Energy Management System and Control of Grid-Connected Solar Energy System

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***Abstract*— This manuscript explains an energy management and control of grid-connected Hybrid Renewable Energy System (HRES). It describes a Solar source and hybrid energy storage system based on hydrogen technology (fuel cell), and battery. DC/DC converters are used to connect all the energy sources and storage system to a common DC bus. The output of DC bus is integrated to the national grid through three phase inverter to increase the continuity of power. The proposed HRES is working under classical-based supervisory control algorithm. According to the proposed algorithm, the wind is used the primary energy source to satisfy the load demands. The fuel cell is used to ensure long-term energy balance by using the hydrogen technology. The battery is utilized as a backup and high energy density device to keep the DC-bus voltage constant. The performance of the HRES is verified under real-world record of wind speed and load variations for the twenty five households at Islamabad, Pakistan. Matlab/Simulink results are provided to show the right performance of the proposed system in terms of load tracking, voltage regulation, and grid stability**

Keywords*— *Energy management, Wind system, Fuel cell, Hybrid storage system, Stability and power quality analysis

I. Introduction

Energy crisis, increasing environmental issues, high depletion rate of fossil fuels and modern advancement in power control technology make the use and integration of Renewable Energy Sources (RESs) more noticeable. Among the major types of RESs, wind energy is considered the fastest evolving technology due to its mature and easily plant installation nature [1], [2]. As a clean candidate, the recent development in wind power technology has opened the path by utilizing wind power for distributed generation to meet the grid demand [3], [4]. However, the output power of wind system is highly dependent on wind passive generator which cannot guarantee perfect services to the grid as wind is an intermittent and uncontrollable energy source [5]. The best way to solve this problem is to design a HRES with an effective management approach.

A HRES eliminates the deficiency of a single energy source by selecting the best possible advantage of each individual energy source and/or storage device [6]. Besides this, it is highly desirable that HRES must have some short term energy storage system such as battery or long term storage medium such as hydrogen technology (fuel cell). The Fuel Cell (FC) utilizes hydrogen as a fuel to generate clean power. There are several types of FCs. Among the major types of FCs, the Solid Oxide Fuel Cell (SOFC) can accomplish efficiency at least 50%, but it has a slow power response time [7]. The weakness of the slow dynamics can be balanced through battery. Since, an integration of FC, Electrolyzer (ELZ) with a wind / battery can represents a an effective HRES. First, surplus power from wind can either used by the ELZ to produce fuel (hydrogen) for FC or to be stored in the battery. Second, the battery has a fast dynamic response, which provides better stability of the HRES during transient stages created by sudden variations of wind and demand. Third, this wind/FC/ELZ/battery integration can increase the efficiency of the entire system by power sharing so as to make the operation of a FC in a high efficiency zone.

Many HRESs have been stated in the literature. For instance, in [8], [9], the author designed and analyzed the life cycle of small wind/FC HRES. In [10], [11], a wind/FC and PV/FC/battery combined systems are modelled and controlled. A wind based power system with hydrogen storage is simulated in [12]. In [13], the author design a management system for FC with a battery hybrid tramway. Power quality problems and reliability assessment of wind based systems are targeted in [14], [15]. In [16], the author proposed power control and synchronization of wind energy system with utility. Similarly, various wind based hybrid systems simulated in [17]–[19]. There are some drawbacks in all the above mentioned studies. For example, some authors include short energy system in their studies, while others concentrate on long term storage medium. Some authors describe power control of wind energy system while others attempt to address the energy management without providing power sharing among different energy sources and/or storage system. In addition to this, most of the authors supported their studies on the basis of virtual generated wind speed.

This manuscript presents a grid connected HRES combining SS, SOFC, battery and ELZ while considering the real wind speed and load variations for the twenty five households at Islamabad, the capital of Pakistan. The proposed HRES works under the supervision of Classical-based Energy Management and Control Algorithm (CEMCA). The proposed algorithm effectively managed all the energy sources and storage system according to different wind speed and load conditions. The proposed combination and algorithm ensures 24 Hrs power flow with better reliability and stability.

This paper is prepared as follows. First, system description is focused in Section II. Next, Section III explains the control of system components. Section IV focuses on the energy management of the entire system. Simulation results are given in Section V followed by the conclusion in Section VI.

II. Description of Hybrid Renewable ENERGY System

The proposed system is structured in two buses-DC bus and AC bus. SS, SOFC, ELZ and battery make the architecture of DC bus, and the power transferring among these components happens through a proper CEMCA. Domestic Load (DL) and National Grid Station (NGS) are connected to AC bus. The output voltages of SS and SOFC are regulated through two DC–DC boost converters while the bidirectional power flow of battery with the rest of the system happens through a buck boost converter. The output of DC bus is integrated to the NGS and/or grid connected load via three phase inverter. The CEMCA works in such way to track the load for 24 Hrs if only one source is available. The dynamic performance and stability of the proposed algorithm requires the simulation of the HRES over a long time. Therefore, steady-state simulation models have been performed for each distinct component. Figure 1 indicates a schematic layout of the proposed HRES.

III. Control of System Components

A. Control of SS System

The output power of SS system depends on the variation of wind speed. To effectively utilize the SS system, it is always operated at Maximum Power Point (MPP). To track the MPP of the SS system, a DC–DC boost converter controlled through torque reference-based Maximum Power Point Tracking (MPPT) is used. This MPPT control method keeps the operating point of the SS on its maximum power coefficient for any wind speeds, adjusting the duty cycle of the DC–DC converter, which produces a variation of its rotational speed. The control system for SS is depicted in figure 2. The relation between optimal torque and mechanical angular velocity of the PMSG rotor is given as

$$ {}_{m\ optopt}\quad {}_{m}^{2} \qquad (1)$$

where α_{opt} is the optimal constant in-terms of optimal tip speed ratio.

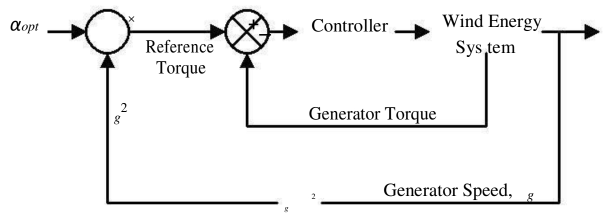

Fig 2: Control of SS system

B. Control of SOFC System

The assembly of SOFC is linked with DC bus through boost converter. Here, the boost converter is controlled via Proportional Integral Differentiator (PID) controller. The PID controller tries to reduce the error, which is the difference of reference voltage by CEMCA and actual voltage of SOFC. The output of PID controller denotes the variation in duty cycle. The output voltage generated by boost converter is based on duty cycle provided by PWM generator. The control system for SOFC is depicted in figure 3.

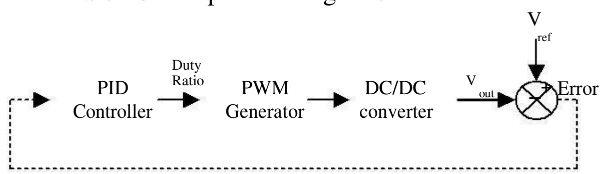

Fig 3: Control scheme of SOFC/ELZ system

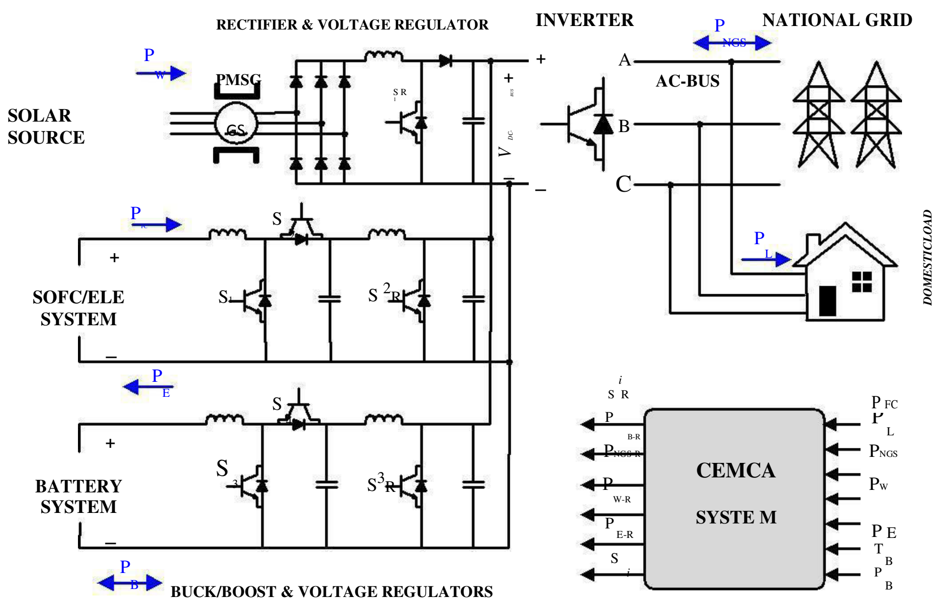

Fig 1: Complete structure of proposed HRES

C. Control of Battery System

The linking of the battery to the DC bus is established though DC-DC buck-boost converter. The power flow from the battery to the DC bus is made via boost mode while the buck mode is used to charge the battery from DC bus. The PID controllers are used to control the battery buck-boost converter. The control diagram of buck-boost converter is depicted in figure 4. I_R is the reference current determined as $I_R = P_{B-R}/V_B$.

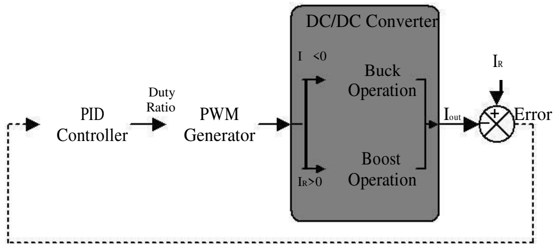

Fig 4: Control scheme of battery system

D. Control of Inverter

The DC bus of the HRES is connected to the grid through a three phase inverter. Here, the inverter is controlled using Proportional Integral (PI) controllers followed by hysteresis current control scheme as depicted in figure 5. The proposed control scheme generates suitable pulses for driving the controllable switches of the inverter. The PI controllers try to reduce the error which is the difference between the reference and actual values of the active and the reactive powers. The PI controllers adjust the error and thus control the corresponding powers. It is essential for the grid current to be in phase with the grid voltage and has unity power factor. Therefore, a phase locked loop is used which estimates and adjusts the phase angle of grid voltage. The estimated phase voltage angle is then used to synchronize the inverter to the grid.

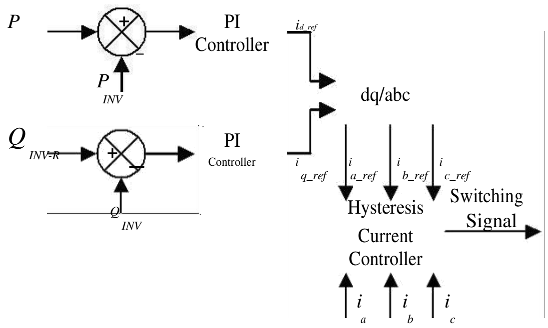

Fig 5: Control scheme of inverter system

IV. CEMCA of Proposed System

The proposed CEMCA is capable to satisfy the load demands for the 24 Hrs using the SS/SOFC/ELZ/Battery HRES. The CEMCA performs the entire energy measurement. Based upon the requirement, the CEMCA provides the control signals for the energy sources and/or power converters attached in the HRES. The operating schemes employed in the CEMCA are as follows:

The power provided by SS system has the priority in satisfying the demand over that supplied by the SOFC and/or the battery system.

If SS system generates more power than the demand, the surplus power will be utilized to charge the battery bank.

If still there is surplus power in the system, then it will be supplied to NGS followed by ELZ to produce hydrogen for SOFC

Likewise, if the total power produced by the SS system is less than the demand, then the required power will be provided from the SOFC.

If the net power supplied by the SS/SOFC combination is less than the demand, then battery system will be transferred the required power.

If still the power demand exceeds, then the difference will be covered from the NGS.

Based on the above stated points, the proposed algorithm work flow is shown in figure 5.

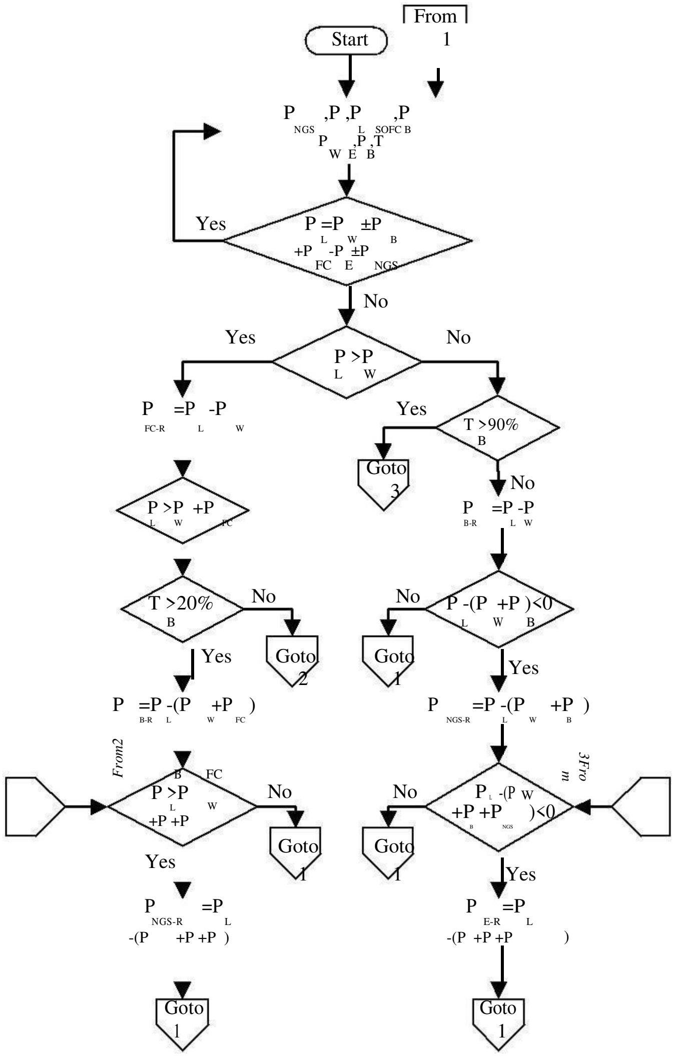

Fig 6: Work flow of proposed algorithm

The proposed algorithm is divided in the following operating modes: Mode A: Excess Power Battery Charging SOFC Disconnected NGS Extracts ELZ Connected (EPBCSDNEEC), Mode B: Deficient Power Battery Charging SOFC Connected NGS Delivers ELZ Off (DPBCSCNDEO), Mode C: Deficient

Power Battery Discharging SOFC Connected NGS Delivers ELZ Connected (DPBDSCNDEC), Mode D: Deficient Power Battery Discharging SOFC Connected NGS Delivers ELZ Off (DPBDSCNDEO), Mode E: Deficient Power Battery Discharging SOFC Connected NGS Extracts ELZ Connected (DPBDSCNEEC), Mode F: Deficient Power Battery Discharging SOFC Connected NGS Extracts ELZ Off (DPBDSCNEEO)

A. Mode A: EPBCSDNEEC

In this mode, the SS generates power more than the load demand. Therefore, there is no need of SOFC in this mode. Since, SOFC is disconnected, while the excess power generated by SS is used for battery charging purposes. There is still excess power presented in the system, because, battery charges only with its predefined rate of charge. This excess power is supplied to NGS while the residual is used for electrolysis.

B. Mode B: DPBCSCNDEO

This operating mode lies for a very short period of time, but this is a very important mode. Here, the system encountered the shortage of power from SS side and needs a backup system. So, SOFC is turned on and start supplying its maximum available power. On the other side, the battery plays an unpredictable role, because, battery is still charging in this mode regardless of deficient power. This behavior of the battery is due to its slow charging/discharging rate. In this state, the CEMCA moves out from mode A (i.e., from excess power to deficient power), but due to predefined charging rate of battery, still it does not restore it to its discharging state. Hence, in this case, NGS facilitates SOFC on overcoming load demand with no residual excess power inside the system which keeps the ELZ in off state.

C. Mode C: DPBDSCNDEC

This is the most common operating mode generated by CEMCA, which lies for the majority of time period. In this case, the system faced a shortage of power from SS side and SOFC is immediately turned on to overcome the shortage. But it falls due to its maximum power limitations. The shortage of power exceeds the maximum power given by SOFC. Therefore, the last options are the battery and NGS. They not only fulfills the load demand, but also produces some excess power which is utilized by ELZ.

D. Mode D: DPBDSCNDEO

This mode is like to mode C. In this mode, the system met the shortage of power which is caused by SS system. The active players of this mode are SOFC, NGS and ELZ. The SOFC providing its maximum power along with battery which provides energy with a predefined rate of discharge and NGS satisfies residual shortage with no excess power remains in the system. Therefore, ELZ has no role in this mode.

E. Mode E: DPBDSCNEEC

Here, the SS is unable to satisfy the load demand. The SOFC provides its maximum available power. The battery also provides its maximum power with pre-defined discharging rate. The NGS extracts power from the system. This abnormal behavior of NGS is due to battery discharging rate. Actually, upon rapid decrease in load demand, the battery output power also starts decreasing, but it only decreases with its defined rate of discharge. Therefore, this power gap leads in injection of excess power inside the system which is consumed by NGS followed by ELZ.

F. Mode F: DPBDSCNEEO

In this mode, the SS is unable to meet the demand and the shortage of power is managed from the combination of SOFC and battery. The NGS absorbs all the excess power generated by SOFC/battery with no residual excess power. Hence, ELZ has no role in this mode.

V. Simulation Results And Discussion

Here, first load data are explored and then simulation results at various conditions are described.

A. Rated Powers

For the real time testing of proposed CEMCA, rated capacity/power of various components of HRES are given in table I.

Table I: Ratings of HRES components

Name	Rating
Solid Oxide Fuel Cell	30kW
National Grid Station	500kVA
Solar source (Cut off Speed)	68kW (12m/s)
Battery Bank	3×200Ah
Main Inverter	100kW
DC/DC Boost Converters	$700V_{out}$

The DL varies from 20 to 70kW considering power factor at unity

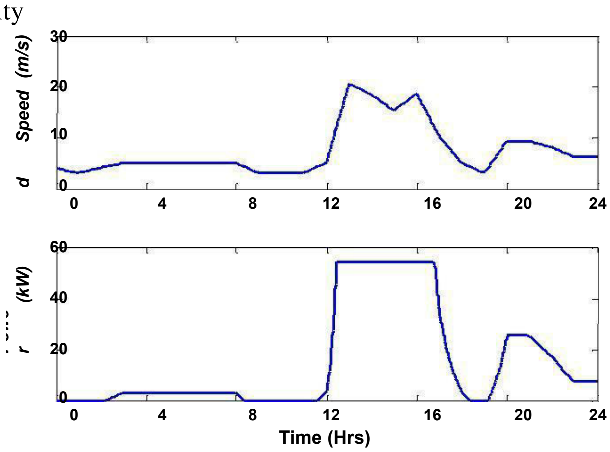

Fig 7: Wind speed and output power vs time

B. Dynamic Load & Wind statistics

The proposed HRES is developed for a small community of homes at Bahria Town, Islamabad Pakistan. The overall demand for a single home is calculated hourly basis by averaging and fixed loads e.g., averaging is used for lighting load while fixed load is determined for refrigerator, air conditioners etc. By using the above strategy, the minimum, average and peak loads are calculated as 0.9 kW, 2.02 kW and 2.98Kw, respectively. The peak load starts from 18 Hrs and ends at 21 Hrs. The wind speed is recorded for the above stated location. The corresponding wind output power is shown in figure 7.

C. Simulation Results

The simulation is performed for one complete day of summer. The output powers of different energy sources for a complete day are shown in figure 8. The results of all operating modes described earlier and the performance of different energy sources and/or storage system are explained below.

Domestic Load: Figure 8 (a) shown the DL for an entire summer day i.e., 10 June 2015. It starts from 22kW and reach to 67kW. This is the first peak of load due to day time with air conditioner load included. Then after 14Hrs, the load reduces due to afternoon time. Later on, due to evening time, the load re-increases and contains the highest peak of day i.e., 70kW.

Solar source: The wind output power is generated under real weather condition taken from different local and international weather channels [20]. From 3Hrs to 8Hrs, SS generates 8kW of power while it generates maximum of 54kW at 12.5-16.7Hrs. After 20Hrs, it also generates 25kW of power.

SOFC: Keeping in-view table I, the maximum power provided by SOFC is 30kW. Considering figure 8(a), the DL demand is less than 30kW for 0-4.2Hrs in entire time period. Therefore, upto 4.2Hrs, SOFC provides its maximum power and satisfies the load demand while after 4.2Hrs to 12.4Hrs, the load demand exceeds SOFC maximum power, then it only provides 30kW of power (maximum). The remaining shortage is handover to other sources. Similarly, after 12.1Hrs, the SS starts generating sufficient power, So SOFC output power starts decreasing and no need at 15.1-17Hrs as shown in figure 8 (c).

Battery: Each battery has its own pre-defined rate of charging and discharging power. This is the main limitation of battery system. From figure 8(d), till 4.1Hrs, there is no need of battery, because, SOFC satisfies all the load demand, so its power is zero. After that till 12Hrs, the SOFC/SS are unable to satisfy the load demand, hence the battery output power starts increasing. Similarly, from 12-16Hrs, the SS satisfies the load demand, so the battery starts charging. Furthermore, after 20Hrs again the SS output power is less than load demand, so battery overfills the shortage created by SOFC.

National Grid Station: For the continuous power supply, the grid contributes its role regardless of the peak and off peak hours. From figure 8(e), till 12Hrs, the grid is not sufficiently required, because, all the load demand is satisfied by SOFC/SS/Battery. From 12-16Hrs, the battery is in discharging mode, because, SS satisfies the load demand. Therefore, due to battery discharging, the system contains an excess power and the power is successfully consumed by grid followed by ELZ. Similarly, for 16-20Hrs, grid delivers 11kW of power.

Electrolyzer: Usually, the system contains excess power at each step change in load demand with higher in magnitude at decreasing load demand. The excess power which is left from NGS is effectively consumed by ELZ as shown in figure 8(f).

The operating mode vs time graph generated by the proposed CEMCA is shown in figure 9. Most of the time, CEMCA lies in mode C and D.

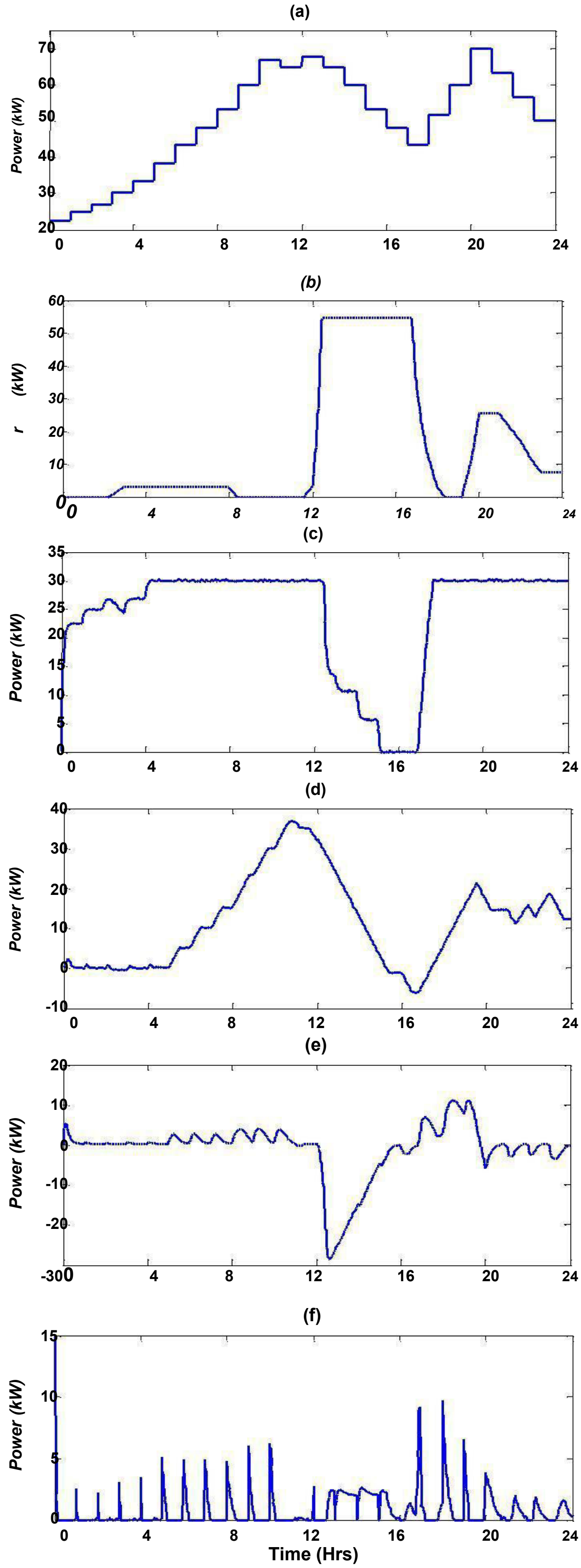

Fig 8: Output powers (a) P_L (b) P_W (c) P_{FC} (d) P_B (e) P_{NGS} (f) P_E

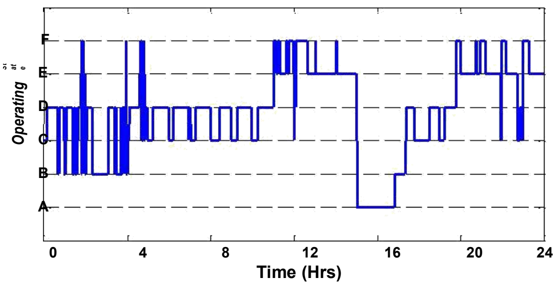

Fig 9: Operating mode vs time graph

For a stable system, it is essential to utilize all the power produced in the system so that the net power inside the system become zero. The stability analysis of this system with CEMCA is shown in figure 10, which represents that the system is stable. Furthermore, figure 11 indicates that the DC bus voltage is inside standard limits

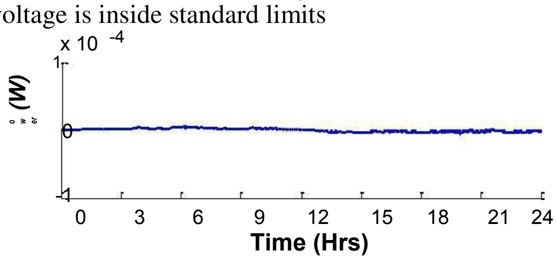

Fig 10: Net power inside the system

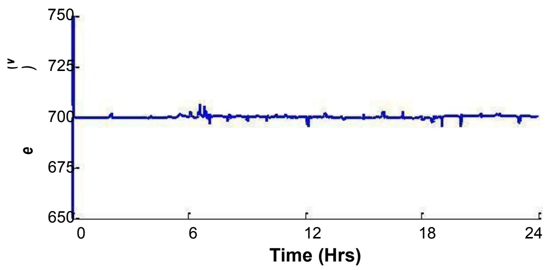

Fig 11: DC-Bus Voltage

VI. Conclusion

This paper concludes a classical based energy management and power control of HRES, which is composed of renewable energy source (SS), hydrogen energy (SOFC), and battery.

The proposed CEMCA removes the deficiency of a single power source and provides a SS/SOFC/ELZ/Battery HRES which meets the load demand for 24 Hrs without any interruption. The dynamic behavior of the proposed HRES is tested under real-world record of wind speed and load variations. Matlab simulation is performed to confirm the effectiveness of the developed system in terms of load tracking, voltage regulation and grid stability

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