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303. Synchronization of Hydrogen Energy with Diesel Engine for Distributed Generation Applications

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Abstract

This piece of work provides modelling, control and synchronization of hydrogen energy (fuel cell system), a super-capacitor with a diesel engine which supplies power to the local grid and domestic load. The developed test-bed works under simple classical based energy management algorithm while all its components are controlled via DC-DC converters embedded with Proportional Integral (PI) controllers. According to the proposed algorithm, hydrogen energy (fuel cell system) is the priority to satisfy the total demand. The diesel engine is added as a back system to increase the reliability of power flow for 24 hours. The slow dynamic response problems of the fuel cell during transient has addressed through a super-capacitor in the proposed architecture. The role of dump load has taken from electrolyzer which produce hydrogen and to decrease power fluctuation during surplus power. Matlab/Simulink has been used in the designing of proposed test-bed. Simulation results prove the feasibility of proposed test-bed in terms of load tracking and reliability.

Keywords: *Distributed generation, Hydrogen energy, Super-capacitor, Load tracking*

1. Introduction

Energy has an imperative role in the wheel of technology evolution and modernization of different communities. However, today’s power systems experience issues such as deregulation when they have no back-up system. To take much benefit from Distribution Generation (DG), generation and load must be integrated as a subsystem. Such system may utilize any combination of generation, storage technologies and load and can operate for on-grid and off-grid applications to facilitate the life standard of people in remote areas. Some typical examples of DG or micro-grid are photovoltaic-battery and/or photovoltaic/super-capacitor serving a remote load and wind/micro-turbine system serving an isolated village. DG comprises of electric or thermal load, and any combination of small hydro, Photovoltaic (PV), wind turbines, fuel cells, micro-turbines, reciprocating engine generators, and energy storage systems such as batteries, supercapacitor and hydrogen.

Modern development in Fuel Cell (FC) has established that hydrogen will have a central role in the near future for power system [1]. Key features of FC include modularity, pollution free, high efficiency and quiet operation. Among the various types of FCs, Solid Oxide Fuel Cell (SOFC) has the highest efficiency FC among others [2]. Nevertheless, SOFC has a higher power density with poor dynamic response. When a SOFC is operated under transient, it takes several seconds to track the load and an instant drop off of the voltage in the I-V curve occur. Furthermore, hydrogen starvation can occur, which decrease the overall performance of FC [3]. Energy storage systems support transient stability during the rapid load variations. Additionally, they are also very convenient for load-smoothing applications.

Various types of energy storage systems such as flywheel energy storage, Super-capacitors (SCs), pumped hydro, and batteries are used for different goals in different applications. Among various types of storage system, SC has high power density and a very fast instantaneous response. Therefore, they can provide better transient stability during the rapid change in power demand. Considering the utilization of higher power density, i.e., SC modules in the SOFC plant can provide the most suitable choice.

Another important and commonly use power source is diesel generator which supply power in remote areas during failure of national grid. Therefore, synchronization of diesel generator with FC and an incorporation of SC can offer highly significant dynamic benefits in term of power reliability for DG. Many FC and Diesel Engine (DE) based power plants have been studied in the literature. For instance, a FC with Electrolyzer (ELZ) and DE hybrid system is designed in [4]. The intermittent nature of wind energy conversion is addressed by DE in [5]. In [6], the poor dynamic response has been solved through SC. Digital control of FC/SC power plant is developed in [7]. In [8], [9], the researchers described FC centred load applications and the combined utilization of FC/micro-turbine. Similarly, the importance of hydrogen energy for hybrid power system is described in [10], [11].

This manuscript presents provides modeling, control and synchronization of hydrogen energy (SOFC), an SC with a DE. The proposed system supports the local grid and domestic load while considering the real load condition at Bahria town Islamabad, Pakistan. The proposed test-bed works under classical based energy management algorithm called Supervisory Control System (SCS) which generates the dynamic references for each subsystem and ensures: (1) to maximize the output power, and (2) proper energy management of storage systems according load conditions and status of utility.

This manuscript is organized as: First, system description is provided in Section 2. Section 3 explains modelling and control of proposed system. Section 4 provides the proposed power sharing and energy management system. Section 5 describes the simulation results. Section 6 concludes the paper.

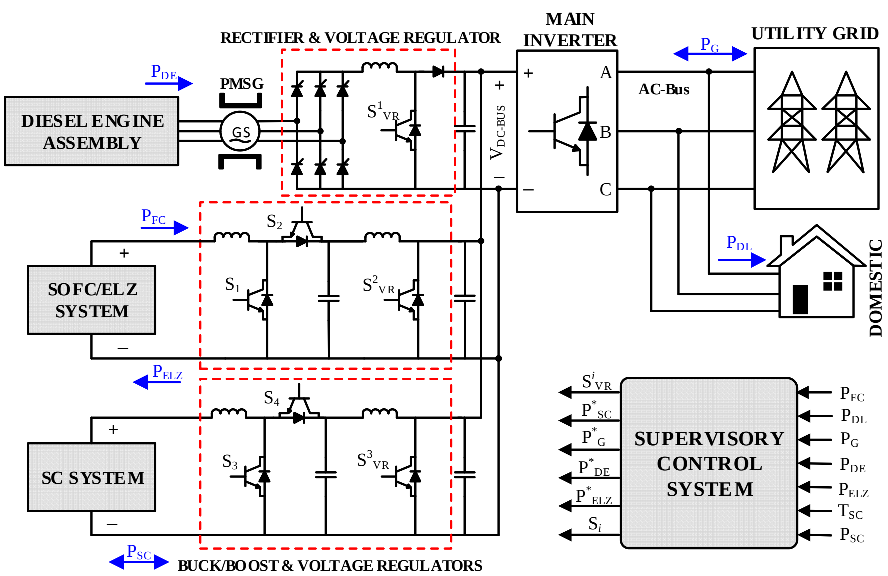


Fig. 1. Architecture of proposed DGS

2. Description of proposed Distributed Generation System

This section briefly explains the proposed Distributed Generation System (DGS). The entire structure of proposed DGS is shown in Fig. 1. It is made up to two-bus system; DC Bus and AC Bus. DC bus is formed by DE, SC and hydrogen system (SOFC) while the AC Bus is structured with utility grid and Domestic Load (DL). DE is mechanically coupled with a Permanent Magnet Synchronous Generator (PMSG). The hydrogen system (SOFC) and SC are connected via buck-boost converter followed by voltage regulator.

3. Modeling and control of proposed DGS components

3.1. Diesel Engine Assembly

In this research, a 40 kW DE is mechanically coupled with a PMSG. A three-phase Pulse Width Modulation (PWM) based inverter is used to transfer power from generator. A boost converter based voltage regulator is used to stabilize the output voltage to DC-bus level.

The governor block diagram is shown in Fig. 2. The generator and engine are operated in torque control and speed control modes via electric governor and PWM inverter. The controllers are constructed in the cascaded manner; and the current regulation loop of the electric governor is the inner loop and the speed regulation loop of the DE is the outer loop. The speed control of DE through Proportional Integral Differentiator (PID) controller is shown in Fig. 3. Then the transfer function of the speed controller can be expressed as follows [12],

$$i^* = \left\{ \frac{\left(K_p + K_d\omega_d\right)s^2 + \left(K_i + K_p\omega_d\right)s + K_i\omega_d}{s(s+\omega_d)} \right\}\left(\omega^* - \omega\right) \tag{1}$$

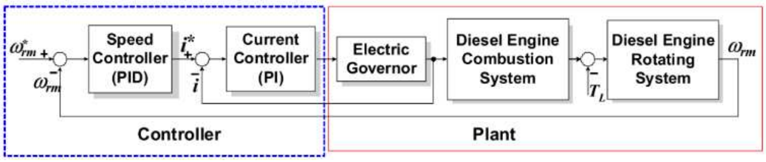


Fig. 2. Block diagram of speed controller with electric governor and diesel engine

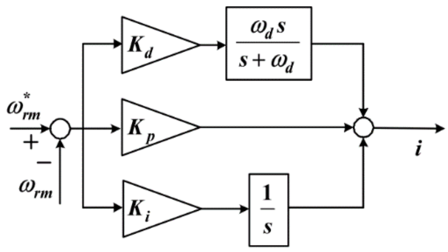


Fig. 3. Implemented PID speed controller

3.2. SOFC System

The model used in this study is based on the dynamic SOFC model explained in [13]. The effective partial pressures associated with system dynamics is given by:

$$\dot{P}_{H_2} = -\frac{1}{t_{H_2}}\left(P_{H_2} + \frac{1}{K_{H_2}}(q_{H_2}^{in} - 2K_r I_{fc})\right) \tag{2}$$

$$\dot{P}_{H_2O} = -\frac{1}{t_{H_2O}}\left(P_{H_2O} + \frac{2}{K_{H_2O}} - K_r I_{fc})\right) \quad (3)$$

$$\dot{P}_{O_2} = -\frac{1}{t_{O_2}}\left(P_{O_2} + \frac{1}{K_{O_2}}(q_{O_2}^{in} - K_r I_{fc})\right) \quad (4)$$

Using the above partial pressures, the output voltage can be calculated using the Nernst's equation given in (5) and complete dynamic model of SOFC is presented in Fig. 4.

$$V_{fc} = N_0\left[E_0 + \frac{RT}{2F}\left\{\ln\left(\frac{P_{H_2}P_{O_2}^{0.5}}{P_{H_2O}}\right)\right\}\right] - rI_{f_0} \quad (5)$$

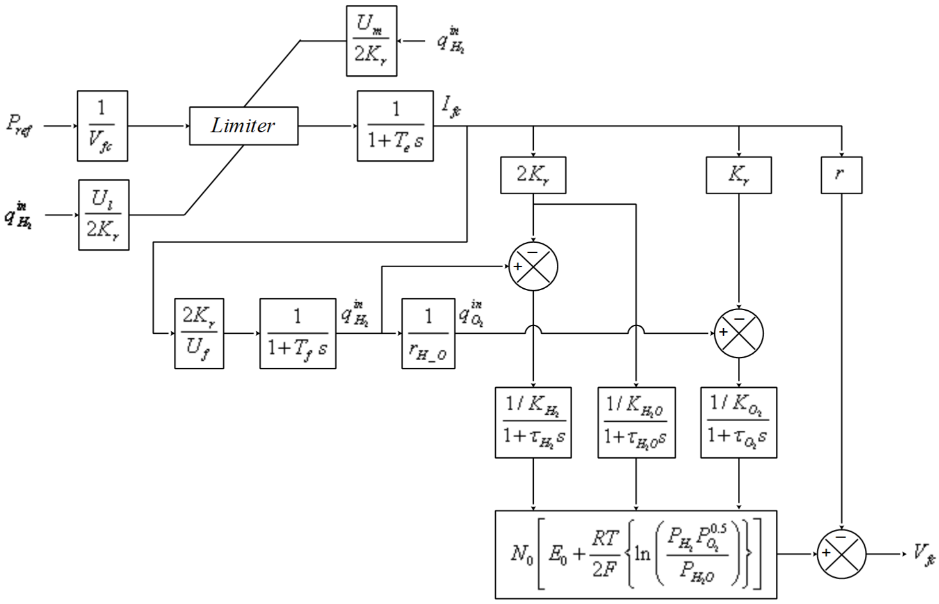


Fig. 4. SOFC dynamic model

In order to control the hydrogen system, the PID based DC-DC buck/boost converter is used. The reference voltage is calculated using reference power generated by SCS. The PID generates appropriate output based on the error of reference and actual voltages. The PWM generator encodes output into a square wave pulse of corresponding duty cycle. The control strategy of hydrogen system is shown in Fig. 5.

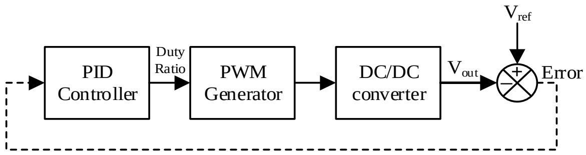


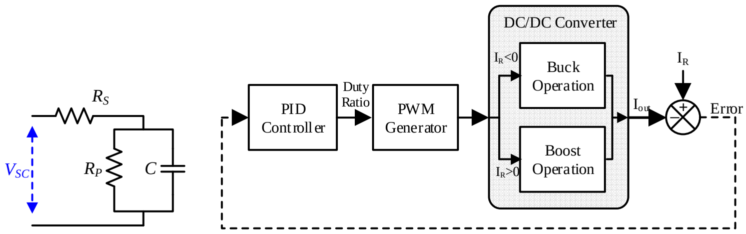
Fig. 5. Control strategy of hydrogen system

3.3. SC System

In this paper, classical model of SC is used which consists of double layer capacitance, an equivalent series and an equivalent parallel resistances as shown in Fig. 6(a). V_{SC} represents the output voltage of single SC unit. The energy produced/consumed by SC depends upon its capacitance, initial voltage and final voltage, respectively and given as:

$$E_{SC} = \frac{1}{2} C (V_i^2 - V_f^2) \tag{6}$$

The UC is connected to the DC-CPC through DC-DC buck-boost converter. The buck-operating mode is used for charging of UC and vice versa. The DC-DC converter control system work on reference current calculated from reference power generated by SCS. The control diagram of buck-boost converter is shown in Fig. 6(b).



(a) **(b)**

Fig. 6. SC system (a) Model of SC (b) Control system of DC-DC converter

3.4. Main Inverter System

The DC-Bus is coupled with load and grid through three phase inverter. The entire control scheme is shown in Fig. 7. Initially, the PI controller is used to minimize the difference actual and reference power of inverter. Based on error, the PI generates corresponding dq-references. Using dq/abc transformation, current in-terms of abc reference is generated. After taking difference with actual currents, it will passed through hysteresis comparator and it generates the corresponding signals for inverter switches.

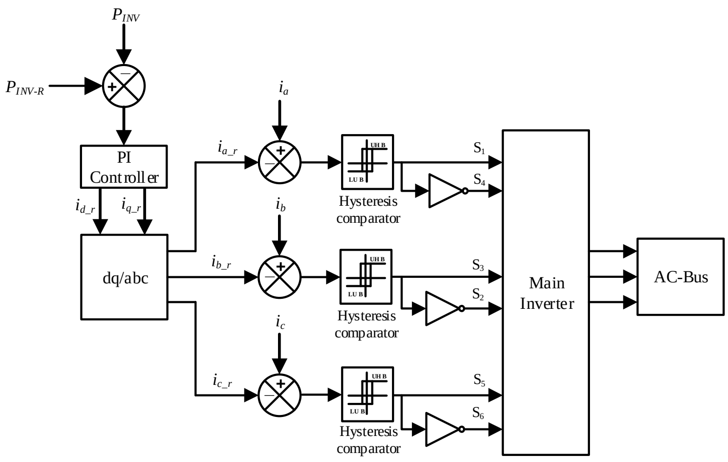


Fig. 7. Control schematic of main inverter

4. SCS of proposed DGS

In order to provide uninterruptable power supply to the DL, the SCS is designed. The key role of SCS is to deliver maximum power from available resources (DE/SOFC/SC/UG) to fulfil the DL demand. The power flow between different energy sources are managed by SCS. Based on available resources, the SCS generates required power references. In order to achieve required power, SCS generates the appropriate signals to control power converter. In this case, SCS operates on several inputs: SOFC actual power (P_{FC}), DL power demand (P_{DL}), DE output power (P_{DE}), UG output power (P_G), Electrolyzer power demand (P_{ELZ}), SC output power (P_{SC}) and its SOC (T_{SC}). Using the above variables, the power balance equation, along with excess and deficient power can be written as;

$$P_{FC} = P_{DL} \pm P_{SC} \pm P_G - P_{DE} + P_{ELZ} \quad (7)$$

$$P_{EX} = P_{DL} - P_{FC} = -(P_{SC} + P_{ELZ} + P_G) \quad (8)$$

$$P_{DF} = P_{DL} - P_{FC} = P_{SC} + P_G + P_{DE} \quad (9)$$

where P_{EX} and P_{DF} represents the excess and deficient power inside the system.

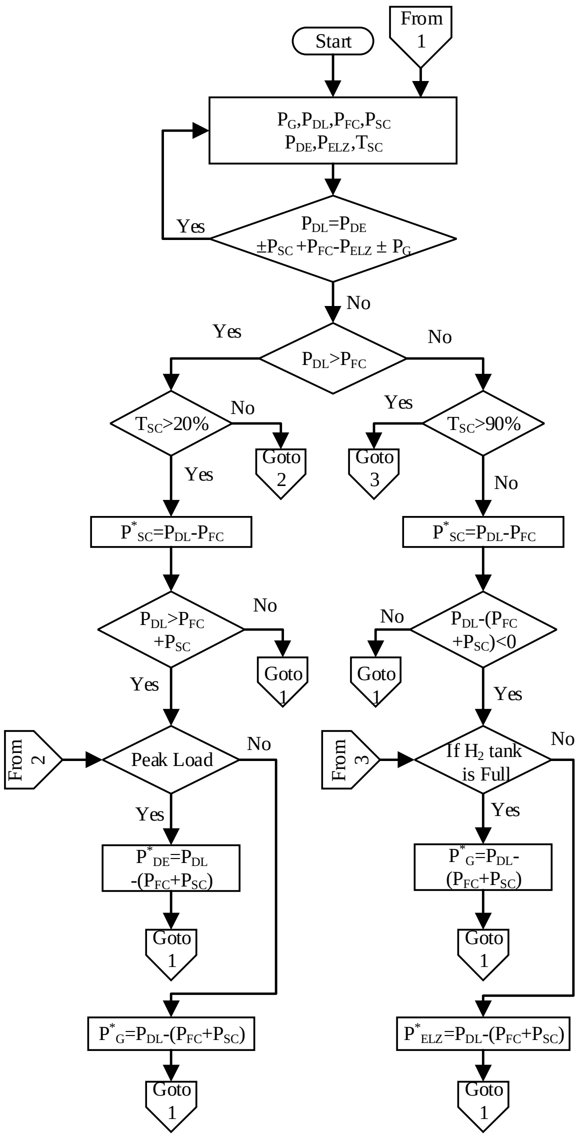


Fig. 8. Flow chart of power management algorithm

In order to prevent system from blackouts or synchronization issues, it is needed to develop the power management algorithm for SCS. This algorithm operates on basic seven inputs (i.e., actual powers of each sources and SOC of SC). The developed algorithm for SCS is shown in Fig. 8, and described below.

Algorithm 1: Power Management Algorithm

1: Power output/demand of all energy sources (and SOC of SC) are monitored.
2: **if** $P_{FC} = P_{DL} \pm P_{SC} \pm P_G - P_{DE} + P_{ELZ}$,
3: Goto 1, **end**
4: **if** $P_{DL} > P_{FC}$,
5: **if** $T_{SC} > 20\%$,
6: Apply reference power to SC: $P_{SC}^* = P_{DL} - P_{FC}$
7: **else** Goto XX
8: **end**
9: **if** $P_{DL} > P_{FC} + P_{SC}$,
10: **if** $P_{DL} > 50kW$,
11: Apply reference power to DE: $P_{DE}^* = P_{DL} - (P_{FC} + P_{SC})$
12: **else** Apply reference power to UG: $P_G^* = P_{DL} - (P_{FC} + P_{SC})$
13: **end**
14: **else** Goto 1
15: **end**
16: **else**
17: **if** $T_{SC} > 90\%$,
18: Goto YY
19: **else** Apply reference power to SC: $P_{SC}^* = P_{DL} - P_{FC}$
20: **end**
21: **if** $P_{DL} < P_{FC} + P_{SC}$,
22: **if** $Tank_P \approx 15kPa$
23: Apply reference power to UG: $P_G^* = P_{DL} - (P_{FC} + P_{SC})$
24: **else** Apply reference power to ELZ: $P_{ELZ}^* = P_{DL} - (P_{FC} + P_{SC})$
25: **end**
26: **else** Goto 1
27: **end**
28: **end**

5. Simulation Results and Discussion

To check the effectiveness and performance of proposed algorithm, a test-bed containing different sources/loads is developed in Matlab/Simulink by means of simpower system toolbox. During development of test bed, the rated power of DE, SOFC, SC, inverter and UG are considered as 40 kW, 50 kW, 100 F an 100 kW and 500 kVA, respectively. The simulation is performed for one day while considering actual domestic load conditions of Behria Town, Islamabad Pakistan.

For better exploration of results, the time interval of one day is divided into four time slots. The power output/demand of different energy sources at different time slots are shown in Fig.s 9 to 12. In these Fig.s, the blue solid represents the actual power of source/load while red dotted line represents the reference power of applied converter for corresponding sourse/load. Before explaining results, it is important to remember that the maximum power output of SOFC is 50 kW.

Fig. 9 shows the simulation results for t=0-6 Hrs. In this time slot, the DL demand gradually increases from 23 kW to 38 kW as illustrated in Fig. 9 (a). From Fig. 9 (c), the UG is at off peak hour and delivers two power peaks (8 kW and 10kW). Therefore, using power balance equation, the power demanded from DC side (i.e., inverter power reference $P^*_I = P^*_{FC} + P^*_{DE} + P^*_{SC}$) is less than 50 kW as shown in Fig. 9 (e). Thus, SOFC easily fulfil the entire load demand. However, due to rapid change in load and slow response of SOFC, the SOFC is unable to track the load. In this case, SC hideout SOFC load tracking drawback by providing rapid power at every hour as depicted in Fig. 9 (f).

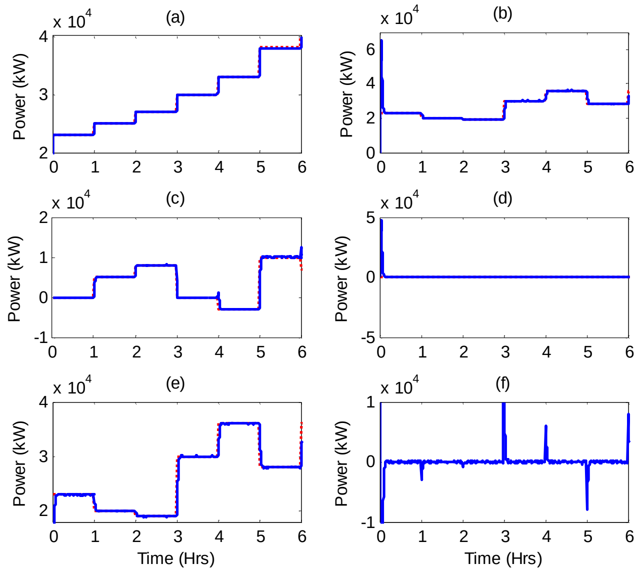


Fig. 9. Actual and reference powers of energy sources for t=0-6 Hrs (a) DL (b) SOFC (c) UG (d) DE (e) Main Inverter (f) SC

Looking towards Fig. 10 (a), the DL demand gradually increases to 67 kW (peak load) from 43 kW. At t=6-8 Hrs, the DL is 48 kW, which is less the maximum power rating of SOFC. While on same side, the UG delivers 10 kW power. Thus, it is not needed to activate DE (its output power is zero). At t=8-12 Hrs, the DL becomes greater than 50 kW. UG is also at isolated mode due to peak load hours. Hence, using last reserve, the SCS turned on the DE, providing maximum output of 24 kW as shown in Fig. 10 (d). As both SOFC and DE have rapid load tracking drawback, SC overfills the power gap created by them at every hour as illustrated in Fig. 10 (f).

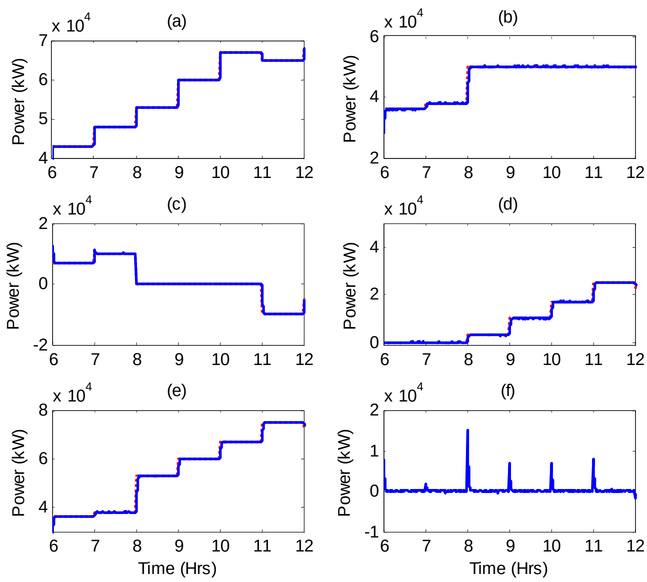


Fig. 10. Actual and reference powers of energy sources for t=6-12 Hrs (a) DL (b) SOFC (c) UG (d) DE (e) Main Inverter (f) SC

The simulation result for t=12-18 Hrs is shown in Fig. 11. The DL load demand decreases from 68 kW to 48 kW as shown in Fig. 11 (a). Additionally, UG is at peak hours while consuming 15 kW of power. Subsequently, SOFC does not hold off DL burden. In this regard, the SCS keep DE on until (17 Hrs) DL demand decreases 50 kW as shown in Fig. 11 (d). In final hour of this slot, the UG back online, assisting SOFC to overcome load demand as shown in Fig. 11 (c).

As stated earlier, SOFC is the primary energy source. But, due to off peak hours, the load burden is less than 50kW for t = 0-8 Hrs. 50kW is the maximum rating of SOFC. From Fig. 9(a), after 8 Hrs, the load demand is greater than 50kW (except 17,18Hrs), Therefore, SOFC delivers it maximum available power of 50kW. The output power vs time graph of SOFC is shown in Fig. 9(b) where red dots shows reference power while blue line shows actual power. On other side SC keep tackling with rapid loads.

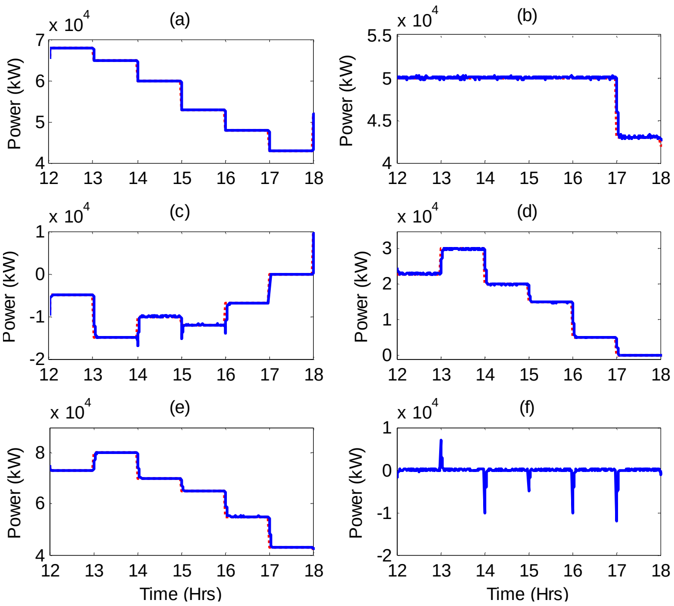


Fig. 11. Actual and reference powers of energy sources for t=12-18 Hrs (a) DL (b) SOFC (c) UG (d) DE (e) Main Inverter (f) SC

The simulation results of final time slot is shown in Fig. 12. The peak load of entire day falls in this time slot at 20-21 Hrs (i.e., 70 kW). At t=18-19 Hrs, the DL demand is 52 kW. However, the UG provides 18 kW, so, overall power demanded for SOFC is 42 kW (below 50 kW). Therefore, DE is kept off by SCS. At t=19-24 Hrs, UG is again isolated from the system due to peak load hours. Thus, in order to achieve high DL, the SCS turned on SOFC and DE as shown in Fig.s 12 (b) and (d). At t=20 Hrs, there is a significant change in load is observed. At this time, the SC provides a peak power of 16 kW.

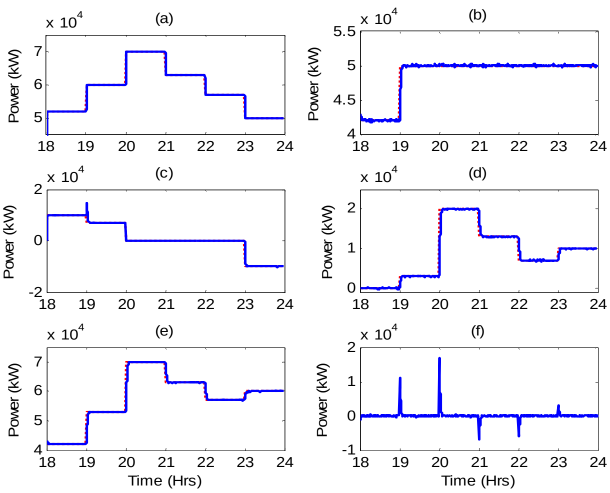


Fig. 12. Actual and reference powers of energy sources for t=18-24 Hrs (a) DL (b) SOFC (c) UG (d) DE (e) Main Inverter (f) SC

6. Conclusion

This study concludes the modelling, control and an energy management for a SOFC/DE/UC hybrid power plant for DG applications. All the energy sources and storage system are controlled by their respective controllers while the overall coordination among SOFC, ELZ, DE, UC storage system and loads is performed by the developed SCS. The weak load following problems of SOFC has addressed by using UC. The proposed system uses the waste fuel of SOFC in order to maximize the overall system efficiency. The proposed plant can be used with or without grid and/or can be synchronized with multiple DG sources to shave the load power during peak hours. The performance of the proposed model is tested for real load conditions. From the simulation, it is clear that the developed system meets all the conditions required for the stability and power quality of power system.

Acknowledgements

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