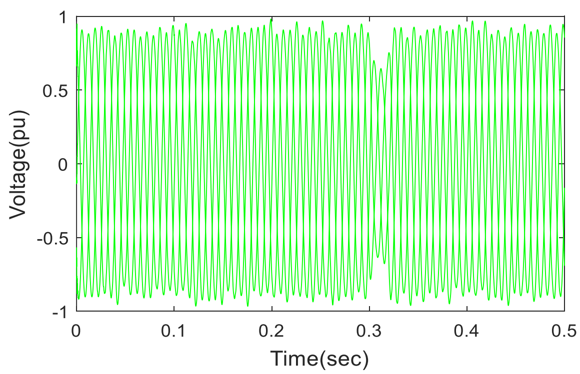
Figure 38: The patterns of voltage waves on the B4 bus without, with STATCOM-PI controller and STATCOM-FLC under three-phase to ground fault within load A introduced at t = (0.3-0.31) seconds



(a) Without STATCOM

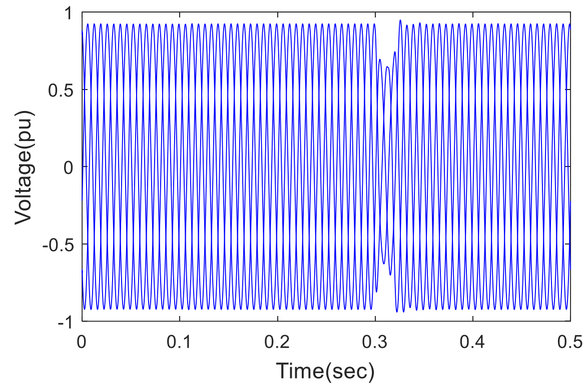


(b) With STATCOM-PI controller

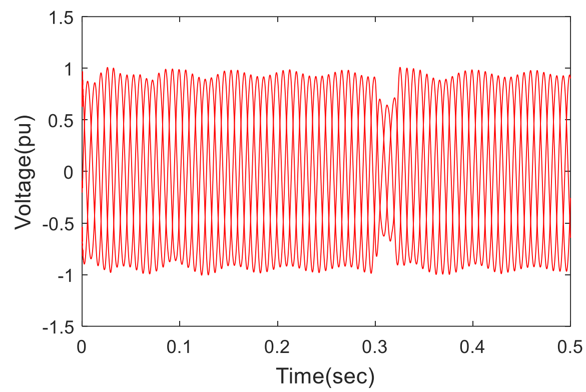


(c) With STATCOM-FLC controller

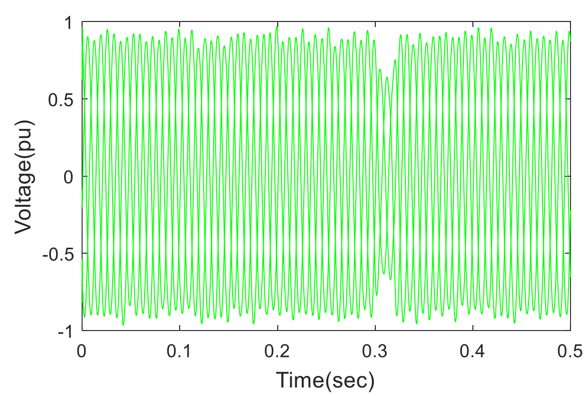
Figure 39: The patterns of voltage waves on the B5 bus without, with STATCOM-PI controller and STATCOM-FLC under three-phase to ground fault within load A introduced at t = (0.3-0.31) seconds



(a) Without STATCOM

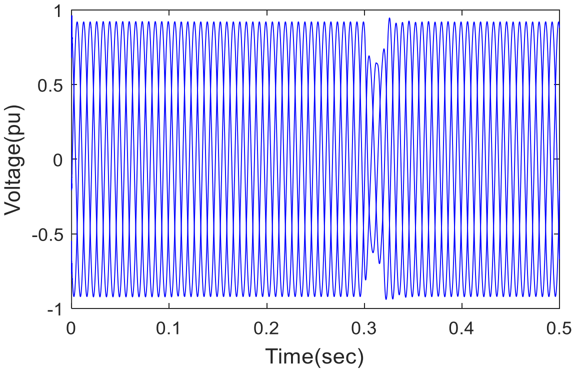


(b) With STATCOM-PI controller

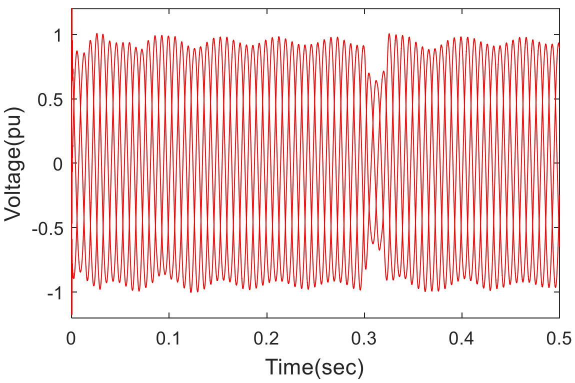


(c) With STATCOM-FLC controller

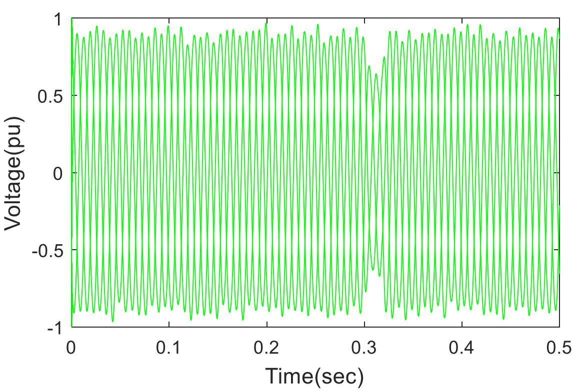
Figure 40: The patterns of voltage waves on the B6 bus without, with STATCOM-PI controller and STATCOM-FLC under three-phase to ground fault within load A introduced at t = (0.3-0.31) seconds



(a) Without STATCOM

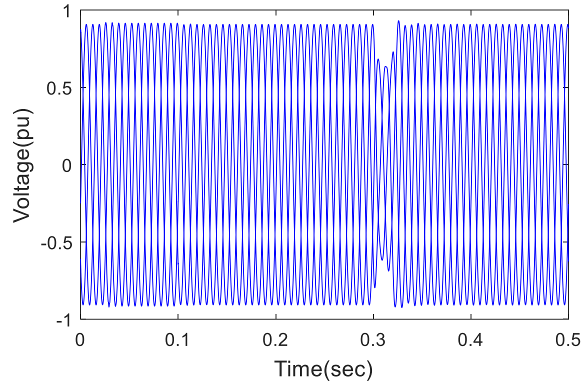


(b) With STATCOM-PI controller

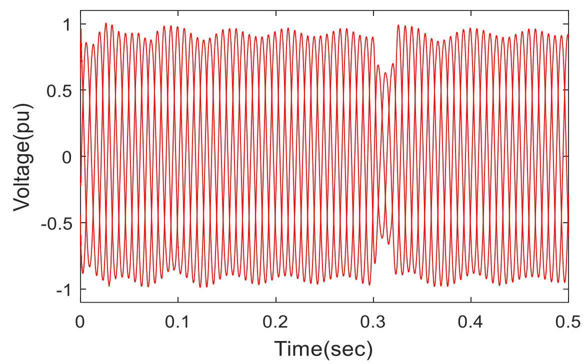


(c) With STATCOM-FLC controller

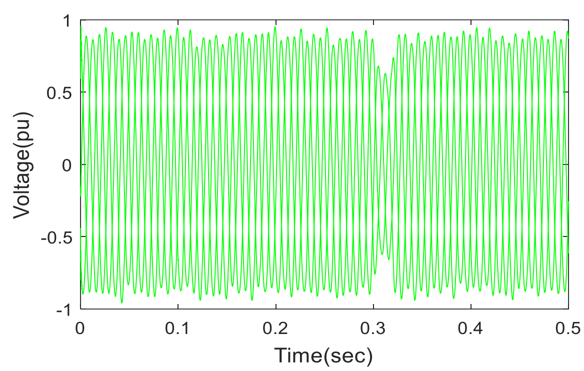
Figure 41: The patterns of voltage waves on the B7 bus without, with STATCOM-PI controller and STATCOM-FLC under three-phase to ground fault within load A introduced at t = (0.3-0.31) seconds



(a) Without STATCOM

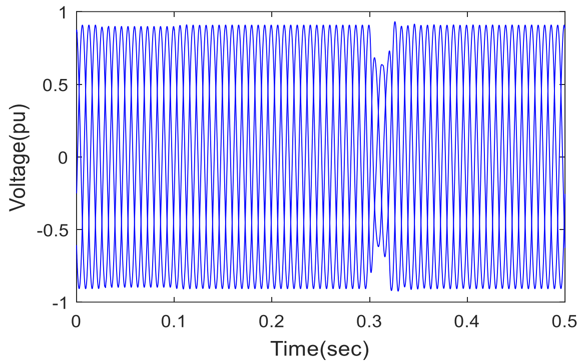


(b) With STATCOM-PI controller

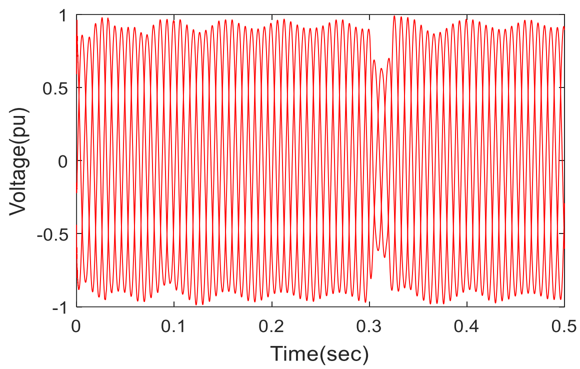


(c) With STATCOM-FLC controller

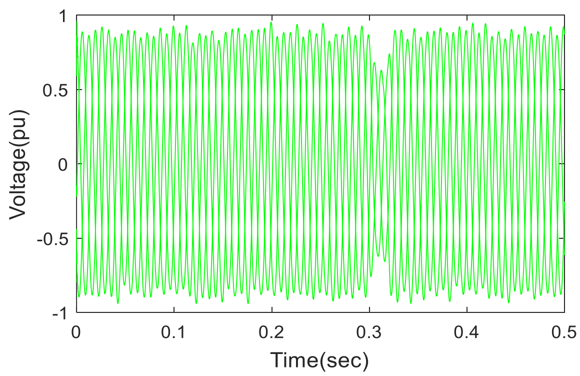
Figure 42: The patterns of voltage waves on the B8 bus without, with STATCOM-PI controller and STATCOM-FLC under three-phase to ground fault within load A introduced at t = (0.3-0.31) seconds



(a) Without STATCOM

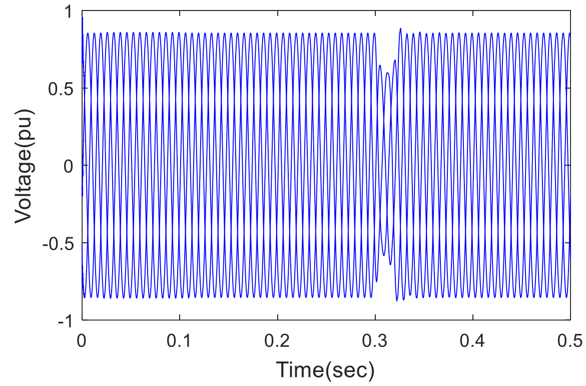


(b) With STATCOM-PI controller

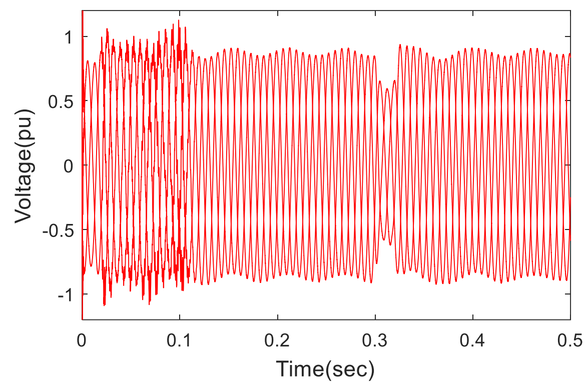


(c) With STATCOM-FLC controller

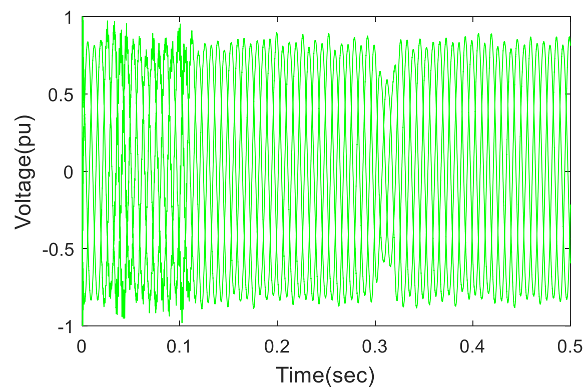
Figure 43: The patterns of voltage waves on the B9 bus without, with STATCOM-PI controller and STATCOM-FLC under three-phase to ground fault within load A introduced at t = (0.3-0.31) second



(a) Without STATCOM

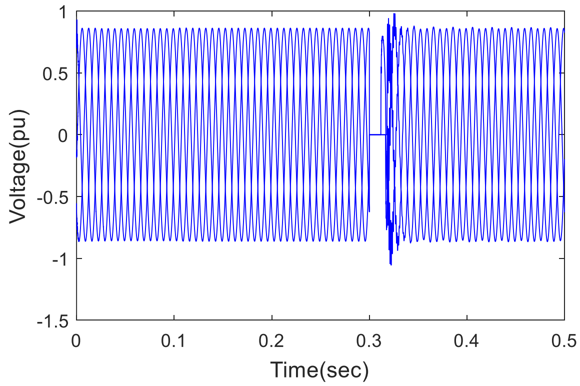


b) With STATCOM-PI controller

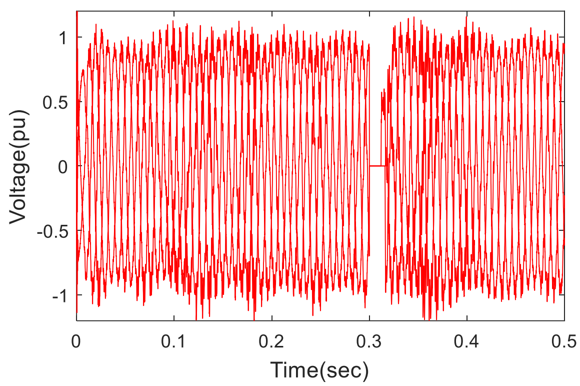


(c) With STATCOM-FLC controller

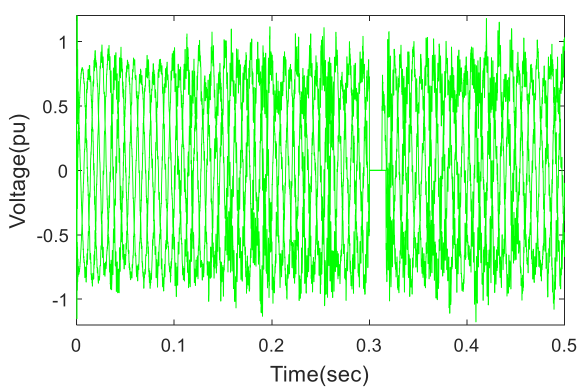
Figure 44: The patterns of voltage waves on the B10 bus without, with STATCOM-PI controller and STATCOM-FLC under three-phase to ground fault within load A introduced at t = (0.3-0.31) seconds



(a) Without STATCOM



b) With STATCOM-PI controller



(c) With STATCOM-FLC controller

Fig. 45: The patterns of voltage waves on the B11 bus without, with STATCOM-PI controller and STATCOM-FLC under three-phase to ground fault within load A introduced at t = (0.3-0.31) seconds

Fig. 46 to Fig. 48 show the voltage waveforms of buses B1, B5 and B11 under three-phase grounding fault was inserted at load A at t = (0.3-0.31) seconds without using STATCOM, with STATCOM-PI controller and STATCOM-FLC. The analysis of these waveforms indicates that voltage stability during a three-phase ground fault at load A is improved by employing a STATCOM with a FLC. This configuration outperforms both the use of a PI controller and the absence of any STATCOM devices under fault conditions.

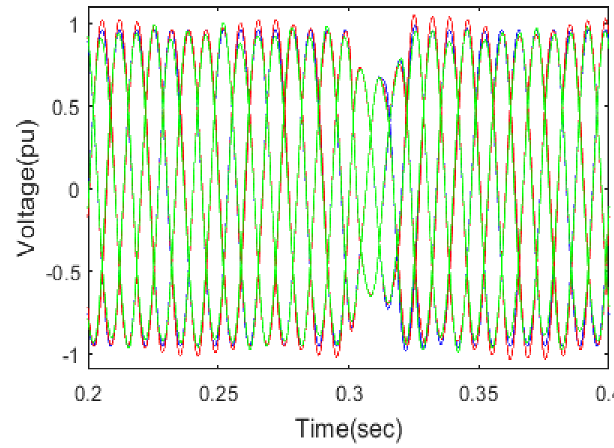


Figure 46: The pattern of voltage waves on the B1 bus without, with STATCOM-PI controller and STATCOM-FLC under three-phase grounding fault within load A introduced at t = (0.3-0.31) seconds

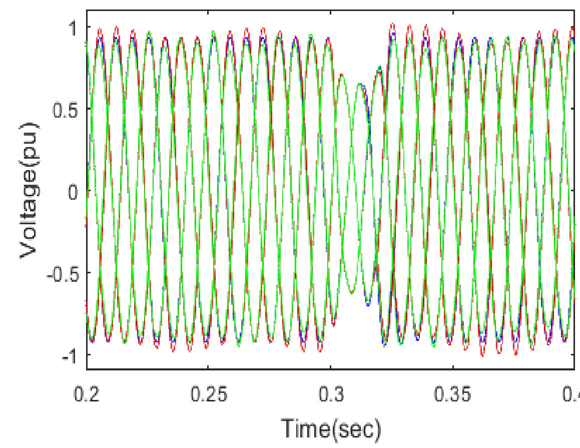


Figure 47. The pattern of voltage waves on the B5 bus without, with STATCOM-PI controller and STATCOM-FLC under three-phase grounding fault within load A introduced at t = (0.3-0.31) seconds

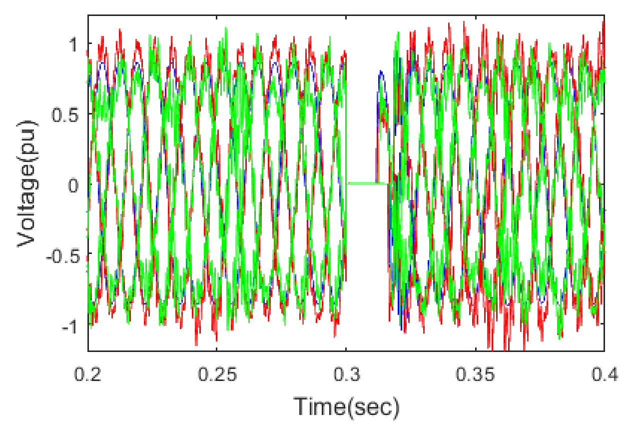


Figure 48: The pattern of voltage waves on the B11 bus without, with STATCOM-PI controller and STATCOM-FLC under three-phase grounding fault within load A introduced at t = (0.3-0.31) seconds

6. Discussion and Future Recommendations

The following presents a summary of the key findings from this research:

- The voltage across all buses in the system is changed significantly according to changing the voltage source and the use of STATCOM can enhance the voltage stability in the system. Besides the utilization of FLC with STATCOM gives the better response than PI controller.
- The voltage is decreased ominously during different faults conditions and the use of STATCOM with PI controller can improve the voltage profile than not using STATCOM device. The best performance is shown using STATCOM with fuzzy controller.
- Consequently, STATACOM utilizing FLC can give better response in the system as compared to PI controller despite of voltage change or faults conditions.

For future work, it is crucial to analyze the system alongside other FACTS technologies under a range of unusual circumstances across various locations within that system. It is also recommended to examine the system combined with renewable energy sources to assess the effects of utilizing FACTS devices under various conditions.

7. Conclusion

Outcomes of the electrical transmission network simulation using STATCOM are carried out at normal operation and across various irregular conditions to enhance the system's voltage stability utilizing the MATLAB/Simulink environment. The STATCOM device is interspersed with power lines at various distances. This STATCOM has been assessed as a voltage stabilizer which is capable of improving the voltage profiles. STATCOM could regulate the power system's voltage profile in response to fluctuations of ±7% relative to its specified voltage value. The STATCOM performance is considered using two diverse controllers: PI controllers and FLCs. A comparative analysis between the voltage wave shapes of the two different controllers under balanced and unbalanced conditions is performed in this work. The outcomes demonstrated that using a STATCOM with a FLC yields better results compared to a PI controller or the absence of FACTS devices, as the percentage deviation of voltage across all system buses is reduced to small values, not exceeding 4.67% during normal operation. Generally, the use of STATCOM devices with FLC could enhance the power system voltage and give better performance as compared to PI controller under different conditions.

Abbreviations

FACTS	Flexible AC Transmission Systems
STATCOM	Static Synchronous Compensation Device
SSSC	Static Synchronous Series Compensation Device
IPFC	Integrated Power Flow Controller
SRs	Saturation Reactors
PI	Proportional Integral
FLC	Fuzzy Logic-Based Controller
SVC	Static VAR Compensator
VSC	Voltage Source Converter
DC	Direct Current
NB	Negative Big
NM	Negative Medium
NS	Negative Small
ZE	Zero
PS	Positive Small
PM	Positive Medium
PB	Positive Big

Conflict of Interest

The authors declare no conflict of interest.

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