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Active Power Management Of Fuel Cell, Photovoltaic Unit, And Supercapacitor Power Conversion System In A Medium Voltage Microgrid

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***Abstract*— This paper presents modeling, active power management strategy, and implementation of a fuel cell, photovoltaic, and supercapacitor power conversion system in MATLAB. The microgrid includes two distributed generation (DG) units. Each DG unit consists of a fuel cell (FC), photovoltaic unit (PV) and supercapacitor (SC). The supercapacitor energy storage compensates the shortage power of FC stack, PV unit and the load demand. The output of DG unit is connected to grid using inverter. Load changes are applied both for balanced and unbalanced conditions. The frequency deviation is fed to adaptive proportional resonance controller which adapts to the changes in frequency. This results in eliminating steady state error and output impedance of DG unit is decreased thereby reducing low frequency oscillations in the power components of the DG units. The system is modelled and simulated using software. The dynamic response of the DG units to both balanced and unbalanced load changes is investigated using software.**

***Index Terms*—Fuel Cell (FC), Photovoltaic Unit (PV), distributed generation (DG), microgrid, supercapacitor (SC).**

INTRODUCTION

Distributed generation, also called on-site generation, dispersed generation, embedded generation, decentralized generation, or distributed energy, generates electricity from many small energy sources. Most countries generate electricity in large centralized facilities, such as fossil fuel, nuclear, large solar power plants or hydropower plants. These plants have excellent economies of scale, but usually transmit electricity long distances and can negatively affect the environment. Distributed generation (DG) allows collection of energy from many sources and may give lower environmental impacts and improved security of supply.

The present work proposes active power management strategy for medium voltage islanded microgrid including hybrid power conversion system. A hybrid power system consists of a combination of two or more power generation technologies to make best use of their operating characteristics and to obtain efficiencies higher than that could be obtained from a single power source. The hybrid power system includes fuel cell, photovoltaic unit and supercapacitor. Since fuel cells directly convert fuel and an oxidant into electricity through an electrochemical process, they produce very low emissions and have higher operating efficiencies**.** The fuel cell used is of proton exchange membrane type, i.e. PEMFC. Due to the low working temperature (80–100 degree C) and fast start up, proton exchange membrane (PEM) fuel cell power plants are one of the promising candidates for residential and commercial applications. Supercapacitor is used as energy storage device.

Fuel cell power plants are electrochemical devices that convert the chemical energy of a reaction directly into electrical energy. This paper focuses on designing and dynamic modeling of a combined PEM fuel cell and ultracapacitor bank system [1]. Different energy sources and converters need to be integrated to meet sustained power generation. This paper focuses on the integration of photovoltaic (PV) unit, fuel cell (FC) and ultracapacitor systems for sustained power generation [2].

Many of the energy sources such as the fuel cells, photovoltaic unit, and wind turbines are connected to the grid via power electronic converters to improve the system integrity, reliability, and efficiency. This paper describes the modeling of power generation system consisting of fuel cell, photovoltaic unit, supercapacitor and converters which are used for connecting the fuel cell, photovoltaic unit and supercapacitor to the dc-link [3].

Today, new advances in technology and new directions in electricity regulation encourage a significant increase of distributed generation (DG) resources around the world. In this paper, a new control strategy for voltage control is proposed [4]. The proposed strategy adaptively regulates the load voltage.

MICROGRID SYSTEM CONFIGURATION

A microgrid is an electrical system that includes multiple loads and distributed energy resources that can be operated in parallel with the broader utility grid or as an electrical island. In the present work, it is assumed that the microgrid system operates in the islanded mode. There are two DG units each comprising of a fuel cell, photovoltaic unit and supercapacitor. A combination of balanced and unbalanced loads are supplied through feeders F1, F2, and F3. The three-wire DG units are connected to feeders through step-up transformers. Each DG unit can supply any amount of real/reactive power within its prespecified limits. The FC stack and SC module are connected to the dc-link by unidirectional and bidirectional full-bridge dc/dc converters respectively.

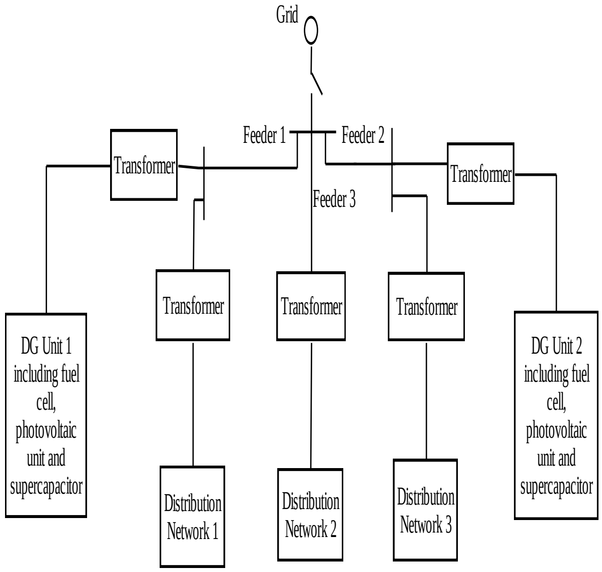


Fig 1. System configuration of microgrid

A. Distributed Generation Unit

The microgrid includes two DG units. Each DG unit consists of a fuel cell, photovoltaic unit, and supercapacitor module. Dc/dc converters are used for boosting the voltage of fuel cell and photovoltaic unit.

B. Fuel Cell

A fuel cell is an electrochemical device which converts the chemical energy of pure hydrogen into electricity through a chemical reaction with oxygen. Fuel cells are classified on the basis of the type of electrolyte material being used, the Proton Exchange Membrane Fuel Cell (PEMFC) and Solid Oxide Fuel Cell (SOFC). The present work uses PEMFC type. A typical fuel cell consists of two electrodes (anode and cathode) where the reactions take place.

Proton exchange membrane (PEM) fuel cells are gaining importance as the fuel cell for vehicular applications because of their low operating temperature, higher power density, specific power, longevity, efficiency, relatively high durability, and the ability to rapidly adjust to changes in power demand. PEM fuel cells can be started easily at ordinary temperatures and can operate at relatively low temperatures, below 100 °C. Since they have relatively high power density, the size could be smaller. Because of the simple structure compared to other types of fuel cells, their maintenance could be simpler. They can withstand the shock and vibrations of the automotive environment because of their composite structure.

C. Photovoltaic Unit

Photovoltaics is the art and science of turning sunlight directly into electricity. The word comes from “photo” meaning light, and “voltaic” referring to electricity or voltage. A photovoltaic system consists of many cells connected in series and parallel. The PV power extracted from solar irradiation mainly depends upon four quantities namely conversion efficiency, measured area, solar irradiation and ambient temperature.

Solar cell is basically a p-n junction fabricated in a thin wafer or layer of semiconductor. The electromagnetic radiation of solar energy can be directly converted to electricity through photovoltaic effect. Since a typical PV cell produces less than 2W at 0.5V approximately, the cells must be connected in series configuration on a module to produce enough high power. A PV array is a group of several PV modules which are electrically connected in series and parallel circuits to generate the required current and voltage.

D. Supercapacitor

Supercapacitors store electrical energy by accumulating charge on two parallel electrodes separated by a dielectric material. The capacity represents the relationship between the electric charge stored in the capacitor and voltage between the two electrodes of the capacitor.

E. Converter

It is necessary to adapt the output voltage of the fuel cell, photovoltaic unit and supercapacitor units to the desired dc-link voltage and smooth the output current. A boost-based dc/dc converter is often utilized as an fuel cell converter and photovoltaic converter. Supercapacitor energy storage connects to the dc-link by using bidirectional converter.

OPERATION PRINCIPLE

The proposed control strategy comprises: i) power management of the hybrid power conversion system; ii) microgrid voltage control; and iv) power sharing among the DG units of the microgrid. The supercapacitor converter control system regulates the dc-link voltage, and the fuel cell converter control system provides the dc-link power demand. The measured voltage of the supercapacitor module will have an undesirable effect on the performance of the control strategy due to the deeply charge or discharge of the SC module during load variations. The supercapacitor voltage control loop uses the dc-link voltage as a feedback signal. The fuel cell current control loop uses a feedback from the fuel cell and dc-link current. In the FC stack, hydrogen flow and FC current are two important parameters that should be appropriately regulated in the control loop.

SYSTEM MODELING

A. *Fuel Cell Modeling*

The performance of fuel cell is affected by several operating variables. This model is based on simulating the relationship between output voltage and partial pressure of hydrogen, oxygen, and water. The Nernst's equation and Ohm's law determine the average voltage magnitude of the FC stack. The assumptions for the model are as follows:

- The gases are ideal
- The fuel cell is fed with hydrogen and air
- The electrode channels are small enough that the pressure drop across them is negligible
- The ratio of pressures between the inside and outside of the electrode channels is large enough to assume choked flow
- The fuel cell temperature is stable
- The Nernst equation applies
- The losses are as follows: Ohmic, Activation, Mass Transport.

The relationship between the molar flow of any gas (hydrogen) through the valve and its partial pressure inside the channel can be expressed as

$$\frac{q_{H2}}{p_{H2}} = \frac{K_{an}}{\sqrt{M_{H2}}} = K_{H2} \qquad (1)$$

q_{H2} = molar flow of hydrogen.
p_{H2} = hydrogen partial pressure.
K_{an} = anode valve constant.
M_{H2} = molar mass of hydrogen.
K_{H2} = hydrogen valve molar constant.

For hydrogen molar flow, there are three significant factors: hydrogen input flow, hydrogen output flow, and hydrogen flow during the reaction.

The relationship among these factors can be expressed as

$$d/dtp_{H2} = RT/V_{an}(q_{H2}^{in}-q_{H2}^{out}-q_{H2}^{r}) \qquad (2)$$

R = universal gas constant.
T = absolute temperature.
V_{an} = volume of the anode.
q_{H2}^{in} = hydrogen input flow.
q_{H2}^{out} = hydrogen output flow.
q_{H2}^{r} = hydrogen flow that reacts.

The flow rate of reacted hydrogen is given by

$$qH2r = \frac{NoI_{FC}'}{2F} = 2K_rI_{FC}' \qquad (3)$$

N_o = number of series fuel cells in the stack.
I_{FC}' = *fuel cell feedback current.*
F = Faraday's constant.
K_r = modeling constant

Applying Laplace transform, the hydrogen partial pressure can be obtained in the *s* domain as

$$p_{H2} = \frac{1/K_{H2}}{1+\tau_{H2}s}(q_{H2}in - 2K_rI_{FC}') \qquad (4)$$

$$\tau_{H2} = \frac{V_{an}}{K_{H2}RT} \qquad (5)$$

FC output voltage may be expressed as

$$V_{cell} = E + \eta_{act} + \eta_{ohmic} \qquad (6)$$

$$\eta_{act} = -B\ln(CI_{FC}') \qquad (7)$$

R^{int} = fuel cell internal resistance

B and C are constants to simulate the activation overvoltage in PEMFC system

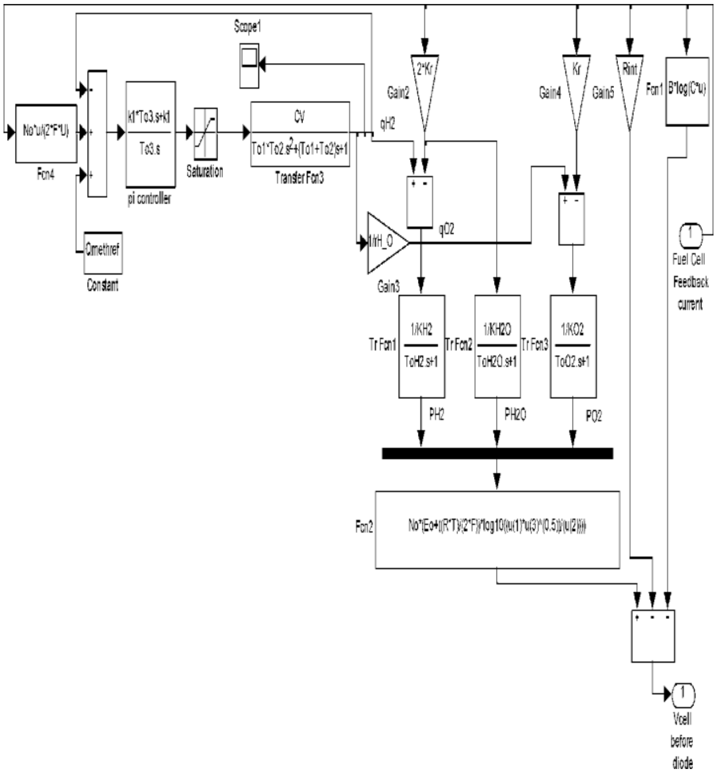
η_{act} = activation over voltage
η_{ohmic} = ohmic over voltage

The Nernst's instantaneous voltage may be expressed as

$$E = N_o[E_o + \frac{RT}{2F}\log[\frac{p_{H2}}{pH_20}\sqrt{P_{O2}}]] \qquad (8)$$

N_o = number of series fuel cells in the stack
E_o =standard no load voltage
p_{H2} =hydrogen partial pressure
P_{O2} = oxygen partial pressure
pH_20 = water partial pressure

DYNAMIC MODEL OF FUEL CELL



B. *Photovoltaic Unit Modeling*

The terminal equation for the current and voltage of the PV array is

$$I = N_p I_{PH} - N_p I_s [\exp\{q(V / N_s + IR_s) / N_p) / kT_c A\} - 1] \quad (9)$$

I_{PH} is light generated current or photon current.
I_s is cell saturation of dark current
T_c is cell's working temperature
q is electron charge
k is Boltzmann's constant.
The photon current mainly depends on the solar insolation and cell's working temperature, which is described as

$$I_{PH} = [I_{sc} + K1(T_c - T_{ref})]\lambda \quad (10)$$

I_{sc} is cell's short circuit current
K1 is cell's short circuit current temperature coefficient
T_{ref} is cell's reference temperature
λ is solar insolation
The cell's saturation current varies with the cell temperature which is expressed as
$Is=I_{RS}(T_c/T_{ref})^3\exp[qE_g (1/T_{ref} - 1/Tc)]/kA$
I_{RS} is cell's reverse saturation current at a reference temperature.
E_g is the band-gap energy of the semiconductor used in the cell.
k is Boltzmann's constant
A is an ideal factor
The reverse saturation current at a reference temperature may be expressed as

$$I_{RS} = I_{sc} / [\exp(qV_{oc} / N_s kT_c A) - 1] \quad (11)$$

V_{oc} is open circuit voltage

C. *Supercapacitor Modeling*

The model consists of a capacitance, series equivalent resistance (ESR) representing charging and discharging resistance, and an equivalent parallel resistance (EPR) representing the self-discharging losses. The classical equivalent circuit of the supercapacitor is shown in figure. Since the EPR models leakage effects and influences long-term energy storage performance of the supercapacitor, only the ESR will be taken into account. The supercapacitor energy storage connects to the dc-link by using bidirectional converter. The classical equivalent circuit of the supercapacitor is shown in figure 2.

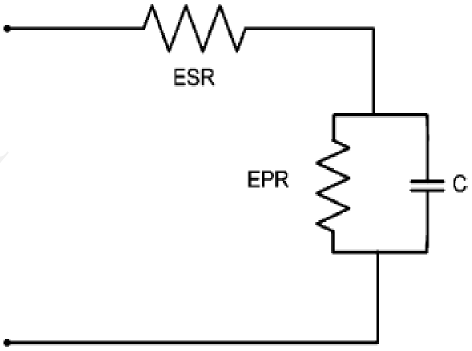


Fig 2. Equivalent model of supercapacitor

ESR- equivalent series resistance
EPR- equivalent parallel resistance

PROPORTIONAL-RESONANT CONTROLLERS

The basic functionality of the proportional-resonant (PR) controller is to introduce an infinite gain at a selected resonant frequency for eliminating steady state error at that frequency, and is therefore conceptually similar to an integrator whose infinite DC gain forces the DC steady-state error to zero. The resonant portion of the PR controller can therefore be viewed as a generalised AC integrator. Due to its superior performance when regulating sinusoidal waveforms and the possibility to compensate for low order harmonics, Proportional Resonant (PR) controller is implemented in a grid connected system. With proportional resonant controllers, the shortcomings associated PI controllers like steady-state error for single-phase converters and need of decoupling for three-phase converters can be reduced.

The P+ Resonant controller can be defined as $G(s) = K_p + K_i(s/(s**2+\omega**2))$ where K_p is proportional gain, K_i is integral gain and ω is resonant frequency.

ADAPTIVE PR CONTROLLER

Adaptive PR controller is used for adapting the frequency to that frequency where the steady state error is eliminated. The PR controller has infinite gain at a selected resonant frequency. Whenever there are frequency deviations, the adaptive PR controller is used for adapting the frequency to the resonant frequency.

The PR controller is designed using MATLAB tool. The designed controller provides good robust stability margins for the overall closed loop system. The PR controller can be considered as a series connection of a fixed part C(s) and a parameter dependent part C_{AD}(s).

$$C_{AD}(s) = \frac{1}{(s**2+(2*\omega_{cut}*s)+\omega**2)}$$

where ω_{cut} is cut-off frequency.

Based on the internal model control theory, zero steady state tracking error for a sinusoidal reference signal can be achieved if the parameter equals the frequency of the reference signal V_{ref}. The frequency of the reference signal is determined by the droop controller and may slightly drift from its nominal value. Thus, the transfer function C_{AD}(s) is implemented such that the parameter can be adaptively adjusted.

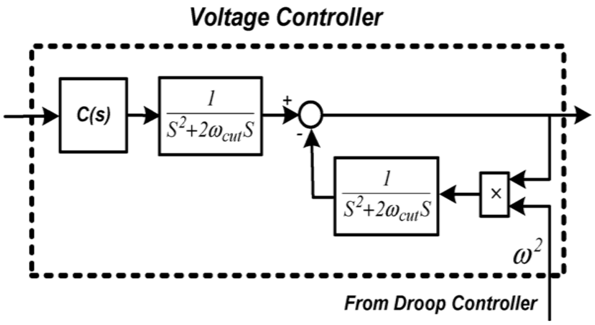


Fig 3. Block diagram of adaptive PR controller

The output impedance of the DG unit is defined as:

$$Z_{out}(s) = -\frac{V_{out}(s)}{I_{out}(s)} / V_{ref}(s) = 0$$

where I_{out} and V_{out} are the terminal current and output voltage of the DG unit, respectively. Z_{out} significantly changes with frequency. Therefore, if the conventional PR controller with a fixed central frequency ω is used, the output impedance will be increased due to the frequency drift imposed by the droop controller. However, the proposed adaptive PR controller dynamically sets its central frequency to keep the output impedance at its minimum value.

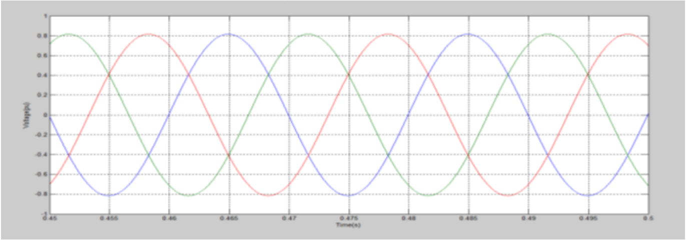
SIMULATION RESULTS

Simulation study is conducted by applying balanced and unbalanced load changes. Two simulation case studies are conducted. Initially operation under balanced load conditions is carried out.

A.Operation Under Balanced Load Changes

For balanced load changes, a three-phase RL load is connected to the low voltage (LV) side of feeder F3. The fuel cell stack increases their output power to reach the reference power. The supercapacitor module compensates the shortage power of the fuel cell stack, and load demand. The power difference between the fuel cell, and the load demand charges the supercapacitor module. The proposed PR controller provides a set of regulated balanced voltages at the DG unit terminals.

(a)



(b)

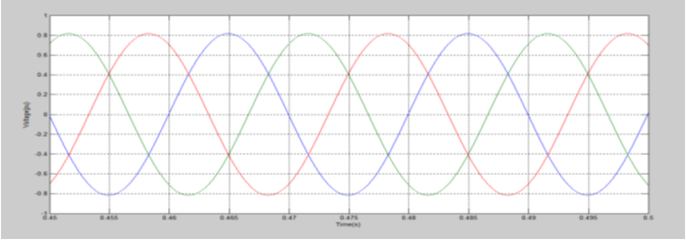
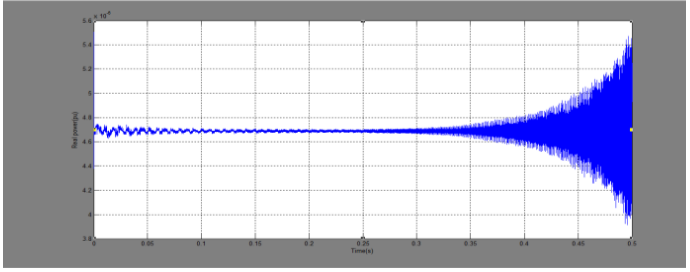


Fig 4. Instantaneous voltages at the DG unit terminals (a) DG1 and (b) DG2

(a)



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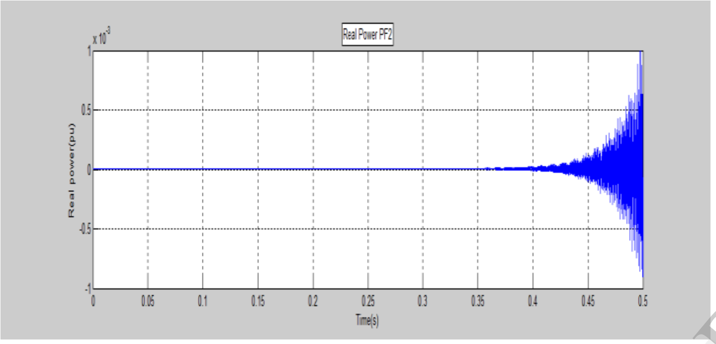


(c)

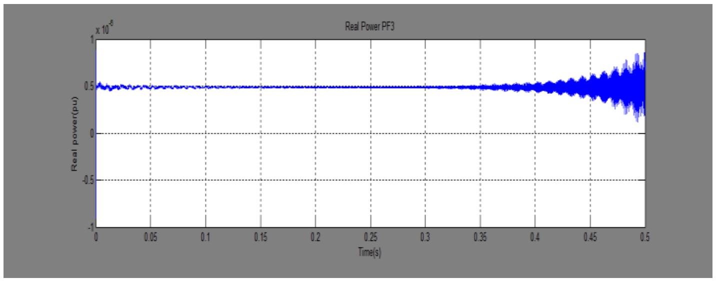
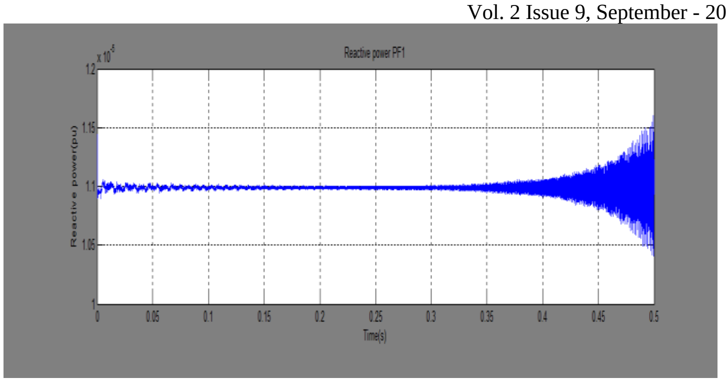
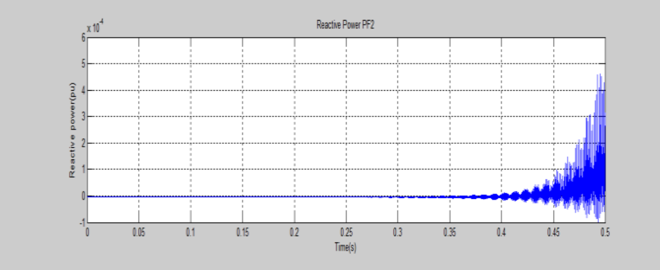


Fig 5. Instantaneous real power components of feeders (a) F1 (b) F2 (c) F3

(a)



(b)



(c)

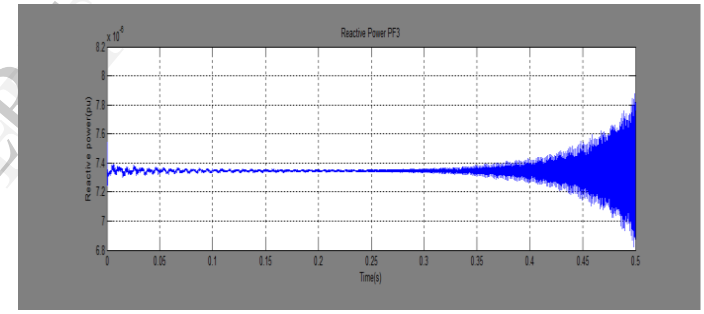
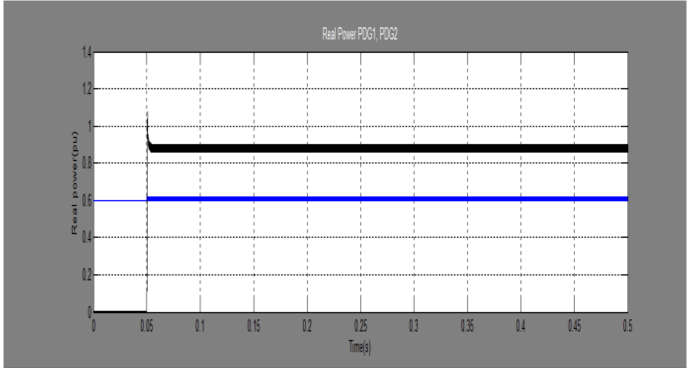


Fig 6. Instantaneous reactive power components of feeders (a) F1 (b) F2 (c) F3

(a)



(b)

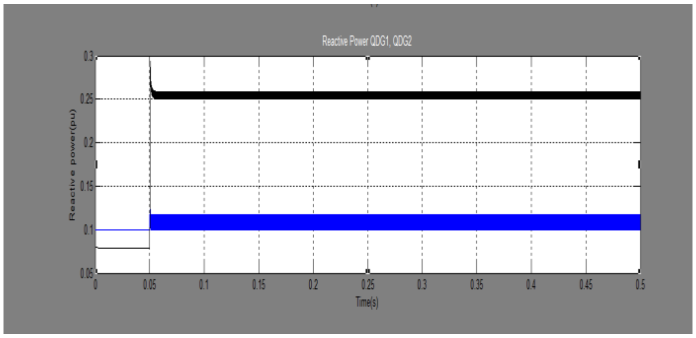


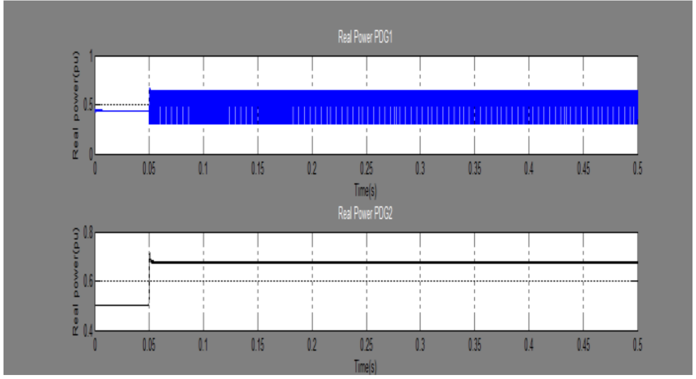
Fig 7. Dynamic response of DG units to balanced load changes (a) real power (b) reactive power

Fig 4 shows the instantaneous voltages of the DG units terminals. The proposed adaptive PR controller provides a set of regulated balanced voltages at the DG unit terminals. Fig 5 shows the instantaneous real power components of three feeders. Fig 6 shows the instantaneous reactive power components of three feeders. Fig 7 shows the instantaneous real and reactive power components of the DG units during balanced load changes. The adaptive PR controller maintains the output impedance of each DG unit at the minimum value. Therefore, the real and reactive power components of the DG units have almost no low frequency oscillatory transients.

B. *Operation Under Unbalanced Load Changes*

Initially, the microgrid system is operating under balanced conditions. Now unbalanced load changes are initiated by connecting a single phase load to the low voltage side of feeder F1.

(a)



(b)

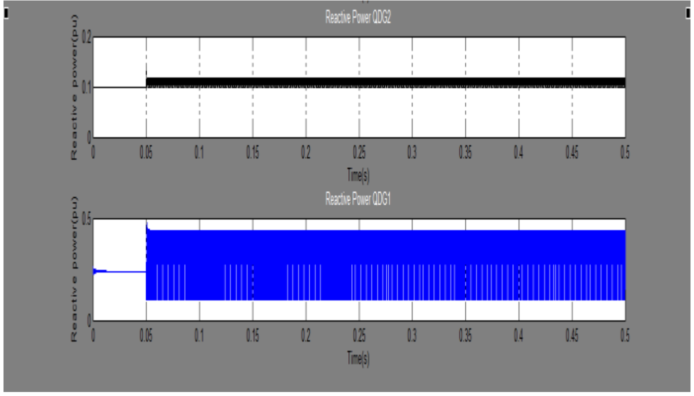
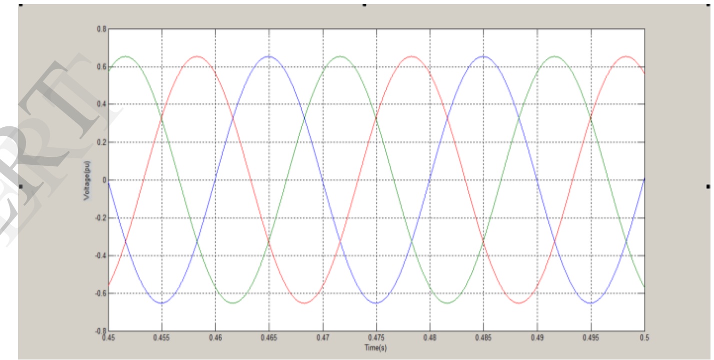


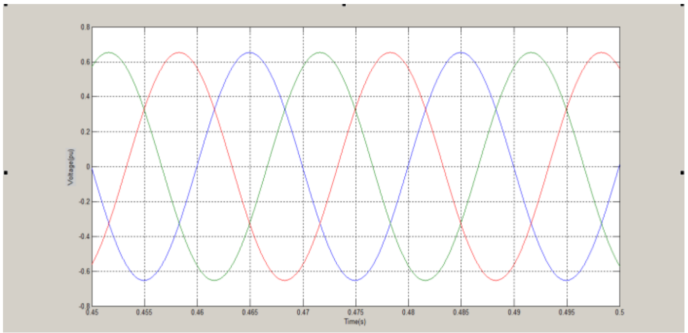
Fig 8. Dynamic response of DG units to unbalanced load changes (a) real power (b) reactive power

Fig 8 shows the instantaneous real and reactive power components of the DG units to unbalanced load changes when adaptive PR controller is used.

DG Voltage With Fuel Cell As Main Source and Supercapacitor as Energy Storage



(a) DG1 Voltage



(b) DG2 Voltage

Fig 9. Instantaneous voltage of DG unit terminals when fuel cell alone is used as energy source

Figure 9 illlustrates the instantaneous voltages at the DG unit terminals when fuel cell alone is used as energy source. Comparing figures 4 and 9, it is seen that the output voltage of the DG unit terminals is increased when photovoltaic unit is added along with fuel cell and supercapacitor.

CONCLUSION

This paper presents active power management of a medium voltage islanded microgrid consisting of two DG units. The supercapacitor energy storage compensates the slow response of fuel cell and photovoltaic unit. An adaptive PR controller is used to regulate the load voltage. The adaptive PR controller provides a set of regulated balanced voltages at the DG unit terminals. By using adaptive PR controller, output impedance of DG units is brought to minimum. Thus low frequency oscillations in the power components of DG units is eliminated. The proposed strategy is able to share the power among the DG units even under unbalanced conditions. Also, it is seen that the output voltage of DG unit terminals is increased when photovoltaic unit is added along with fuel cell and supercapacitor. Thus power generation is enhanced using two energy sources, fuel cell and photovoltaic unit.

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