**Indonesian Journal of Electrical Engineering and Computer Science**
Vol. 30, No. 2, May 2023, pp. 633~642
ISSN: 2502-4752, DOI: 10.11591/ijeecs.v30.i2.pp633-642 

# An intelligent mitigation of disturbances in electrical power system using distribution static synchronous compensator

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**Article Info**

***Article history:***

Received Sep 4, 2022
Revised Jan 23, 2023
Accepted Jan 27, 2023

***Keywords:***

ANFIS
D-STATCOM
Fuzzy logic
Response optimizer
Sag
Swell

**ABSTRACT**

The power quality of an electrical system is critical for industrial, commercial, and housing applications, and with the increasing use of sensitive loads, customers and utilities are beginning to pay more attention to it. A distribution static synchronous compensator (D-STATCOM) represents one of the best custom power devices (CPDs) for improving the power quality of a distribution system. The performance of this device relies upon the algorithm and strategy used for its control. Artificial intelligence was utilized to overcome these shortcomings, while a response optimizer tool was used for the tuning process. An adaptive controller design was also proposed, based on the integration of fuzzy logic with traditional proportional-integral (PI) controller. The fuzzy logic controller system was designed using the adaptive neuro fuzzy interference system (ANFIS) editor. In this work, a D-STATCOM controller was used to mitigate sag and swell problems, while the ANFIS together with the optimization method was used to improve the system response. This study was carried out using MATLAB/Simulink, and the results showed a superior and adaptive performance in mitigating voltage sag and swell problems at different loading conditions compared to the traditional PI.



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## 1. INTRODUCTION

Until a few years ago, reliable electricity supply was the main concern of consumers. Today, consumers are looking for more than simply distribution reliability; they are seeking power quality. Hospitals (life support, operating rooms), semiconductor manufacturing plants, air traffic control, and financial institutions all require clean, uninterrupted power [1]. Voltage sags of short duration can ruin a batch of products in numerous processes such as in semiconductor fabrication plants. Customers are leery of such disruptions since they cost them a lot of money. As a result, customers are increasingly demanding high-quality electricity, and the term power quality (PQ) has gained importance. The issue of power quality in power distribution networks is not new. Similarly, a number of traditional solutions to (PQ) problems have been around for a long duration. However, these traditional methods rely on passive parts and do not always adapt appropriately to changes in the nature of a electrical power system [2].

A phrase ‘power quality’ has several definitions in electrical engineering, including current quality, voltage quality, service quality, source quality, and supply dependability [3]. Many issues can affect the power quality of a system, including voltage swell, voltage sag, harmonic distortion, the absence or presence of a volt-ampere reactive (VAR) compensation device, voltage interruptions, and transient states [4]. There are many classifications of PQ issues, and the most important factor is the duration, so it can be classified as transient, short-term, or long-term. In general, PQ problems are caused by the customer, utility, unexpected events, and the manufacturer [5].

Utilities must provide consumers with good power quality to enable them to operate their equipment properly, and manufacturers must build electrical equipment that is either immune to or capable of overriding such disturbances. Many approaches for mitigating these issues have emerged, either in existing systems or in technologies that may be produced in the near future [6]. Custom power refers to the technology of using power electronics in electrical distribution systems for the usefulness of one or a group of consumers, where utilities can use this technology to supply value-added electricity to these clients [7].

Custom power devices (CPDs) are electronic power controllers that are used in distribution systems as opposed to flexible AC transmission systems (FACTSs), which use such controllers for transmission systems. FACTSs enhance power transmission reliability and quality by simultaneously boosting power transfer capability and stability, whereas CPDs enhance the quality and reliability of distribution systems by effectively mitigating system disturbances in diverse scenarios (steady-state and transient) [8], [9]. There are two types of CPDs, namely, network reconfiguration and compensating CPDs [10]. The solid-state breaker, solid-state current limiter, and solid-state transfer switch are examples of network reconfiguration devices (also known as switchgears). The shunt-type distribution static synchronous compensator (D-STATCOM), series-type dynamic voltage regulator (DVR), and ultimate-type unified power quality conditioner (UPQC), which is a combination of the series and shunt types, are all compensating CPDs [11]. A DVR is utilized to control power flow and enhance voltage stability [12], whereas a D-STATCOM, on the other hand, is used to accurately regulate the voltage of a system, enhance the voltage profile, minimize the distortion of the voltage, mitigate the transient disturbances, as well as compensating the load [13]. Almost all forms of power quality issues can be compensated by using a UPQC [14].

Several researchers looked at some issues related to D-STATCOM. Kim *et al*. [15], Manmek *et al*. [16], Kumar and Prakash [17] used different algorithms to operate the D-STATCOM, while [18]–[20] used different algorithms to estimate an optimum location and sizing of a D-STATCOM in a distribution network, and [21], [22] investigated the integration of the D-STATCOM with renewable energy (PV and wind). Also, DSTATCOM with different topologies has been proposed based on research conducted in this regard, as each power quality (PQ) problem and application requires a special design to mitigate it. Most of this research stems from problems facing clients and utilities in practicality [23].

Eltamaly *et al*. [24] the researcher used a PI controller in the AC voltage regulator to mitigate sag and swell problems. During the validation, modification, and operation processes, the response changed, and the system became unstable with changing load conditions. The disadvantages of using a PI controller are that it is not adaptive to load variations, and the conventional proportional–integral–derivative (PID) controller tuning methods, like the trial-and-error method, are time-consuming, cumbersome, and tedious. As the power network is completely nonlinear, thus, PI controllers need to be continuously tuned with changing operating conditions.

In this work, D-STATCOM was used to mitigate sag and swell problems. Due to the disadvantages of a conventional PI controller, an intelligent controller was proposed by combining fuzzy and proportional–integral (PI) units. The fuzzy system was designed using the adaptive neuro-fuzzy inference system (ANFIS) editor. In addition, a response optimizer tool was employed in the optimization method to tune the PI gains to improve the response of the system. The research work was carried out using MATLAB/Simulink.

## 2. DISTRIBUTION STATIC SYNCHRONOUS COMPENSATOR (D-STATCOM)

The D-STATCOM is a quick-response CPD that includes a solid-state power controller that improves power quality by regulating the voltage at the connection point to a distribution feeder [25]. By adjusting the amplitude of the converter voltage relative to the line terminal voltage, reactive power can be exchanged with the distribution system. As a result, a controlled flow of current is achieved between the D-STATCOM and the distribution bus through a coupling transformer [26]. This allows D-STATCOM to reduce voltage disturbances such as sag and swell in distribution systems. Generally, the D-STATCOM can be used for power factor correction, voltage control, neutral current compensation, harmonic filtering, and load balancing [27]. Due to its multiple benefits, such as low losses and low harmonic contents, automatic operation, insignificant size, no resonance difficulties, and continuous operation, it also improves the reliability and efficiency of distribution systems [23]. The basic configuration of a D-STATCOM is shown in Figure 1.

### 2.1. Operating principle of the D-STATCOM

D-STATCOM mainly consists of a coupling transformer, a voltage source inverter, a DC energy storage device, and an output filter [25]. The inverter produces a set of three-phase AC voltages from the DC voltage across energy storage device. The generated voltages are in phase with grid voltages, and a coupling transformer connects them to the grid [8]. A suitable adjusting of the magnitude and the phase values of the D-

STATCOM output voltages led to controlling both the reactive and active power flow between the grid the and D-STATCOM [28].

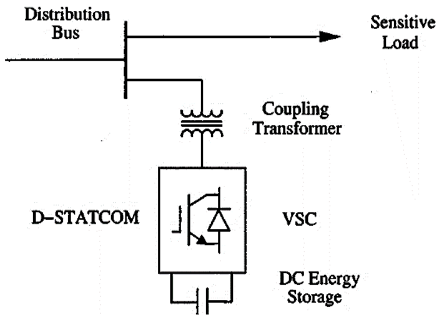



Figure 1. The basic configuration of a D-STATCOM

An equivalent scheme of a single-phase electrical grid with D-STATCOM is depicted in Figure 2. The inverter output voltage, coupling transformer voltage drop, voltage at the common coupling point (PCC), and supply voltage are represented by $V_I$, $V_{Coupling}$, $V_{PCC}$, and $V_S$, respectively. There is no reactive power transferred between the grid and the D-STATCOM when the value of $V_I$ is equal to $V_{PCC}$ That means the D-STATCOM will not absorb or generates reactive power from the grid. When $V_I$ is greater than $V_{PCC}$, current passes from the D-STATCOM to a grid through the coupling reactance, thus, generating capacitive reactive power. If the $V_{PCC}$ is greater than the $V_I$, the current then passes from a grid to D-STATCOM, leading to the device's absorption of inductive reactive power [29]. Figure 3 Shows the operational characteristics of D-STATCOM, where Figure 3(a) represents V-I characteristic of the D-STATCOM while Figure 3(b) represents the V-Q characteristics and it shows the transferred reactive power between the grid and the D-STATCOM. The nominal voltage at the PCC is $V_{ref}$.

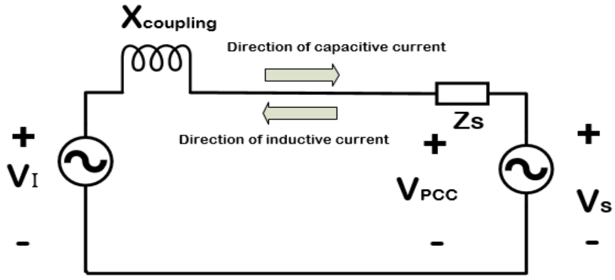



Figure 2. Equivalent scheme of the single-phase electrical grid with a D-STATCOM

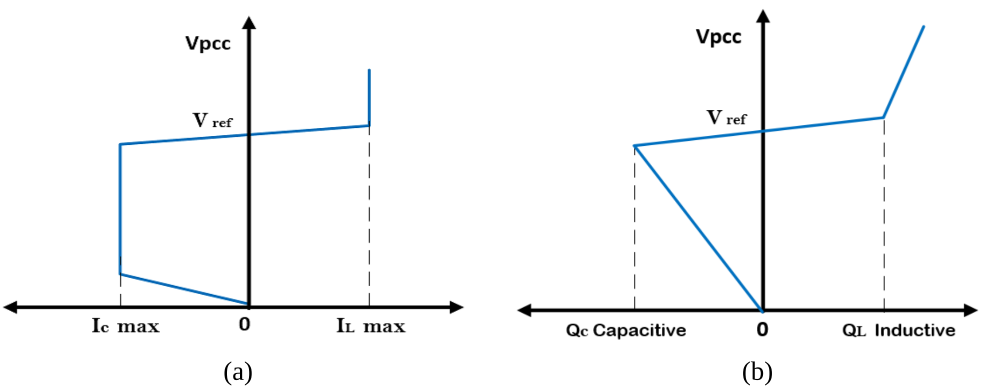



Figure 3. D-STATCOM operational characteristics; (a) V-I and (b) V-Q

By modifying the phase shift angle between the grid voltages and the D-STATCOM output voltage, the active power transmitted between the grid and the D-STATCOM is controlled [30]. This interchange can be utilized to reduce the inverter's internal losses and to keep the DC capacitor charged to the correct DC voltage, thereby enabling the magnitude of the D-STATCOM output voltage to be changed. Figure 4 shows the D-STATCOM vector diagram for the transition from the capacitive to inductive mode and vice versa at the fundamental frequency. Changing the shift angle from zero to negative values enables the transition to occur from an inductive to a capacitive mode. Active power will be transmitted from a grid to a DC capacitor, causing an increase in the DC link voltage. But shifting the angle from zero to positive values will result in a transition from the capacitive to inductive mode. The active power of the DC capacitor is transferred to a grid, causing a drop in the voltage in the DC link. Table 1 sums up these operating states [31]. The active and reactive power between the D-STATCOM and the grid can be computed according to (1) and (2), respectively:

$$P = \frac{V_{pcc}\, V_I}{X_{couplig}} \sin\delta \quad (1)$$

$$Q = \frac{V_{pcc}(V_{pcc} - V_I \cos\delta)}{X_{coupling}} \quad (2)$$

where δ is the transfer angle of the system, P is the active power, and Q is the reactive power of D-STATCOM.

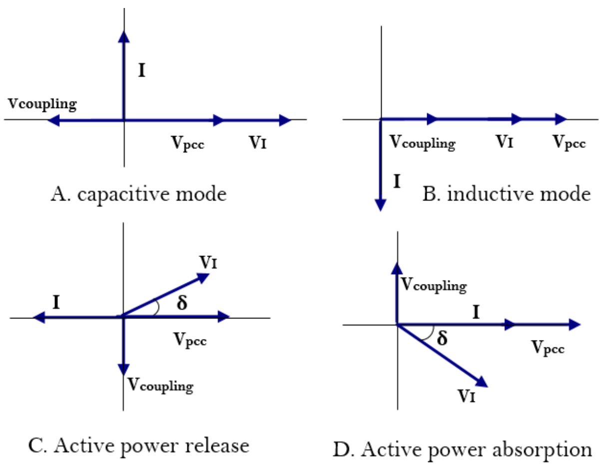



Figure 4. The vector diagrams of D-STATCOM

Table 1. The necessary conditions for the interchange of power between D-STATCOM and a grid

| Relation | D-STATCOM | ⟷ | grid |
|---|---|---|---|
| $\|V_I\|>\|V_{pcc}\|$ | Q | → | |
| $\|V_I\|<\|V_{pcc}\|$ | | ← | Q |
| $\delta < 0$ | P | ← | |
| $\delta > 0$ | | → | P |

## 2.2. Control strategy of D-STATCOM

The control strategy plays a vital role in D-STATCOMs performance. Therefore, a combination of fuzzy and PI controllers in the alternating current (AC) voltage regulator was proposed to benefit from the features of each. The system's exceptional performance in terms of its robustness, accuracy, and adaptiveness was attributed to this combination of controllers. The fundamental strategy was to identify the inputs to the controller and, then, modify the PI gains to enhance performance.

### 2.2.1. PI controller

Simple and robust PI controllers were used. Their performance was determined by the values set of the Kp and Ki. The PI controllers (namely Kp, and Ki settings) had to be tuned to the D-STATCOM through installation in the electrical system. However, the trial-and-error method was slow as the standard control strategy for this device involved multi-PI controllers. An incorrect choice of the coefficients may hamper the response of the device [32]. In addition, the controllers may need to be re-tuned in an 'off' state when certain variations happen in the system parameters or conditions [33]. To avoid tuning problems, the parameters (Kp, Ki) for the PI controllers were obtained by applying a response optimizer in the Simulink environment. This saved time and effort, and provided proper values. The gradient descent method and sequential quadratic programming algorithm were used for the optimization, and the sum absolute of the error signal resulting from a comparison between the AC reference voltage and measured AC voltage was selected for minimization. The PI parameters were optimized for all the work points, and tables were created for these values (active power of load (PL), reactive power of load (QL), power factor of load (PFL)) against the values of Ki and Kp as the input/output dataset to be entered into the ANFIS system to create a fuzzy logic control as shown in Figure 5, where Figure 5(a) represents the fuzzy controller of Ki, while Figure 5(b) represents the fuzzy controller of Kp. These fuzzy logic controllers change the values of Ki and Kp for each state online during the operation.

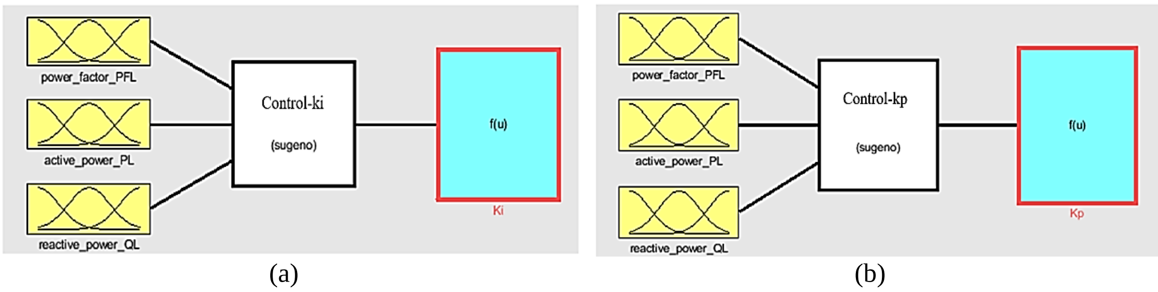



Figure 5. Proposed fuzzy logic system; (a) fuzzy logic controller of Ki and (b) fuzzy logic controller of Kp

### 2.2.2. Fuzzy logic controller

Artificial neural networks (ANNs) or fuzzy logic controllers (FLCs) have recently been used to control systems with nonlinear structures and variable parameters and conditions [34]. It is commonly recognized that there are some challenges involved in designing controllers. For example, there is no standard method for establishing the rules base, spans, and membership shapes in FLC designs. Issues with the FLC design can be solved by utilizing the ANFIS system. Additionally, a mathematical model of a control system is not required, so, without it, a fuzzy controller can be developed using human operators and language rules. Artificial networks, on the other hand, are adept at observing patterns and can train the parameters of the control system, but they cannot describe how they arrived at their decisions. The fuzzy modelling process can obtain knowledge about a dataset using neuro-adaptive learning strategies. Through this method, the fuzzy inference system can efficiently track the provided input and output data by enabling fuzzy logic to compute the membership function parameters and find the base rules [35]. Fuzzy logic rules are produced by the ANFIS editor in MATLAB. The control scheme proposed to the D-STATCOM used two FLC units in the AC voltage controller, with PL, QL, and PFL being the FLC inputs while $K_p$ and $K_i$ being the outputs of the FLC units as PI controller parameters, as shown in Figure 6.

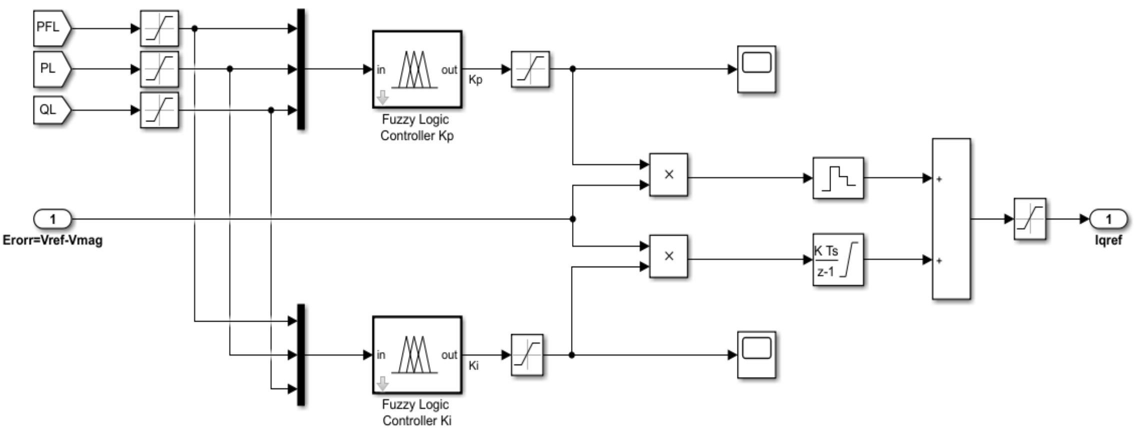



Figure 6. Proposed control scheme

## 3. SIMULATION RESULTS

The radial system (25 kV/100 mVA) being studied was comprised of three buses ($B_1$, $B_2$, and $B_3$). It had a sensitive load at $B_3$, two loads across the circuit breakers at $B_2$, and a capacitive load at $B_1$ for the power factor correction and power oscillation damping. The IGBT-based D-STATCOM (± 9 mVA, 3 levels) with twin converters decreased the harmonic distortion, where each converter was a 12-pulse three-level diode-clamped converter. The circuit diagram is shown in Figure 7, while the system parameters are given in Table 2. The D-STATCOM was connected in parallel with the system at $B_3$ through three parallel transformers. This D-STATCOM would be able to inject/absorb reactive power for voltage regulation when fed to a sensitive load**.** To demonstrate the performance of the D-STATCOM in mitigating system disturbances, two different control strategies were implemented for two scenarios of voltage sag and swell.

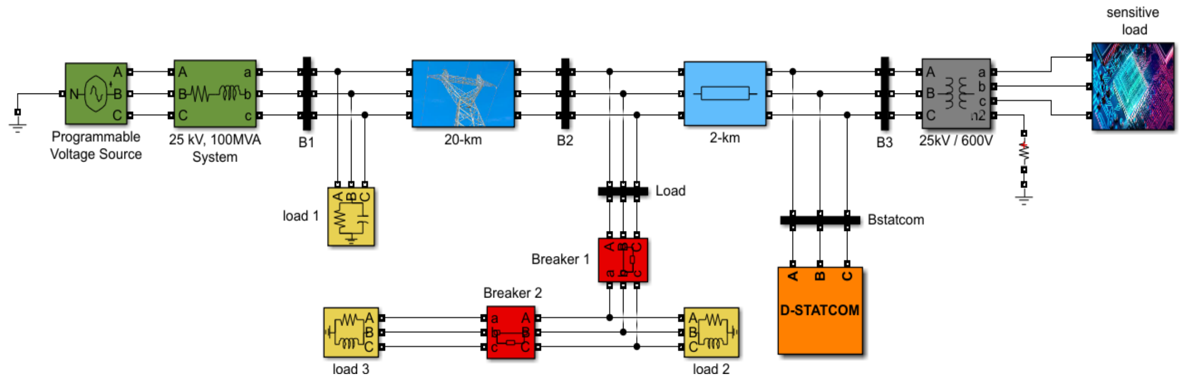



Figure 7. Simulink model of the proposed system

Table 2. System parameters

| Parameter | Value |
|---|---|
| Source voltage | 1.164*25 kV |
| Bus 3 voltage | 25 kV (1 p.u) |
| frequency | 50 Hz |
| Sensitive load | (1+j0.5) mVA |
| Load 1 | (2-j0.3) mVA |
| Load 2 | (10+j4) mVA |
| Load 3 | (8+j3.2) mVA |
| Dc capacitors | 10000 µF (two) |
| Dc voltage | 3450 V |
| Distribution Transformer | (25kV/600V) 6 mVA |
| D-STATCOM transformers | (25kV/√3)/1250V, 3 MVA (three) |
| Ac voltage PI gains | Kp=0.2214, Ki=211.1 |
| Dc voltage PI gains | Kp=0.001, Ki=0.15 |
| Current PI gains | Kp=1.5, Ki=200 |

### 3.1. Increasing load

To simulate the sag state in the system voltage, a sudden load of (8+j3.2) mVA was added to the system at $B_2$ through circuit breaker 2, which caused the voltage to drop to 0.895 p.u (sag of 10.5%) at $B_3$ for a period of 0.3-0.7 seconds before the D-STATCOM was connected, as shown in Figure 8. The D-STATCOM was then connected to the system and the simulation was run again, as depicted in Figure 9. It was noted that when the PI controller was applied, the voltage during the period of the load increase was not fixed and there was a large oscillation in the voltage compared to the nominal value (red curve), while in the case of the use of the fuzzy-PI controller, the sag was mitigated within a short period at a fixed value of 1 p.u without oscillation (blue curve).

### 3.2. Decreasing load

Another form of disturbance that occurs in electrical systems is the reduction of loads or their complete disconnection, which leads to swelling of the system voltage, thus affecting the operation of sensitive loads. This scenario was simulated by disconnecting almost all the loads on $B_2$ for a duration of 0.3-0.7 seconds, thereby raising the voltage at $B_3$ to 1.147 p.u. (swell of 14.7%) in the absence of the D-STATCOM as shown in Figure 10. After connecting the D-STATCOM to the system and re-running the simulation for the two control strategies, the voltages were as shown in Figure 11. With the PI controller, the system showed an unacceptable response as the voltage did not return to the nominal value (red curve), and there was continuous oscillation and a large overshoot, unlike with the FLC, which showed a great performance in refixing the voltage to 1 p.u (the desired value) within a very short time, with little overshoot and without oscillation (blue curve).

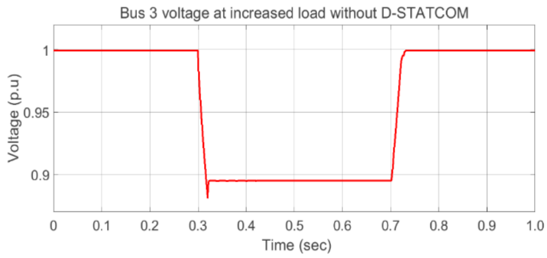



Figure 8. Comparison of the voltage in $B_3$ under increasing loads before the installation of D-STATCOM

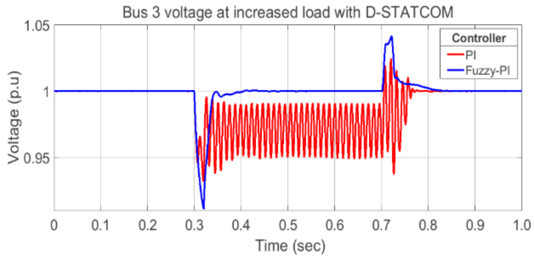



Figure 9. Comparison of the voltage in $B_3$ under increasing loads after the installation of D-STATCOM

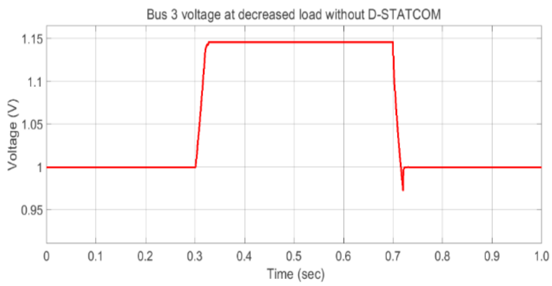



Figure 10. Comparing the voltage of $B_3$ with decreasing load before the addition of D-STATCOM

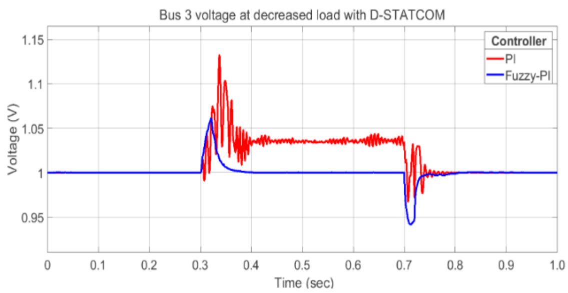
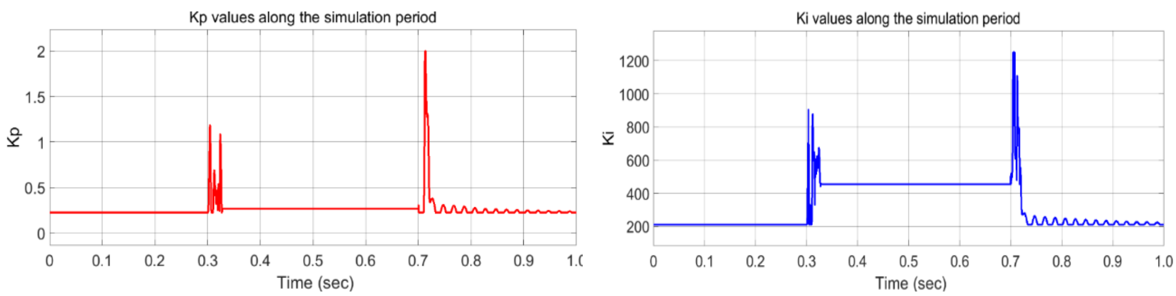


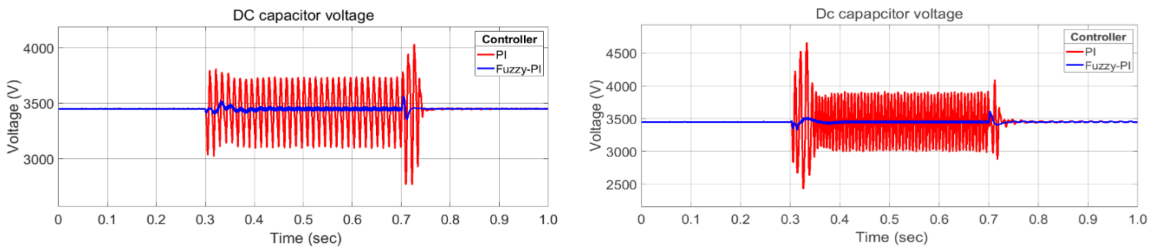

Figure 11. Comparing the voltage of $B_3$ with decreasing load after the addition of D-STATCOM

The parameters of the PI controller were changed online to the optimized values with changing load conditions as shown in Figure 12, where Figure 12(a) shows Kp values during the simulation period, while Figure 12(b) shows Ki values during the simulation period, thus proving the adaptive work of the proposed PI-fuzzy controller. The overall performance of the D-STATCOM had improved with the use of the proposed strategy compared to the PI method, as shown in Figures 13-15. The DC capacitor voltage, phase voltage, and current of the D-STATCOM being examples of these improvements. From these figures it can be concluded that the performance of the system using the new control method used in this research is better than other traditional methods.




(a) (b)

Figure 12. Fuzzy output during the simulation period for (a) Kp values and (b) Ki values




(a) (b)

Figure 13. DC capacitor voltage at (a) voltage sag and (b) voltage swell

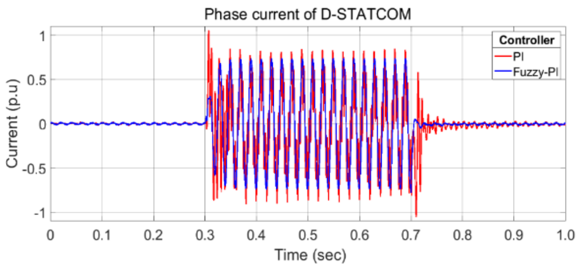



Figure 14. Phase current of D-STATCOM at the swell

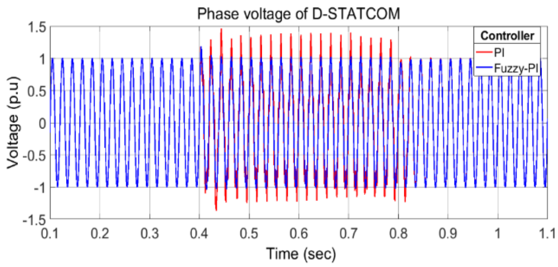



Figure 15. Phase voltage of D-STATCOM at the swell

## 4. CONCLUSION

This paper included a presentation of the importance of power quality, and the modern techniques used to mitigate problems in relation to it, with D-STATCOM being one of the best techniques. The advantages of the traditional PI control strategy, which is the most used strategy, were described. However, one of the disadvantages of this type of control strategy is its lack of adaptability to changing operating conditions, in addition to its cumbersome parameter tuning method. Artificial intelligence was employed to overcome these disadvantages, where a response optimizer tool was used for the tuning process. An intelligent controller design was also proposed based on the integration of a fuzzy control system with the PI. A superior response and better solution to sag and swell problems were obtained using ANFIS and the optimization method compared to the conventional PI in different conditions. The simulation results using the proposed controller showed mitigation for the voltage sag of 0.895 p.u and voltage swell of 1.147 p.u, and the voltage was maintained at one p.u by the D-STATCOM.

## ACKNOWLEDGMENTS

The authors wish to take this opportunity to extend their appreciation to the Electrical Engineering Department of the University of Mosul College of Engineering for their contribution to this effort.

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