Supervisory control of a resilient DC microgrid for commercial buildings

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Abstract: This paper presents a supervisory controller for DC microgrid consists of a solar photovoltaic (PV) system, fuel cell, a supercapacitor and battery bank. The DC microgrid is proposed for more efficient resilient electricity distribution in a commercial building. The operation strategy of energy storage systems (ESS) is proposed to solve the power changes from PV array and building loads fluctuations locally, instead of reflecting those disturbances into the utility grid. Furthermore, the ESS energy management scheme will help to achieve the peak reduction of the building daily electrical load demand. The DC microgrid studied in this paper is interfaced with the battery bank by using a bidirectional DC-DC converter, whilst the building electrical AC load is interfaced to grid using DC-AC inverter. The control of the studied microgrid is designed as a method to improve microgrid resilience and incorporate renewable power generation and storage into the grid.

Keywords: smartgrid; distributed energy resources; DERs; DC microgrids; supervisory control; energy management.

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1 Introduction

Recently, the electrical demand for commercial and industrial loads in urban and rural areas has grown massively over the last years. Electrical power can be produced from a diversity of renewable energy resources, such as solar photovoltaics, the wind, fuel cells and water. These energy sources are able to supply the energy needs of residential and commercial communities efficiently when designed and installed correctly (Kanchev et al., 2011; Reddy et al., 2012). Renewable and clean energy technologies such as the wind and photovoltaic systems present a long-term non-depletable power generation; hence, there is an increasing interest for their use. Furthermore, as the decreasing of total capital cost, the increase of system efficiency and increasing global realisation towards protecting the environment, the demand of renewable sources is prospected to grow (Thounthong et al., 2015; Byeon et al., 2013). The increasing demand for a higher power quality, more reliable and clean electricity supply has increased the importance of the concept of distributed generation (DG). A small electricity generation units, including renewable sources, can be installed in the location of energy consumption field. The integration of onsite generating and energy storage along with advanced load management of the commercial building and for DC microgrid to take part in emerging energy markets. Building energy management systems (BEMS) must consider the improvement of efficient energy utilisation, reducing the cost of energy, and deployment of renewable energy technologies in order to supply electrical loads in buildings with distributed energy resources (DERs). The combination of renewable energy sources and its optimal management can be a complement or an alternative to conventional diesel generators commonly utilised to produce electricity in the isolated or remote areas from the utility grid. The main trend in the energy management is to satisfy the load energy demands efficiently, encouraging renewable energy sources and reducing cost. Various research studies have been made to meet these issues by finding the optimum size of the system, energy management systems (EMS) and smart microgrids (Kanchev et al., 2011; Reddy et al., 2012; Thounthong et al., 2015; Byeon et al., 2013; Cingoz et al., 2016).

PV and fuel cell have obtained wide attraction for residential, commercial and industrial applications due to its free of cost availability and due to its secure and continuous output and higher efficiency (Farooque and Maru, 2001; Pera et al., 2007;

El-Sayed and Al-Naseem, 2011). Due to the outstanding research progress in the area of the smart grid, and renewable energy, power electronics industries have gained a great interest. Energy storage systems (ESS) such as batteries and supercapacitors have an important role in ensuring continuous power supply for the most critical electric loads (Rabhi et al., 2015; Valenciaga et al., 2005). They act as an energy buffer, either absorbing excess generation or discharging energy to meet minimum load requirements and smooth fluctuations in renewable energy sources output. Therefore, ESS has an important part in helping to maintain the stability of microgrids, as well as the utility-scale grid. Supercapacitor is considered a better choice owing to several merits like better power density, long life cycle, very good charge/discharge efficiency and can be constructed in a modular structure (Amer et al., 2013; Drolia et al., 2003; Uzunoglu and Alam, 2006). Supercapacitors have more charging and discharging cycles during their lifetime and providing maintenance free operation which can serve as a cost-effective alternative to batteries for residential or industrial applications particularly during short peak demand or transient periods (Rathore, 2012; Yu et al., 2014). Existing power distribution networks may cause the effects of wildly fluctuating, an unpredictable power output of the building-integrated-photovoltaic (BIPV) to be injected to the utility grid. As aforementioned, one possible solution would be to absorb the fluctuating PV power at the local building's power distribution network instead of passing the fluctuation to the utility grid. The DC microgrid solution would rely on energy storage technologies and cooperative operation strategy of the storage system. The proposed DC mirogrid may help to gain self-sustaining power during emergency such as the utility grid failure, the resilient network, originally emergency network, will work completely in an isolated mode with the storage electricity within the ESS as well as the BIPV power output during the day time. The flexibility of operating in both grid parallel and islanded modes; allow the BIPV power to be consumed locally, thereby continuing the investment of upgrading the DC/AC microgrids when the power demand of the building increase. The possibility to participate in the ancillary service through the existing infrastructure with the help of the intelligent switches, and to enhance the reliability and stability of the commercial building microgrids. The commercial and industrial microgrid architectures include several renewable energy resources comprising generation and storage (Gonzalez-Espin et al., 2014). The storage device is a Li-ion battery with a bidirectional power electronics converter. Both devices are able to deliver active power and reactive power as required by a BEMS. Moreover, the commercial and industrial building microgrid can manage the mode transition between the islanded and grid-connection modes as well as the load sharing in the islanding mode by using various control schemes depending upon a smart automation strategy programmed in the BEMS.

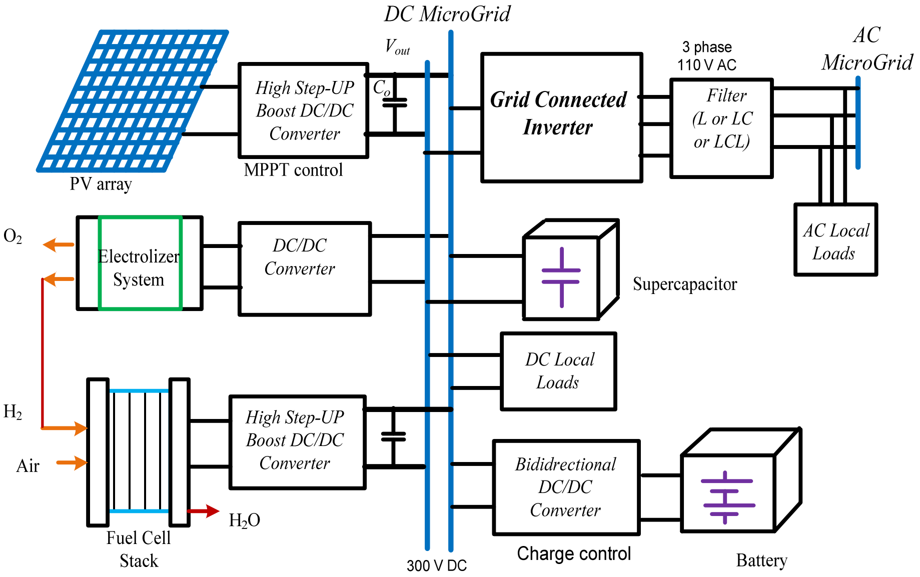
Several energy management schemes for microgrid including fuel cell and PV systems have been presented in the literature (Garcia et al., 2010; Ke et al., 2009). The performance of these strategies relays on how well the designer is familiar with the operation of each component in the microgrid. The design of these EMS should be made in such a way to achieve an efficient performance while ensuring that each generation source and storage device works within its predefined limits. Furthermore, the EMS effect on the life cycle of the whole microgrid should be limited as possible (Motapon et al., 2013). A coordinated control scheme for an isolated microgrid has been proposed in Sekhar and Mishra (2015) that consisting of decentralised and distributed generation (DDG), PV and FC without using any storage such as battery banks or SCs. The PV generator is properly derated to deliver maximum possible power and hence making its output power dispatchable (controllable source). The power produced by the fuel cell is usually limited by the amount of hydrogen fuel that can be stored onsite. This may cause a widespread lack of power during extreme weather events when obtaining additional fuel may be exceedingly difficult. Because of this, even if the fuel cell does work fairly in an emergency condition, they may become useless during an extended power failure. Solar PV arrays and energy storage technologies have become an applicable and more reliable option for microgrids because of the steadily decreasing costs to more resilient and distributed power systems (García et al., 2013; Marquezini et al., 2008; Guerrero et al., 2011; Zarina et al., 2014). This DC distribution system is appropriate for DC output type DGs such as photovoltaic and fuel cells, and energy storages such as secondary batteries and supercapacitors. The DC microgrid is designed to provide resilient power, though improving the control system to improve the microgrid resilience and incorporation of several renewable power generation and storage into the microgrid. While there are a number of various definitions for resiliency, possibly the one most germane to microgrids is the ability of a system to gradually degrade under increasing apparatus stress, and then to make system restoration to its pre-disturbance condition when the disturbance is revealed (Arghandeh et al., 2014). A resilient power microgrid should not experience a sudden, catastrophic system collapse, but rather should be able to keep at least some level of power supply service even in the situation of severe power system disturbances. The DERs and energy storage devices ESS are used for enhancing grid resilience, particularly in commercial and industrial distribution networks. It can also optimise power flow with the microgrid by balancing energy consumption, power generation, and energy storage within an industrial facility. That can mitigate stress on the utility grid and create a more resilient and flexible power system. The commercial building can be islanded, so it can use its distributed resources for its own individual benefit (Marwah et al., 2012).

This paper presents an energy management technique for a DC microgrid. A localised PV-FC generators control scheme is proposed for load management and connected in a hybrid system to an AC and DC loads as a viable solution to some domestic, commercial and industrial load requirements. The steady-state operation and dynamic performance of the DC microgrid are studied to verify the proposed energy management strategy. The energy management control system is designed to accommodate FC status, battery state of charge, and load demand according to power management control. Dynamic and steady state simulation results are provided to prove the feasibility of the DC microgrid design.

2 Proposed system

The studied microgrid is composed of a PV array, fuel cell, together with storage devices supercapacitors (SC), batteries, electrolyser load and DC loads. These systems are forming DC microgrid interconnected to a low voltage distribution AC microgrid system or islanded. Figure 1 shows the configuration of the DC hybrid power system for the distribution microgrid. The fuel cell system (FCS) is connected to the DC bus by a boost converter, the battery is connected through the charge regulator bidirectional DC-DC converter and supercapacitors are connected to the DC bus directly. A unidirectional boost DC/DC converter connects the FC with the DC bus maintaining the converter system stable despite variations in load (Sayed et al., 2012; Kwon and Sayed, 2008; Sayed and Abdel-Salam, 2016). Unidirectional means that the energy only can flow from the FC to the DC bus. In the case of battery, bidirectional DC-DC converter is used to connect it to the DC bus. The battery and supercapacitor (SC) SOCs are kept around their reference values in order to achieve high charge efficiency.

Figure 1 Block diagram of the proposed PV/FC system (see online version for colours)



3 Control strategy for PV/FC/storage hybrid system

3.1 Control of the DC/DC boost converter interfaced fuel cell

Typical control of boost converter, with output voltage stabilisation and current limitation, has been applied (Figure 2). This converter is composed of a high-frequency inductor L, an output filtering capacitor C_{dc}, a diode D, and the main switch S_1, as shown in Figure 2. The current limitation is set on fixed level, however for different sources it can be modified (e.g., for fuel cell it should be proportional to the H_2 fuel injected, due to the fuel cell characteristics). For simulation tests, the current of the boost converter is limited to 30 A. The reference value of the DC voltage is set also on fixed level required by the inverter integrating the energy source with grid or load. Any deviation from the reference value is treated as energy surplus or deficit, and can be used by power management system as an indication of these states. Reference voltage in this control structure is the maximum value. The DC voltage higher than this value causes reduction of the inductor current. When the SOC is below the reference, the fuel cell provides almost the load power. This scheme is easier to implement compared with previous strategies, and the PI gains are tuned online for a better response.

Figure 2 Control of the FC boost converter with DC link voltage stabilisation (see online version for colours)

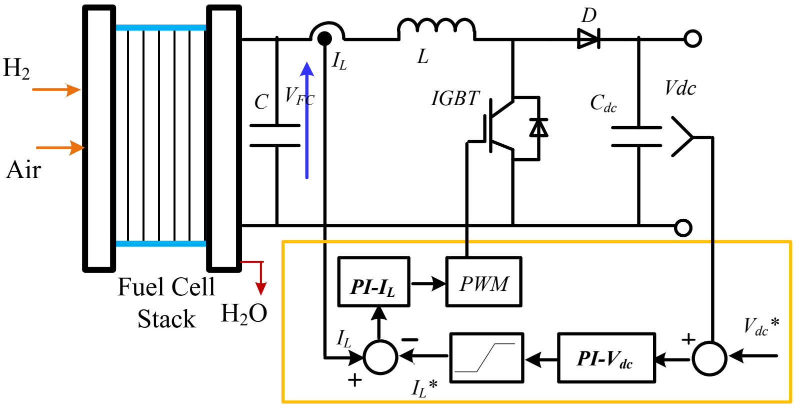
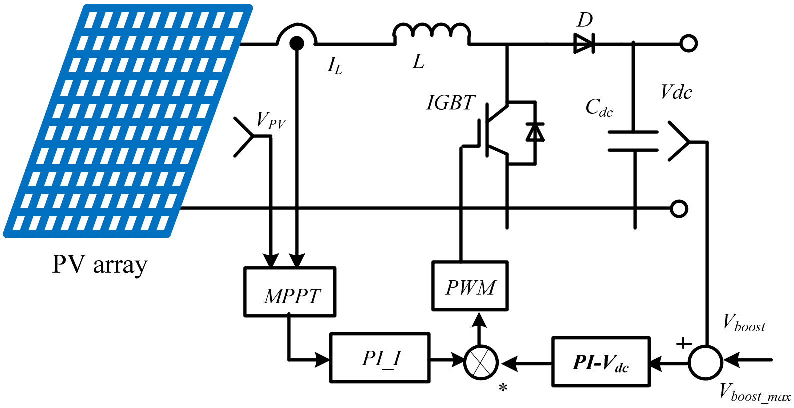


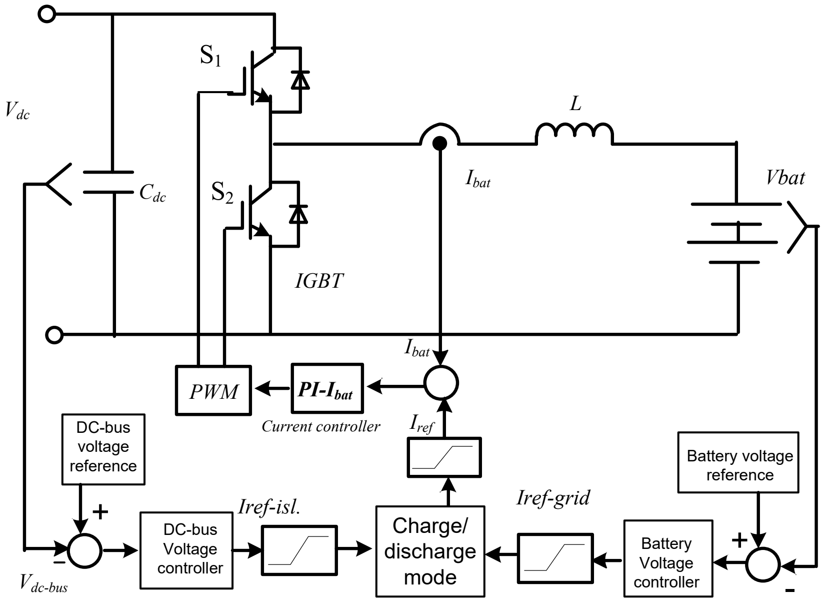
Figure 3 Boost with MPPT control diagram (see online version for colours)



3.2 *Control of the DC/DC boost converter interfaced PV array*

The single-phase boost stage is used to boost the voltage from the panel and track the MPP. The input current I_{pv} is sensed before the input capacitance C_i along with the panel voltage V_{pv}. These two values are then used by the MPPT algorithm, which calculates the reference point the panel input needs to be maintained at to be at MPP. The MPPT is realised using an outer voltage loop and an inner current loop, as shown in Figure 3. Increasing the current reference of the boost (current drawn through the boost loads, the panel and resulting in the panel output voltage drop). Therefore, the sign for the outer voltage compensator reference and feedback are reversed. It is noted that the output of the boost is not regulated. To prevent the output voltage from rising higher than the rating of the components, the voltage feedback is mapped to the internal comparators, which can do a cycle-by-cycle trip of the PWM in the case of over voltage.

Figure 4 Control scheme of battery energy storage



3.3 Control of bidirectional DC-DC converter interfacing battery bank

In this study, the bidirectional converter consist of a high-frequency inductor L, an output filtering capacitor C_{dc} and two switches (S_1 and S_2), which allow the bidirectional current flow, as shown in Figure 4. In the power management method, there are two voltage controllers with adequate limitation blocks to achieve required energy flow in different conditions. These controllers produce a reference current of energy storage. The first controller is for DC-bus voltage regulating, and the second controller is for battery voltage control. In order to improve the power management in the DC microgrid, backup energy storage is included. It consists of a battery bank connected to the DC-bus by means of a bidirectional DC/DC converter. This converter performs multiple functions: it serves as a battery charge regulator in grid-connected operation, and a boost converter to deliver energy from the batteries to the microgrid when the PV and fuel cell sources have insufficient power to feed the local loads in islanded operation. In island mode, the most favourable operating condition occurs when the load power and the PV extracted power agree, i.e., when the DC/DC does not process power. Figure 4 shows the simplified DC/DC converter power stage and its bidirectional control structure. Too deep discharge of the energy storage is not advisable, as, at a low voltage of energy storage, there is a limited range of charging power, what may cause over-voltage in DC link during, e.g., energy recovery from the load side. In the case of an electrochemical battery, there is a limited range of the discharge, and the battery has to be protected.

3.4 DC microgrid control method

In the studied DC microgrid, a control scheme has been implemented to balance the DC voltage bus and to control the power supply to meet the load demand in islanded mode. Table 1 shows the energy management design requirements. In this control, one unit source acts as a master controlling the full system, while the rest of the units work as current sources (i.e., as 'slaves'). In this way, there will not be voltage different between the outputs of the DC sources, because the master unit regulates the voltage values of all the output units, therefore, will not circulate current between the sources.

Table 1 Energy management design requirements

Item	*Symbol*	*Value*
Fuel cell power	PFCmin–PFCmax	1–10 (kW)
Battery power	Pbattmin–Pbatmax	–1.2–4 (kW)
Battery state of charge	SOCmin–SOCmax	60–90 (%)
DC bus voltage	Vdcmin–Vdcmax	250–280 V
Fuel cell current maximum slope	(A/s)	40 (A/s)

The DC bus voltage in the microgrid is measured and compared with the reference voltage was chosen (300 V), the error is processed through a compensator (PI block) to obtain the desired impedance current reference for the current loop. This compensator can be expressed in the following way:

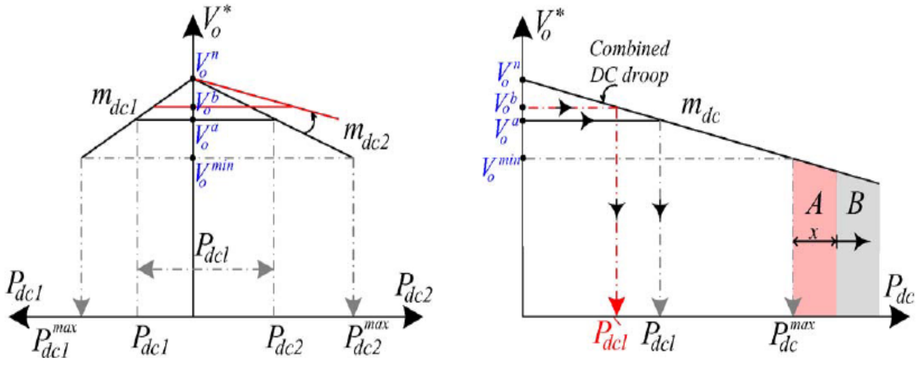
$$I_{Lref} = k_p \left(V_{ref} - V_{MG} \right) + k_i \int \left(V_{ref} - V_{MG} \right) dt \tag{1}$$

The power flow is controlled by a current controller who compares the impedance current in the master unit with the reference current desired to stabilise the system, the error is processed through another PI block to obtain the desired duty cycle for the converter which acts as a Master. The PI block can be expressed as:

$$d = k_p^{\sim} \left(I_L^* - I_L \right) + k_i^{\sim} \int \left(I_L^* - I_L \right) dt \tag{2}$$

The problem of this control topology is the dependence on the master unit, if there is a fault in this unit, the control will stop working properly (Garcia et al., 2013). To increase the reliability of the system, three different sources are able to act as a master unit, decreasing the chance to have a fault in the microgrid control. In the studied model, the voltage source converter (VSC) inverter of the grid will act as a 'master' when the microgrid is connected to the grid, there are also implemented a voltage loop and a current loop to control the voltage level, so the VSC is not able to regulate the power flow. The ESS is able to control the voltage level and the power flow through a bidirectional converter. When the microgrid is working in islanded mode, this source will act as a 'master' remaining the voltage at 300V and meeting the load demand. If there is a fault in the ESS or the SOC level is not properly to control the microgrid in islanded mode. There is a voltage controller implemented with a voltage and a current loop as it is shown in Figure 5.

Figure 5 DC droop – the droop curve of unit-1 is mirrored for better representation – assume lossless transmission lines, (a) the individual droop of two DG units (b) combined droop for the entire DC subgrid (see online version for colours)



(a) (b)

The DC DG units are DC/DC converters fed from a DC voltage source. The conventional droop-based power sharing in the DC subgrid is shown in Figure 5(a). The terminal DC-link voltage of each DC/DC converter is drooped with the generated DC power (P_{dcj}) via the droop coefficient m_{dcj} as shown in

$$V_{oj}^* = V_{oj}^n - m_{dcj} P_{dcj} \tag{3}$$

where V_{oj}^*, V_{oj}^n are the reference and no-load DC-link voltage of the DC/DC converter whereas the subscript j represents a DG unit in the DC subgrid. The injected DC power from each DG unit (P_{acj}) is wirelessly determined to supply the common DC-load (P_{dcl}), following the equality $m_{dc1}P_{dc1} = m_{dc2}P_{dc2}$, where $P_{dcl} = P_{dc1} + P_{dc2}$.

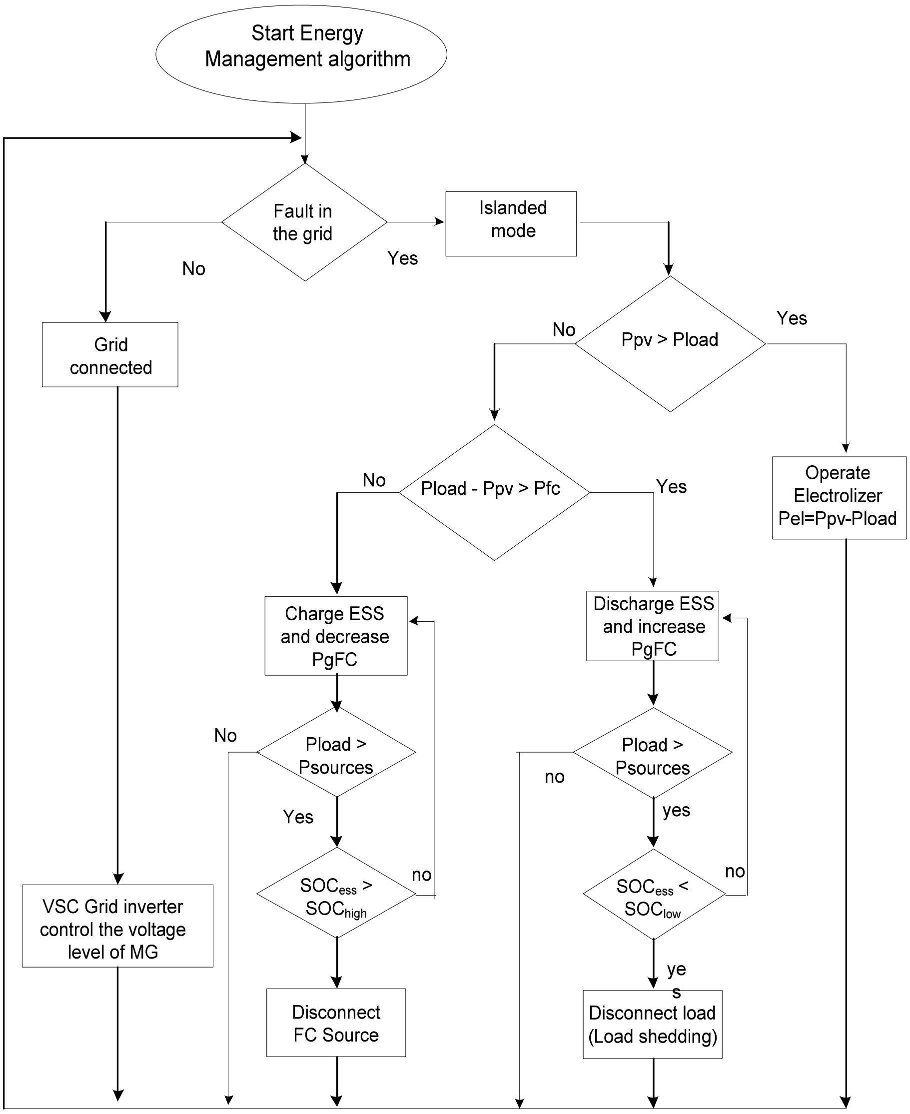
4 Supervisory control strategy

The input data such as solar radiation and ambient temperature are fed in to calculate the amount of energy that can be generated by the PV generator. The value of PV output power (P_{pv}) is compared with the load demand energy (P_L) to determine the distribution of energy flow between the storage unit and the load. Surplus PV energy is stored in the form of hydrogen by the electrolyser (P_{el}) and deficit energy can be taken from hydrogen by the fuel cell (P_{fc}) backup generator. A flow diagram of the control strategy for the PVFC hybrid system is shown in Figure 6. According to Figure 6, the control strategy is based on the following three different cases:

- If $P_{pv} > P_L$, then $P_{el} = P_{pv} - P_L$. That is, if the radiation level is high enough, the PV array empowers the load and the excess power is stored in hydrogen by the electrolyser.
- If $P_{pv} < P_L$ and $P_L - P_{pv} \leq P_{fc}$, then $P_L - P_{pv} = P_{fc}$. That is, if the PV generator cannot power the load, then the load is connected directly to the PV generator and the fuel cell is switched on.

- If $P_{pv} < P_L$ and $P_L - P_{pv} > P_{fc}$, then $P_L = P_{fc} = 0$ and $P_{el} = P_{pv}$. That is, if the PV generator cannot power the load and the fuel cell fails to start, then the load and fuel cell are disconnected and the electrolyser is connected directly to the PV generator, then the load is connected according to the conditions in 1 or 2. Thus, the supercapacitor module which represents a storage unit for short-term operation, to provide a more stable power response to transient changes in load demand or to stabilise the fuel cell operation, is not considered here.

Figure 6 Energy management control flow chart for the PV/FC/storage system



The higher-level controller is divided into two levels. The first level identifies the mode of operation based on the status of individual components. The second level is incorporated into intelligent systems that determine how the individual components should perform in that mode of operation. The different modes of operation are a standby mode, transient mode, supercapacitor charging mode, normal mode, and battery charging mode. In the standby mode, all the controllers are disabled except that of the DC/DC converter. When load power increases beyond a certain threshold, controllers switches from standby to transient mode. In this mode of operation, controllers of all controllers are set. Any deficiency in power from the fuel cell and battery is automatically supplied by the supercapacitor, whenever fuel is available to control switches to the supercapacitor charging mode. A supercapacitor can be charged to any amount of current as long as its state of charge is not full. Fuel cell supplies power to both the load and supercapacitor at this stage. Whenever there is deficiency battery supplies power. When the supercapacitor is fully charged, controller switches to the normal load. Fuel cell will alone supply power to the load. In this mode battery is disabled, but supercapacitor is still active. If there is any sudden increase in load, then controller switches back to the transient mode. There are two ways to switch to battery charging mode. The switch over takes place either when the state of charge of battery is less than the minimum or when there is a sudden decrease in load power and state of charge of battery is less than maximum. Thus when load power decreases, extra power available is used to charge the battery if it is not full. When the complex control system is divided into multiple levels, the individual components can be modelled and controlled easily. They are the lower level controllers. They include the balance of plant controller and the DC/DC converter controller. An EMS has been considered for the optimal operation of the microgrid both in grid connected and islanded modes. The overall control is shown in Figure 6 and an overview is given below.

In the case of grid-connected, the VSC grid inverter is able to work as ‘master’ and all the sources from the microgrid act as a current source or as ‘slaves’. Therefore, the VSC is able to balance the DC voltage bus. In the case of unplanned events as faults, the microgrid has to be separated to the grid and work in islanded mode. In this case, the ESS will work as “master” controlling the voltage level and the power flow of the microgrid. In all the operating conditions the PV and FC sources will be operating as slave ones. The energy management control copes the unbalances between power production from DG units and load by means of the ESS if their SOCs are sufficient, or with the FC (gas engine). In this case, it must be noticed that the fuel cell (FC) response is slower than the ESS response due to the chemical reaction. In the case of ESS failure or an inappropriate SOC value, the master unit becomes the FC. If the control of the microgrid is not able to balance the power flow of the system, the last countermeasure in case of a load greater than the available generation is the load rejection. In case that the power generated by the sources would be bigger than the load consumption, one of the distributed generators will be disconnected from the microgrid.

5 Commercial building power management

Power management in commercial building adds intelligence to reduce energy consumption, enhance safety and improve uptime. The modelling and the control system of the fuel cell and the photovoltaic plant are designed. This strategy is based on the control of the main performance parameters, such as the battery state of charge (SOC), the supercapacitor voltage, or DC-bus voltage using proportional-integral (PI) controllers (Zenith and Skogestad, 2007). The PI controllers can be easily tuned online for better tracking. The load power is distributed in such a way to allow the fuel-cell system to provide the steady-state load demand. The coupling of these three systems is performed by the sum of currents at the connection point to the DC microgrid. The microgrid real power exchanged with the grid p_{grid} is the sum of the fuel cell generation system p_{fc}, the photovoltaic generation system p_{pv}, the SCB p_{scb} and loads p_{loads} (Figure 1).

$$p_{grid}(t) = p_{fc}(t) + p_{pv}(t) + p_{scb}(t) - p_{loads}(t) \tag{4}$$

During such a long time rang, the fast power variations exchanged with the supercapacitor p_{scb} can be neglected. The equation (4) in long time range is expressed as:

$$\{P_{grid}\}T = \{P_{fc} + P_{pv} - P_{loads}\}T \tag{5}$$

During short periods, the supercapacitor bank (SCB) masters the power flow thanks to its fast response time. The power reference of the supercapacitor p_{scb_ref} can be calculated by the inversion of the equation (4) as:

$$P_{scb\_ref}(t) = P_{grid\_ref}(t) - P_{FC}(t) - P_{pv}(t) + P_{loads}(t) \tag{6}$$

Supercapacitors (SCs) have an extremely fast discharge and charging response, and so in this study, supercapacitors are used for the DC bus voltage control of the DC microgrid. The storage capacity of super capacitor is subject to the following constraints:

$$E_{sc\min} \le E_{sc}(t) \le E_{sc\max} \tag{7}$$

where $E_{sc\max}$ and $E_{sc\min}$ are the maximum and minimum allowable storage capacities of SC. $E_{sc\min}$ is determined according to the following equation:

$$E_{sc\min} = SOC_{sc} * E_{sc\max} \tag{8}$$

where $SOC_{sc} = 0.25$ is the minimum allowable state-of-charge level of the UC. Another function of the microgrid central controller is to supervise the storage level of the SCB. If its level reaches a high level, a reduction of the active power generated by the fuel cell can be used. Hence more power will be extracted from the SC and will reduce the stored energy.

$$E_{sc\_ref} = \int \Delta P_{FC}(t)dt \tag{9}$$

$$\Delta P_{FC\_ref}(t) = k_{pe}\left(e_{sc\_ref}(t) - \hat{e}_{sc}(t)\right) \tag{10}$$

The commercial building microgrid can exchange power with local grid. The surplus produced power of the PV arrays after charging batteries is sold to the grid. If the total produced power of the microgrid cannot satisfy the demand, power will be purchased from the grid.

$$P_{FC\_ref}(t) = P_{grid\_ref}(t) - \hat{P}_{pv}(t) + \hat{P}_{loads}(t) + \Delta P_{FC\_ref}(t) \tag{11}$$

Energy management and power control are very critical for a DC microgrid based on an intermittent source. The control of solar PV: provides a reference voltage (Vmpp) for the unidirectional DC-DC boost converter. The control of the DC-DC boost converter at the PV output: forces the solar array to operate at a voltage to harness the maximum power. Supercapacitor charging and discharging circuit control: maintains the DC link voltage at a constant value of 270 V. The DC-DC converter control at the load end: smooth the load voltage as far as possible even when the DC-link voltage undergoes ripples. Since fuel cells can immediately deliver their maximum power, the DC/DC converter will set the performance limit. Lower values of the capacitance and the inductance will increase the transient's speed and accelerate the overall response, but will require faster switching. In this paper, the design parameters are used in a boost converter designed in Kwon and Sayed (2008) and Zenith and Skogestad (2007).

6 Simulation results

The hybrid system model is verified by implementing the detailed models in a MATLAB/Simulink environment. This model presents an alternative emergency power system based on fuel cells, lithium-ion batteries and supercapacitors. This model also features different energy management systems for a fuel cell hybrid electric source. The Simulink model of the studied DC microgrid is shown in Figure 7. Simulation results are obtained based on the typical daily load profile of the studied commercial building presented in Figure 8. The specifications of the studied power system are shown in Table 2.

Figure 7 The Simulink model of the studied DC microgrid (see online version for colours)

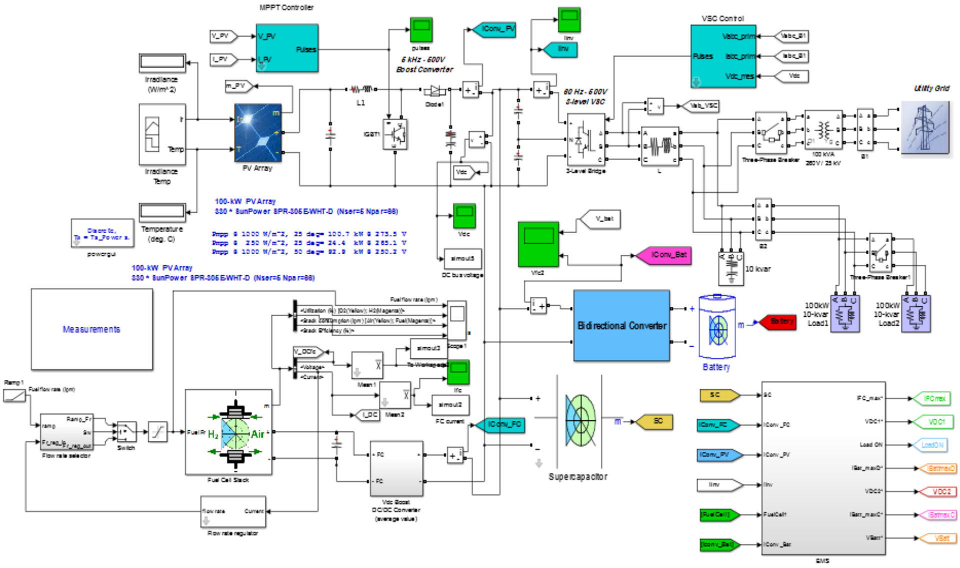


Figure 8 Oshawa selected building electricity load profile on March (see online version for colours)

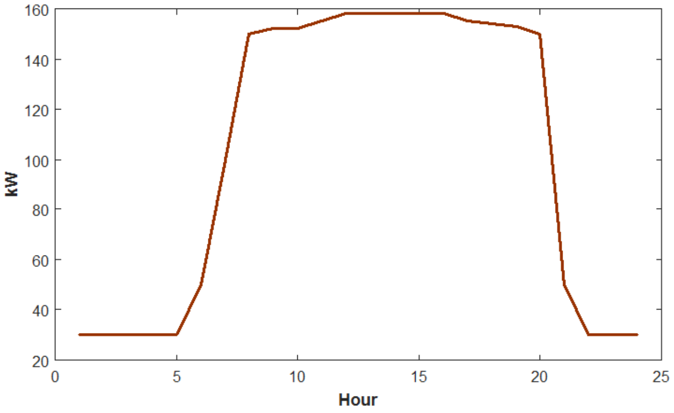


Table 2 System parameters

Item	*Description*
PV Array	Composed of 330 modules SunPower SPR-305E-WHT-D with series and parallel combination (Nser = 5 Npar = 66) rating 100 kW
proton exchange membrane (PEM) fuel cell	A 50 kW (peak), 625 V with nominal power of 40 kW.
Li-ion battery	A 48 V, 500 Ah, system
Supercapacitor	A 291.6 V, 15.6 F, (six 48.6 v cells in series)
Fuel cell bidirectional DC/DC converter	A 50 kW, with regulated output voltage and input current limitation.
Inverter system	A 150 kVA, 270 V DC in 200 V AC, 60 Hz.

Figure 9 PV voltage and current (see online version for colours)

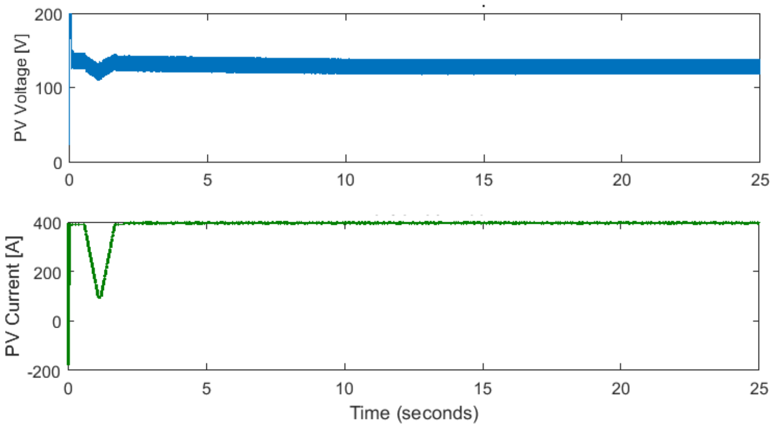


Figure 10 DC bus voltage and fuel cell power (see online version for colours)

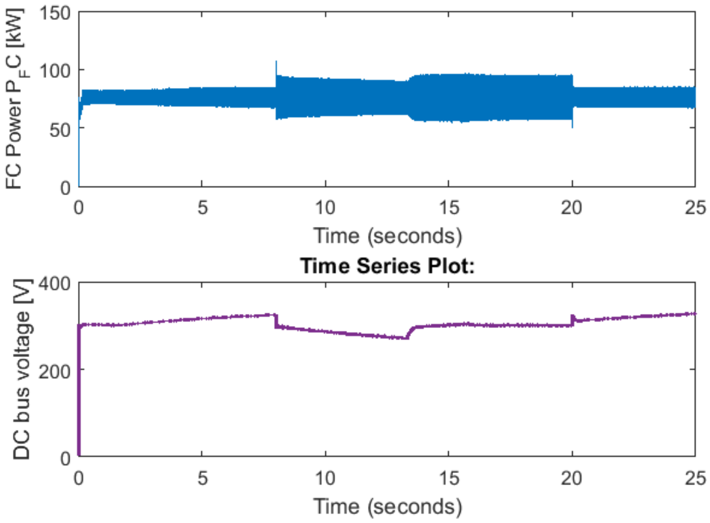
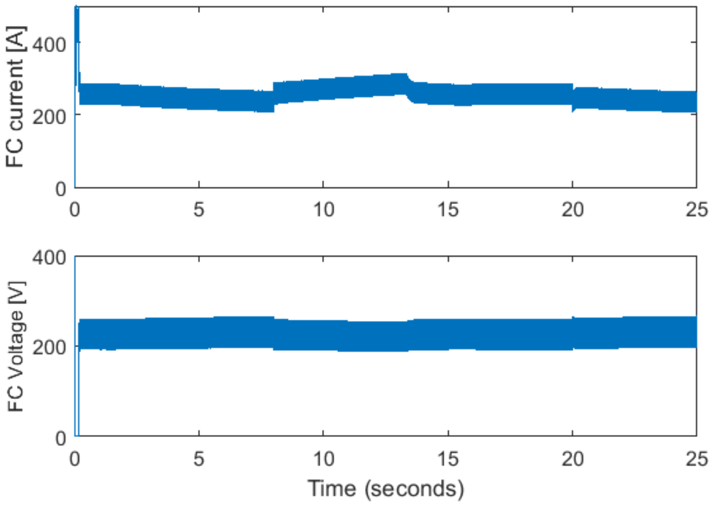


Figure 11 FC voltage and current (see online version for colours)



A 3-phase AC load with variable apparent power and power factor, to emulate the commercial building load profile. An energy management system, which distributes the power among the energy sources according to a given energy management strategy.

The peak electrical load is 158 kW at 2 pm, while the minimum load occurs during 9 pm to 8 AM at 30 kW. The load profiles were generated using Simulink then the hourly end-use energy results were configured into a friendly format. For each month, three-day types were used to represent the annual load: peak day, weekday, and weekend.

Figure 9 represents the PV voltage and current. The photovoltaic power plant generation is set to the Maximal Power Point Tracking, which is proportional with the irradiance. The weather data of PV/FC hybrid generation system is solar radiation

(W/m^2) and the ambient temperature (°C). These typical weather data at intervals of one hour is collected. There is much meteorological software can calculate the solar radiation and the ambient temperature. The microgrid power generation reference is set to one real power step (at 25 s, Figure 9), and the sensed power between the microgrid and the main is very close to the power reference. The battery and super capacitor compensate the fluctuations of the difference between the microgrid reference power and all the passive power variations of the microgrid (PV power and total loads).

Figure 12 Supercapacitor current and SOC (see online version for colours)

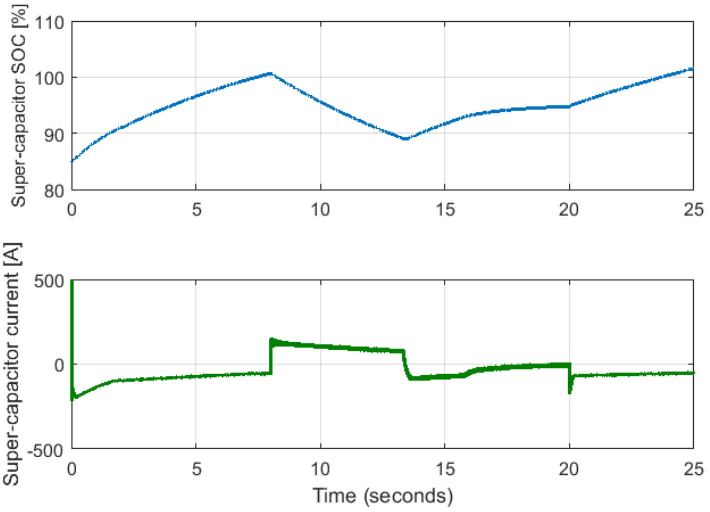
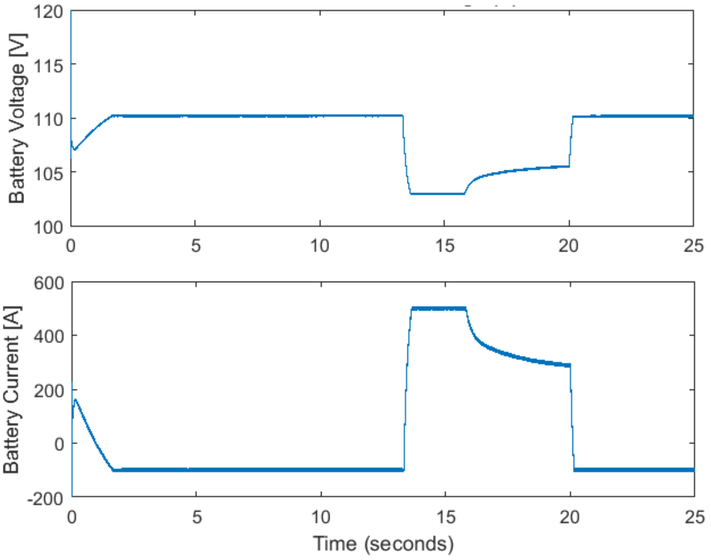


Figure 13 Battery voltage and current waveforms (see online version for colours)



It can be observed that the fast power fluctuations due to the slow response time of the fuel cell are reduced by the short-term ESS – SCB (Fig. 10). The FC will try to charge the SC to increase the *SOC* if the load is not too high. Figure 11 shows the fuel cell voltage and current. It should be noted that the positive current of SC means that the SC supply the loads and the negative one means that the SC is charged. It can be noticed that, in this case, the bus voltage fluctuates in an acceptable range of 226–270 V. The SC terminal voltage is well controlled between 226 V and 270 V (Fig. 12). The supercapacitor SOC ranges from 85 to 100%. The battery voltage and current waveforms are shown in Figure 13. The AC load voltage and current are shown in Figure 14. The load current increase at 8 s and decrease at 20 s. The terminal voltage drops due to the sudden increase in the load current as shown in Figure 15. The simulation results validate the PMS of the hybrid power system under different states.

Figure 14 Load voltage and current (see online version for colours)

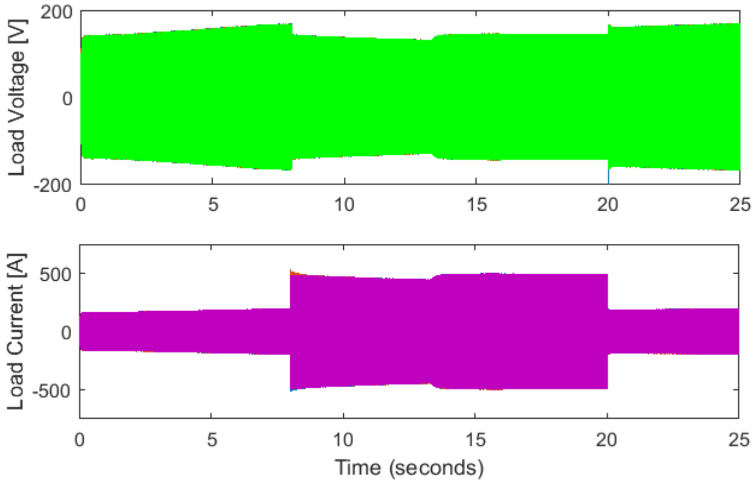
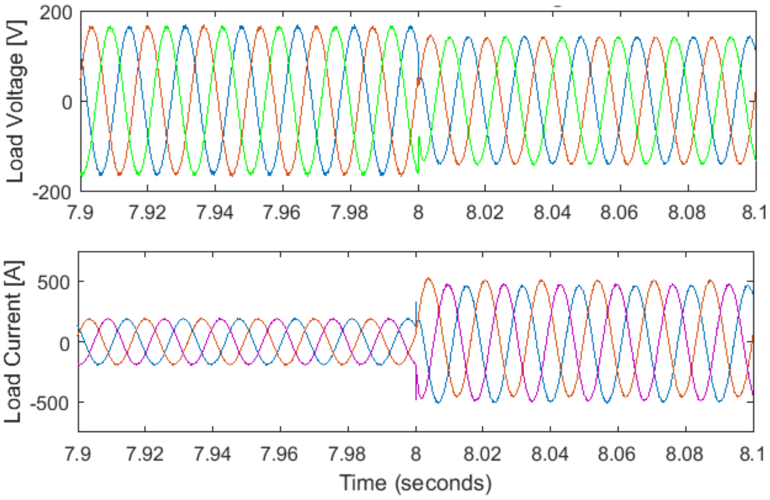


Figure 15 Step change in load voltage and current at 8 am (see online version for colours)



In this paper, the PV/FC hybrid generation system is either standalone or grid connected modes. Load demands are as determined by a fixed power. However most of the civilian power consumption, such as lighting and equipment, power consumption is always changing. Depending on the energy management strategy, the energy management system controls the power of each energy source devices through the reference signals (output voltage and maximum current) of the fuel cell and PV DC/DC converters (showing the power distribution referred to the 270 V DC bus) together with the fuel cell, supercapacitor and loadscopes.

The following explains what happens during this simulated emergency scenario: at t = 0 s, the essential loads are supplied by the main generators and the fuel cell hybrid power system is turned ON to prepare for an emergency situation.

At this time, the fuel cell begins to recharge the battery and super capacitor with its optimal power. At t = 8 s, all loads are connected and the loads jumps to 150 kW. At this time the extra power required is instantly supplied by the supercapacitor due to its fast dynamics, while the fuel cell power increases slowly. At t = 13 s, the supercapacitor is discharged below the required DC bus voltage (270 V) and the battery starts providing power to regulate the bus voltage back to 270 V. At t = 20 s, the DC bus or supercapacitor voltage reaches 270 V and the battery reduces its power slowly to zero. The fuel cell provides the total load power and continues to recharge the supercapacitor. At t = 13 s, the battery also reaches its maximum power and the supercapacitor provides the extra load power. At t = 20 s, the load power reduces below the fuel cell maximum power. Due to the slow fuel cell dynamics, the extra fuel cell power during transients is transferred to the supercapacitor. At t = 20 s, the load power reduces below the fuel cell maximum power and the extra fuel cell power is transferred to both the battery and supercapacitor. At t = 23 s, the load power decreases suddenly. The extra fuel cell energy is stored in the battery and supercapacitor. The fuel cell supplies nearly the total load power required and reduces its power slowly to its optimal power and recharges the battery.

7 Conclusions

In this paper, an algorithm for intelligent control and management have been developed to ensure optimal operation of a DC microgrid composed of two renewable energy sources (solar and the fuel cell) and a two storage sources (battery bank and supercapacitor). An energy management algorithm, as well as the control of power converters, were developed. The DC microgrid is modeled and simulated in MATLAB/Simulink environment. The simulation results show that the proposed energy management supports the minimal use of utility power. The supercapacitor energy storage compensates the slow response of fuel cell and photovoltaic unit. 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 the photovoltaic unit is added along with fuel cell and the supercapacitor. The commercial building loads for the DC microgrid were considered and the DC microgrid can exchange power with the grid. Since FCs were utilised as a backup for the PV arrays, especially in islanded operation. The DC microgrid that was used in this study has high reliability.

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