An efficient dynamic power management model for a stand-alone DC Microgrid using CPIHC technique

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ABSTRACT

The power generation using solar photovoltaic (PV) system in microgrid requires energy storage system due to their dilute and intermittent nature. The system requires efficient control techniques to ensure the reliable operation of the microgrid. This work presents dynamic power management using a decentralized approach. The control techniques in microgrid including droop controllers in cascade with proportional-integral (PI) controllers for voltage stability and power balance have few limitations. PI controllers alone will not ensure microgrid's stability. Their parameters cannot be optimized for varying demand and have a slow transient response which increases the settling time. The droop controllers have lower efficiency. The load power variation and steady-state voltage error make the droop control ineffective. This paper presents a control scheme for dynamic power management by incorporating the combined PI and hysteresis controller (CPIHC) technique. The system becomes robust, performs well under varying demand conditions, and shows a faster dynamic response. The proposed DC microgrid has solar PV as an energy source, a lead-acid battery as the energy storage system, constant and dynamic loads. The simulation results show the proposed CPIHC technique efficiently manages the dynamic power, regulates DC link voltage and battery's state of charge (SoC) compared to conventional combined PI and droop controller (CPIDC).

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1. INTRODUCTION

In the recent days, as the demand for energy is increasing at a faster rate, the focus of research is towards generation of energy using alternate sources of energy as well as generation of green energy [1], [2]. Integration of distributed energy resources (DER) into the conventional grid to reduce the demand and to improve the reliability of the system has gained popularity across the world [3]-[7]. With an advanced control system, a microgrid will be capable of operating in a coordinated manner and give optimized performance to its consumers. A DC microgrid architecture is as shown in Figure 1.

In this work, we have simulated a microgrid working in islanded condition, having lead acid battery as storage system and supplying the DC and AC loads through a voltage source converter. Incremental conductance MPPT algorithm has been incorporated for the solar array to extract maximum power. A CPIHC based DC-DC converter is used to connect the battery to the DC bus. The VSC is decoupled controlled to regulate the frequency and voltage of the AC side. The entire system is simulated in Simulink and the power waveforms of the solar array, load, battery, DC link voltage, voltage and current of the load are carefully analyzed. This system proves to be an economical alternative for the power supply in the near future with the growing popularity for renewable energy and rooftop solar PV generation in particular.

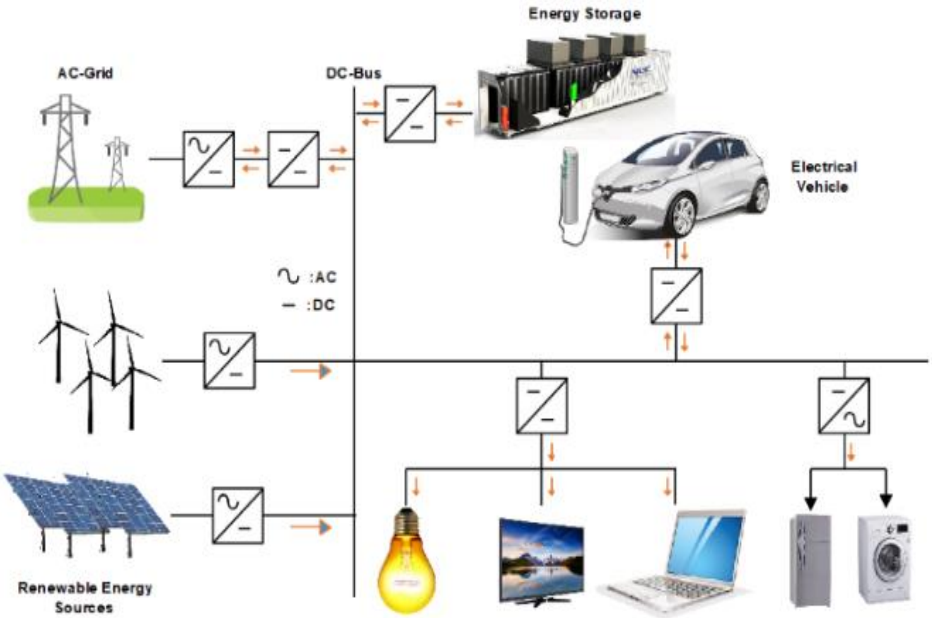

Figure 1. Fundamental structure of DC microgrid

Sedhom *et al.* [8] a protection scheme has been designed for a low voltage microgrid to ensure stability. SJha *et al.* [9] the authors have made a study on different control and communication techniques for an islanded microgrid. Different control techniques to improve voltage and frequency regulation, maintain power balance and ensure stability of the microgrid have been discussed in [10]-[14].

The PI controller is a classical controller and has been widely used in the control of microgrid. It finds application in many process control industries due to its robust performance. The DC offset gets removed by the integral action in the PI algorithm. The PI controller has slower time response which reduces the maximum overshoot and improves the damping and causes zero offset values. The major limitation of this controller is the increase in rise time. In the microgrid, the error signal is the difference between the measured voltage and the desired voltage. The PI controller can regulate the frequency at AC bus of the microgrid and causes very little oscillations when the load fluctuates [15], [16]. For a PI Controller the standard equation used to denote the output signal is given in (1).

$$y(t) = y_o(t) + K\,e(t) + \frac{K}{\tau}\int_0^t e(t)dt \tag{1}$$

Where y(t) is the desired output and fed into the system or process as the modulated input, $y_o(t)$ is the actual output of the system, e(t) is the error signal, K is the controller gain and τ is the integral time constant of the controller. Figure 2 shows the PI control implemented in PWM Voltage Source Inverters, where outer power control loop generates reference current values(i'_d and i'_q) and inner current control loop generates reference voltage values (v'_d and v'_q). These reference values are compared with actual value to generate error signals and converted to 'abc' frame to generate gating signals.

Hysteresis controller is a simple non-linear controller with no complex control circuitry involved for the current control and has fast response. It employs feedback current control method. The In the controller action, a VSI makes the grid current to follow a reference pattern. The error generated by the controller produces the switching waves, as shown in Figure 3. Here, currents i'_d and i'_q are converted into 'abc' frame i'_a, i'_b and i'_c using dq/abc converter. An error signal is generated by comparing these reference currents with their actual values. The error signal is fed to the hysteresis controller to generate gating pulses. A minimum width hysteresis band is maintained in order to minimize the error [17]-[19].

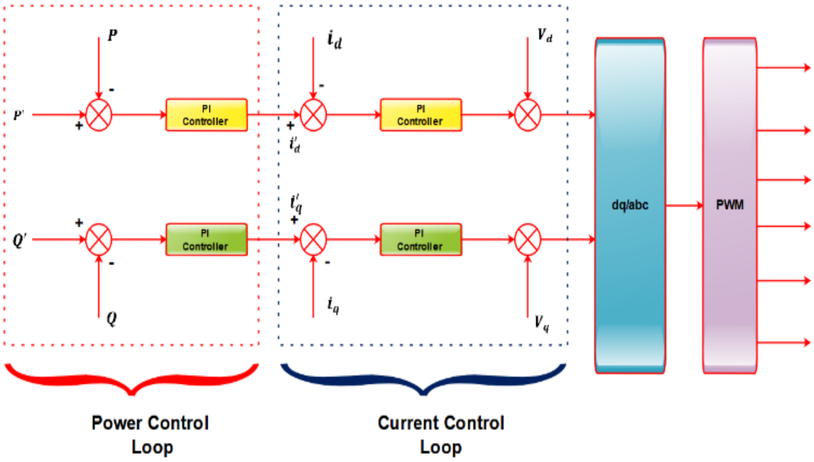

Figure 2. Double loop control scheme using PI controller

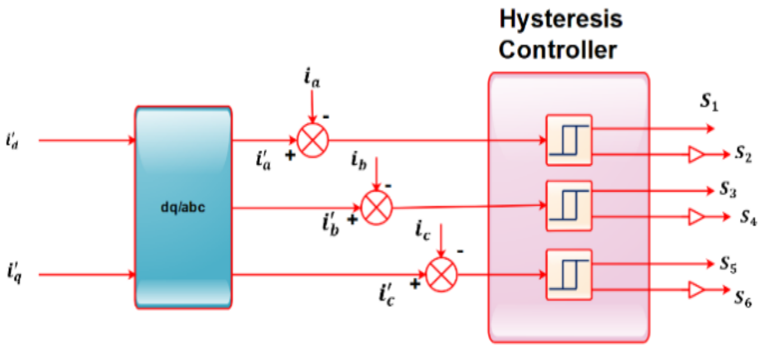

Figure 3. Generation of switching pulses using hysteresis controller

2. PROPOSED MODELING OF STAND-ALONE DC MICROGRID

The proposed stand-alone DC microgrid architecture is shown in Figure 4. The design is simulated in MATLAB/Simulink to observe the working and to analyze the system performance.

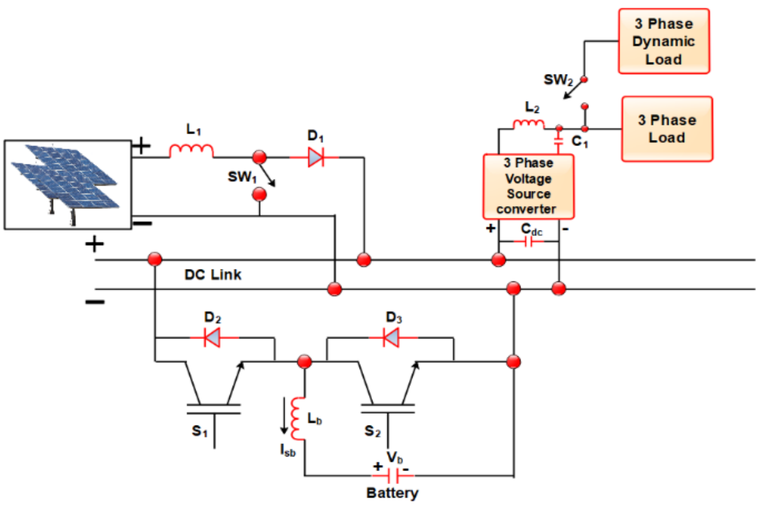

Figure 4. Architecture of proposed stand-alone DC microgrid

2.1. Modeling of solar PV panel

Solar PV finds extensive application in generation of electricity, ranging from residential application to large power plants. Work on various methods of modelling the PV panel has been done in literature [20], [21]. Figure 5 shows the equivalent circuit of a practical solar cell used for modelling of PV array. Here, I_{PV} indicates photo current of solar cell in ampere, R_{sh} is the shunt resistance of the solar cell, R_j is the non-linear impedance of the p-n junction, R_s is series resistance of the solar cell. The total load current is given by (2).

$$I = n_p I_{PV} - n_p I_{rs}[\exp(\frac{qV}{kTAn_s}) - 1] \quad (2)$$

Where I is the PV array output current in amperes, V is the PV array output voltage, n_s represents number of cells connected in series, n_p represents number of modules connected in parallel; q gives the charge of electron, k is Boltzmann constant, A is the p-n junction ideality factor (determines the cell deviation from ideal p-n junction characteristics, ranging from 1 to 5, 1 being the ideal value); T represents cell temperature in Kelvin; I_{rs} is cell reverse saturation current in ampere.The cell reverse saturation current I_r varies with changes in temperature according to the (3).

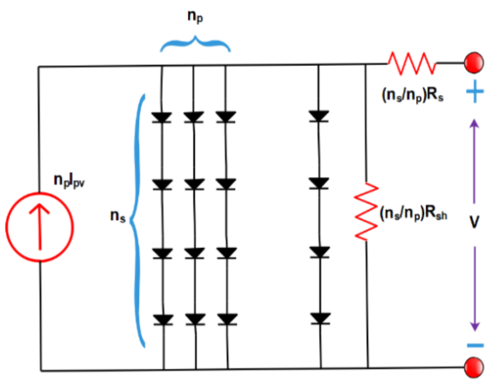

Figure 5. Equivalent circuit of solar cell

$$I_r = I_r' \left(\frac{T}{T_r'}\right) [\exp\left(\frac{qE_g}{kA}\right) (\frac{1}{T_r'} - \frac{1}{T_r})] \quad (3)$$

Where T_r' indicates the cell reference temperature (298K), I_r' represents reverse saturation current at Tr′ , E_g gives the band-gap energy of semiconductor used in cell. As shows (4) gives the value of solar PV current (I_{PV})in ampere.

$$I_{PV} = I_{SCref} + k_i(T - T_r') (\frac{S}{100}) \quad (4)$$

Where I_{SCref} indicates cell short circuit current at reference temperature and radiation; k_i is the short circuit current co-efficient; S represents solar radiation in mW/cm2. The power from the PV array can be calculated using the (5) and (6).

$$P = VI \quad (5)$$

$$P = n_p I_{PV} V - n_p I_r V \left[exp\left(\frac{qV}{kTAn_s} - 1\right)\right] \quad (6)$$

2.2. Maximum power point tracking algorithm

Incremental conductance (IC) has been implemented to compute and extract maximum power from the solar PV. The technique is simple and offers better performance in comparison with the perturb and observe MPPT algorithm. The oscillation about the maximum point is less and has faster response in dynamic conditions. The flowchart in Figure 6 shows the implementation of IC MPPT algorithm.

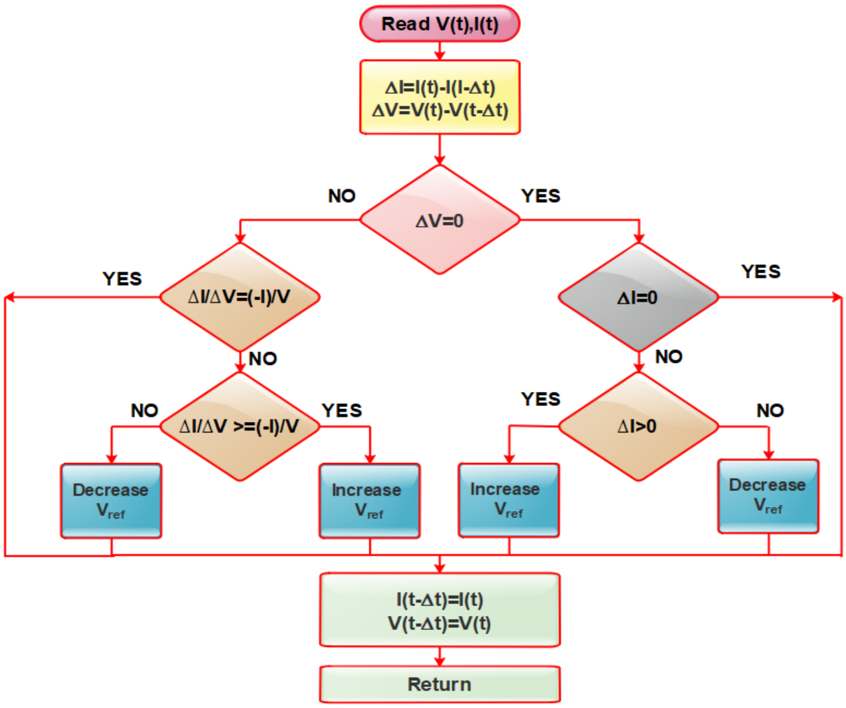

Figure 6. Flowchart of IC MPPT algorithm

2.3. Modeling of boost converter for solar PV system

A DC-DC boost converter acts as an interface between solar PV to the DC bus. The converter along with the Incremental Conductance algorithm helps in extracting maximum power from the solar PV, boosts the output voltage of the solar PV and connects the solar PV system to DC bus. The values of inductance L and capacitance C is given by (7) and (8) respectively.

$$L = \frac{V_{ip}(V_{op}-V_{ip})}{f_{sw}\times\Delta I\times V_{op}} \quad (7)$$

$$C = \frac{I_{op}(V_{op}-V_{ip})}{f_{sw}\times\Delta V\times V_{op}} \quad (8)$$

Where V_{ip} is the input voltage in volts, V_{op} represents the output voltage in volts, f_{sw} is the switching frequency in hertz, ΔV represents the voltage ripple and ΔI represents the current ripple.

2.4. Modelling of battery energy storage

As renewable energy resources are dilute and intermittent in nature, energy storage system plays a vital role in storing the generated energy. Lead acid batteries are the most popularly used energy storage system, providing considerable performance in a microgrid system [22]. The circuit representation of a battery is shown in Figure 7. The battery voltage is non-linear in nature and depends on the electrolyte temperature T and the battery's state of charge SoC as given by the (9).

$$V_m = V_{mo} - K\,[273 + T]\,[1 - SoC] \quad (9)$$

Where V_m represents open circuit voltage in volts, V_{mo} gives open circuit voltage at full charge in volts, K is the constant in volts/°C, T is the electrolyte temperature in °C, SoC represents state of charge of battery [23]-[29]. The approximated value of resistance as seen from battery terminals is assumed to be temperature independent and is a function of State of Charge(defined as ratio of battery's current capacity to the nominal capacity) of the battery and given by (10)

$$Rs = Rsref\,[1 + A\,(1 - SoC)] \quad (10)$$

Where R_{sref} is the value of Rs for SoC=1 in ohms, A is a constant and SoC is the battery SoC. The maximum SoC limit is 80% and minimum SoC is 20%.

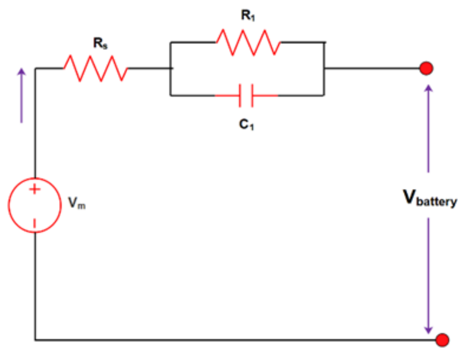

Figure 7. Battery equivalent circuit

2.5. Control algorithm for battery converter system

Bidirectional converter is used for the battery and the control algorithm regulates the DC link voltage if the load or solar irradiance varies. If the demand on the system decreases than the solar PV generated power, then the DC link voltage increases. If the demand it is more than the solar PV generated power or there is a decrease in irradiance, then the DC link voltage decreases affecting the performance of the three phase voltage source converter connected in the grid.

The control algorithm is aimed to improve the performance of the battery, regulate the DC link voltage and improve the steady state performance of the grid by controlling the gating pulses to the battery. The proposed control technique is implemented as shown in Figure 8. It makes a comparison between the actual and reference values of dc link voltage and generates error signal, which is fed to the PI controller. The total reference current obtained from PI controller is filtered using a moving average filter. A ramp rate limiter limits the charge/discharge rate and provides reference value of battery current, as shown in Figure 8 (a). This reference value of battery current I_{batRef} is compared with actual value I_{bat} in a hysteresis control block to generating the switching pulses for switches in converter circuit, as shown in Figure 8 (b). The bidirectional converter interfaces the battery with the DC link and efficiently supplies/absorbs the deficit/excess power to regulate the dc link voltage. The converter designed is a half bridge buck boost hysteresis controlled converter.

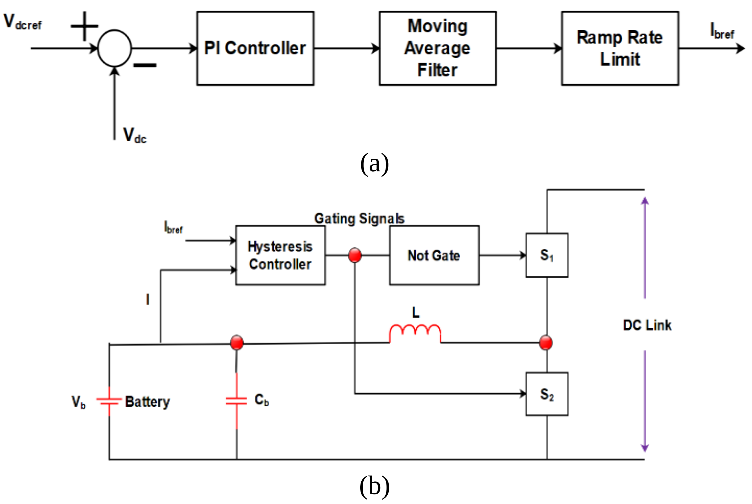

Figure 8. (a) generation of reference battery current and (b) generation of switching pulses for the battery circuit

3. SIMULATION RESULTS

The microgrid system is designed with a 10kW solar PV system, connected to DC link through a boost converter. The DC link is regulated at 760 V. Lead acid battery is used as storage system, connected through a bidirectional DC-DC converter to the DC link. Constant and dynamic resistive loads are applied to the system. The load occurring on the system is varied at 0.3, 0.6 and 0.8 seconds. Table 1 shows the details of the parameter values used for simulation of the grid.

Table 1. Proposed system parameter details

SI.No	Particular	Rating
1.	Maximum power of solar PV array	10 kW
2.	Voltage at maximum power V_{MP}	445V
3.	Current at maximum power I_{MP}	22.4719 A
4.	Rated capacity	200Ah
5.	State of Charge	80%
6.	DC Link Voltage	760V

The variations in DC link voltage, battery voltage and current, battery SoC is observed. Figure 9 shows the variation in power of solar PV, load and battery with respect to time. Figure 10 shows regulation of DC link voltage irrespective of the change in load. Figures 11, 12, 13 show the variations in battery current, voltage and SoC with respect to time. The graphs show quick and smooth transition when load changes.

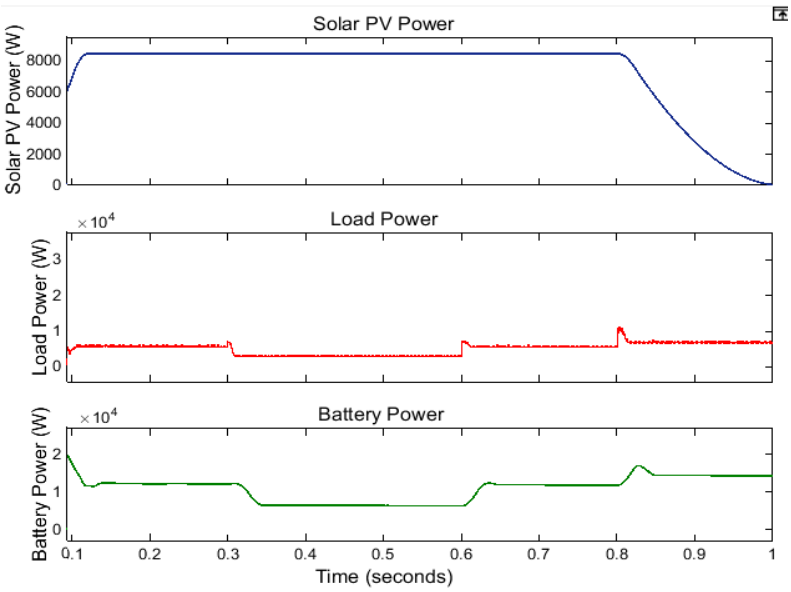

Figure 9. Variation of solar power, load and battery power with respect to time

Figure 14 shows the active and reactive power of inverter circuit and constant frequency of inverter. Figure 15 shows the load voltage regulation and variation of load current due to dynamic load. The load voltage is maintained constant and current varies according to variation in load. The droop control cannot perform effectively in minimizing circulating currents where critical communication does not exist. The voltage and frequency of such system vary due to load variation. In comparison to such systems, the proposed microgrid has acceptable performance in terms of dynamic power sharing as well as maintaining voltage and frequency of the microgrid under variation in load. The system can be further improved to minimize power fluctuations by incorporating economically feasible hybrid storage system. Figure 16 and 17 show the change in battery current and voltage due to dynamic load variation. As the load connected to the grid changes, variation in battery voltage and current is observed. The proposed technique offers better dynamic response in comparison to the conventional CPIDC technique. The settling time decrease with smooth transition with respect to load variation.

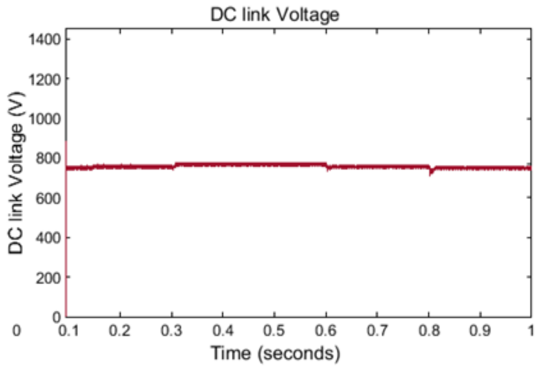

Figure 10 Regulation of DC link voltage irrespective of load variation

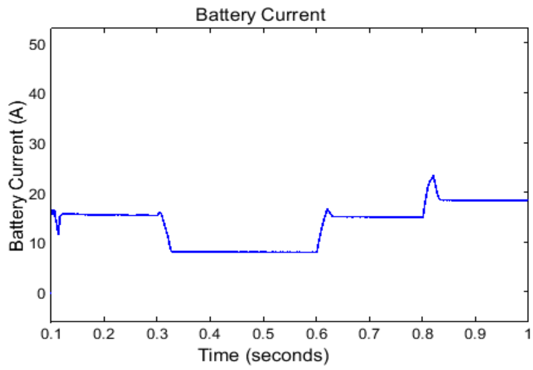

Figure 11. Variation in battery current due to variation in dynamic load

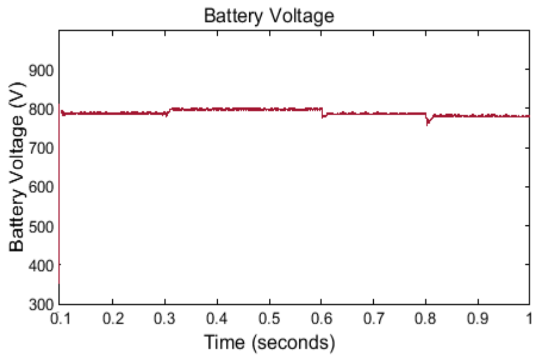

Figure 12. Battery voltage variation with respect to time

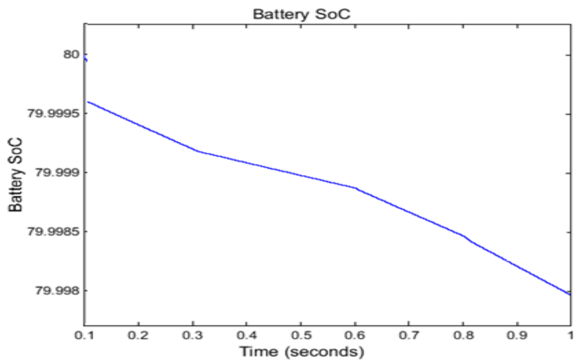

Figure 13. Battery State of Charge variation with respect to dynamic load variation

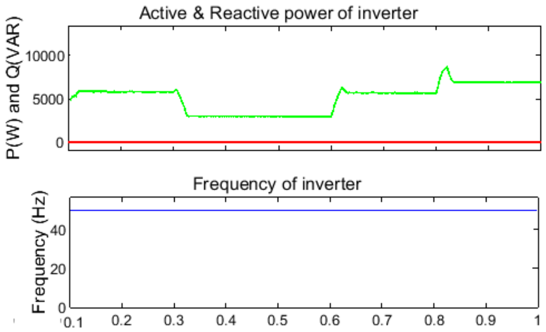

Figure 14. Variation of active and reactive power of inverter and Inverter frequency with respect to time

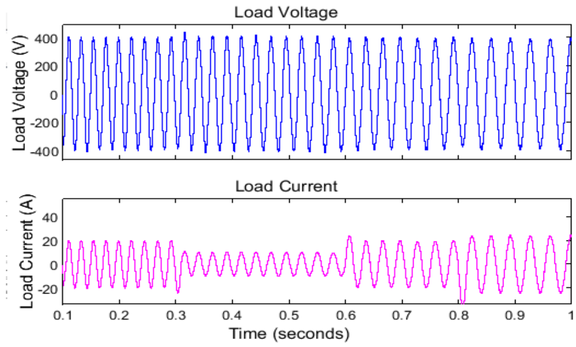

Figure 15. Regulation of load voltage and variation of current due to dynamic load

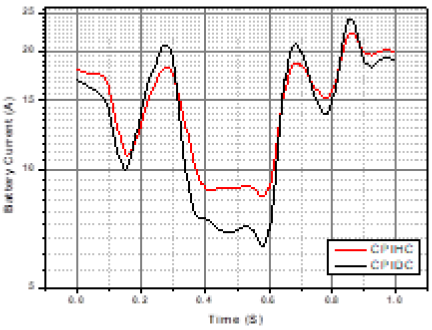

Figure 16. Comparison of variation in battery current with systems using CPIHC and CPIDC

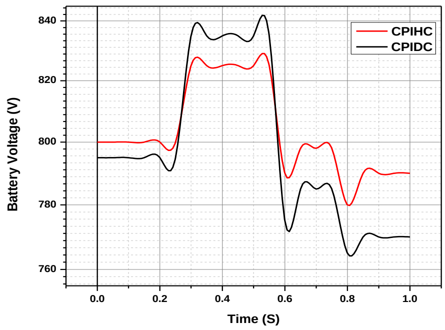

Figure 17. Comparison of variation in battery voltage with systems using CPIHC and CPIDC

4. CONCLUSION

The simulation results show that the proposed control technique has an improved stable operation compared to conventional CPIDC controller. The higher value of droop parameters lead to increase in DC link voltage variation which is overcome by the proposed CPIHC technique. The dynamic response of the grid shows an improvement with the proposed technique. In comparison to conventional method, the system has better DC link voltage regulation and battery current control. The system has smooth power sharing. The transient response affects the life of battery since it has low power density. The proposed system considers resistive load for analysis. The performance of the proposed microgrid can be further improved by incorporating super capacitor and making the energy storage system hybrid.

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