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# Intelligent static synchronous compensator with super-capacitor for enhancement of power network security

Prajakta Vaidya *, Vinod Chandrakar

*Department of Electrical Engineering, G. H. Raisoni College of Engineering, Nagpur, India*

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ABSTRACT

Power network security becomes an important issue for power system economics. A proportional integral-based static synchronous compensator in flexible AC transmission systems is generally used to enhance power network security. But, it takes more time to make the network stable and secure. A PI-controlled STATCOM with a super-capacitor as an electrical storage device and transient performance improver helps the network become stable and secure. As the PI controller depends on mathematical modeling, it may respond slowly, affecting the stability and security of the network. A fuzzy logic controller, as an intelligent controller with logical rules, can overcome the slow response problem of PI controllers. Hence, to enhance power network security, an intelligent static synchronous compensator in coordination with a super-capacitor is suggested here. A multimachine network is modeled in a MATLAB environment with severe faults near the generator, making it unstable and unsecure. The validation of the proposed combination is observed by comparing the performance of the network without STACOM, with conventional PI STATCOM, with intelligent STATCOM, and with intelligent STATCOM coordinated with a super-capacitor.



## 1. Introduction

Power networks get more complex as they become more interconnected to balance the supply-demand cycle. Interconnection may lead to the generation of various power network stability issues. Due to economic concerns, it is necessary to guarantee the stability and dependability of the power network, since stability issues restrict the network's capacity to transmit energy and maintain the security of the power network. Transient stability is among the most imperative types of stability, which relates to the study of a power network after significant disruptions. When a transitory disturbance occurs, the network's stability is influenced by the original operating conditions and the kind of disturbance, which may result in a poor voltage profile (Kothari and Nagrath, 2011). Hence, it becomes a prime job to gain power network stability. Shunt power devices like Static Synchronous Compensator (STATCOM) can be connected to the power network to enhance the maximum transmittable power (Singh et al., 2009). By which the change in the power flow in the network is attained during and in dynamic disturbance so as to enhance the limit of transient stability, real power oscillation resulting in power network security enhancement. STATCOM has the advantage of providing more capacitive reactive power to the network during a fault than other compensators. Generally, proportional integral controller-based STATCOM is more commonly used, but it may have several difficulties like, performance depends on the mathematical model of the network, high operating conditions of the network, and on a large scale, computational complexity theory and structure of network increases. All these difficulties will be resolved by using a Fuzzy logic controller as an intelligent controller based on STATCOM. Energy storage devices play a significant role in power networks by storing energy due to large variations in power demand. Super-capacitors are unusual electrical storage devices that have a higher power density than batteries and can store a lot more energy than normal capacitors. Energy storage devices are used with shunt FACTS devices to provide real power exchange in the power network, hence extending network stability margins and

* Corresponding Author.
Email Address: prajakta.vaidya@raisoni.net (P. Vaidya)
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Corresponding author's ORCID profile:
https://orcid.org/0000-0002-2775-7439

ultimately the security of the power network (Hingorani and Gyugyi, 2001). Here, some research from different researchers is noted.

In Vaidya and Rajderkar (2011), power system security has been improved by a real power flow performance index (PI) sensitivity-created approach and the line outage distribution factor for optimal location of FACTS device. However, this method requires more computational time. Power system stabilizers and STATCOM devices are used to improve the performance of multi-machine systems (Shahgholian et al., 2017). According to Akhtar and Chandrakar (2019), STATCOM is used to enhance the security of hybrid sources with the grid. For power quality enhancement hybrid STATCOM is used (Adware and Chandrakar, 2022). Here, for the determination of improving the stability of the power system, the concurrent design of fuzzy PSS and fuzzy STATCOM controllers. In Awasthi et al. (2015), fuzzy logic-based STATCOM is designed for the IEEE 9 bus system. An Interline Power Flow Controller [IPFC] supplementary controller based on fuzzy logic is implemented to dampen low-frequency oscillations. Belwanshi et al. (2011) presented a contingency analysis to identify the IEEE 14 bus network's weakest bus in order to optimally position STATCOM for preserving security and enhancing the voltage profile of a wind-connected network.

With PI and fuzzy logic controllers, the STATCOM's performance is assessed, and their respective performances are compared under various load scenarios (Chandrakar and Kothari, 2007a). Chandrakar and Kothari (2007b) compared the performance of static synchronous compensators (STATCOM) based on voltage source converters (VSC) and radial basis function networks (RBFN) in terms of increasing the line's power handling capacity, enhancing transient stability, and dampening oscillations in single-machine infinite bus systems (SMIB) and multi-machine systems. Kakde et al. (2018) examined how ultra-capacitors can be reconfigured to transfer energy more quickly while being subjected to both static and dynamic loads. At 50% state of charge (SOC), the ultra-capacitors are switched from parallel to series within the bank. In Mak et al. (1999), a primary and supplemental control with fuzzy logic STATCOM is recommended for interarea power oscillation dampening and voltage support in the middle of tie lines. The STATCOM's performance is assessed, and their respective performances are compared under various load scenarios (Mohanty and Pati, 2016). To increase the voltage stability and power quality in the AC-DC micro-grid network, PI and PID fuzzy based current-controllers with distribution static synchronous compensator (D-STATCOM) are used (Nafeh et al., 2022). In order to improve the STATCOM controller's working efficiency, the proposed ANFIS-PSO and ANFIS-GA controllers have been studied and used to the analyzed power system in Nguyen et al. (2019). Rajderkar and Chandrakar (2022) used the fuzzy-based Unified Power Flow Controller to increase security. Two bidirectional DC-DC converters are used to create a novel STATCOM model with a hybrid energy storage system, and the performance of both the traditional STATCOM and the STATCOM with the hybrid energy storage system is compared (Renuka and Kesavarao, 2017). In Vaidya and Chandrakar (2022), STATCOM performance for transient condition was shown improved with super-capacitor energy storage system. In Zeng (2019), Fuzzy-PI-based controller is suggested for Static Synchronous Compensator, focusing on the demands of the power distribution network on transient load voltage.

Very few researchers have tested fuzzy-based intelligent STATCOM with a super-capacitor to enhance the security of the power grid. As fuzzy based STATCOM does not require any mathematical model and simple logic based rules can be applied as an advantage of the proposed network. Another benefit of a super-capacitor comes as it improves the transient performance of conventional STATCOM by providing real power. This article enlarges both the benefits of a fuzzy logic STATCOM controller and an energy storage device. The proposed model is tested on MATLAB during transient conditions. For unsecured conditions, a three-phase fault of duration 0.3 seconds is created in a multi-machine network. Performance is evaluated during faulty conditions, adding PI STATCOM, intelligent STATCOM, and during intelligent STATCOM with a super-capacitor. Different performance parameters like generator speed, terminal voltage, and real and reactive power are checked. Unambiguously this article develops an intelligent STATCOM controller with super-capacitor for power network security enhancement.

## 2. Static synchronous compensator (STATCOM)

A Static Synchronous Compensator is an AC shunt controller flexible transmission device linked to the power grid to manage terminal voltage. It may improve transient stability by maintaining transmission voltage in the face of increasing power flow encountered right after disturbance (Hingorani and Gyugyi, 2001). Mathematically the real (P) and reactive (Q) power of STATCOM is represented as,

$$P = \frac{V_1 V_2}{X} \sin\delta \quad (1)$$

$$Q = \frac{V_1 (V_1 - V_2 \cos\delta)}{X} \quad (2)$$

AC and DC voltage regulators are the essential components of the STATCOM controller. Although DC voltage regulator controls the dc voltage across the capacitor, which is used to conduct the real power addition from the STATCOM to the power network, AC voltage regulator regulates the reactive power interchange between STATCOM and the power network.

## 3. PI controlled STATCOM

The proportional integral (PI) controller is a conventional controller present in STATCOM.

Normally, STATCOM's internal structure has two PI controllers, both for adjusting DC capacitor Vdc and controlling AC line voltage Vac. Kp and Ki are the two control parameters. Fig. 1 shows the STATCOM PI controller. It computes a discrete-time PI controller utilizing the error signal as well as inputs for proportional and integral gain. The discrepancy between the reference signal and the observed feedback is the error signal. A weighted sum of the input error signal and its integral is output by the block. Kp is the gain proportional value, and Ki*Ts is the gain integral input.

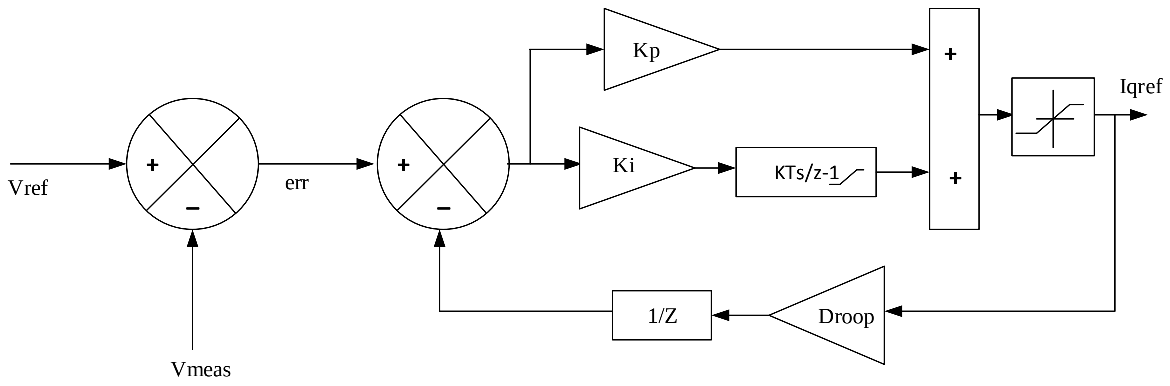


**Fig. 1:** STATCOM PI controller

Generated error and feedback signals are compared to give an output signal by adding gain, discrete time integration, unit delay, and saturation block. The same PI controller is incorporated into the current controller. PI controller provides stabilizing control when AC and DC regulators are designed independently. The PI controller is a linear control technique with a simple structure and is inexpensive. But PI controllers may have some snags like performance depending on the mathematical model of the network, high operating conditions of the network, and on a large scale, computational complexity theory and structure of network may occur. It responds slowly because of the greatest overshoot values and settling times (Ansari et al., 2022).

## 4. Fuzzy controlled STATCOM

The fuzzy controller provides an alternative to the standard PI controller. The control inputs and network parameters do not need to have exact numerical values for fuzzy controllers. By using logical thinking, it enables the information gained from experiences to be built into the control system. It is a rule-based controller, which means that a collection of rules serves as a method for controlling the impact of various network situations. Each input variable is fuzzified into a collection of linguistic values and given the proper membership grade in fuzzy. For each system state, a suitable language control output is assigned. The fuzzy rules look-up table is how the system's previous knowledge is constructed. A defuzzifier combines the linguistic output values that are produced to produce a controller output. FLC may accommodate a larger range of operating situations since they don't need a system's mathematical model (Mohanty and Pati, 2016). Fig. 2 shows the proposed STATCOM intelligent controller structure and Table 1 shows the Mamdani FI-based rules.

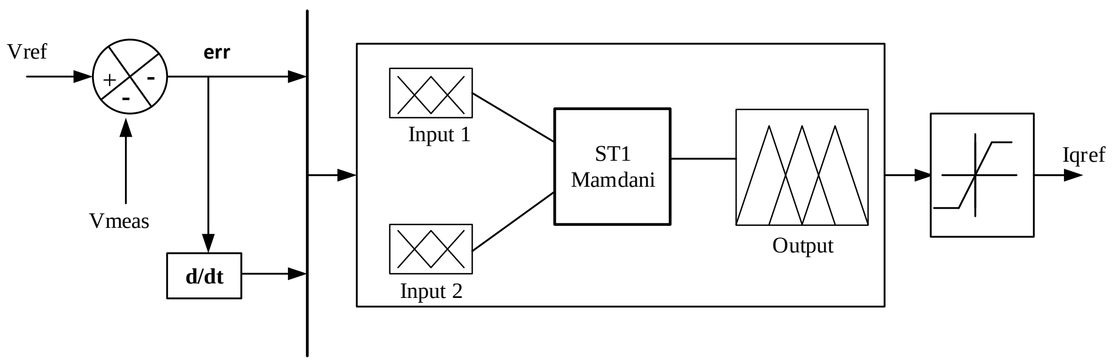


**Fig. 2:** STATCOM intelligent controller

Two inputs are considered as error and change in error is given to fuzzy with one output. Nine linguistic variables are considered for input and output which are ENVL, ENL, ENM, ENS, EZ, EPS, EPM, EPL, and EPVL. Five linguistic variables are considered for change in input which are ENL, ENS, EZ, EPS, and EPL. Where, ENVL stands for the error negative very large, ENL for the error negative large, ENM for the error negative medium, ENS for the error negative small, EZ for error zero, EPS for the error positive small, EPM for the error positive medium, EPL for the error positive large, and EPVL for the error positive very large.

**Table 1:** Rule base for fuzzy logic

| E / CE | ENVL | ENL | ENM | ENS | EZ | EPS | EPM | EPL | EPVL |
|---|---|---|---|---|---|---|---|---|---|
| ENL | EPVL | EPVL | EPVL | EPL | EPM | EPS | EZ | ENS | ENM |
| ENS | EPVL | EPVL | EPL | EPM | EPS | EZ | ENS | ENM | ENL |
| EZ | EPVL | EPL | EPM | EPS | EZ | ENL | ENM | ENL | ENVL |
| EPS | EPL | EPM | EPS | EZ | ENS | ENM | ENL | ENVL | ENVL |

E: Error; CE: Change in error; ENVL: Error negative very large; ENL: Error negative large; ENM: Error negative medium; ENS: Error negative small; EZ: Error zero; EPS: Error positive small; EPM: Error positive medium; EPL: Error positive large; EPVL: Error positive very large

## 5. STATCOM coordinated super-capacitor

A capacitor is utilized in STATCOM to supply the DC voltage for the voltage source converter (VSC). Energy storage systems can fulfill the dual goal of delivering DC voltage and real power by expanding the stability margin since the power conversion systems needed for them are comparable to the VSC of FACTS devices. Various electrical energy storage systems are super-capacitors, Superconducting magnetic energy storage, flywheel storage devices, and battery energy storage systems. Super-capacitors, however, offer both the advantages of electrochemical batteries and capacitors, with the exception that there is no chemical reaction, which significantly boosts cycle capacity. Super-capacitors are unusual electrical storage devices that have a higher power density than batteries and can store a lot more energy than normal capacitors. Supercapacitors are utilized to enhance the dynamic compensation of conventional STATCOM as compared to other energy storage devices (Hingorani and Gyugyi, 2001). Super-capacitor banks are represented by an electric circuit $r_{sc}$ and $c_{sc}$, which delivers the Vsc of super-capacitor voltage (Renuka and Kesavarao, 2017).

$$V_{sc} = r_{sc} i_{sc} + \frac{1}{C_{sc}} \int i_{sc} dt \qquad (3)$$

where, $c_{sc}$ is the capacitance and $r_{sc}$ is the super-capacitor internal resistance. The state of charge (soc) of the super-capacitor is calculated by,

$$\%SOC_{SC} = \frac{V_{SC}}{V_{SCmax}} * 100 \qquad (4)$$

The super-capacitor energy is directly proportional the DC voltage and its capacitance (Rajderkar and Chandrakar, 2023).

$$E_{sc} = \frac{1}{2} C V_{sc}^2 \qquad (5)$$

The maximum power of a super-capacitor is,

$$P_{max} = \frac{V_{sc}^2}{4R_{eq}} \qquad (6)$$

where, $R_{eq}$ is the equivalent resistance of the super-capacitor.

## 6. Simulation results

In this paper, a multi-machine network based on MATLAB with three generators, two loads, a transformer, and four buses has been considered. All the network data is available in the toolbox of the software. A severe three phase fault is enforced to the network near generator 1 of 0.3 seconds resembles an unsecured condition. Fig. 3 shows the test case multi-machine network with STATCOM-SC.

The network is first monitored during unsecured conditions without a STATCOM device. Then, with the same initial conditions PI-based STATCOM, Fuzzy-based STATCOM, and Fuzzy STATCOM coordinated super-capacitor is connected at bus number 4 for evaluating network performance. Super-capacitor is connected across the DC link voltage terminal of STATCOM $V_{dc}$. The operating time of SC is during fault duration. For each case terminal voltage, speed of the rotor, real, reactive power, and bus voltages are checked.

Fig. 4 shows the rotor speed of the proposed scheme without STATCOM, with PI STATCOM, with fuzzy STATCOM and with fuzzy STATCOM coordinated with SC. Three phase fault occurs at 5 seconds for 0.3 seconds. With the proposed scheme, rotor speed stabilizes by damping oscillations before 16 seconds only, and thus enhances the stability of the complete network. Also, during the first cycle, the peak also reduces with the proposed network.

The terminal voltage of the generator is shown in Fig. 5. With the proposed scheme, the terminal voltage does not drop as much as others and maintains the voltage quickly near 1 per unit (p.u) without variations. Fig. 6 and Fig. 7 show the real and reactive power oscillations being damped quickly.

Fig. 8 displays the bus voltage representing 1 per unit volt with fuzzy-based STATCOM co-ordinated SC after the disturbance as compared to other combinations. The network settling time, rotor speed peak value, and overshoot values are tabulated in Table 2.

**Table 2:** Peak, settling time, and over-shoot

| Network | Peak value of rotor speed (p.u) | Settling time (sec) | Over-shoot (%) |
|---|---|---|---|
| Without controller | 1.069 | 11.3 | 3 |
| With STATCOM PI controller | 1.058 | 4.3 | 3 |
| With STATCOM FLC controller | 1.055 | 3.9 | 3 |
| With STATCOM SC FLC controller | 1.042 | 2.5 | 2.5 |

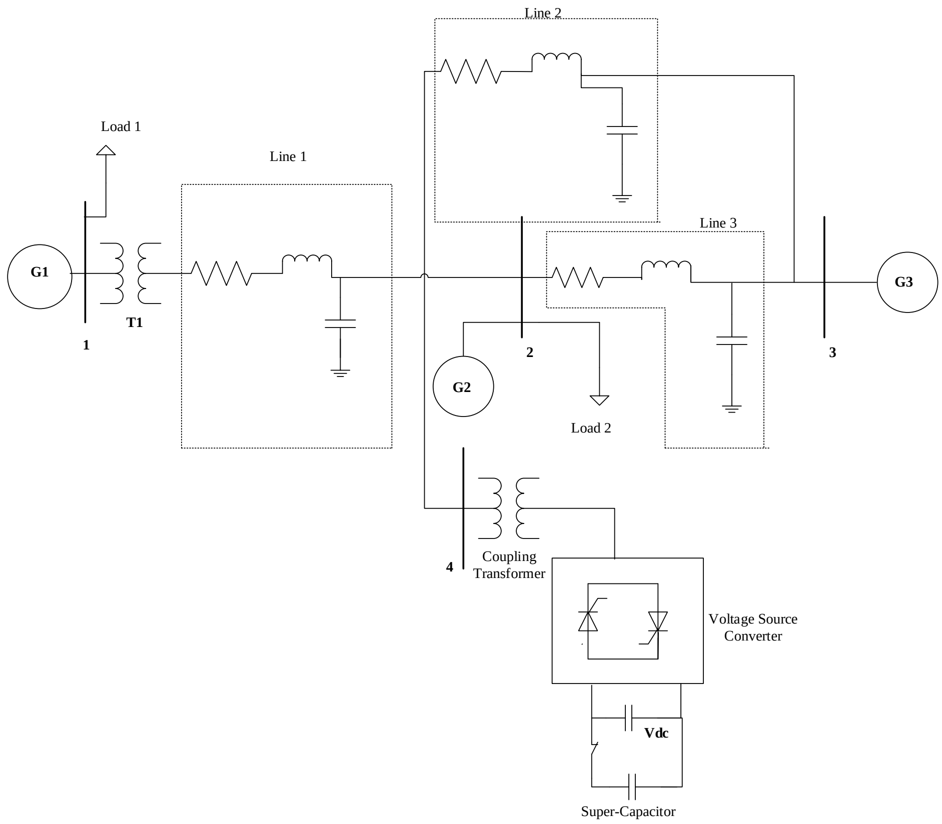


**Fig. 3:** Multi-machine network with STATCOM-SC

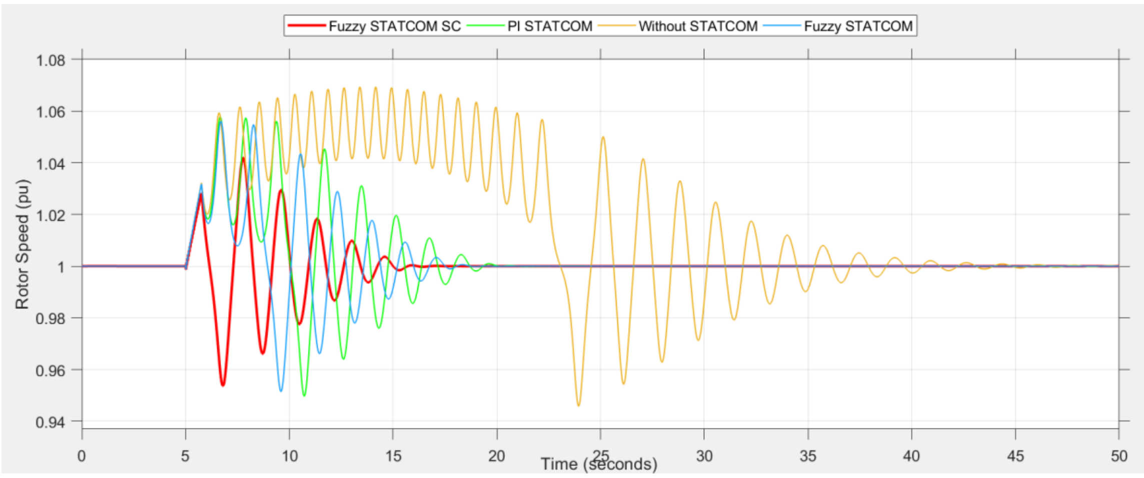


**Fig. 4:** Rotor speed

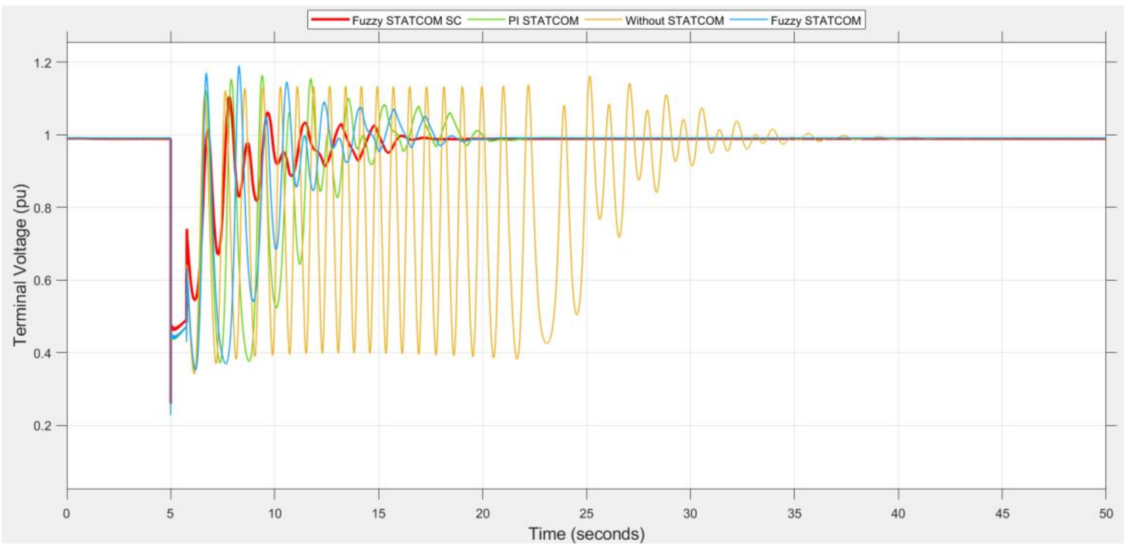


**Fig. 5:** Terminal voltage

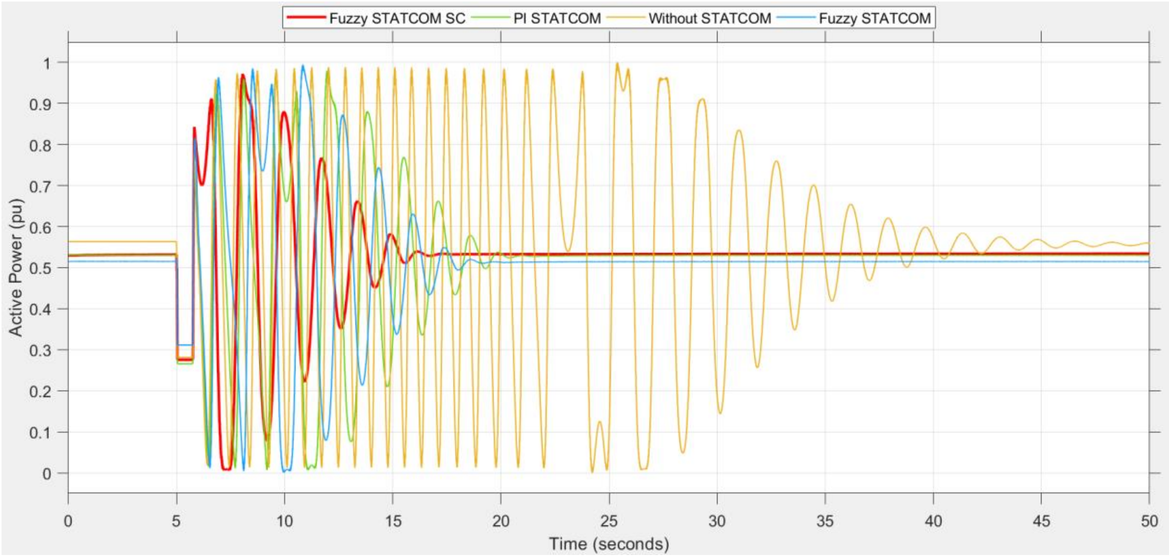


**Fig. 6:** Real power

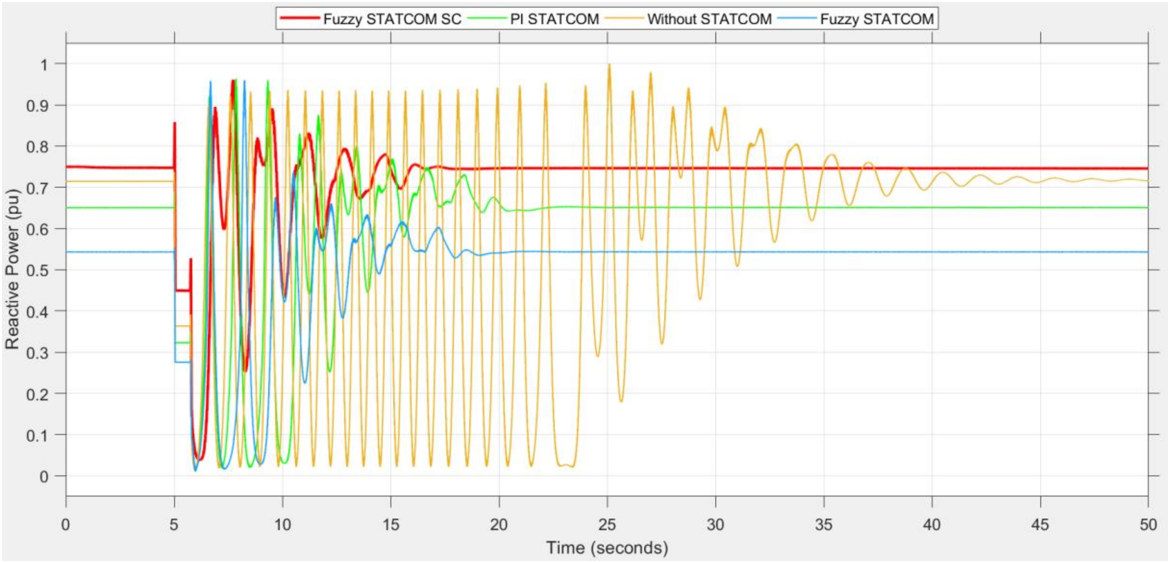


**Fig. 7:** Reactive power

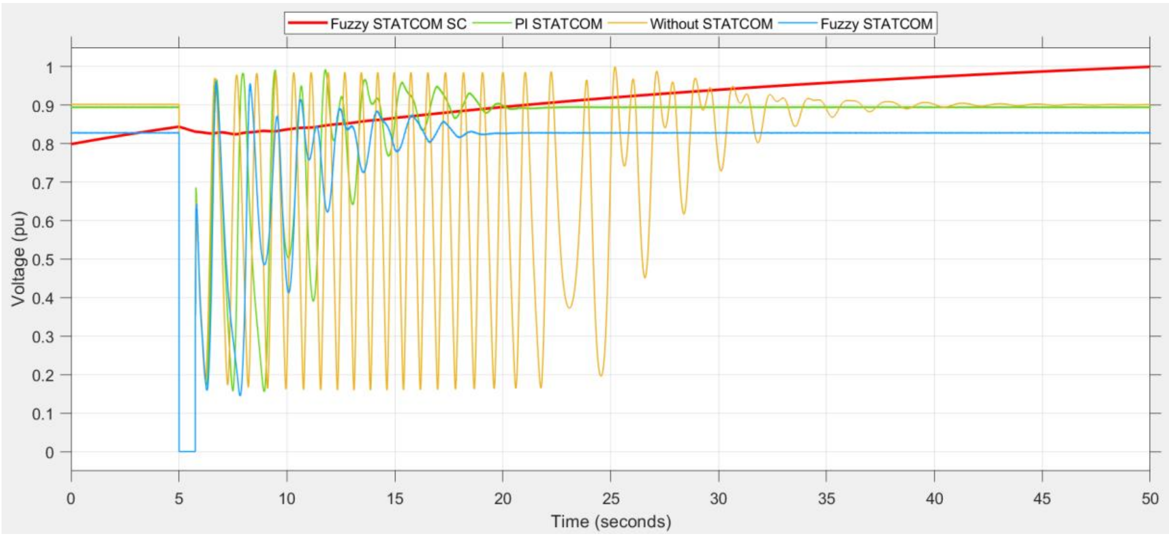


**Fig. 8:** Bus voltage

From Table 2, it is clearly observed that with fuzzy-based STATCOM co-ordinated SC the peak value of rotor speed, settling time and Over-shoots are reduced, and thus enhanced the network stability and security of the network.

## 7. Conclusion

This article explores the intelligent fuzzy-based STACOM with a super-capacitor that enhances the security of power networks. With a traditional PI STATCOM controller, it has been observed that the response has a longer settling time, a greater peak value, and a significant overshoot, which causes a delay in enhancing the security of the network. Only with an intelligent controller with super-capacitor, transient response is enhanced. Hence with the suggested model, it has been observed that the network may swiftly regain network stability and security by decreasing voltage fluctuations, oscillations and quickly coming out of fault conditions.

## Compliance with ethical standards

## Conflict of interest

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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