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Research Article

Modelling of solar PV-fuel cell based micro-grid system and harmonics mitigation using fuzzy controlled dynamic voltage restorer

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Abstract

Renewable energy sources are increasingly preferred for power generation due to their environmentally friendly processes. Micro-grids, in particular, have gained significant traction in the energy market for their reliability and sustainability benefits in distributed systems. However, grid-interactive systems are often subjected to disturbances caused by system-level faults and external factors. Both symmetrical and unsymmetrical faults, especially under harsh environmental conditions, can lead to equipment failures and even complete system blackouts. To enhance reliability and efficiency, hybrid renewable energy systems have emerged as optimal solutions for sustainable energy production. The rising use of power electronic converters in industrial and household applications, however, introduces severe power quality issues. This paper analyzes the dynamic performance of a micro-grid system comprising solar Photovoltaic (PV) and proton exchange membrane fuel cell (PEMFC) technologies under symmetrical and unsymmetrical fault conditions. Here, voltage compensation is achieved using the d_{qo} algorithm. To mitigate harmonic distortions, a custom power device with an intelligent controller is considered more efficient and cost-effective. In the proposed hybrid micro-grid, a fuzzy controlled dynamic voltage restorer (FC-DVR) is employed for harmonic mitigation, implemented through a pulse width modulation (PWM) generator using MATLAB/Simulink models. The effectiveness of the FC-DVR on power quality improvement is assessed based on total harmonic distortion (THD). Simulation results under various fault conditions, such as line to ground (LG), line to line (LL), double line to ground (LLG), and three-phase (LLL), demonstrate that while a conventional dynamic voltage restorer (DVR) reduces THD by up to 26%, the FC-DVR achieves a reduction of up to 51%. This highlights the FC-DVR's ability to mitigate voltage harmonics and significantly enhance power quality. The FC-DVR has been demonstrated to be an effective controller for mitigating harmonics in hybrid micro-grid environments.

Keywords

Hybrid renewable energy systems, Clean energy, Micro-grids, Power quality improvement, Symmetrical and Unsymmetrical faults, Fuzzy controlled dynamic voltage restorer.

1.Introduction

Power generated from the renewable energy resources may contain harmonics due to the presence of power electronic switching devices. It leads to distortion in the output voltage. Stability of the interconnected electricity grid system is mainly depending on the violation of vital power system parameters such as system frequency and bus voltages.

For improving grid-stability and the quality of power delivery, it is required to develop an effective control strategy. For the compensation purpose, capacitors may also be preferred.

But it lacks attraction as it introduces resonance effect which may cause thermal degradation and the component failure [1, 2]. The utilization of flexible alternating current transmission systems (FACTS) improves stability and regulates voltage levels. Major issue with static var compensator (SVC) is the selection of correct size, whereas the static

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synchronous compensator may cause for instability under oscillating conditions same as that of SVCs [3-5]. SVC and other compensating devices suffer due to high cost, more space environment and maintenance difficulty. Hence, dynamic voltage restorer (DVR), a series compensator and non-linear devices which consists of voltage source inverter (VSI) become vital player in voltage compensation [6]. DVR plays a major role in mitigation of voltage fluctuations by injecting a three-phase (LLL) voltage in synchronism with system voltage [7]. DVR can minimize voltage variations and outages at the lowest possible cost. Voltage distortions and prolonged power outages are the main causes of power quality issues [8]. Large non-linear loads, sophisticated power electronics based distributed generation contribute for power quality issues. Power quality performance and equipment durability are both improving modestly [9, 10]. Harmonics, voltage sag, voltage swell, transients in voltages are the reasons for the power quality problems. Since the voltage sag is identified as a commonly occurring event causing heavy damage to the sensitive loads [11, 12]. Power quality is addressed by flexible alternating current (AC) transmission system components. Unified power quality conditioners response would be influenced by suitable design and controller choice [13–15]. A sudden drop in utility supply voltage that can range from 90% to 10% of its nominal value is known as voltage sag. While voltage swell, which can range from 110% to 180% of its nominal value, is a sudden increase in supplied voltage [16]. As per IEEE standard, voltage sag and swell typically last between 10 ms and 1 minute.

Numerous studies with more emphasis on the design and operation of DVRs have been conducted [17–19]. Major challenge in utilization of hybrid renewable energy sources and their interconnection with the grid system is the development of control strategy for suppressing unwanted harmonics. Stability of the hybrid electrical system may also be greatly impacted by various contingency conditions on the occurrence of faults. It is mainly caused by adverse weather conditions such as heavy lightning and thunderstorms [20]. Since the grid-connected electrical system is very dynamic and subjected to contingency stages, the occurrence of these faults may even lead to equipment failures [21, 22]. Dynamic study of hybrid energy system (HES) considering the possible fault conditions is required to ensure the power quality which can further encourage the utilities to plan for effectively using the renewable energy sources for their energy needs [23]. The main motivation behind this research work is to improve reliability of solar photovoltaic (PV) proton exchange membrane fuel cell (PEMFC) HES by integrating renewable energy sources as a hybrid system, mitigating harmonics with the help of state-of-art control technique. The objective of the research work is to develop the sugeno model based fuzzy control scheme for DVR and effectively improve the power quality. It includes various contingency studies under different fault conditions and analyse the total harmonic distortion (THD) values.

This paper is structured such that Section 2 provides the literature review spanning from renewable energy system and the possible controllers. The modelling of solar PV and fuel-cell system suitable for HES and the control techniques for DVR are presented elaborately in Section 3. Dynamic performance of the system has been analysed and presented in Section 4. The comprehensive analysis of various cases, covering the impact analysis of DVR and fuzzy logic-controlled DVR based on the THD values are presented. Followed by this, Section 5 discusses the results and presents the limitations of this particular study. Finally, the conclusion of this investigations has been summarized in Section 6.

2.Literature review

Global level energy demand and environmental concerns have created pressure among all countries to switch from fossil-fuel-based power generation to renewable and cleaner energy sources-based generation [24]. Solar energy source has emerged as a fastest-growing source because of its cost reduction, scalability and advancements in energy extraction technology [25]. Solar PV deployment index of various countries has been obtained for the period 2010 to 2018 and compared with the countries having similar economic, social and geographic conditions [26]. It indicates that the solar PV deployment of India is less by 1.5 gigawatts (GW) than the expected capacity when compared with similar countries. India is progressing well towards its mission of net-zero emissions, having a solar potential of 749 GW with 5,000 trillion kWh per year of solar irradiation as reported by Ministry of new and renewable energy, Government of India, on October 2024 [27]. Energy production from wind energy sources could be very high as compared to solar PV. Wind energy penetration is remarkably high in last decade and tend to increase drastically in future too [28]. However, the availability of wind source is again unpredictable and unreliable as it is seasonable source [29]. Micro-grid system with hybrid set-up of renewable energy system is primarily aimed to improve the power system reliability and stable operation [30, 31]. Since the solar and wind energy system are intermittent, hybrid-combination of these sources may not help to sustain the power delivery. Fuel-cell technology is now-a-days emerged as a highly preferable alternative for the sustainable operation of electrical grid [32]. Among all types of fuel-cells, PEMFC is on high-demand in power production because of its features such as high efficiency, quick start-up time and its ability to operate at low temperature as well. Micro-grid structure of renewable energy sources can increase the energy security and can balance the sources based on the source availability whenever the load demands excess power [33]. An aggregate technical and commercial losses in the transmission and distribution network can also be reduced with the help of distributed energy sources such as solar PV, wind etc. or the combination of more than one renewable source [34]. Considering these facts, clean energy sources viz., solar and fuel-cell are used in this paper. Integration of solar PV and hydrogen would become complete clean energy solution with increase in system operability [35–37]. Solar PV and fuel-cell generation system mainly rely on the power converters for meeting the energy requirement.

Incorporating renewable energy sources increases the robustness of the control topology used in the DVR in eradicating power quality issues [38–40]. More emphasis has been given on controllers to ensure sustained power delivery and resolve these conflicts. A battery and solar PV module combination can also result in a more efficient and dependable power output. Future environmental technology focuses on fuel cell and solar PV systems [41]. This research work also explored a grid-interactive renewable system which consists of a solar PV and PEMFC system, with an eye on producing sustainable energy. It is also witnessed the voltage fluctuations in HES under distributed and smart-grid environments has severe impact in real-life problems [42–44]. Researchers have attempted to analyse the energy management and economic impact that was suited with solar photovoltaic proton exchange membrane fuel cell (PV-PEMFC) [45]. It was also attempted towards optimal sizing and control of the hybrid power system [46, 47].

In contrast, researchers have developed a variety of techniques throughout the years to supply the reliable power and combat harmonics issues. Efforts have also been made to track the maximum point using methods such as fuzzy logic [48], neuro-fuzzy systems [49], and fuzzy-based particle swarm optimization [50]. However, the researchers did not attempt to analyse the impact of DVR with different fault conditions such as symmetrical and unsymmetrical faults. Symmetrical LLL fault is very severe fault but rarely occurring fault. Therefore, it is decided to consider all possible fault conditions and analyse the power quality status. Additionally, numerous researchers have employed techniques to manage the load voltage for different voltage disturbances [51–54]. In comparison to distribution static synchronous compensator (DSTATCOM), unified power flow controller (UPFC), etc., DVR is more affordable, compact and has a higher energy capacity [55]. In 1960s, fuzzy expert system-based controller is proposed which relies on people's ability to understand system behaviour and is based on quality control standards. Instead of true or false, fuzzy is based on "degrees of freedom" ranging from 0 to 1. Some literature also witnessed the usage of DVR for various isolated renewable energy system with storage facility [56].

Overall analysis of the literatures conveys that energy security of the grid connected network can be improved by combining the distributed energy sources. It is also highlighted that, despite being environmentally friendly, solar PV and wind energy sources lack appeal due to their intermittency and unreliability. Potential features of solar PV and fuel-cell based energy conversion is highlighted in literature. Literature review emphasized that the hybridization of renewable sources can increase the energy security and grid stability. Various FACTS devices namely SVC, DSTATCOM and UPFC, useful for the voltage balancing in grid-connected network were also attempted by previous researchers. DVR has been found to be more beneficial because of its higher energy capacity, compactness and affordability than the other compensating devices. Under abnormal conditions such as line to ground (LG), line to line (LL), double line to ground (LLG), and LLL, presence of harmonics affects the equipment performance and finally the entire system operation gets affected. This scenario may even lead to total blackout of the system. In previous research works, behaviour of solar PV and fuel cell-based HES has not been analysed under uncertainties. Further, the soft-computing based controllers mainly fuzzy-logic technique has not been incorporated for the DVRs to mitigate the harmonics. From the power quality perspective, it is still maintained as a research gap. Therefore, efforts have been made to address these issues by developing an efficient controller for the DVR, aimed at harmonic mitigation in solar PV and fuel cell-based microgrid systems.

3.Methods

Most of the power quality problems are due to the different fault conditions [57]. The proposed HES consists of the 160 W PV panel and 6 kW PEMFC sources which are linked with electricity grid via suitable converter. Boost converter raises the output to 100 V direct current (DC) as the PEM fuel cell and solar PV offer less output. Firing pulses are generated by pulse width modulation (PWM) generator and it serves as the gate signal to the DC/AC inverter. Next, the DC/AC converter receives the output from the boost converter, reverses it, and increases to 400 V AC on the output side of the DC/AC converter. In order to overcome the power quality problems, an appropriate modelling and the selection of controller becomes a vital step. Modelling of hybrid solar PV and PEMFC system is shown in *Figure 1*. Simulink and fast Fourier transform (FFT) analysis of the system has been performed during analysis. DVR has also been designed and implemented with the system.

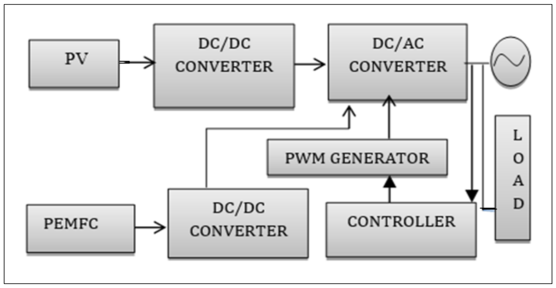


Figure 1 Hybrid solar PV-PEMFC energy system

The direct axis ('d' axis) component of voltage is set at 1.0 p.u (per unit) with quadrature axis ('q' axis) voltage is set to 0.0 p.u. The fuzzy logic-based phase-locked loop (PLL) keep track of voltage phasor of each phase and generates reference signals using a fuzzy matrix. Then the voltage error is calculated from each phase voltages. Consequently, it injects voltage based on the error signals generated against the reference.

3.1Modelling of solar PV-fuel cell hybrid system

In order to achieve a reliable operation with improved power quality, it is required to model the solar and fuel cell system appropriately and the same is presented below. Mathematical modelling of solar PV and fuel cell system is presented below. Based on the mathematical models of both energy conversion system, the MATLAB/Simulink blocks are modelled and connected upto point of common coupling through the DC/DC converter. Then they are converted to AC output signal using DC/AC inverter as explained in section 3.1.1.

3.1.1Solar PV modelling

Solar PV system is generally an energy conversion system comprises of solar panels and the DC-DC converter arrangement. The converter may be of buck, boost or buck-boost types according to the application. Sunlight is passed through a semi-conductor (PV cell), where it is converted into electrical energy. Generated electrical output is non-linear in nature as it depends on temperature and the level of solar irradiance [58].

Solar PV module converts light into electricity with a temperature and weather data as input signals and the current, voltage and power etc. as output [59]. Solar energy is intermittent and hence the output voltage would be fluctuating [60]. By an effective modelling, the performance of solar PV system can be analysed. It is considered that the PV panel is composed of series-parallel connected PV cells along with series and parallel resistors, R_s and R_P respectively [61]. According to the ambient temperature and solar irradiance, the PV array generates characteristic current as expressed below. Kirchoff's current law is applied to the PV model equivalent circuit as furnished in Equations 1 and 2. Considering, T as instantaneous temperature in (° K) and T_{ref} as reference temperature in (° K), the change in temperature ΔT is obtained from $(T - T_{ref})$. In this modelling, G and G_{ref} represents the instantaneous and reference solar irradiance levels in W/m^2 respectively. Here, K_i is the short-circuit temperature co-efficient. PV model has been presented in *Figure 2*. In the PV model, 'G' is the function of irradiance of I_{pv} in W/m^2, I_o is the diode saturation current and I_{rs} is the reverse saturation current at reference temperature. Diode saturation current, I_o is expressed in Equation 3.

$$I = I_{PV} - I_0\left[e^{\frac{q(V+IR_S)}{aK_T}} - 1\right] - \left[\frac{V+IR_S}{R_P}\right] \tag{1}$$

$$I_{pv} = \frac{G}{G_{ref}}(I_{sc} + K_i * \Delta T) \tag{2}$$

$$I_O = I_{rs}\left(\frac{T_{op}}{T_{ref}}\right)^3 * e_p\left[\frac{qE_g}{a_k}\left[\frac{1}{T_{op}} - \frac{1}{T_{ref}}\right]\right] \tag{3}$$

For a given open-circuit voltage, V, short-circuit current rating, I_{sC} with the constants, $q = 1.6 \times 10^{-19}\ C$ of electron charge and the Boltzmann constant, $K = 1.38\ X\ 10^{-23}\ J/K$ and P as the characteristics function of P-N junction, the power generated by solar PV is given as the product of V and I.

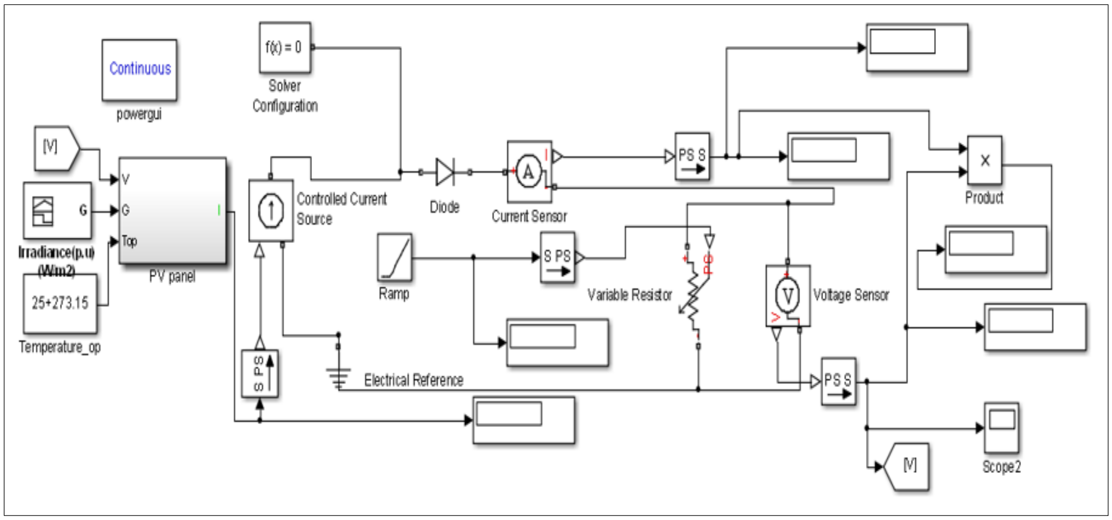


Figure 2 Solar PV model using MATLAB/Simulink

3.1.2Modelling of fuel cell system

Due to the compactness and low cost, fuel cell-based research works are being carried out very widely. The DC output voltage is found based on the flow rate and the fuel cell configuration [62]. In this research work, the general electrical model is done as proposed by Mann et al. (2000) and Amphlett (1995) [63, 64]. Generally, the chemical reaction taking place in fuel-cell is expressed in Equation 4.

$$H_2(g) + \frac{1}{2}\, O_2(g) \xrightarrow{\qquad} H_2O(l) + e^- \quad (4)$$

By assuming ‘n’ no. of cells, fuel-cell voltage, V_{FC} and fuel-cell current, I_{FC} and temperature, T, the fuel-cell output voltage is obtained as given in Equation 5, in terms of thermodynamic equilibrium potential (E), activation over voltage (η_a) and the ohmic overvoltage (η_o) [65]. The equilibrium potential (E) is given in Equation 6.

$$P_{FC} = n.V_{FC}.I_{FC} = n.I_{FC}\,[E - \eta_a + \eta_o] \quad (5)$$

$$E = 1.229 - 0.83\ X\ 10^{-3}(T - 298.15) + 4.308\ X\ 10^{-5}\ T\ [\ln(PH_2) + 0.5\ln(PO_2)] \quad (6)$$

MATLAB/Simulink model of the 6 KW, 45V PEMFC been modelled as shown in *Figure 3*. It has 65 number of cells with fuel cell resistance as 0.7833Ω and nominal stack efficiency (%) as 55. The hybrid micro-grid system has been modelled by combining solar PV and PEMFC as in *Figure 4*.

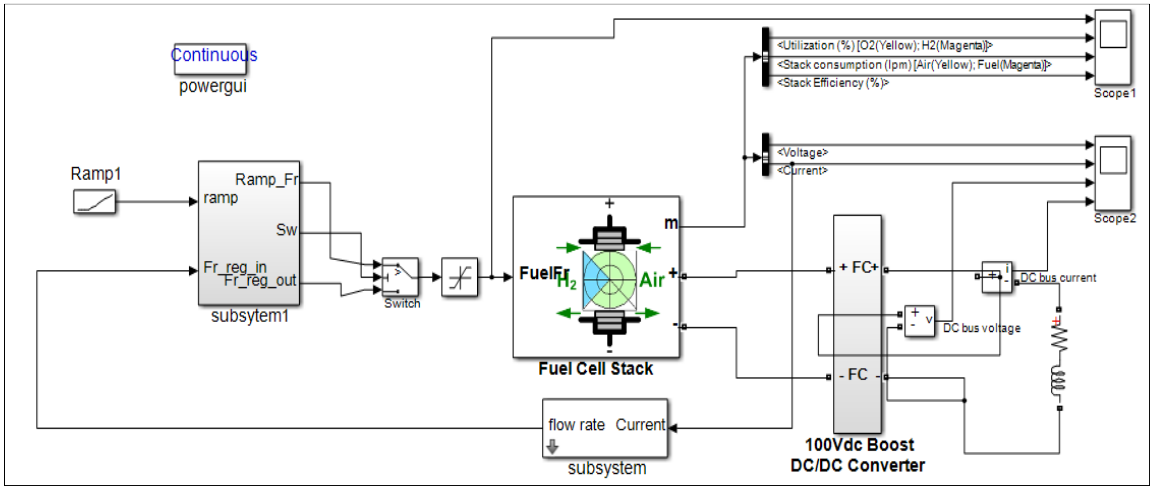


Figure 3 PEMFC model using MATLAB/Simulink

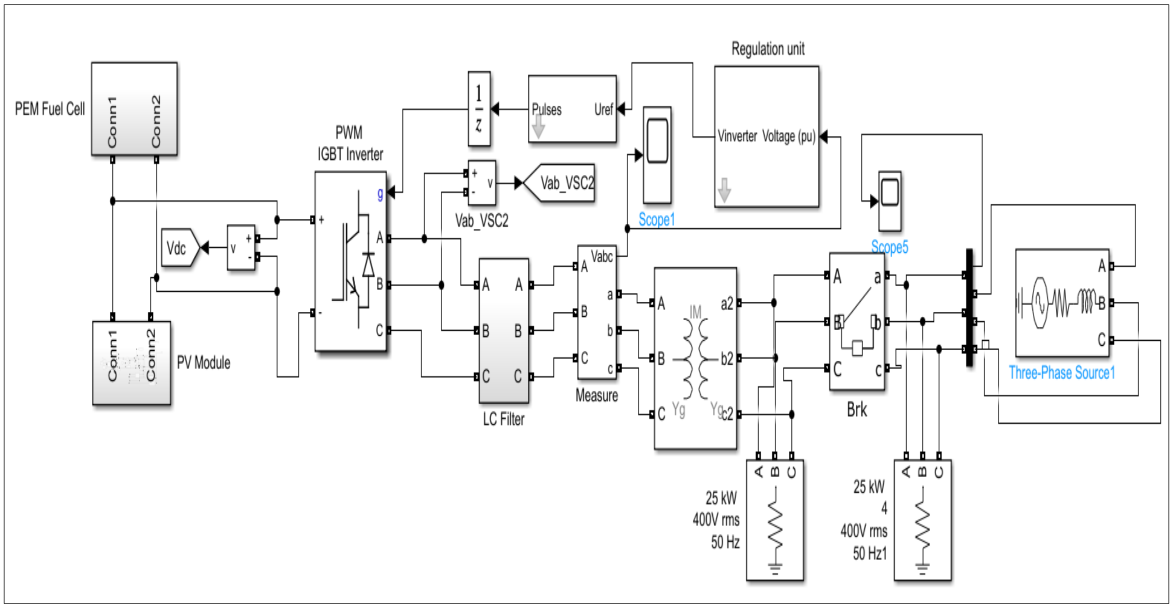


Figure 4 Solar PV-fuel cell HES

3.2Modelling and control of DVR

3.2.1DVR modelling

Custom power devices are being introduced in renewable energy-based power generation systems. It is nothing but the power electronic devices that are used to overcome the power quality issues [56, 57]. One of those devices is DVR, which injects the voltage in order to regulate the voltage at the load end. DVR is the modern custom power device which compensate for voltage fluctuations. In DVR the system impedance Z_S is designed based on the fault level in bus. Equivalent structure of DVR is given as shown in *Figure 5*. For maintaining the load voltage, V_l, injection transformer in DVR circuit injects the voltage, V_{dvr}, whenever the load voltage disturbance happens in the power network.

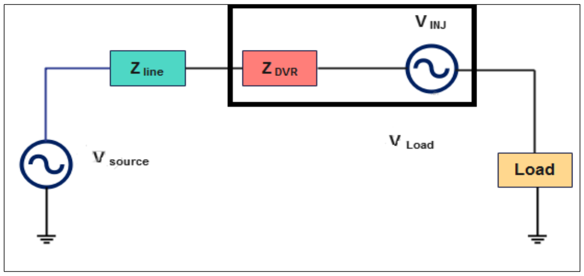


Figure 5 Equivalent structure of DVR

DVR modelling has been performed by considering the system impedance, Z_s and the load voltage and load current as V_l and I_l respectively. If the system voltage, V_s drops during fault condition, the injected voltage of DVR, V_{dvr} has been supplied along with existing V_s. It can be calculated using the Equations 7 and 8. Load current can be obtained as a function of P_i and Q_i as shown in Equation 9. Assuming the angles, δ, α and ,β are respectively belonging to V_s, V_{dvr} and Z_s and the load side angle θ, the polar form of V_{dvr} is expressed in Equation 10. The load power factor angle θ is obtained from P_i and Q_i as depicted in Equation 11. The DVR injected power in simplified form is written as shown in Equation 12.

$$V_{dvr} + V_s = V_l + Z_S I_l \quad (7)$$

$$V_{dvr} = V_l + Z_s . I_l - V_S \quad (8)$$

$$I_l = \frac{(P_i + jQ_i)}{V_i} \quad (9)$$

$$V_{dvr} \angle\alpha = V_l \angle 0 + Z_s . I_l \angle(\beta - \theta) - V_s \angle\delta \quad (10)$$

$$\theta = tan^{-1}\left(\frac{Q_i}{P_i}\right) \quad (11)$$

$$P_{dvr} = V_{dvr} . I_l \quad (12)$$

In this work, DVR has been used for the purpose of power quality improvement. The control circuit of DVR is developed and implemented in MATLAB/Simulink as given in *Figure 6*. The control technique takes the control action based on the voltage error. It is made possible by PWM generator which generates the control signal according to the voltage variation. Load voltage is given as input to 3-phase sequence analyser block which analyses input voltage. The voltage magnitude is compared with that of the reference voltage of 1.0 p.u. It is then multiplied with sine function, the output of which is supplied to pulse generator. Based on the magnitude of input signal, pulse is generated which serves as a gate signal of the inverter. Then the inverter output is given to feeder line through the injection transformer as shown in *Figure 7*. The overall operation of DVR under voltage deviations is depicted in *Figure 8*.

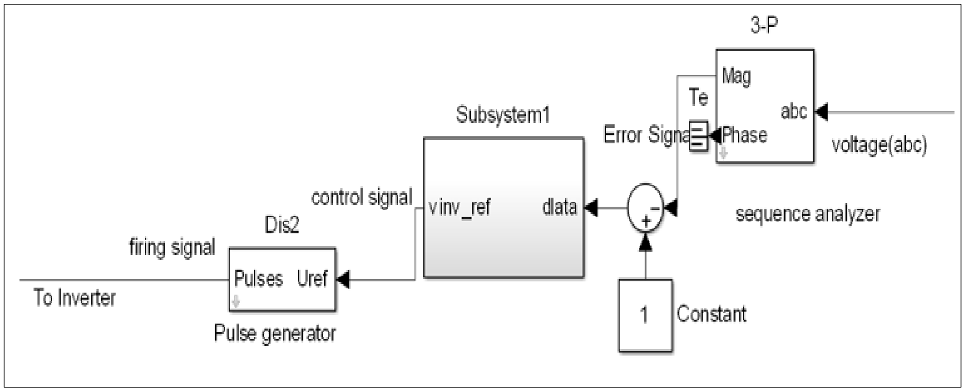


Figure 6 Control circuit of DVR

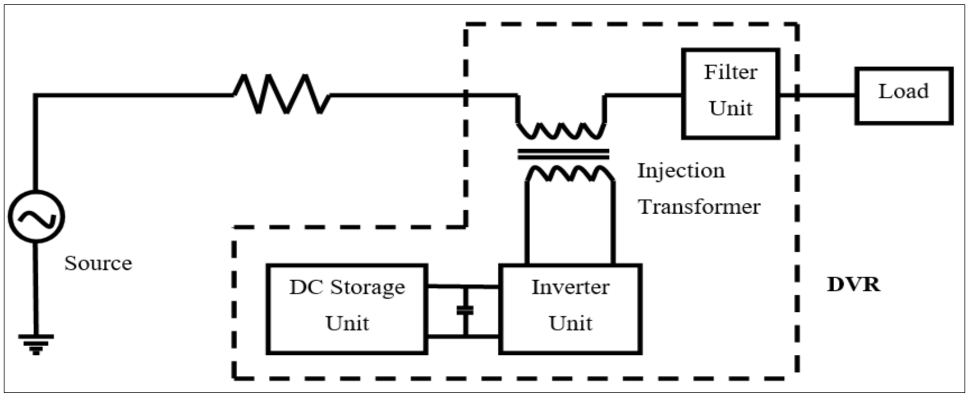


Figure 7 Structure of DVR

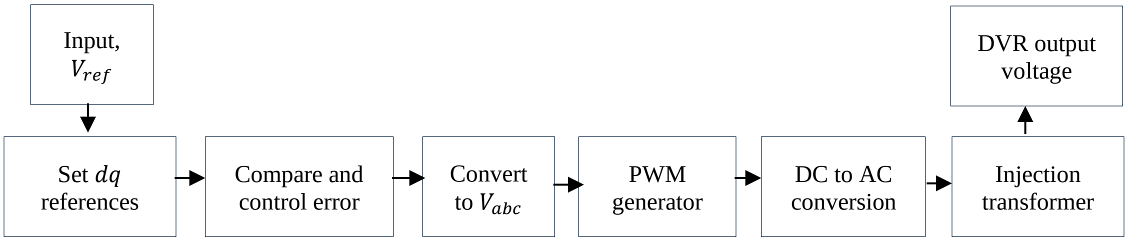


Figure 8 Operational flow of DVR under voltage deviations

3.2.2Fuzzy controlled dynamic voltage restorer (FC-DVR)

Overall reliability of the power system network depends on the frequency and voltage stability. For an effective voltage management in power network under contingency conditions, voltage injection by the DVR needs to be appropriately regulated by using suitable controller. In this article, it is attempted to introduce fuzzy inference-based controller for the harmonic mitigation under different fault conditions namely symmetrical and unsymmetrical faults. Generally, proportional-integral-derivative (PID) controllers are most widely preferred for an industrial application. However, the gains of PID controller are fixed and are not adaptive to the changes in system conditions. On the other hand, fuzzy logic technique is the featured technique, as it can change the output control signal automatically for variation of the input signals in a particular range [66]. This makes the fuzzy controller more efficient for any dynamic systems. In this work, fuzzy control technique has been proposed for the control of DVR voltage. This section further discusses about the dq_0 transformation procedure and the implementation of fuzzy logic for the DVR control loop.

3.2.2.1 dq_0 transformation

The primary function of the DVR controller is to identify any voltage fluctuations in the system and produce the proper trigger pulse for the PWM inverter. In this research work, the dq_0 transformation is used. It is a transformation of LLL stationary coordinates (V_a, V_b, V_c) into rotary co-ordinates (V_d, V_q, V_o). The LLL voltages V_a, V_b, V_c as shown in Equations 13 to 15 has been converted to constant voltages V_d, V_q and V_o. It is expressed in Equations 16 to 18. The control logic adapted for abc to dq_0 transformation and then back from dq_0 to abc transformation is shown in *Figure 9*.

$$V_a = \left[V_d sin(wt) + V_q \cos(wt) + V_o\right] \tag{13}$$

$$V_b = \left[V_d \sin\left(wt - \frac{2\pi}{3}\right) + V_q \cos\left(wt - \frac{2\pi}{3}\right) + V_O\right] \tag{14}$$

$$V_c = \left[V_d \sin\left(wt + \frac{2\pi}{3}\right) + V_q \cos\left(wt + \frac{2\pi}{3}\right) + V_O\right] \tag{15}$$

$$V_o = \frac{1}{3}(V_a + V_b + V_c) \tag{16}$$

$$V_d = \frac{2}{3}\left[V_a \sin wt + V_b \sin\left(wt - \frac{2\pi}{3}\right) + V_c \sin\left(wt + \frac{2\pi}{3}\right)\right] \tag{17}$$

$$V_q = \frac{2}{3}\left[V_a \cos wt + V_b \cos\left(wt - \frac{2\pi}{3}\right) + V_c \cos\left(wt + \frac{2\pi}{3}\right)\right] \tag{18}$$

Proportional-integral (PI) controller is the most frequently used controller in industries. But it suffers to perform well under varied operating conditions. Conventional PID controller is used in most of the industrial applications due to its robustness and simple tuning procedure. Output of the PID controller depends on the controller parameters namely K_p, K_i and K_d [67]. Gains of controller are fixed and tuning of which is not always easy for PID controller. In order to avoid these drawbacks, it is necessary to identify the most efficient and adaptive controller for DVR.

3.2.2.2 Fuzzy controlled DVR

Soft computing is a versatile and efficient approach to solve complex optimization problems that are difficult to tackle using traditional methods [68]. It falls under the domain of artificial or computational intelligence, encompassing various techniques to find solutions for dynamic engineering problems. One prominent method within soft computing is the fuzzy logic technique [69]. In the proposed fuzzy inference system, five triangular membership functions are used for both input signals and output signals for error signal-d and error signal-q. Five linguistic fuzzy levels namely negative big (NB), negative small (NS), zero (Z), positive small (PS), positive big (PB) are chosen for input signals, meanwhile, there are 5 fuzzy sets, namely NB, NS, Z, PS, PB have been selected for output signals. Then the fuzzy rules base is framed. The triangular function used for both incoming and outgoing signals of inference mechanism is presented in *Figure 10*. The control output signal, $v(t)$ from the fuzzy controller is given as the input to the PWM Generator. Here the voltage error and change of error are obtained based on the deviation of $V_{abc}(p.u)$ from the desired reference voltage, V_{ref} as depicted in Equations 19 and 20.

$$Errror(e) = V_{ref} - V_{abc}(p.u) \tag{19}$$

$$Error\ rate = e(n) - e(n-1) \tag{20}$$

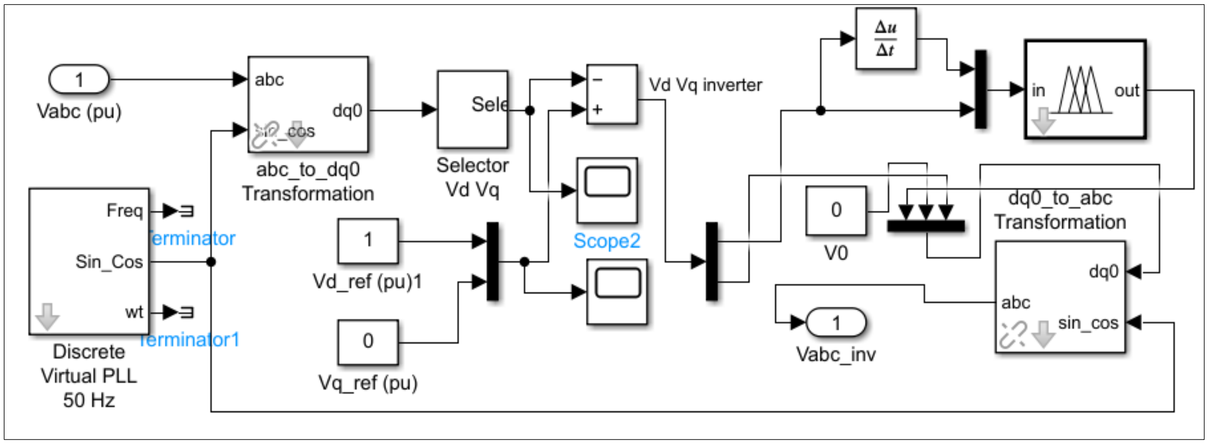


Figure 9 Control logic for abc to dq_0 and dq_0 to abc transformation

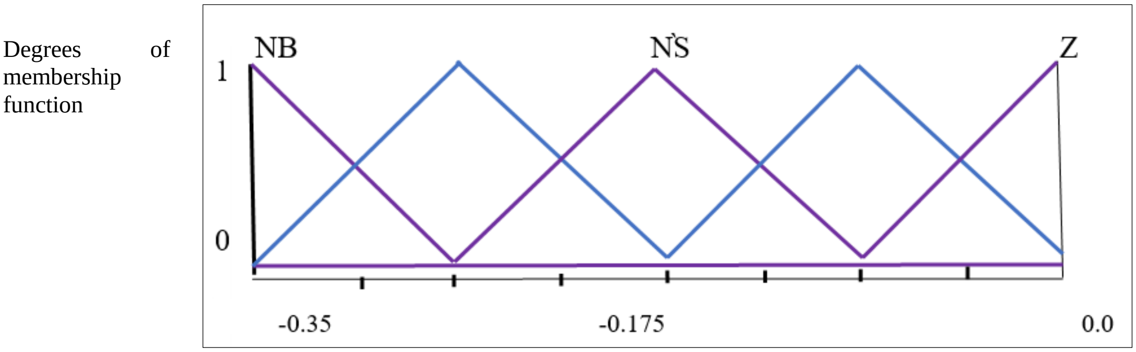


Figure 10 Membership function for input and output signals

In the context of a dynamic voltage restorer- phase-locked loop (DVR-PLL) system, the desired response differs significantly from other applications. The primary objective is to maintain the phase of the supply voltage. If the PLL reacts too quickly to phase changes during the sag, it might not adequately compensate for the phase jump, leading to an ineffective correction. To address this, a conventional approach is employed where, upon detecting a sag, the voltage reference's target phase is set to the pre-sag phase. By ensuring accurate tracking of the reference, load voltage remains unaffected. The response of the hybrid micro-grid system with conventional DVR and fuzzy controlled DVR (FC-DVR) against various fault conditions are presented in Section 4.

4.Results

In this paper, a detailed harmonic analysis of a solar PV-PEMFC microgrid is conducted under various contingencies.

The DVR with fuzzy logic controller as shown in *Figure 11* is implemented in the proposed HES. The simulation responses are obtained using MATLAB/Simulink for both balanced and unbalanced faults by simulating the model upto 0.1 second. The frequency spectrum and voltage waveform are obtained using FFT analyser from powergui tool. The output responses are obtained for two cases viz., (i) without secondary controllers and (ii) with fuzzy controlled DVR. Finally, the results are compared to identify the impact of controllers based on THD. Initially, the symmetrical fault has been created and its harmonics characteristics has been analysed. Under LLL fault condition without the controller, the output voltage and frequency spectrum are obtained as shown in *Figure 12*. *Figure 12(a)* depicts that under LLL fault condition, the voltage of all phases become zero until the fault cleared at 0.05 seconds. Frequency spectrum as shown in *Figure 12(b)* with LLL fault indicates that the THD value of hybrid system without controller is very high as 79.88 %. However, the THD value of LLL fault in the proposed system with FC-DVR is improved as shown in *Figure 13*. Output voltage response after the implementation of FC-DVR has avoided the system to become zero volts as shown in *Figure 13(a)*. This phenomenal change has improved the power quality, as it is witnessed in terms of THD value which is 39.28 % as shown in *Figure 13(b).*

After witnessing the great improvement in power quality under symmetrical fault with FC-DVR, the HES is subjected to various unsymmetrical faults and its harmonics characteristics are studied. Initially, the single LG fault which is a shunt type and unsymmetrical fault is created and analysed. Under this LG fault, the voltage of the faulted phase becomes zero as indicated in *Figure 14(a).* The harmonics produced without controller is found to be 79.63 % as indicated in frequency spectrum in *Figure 14(b).* However, the implementation of the FC-DVR controller proposed in this work has increased the average voltage as shown in *Figure 15(a).* It also causes for the further reduction of THD values to 39.18 % as presented in *Figure 15(b).*

Moreover, the system conditions are also analysed with LL fault and indicated in *Figures 16* and *17.* Since the faulted lines are short-circuited under LL fault, their voltages are not become zero, but it is modified from the regular line voltage magnitude. *Figure 16(a)* indicated that voltages of the faulted phases are distorted leaving the healthy phase voltage as normal. THD value obtained without controller under LL fault is 79.81 % as shown in *Figure 16(b).* For the purpose of improving the power quality, FC-DVR controller has been implemented and the responses are shown in *Figure 17*. The output voltage has been improved as indicated in *Figure 17(a)*. The frequency spectrum as shown in *Figure 17(b)* indicates the impact of the LL fault on the proposed hybrid micro-grid system with FC-DVR. It again proves that the FC-DVR mitigates the harmonics from 79.81% to 39.18%.

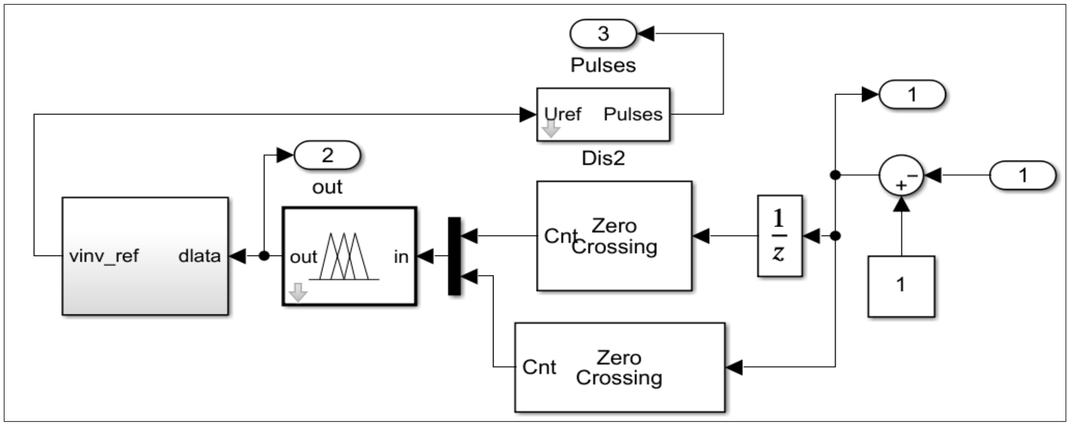
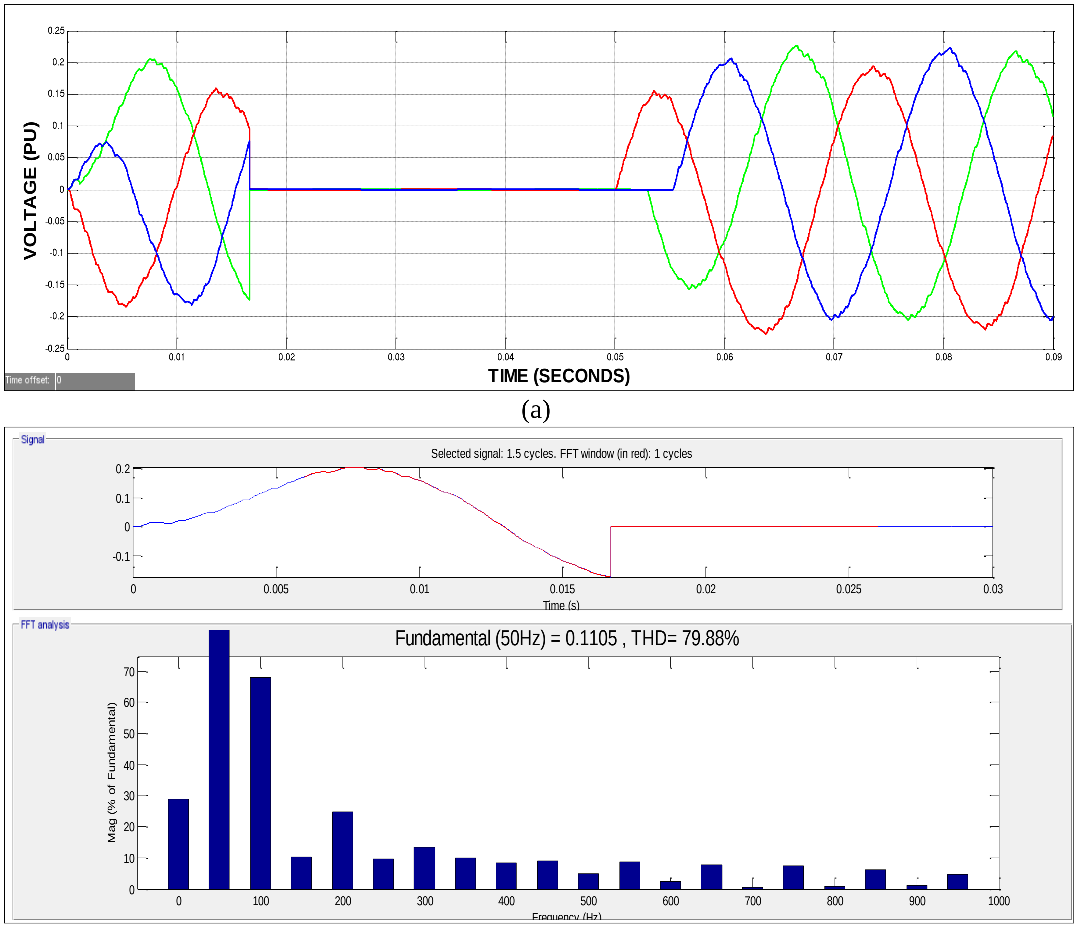


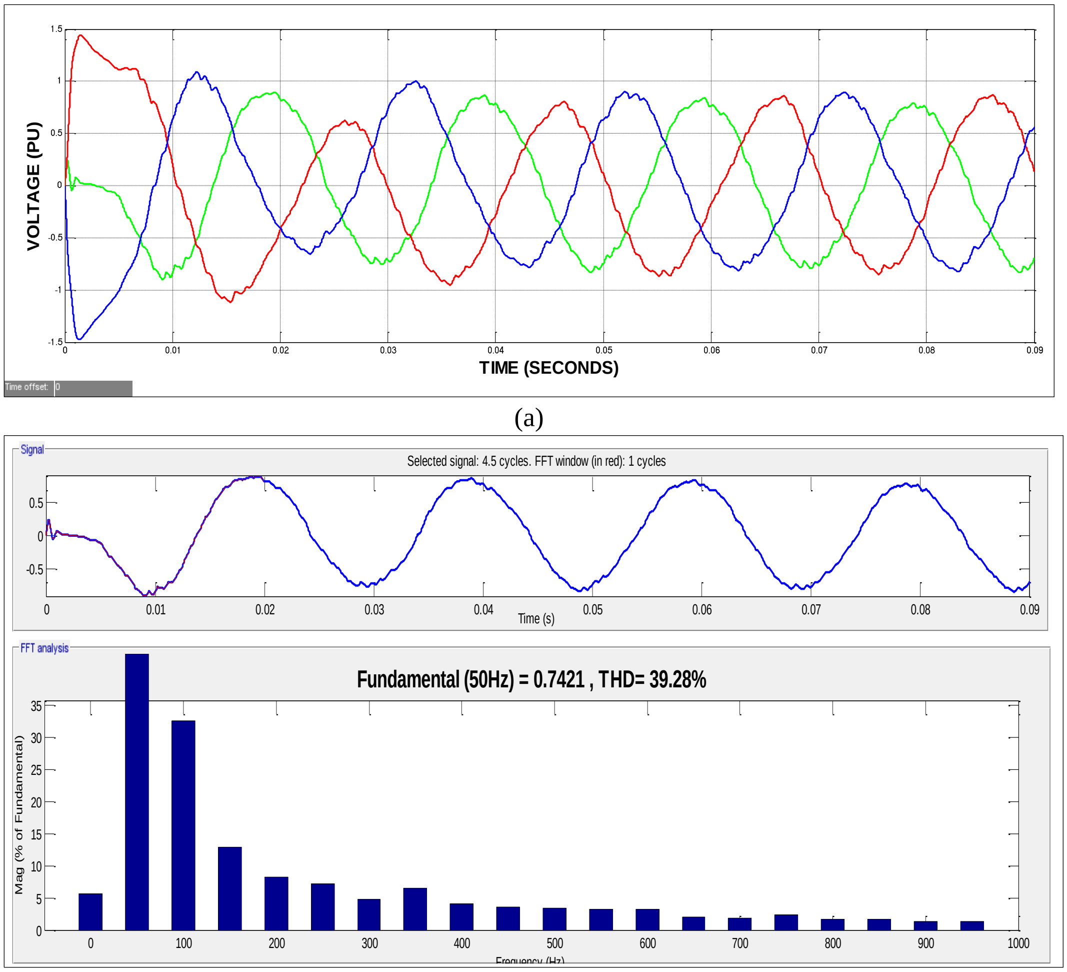
Figure 11 Fuzzy logic-based DVR control circuit



(a)

(b)

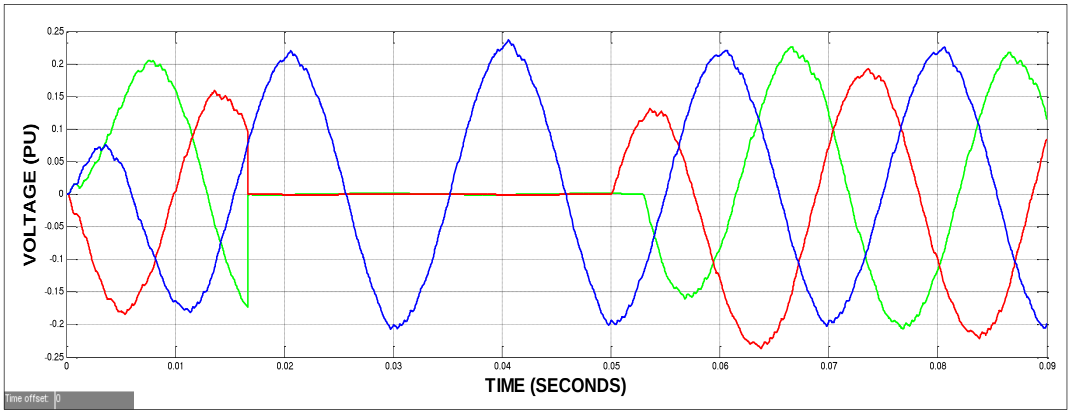
Figure 12 a) Output voltage b) Frequency spectrum during LLL fault without controller



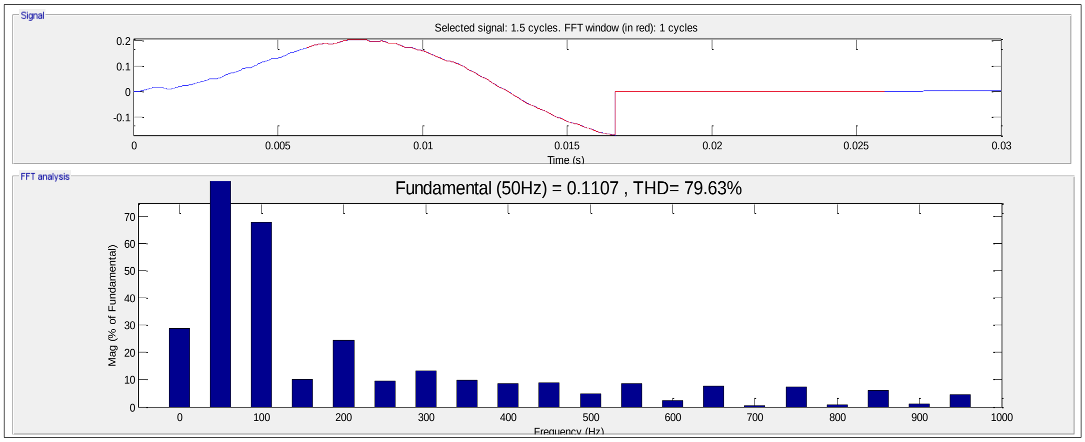
(a)

(b)

Figure 13 a) Output voltage b) Frequency spectrum during LLL fault with FC-DVR

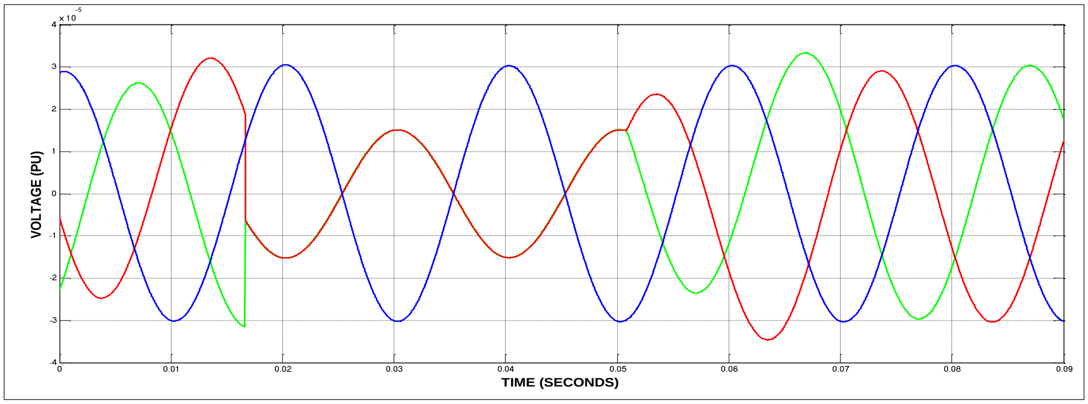


(a)

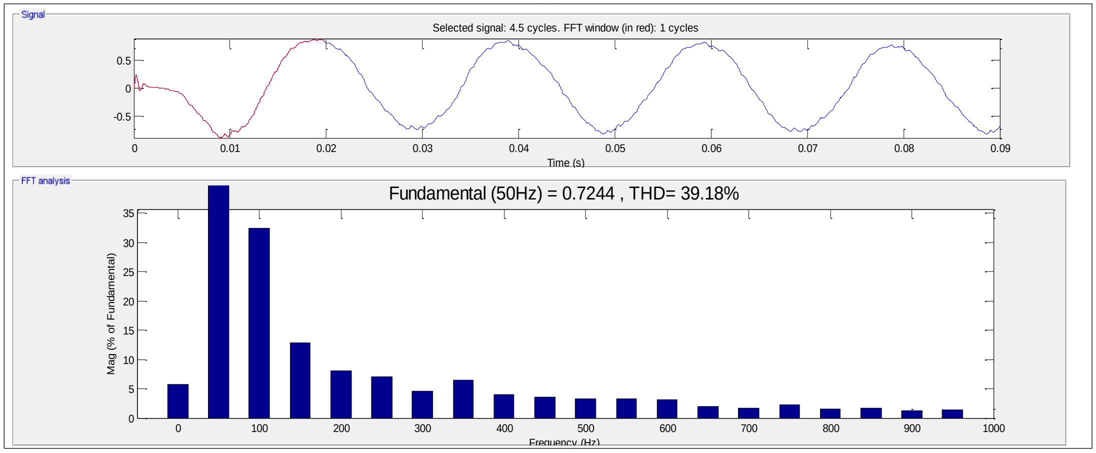


(b)

Figure 14 a) Output voltage b) Frequency spectrum during LG fault without controller



(a)

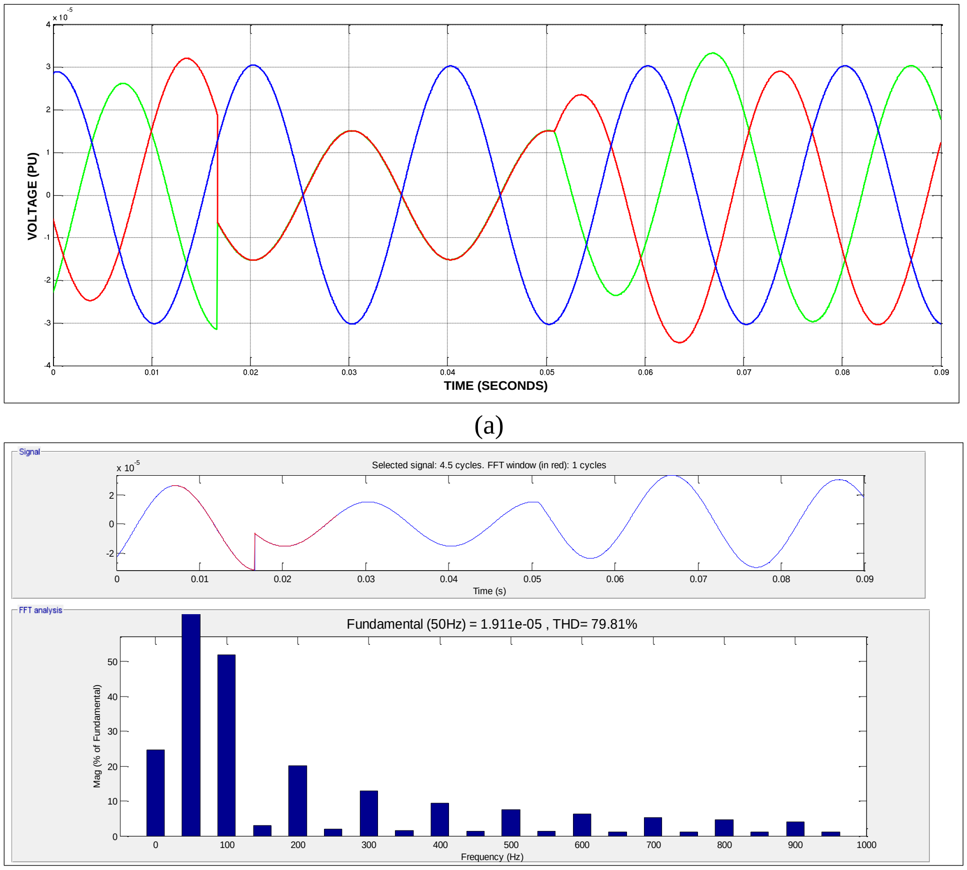


(b)

Figure 15 a) Output voltage b) Frequency spectrum during LG fault with FC-DVR

On comparing to other unsymmetrical faults, frequency of occurrence of LLG fault would be less. The power quality impact of this fault on the proposed micro-grid system is indicated in *Figures 18* and *19*. Without the usage of controller, the voltage magnitude of the faulted phases is highly distorted as shown in *Figure 18(a)* and the frequency spectrum under this condition is presented in *Figure 18(b)*. It is found that the THD value is identified as 79.44 %.

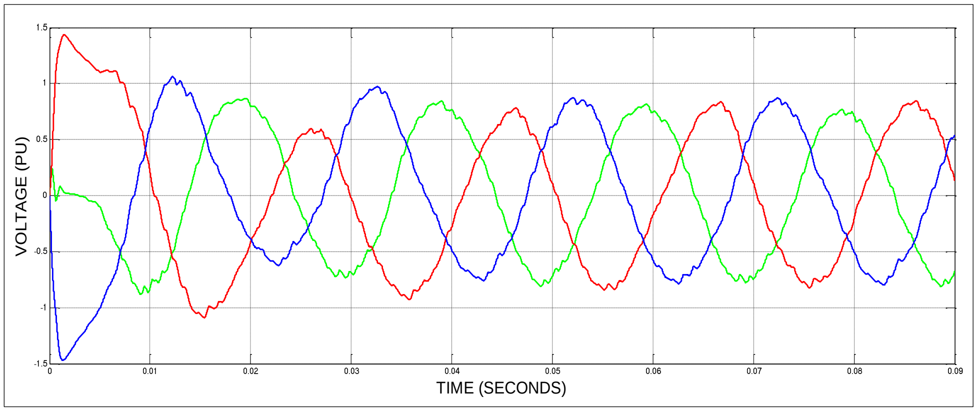
After the introduction of FC-DVR into the proposed micro-grid system, the voltage magnitude is also improved and THD value has been found to be reduced to 39.17 % as seen from *Figure 19(a)* and *19(b)* respectively.



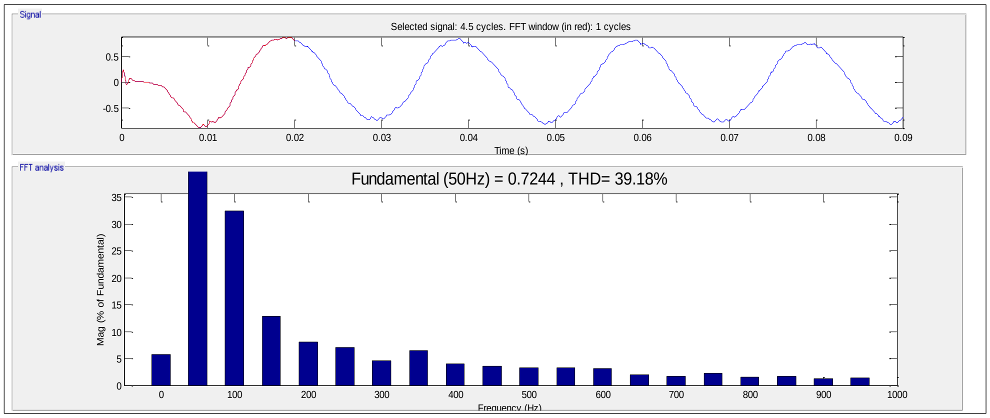
(a)

(b)

Figure 16 a) Output voltage b) Frequency spectrum during LL fault without controller

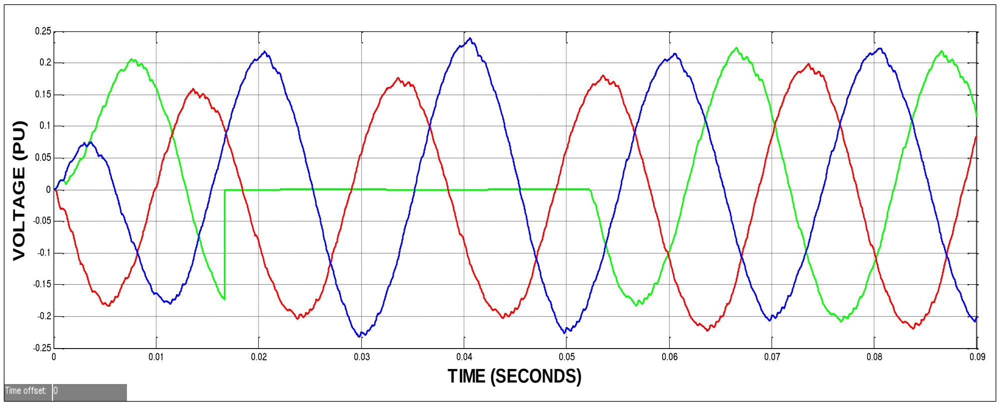


(a)

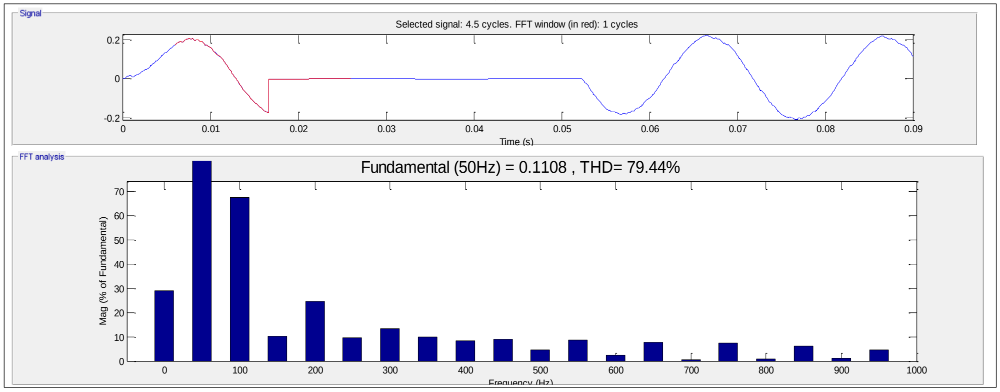


(b)

Figure 17 a) Output voltage b) Frequency spectrum during LL fault with FC-DVR



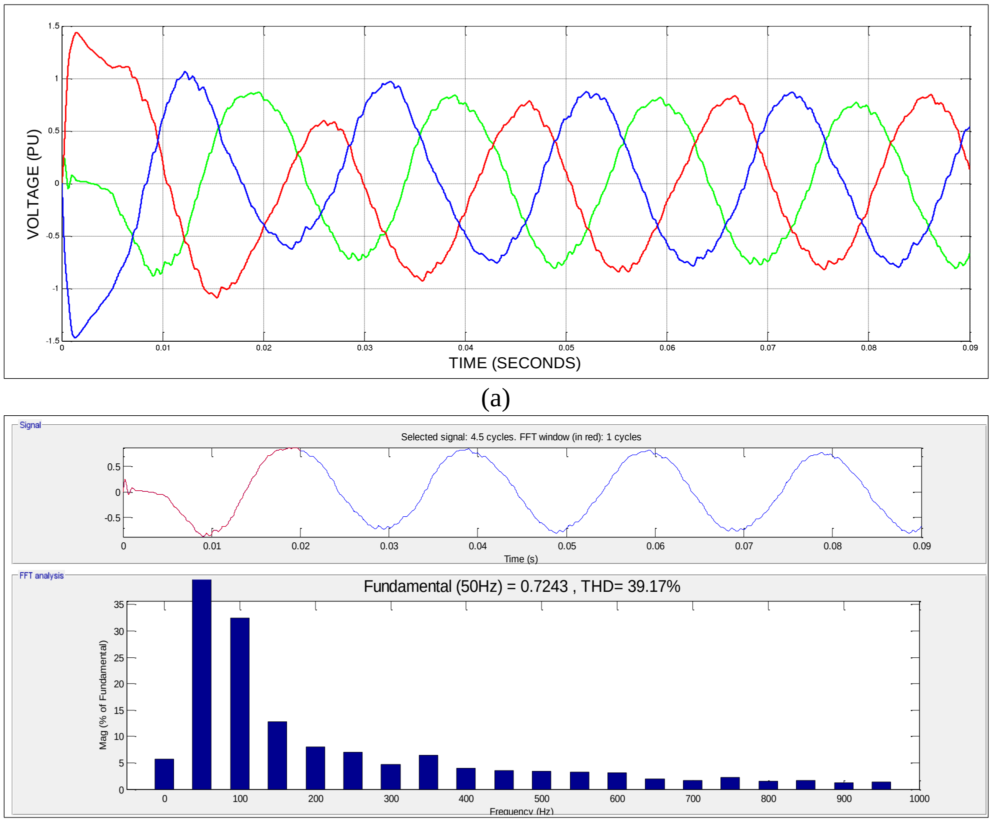
(a)



(b)

Figure 18 a) Output voltage b) Frequency spectrum during LLG fault without controller

Overall analysis of the system behavior indicates that the voltage magnitude of the proposed HES with LG, LL, LLG and LLL fault conditions witnesses the deviation because of the harmonics. Under LLL fault condition, all bus voltages become zero as seen in *Figure 12(a)*. The same effect is observed when LG and LLG faults which are occurring with respect to ground as indicated in *Figures 14(a)* and *18(a)* respectively. When LL fault occurs, there is a deviation in line voltages observed as shown in *Figure 16(a)*. It is worth to note from the *Figures 13(a), 15(a), 17(a)* and *19(a)* that the that the voltage fluctuations are being compensated when the FC-DVR is implemented.



(a)

(b)

Figure 19 a) Output voltage b) Frequency spectrum during LLG fault with FC-DVR

5.Discussion

The key finding of this hybrid renewable energy system research work is that the Sugeno-model-based fuzzy-logic-controlled DVR mitigates the harmonics to greater extent under all possible faulty conditions. In this work, the balanced LLL fault and unbalanced fault events are created and the dynamic response of hybrid solar PV-PEMFC system is analyzed. It has been witnessed from the results obtained from MATLAB/Simulink model for the LLL fault is that the THD value without DVR is obtained as 79.88%; whereas THD value has been reduced to 58.87% when DVR is implemented. Since the fuzzy logic-based expert system has been identified as an adaptive control logic for any dynamic system, fuzzy-controlled DVR has been developed. The simulation result with FC-DVR improves power quality by reducing the THD value further down to 39.18%. The voltage waveform also indicates that all the phase voltages become zero during fault period. With the presence of FC-DVR, the voltage has been injected into the system for balancing the voltage fluctuation caused due to LLL fault. The voltage injected by FC-DVR becomes the major reason for improving the power quality by mitigating the harmonics. Similar approach has been followed for the LG, LL and LLG fault conditions. It is observed that the THD value of the hybrid system is 79.63% without any controller when LG fault occurs in the system. The results convey that the THD value is reduced to 58.87% when DVR is incorporated with the system. Further improvement in power quality has been noticed when the fuzzy logic-based FC-DVR is used and its THD is reached to 39.18%. The above results can be seen in voltage waveform and the frequency spectrum as well.

On the other hand, the occurrence of LL and LLG fault in the proposed system causes for the power quality issues and their respective THD values without any secondary controller is noted as 79.81% and 79.44%. Similar to the previous cases, the attempt to mitigate the harmonics using DVR yield the THD value of 58.61% on both fault conditions. Further the implementation of fuzzy logic-controlled DVR reduces the harmonics to the greater extent where the THD values with FC-DVR for LL and LLG fault are observed as 39.18% and 39.17%

respectively. It is observed that the THD value of 3-phase fault is very high than the other faults as it is the severe fault. It is observed as 39.28 % THD as compared to that by using only DVR, which is 58.86%.

Comparison of all the fault conditions indicated that the LLL fault is more severe followed by LL, LLG and LG fault conditions in the proposed HES. It has also been witnessed through this detailed analysis that the FC-DVR mitigates the harmonics which are created due to abnormal fault conditions irrespective of the severity of the fault conditions. Based on this particular research work, it has been concluded that the FC-DVR yields superior performance and improves the power quality of hybrid solar PV-PEMFC energy system. *Table 1* compares the THD values of output voltages from the micro-grid system and the impact of DVR, fuzzy logic-controlled DVR and without DVR control cases are analysed during different fault conditions. For the validation purpose, the percentage reduction of harmonics for various control actions under different fault conditions are obtained and presented. Results indicates the percentage reduction in THD values when using only DVR and FC-DVR. It witnesses that FC-DVR reduces the THD values more than 50% irrespective of the fault types. However, the DVR without controller could reduce the THD values only by 25%. On analyzing the results, the drastic change is witnessed in THD values in the proposed system, when the DVR with fuzzy logic controller is used for harmonics mitigation.

Table 1 THD values for the various control schemes

	Values of THD (%)			**% reduction of THD**	
Fault type	**Without DVR**	**With DVR**	**With FC-DVR**	**With DVR**	**With FC-DVR**
LG Fault	79.63	58.87	39.18	26	50.79
LL Fault	79.81	58.61	39.18	26.6	50.91
LLG Fault	79.44	58.61	39.17	26.2	50.69
LLL fault	79.88	58.86	39.28	26.31	50.82

5.1Limitations

In this research work, the solar PV and fuel cell has been considered for the hybrid system from the clean energy perspective. However, the wind energy conversion system with doubly-fed induction generator and permanent magnet synchronous motor drives would need to be considered for future analysis. For a solar PV system, the standard atmospheric conditions of temperature and irradiance level are considered. However, the impact of variation in atmospheric temperature and solar irradiance has not been considered in this particular research work. Since the main focus of this work is for analysing the impact of fuzzy logic technique-based DVR on power quality mitigation, all these conditions may be attempted in future work. A comprehensive list of parameters and abbreviations is provided in *Appendix I* and *Appendix II*.

6.Conclusion and future work

As a step towards achieving sustainable development goals, this research provides a state-of-the-art solution for energy sustainability. In this research work, clean energy resources namely solar and fuel-cell based micro-grid system has been modelled. For ensuring reliable power to the end-users, it is necessary to assure the quality power to their needs. Power quality behaviour of the hybrid micro-grid network has been analysed under various fault conditions viz., LG, LL and LLG. FFT analysis of the system has also been performed in MATLAB/Simulink environment under all possible abnormalities. In this work, an efficient compensator namely DVR has also been designed and implemented with the system for maintaining the system voltage through voltage injection principle. Based on the expert knowledge about the HES, Sugeno-model-based fuzzy inference mechanism has been developed using fuzzy IF-THEN rules. DVR performance has been controlled by fuzzy logic technique useful for the solar PV-PEMFC, HES. The simulation results of the HES with FC-DVR are analysed based on the distortion in the output voltage and the THD values obtained from the frequency spectrum. Extensive analysis of the hybrid micro-grid system behavior with LG, LL, LLG and LLL fault conditions witnesses the voltage fluctuation because of the harmonics. Under the symmetrical LLL fault condition, voltage magnitude of all LLLs become zero. However, for the unsymmetrical faults namely LG and LLG faults, deviation in line voltages is observed. Irrespective of the fault whether symmetrical or unsymmetrical, it has been observed that the DVR can directly reduce the THD upto 26%. Further analysis using FC-DVR witnesses the superior performance on harmonics mitigation. It is worth to note that the that the voltage fluctuations are being compensated when the FC-DVR is implemented and the THD is reduced to the greater extent upto 51%. With an effective control action taken by FC-DVR, the voltage injection is controlled in case of voltage disturbances. The result show that the fuzzy logic-controlled DVR is an efficient solution for mitigating harmonics at different fault conditions like LG, LL, LLG and three phase faults. From the detailed analysis, it is identified that the FC-DVR proposed in this work is an optimal controller for the hybrid micro-grid energy system. In the future, this approach can be extended with various other controllers for HESs, incorporating additional renewable sources such as wind and biomass, along with other custom power devices.

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Conflicts of interest

The authors have no conflicts of interest to declare.

Data availability:

None.

Author’s contribution statement

Mohamed Iqbal M: Problem formulation, investigation, writing original draft, controller design, supervision, analysis, and interpretation of results. **Divya R:** Review of related articles, data collection, harmonic study and analysis. **Pavithra C V**: Simulation and analysis, draft preparation and writing review. **Vishalini G:** Modelling of hybrid system, design of DVR, contingency and fault study, analysis, and interpretation of results. **Shanmugasundaram R:** Harmonic study, analysis and, interpretation of results.

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Appendix I

Symbol	Parameters	Unit
I_0	Diode saturation current	*Amp*
k	Boltzmann's constant	J/K
Ipv	Photovoltaic current	*Amp*
In,sc	Nominal short circuit current	*Amp*
Eg	Band gap energy of the semiconductor	*eV*
q	Electron charge	*coulumb*
$Tref$	Nominal temperature	*K*
$T_{n,op}$	Nominal operating temperature	*K*
Ki	Short circuit current of cell	w/m^2
a	Ideality factor of diode	-
Ins	Nominal saturation current	*Amp*
V_{dvr}	DVR voltage	*V*
Ir	Solar irradiation	w/m^2
I	Current output of PV module	*Amp*
N_P	Number of PV modules connected in parallel	-
R_s	Series resistance	*ohms*
R_{sh}	Shunt resistance	*ohms*
N	Ideality factor of diode	-
N_s	Number of PV modules connected in series	-
I_{sh}	Short circuit current	*Amp*
V_t	Diode thermal voltage	*V*
V_l	Load voltage	*V*
I_l	Load current	*Amp*
Z_s	System impedance	*ohms*
V_s	System voltage during fault condition	*V*
$V_{n,oc}$	Nominal open circuit voltage	*V*
G	Actual radiation	KW/m^2
G_{ref}	Nominal radiation	KW/m^2

ΔT	Difference between reference and operating temperature of solar cell	K
Θ	Load power angle	-

Appendix II

S. No.	Abbreviations	Description
1	AC	Alternating Current
2	DC	Direct Current
3	DSTATCOM	Distribution Static Synchronous Compensator
4	DVR	Dynamic Voltage Restorer
5	DVR-PLL	Dynamic Voltage Restorer- Phase-Locked Loop
6	FC-DVR	Fuzzy Controlled Dynamic Voltage Restorer
7	FFT	Fast Fourier Transform
8	GW	Gigawatts
9	HES	Hybrid Energy System
10	LG	Line to Ground
11	LL	Line to Line
12	LLG	Double Line to Ground
13	LLL	Three-Phase
14	NB	Negative Big
15	NS	Negative Small
16	PB	Positive Big
17	PS	Positive Small
18	PEM	Proton-Exchange Membrane
19	PEMFC	Proton Exchange Membrane Fuel Cell
20	PI	Proportional-Integral
21	PID	Proportional-Integral-Derivative
22	PLL	Phase-Locked Loop
23	PV	Photovoltaic
24	PV-PEMFC	Photovoltaic Proton Exchange Membrane Fuel Cell
25	PWM	Pulse Width Modulation
26	SVC	Static Var Compensator
27	THD	Total Harmonic Distortion
28	UPFC	Unified Power Flow Controller
29	VSI	Voltage Source Inverter
30	Z	Zero