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Intelligent fuzzy-based controllers for voltage stability enhancement of AC-DC micro-grid with D-STATCOM

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Fuzzy-PID current-controller;
Hybrid micro-grid;
Power quality and Voltage stability

Abstract Voltage stability and power quality play very effective issues in power systems. This paper aims to improve the voltage stability and enhance system power quality in the AC-DC micro-grid system based on intelligent fuzzy controllers. These controllers are fuzzy-PI (FPI) and fuzzy-PID (FPID) current-controller with the existence of distribution static synchronous compensator (D-STATCOM). The capability of proposed system has been applied in two case studies that emulate abrupt fault and dynamic load changes on AC-DC hybrid micro-grid that collects different types of renewable energy sources. In addition to, the proposed fuzzy-based controllers produce the optimum dynamic response and resolve the power quality issues. Numerical simulations associated with detailed comparisons between different controllers are provided. It was found that when the studied system is subjected to a 3-phase fault, the voltage fluctuation at the D-STATCOM is reduced by 7.86% and 4.62% and the dynamic system performance is improved by 12.9% and 8.8% with using Fuzzy-PID and fuzzy-PI, respectively. Also with the dynamic load changes, the fluctuation of system voltages at the D-STATCOM is reduced by 0.982% and 0.577 % and the dynamic system performance is improved with 6.67%, 5.71% when comparing Fuzzy-PID controller and Fuzzy-PI to the uncontrolled system. The Fuzzy-PID provides a capability to enhance dynamic performance and system power quality because achieve less fluctuation and more smoothing for signals makes it is superior for voltage control for AC-DC micro-grid.

1. Introduction

The rapid improvements in electrical power systems lead to enormously increase in the reliable and high-quality electrical

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Nomenclature

D-STATCOM	Distribution Static synchronous compensator
FLC	Fuzzy logic controller
FPI	Fuzzy-PI Current Controller
FPID	Fuzzy-PID Current Controller
DG	Distributed Generation
VSC	Voltage Source Converter
PV	Photovoltaic
IC	Interlinking Converters
FACTS	flexible AC transmission systems
PWM	Pulse Width Modulation
UPQC	unified Power quality conditioner
PLL	phase-locked loop

power demand. So, the electrical power distribution systems are suffered from power quality problems and voltage stability requirements in most regions in world [1]. The quality of power system is a major concern in distribution system because its voltage and current signals are transmitted to customers [2]. The low power quality has negative impacts in power system which reduces the lifelong of electrical instruments and decrease effectiveness of loads and then lead to power quality problems such as voltage instability and current harmonics [3]. Enhancing the operation of distribution systems is carried by adding various devices like fixed capacitors as in [4], combination of distributed generation (DG)/capacitors [5], allocation of reactive power resources [6], optimal siting of series compensators like in Ref. [7].

Voltage instability problems represented the voltage fluctuation, sag and swell… etc. it can be described as abrupt increasing or reduction in the line voltage and current amplitudes compared with reference voltage level. These problems are produced in distribution power systems due to sudden changes in the system such as 3-phase faults and dynamic load changes. To face the voltage instability problems, it is important to utilize micro-grids concept which is prospected to perform a vital role in the developing of the power systems [8].

Micro-grids (MG) consist of multiple distributed generation units that operate together with a robust control algorithm. This controller gives the opportunity to improve voltage stability, ensure system power quality and enhance power system performance. Micro-grids present many merits to achieve the optimal utilization of electric networks [9]. The AC/DC hybrid micro-grid combines the merits of both AC micro-grid and DC micro-grid to obtain a big complicated system. Therefore, it helps in restraining the probabilities of exaggerated power losses, voltage instability problems and reliability issues in power systems [10]. The hybrid micro-grids need a perfect control algorithm to restrain voltage unbalanced problems and enhance system power quality.

Different methods aim at enhancing power quality problems. One of these solutions is static synchronous compensator (STATCOM). The STATCOM is a member of the flexible AC transmission systems (FACTS) devices which are used in power system. In distributed network, a distributed STATCOM (D-STATCOM) efficiently helps in achieving satisfactory solution for power quality issues [11]. The D-STATCOM is multi-function power quality regulator based on the inverter connected in parallel to the AC grid used to improve power quality problems of the proposed system (i.e. power factor, voltage profile, voltage stability) and to support the reactive power compensating in the distribution systems [12]. The DSTATCOM was developed for voltage stabilization as reported in [13,14].

The micro-grids are small-scale systems that are integrated with group of distributed generation (DG) units, which is permanently connected with power electronic-based devices (voltage source inverter) to the public grid. AC-DC hybrid micro-grid has been suggested for making the connection of renewable energy sources as photovoltaic (PV), fuel cell, and wind turbine to classical Ac systems easy via voltage source converter (VSC) called interlinking converters (IC). When the system becomes unstable, the controller's role must limit exaggerated power losses, voltage profile problems, voltage fluctuation, and reliability problems. When the AC/DC hybrid micro-grid are subject to insufficient capability to feed the power demand for customers, power unbalance is occurred, and the compensation of reactive power is necessary for achieving stability for the system. To overcome this, the D-STATCOM has been used for improving power factor, balancing voltage and restraining harmonics for power systems.

Fuzzy logic mimics the decisions making principles. Many applications are dicussed in the literature in power systems engineering as those reported in [15–17]. It gives the way for using the fuzzy logic controller (FLC) based on D-STATCOM instead of conventional controllers that it is predicted to achieve the improvements in the hybrid micro-grid performance [18].

The proportional integral (PI) controller distinguishes with its ability for restraining a high disturbance and limits noise in voltage and current waveforms and obtained an acceptable damping during power system operation. On the other hand, its response has highest overshoot values and settling time which resulted in slow response. So, the FLC used with PI controller to mitigate overshooting and enhanced settling time to enhance system performance. Whereas the proportional integrated differential (PID) can be classified as robust performance with limitation for those conditions as usual, in addition to their functional simplicity [19]. The D-STATCOM can be used with the PID controller for providing better support to overcome its response's time delay. So, FL controller is used with PID controller to provide better response and enhance power quality of power system. Therefore, the proposed control algorithm based on D-STATCOM that controlled by Fuzzy-PI and Fuzzy-PID is needed to enhance the voltage stability and to improve the power quality against any sudden changing in reactive power demand. The design of D-STATCOM for voltage stability enhancement is presented in [20]. In [21], the voltage profile management associated with minimizing the power loss minimization in a grid-connected microgrid system using fuzzy was presented. The authors in [22] presented a study for evaluating the performance of fuzzy based controlled voltage source inverter as a basic of the unified power quality conditioner was proposed for effective scheme for mitigation of resulted harmonics in voltage and current signals. Reference [23] presented fuzzy based proportional integral controller to compensate the reactive power on a network that are connected with solar energy system in the existence with d-STATCOM. Many efforts have been done by researchers to keep power system in stable mode and to improve its power quality. These efforts aim at enhancing the power system performance regardless the conditions which might expose to severe disturbance such as various load, fault occurrence and resource condition. The authors in Ref. [24] presented an approach to ensure system reliability, increased efficiency and reduced device costs. In Ref. [25], it presented an approach based on STATCOM controlled by genetic algorithms (GA) and Bacteria Foraging Algorithm (BFA) for performing an acceptable response to improve system stability for micro-grid. The authors in Ref. [23] presented an approach based on micro-grid system with Enhanced Dynamic Voltage Restorer (EDVR) efficiently operated to restrain voltage fluctuations in grid and achieved more secure during system operation. The authors in [21] presented an approach based on STATCOM controlled fuzzy-PI to improve the fluctuation and line losses. Reference [26] proposed a hybrid AC/DC microgrid based on bi-directional resonanent DC transformer (BRDT) and verified the performance of BRDT with different topologies and also hybrid AC/DC micro-grid in different operating scenarios. The authors in Ref. [27] presented an approach based on super-capacitor (SC) in hybrid energy system (HES) under the weak grid condition and the proposed system performance has improved, achieved good dynamic response as well as reduced ripples in DC link voltage profile. The authors in Ref. [28] proposed fuzzy logic-based robust control mechanism for achieving stabilize the frequency and direct current bus voltages in large fluctuations caused by sudden changes in power generation or load side.

The authors in Ref. [29] presented an approach based on an intelligent controller with PID-D-STATCOM to provide adequate compensation that efficiently help to conclude the response time is perfectly. The authors in [20] presented a model connected to D-STATCOM with LCL passive filters which are based on VSC principles and pulse width modulation (PWM) technique to improve the voltage sag, harmonics distortion and low power factor in the distribution system. The authors in [30] presented an approach to mitigate voltage sag and improve DC-Link voltage profile in a distribution system under sudden changing in load condition based on fuzzy PI-controlled with current source converter (CSC)-based D-STATCOM. The authors in [31] presented a technique to obtain optimum usage of energy from wind and protection of environment based on cascaded H-bridge five level inverter-based D-STATCOM structure for wind energy systems. The authors in [32] achieved a robust stability and better dynamic response better for voltage control of the DC micro-grid based on Fuzzy-PID controller. Reference [33] presented grid-connected PV generation model based on D-STATCOM model and achieved reactive power compensation for different loads with keeping grid voltage stability. The authors in [34] presented combination between the traditional PID controller and fuzzy logic control then build a fuzzy-PID controller to operate in unified power quality conditioner (UPQC) DC-link capacitor voltage control links and observed that it could overcome the effect of nonlinear factors of power system and achieved effectively compensation for the voltage distortion and harmonic current.

Among the previous studies, several researchers discussed the behavior of intelligent controllers for improving the stability for off- micro-grid or mitigate power quality issues of the power system, whatever different methods of applying disturbance on the network. But the dynamic system performances and voltage stability are extremely influenced by the controller parameters gains. In addition to the hybrid micro-grid can face instabilities due to the above-mentioned factors to obtain the optimum power sharing. So, it is necessary to find the robust control algorithm that is able to improve the voltage stability of the power system and mitigate power quality problems under the different operation conditions. Moreover, it can achieve the optimum power exchange in AC/DC hybrid micro-grid according to power generation and demand.

This paper aims at improving voltage stability of AC/DC hybrid micro-grid and resolving power quality issues. Whereas, these problems are produced by existence an abrupt change in loads or over-current condition especially due to faults that causes the unbalance in power at generating side and load side. The main contribution of this paper is to propose a new control mechanism, based on intelligent fuzzy control with D-STATCOM, to mitigate voltage imbalance and resolve system power quality issues of hybrid AC-DC micro-grid. These problems are caused by exposing proposed power system to unexpected changes such as 3 phase fault occurrence or sudden dynamic load changes. With keeping in mind, the above-mentioned difficulties, this proposed algorithm focuses on designing Fuzzy-PI controller and Fuzzy-PID controller. The controllers are simulated in the MATLAB/Simulink environment and then the simulation results of the dynamic performance for proposed system will assess at standard case, Fuzzy-PI, Fuzzy-PID, PI and PID controller within the two case studies. These results will present as a comparison that will show the behavior of each controller under disturbance that occurring due to the different operation condition to check from its effectiveness in achieving better results than previous studies.

The next sections of the paper are organized as follows. Section 2, Describe the configuration of the AC-DC hybrid micro-grid based on D-STATCOM and its principal operation and modeling, Design procedures for conventional PI, PID, Fuzzy-PI and Fuzz-PID controller is shown in Section 3. Section 4 shows the simulation results of the proposed controllers and comparison between the simulation results of power system without controller Finally, Section 5 concludes this paper.

2. Modelling of the tested system

2.1. System configuration

The proposed AC/DC Hybrid micro-grid consists of DC renewable energy recourses such as photovoltaics' array, fuel cell and energy storage system (Battery) and AC grid such as wind turbine as displayed in Fig. 1 and the capacity for each of them are recorded in Table 1. The DC generating units are connected to a utility grid via a DC-DC boost chopper

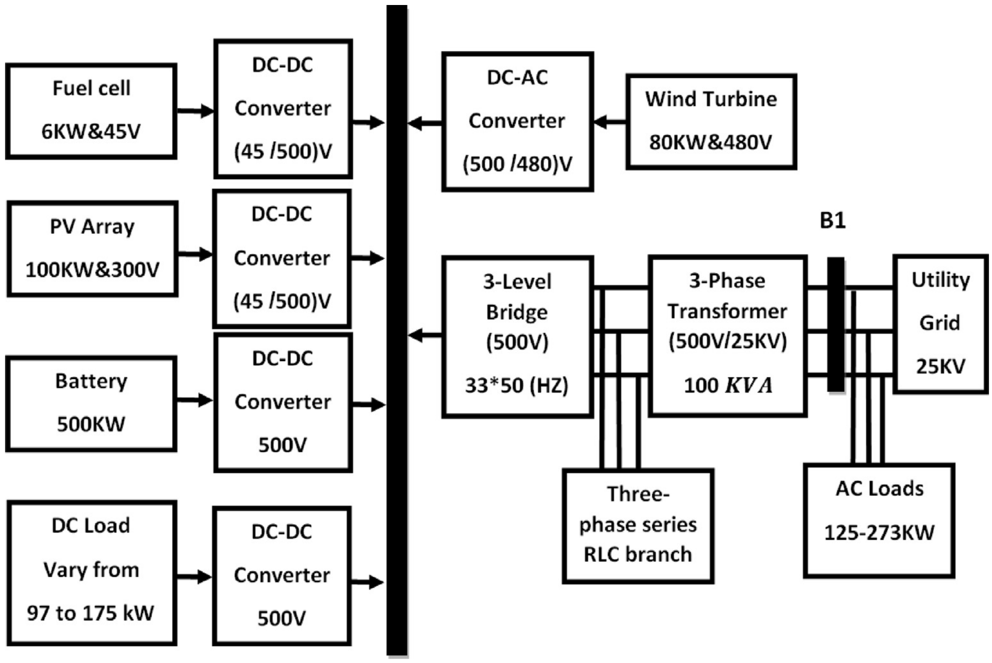

Fig. 1 Suggested AC/DC hybrid micro-grid system.

Table 1 AC/DC Hybrid micro-grid.

Item	Nominal voltage	Power	Specifications
Fuel cell	45 V	6 kW	Proton Exchange Membrane (PEM)
Photovoltaics' array	300 V	100.7 kW	66 Parallel strings- 5 Series-connected modules per string-
Wind turbine	480 V	80 kW	Wind-Turbine Asynchronous Generator (Wind Diesel)
Variable load	25 kV	Normal load: 100 kW Max.load:500 kW	PQ model-unity power factor- Filtering time constant 0.01 (sec)
Battery	–	500 kW	Rated Capacity 100 kWh- Overall System Efficiency 96%-SOC to Recharge 11%-Initial State-of-Charge 80%
DC Bus	500 V	–	–
Pulse width modulation generator (3-level)	500 V	–	Carrier frequency 33*50 (HZ)- Sample time 2eˆ-06 (sec.)
Three-phase series RLC branch	500 V	–	Resistance R = 500e6*377/50/2(Ω) Inductance L = 500e-6/2 (H)
AC Loads	–	125–273 kW	–
DC load	500 V	97–175 kW	DC variable load at 5 Hz
Sample time control(T_s)	–	–	4.0e-05sec
Nominal frequency	–	–	50HZ

and a three-phase three-level Voltage Source Converter (VSC). The objective of VSC converts the 500 V_{DC} to V_{AC} to maintain unity power factor according to the control loops. These control loops are classified into two types of external control loop and internal control loop. The external control loop is used to adjust DC voltage to ± 260 V. the internal controls loop are used to adjust active current component (i_d) as the output of the DC voltage external controller and reactive current (i_q) component and keeps it zero to maintain unity power factor, V_d and V_q voltage outputs of the current controller are converted to three modulating signals V_{abc_ref} used by the PWM Generator then connected to three-phase coupling transformer (100-kVA 260 V/25 kV) and (25 kV) distribution feeder and then connected to equivalent transmission system (120 kV). The proposed micro-grid is connected to 25 kV distributed system and then connected to D-STATCOM at bus (B_7). The D-STATCOM is used for regulating voltage at bus (B_7) as shown in Fig. 2.

The D-STATCOM will be controlled by fuzzy intelligent control with PI and PID controllers and the suggested power system will be tested with two cases study. The first case study will discuss the system performance with fault condition at bus (B_7) before three-phase coupling transformer (47-MVA 25KV/120 kV) as shown in Fig. 3. The second case study will discuss the system performance with causing changes in load at bus (B_7) before three-phase coupling transformer as shown in Fig. 4. The D-STATCOM controllers will operate based on d-axis and q-axis currents, as the controller used in d-axis current

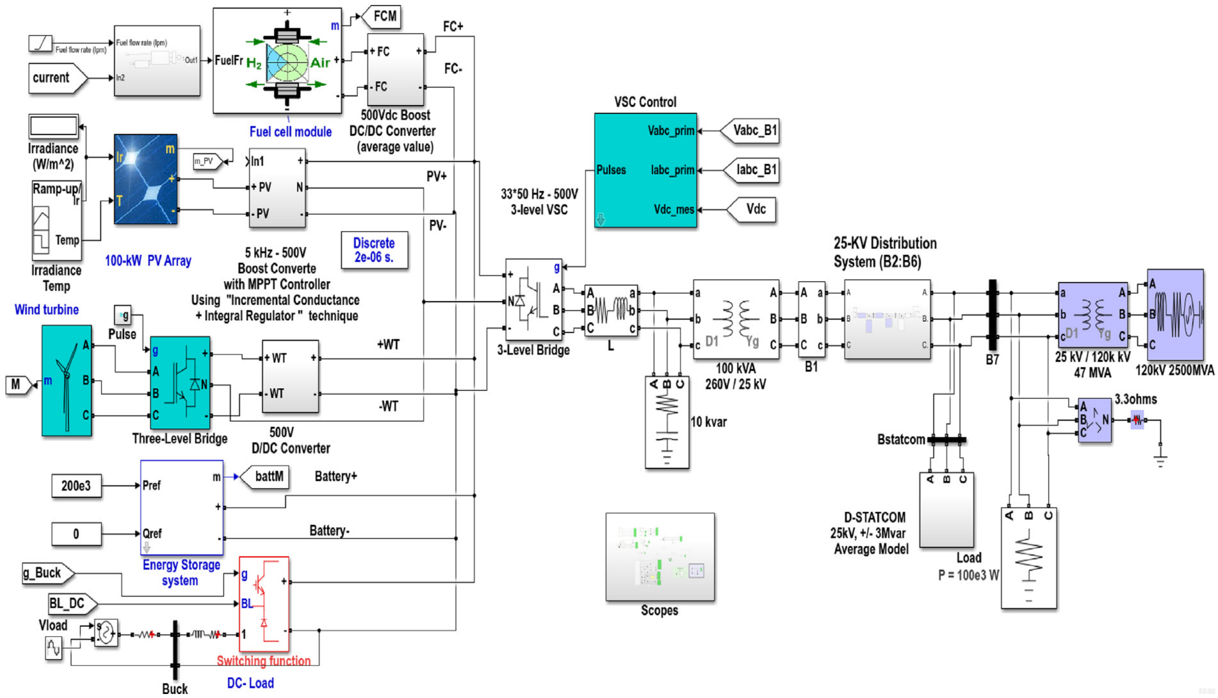

Fig. 2 Detailed proposed AC/DC hybrid micro-grid system in Simulink.

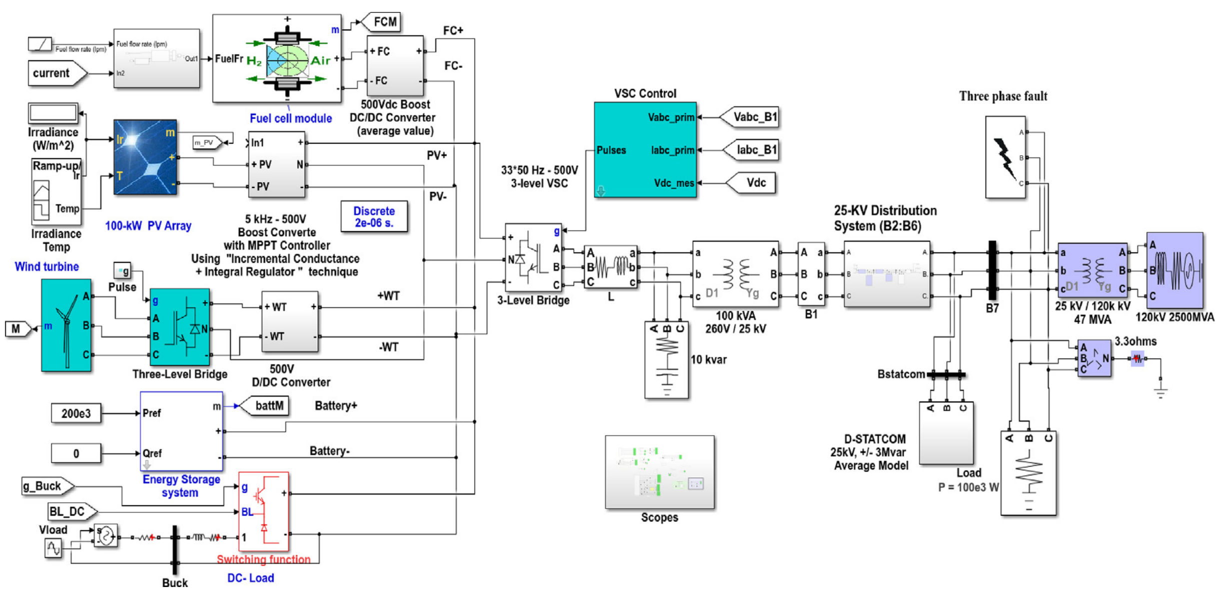

Fig.3 D-STATCOM connected to the proposed system for fault condition.

is the same in q-axis current. The D-STATCOM controller constantly keeps an eye on bus voltage at Bus (B_7) and current values and then it determines the quantity of compensation required by the AC grid for dealing with a disturbance which is produced within the case studies [6]. Figs. 3 and 4 show the D-STATCOM connected to the proposed system in the two case studies under different conditions like an abrupt fault occurrence and causing changes in loads. Thus, the voltage fluctuations restrain, and the battery storage system utilizes to improve the system stability and enhance power system performance. The intelligent fuzzy controller based D-STATCOM will keep the voltage levels at standard values that will enhance the power quality issues to ensure the efficiency of Hybrid micro grid according IEEE standards like IEEE std 519 [35], IEEE Std 3002.8–2018 [36] and IEEE Std 1547.3–2007 [37].

2.1.1. Photovoltaics' array

A photovoltaic (PV) module consists of a series and parallel collections of PV cells that are electrically connected to obtain the output voltage and current for the PV array. The PV array obtains constant a DC voltage and thus it is necessary to con-

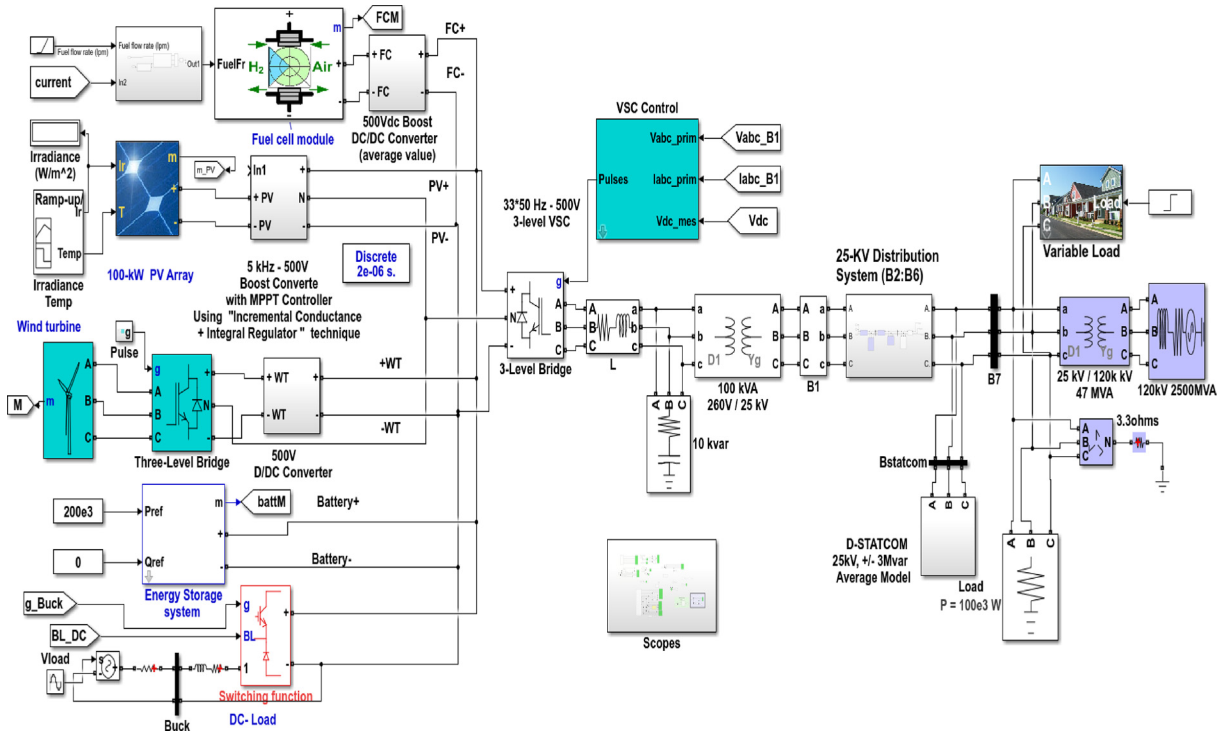

Fig. 4 D-STATCOM connected to the proposed system for variable load.

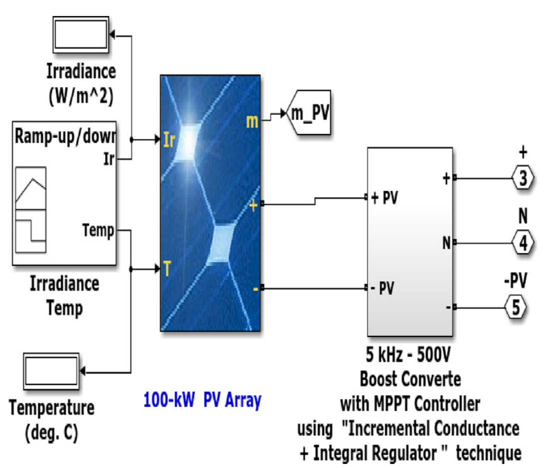

Fig.5 The configurations of photovoltaic module.

trol the output voltage to enhance system efficiency as possible by using maximum power point tracking (MPPT) technique. This technique is performed to maximize the produced power by various PV modules under various cases of the weather. The PV module consists of 66 parallel strings and 5 series connected modules per string, and the configuration of Photovoltaic module is illustrated in Fig. 5.

2.1.2. Wind turbine module

The wind turbine module converts mechanical energy to electrical energy. Wind turbines are designed to operate at a specified speed to achieve maximum energy production and to have a specified capacity with obtaining maximum output power. For obtaining a maximum output power, the turbines should be continuously adapted with the changing in wind speed conditions. The wind turbine module is considered as a distributed generating unit included in the proposed micro-grid by using AC/DC converter that is operated in the range 50– 85 kW which is driven by high-speed double fed induction generator (DFIG) of 3000 rpm.

2.1.3. Fuel cell module

Fuel cells are defined by the electrolyte material type that used in the module. The proton exchange membrane (PEM) fuel cell is proposed to use, it consists of a cathode, an anode and an electrolyte membrane as illustrated in Fig. 6 The PEMFC has high efficiency, and it has a flexible operation to obtain the fuel cell output voltage with range 45 V and get the output power within range at 6 kW.

2.1.4. Battery storage system

Whereas the demand has been more than supply, it is necessary to find a new option to keep the balance between the demand and supply. The battery is used for storing exceed generated power to utilize it when needed it. In the suggested micro-grid, the battery is connected to VSC for regulating active and reactive power compensation according to two control loops. The control algorithms are preformed to maintain the battery state of charge (SOC) as illustrated in Fig. 7.

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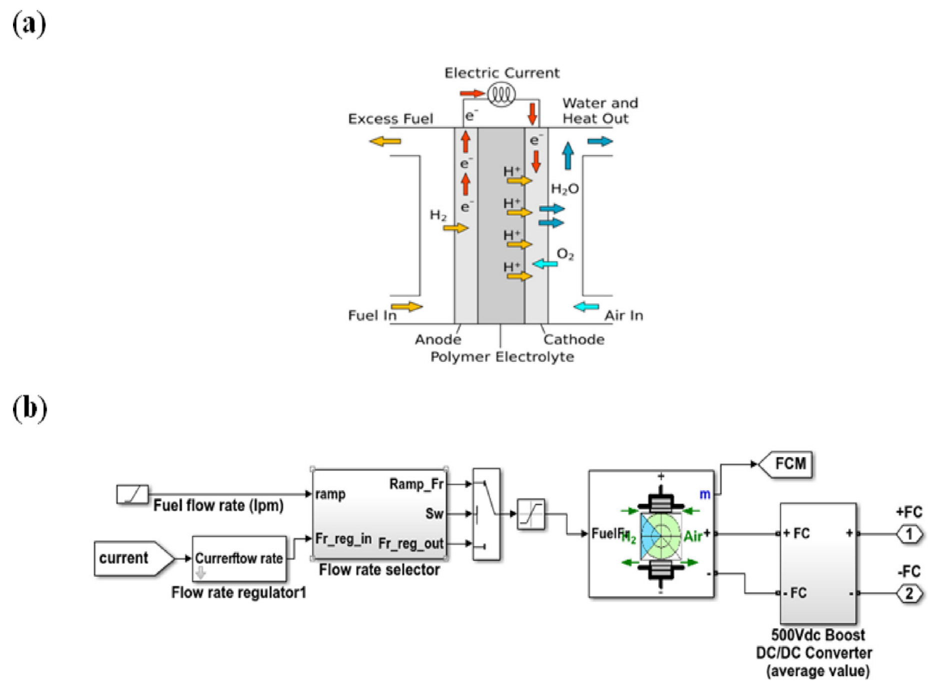


Fig. 6 The configurations of fuel cell module.

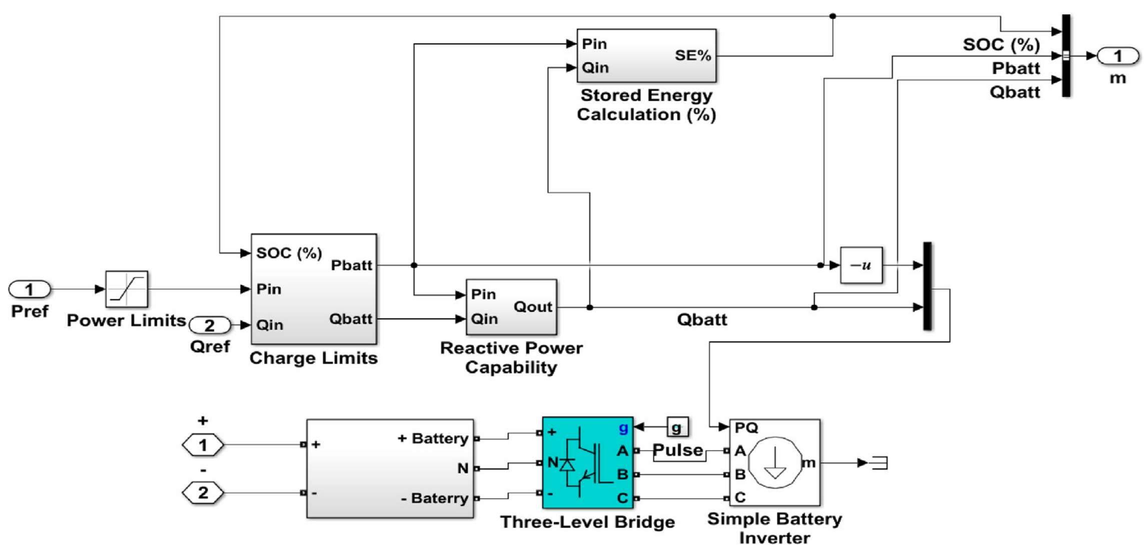


Fig.7 The configurations of power storage element.

battery is necessary to compensate unbalance in power which obtains during the system disturbance due to cases of the study.

The total generated power, which is provided power to load side, includes the output power of photovoltaic system, wind turbine, fuel cell module, and energy storage system as in Eq. (1) as:

$$\mathbf{P_{loads}} = \mathbf{P_{pv}} + \mathbf{P_{FC}} + \mathbf{P_{WT}} \pm \mathbf{P_{battery}} \tag{1}$$

The battery should be ready to start charging or discharging power so its recharge rate according 50% from rated power and its overall efficiency is 96%. Thus, the battery is ready to operate with rated capacity according 100 kWh and its efficiency and life are based on the discharge rate.

2.2. Proposed control scheme

AC/DC hybrid micro-grid is in essential need for secure protection against faults and various load dynamic changes to achieve balance in power between demand and supply. The controller is operating as a circuit breaker and its main function is receiving data from distributed generating units and monitoring system components in the AC/DC hybrid micro-grid. At the normal condition, the controller output is one (1) for the breaker and thus the circuit is closed. Unlike when the fuzzy controller detects any abnormal conditions, the controller output is zero (0) for the breaker and thus the circuit has opened until repairing power system. With keeping in mind,

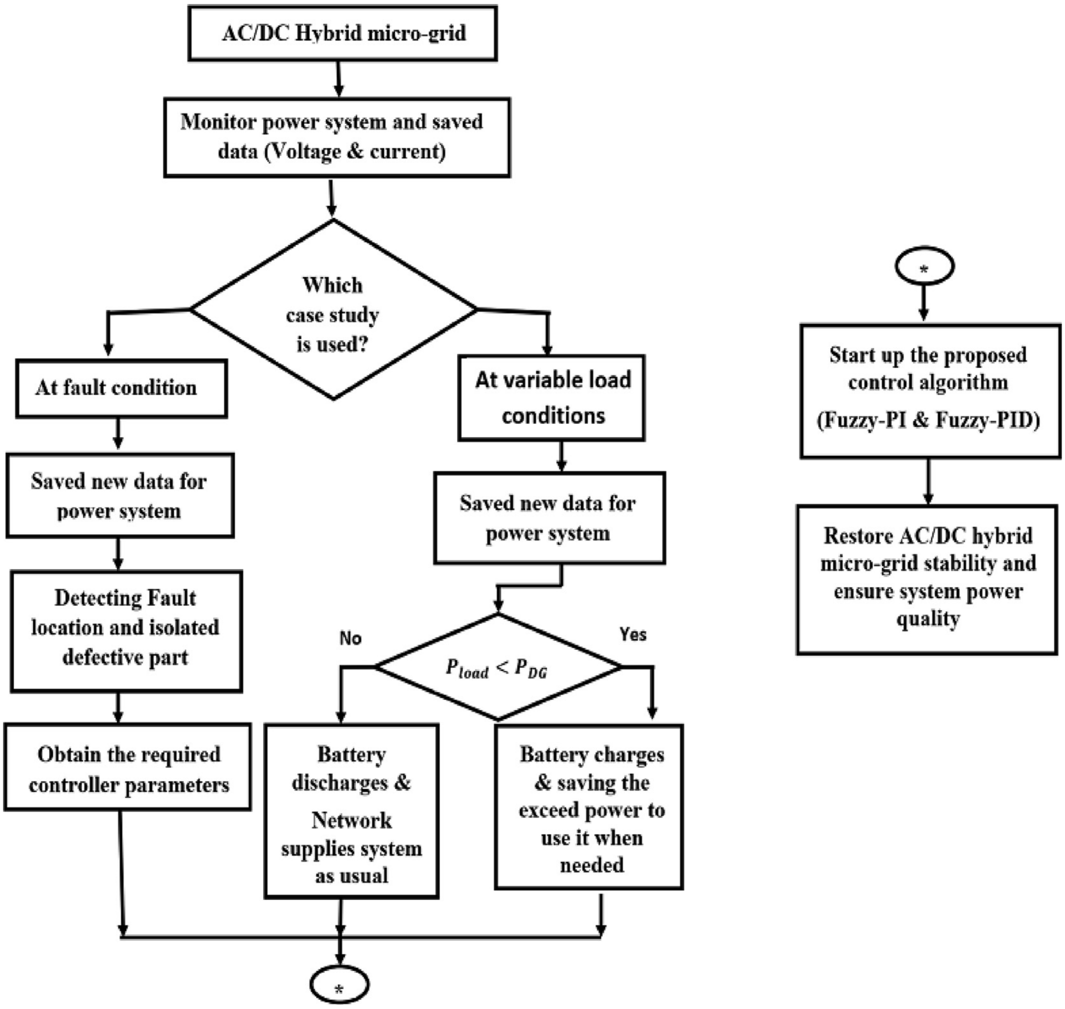


Fig. 8 Flow chart suggested for proposed controller algorithm.

the initial state of battery charge (SOC) is supposed at 100 % from its rated charge capacity. When the power system is subjecting under test conditions, the disturbance is occurring in the system and causing variations in voltage and current. So, it is necessary to monitor and record them well because it is using for setting the controller algorithm to ensure system stability and enhance its performance as illustrated in Fig. 8.

- When the fault occurs in the power system, the VSC converters cannot control the current and the system loses its stability. Because of low fault impedance, the fault current rapidly rises with high values which mean that fault detection and isolation must be determined fast as possible. The detection of fault location has considered as the prime tasks in power system for better control strategies, so it is very necessary to make a quick identification of fault because of any insufficient measurement data may lead to get power system into trouble.

- When the step increase in load happens, it has a significant impact on the system stability at the two sides of the hybrid micro-grid thus the system may been fall in trouble then produced unbalance in power. So, the main task of controller is maintaining the power balance between demand and supply to reduce the voltage fluctuations and resolve power quality problems then finally executing the proposed control approach for ensuring system secure according to Eq. (1):

a. If the output power of distributed generating power is less than load power as:
($\boldsymbol{P_{load} > P_{PV} + P_{WT} + P_{FC}}$), then the battery is in discharge state to supply the required power to load side, and the battery output current is positive. In addition to the public grid also operates as usual to compensate the load shortage.
b. If the output power of distributed generating units is more than load power ($\mathbf{P_{load} < P_{PV} + P_{WT} + P_{FC}}$), thus, the battery is in charging state and its output current is negative with the spare power of the public grid.

The Battery has an efficient role with proposed controller, so it is qualified to use with DC/DC bidirectional converter to charge through DC bus from distributed generating units or AC utility grid and discharge at fault conditions or sudden changes in load to validate the voltage stability and enhance system power quality for AC/DC hybrid micro-grid. Thus, power system is being able to face load consumption and loss of mains. The D-STATCOM based on fuzzy logic controller continuously monitors system performance and then determines the required quantity of compensation by the AC grid for dealing with a disturbance during test conditions.

2.3. Principal operation of D-STATCOM

The primary D-STATCOM function is to generate or absorb the reactive power to regulate and preserve the bus voltage at an acceptable level. The reactive power quantity is proportional to the difference between the bus voltage and the D-STATCOM output voltage, then the compensation is Validated by the control of direct axis and quadrature axis currents by using instant reactive power theory for balanced three-phase AC system to achieve perfect response and make system more reliable and flexible as shown in Fig. 9. The quantity of reactive power flow is proportional to the difference of D-STATCOM output voltage and AC bus voltage at bus (B_7), then the compensation is verified by the control of direct axis and quadrature axis currents, then by using instant reactive power theorem for balanced three-phase AC system in order to achieve fast response, flexible and easy implementation.

The working principle of D-STATCOM for mitigating voltage variation and control of active and reactive power exchanges between the voltage bus B_7 and system voltage are shown as following:

1. If D-STATCOM output voltage is equal to the bus voltage at the load bus (B_7), reactive power is delivered to the ac grid, thus D-STATCOM works as stand-by mode.
2. If D-STATCOM output voltage is greater than the bus voltage at the load bus (B_7), thus D-STATCOM is on capacitive mode.
3. If D-STATCOM output voltage is smaller than the bus voltage the load bus (B_7), reactive power is absorbed from the system.

D-STATCOM consists of two-level voltage source converter (VSC) which used for regulating bus voltage at the load bus (B_7) and filtering out the current harmonics, control unit to produce PWM signals for switches of the inverter, dc-link capacitor (C) to support the inverter by DC voltage and convert into three-phase AC voltages by the storage unit and coupling transformer that is connected in Shunt to match the inverter output to the line voltage as illustrated in Fig. 10 [38].

3. Design procedures for both controllers

3.1. Proportional-integral (PI) current controlled D-STATCOM

The purpose of the PI controller is to maintain voltage magnitude at a constant value within accepted operating range under system disturbance at test condition [29]. It is used for control of average dc voltage and d-axis and q-axis currents. PI controllers are designed to determine the instantaneous value of the error value without considering disturbance effect between the d-axis and q-axis. The VSC switching concept is depending on a sinusoidal PWM mechanism which produces a good and simple dynamic response. The controller input is formed by computing the difference between the reference voltage and the R.M.S voltage system at bus (B_7) that which is called error signal at different conditions like abrupt faults and dynamic load changes to generate the required angle that drives error to zero, therefore saving the measured R.M.S value of system voltage at bus (B_7) to the reference voltage value and following with synchronization between inverter output-voltage with system voltage is based on phase-locked loop (PLL).

The measured currents are converted to d and q components by using phase angle that produced by PLL, the d-axis and q-axis current are compared with their references' and their error values are applied to the PI controller. To recognize the decoupled control of d and q-axis currents, cross-coupling terms and disturbed voltage are added to outputs of current controllers. The produced values of V_{id} and V_{iq} are converted to modulation signals and gate pulses are generated by comparing modulation signals with carrier wave.

Fig. 11.a shows the complete configuration for the structure of conventional PI current controlled D-STATCOM. Fig. 11.b had shown the representation of subsystem of d-axis and q-axis currents control for conventional PI controller in MATLAB/Simulink environment.

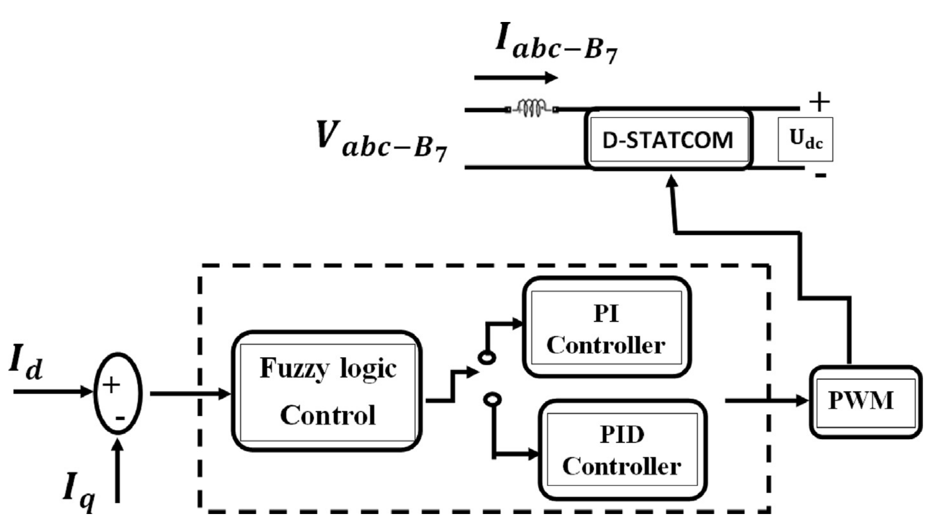


Fig. 9 Detailed of D-STATCOM controller.

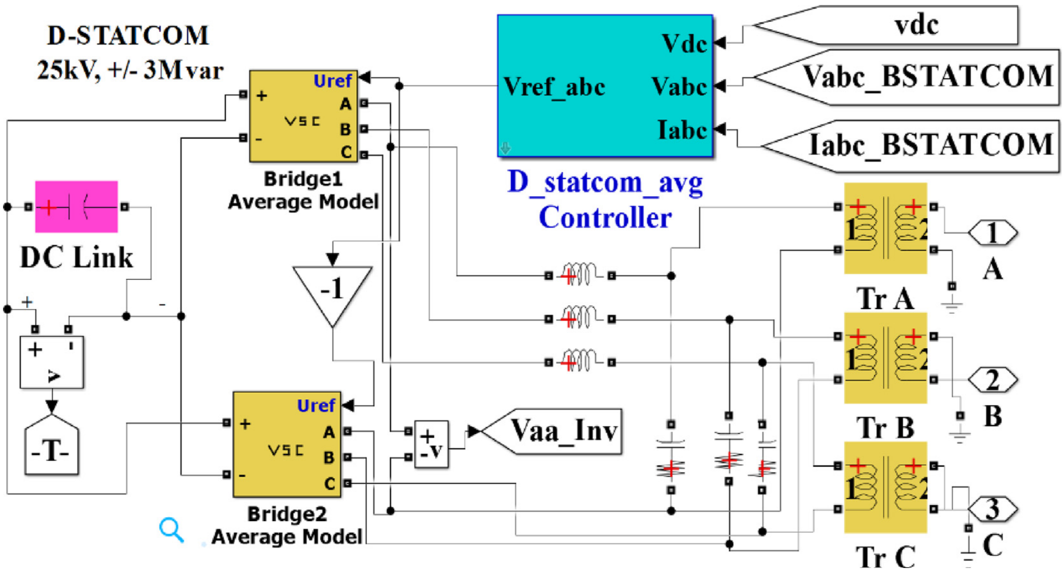


Fig. 10 Schematic presentation of D-STATCOM.

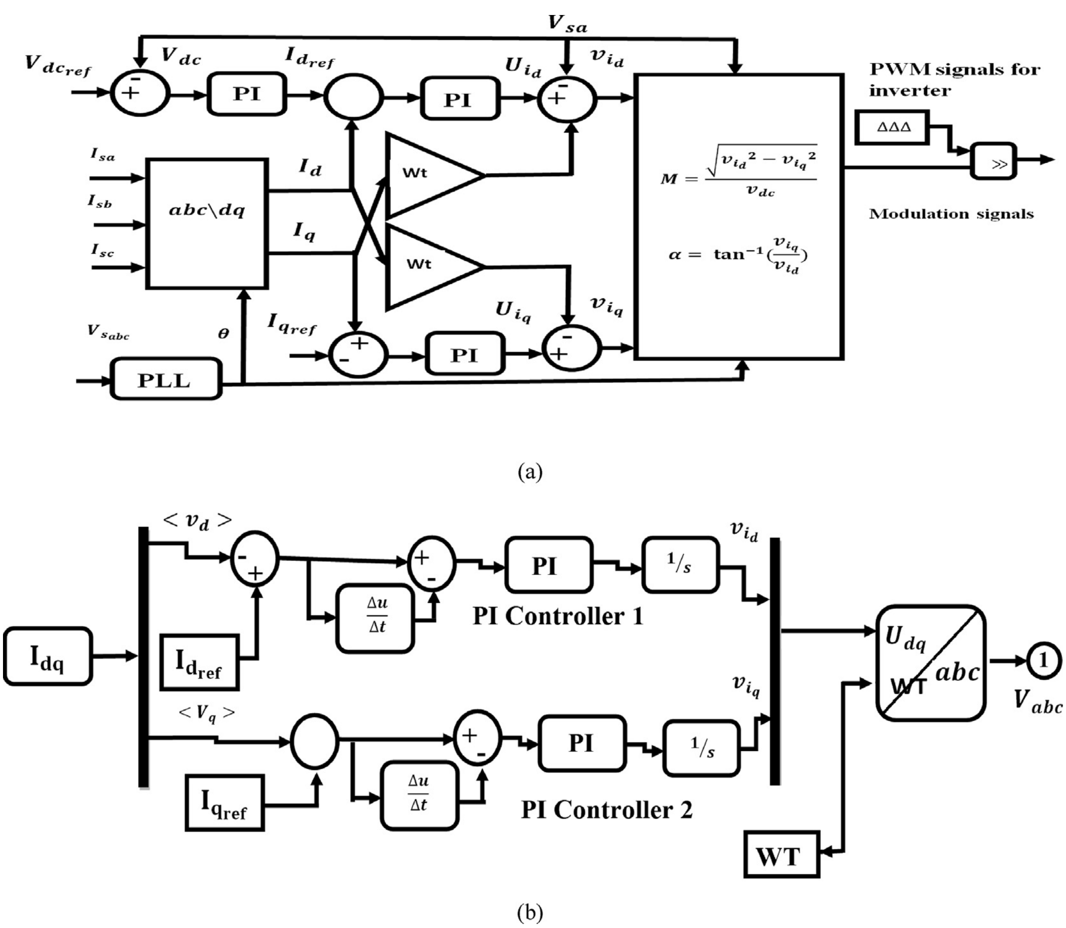


Fig.11 Conventional PI current controlled D-STATCOM; (a) Complete configuration for controlling of d-axis and q-axis current; (b) subsystem of d-axis and q-axis currents control in MATLAB/Simulink environment.

3.2. Proportional-integral- differential (PID) current controlled D-STATCOM

The Proportional-integral- differential (PID) controller is considered as robust controller and distinguished with its functional simplicity. The purpose of PID is maintaining voltage amplitude at a constant value within the accepted operating range under system disturbance at test condition [39]. It is used for control of average dc voltage and d-axis and q-axis currents. The PID controllers are designed to determine the instantaneous value of the error value without considering disturbance effect between the d-axis and q-axis as shown in Fig. 12.

The construction of the PID controller has two inputs and one output. The error signal and the change in the error $(e(t), \Delta e(t))$ of d-axis current are the controller inputs that are used for controlling of d-axis current. This controller is the same as that used for controlling of q-axis current. The output of PID controller based on D-STATCOM is acquired to obtain the desired voltage $(v_{i_d},\ v_{i_q})$ and then added to an external integrator to get rid of the steady-state error. Finally, the output is connected to inverse park transform block, which in turn converted it to three-phase system components (v_{abc}). Fig. 12 had shown the representation of subsystem of d-axis and q-axis currents control for PID controller in MATLAB/ Simulink environment.

3.3. Fuzzy-PI current-controlled D-STATCOM

The disadvantages of PI controller and its deficiency while dealing with sudden changes in the error signal (e) [40,41], because it is only able to determine the instant value of the error value regardless any changes of increasing or falling of the error values, which in the mathematical term is the derivative of the error indicated as (Δe), as well as it cannot be operated with optimum performance for different testing points. On the other hands, PID controller does not act well in the high nonlinear of power system, in addition to its response as it takes more time to finish compensation which troubles the power system. To avoid this problem, Fuzzy logic control is suggested. The main role of the fuzzification part makes crisp values suitable to be represented in the rule base. The fuzzy interference determines which fuzzification strategy can be performed; by using knowledge base consists of the system data base. The rule base is a basic system control strategy. It is usually represented as a group of If-Then rules. In this paper, Mamdani method is used to deal with Fuzzy-PI and Fuzzy-PID as it is suitable for slow-change dynamics.

An FLC can be designed as a current regulator, AC voltage regulator and DC voltage regulator. The DC and AC voltage regulators evaluated from the outer regulation loop of the D-STATCOM control system, unlike current regulator is evaluated from the inner loop. The output of the AC voltage regulator is the reference (i_{qref}) for the current regulator, where (i_q) is the current in quadrature with a voltage which controls the reactive power flow. DC voltage regulator output is based on the reference of the current regulator (i_{dref}), where the current (i_d) is in phase with a voltage which in turn controls the active power flow. Thus, the current regulator formed V_{2d} and V_{2q}dependant on terms of $(i_{dref} - i_d)$ and $(i_{qref} - i_q)$. The PWM modulator produces pulses which also control IGBT in the VSC based on V_{2d} and V_{2q} to achieve the synchronizing with the output of the PLL (θ) [42]. Fig. 13 illustrated the complete configuration of fuzzy-PI (FPI) current controlled D-STATCOM (Fig. 13.a). The configuration of the Fuzzy-PI current controller has two inputs and two outputs. The error signal of d and q-axis current and derivate of these errors are the inputs of Fuzzy-PI current controller, and then adding an external integrator to get rid the steady-state error in output of the proposed controller technique [43]. The required d and q-axis voltages $(V_d,\ V_q)$ which are obtained and converted to three-phase voltage by the inverter to generate modulation signals which is needed to control the inverter switches, considering that synchronization between system voltage and inverter output voltage is based on phase-locked loop (PLL).

The structure of the FPI controller has two inputs and two outputs. The inputs of proposed controller that are used for controlling of d-axis current are error signal and the change in the error of d-axis current is the same as these that used for controlling of q-axis. The outputs of FPI controller with D-STATCOM are defuzzied to obtain the required voltage $(V_d,\ V_q)$ and converted to per unit (pu) to get modulation

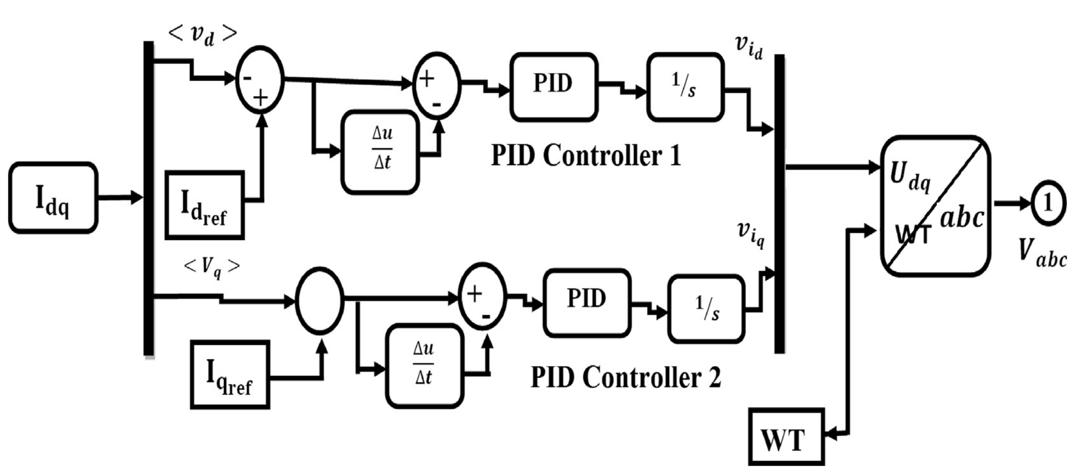


Fig.12 Complete configuration for controlling of d-axis and q-axis current for conventional PID current controlled D-STATCOM in MATLAB/ Simulink environment.

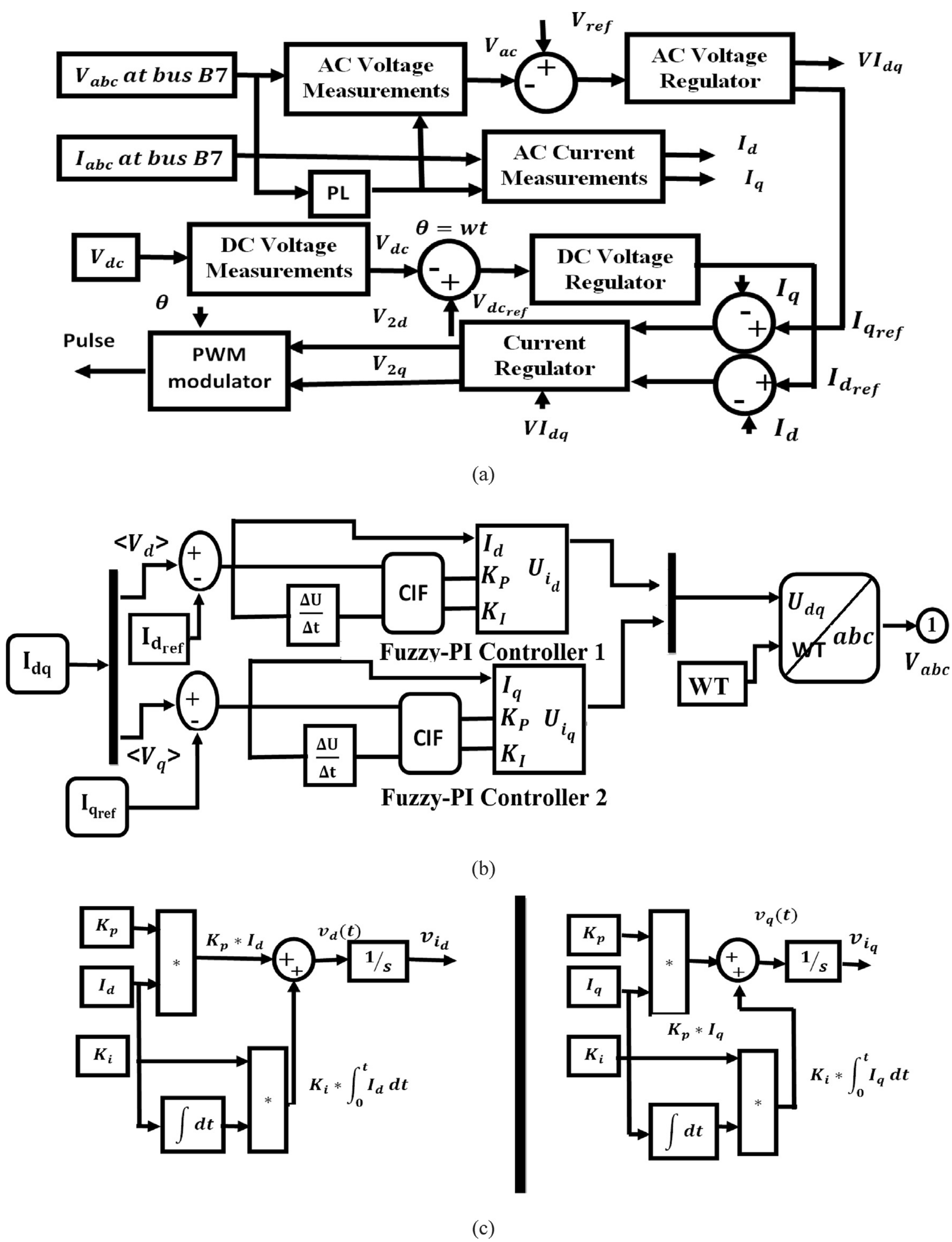


Fig. 13 Fuzzy-PI current controlled D-STATCOM; (a) Complete configuration; (b) Simulink system configuration for d-axis and q-axis currents control; (c) Detailed description for obtaining the outputs of Fuzzy-PI controller.

signals in per unit, which have to be generated by inverter with adding an external integrator to get rid of the steady-state error in output of FLC, then connected to inverse park transform block, which in turn converts direct, quadrature, and zero components in time-domain to three-phase system components in an (*abc*) standard form as shown in Fig. 13.b.

Fig. 13.a shows the complete configuration for the structure of Fuzzy-PI current controlled D-STATCOM. Fig. 13.b shows the representation of subsystem of d-axis and q-axis currents control for Fuzzy-PI controller in MATLAB/Simulink environment.

The design of Fuzzy-PI controller is stated as follows:

a. Determining the inputs of Fuzzy-PI controller, which are the error in terms of both d and q axis current ($e(t)$) and the deviation of these error ($\Delta e(t)$) and the outputs of the controller are (K_p, K_i) then get the required d and q-axis voltages (v_{i_d}, v_{i_q})as shown in Fig. 8b by the following equation:

$$V_{(t)} = K_P.e_{(t)} + K_I.\int_0^t e_{(t)}dt \quad (2)$$

to select membership functions that required for representing the inputs of proposed controller, the fuzzy membership functions are represented for modling the input variables $(e(t), \Delta e(t))$ and output variables(K_p, K_i)) as illustrated in Fig. 14a-d, Fig. 14 shows the inputs and outputs membership function for Fuzzy-PI controller.

Triangular functions are chosen for representing input variables and linear membership function for the output variables which it helps with fuzzy-PI controller to be more efficient as compared with the others [21,22] and minimize stability issues and enhance power system performance [23].

b. The preferred linguistic variables are Positive Gain (PG), Negative Gain (NG), Negative Medium (NM), Positive Medium (PM) and Equal Zero (EZ), for (N) linguistic variables for two inputs, there are (N^2) possible rules, so ($5^2 = 25$) possible rules with all combinations for the inputs.

c. A group of decision rules linking the inputs with the output is collected and stored in the form of a 'decision table' as shown in Table.1. The rules are in the form of IF "e" is Equal Zero (EZ) & "Δe" is Negative Gain (NG) at constantsC_1, C_2, 0, C_3, C_4 respectively, then controller parameters $(K_P, K_I)$are "K_P" is (G) & "K_I" is (G).

d. The condition part for each rule is calculated by the following equation:

$$\mu_{(x_j)} = \mu((\mathrm{e}\ is\ \ \mathrm{EZ}),\ and\ (\Delta\mathrm{e}\ \ is\ \ \mathrm{NG})) \quad (3)$$

$$\mu_{(x_j)} = \min[\mu(\mathrm{e\ is\ EZ}), (\mu(\Delta\mathrm{e\ is\ NG})]; \quad j = 1, 2, \cdots\cdots, N^2 \quad (4)$$

e. The output fuzzy membership functions are applied to a linear function between the minimum and maximum values according to linguistic variables, The output values are "K_P" is (G) & "K_I" is (G) and EZ $\subset$ NM, then the output values can be obtained by the following equation:

$$\mu_{K_P}(x_j) = \min\left[\mu(x_j, EZ), \mu(x_j)\right] \quad (5)$$

$$\mu_{K_I}(x_j) = \min\left[\mu(x_j, EZ), \mu(x_j)\right] \quad (6)$$

$$\mu_{K_p}(x_j) = \max\left[\mu_{KPs}(x_j, EZ)\right] \quad for\ \ all\ \ x_j \quad (7)$$

$$\mu_{K_I}(x_j) = \max\left[\mu_{KIs}(x_j, EZ)\right] \quad for\ \ all\ \ x_j \quad (8)$$

(x_j) is the j_{th} value of the (N^2) possible rules?

$(\mu_{(x_j)})$ is the membership function of x_j rule?

$(\mu_{K_p}, \mu_{K_I}, \mu_{KPs}, \mu_{KIs})$are the Fuzzy-PI outputs

f. The fuzzy output $(\mu_{K_p}, \mu_{K_I}, \mu_{KPs}, \mu_{KIs})$ are then defuzzied to obtain $(K_P \& K_I)$ and acquired the desired d and q-axis voltages (v_{i_d}, v_{i_q}), the most methods of defuzzification used are the centroid and the weighted average methods, by using the weighted average method, the output parameters of the Fuzzy-PI controller are obtained as:

$$K'_p = \sum_1^{25} \frac{\mu_{K_p}(x_j) * constantofx_j}{\sum \mu_{K_p}(x_j)} \quad (9)$$

$$K'_I = \sum_1^{25} \frac{\mu_{K_d}(x_j) * constantofx_j}{\sum \mu_{K_d}(x_j)} \quad (10)$$

$$K_P = K'_p * G_{K_P} \quad (11)$$

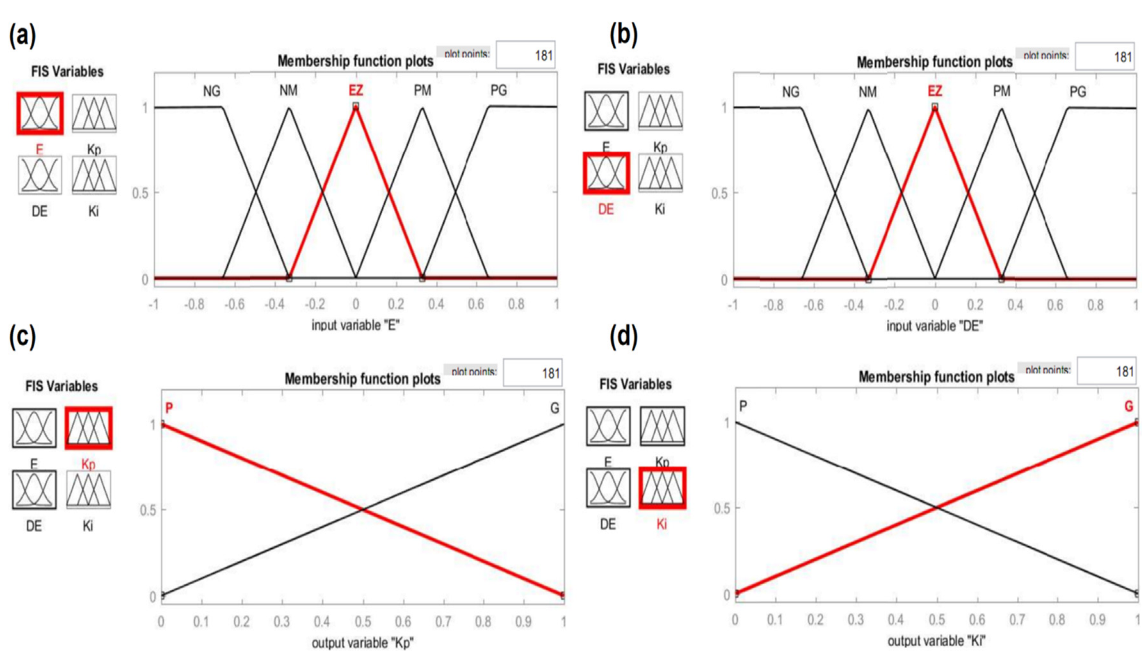


Fig. 14 Membership functions for Fuzzy-PI current controlled D-STATCOM of triangular membership; (a), (b) for the input variables; (c), (d) for the output variables.

$$K_I = K'_I * G_{K_I} \quad (12)$$

$$V_{d_{(t)}} = K_P.i_d + K_I.\int_0^t i_d dt \quad (13)$$

$$V_{q_{(t)}} = K_P.i_q + K_I.\int_0^t i_q dt \quad (14)$$

In this paper, the triangular membership functions are suitable for modeling the input variables and linear membership functions. The steps that including the design of Fuzzy-PI controller are represented in flow chart as shown in Fig. 15. The decision rules of 25 possible states for Fuzzy-PI controller are represented in Table 2.

3.4. Fuzzy-PID current-controlled D-STATCOM

The Fuzzy-PID (FPID) current controller technique which is used in this simulation is illustrated in Fig. 16.a, the configuration of the FPID current controller has two inputs and three outputs. The error signal of d and q-axis current and derivate of these errors are the inputs of Fuzzy-PID current controller, and (K_p, K_i, K_d) are the outputs of Fuzzy-PID controller which are following by an external integrator to get rid of the steady-state error in output of the proposed controller technique.

The outputs of the Fuzzy-PID current controller are to obtain the required voltage (V_d, V_q) which are converted to three-phase voltage (V_{abc}) by using to inverse park transform block as shown in Fig. 16. b. Fig. 16.b shows the detailed description for obtaining outputs of Fuzzy-PID controller.

The next steps include designing of Fuzzy-PID controller are stated as following:

a. Determine the inputs of Fuzzy-PID controller, they are the error in terms of both d and q axis current $(e(t))$ and the deviation of these error $(\Delta e(t))$ and the outputs of the controller are (K_P, K_d, α) then get the value of (K_i) and the required d and q-axis voltages (v_{i_d}, v_{i_q}) as shown in Fig. 5b by the following equation:

$$V_{(t)} = K_p + K_i * e_{(t)} + K_d. * \Delta e_{(t)} \quad (15)$$

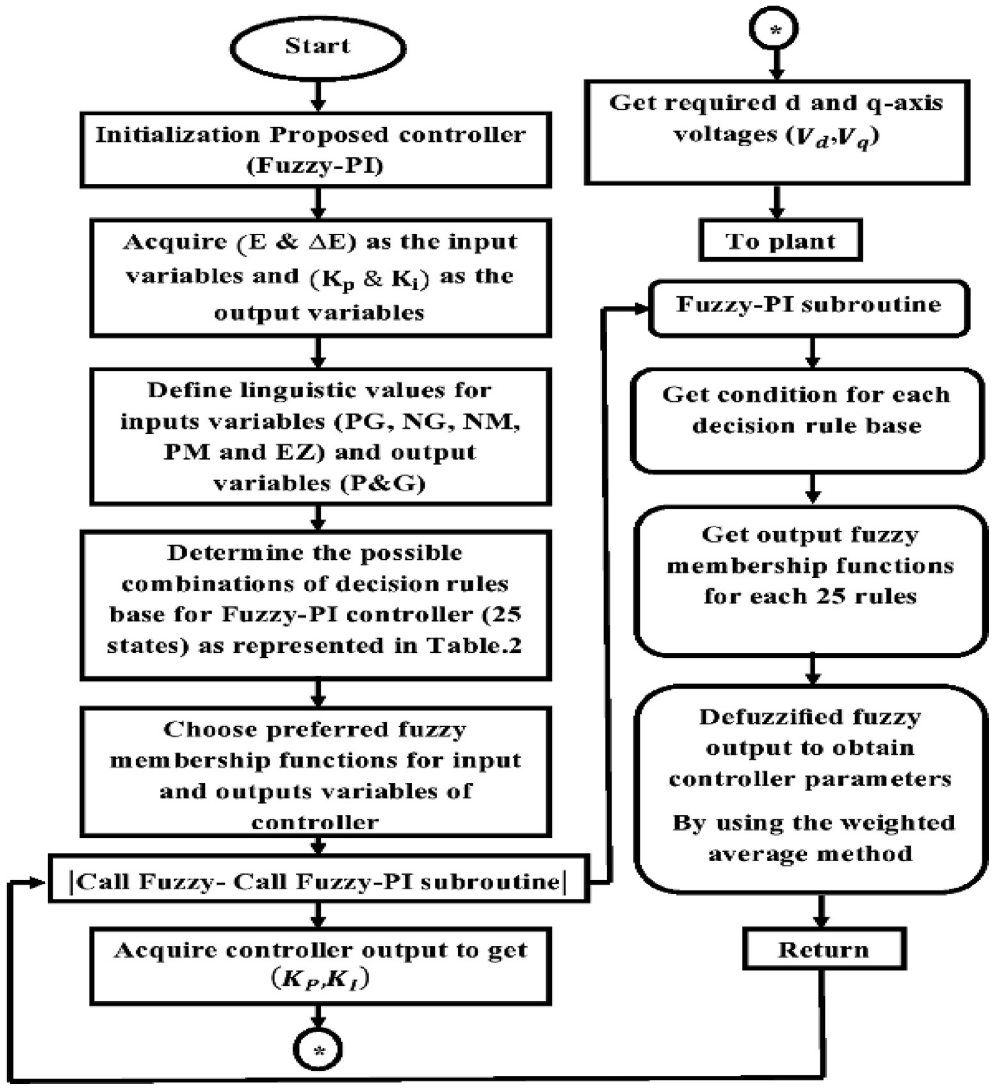


Fig.15 Flow chart for Fuzzy-PI current controlled D-STATCOM.

Table 2 Choice table for Fuzzy-PI controller.

E	ΔE									
	NG		NM		EZ		PM		PG	
EZ	K_P	K_I	K_P	K_I	K_P	K_I	K_P	K_I	K_P	K_I
	G	G	G	G	G	G	G	G	G	G
NG	K_P	K_I	K_P	K_I	K_P	K_I	K_P	K_I	K_P	K_I
	G	G	G	P	G	P	G	P	G	G
NM	K_P	K_I	K_P	K_I	K_P	K_I	K_P	K_I	K_P	K_I
	P	G	G	G	G	P	G	G	G	P
PM	K_P	K_I	K_P	K_I	K_P	K_I	K_P	K_I	K_P	K_I
	P	G	G	G	G	P	G	G	G	P
PM	K_P	K_I	K_P	K_I	K_P	K_I	K_P	K_I	K_P	K_I
	G	G	G	P	G	P	G	P	G	G

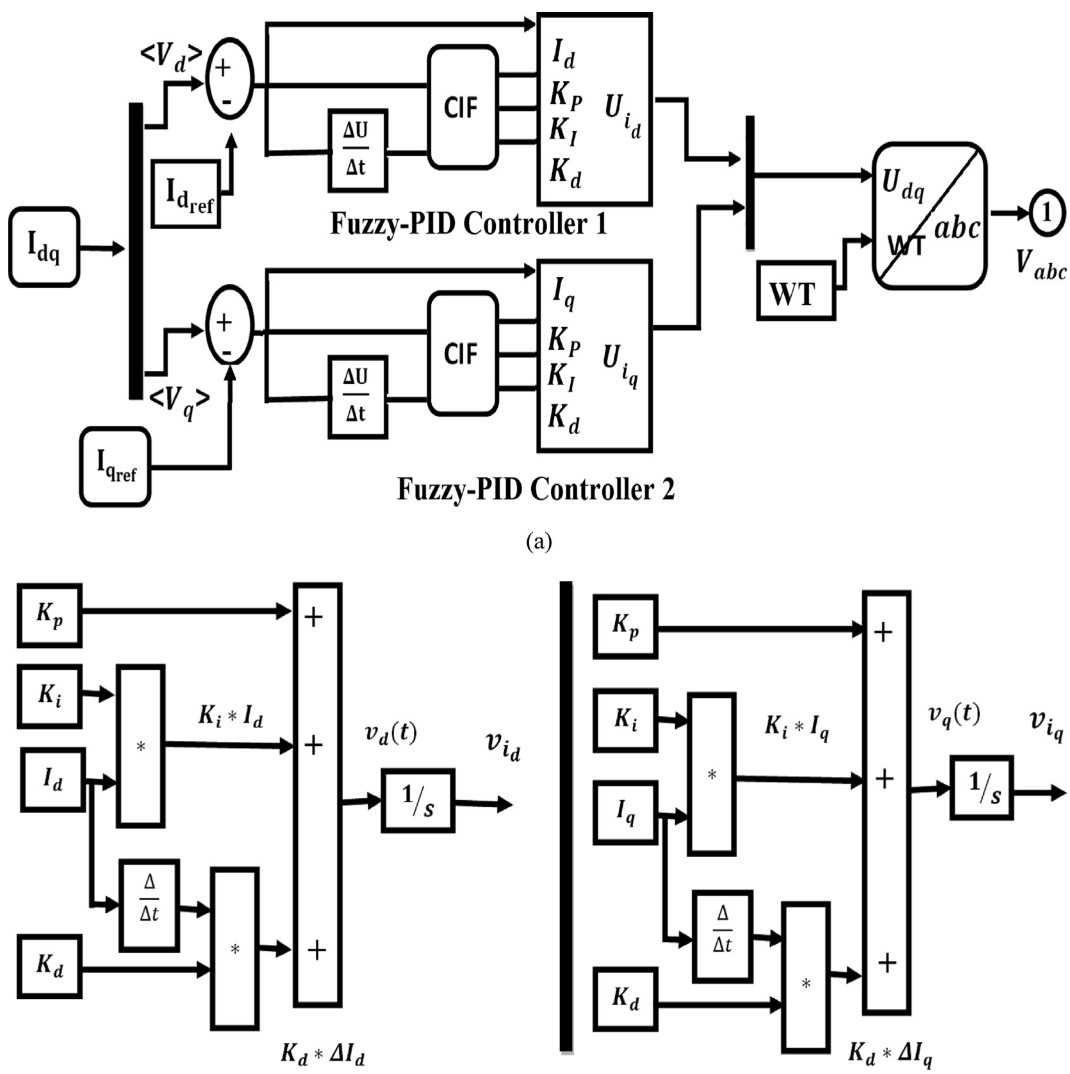


Fig. 16 Fuzzy-PID current controlled D-STATCOM; (a) Simulink system configuration; (b) Detailed description for obtaining the outputs of Fuzzy-PID controller.

b. Select membership functions that required for representing the inputs of proposed controller, the fuzzy membership functions for input variables and output variables are represented as illustrated in Fig. 17a-e.

c. The preferred linguistic variables are Positive Small (PS), Positive Medium (PM), Positive Big (PG), Zero (EZ), Negative Small (NS), Negative Medium (NM), Negative Big (NB) and Equal for (N)linguistic variables for two inputs, there are (N^2) possible rules, there are ($7^2 = 49$) possible rules with all combinations for the inputs.

d. A group of decision rules linking the inputs with the output is collected and stored in memory in the form of a 'decision table' as shown in Table 2. The rules are in the form of IF "e" is Negative Big (NB) & "Δe" is Positive Medium (PM) at constants C_1, C_2,C_3, 0, C_4, C_5,C_6, respectively, then controller parameters $\left(K_p, K_d, \alpha\right)$are "$K_P$" is (B) & "α" is (2),& then the linguistic values of input and output variables are presented in Table.3:

e. The condition part for each rule is calculated by the following equation:

$$\mu_{\left(K_p,K_d,\alpha\right)} = \frac{\sum_1^{49} \mu_j * C_j}{\sum_1^{49} \mu_j} \tag{16}$$

f. The fuzzy output is defuzzied to obtain ($K_P, K_d \& K_i$) and acquired the desired d and q-axis voltages (v_{i_d},v_{i_q}), by using the weighted average method, the output parameters of the Fuzzy-PID controller are obtained by the following equations:

$$K_p = \sum_1^{49} \mu_j * K_p \tag{17}$$

$$K_d = \sum_1^{49} \mu_j * K_d \tag{18}$$

$$K_i = \frac{K_p{}^2}{\alpha * K_d} \tag{19}$$

$$V_{i_d} = K_p + K_i * Id + K_d. * dId \tag{20}$$

$$V_{i_q} = K_p + K_i * Iq + K_d. * dIq \tag{21}$$

In this paper, the triangular membership functions are perfect for input variables and Gaussian membership functions are preferred for output variable, the steps that including the designing of Fuzzy-PID controller are represented in flow chart as shown in Fig. 18. The decision rules of 49 possible states for Fuzzy-PID controller are represented in Table 3:

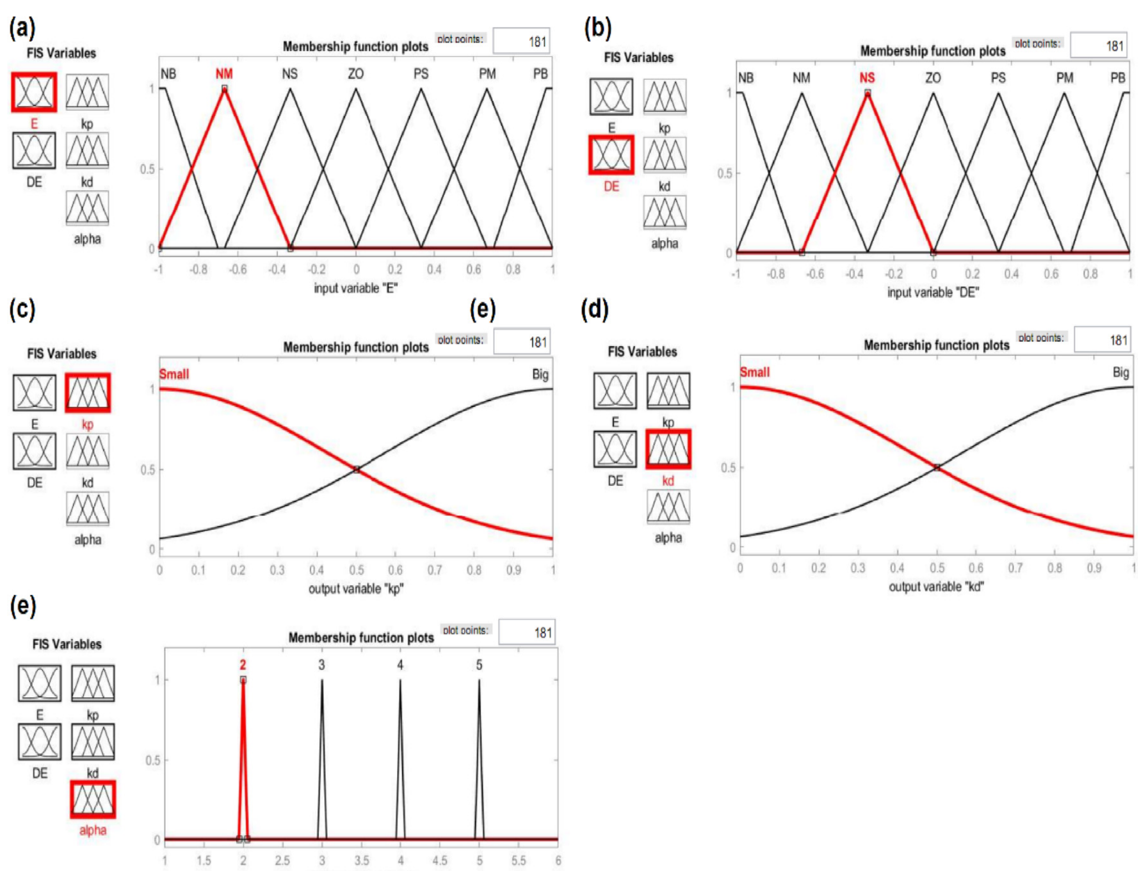


Fig. 17 Membership functions Fuzzy-PI current controlled D-STATCOM of triangular membership; (a), (b) for the input variables; (c), (d), (e) for the output variables.

Table 3 Decision table for Fuzzy-PID controller.

E	ΔE																				
	NB			NM			NS			EZ			PS			PM			PB		
NB	K_p B	K_d S	α 2	K_p B	K_d S	α 2	K_p B	K_d S	α 2	K_p B	K_d S	α 2	K_p B	K_d S	α 2	K_p B	K_d S	α 2	K_p B	K_d S	α 2
NM	K_p S	K_d B	α 3	K_p B	K_d B	α 3	K_p B	K_d S	α 2	K_p B	K_d S	α 2	K_p B	K_d S	α 2	K_p B	K_d B	α 3	K_p B	K_d B	α 3
NS	K_p S	K_d B	α 4	K_p S	K_d B	α 3	K_p B	K_d B	α 3	K_p B	K_d S	α 2	K_p B	K_d B	α 3	K_p S	K_d B	α 3	K_p S	K_d B	α 4
EZ	K_p S	K_d B	α 5	K_p S	K_d B	α 4	K_p S	K_d B	α 3	K_p B	K_d B	α 3	K_p S	K_d B	α 3	K_p S	K_d B	α 4	K_p S	K_d B	α 5
PS	K_p S	K_d B	α 4	K_p S	K_d B	α 3	K_p B	K_d B	α 3	K_p B	K_d S	α 2	K_p B	K_d B	α 3	K_p S	K_d B	α 3	K_p S	K_d B	α 4
PM	K_p S	K_d B	α 3	K_p B	K_d B	α 3	K_p B	K_d S	α 2	K_p B	K_d S	α 2	K_p B	K_d S	α 2	K_p B	K_d B	α 3	K_p S	K_d B	α 3
PB	K_p B	K_d S	α 2	K_p B	K_d S	α 2	K_p B	K_d S	α 2	K_p B	K_d S	α 2	K_p B	K_d S	α 2	K_p B	K_d S	α 2	K_p B	K_d S	α 2

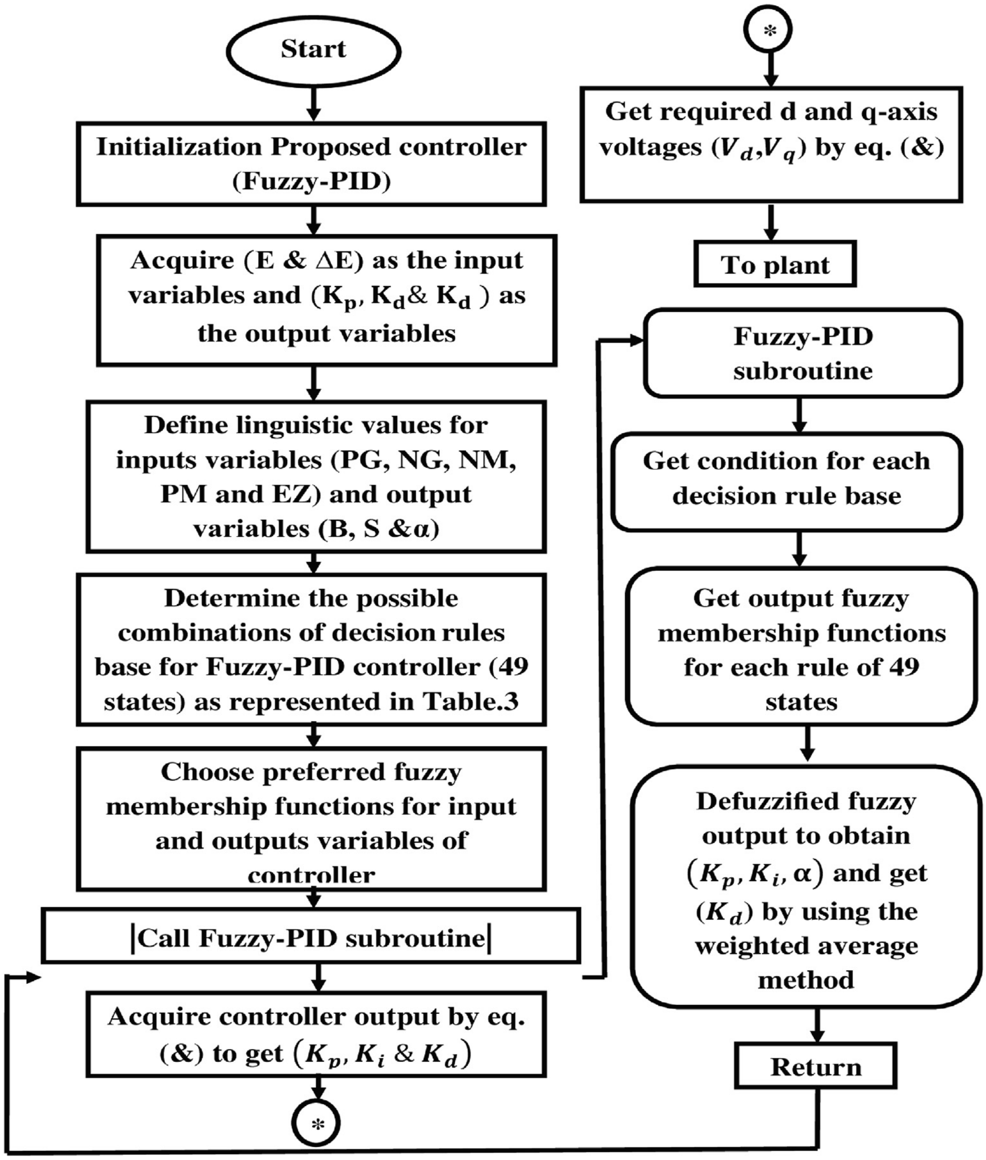
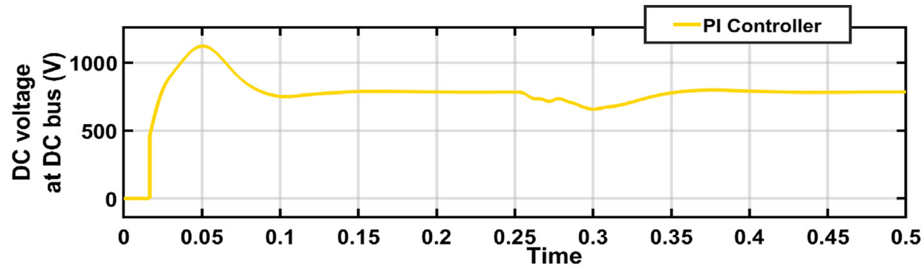
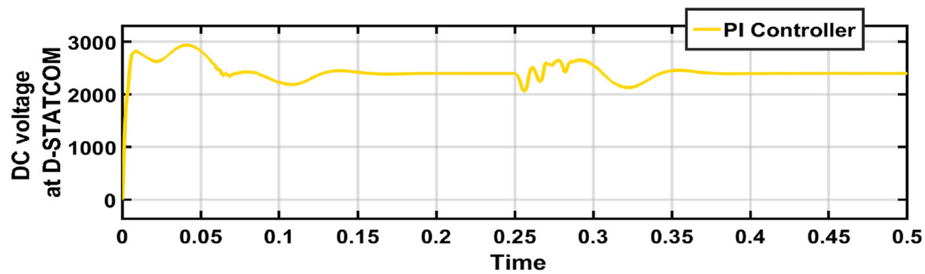


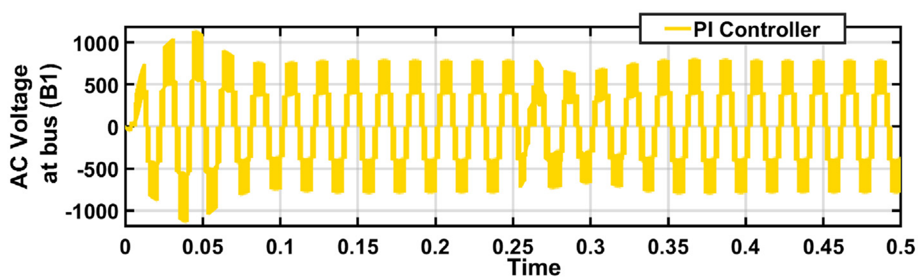
Fig.18 Flow chart for Fuzzy-PID current controlled D-STATCOM.



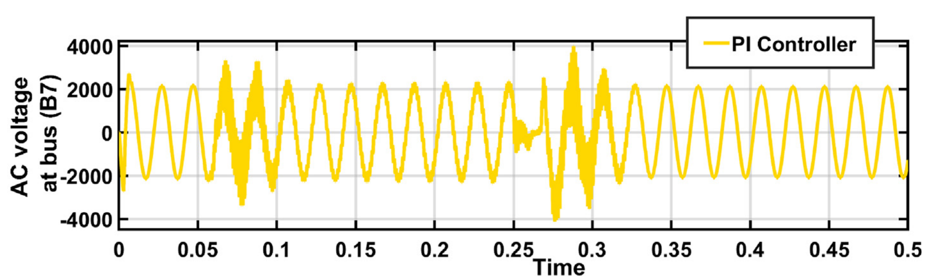
(a)



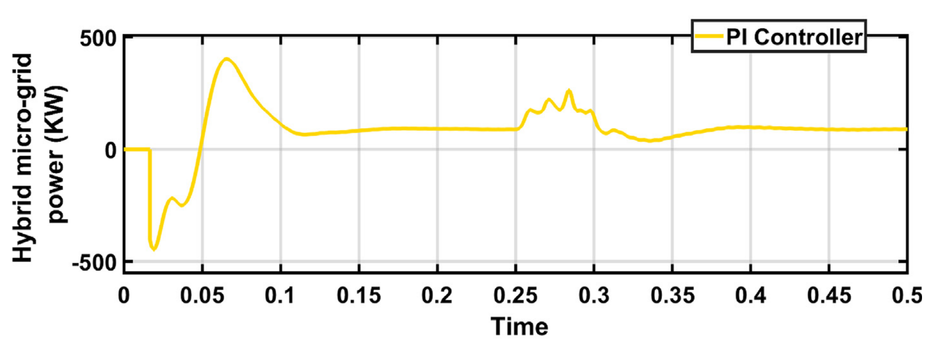
(b)



(c)



(d)



(e)

Fig. 19 Simulation output of conventional PI current controlled D-STATCOM with a fault condition; (a) DC bus voltage before 3-level bridge; (b) Average DC voltage at dc link in D-STATCOM; (c) AC bus voltage at bus (B_1); (d) AC bus voltage at bus (B_7); (e) System power at bus.(B_1)

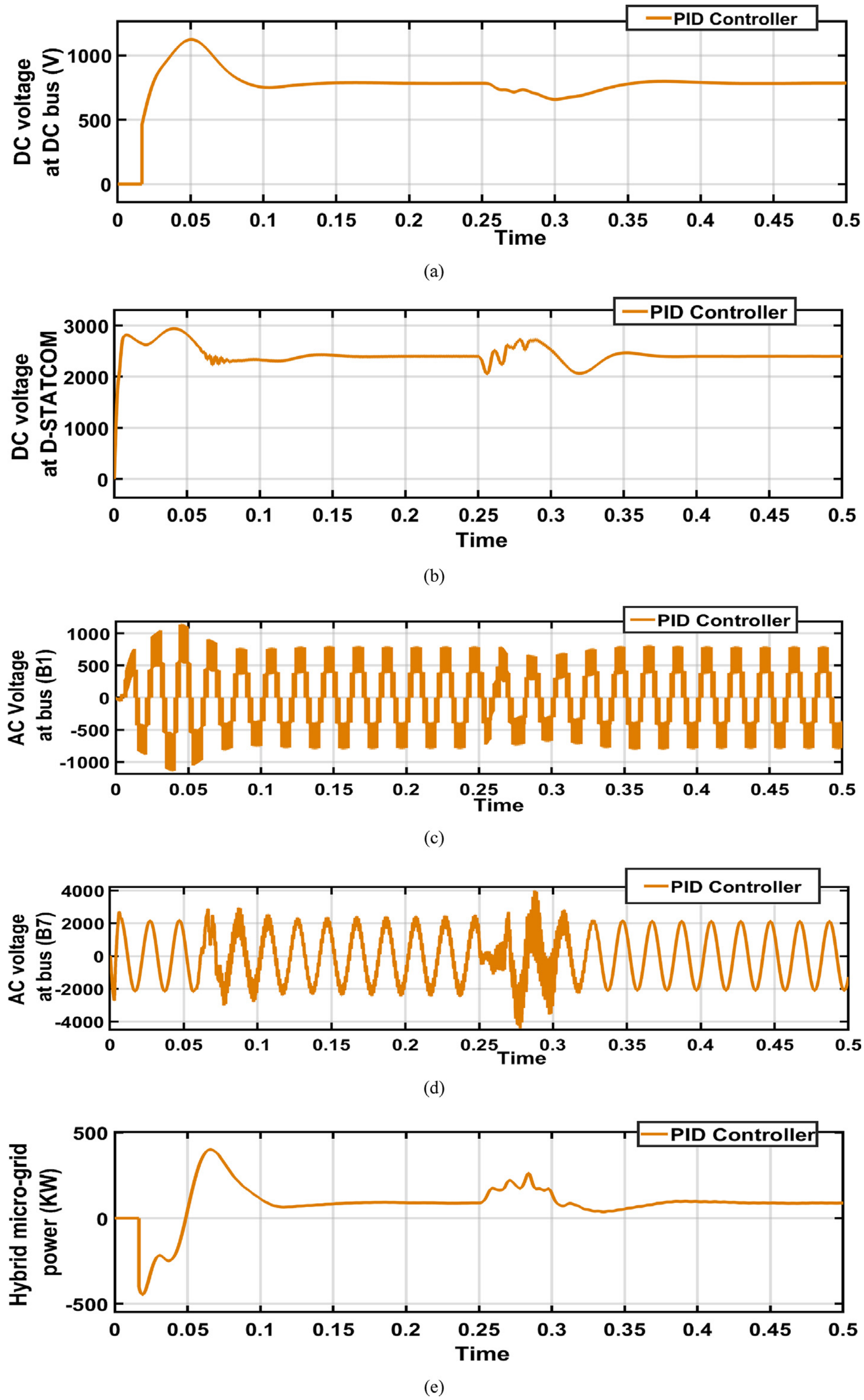
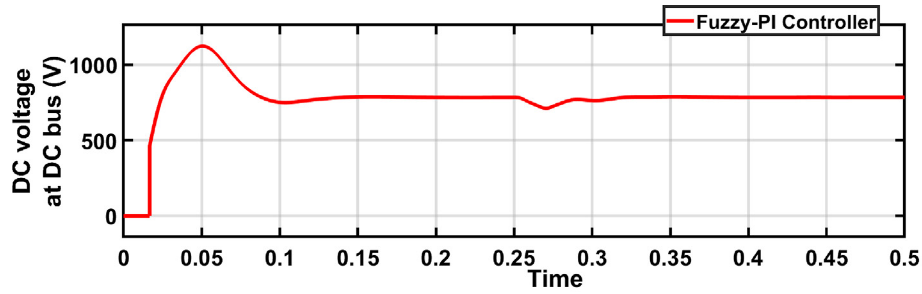


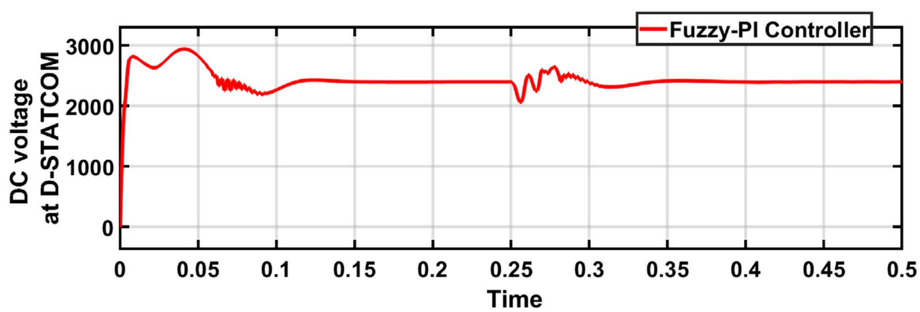
Fig. 20 Simulation output of conventional PID current controlled D-STATCOM with a fault condition; (a) DC bus voltage before 3-level bridge; (b) Average DC voltage at dc link in D-STATCOM; (c) AC bus voltage at bus (B_1); (d) AC bus voltage at bus (B_7); (e) System power at bus.(B_1)

4. Simulation results of the proposed controllers

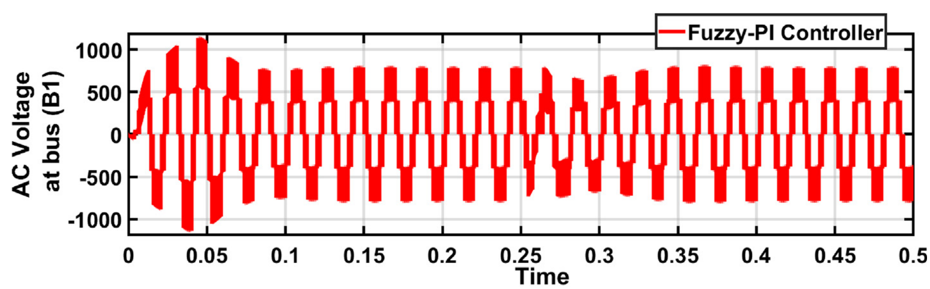
The performance of the suggested system which is tested under two test conditions like an abrupt faults and dynamic load changes at the load bus ($\mathbf{B}_7$) is represented. At the time of test condition, the current raises to high values, and lead to AC / DC hybrid micro-grid might be fall in trouble which would have produces in a severely damage on the entire power sys-



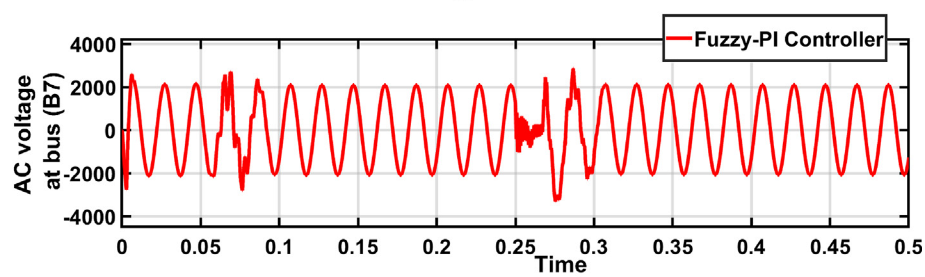
(a)



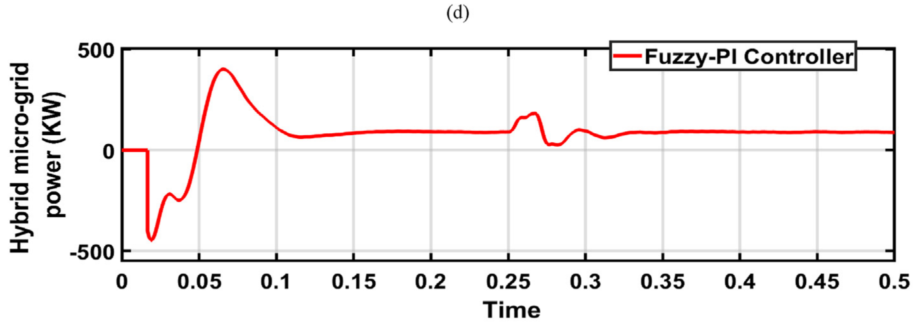
(b)



(c)



(d)



(e)

Fig. 21 Simulation output of Fuzzy-PI current controlled D-STATCOM with a fault condition; (a) DC bus voltage before 3-level bridge; (b) Average DC voltage at dc link in D-STATCOM; (c) AC bus voltage at bus (B_1); (d) AC bus voltage at bus (B_7); (e) System power at bus.(B_1)

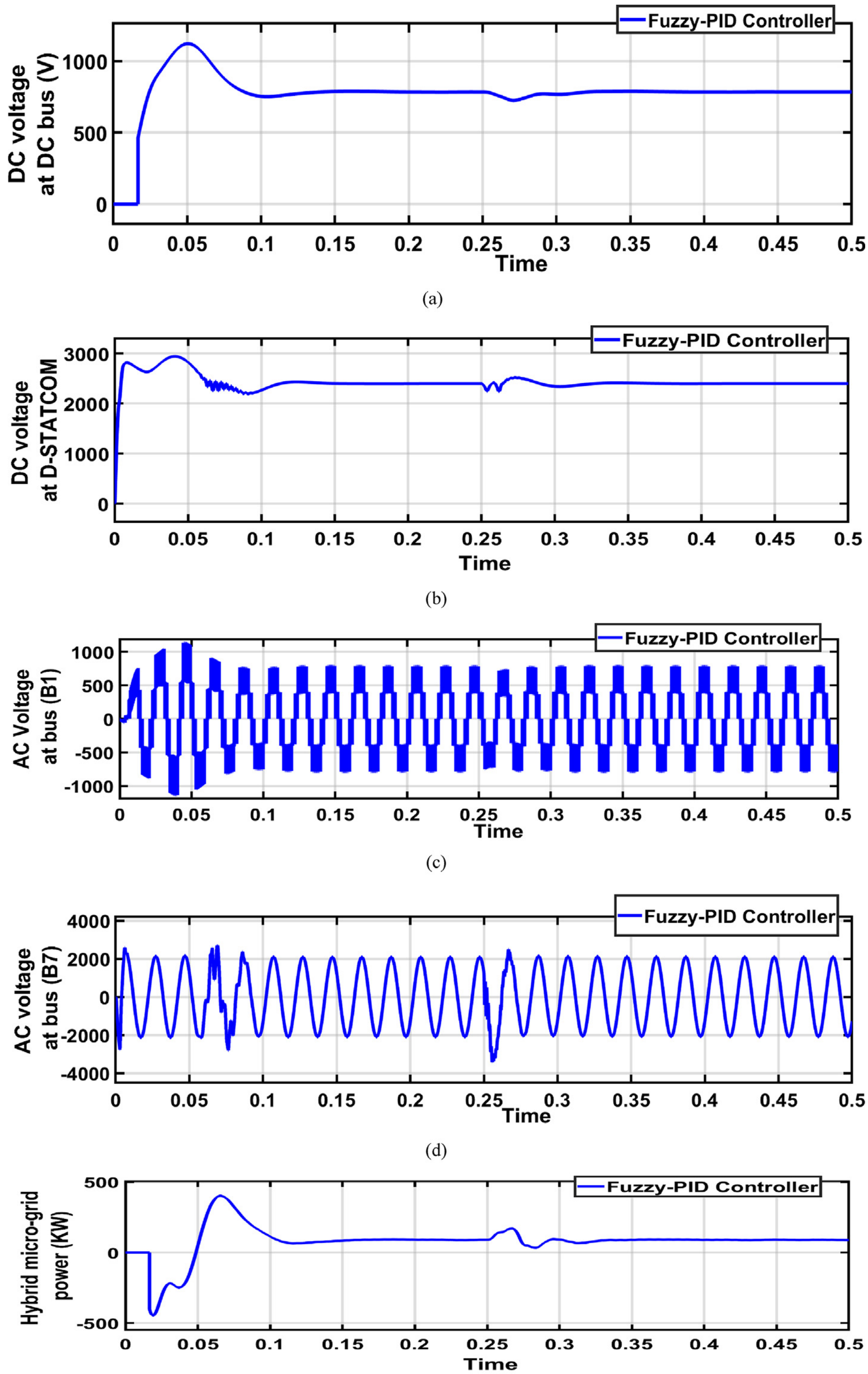
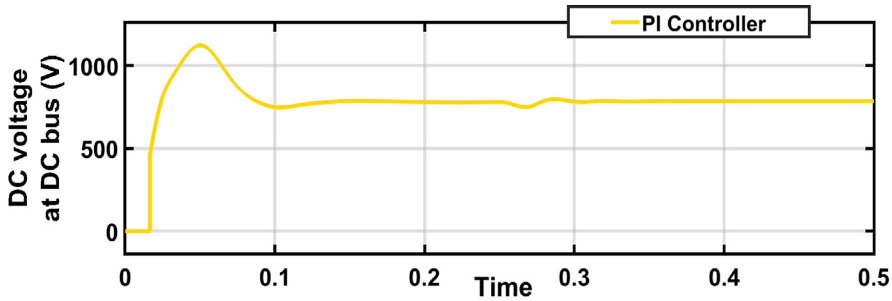


Fig. 22 Simulation output of Fuzzy-PID current controlled D-STATCOM with a fault condition; (a) DC bus voltage before 3-level bridge; (b) Average DC voltage at dc link in D-STATCOM; (c) AC bus voltage at bus (B_1); (d) AC bus voltage at bus (B_7); (e) System power at bus.(B_1)

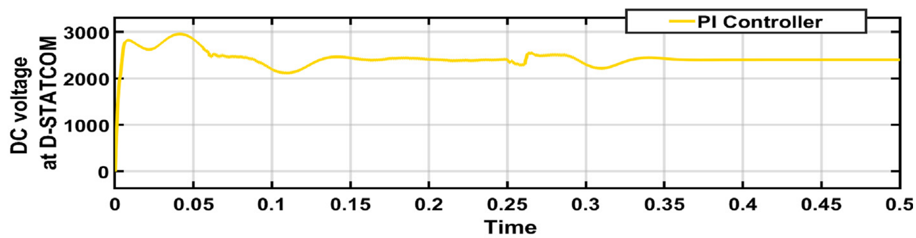
tem. So, the suggested control technique has extremely important role to restore system stability, resolve system power quality problem and thus enhance the system performance. The simulation results were obtained by software MATLAB/SIMULINK.

4.1. Simulation results with fault condition

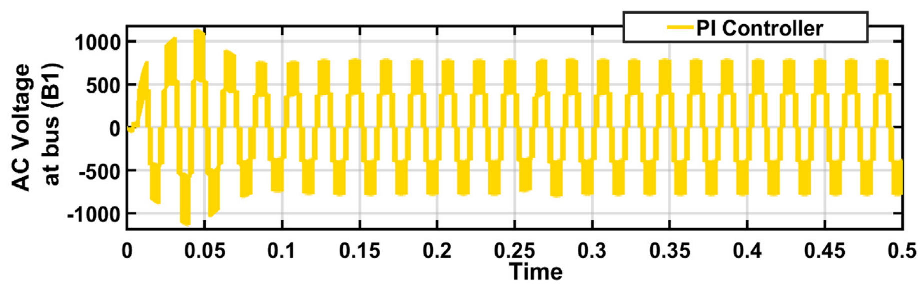
The first case study is represented with three-phase fault before bus ($\mathbf{B}_7$) which is occurred at (0.25 sec) as shown in Fig. 3a.



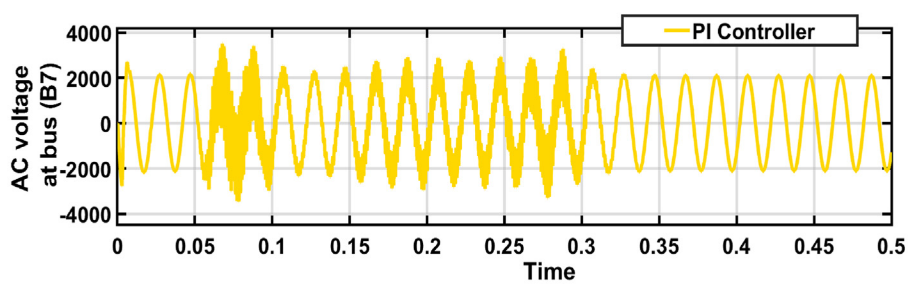
(a)



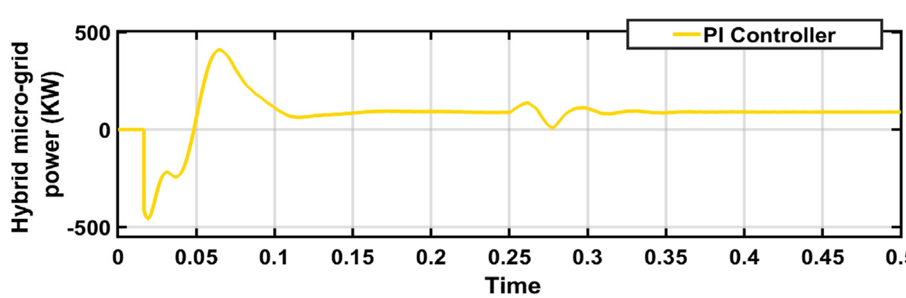
(b)



(c)



(d)



(e)

Fig. 23 Simulation output of conventional PI current controlled D-STATCOM with a fault condition; (a) DC bus voltage before 3-level bridge; (b) Average DC voltage at dc link in D-STATCOM; (c) AC bus voltage at bus (B_1); (d) AC bus voltage at bus (B_7); (e) System power at bus.(B_1)

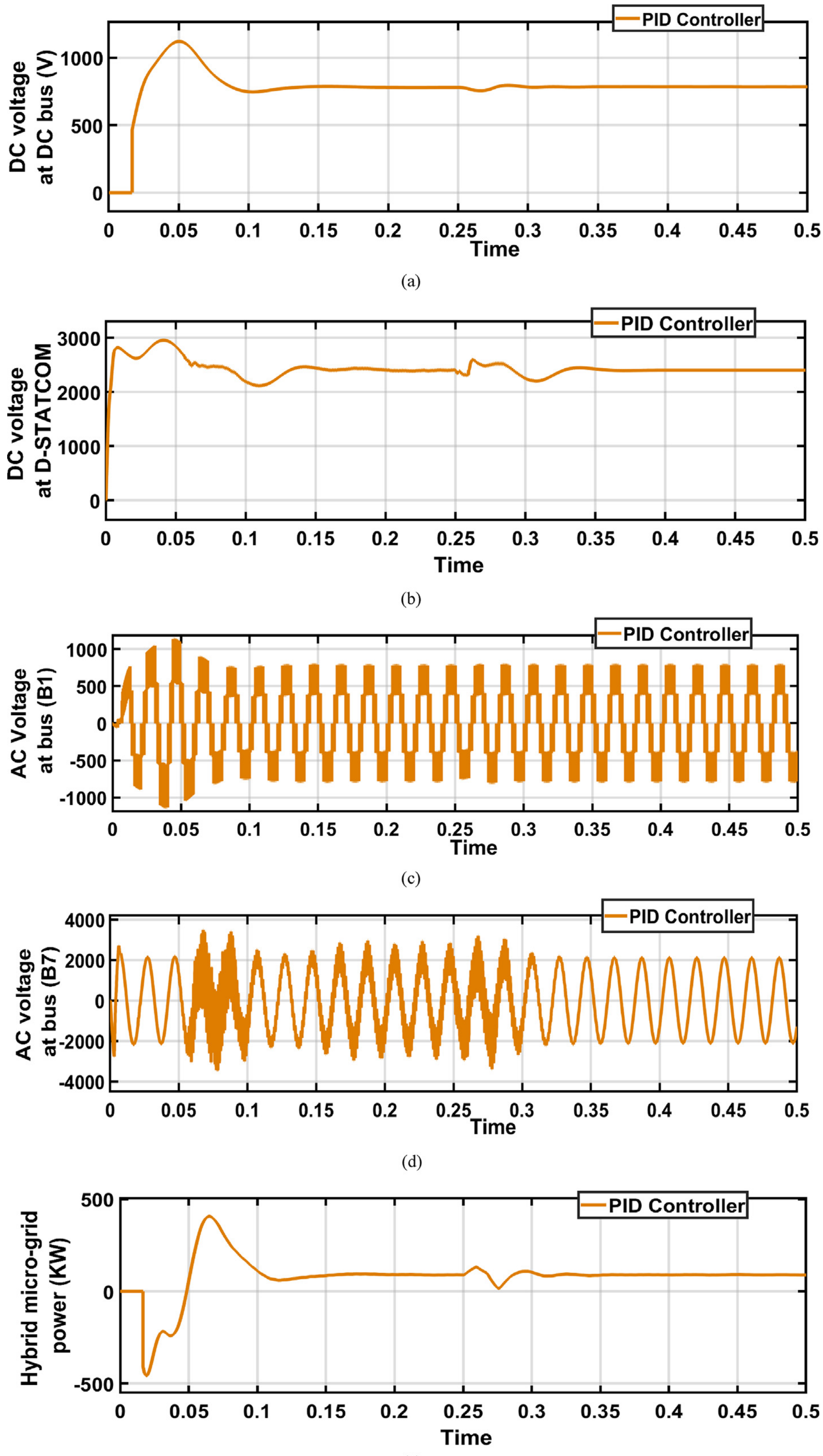
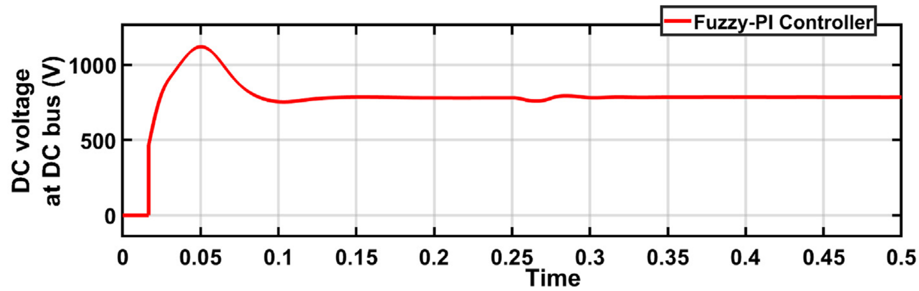
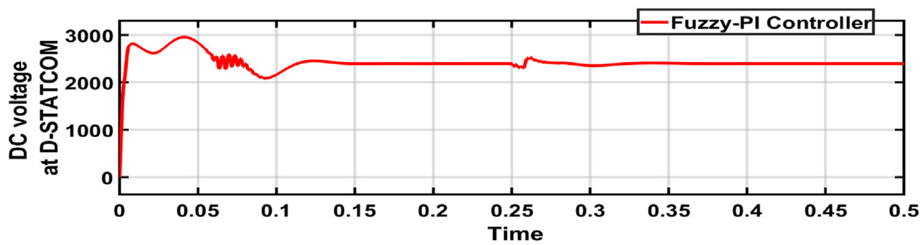


Fig. 24 Simulation output of conventional PID current controlled D-STATCOM with a fault condition; (a) DC bus voltage before 3-level bridge; (b) average DC voltage at dc link in D-STATCOM; (c) AC bus voltage at bus (B_1); (d) AC bus voltage at bus (B_7); (e) system power at bus.(B_1)



(a)



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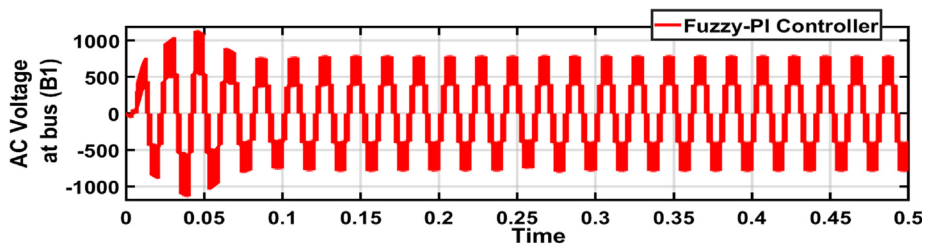
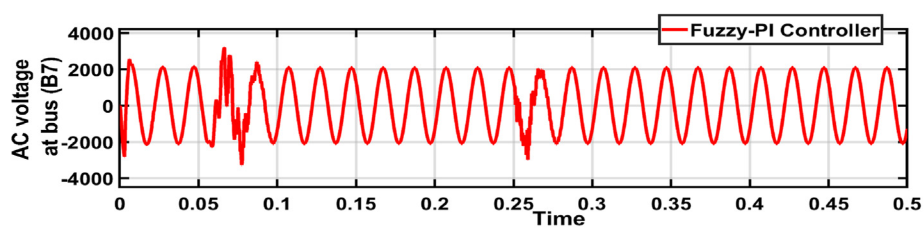


(c)



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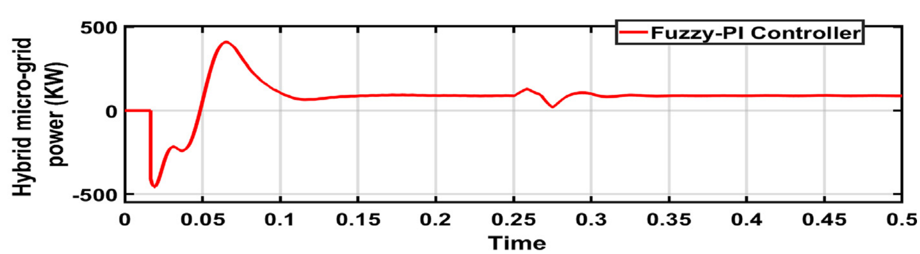


(e)

Fig. 25 Simulation output of Fuzzy-PI current controlled D-STATCOM with a fault condition; (a) DC bus voltage before 3-level bridge; (b) average DC voltage at dc link in D-STATCOM; (c) AC bus voltage at bus (B_1); (d) AC bus voltage at bus (B_7); (e) system power at bus.(B_1)

When the fault has occurred in the power system, it might be caused trouble and thus it has produced voltage fluctuations and ripples. These fluctuations lead to instabilities problems and then decrease system reliability and continuity. So, it is necessary to begin the control algorithm and perform the required procedures to locate fault, disconnect the infected part before caused damage to the other parts in AC/DC hybrid micro-grid and restore its function as soon as probable. Thus, the controller has applied to resolve stabilities problems and ensure its reliability.

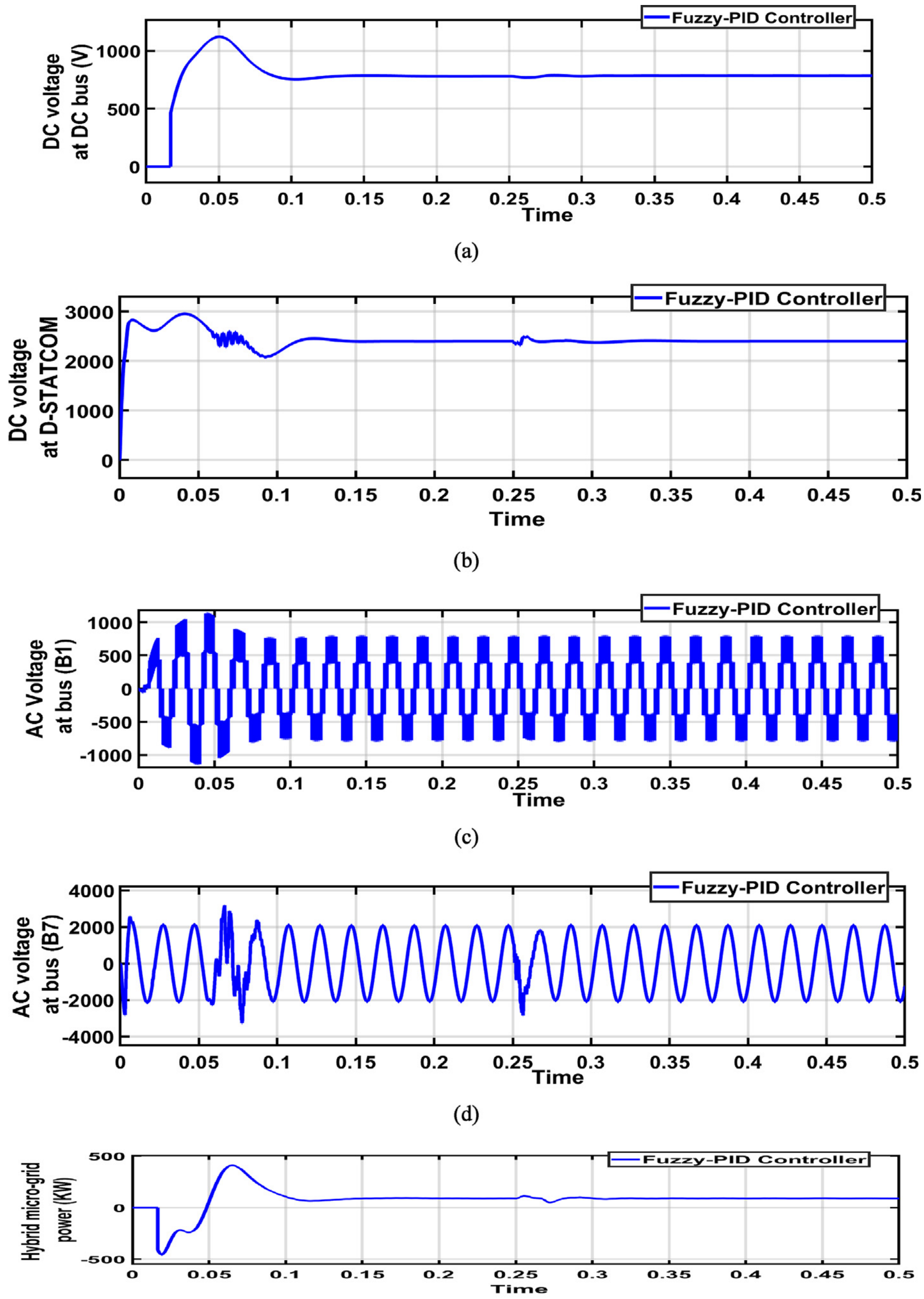


Fig. 26 Simulation output of Fuzzy-PID current controlled D-STATCOM with a fault condition; (a) DC bus voltage before 3-level bridge; (b) average DC voltage at dc link in D-STATCOM; (c) AC bus voltage at bus (B_1); (d) AC bus voltage at bus (B_7); (e) system power at bus.(B_1)

4.1.1. Simulation results of PI controller during fault condition

The simulation results are presented as the following: DC output voltage before 3-level Bridge, DC output voltage of classical PI controlled D-STATCOM as shown in Fig. 19 (a, b) and AC bus voltage at bus (B_1), AC output voltage at bus (B_7) and Simulation of and the system power at bus (B_1) as shown in Fig. 19c-e.

4.1.2. Simulation results of PID controller during fault condition

The simulation results are presented as the following: DC output voltage before 3-level Bridge, DC output voltage of classical PID controlled D-STATCOM as shown in Fig. 20 (a, b) and AC bus voltage at bus (B_1), AC output voltage at bus (B_7) and Simulation of the system power at bus (B_1) as shown in Fig. 20c-e.

4.1.3. Simulation results of Fuzzy-PI controller during fault condition

The simulation results are presented as the following: DC output voltage before 3-level Bridge, DC output voltage of Fuzzy-PI controlled D-STATCOM as shown in Fig. 21 (a, b) and AC bus voltage at bus (B_1), AC output voltage at bus (B_7) and Simulation of the system power at bus (B_1) as shown in Fig. 21-c-e.

4.1.4. Simulation results of Fuzzy-PID controller during fault condition

The simulation results are presented as the following: DC output voltage before 3-level Bridge, DC output voltage of Fuzzy-PID controlled D-STATCOM as shown in Fig. 22 (a, b) and AC bus voltage at bus (B_1), AC output voltage at bus (B_7) and Simulation of the system power at bus (B_1) as shown in Fig. 22.c-e. Fig. 23.

4.2. Simulation results with dynamic load changes

The second case study is represented with the variable load which is connected before bus (B_7) as shown in Fig. 3b. When the load starts increasing, it effects on system stability at the two sides of the power system thus it may be fall in trouble then generates unbalance in system power. So, the major task of controller is maintaining the power balance between demand and supply to reduce the voltage fluctuations and resolve power quality problems then finally executing the proposed control approach for ensuring system stability. These figures show the dynamic voltage response for PI, PID, Fuzzy-PI and Fuzzy-PID controller with applying load increasing (100 kW to 500 kW) at 0.25sec. After removing the disturbance, it is cleared that, the Fuzzy-PID controller has fast response, and the system stability is restored with higher level than Fuzzy-PI. Therefore, the voltage profile at variable load bus is improved.

4.2.1. Simulation results of PI controller with applying load increasing (100 kW to 500 kW):

The simulation results are presented as the following: DC output voltage before 3-level Bridge, DC output voltage of classical PI controlled D-STATCOM as shown in Fig. 27 (a, b) and AC bus voltage at bus (B_1), AC output voltage at bus (B_7) and Simulation of the system power at bus (B_1) as shown in Fig. 27-c-e.

4.2.2. Simulation results of PID controller with applying load increasing (100 k to 500 k):

The simulation results are presented as the following: DC output voltage before 3-level Bridge, DC output voltage of classical PID controlled D-STATCOM as shown in Fig. 24 (a, b) and AC bus voltage at bus (B_1), AC output voltage at bus (B_7) and Simulation of the system power at bus (B_1) as shown in Fig. 24c-e.

4.2.3. Simulation results of Fuzzy-PI controller with applying load increasing (100 kW to 500 kW)

The simulation results are presented as the following: DC output voltage before 3-level Bridge, DC output voltage of Fuzzy-PI controlled D-STATCOM as shown in Fig. 25 (a, b) and AC

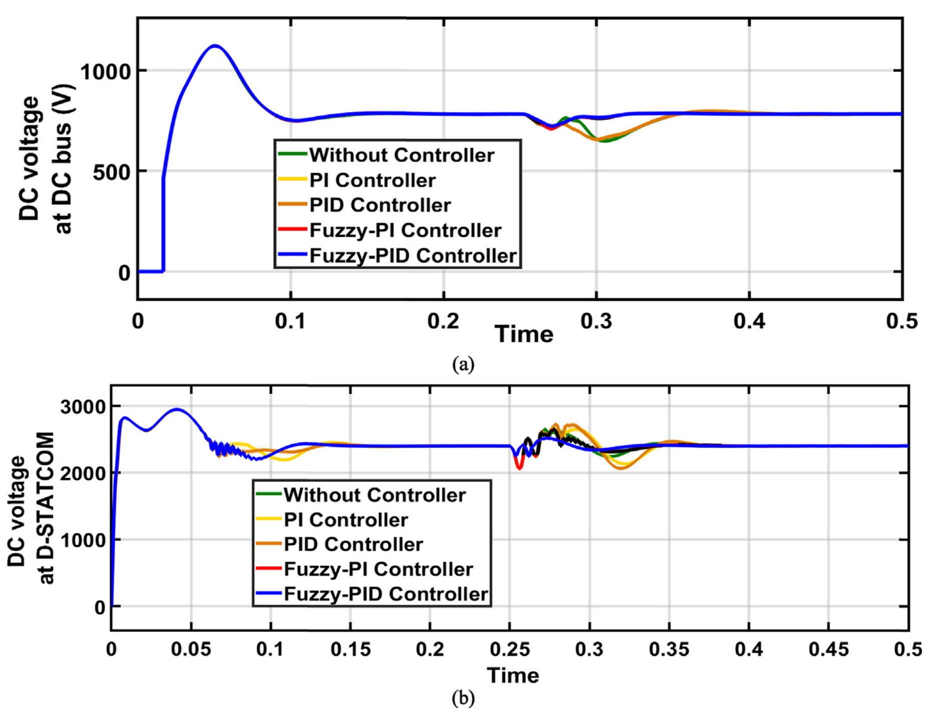
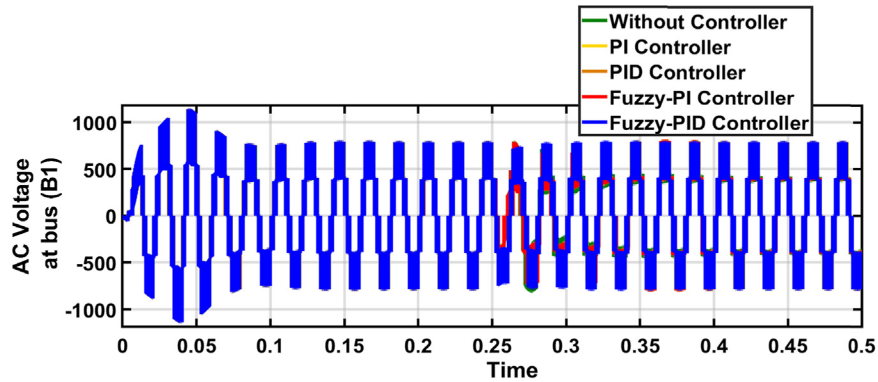
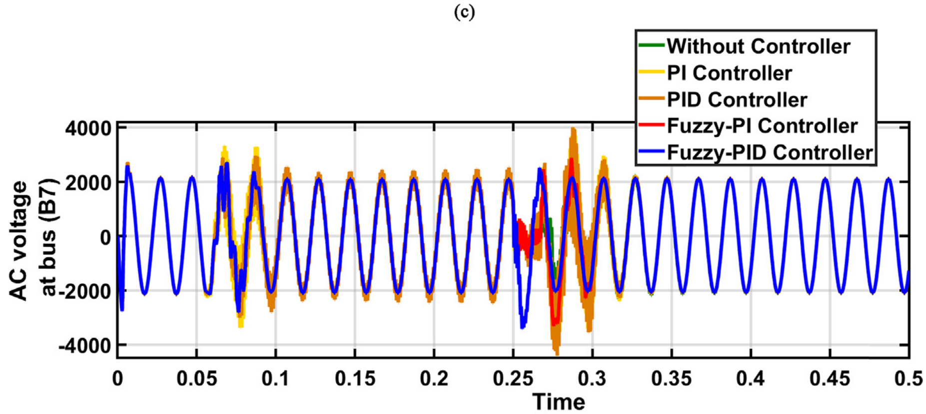


Fig. 27 Simulation output for AC/DC hybrid micro-grid controlled by PI, PID, Fuzzy-PI, Fuzzy-PID respectively with a fault condition at 0.25Sec.; (a) DC bus voltage at DC bus; (b) average DC voltage at dc link in D-STATCOM; (c) AC bus voltage at bus (B_1); (d) AC bus voltage at bus (B_7); (e) system power at bus.(B_1)



(c)



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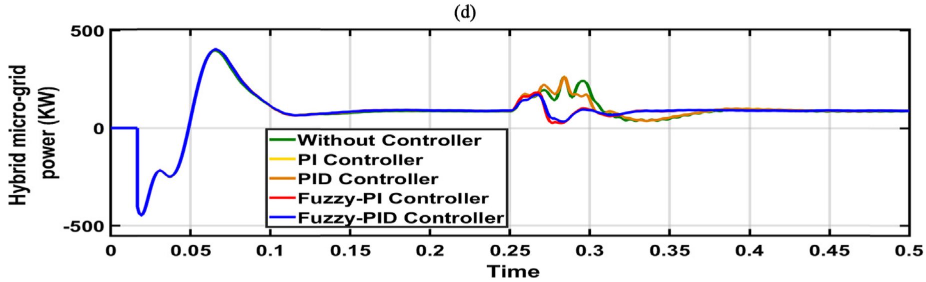


(e)

Fig. 27 (*continued*)

bus voltage at bus (B_1), AC output voltage at bus (B_7) and Simulation of the system power at bus (B_1) as shown in Fig. 25-c-e.

4.2.4. Simulation results of Fuzzy-PID controller with applying load increasing (100 kW to 500 kW)

The simulation results are presented as the following: DC output voltage before 3-level Bridge, DC output voltage of Fuzzy-PID controlled D-STATCOM as shown in Fig. 26 (a, b) and AC bus voltage at bus(B_1), AC output voltage at bus (B_7) and Simulation of the system power at bus (B_1) as shown in Fig. 26.c-e.

The comparison between the performance of AC/ DC hybrid micro-grid that controlled by PI, PID, Fuzzy-PI, Fuzzy-PID respectively had shown in four curves compared to the system performance without controller during cases study respectively. Figs. 27 and 28 show the system performance under fault condition with applying load increasing (100 k to 500 k), respectively.

The D-STATCOM efficiently helps in mitigating harmonics and reactive power compensation. The proposed technique methods are based on intelligent fuzzy control. To validate of the effectiveness of D-STATCOM in reducing harmonics and ensuring power factor compensation, the performance was assessed during fault conditions and with applying load increasing. Figs. 29 and 30 illustrate the simulation results of active power and reactive power compensation, total harmonic distortion at Bus voltage (B_7) and ripples for DC voltage at D-STATCOM during cases study respectively. It is proved that the D-STATCOM based on proposed controllers was able to achieve the required compensation to make the bus voltage is pure sinusoidal especially with Fuzzy-PID. It can be proved that the total harmonics distortion was decreased significantly from 9.167% to 2.981% with using Fuzzy-PI and to 1.075% with using Fuzzy-PID. In addition to the DC ripples was restrained significantly from 10.99% to 2.352% with using Fuzzy-PI and to 0.9381% with using Fuzzy-PID. So, the D-STATCOM based on the proposed controllers is validated that, it has the ability to achieve the desired power compensation and harmonic mitigation and removing ripples in the power system during operating conditions.

The time response of the controller parameters for Fuzzy-PI and Fuzzy-PID are illustrated at Table.4. The controllers deal with the fluctuations in micro-grid real power which is produced by cases study to improve the AC/DC hybrid micro-grid voltage profile and ensure system performance. In this paper, the fast adapting with the sudden changes, taking suitable action and restoring system stability quick as possible were studied. The high peak values of the current were considered as the alarm for starting up the protection algorithm that deals with test conditions. Figs. 31 and 32 show the current at buses (B_1, B_7) and assessed the performance of the controllers during operating conditions.

Tables 5 and 6 summarize the system parameters that reflect the control performance indices for different controllers and for the two studied cases, respectively.

It is validated that the Fuzzy-PID is performed as a perfect protection algorithm for the following:

- Provided better system dynamics and improved transient behavior, then ensured system reliability.

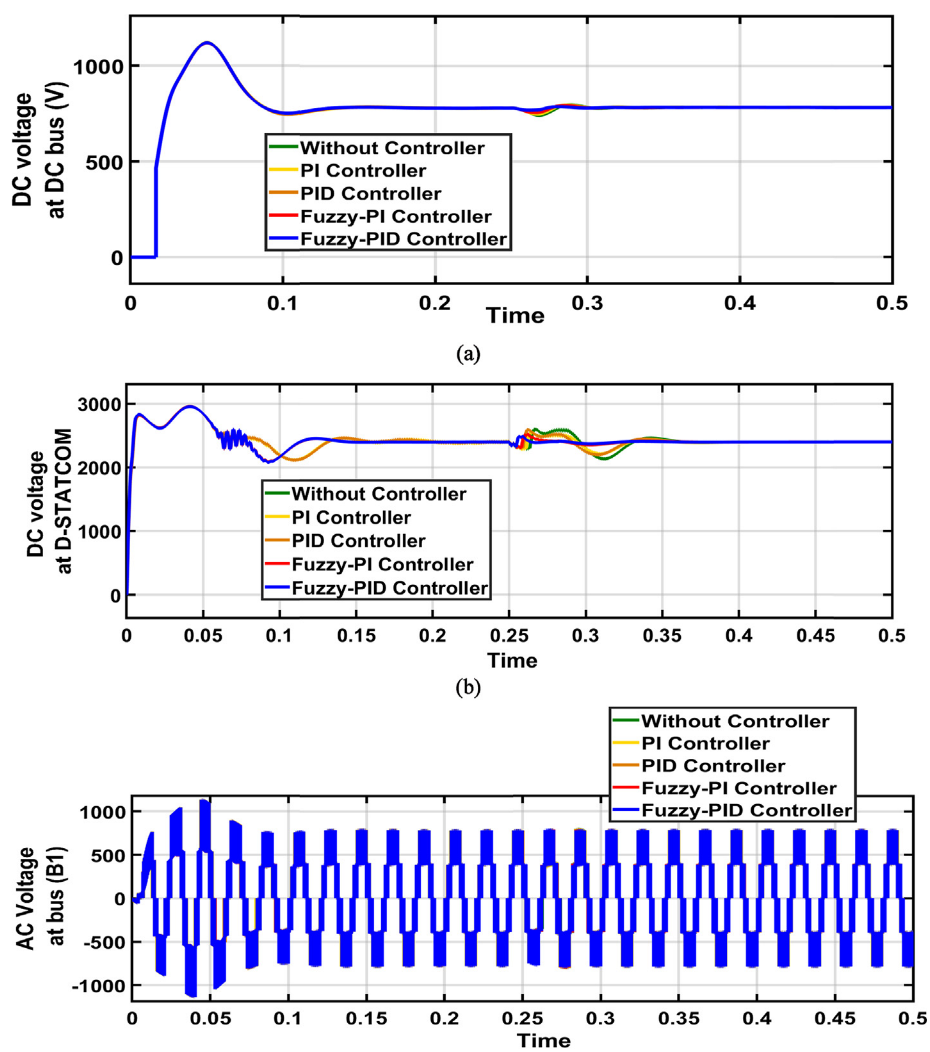
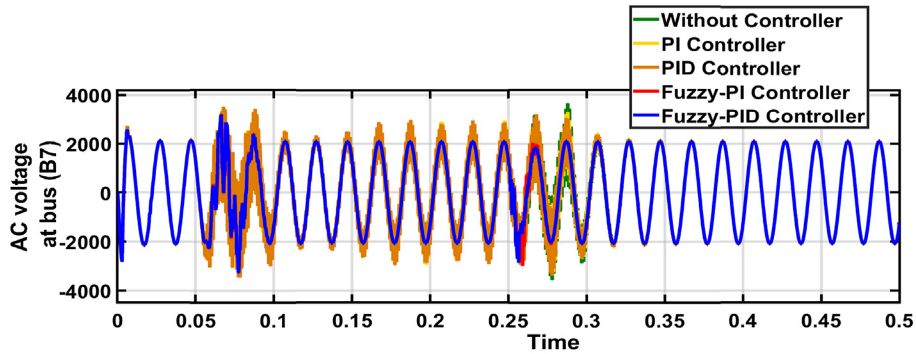


Fig. 28 Simulation output for AC/DC hybrid micro-grid controlled by PI, PID, Fuzzy-PI, Fuzzy-PID respectively with applying load increasing (100 k to 500 k) at 0.25sec; (a) DC bus voltage at DC bus; (b) average DC voltage at dc link in D-STATCOM; (c) AC bus voltage at bus (B_1); (d) AC bus voltage at bus (B_7); (e) system power at bus.(B_1)



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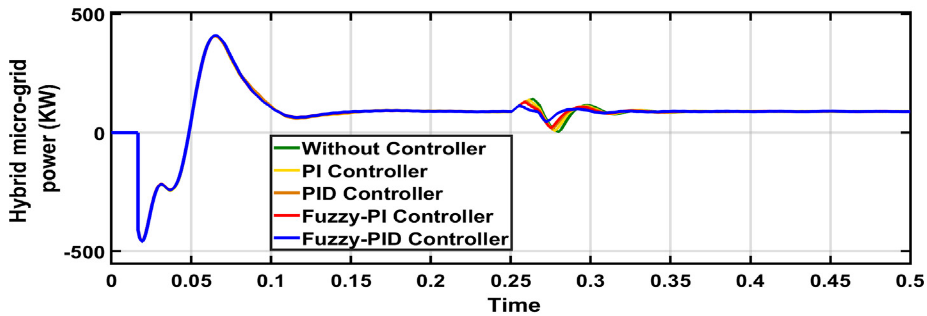


(e)

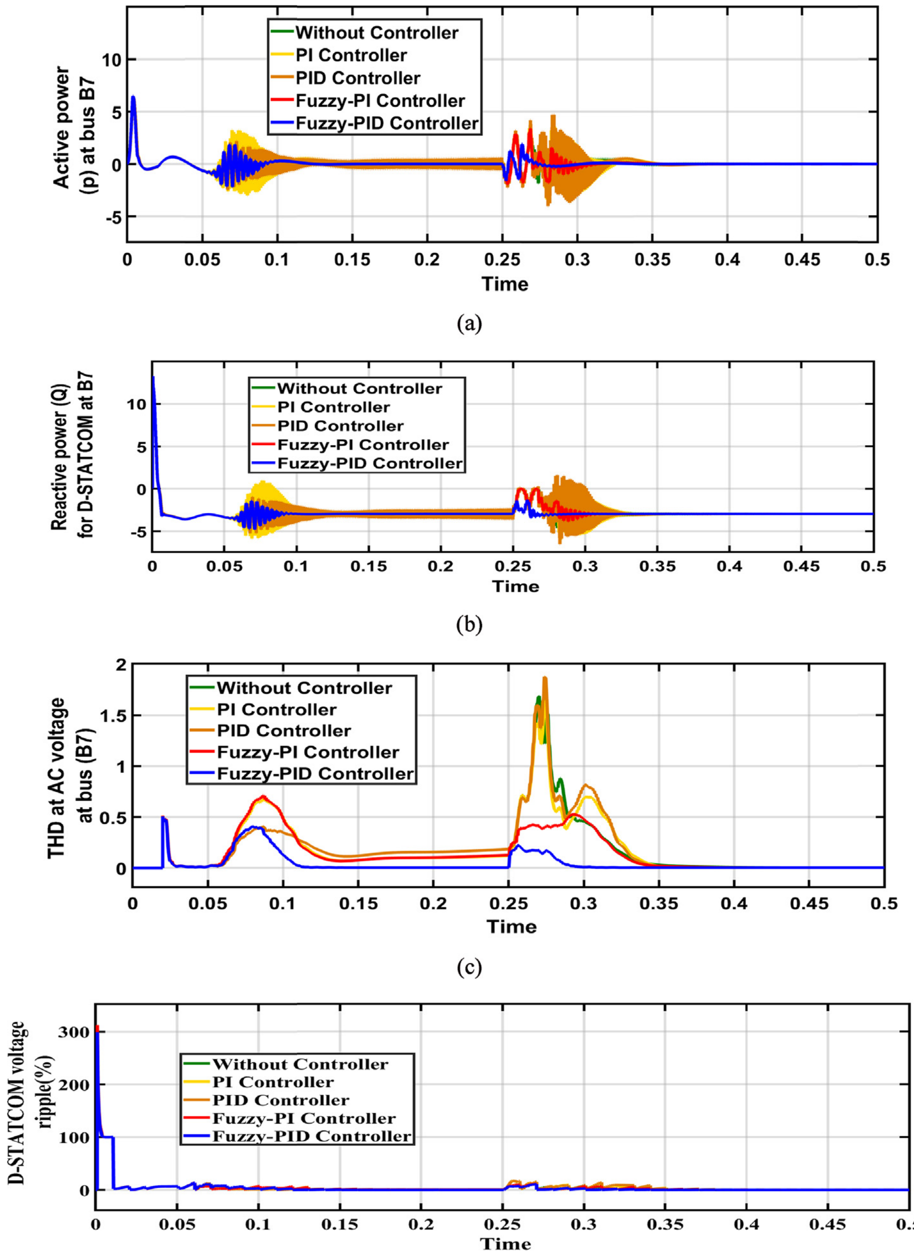
Fig. 28 (*continued*)

- Reduced voltage variations and achieved less overshooting and more smoothing for the proposed hybrid MG.
- High Capability to detect fault location, perform isolation as quick as probable thus give a good chance to retrieve system stability and clear fault quickly (take good action with fault condition)
- It consumes a few times to restore system stability (60msec)

From the above dynamic response and assessment indices the paper findings prove the applicability of the proposed controllers in real time domain. The PV array, Fuel cell module, wind turbines, battery, utility grid connection and loads are operated as one group of pre-specified controllable units are combined into the hybrid micro-grid. The controllable sources to supply power shortage and to save the surplus power are Battery and the utility grid during the on-grid operation of the hybrid micro-grid, battery has major priority to ensure system reliability and decrease the utilization of utility grid. The battery is constrained by its power limitation and state of charge to ensure safe operation normally for a long lifetime, in addition to the utility grid is constrained by the power limitation received from the distribution system operator to ensure survivability of the micro-grid then aimed to reduce the energy cost.

5. Conclusions

The current study has been discussed the improvement of voltage stability and power quality issues in hybrid AC-DC micro-grid. Simulation results are implemented on MATLAB/Simulink for modelling the tested micro-grid associated with two proposed fuzzy based controllers. Two cases are considered to emulate abrupt fault and dynamic load changes. The obtained results are compared with the uncontrolled system, the fuzzy-PID, fuzzy-PI and classical PI controlled D-STATCOM. The used D-STATCOM based controllers assisted to improve several system power quality problems, voltage stability, and dynamic performance of the power system. Numerical simulations associated with detailed comparisons between various controllers are provided. It was found that when the studied system is subjected to a 3-phase fault, the voltage fluctuation at the D-STATCOM is reduced by 7.86% and 4.62% and the dynamic system performance is improved with 12.9% and 8.8% with using Fuzzy-PID and fuzzy-PI, respectively. Also with the dynamic load changes, the voltage fluctuation at the D-STATCOM is reduced by 0.982% and 0.577 % and the dynamic system performance is improved with 6.67%, 5.71% when comparing Fuzzy-PID controller and Fuzzy-PI to the uncontrolled system. Hence,



(a)

(b)

(c)

(d)

Fig.29 Simulation output for system performance during fault condition; (a) Active power at bus (B_7), (b) reactive power at bus (B7), (c) Total harmonic distortion for AC voltage at bus (B_7), (d) Ripple for DC voltage at dc link in D-STATCOM.

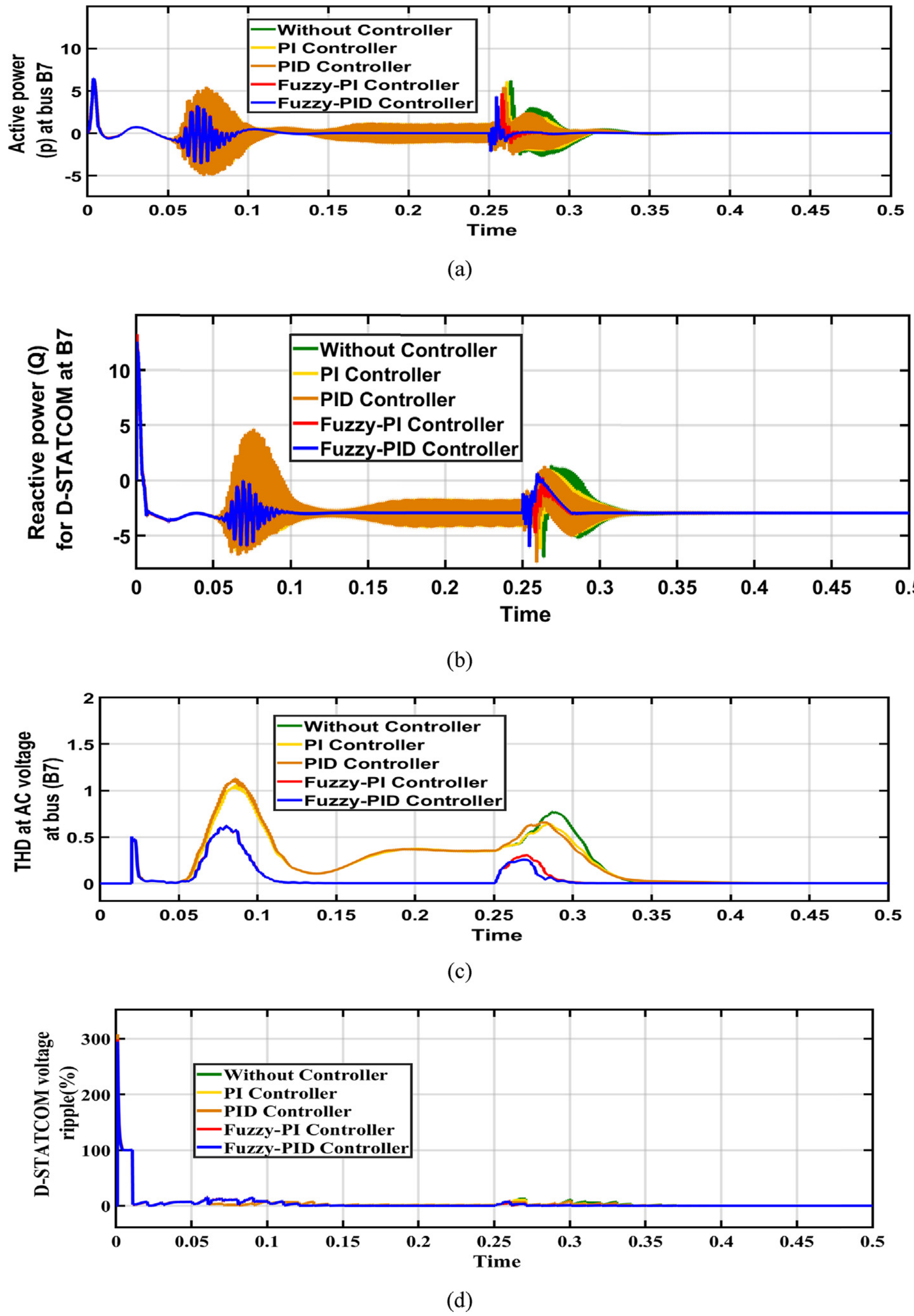


Fig.30 Simulation output for system performance with applying load increasing (100 k to 500 k) at 0.25sec; (a) Active power at bus (B_7), (b) Reactive power at bus (B7), (c) Total harmonic distortion for AC voltage at bus (B_7), (d) Ripple for DC voltage at dc link in D-STATCOM.

Table 4 Time response for proposed controllers.

Controller type	Time response parameters				
	Clearing time within	Steady state Error (%)	Over-shoot (%)	Ripples in DC voltage (%)	THD in AC voltage (%)
PI	82 m second	0.9234	4.6	1.9	4.8
PID	80 m second	0.7234	4.1	1.78	4.2
Fuzzy-PI	73 m second	0.6323	3.2	1.6	3.4
Fuzzy-PID	60 m second	0.2334	2.1	1.2	2.3

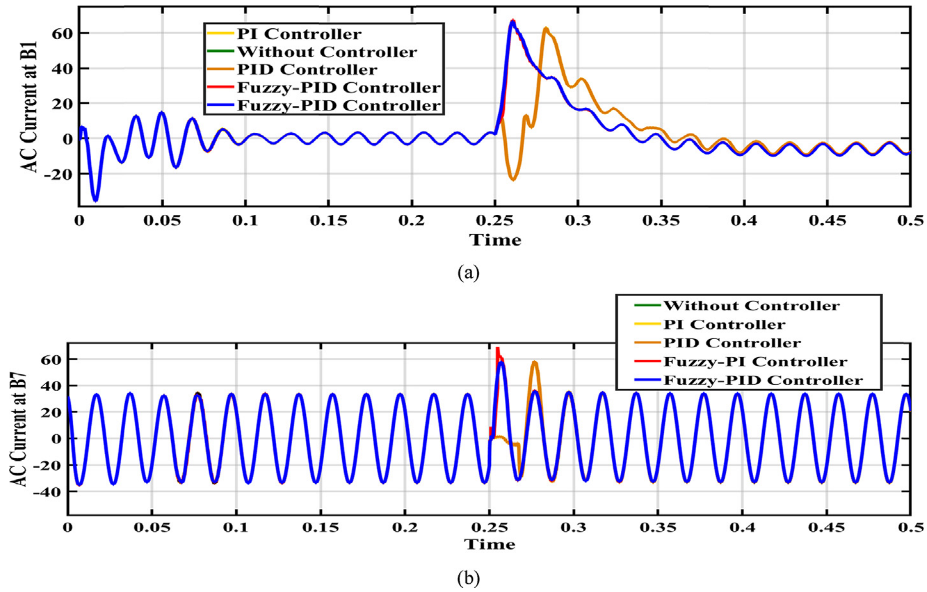


Fig.31 The performance of PI, PID, Fuzzy-PI and Fuzzy-PID controller during Fault condition at 0.25 sec; (a) AC current at bus(B_1), (b) AC current at bus (B_7).

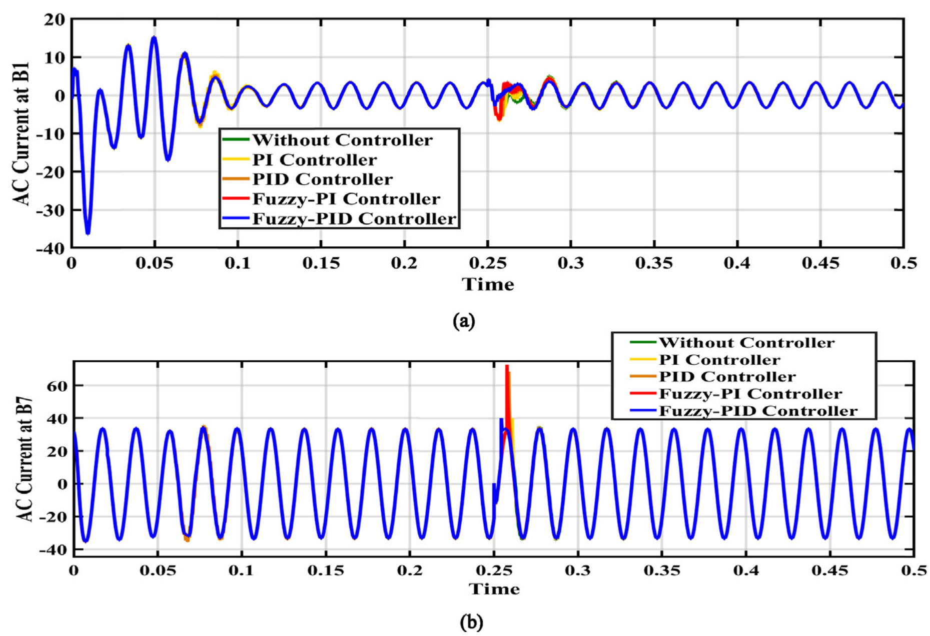


Fig. 32 The performance of PI, PID, Fuzzy-PI and Fuzzy-PID with applying load increasing (100 k to 500 k) at 0.25sec; (a) AC current at bus(B_1), (b) AC current at bus (B_7).

Table 5 System parameters at fault condition.

	Pre-fault at 0.25 sec.				After clearing time.			
D-STATCOM controller	Standard case	PI controller	Fuzzy-PI controller	Fuzzy-PID controller	Without controller	PI controller	Fuzzy-PI controller	Fuzzy-PID controller
DC Bus voltage (v)	647.6	649.8	648.9	648.2	647.6	649.8	648.9	648.2
AC voltage at bus B_1(v)	−647.6	−649.8	−648.9	−648.2	−647.6	−649.8	−648.9	−648.2
DC voltage at D-STATCOM (v)	2399.97	2399.87	2400.76	2400	2399.97	2399.87	2400.76	2400
AC voltage at bus B_7 (v)	−2399.97	−2399.87	−2400.76	−2400	−2399.97	−2399.87	−2400.76	−2400
$I_q$at D-STATCOM	0.899	0.923	0.998	1	0.8999	0.923	0.998	1
power at bus B_1 (K_w)	198.8	189.7	199.8	199.8	198.8	189.7	199.8	199.8

Table 6 System parameters at dynamic load changes.

Selected time	After power system has been brought back to its stable state at			
D-STATCOM controller	Standard case	PI controller	Fuzzy-PI	Fuzzy-PID
DC Bus voltage (v)	647.6	649.8	648.9	648.2
AC voltage at bus B_1(v)	−647.6	−649.8	−648.9	−648.2
DC voltage at D-STATCOM (v)	2399.97	2399.87	2400.76	2400
AC voltage at bus B_7 (v)	−2399.97	−2399.87	−2400.76	−2400
$I_q$at D-STATCOM	0.8999	0.923	0.998	1
power at bus B_1 (K_W)	198.8	189.7	199.8	199.8

the system has a superior-performance while using Fuzzy-PID comparing to Fuzzy-PI and conventional PI current controlled D-STATCOM at reduced voltage fluctuation and achieved less overshooting and more smoothing for the proposed power system.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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