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Original Article

Fractional Order Fuzzy Logic Controller based Energy Management System for Grid Integrated Microgrid

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Abstract - *Electric energy security is critical, but high costs, limited fossil fuel sources, need to reduce greenhouse gas emissions make renewable resources appealing in world energy economies. A new control scheme is proposed to improve the EMS and microgrid system's reliability and effective efficiency, Fractional-Order Fuzzy Logic Controller (FOFLC). The performance of an intelligent FOFLC is investigated in this manuscript. The controller's performance is studied under load disturbances and changes in set-point conditions to underline the benefits of the proposed control strategy. With FOFLC, the comparative study is also implemented. The incremental conductance approach is utilized to maximize the power generated based on the application of MPPT. The proposed model's transient state is investigated under various operating scenarios. Design and implementation of an EMS with FOFLC for an AC/DC micro-grid system to extend the battery life cycle, with FOFLC controller providing the desired SoC. As a result of findings, the system negotiated power balance, and battery "SoC" defends desired value for extending the life of an AC/DC microgrid controller. The obtained results with a proposed controller are validated by applying MATLAB/SIMULINK.*

Keywords - *EMS, MPPT, AC/DC microgrid, SoC. FOFLC.*

1. Introduction

Renewable energy resources (RES) have huge potential, far exceeding global energy consumption; as a result, these resources will play a key part in the global energy portfolio in the future [1]. Renewable energy (RE) can provide various benefits, including carbon dioxide reduction, improved energy access, advancement of energy security goals through expansion of energy technologies, and improved social and economic development through potential job opportunities [2]. The utilization of renewable energy in different regions of the world varies significantly. This is because contextual factors like geographic, socioeconomic, cultural, and regulatory policy frameworks significantly impact RE use [3]. Solar power, hydropower, and wind power are now considered well-established technologies. The digitalization of the Energy System (ES) is intelligent, predictable, and sustainable. Through sensors that can be managed and monitored via smart devices. The technical challenges engaged in integrating RES with grids are storage technologies, variable, dispatchable RE based on the country's availability of resources, power grid infrastructure, transmission requirement, and distribution infrastructures [4]. To reduce this technical challenge, extract MPPT, and improve power quality in grids, intelligent controllers like the Fractional Order Fuzzy Logic controller are introduced [5]. The factors driving Microgrid (MG) development in locations with existing electrical grid infrastructure are divided into three categories: energy security, economic benefits, and clean energy. MG's have unique control strategies for performing local balancing and maximizing economic benefits. The objectives of the proposed strategies are 1) A "peer-to-peer" architecture2) To reduce system costs, cogeneration facilities nearby thermal loads[6]. The structure of MG consists of (a) Micro sources, (b) Flexible loads, (c) Distributed Energy storage, (d) Control systems(e)Point of Common Coupling. MG is a localized grid that can run independently while the main grid is down, strengthening grid resilience, assisting in mitigating grid disturbances, and serving as a grid resource for speedier system reaction and recovery.

An autonomous MG presents power quality metrics like voltage regulation, frequency regulation, steady-state response, dynamic response, and THD analysis. Harmonics introduced into utility grid increase due to sensitive power electronics equipment in industrialized areas increases [7]. When loads are transferred from grid-connected mode to islanded mode, additional power quality disturbances occur [8]. To improve power quality and deal with nonlinear loads with DG systems, an algorithm is proposed, Particle Swarm Optimization (PSO), which regulates power quality using compensators. Using the Selective Harmonic Elimination (SHE) technique based on the PSO algorithm may eliminate odd harmonics in output voltage. The PWM inverter suppresses the presence of higher-order harmonics by varying carrier wave phase angles that can generate dominant harmonics [9]. To provide clean, eco-friendly energy, deliver continuous power, and improve power quality, an EMS-based hybrid energy system (HES) is introduced in this work, presented in Fig.1.

Introducing extraction of MPPT from solar panels has been increased [10]. The proposed HES two different MPPT techniques are applied like Perturb & Observe(P&O) and Incremental Conductance (IC) method. This HES is also applied to optimize the operation of the wind turbine. A two-stage optimization is required to reduce power deviation for the Wind Turbine (WT) set points. An advanced Fractional Order Fuzzy Logic Controller (FOFLC) is developed to distribute power among hybrid systems and manage to charge and discharge the battery to improve the battery's life [11]. The proposed method also improves the reliability and dynamic performance of the grid [12]. The organization of the manuscript is Section II deals with block diagram representation, Section III deals with MPPT algorithms using P&O IC methods, Section IV represents FOFLC methods, mathematical equations involved in the proposed method, Section V deals with results, and section VI deals with the conclusion, future scope of this research.

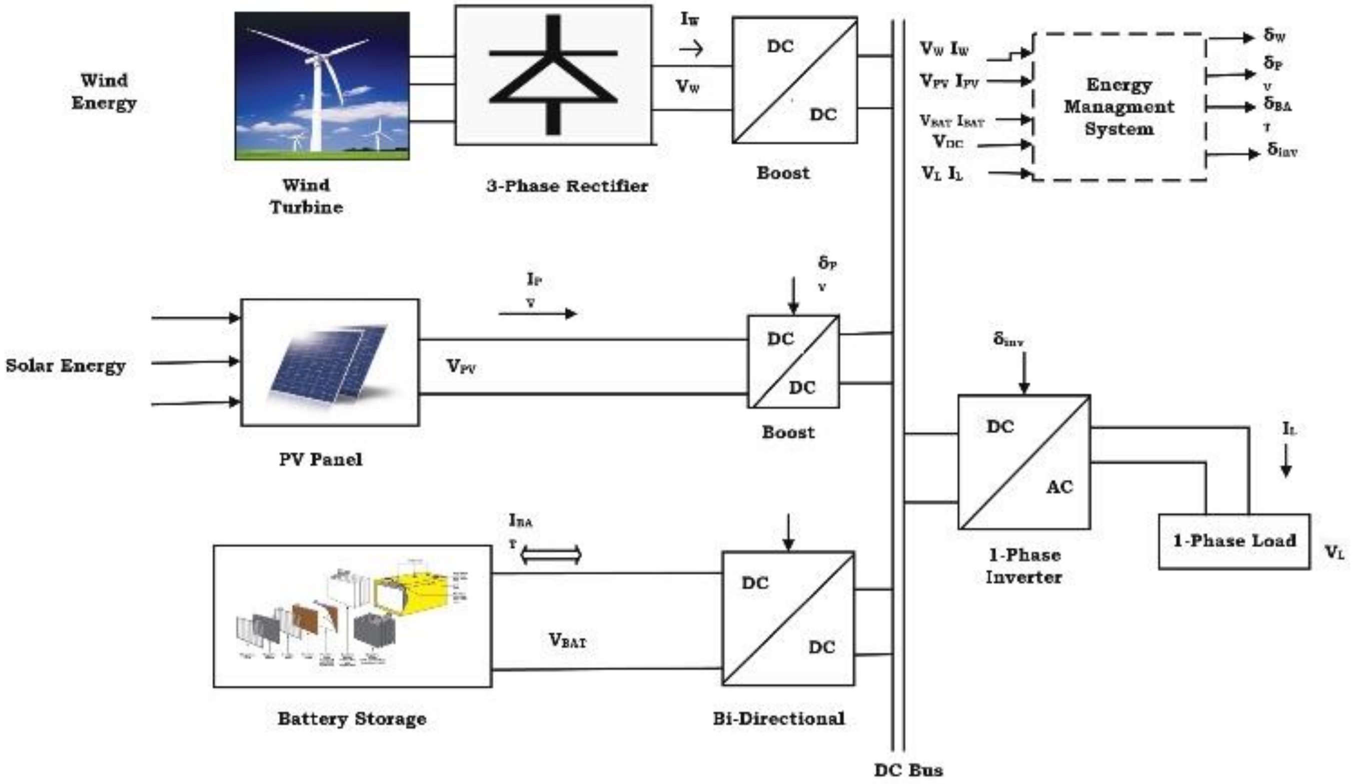


Fig. 1 Basic Structure of Microgrid with EMS

2. Methodology of Proposed System

PV, WECS, and Battery Energy Storage System are all part of the proposed system connected to the main grid. Excess energy generated from sources is stored in batteries, used to satisfy increased demand [13]. HES is coupled to CC-VSI for grid interface via energy storage in the system as mentioned above, with DC-link capacitor voltage sensors (VS) used to monitor, compute, and determine the supply of voltage and manage the level of AC or DC voltage. The voltage is input to VS, output switches, a current signal, and an audio signal are outputs. The current sensor (CS) informs BESS about the current and temperature. The CS has a small design with an integrated bus bar suitable for 400V/800V, which has high voltage battery systems and galvanic isolation of high, low voltage channels. The CS measures ranging upto±2000A with the accuracy of ±1.0, temperature -400c to +850c.The crucial task of HES with CC-VSI is current control and synchronism. Current distortion is caused by various factors, including grid voltage variations, unbalances, harmonics, and inverter nonlinearities. To boost reliability, IGBTs in this system are larger. In this manuscript, FOFLC is implemented to pursue variations in PV and battery voltages and maintain the constant output voltage. The proposed system with a control circuit is shown in Figure 2.

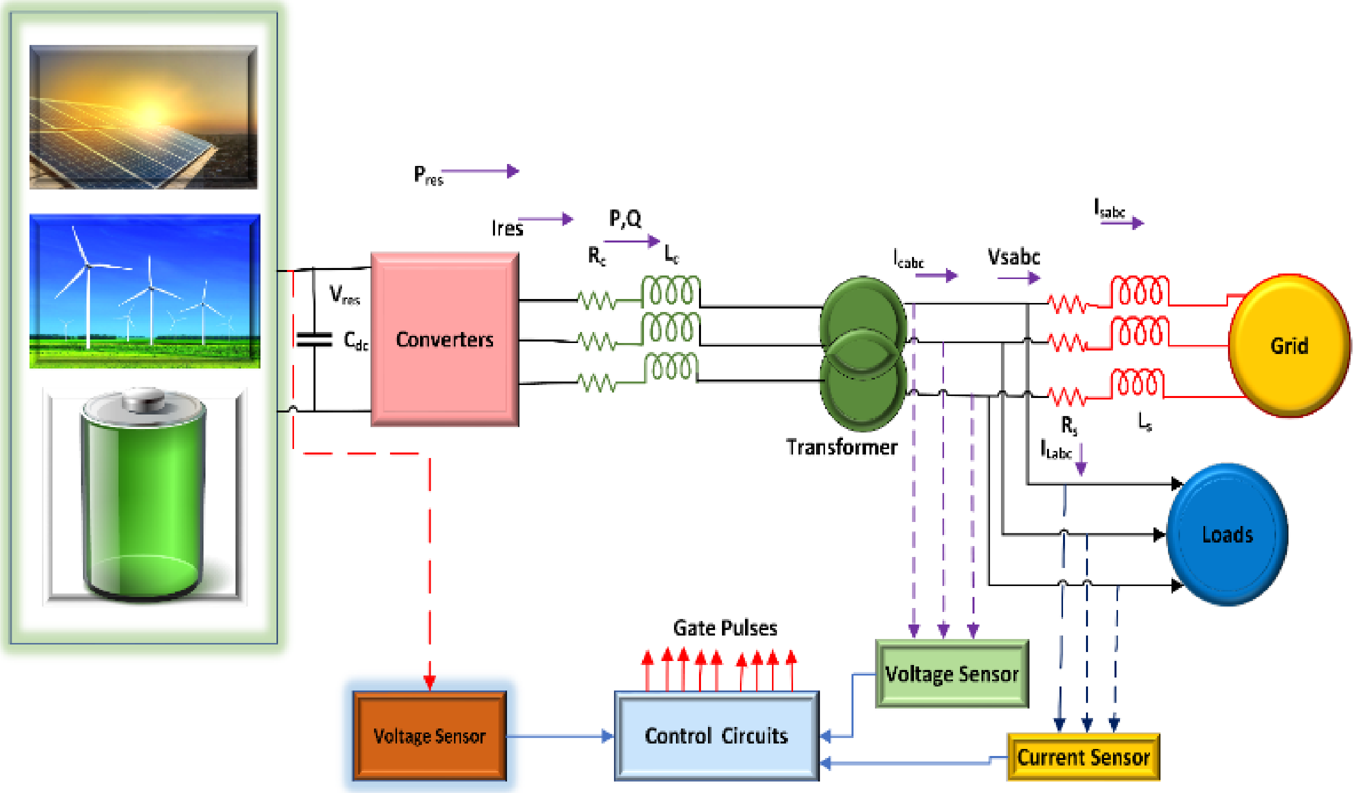


Fig. 2 General Configuration of the proposed system

3. MPPT Method

3.1. P&O Method

An MPP tracker is employed to extract maximum power from the solar PV module and convert it to load. The goal of the DC-DC converter is to convert maximum power to load. A DC-DC converter is a device that connects the load to the module by changing the duty cycle ratio; the load's impedance, as seen by the source, is modified at peak PowerPoint with a source to convert the greatest power [14]. The P&O, IC method and constant voltage methods are famous MPPT methods.

The P&O technique is widely used for controlling the MPPT algorithm for PV generators because of its low cost, simple structure, easy implementation, reduced parameters, and possible improvements. This approach is based on analyzing the relationship between PV module output power and voltage [15]. The P&O states that the PV system's working voltage is increased only slightly if any change in control irritates power; the system will move toward MPP and continue perturbing in the same manner. Also, P&O calculates current and voltage estimation from photovoltaic. The disturbance causes the solar module's power to fluctuate over time[16]. If the power of perturbation is increased, the perturbation will continue in the same direction. At peak power at the following instant falls, perturbation reverses. When the algorithm reaches a stable state, it oscillates about the peak point[17]. To keep power variation to a minimum, perturbation size is maintained minimal. The approach is designed to set module reference voltage that corresponds to the peak voltage of the module.

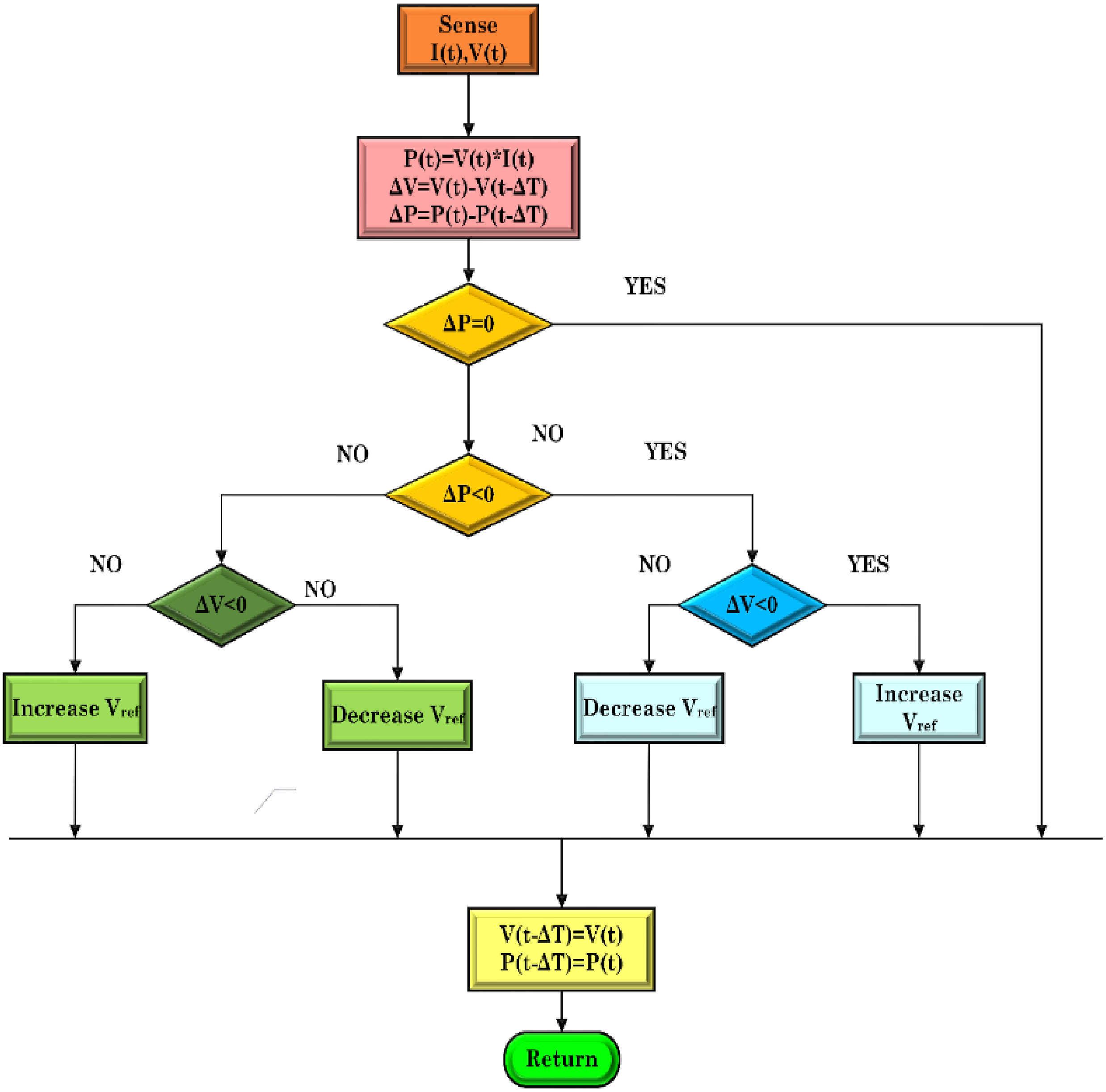


Fig. 3 Flowchart for Perturb & Observe Algorithm

3.2. Incremental Conductance (IC)method

If MPPT has reached maximum power, the IC technique extracts no longer perturbing operational points. If this criterion is not met, the direction in which MPPT operating point must be perturbed can be determined using dl/dV, –I/V. This approach can tell if MPPT has reached MPP or the perturbed operational point. If this requirement isn't met, dl/dV,–I/V is used to determine how the MPPT operating point should be perturbed. With greater accuracy, the IC technique can follow quickly increasing, declining irradiance circumstances. The IC approach has the advantage of determining the exact direction of a disturbance at any point in time, and operating point oscillation can be avoided.

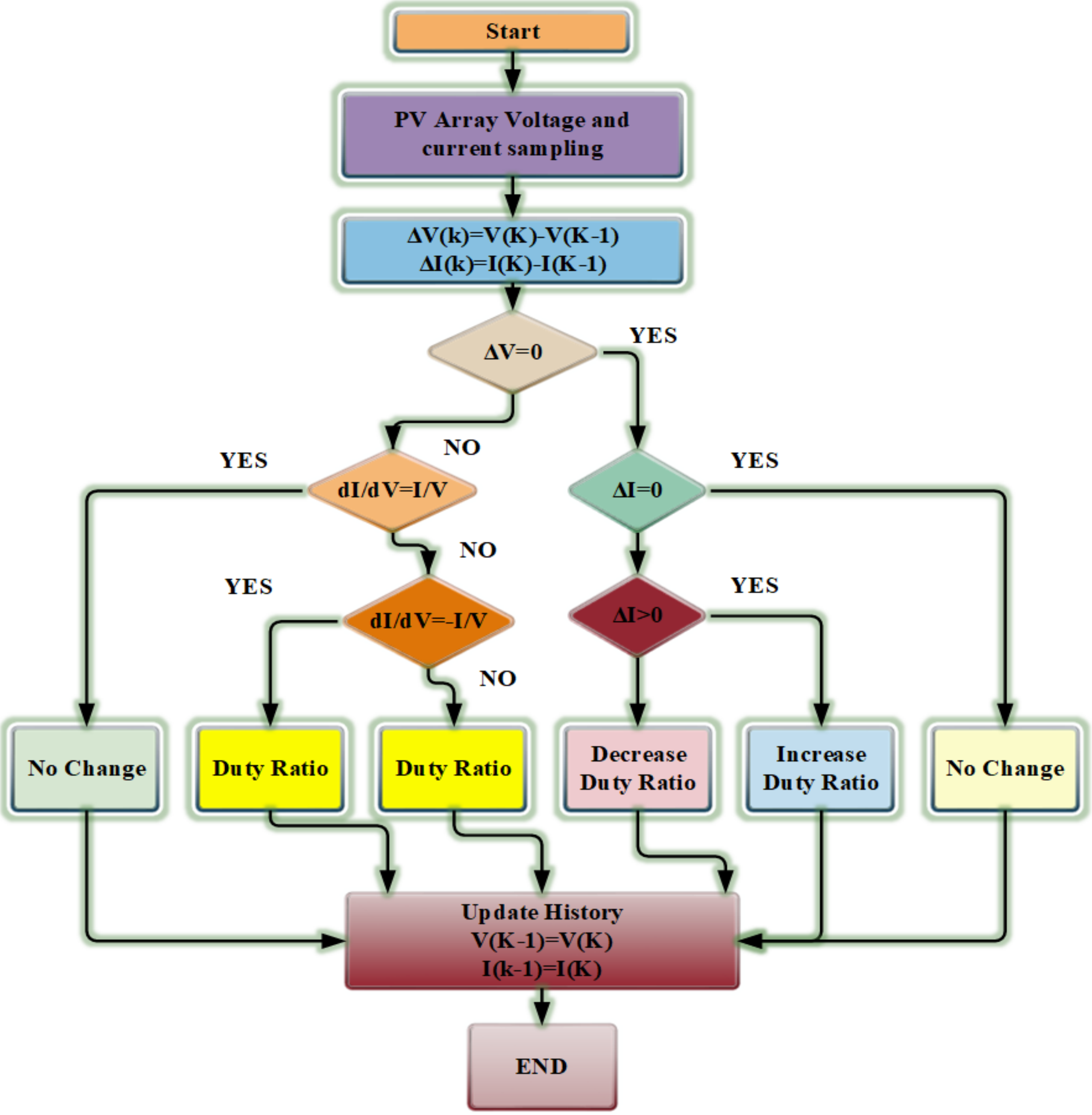


Fig. 4 Flowchart for Incremental Conductance Method

4. Energy Management Systems (EMS) and Power Quality

4.1. Energy Management Systems (EMS)

The majority of EMS research is focused on accomplishing economic objectives. The optimization of EMS provides the best economic performance. An EMS has a centralized structure with a central controller, a high-performance processing system, and specialized network connectivity. The EMS controller, either an aggregator or a utility, collects all data from each node, like load consumer consumption patterns and DER energy generation, to run optimization algorithms [18]. The parameters of uncertainty management in EMS are technical and economical. The technical factors are topological or operational. The topological characteristics contain information online or manufacturing unit disturbances, while operational parameters include demand and renewable generation information. EMS is adopted to manage MG uncertainty reliability, PEV load profile, and power quality [19].

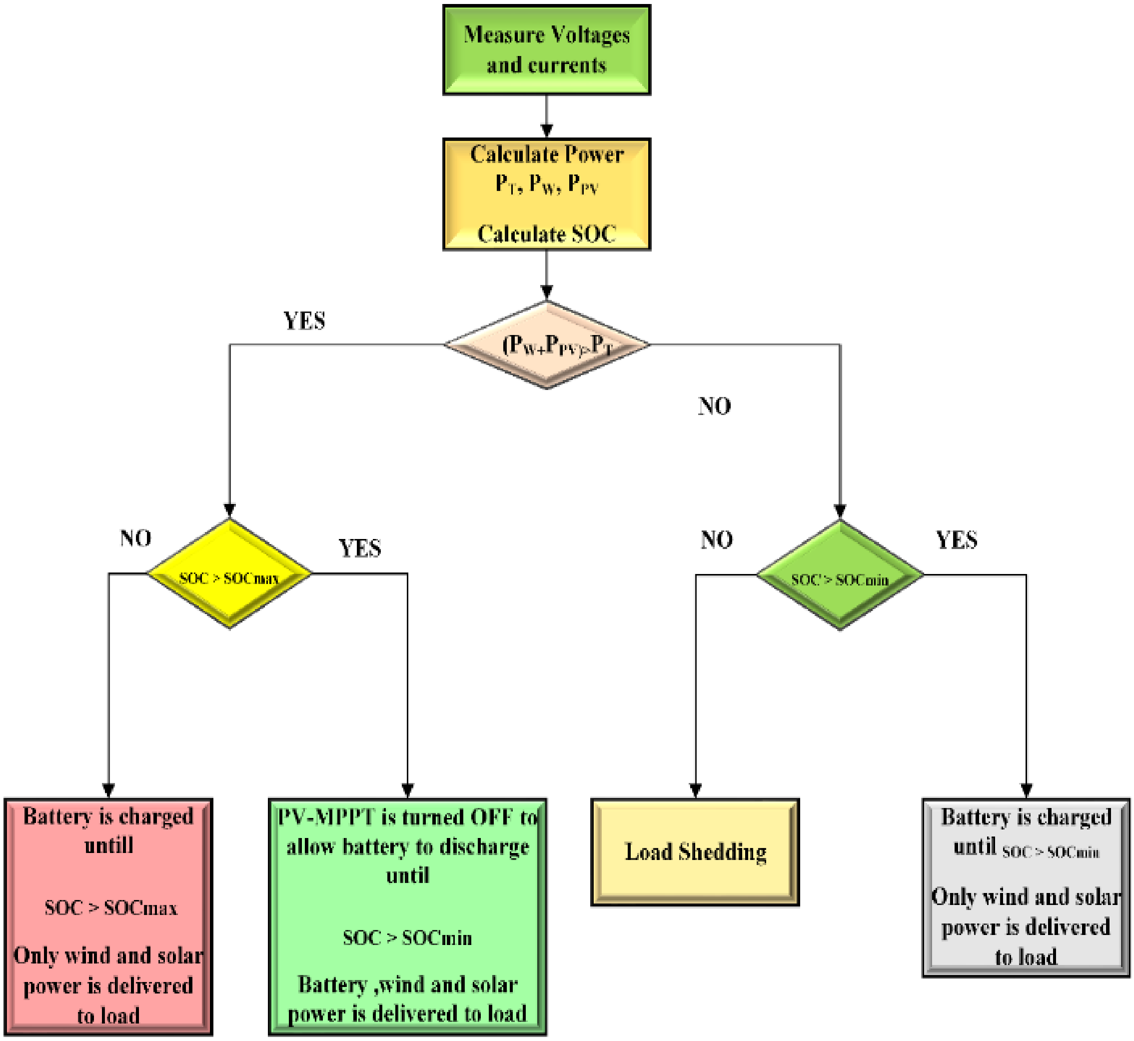


Fig. 5 Energy Management Systems (EMS)

4.2. Power Quality

The Power Quality in the grid can be improved by adopting a controller. The power quality in grids can be improved by adopting controllers. At the primary level, the local controllers like PI can be employed with DG to generate unbalanced compensation references for MG DG's [20]. Because of voltage balance compensation, linear unbalanced load, and load current compensation problems. The researchers adopt intelligent controllers like fuzzy, adaptive fuzzy, and FOFLC to improve THD, active and reactive power, and power quality management in MG's [21].

5. Fractional Order Fuzzy Logic Controller (FOFLC)

The FOFLC is very much famous for understanding the derivative operator. The numerical expression for FOPI is

$$C(s) = Kp + \frac{Ki}{s^{\lambda}} \qquad (1)$$

λ is the range of (0,1). If λ≥2 is changed to high-order construction is equal to the PI controller. The FO is described in (1) as a common character of the PI controller [26]. To resolve the issues in the FOFL controller, effective filters can be used. The fitting range is (ω_b,ω_h). The fractional-order function is

$$K(s) = (1 + bs/d\omega b)/(1 + bs/d\omega h)^{\lambda} \qquad (2)$$

Where 0<λ<1, s=jw, b>0, d>0, and

$$K(s) = (\frac{bs}{d\omega b})^{\lambda} (1 + \frac{-ds+d}{ds^2+b\omega hS})^{\lambda} \qquad (3)$$

In frequency range between $\omega b < \omega < \omega h$ by including Taylor polynomial expansion form which occurs

$$K(s)= (\frac{bs}{d\omega b})^{\lambda}(1 + \lambda P(S) + \frac{\lambda(\lambda-1)}{2} p^2(s) \qquad (4)$$

Where $p(s) = \frac{-ds^2+d}{ds^2+b\omega hs}$ (5)

It is initiated that

$$s^{\lambda} = \frac{(d\omega b)^{\lambda b-\lambda}}{\left[1+\lambda P(S)+\frac{\lambda(\lambda-1)}{2}p^2(s)\right]} \left(\frac{1+\frac{bs}{d\omega b}}{1+\frac{ds}{d\omega h}}^{\lambda}\right) \qquad (6)$$

Estimated the Taylor polynomial leads to

$$S^{\lambda}=\frac{d\omega b}{b}\frac{ds^{2}+b\omega hs}{d(1-\lambda)s^{2}+b\omega hs+d\lambda}\left(\frac{1+\frac{bs}{d\omega b}}{1+\frac{ds}{d\omega h}}\right)^{\lambda} \quad (7)$$

The FO is defined as

$$S^{\lambda}=\frac{d\omega b}{b}\frac{ds^{2}+b\omega hs}{d(1-\lambda)s^{2}+b\omega hs+d\lambda}\left(\frac{1+\frac{bs}{d\omega b}}{1+\frac{ds}{d\omega h}}\right)^{\lambda} \quad (8)$$

Equation (8) is balanced if poles on LHS of complex s-plane. The poles of equation (8) is

$$d(1-\lambda)s^{2}+b\omega hS+d\lambda \quad (9)$$

The negative poles in the real part for $0<\lambda<1$. The poles in equation (7) are in the range of $(\omega l|\omega h)$. The (6)th equation is approximated by uninterrupted -time coherent simulation.

$$K(s)=\lim_{n\to\infty}Kn(s)=\lim_{n\to\infty}=-N\frac{1+\frac{S}{\omega k}}{1+\frac{S}{\omega k}} \quad (10)$$

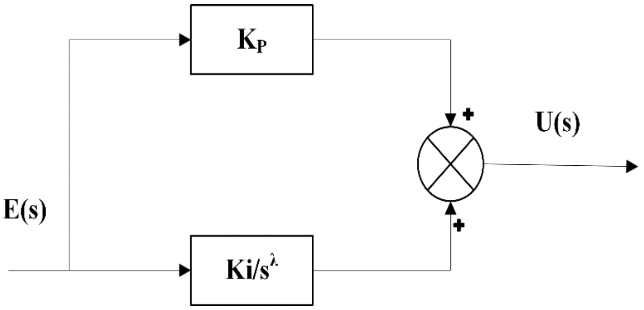


Fig. 6 Control structure of the Proposed system

5.1. The Proposed Fractional-Order Fuzzy Logic Controller

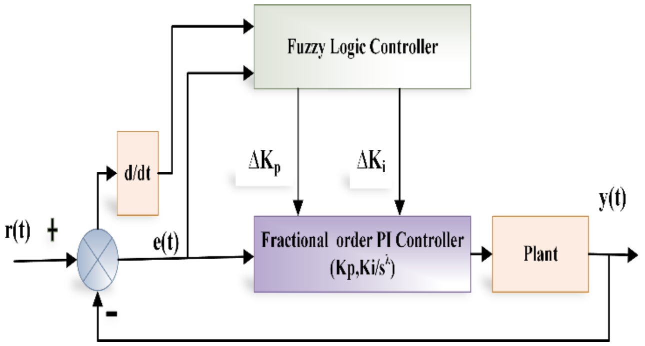


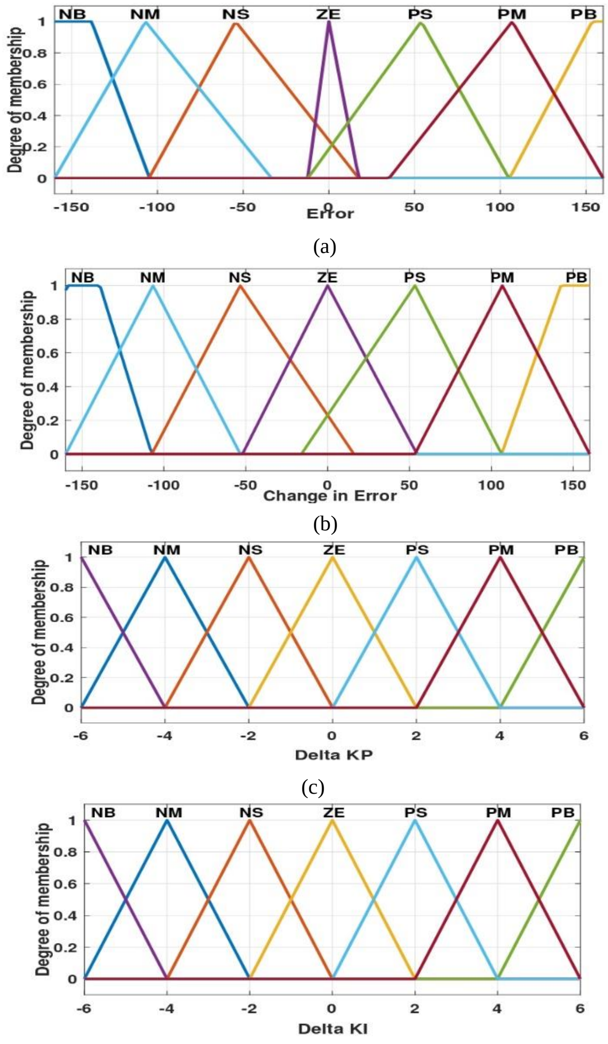
Fig. 7 Structure of Proposed FOFL controller

The structure of the Proposed FOFL controller, as shown in Fig.7, involves the following steps.

- Define states, input/output control variables, and variation ranges.
- Create a degree of fuzzy membership function, complete fuzzification.
- The proposed action will be executed by assigning strengths to rules.
- Combine rules and defuzzify output.

The input signals to triangle membership functions of fuzzy variables f and P are converted. The following terms are used to describe settings: m (high), ml (middle), and l (low)[24]. These parameters are applied consistently to improve transient, steady performance precision. A collection of inference rules generates fuzzy (fuzzification) phase optimization of fuzzy variables [25-27]. The fuzzy control work is explained in the following two steps.

- The membership functions represent fuzzy inputs' stabilizers.
- Set output membership function



(a)

(b)

(c)

(d)

Fig. 8 Membership Function for (a) error, (b) Change in error (c) ΔKp and (d) ΔKi

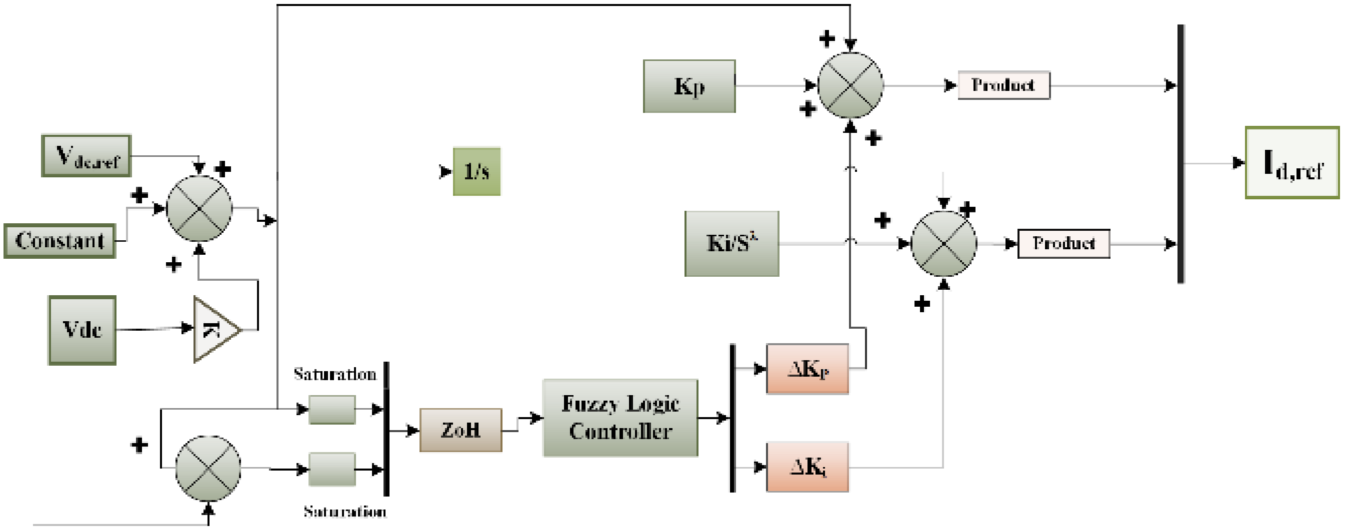


Fig. 9 The control structure for Fractional-order FLC

6. Results and Discussions

The simulation results are explained in this section. This result includes Grid, PV voltage, EMS system with adaptive FLC and Fractional-order FLC, and variations in Fig.12 and Fig.13.

In Fig.10, there are variable conditions

Condition 1: Grid is 'ON,' Battery is 'OFF'
Condition 2: Grid is 'OFF,' Battery is 'ON'

This idea improves reliability, RES capability, functional load control, and efficiency of major grids. The controller controls the power efficiently via switching events. The battery is turned off when the grid is switched on; loads are turned on as required. The powers of EMS are represented in Fig.13.Using an efficient controller, the grid power reached a steady state in the shortest possible period, 0.03seconds. The controller reduces the transient period. After In 4 seconds, the battery begins to charge. Load1 is turned on at 1sec, and load1 transients are minimized at 1. 003sec. The transients occur at 4sec and are removed at 4.03sec, bringing load power1 to a stable state, whereas load2 is switched on at 3sec, and transients occur at 4sec, bringing load power 2 to a stable state at 4.02 sec. Fig.12 depicts the use of FOFLC to manage power, battery power, and load powers. Fig.12 depicts a variation of grid voltage and current, respectively. The comparison of DC voltage regulation

Adaptive and the proposed controller are shown in Figure 12 and Fig.13, respectively.

The improved %SoC with FOFLC.It is observed that %SoC improved from 80.8% to 85.5% within the permissible time compared to adaptive FLC, and also BMS parameters are improved. The proposed controller mitigates source voltage with odd harmonics.

The proposed controller regulates voltage faster than the adaptive FLC controller quickly than adaptive FLC. In the proposed system, it is observed that the source current and the load current are well balanced and reduce distortions compared to the proposed controller.

Fig.14 shows the results of compensated load voltage. Fig. 15 indicates that simulation results of the proposed control strategy and compensated device inject voltage from phase to load voltage and a phase to load current.

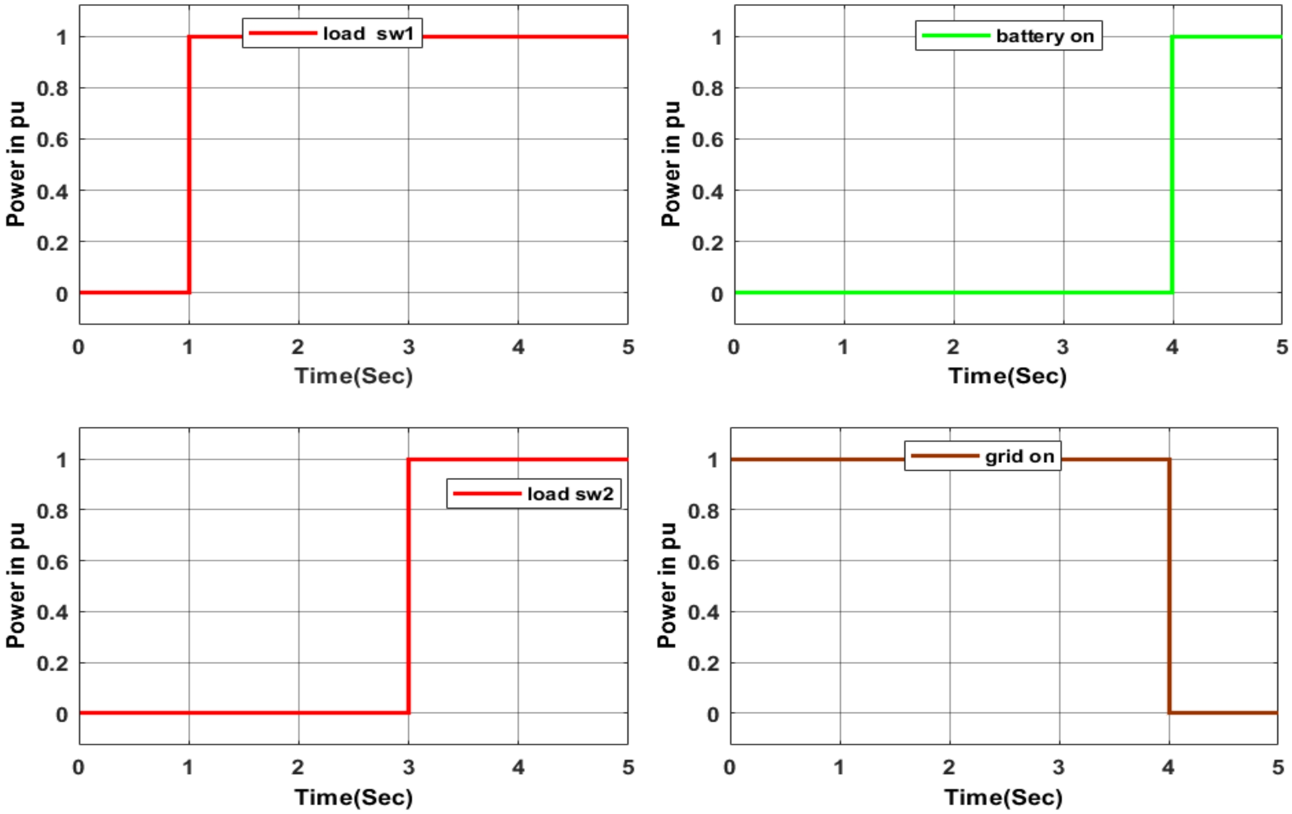


Fig. 10 Variation of power under variable conditions with FOFLC

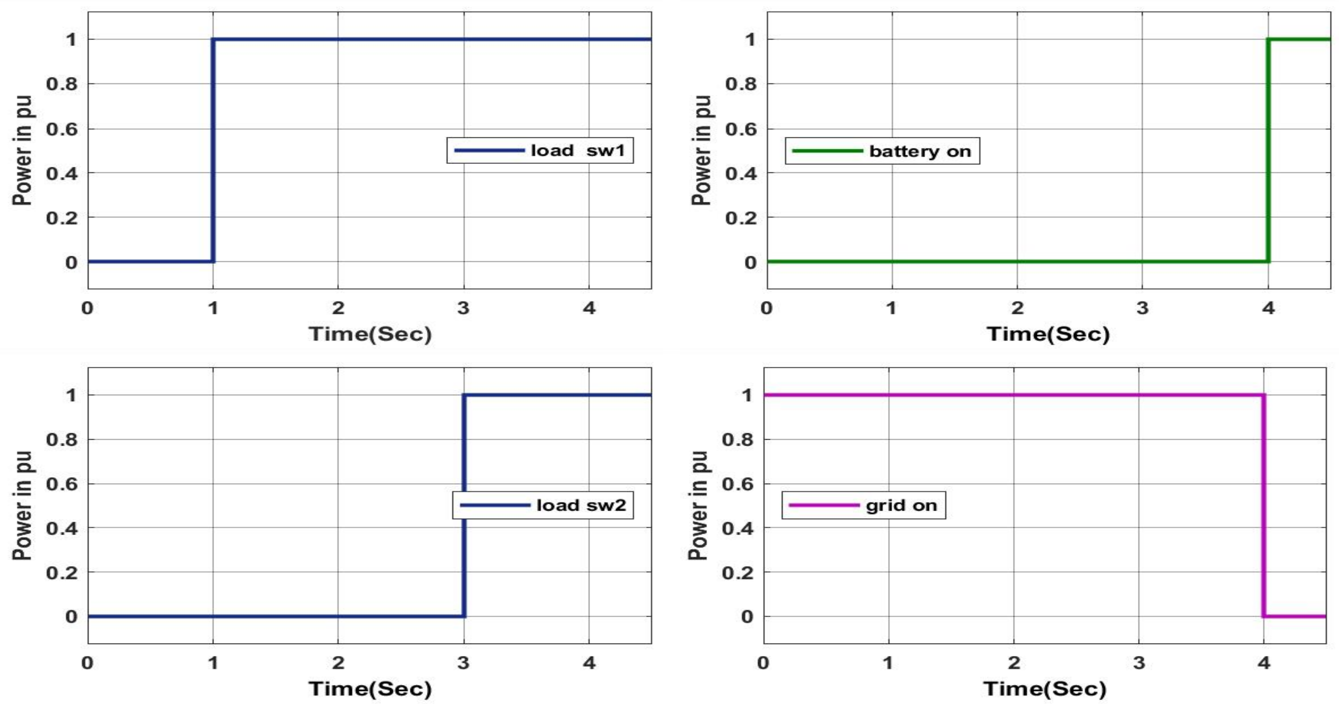


Fig. 11 Variation of power under variable conditions with adaptive FLC

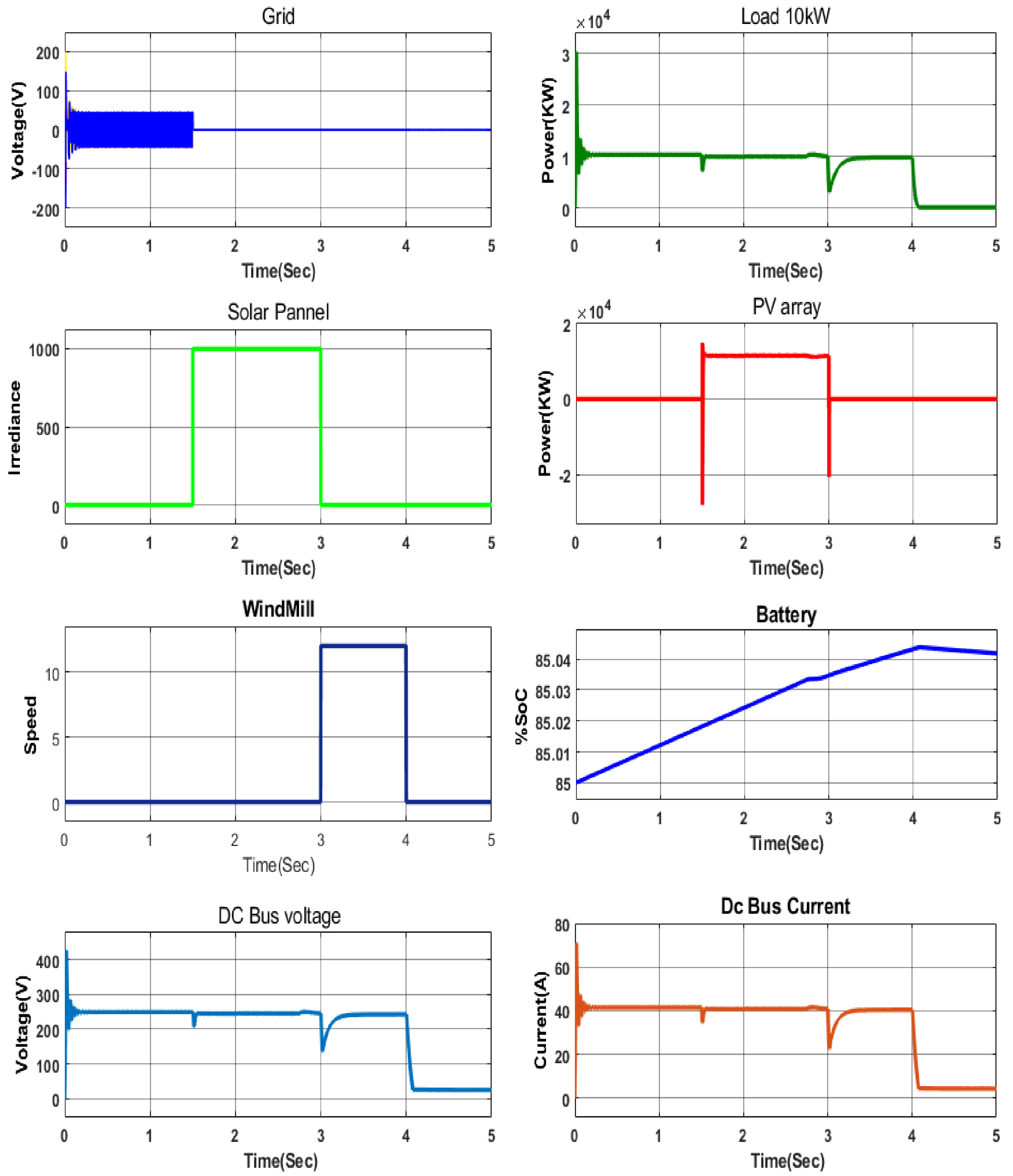


Fig. 12 Simulation Results of Grid power, Solar irradiance, wind speed, DC link Voltage, Load power. PV Power, % SoC and DC bus Current with Adaptive FLC

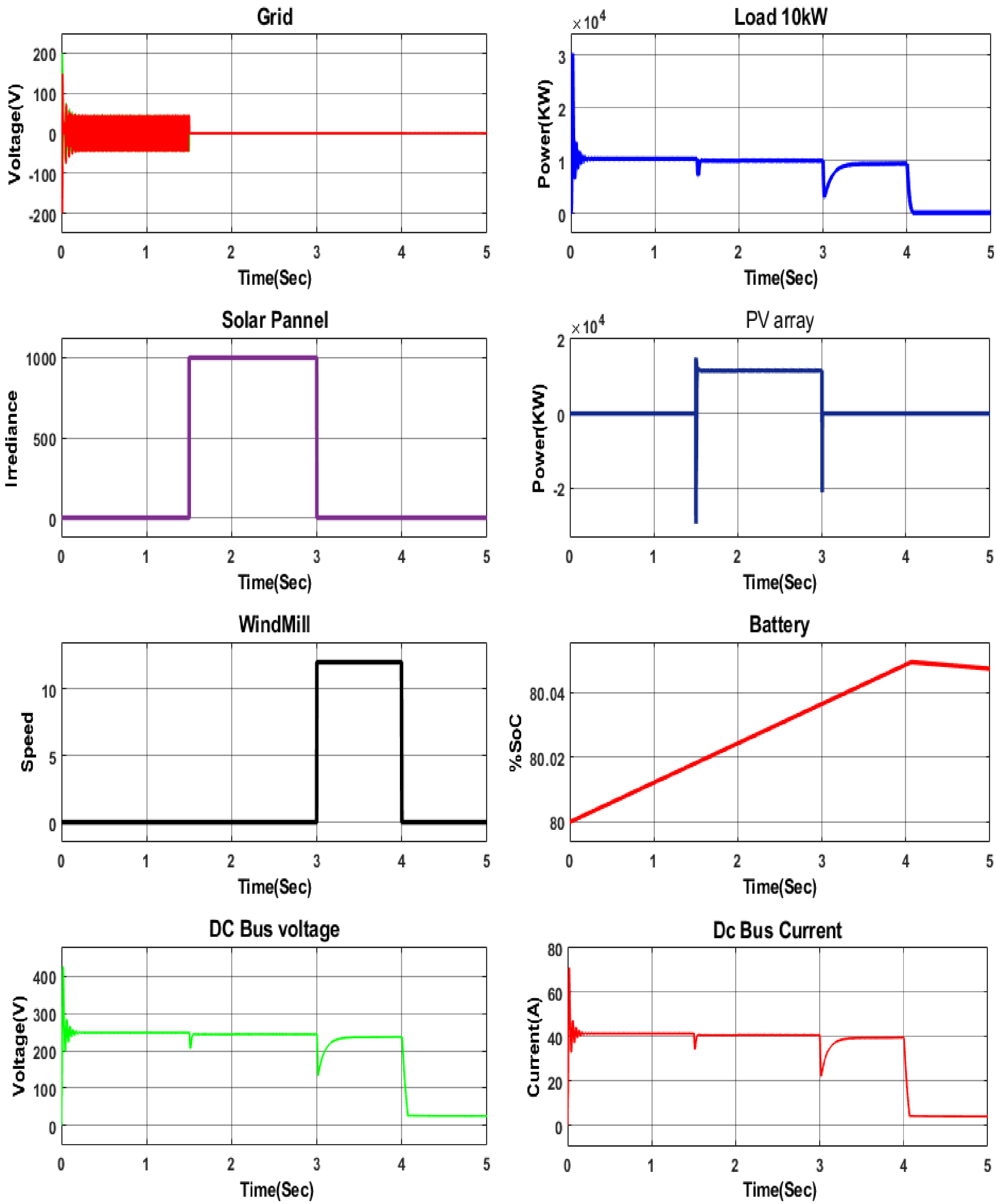


Fig. 13 Simulation Results of Grid power, Solar irradiance, wind speed, DC link Voltage, Load power. PV Power, % SoC, and DC bus Current with FOFLC

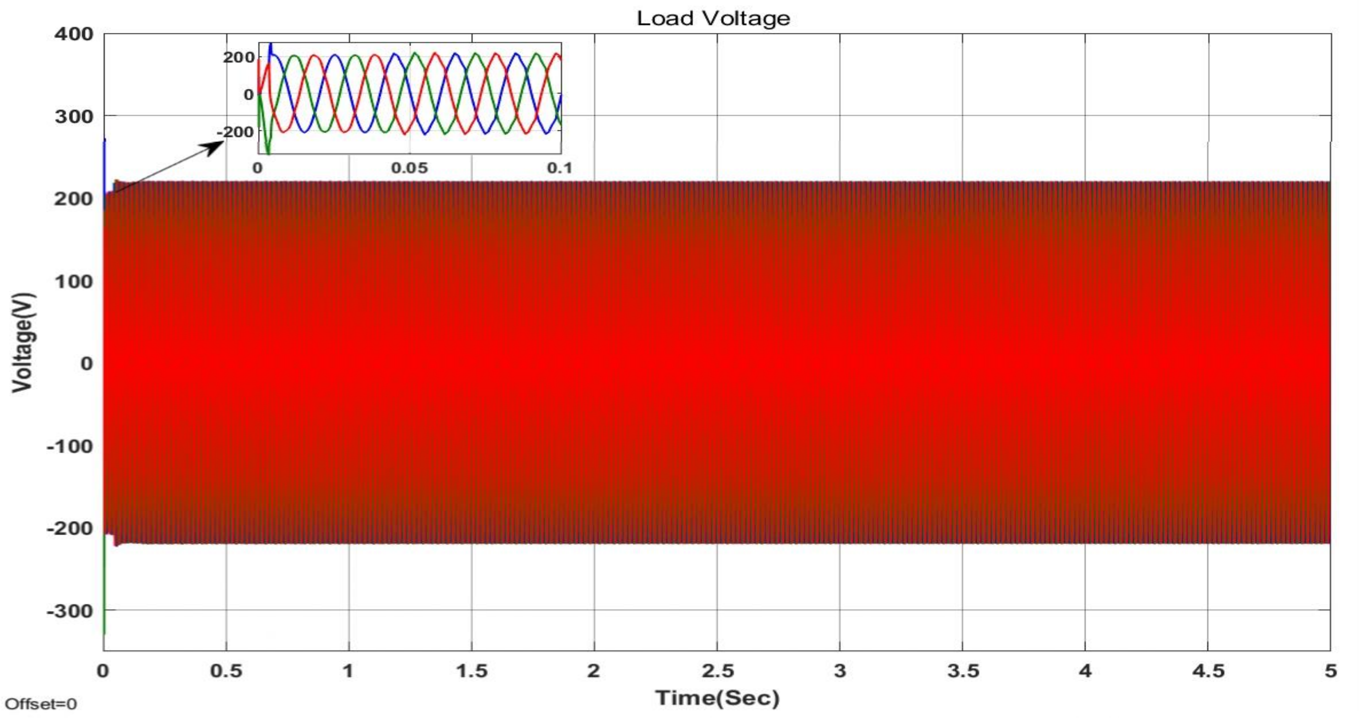


Fig. 14 Simulation Results of Load Voltage

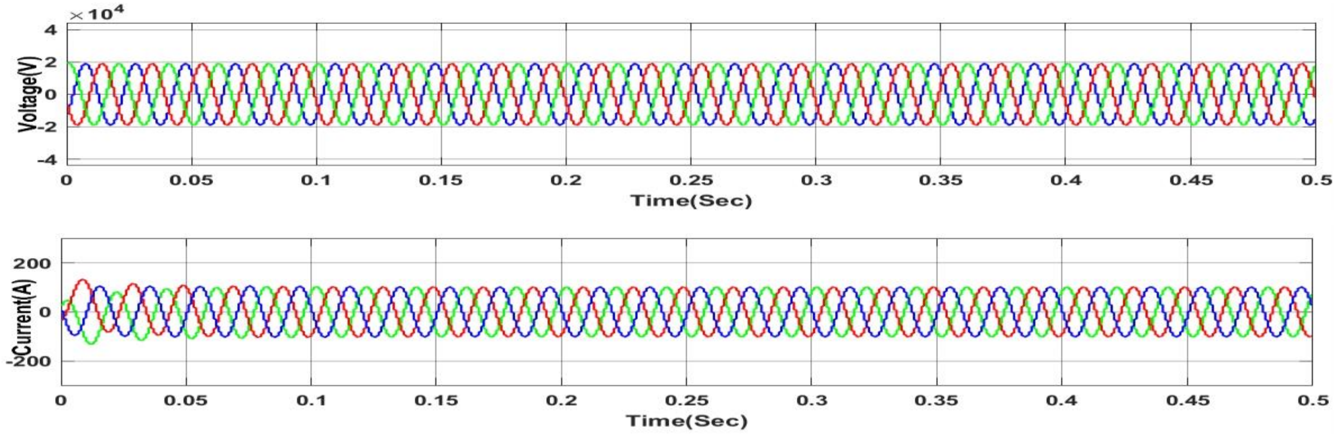


Fig. 15 Simulation Results source Voltage and Current

7. Conclusion

FOFLC-based EMS is designed for integrated MG and is connected to distribution power systems using MATLAB/SIMULINK. The advantage of EMS is to improve reliability by applying suitable FOFLC. The result shows that the transition period is shortened. The secondary objective is the efficiency of EMS. The third objective is monitoring MPP points that are carried out with the MPPT algorithm. In this paper, FOFLC is based on energy management systems and tracks the maximum power. P&O, incremental conductance methods are developed to enhance power quality and reduction of THD in MG's.

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