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Coordinated Energy Management of A Hybrid PEMFC-Based Microgrid Using Cascaded PI Control

Vishal Pandhari Porje#1**, S. S. Hadpe***2**, Dr. S. S. Khule****3 #**M.E.Student,**
1vishalporje38@gmail.com

Assistant Professor,

2somnath.hadpe@matoshri.edu.in

***Head of Department,*

3 shridhar.khule@matoshri.edu.in

Electrical Engineering Department

Matoshri College of Engineering and Research Centre, Nashik., Maharashtra, India

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***Abstract*—** In this paper, designed and controlled a hybrid microgrid with proton exchange membrane fuel cell (PEMFC), lithium-ion battery, and supercapacitor to achieve a reliable and efficient power source under dynamic load changes. To enable this, a cascade proportional and integral (PI) control strategy is developed for managing the power allocation amongst different storage sources while simultaneously maintaining the state of charge (SoC) of battery and stabilizing DC bus voltage. With this approach, fuel cell is primarily responsible for supplying the average power demand, while the battery and supercapacitor handle the transient and peak power requirements. A thorough system modelling is carried out using MATLAB/Simulink and simulations are performed to verify the proposed strategy under several load conditions with the real component parameters and various load profiles. The results show that the PI based controller properly allocates the power flow among the sources, which helps to maintain the DC bus voltage stable during sudden changes in load, and in faulty cases. Several performance metrics including voltage regulation, power allocation efficiency, and transient response of the system are evaluated. The comparison with the optimal power management algorithms shows that this simple PI control strategy has lower computation cost than the optimization methods.

Keywords*— *Battery energy storage, Cascade control, Microgrid, Proton exchange membrane fuel cell (PEMFC), and Supercapacitor

I. INTRODUCTION

Due to the increased usage of renewables and the trend of distributed power generation, microgrids become flexible and resilient distributed energy systems. Microgrids integrate various energy sources, storage systems, and loads to increase the grid's sustainability, resilience, and efficiency. However, the unpredictability of renewable sources and load fluctuation cause a number of operating issues. The challenges include the maintenance of voltage, power sharing between sources, system stability and others. Hybrid microgrid systems comprising the fuel cells, batteries and supercapacitors have been a major area of research in recent years due to the unique attributes of individual components.

PEMFC is a most frequently considered power source due to its high-power density, negligible emission and ability to operate under varying conditions. The primary constraint on fuel cell use is its slow dynamic response and limited capability to cope with rapid load variations. On the contrary, the battery has medium power density and good performance in bridging the short-term load variations while supercapacitor has large power density and quick dynamic response making it more suitable for transient load compensation and fast dynamic characteristics of the load.

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These issues need careful coordination. Development of the appropriate energy management and control strategy to distribute energy effectively is crucial. Various control strategies, such as fuzzy logic control, artificial intelligent based approaches and metaheuristics, have been applied for managing energy resources and they provide excellent control performance in terms of system stability and dynamic behaviour. However these controllers tend to be complicated, they usually require numerous parameters and careful tuning. Moreover, the advanced methods are highly dependent on rule-based information or training data. Therefore, simple, reliable and easily implemented controllers are required for practical use in microgrids.

Conventional proportional integral (PI) controllers are widely used because of their simplicity in terms of implementation, computation efficiency and stable performance, but conventional PI controllers often demonstrate sluggish dynamic performance when coupled with other energy sources. Thus, a better PI based control strategy is proposed for this paper that addresses stability and energy flow.

The proposed cascade control strategy consists of a PI controller and a proportional controller for regulating power flow between the energy storage systems and loads. The outside loop is responsible for determining reference battery current based on SOC of battery while inside loop decides the current reference from fuel cell according to tracking of operating point by tracking of desired power generation from fuel cell. Another PI based controller manages the battery to ensure battery is not overcharged/ discharged.

A comprehensive simulation is carried out in MATLAB/Simulink for this system. The system comprised of fuel cell, battery, supercapacitor, DCDC converters, and DCAC inverter. A dynamic load profile varying with time has been considered in the simulation study for different scenario analysis. In this case, fuel cell provides average load while battery supports the transitional loads, sudden load variations, and peak loads. Simulation results prove that the proposed cascaded PI based control strategy can efficiently control power balance in microgrid systems and maintain the voltage across DC link. Sudden load variations are dealt with effectively by the supercapacitor and a smooth transition is obtained while maintaining voltage stability using battery, which limits voltage drop under load and compensates voltage spikes by reducing excess generated power when loads are minimum. A gradual change in fuel cell power to meet average load can be achieved with these strategies.

As compared to previously proposed intelligent control systems, this PI based controller is simpler and has lower complexity. This paper presents an approach that has potential to be used for real applications with microgrids.

II. LITERATURE REVIEW

Rapid development and distributed generation adoption have tremendously accelerated the control, energy management, and power quality improvement requirement for microgrids. Prior work mainly focused on conventional and intelligent control strategies to maintain system stability under different operating condition such as adaptive PI controller with fuzzy and hysteresis current regulation which had better dynamic response and damping for islanded microgrids [1]. However, such strategies have their limitation such as dependent on the given rule bases, and thus can hardly learn systematically or used efficiently in large network.

For this reason, optimal based control strategy with the help of metaheuristic algorithm have become the focus of both tuning controller parameter and energy management. In particular, combination of battery and supercapacitor energy storage system is optimized with the help of algorithms of weighted superposition attraction and competitive optimization, they yield better transient behaviour and THD but are formulated by single-objective criteria, and most of them cost too much computation for real time implementation which make it hard for microgrid to implement [2],[5]. Traditional PI controller-based MPPT and converter control strategy are improved by optimization to achieve energy harvest and stabilize system operation, but they rely on traditional PI scheme and lack experimental verification [3].

Besides research studies, there are reviews available on critical issue of microgrid control including power imbalance, harmonics, and complexities related to renewable integration and these works suggest the usage of advanced control, protective strategies and alternative storage technology such as flywheel, etc. However, the reviews don’t provide unified strategies and comparison to pave the way for performance-oriented data-driven control approach [4],[8].

Advanced hybrid control based on combination of fuzzy, optimization technique and coordination of storage have proposed, it provides good performance on accuracy of power sharing and reduction of THD and dynamic response, but with the trade-off of increased computation load and difficulty in tuning, thus less practical in real time system. Alternatively, fuzzy logic and intelligent based control is implemented with FACTS devices such as STATCOM controlled by BCO with better voltage control, but lack experimental verification [6],[7].

In recent days, application of AI based technology on improving power quality of microgrid is a mainstream which has explored in deep learning-based models and ANN based strategy such as kernel based deep NARX model and ANN controlled DVR, and yield excellent results for THD and voltage restoration, but have high computational complexity and cannot adapt dynamically

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without retrain. Hardware-in-loop has been used to examine these systems but still are difficult to implement in real time system due to processing bottleneck [11],[13]. Besides that, a new metaheuristic control algorithm, prairie dog optimization, has shown a superior performance but still with scalability bottleneck and high computation load [12].

There are also reviews which summarize the existing method on microgrid PQ improvement such as passive and active filtering, FACTS devices, optimal based methods and machine learning based approaches along with economic and standardization aspects. Still a framework on real time coordinated control with AI and optimal scheme on hybrid microgrid is still an open issue [14].

Another group of researchers investigated the application of hybrid microgrid with electrical vehicles, fuel cell and advanced power electronic converter, with the integration of ANN and GA based MPPT and multi-port high gain DC-DC converter. However, the architecture has been complicated into multiple layer structure with a burden for computational complexity and difficult in real-time implementation on embedded systems [15].

In conclusion, despite the evolution of control methods from conventional to intelligent and optimal based strategy has led to much performance improvement in microgrid, still face tremendous challenge such as high computation load, difficulty in scaling up the controller structure, uncoordinated objective functions, and in practical real-time implementation. These issues imply that there is a definite need of control technique that is capable to trade off performance with computation load.

Although the evolution of microgrid control from the conventional PI controller to smart and optimization-based control strategy has led to significant performance improvements, microgrid still face several critical issues such as complexity, scalability, and practical implementation. Although PI controller is commonly employed due to its ease in implementation, its limitation in adaptation on fast dynamic or uncertainties restricts the system performance. Furthermore, smart control method increases the computational load and require excessive tuning or retraining time. Multiple objective control coordination has yet to be properly resolved. The aforementioned factors bring up a requirement for an improved PI-based control structure that maintains its structural simplicity while possessing adaptive functionality for real-time implementation.

III. SYSTEM DESIGN AND PARAMETERS

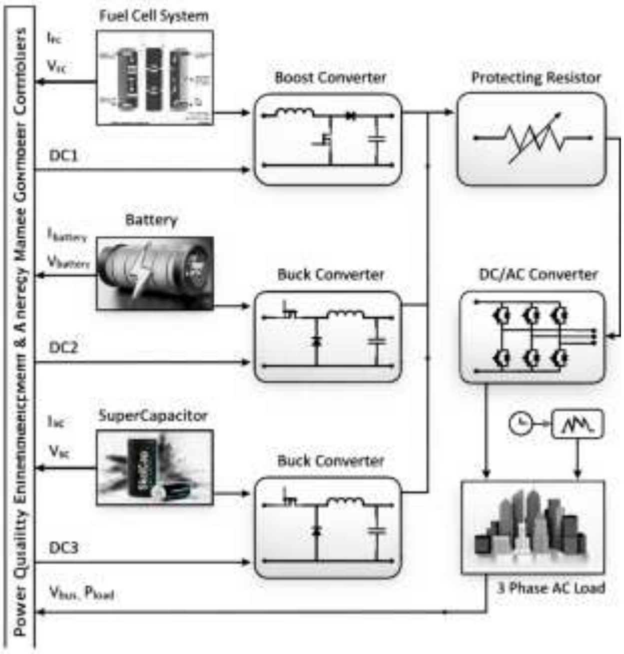

Fig. 1 Configuration of the Microgrid System

The main components of the system represented in Fig. 1 are:

A. The Fuel Cell

The 12.5 kW, DC 30 - 60 V, liquid cooled PEM fuel cell power module used is equipped with auxiliary functions such as integrated components: air blower, filtering unit, H_2 recirculation pump, H_2 pressure regulator with valves, coolant circulation pump and cooling fan. The fuel cell power module is also equipped with an internal controller to communicate with the master controller and with the safety functions (H_2 low pressure, stack high temperature, over current and under voltage).

TABLE I
PARAMETERS OF FUEL CELL

Parameter	**Value**
Rated output power	10300 W
Rated stack efficiency	50 %
Operating stack temperature	45^{0}C

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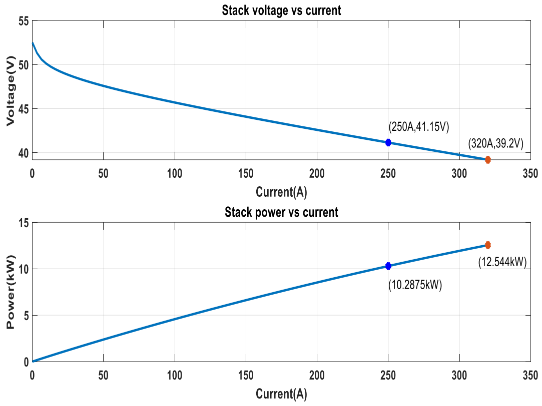

Fig. 2 V-I and P-I Characteristic of PEMFC Stack

B. *Battery*

The battery system employs four 12 V lithium-ion battery units connected in series configuration. Each module integrates an onboard controller designed for cell equalization (also termed intra module balancing), sensing cell temperature and voltage/current signals, SOC calculation..

TABLE II
PARAMETERS OF BATTERY

Parameter	Value
Rated voltage	48 V
Specified capacity	40 Ah
Starting SOC	65 %

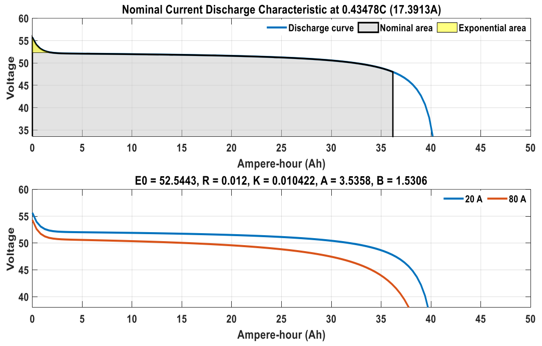

Fig. 3 Battery Discharge Characteristics

C. *The Supercapacitor System*

A series configuration is formed using six 48 V, 90 F super capacitor modules within the system.

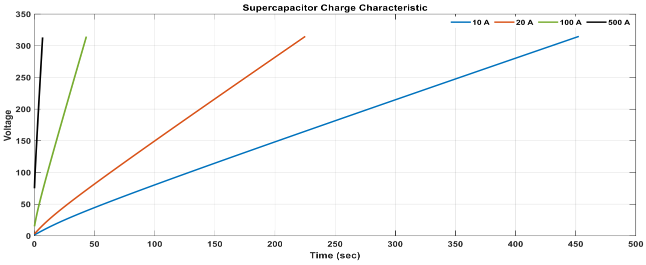

Fig. 4 Supercapacitor Charge Characteristic

TABLEIII
PARAMETERS OF SUPERCAPACITOR

Parameter	Value
Specified capacitance	16 F
Total number series capacitors	106
Nominal voltage	288 V

IV. CASCADED CONTROL LOOP STRATEGY

The main purpose of this approach is to ensure balanced power distribution while maintaining the battery SOC within predefined safe limit. Instead of directly assigning power references, the proposed method links energy management with SOC regulation. The control system is therefore arranged in two levels, where the slower dynamics of SOC correction are separated from the faster electrical response of the sources.

At the higher level, the deviation between the measured SOC and its target value is evaluated. Based on this deviation, a reference current for the battery is generated using a proportional action. The charging and/or discharging current that is required in order to achieve the desired energy state is given by this reference. Physical limitations are put on this reference to avoid too high stress on the battery. At the lower level, the control objective shifts to enforcing the current demand obtained from the upper stage. A proportional–integral (PI) regulator reduce mismatch between the actual and reference battery current. The output of this controller determines the power contribution expected from the fuel cell, thereby allowing it to compensate for any imbalance in the system. This signal is also constrained within the allowable operating region of fuel cell. In parallel, power from battery command is derived from regulated current signal through an additional PI-based adjustment, ensuring smooth charge–discharge transitions and avoiding abrupt variations in battery operation.

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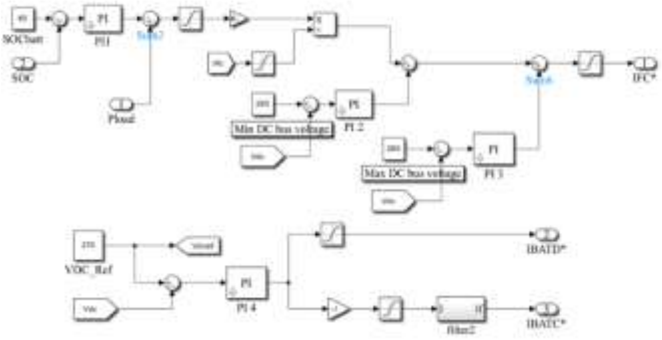

Fig. 5 Cascaded Loop Control

By separating energy regulation and dynamic tracking into two coordinated layers, the proposed cascade structure improves stability and responsiveness. The upper loop governs long-term energy balance, whereas the inner loop provides rapid correction, enabling reliable operation of the hybrid microgrid under varying load conditions.

V. SIMULATION AND RESULTS

In the present study, a microgrid, the three phase AC load supply and its associated control were modelled under MATLAB/Simulink environment as depicted in Fig. 6. The fuel cell was sized in such a way to provide steady state power of the microgrid. The bank of battery units was dimensioned so that they can aid to the fuel cell in the steady state operating conditions, while the unit of supercapacitor is designed to act for the fast dynamic load demand.

The DC-link voltage was kept constant, and stabilized by means of using boost and buck DC-DC converter topology to represent primary and secondary sources of energy respectively. The DC/AC stage was aimed at changing DC bus voltage to alternating signal to be supplied for the AC load connected to the microgrid system. A protection resistor was placed across the supercapacitor bank or inverter terminals to mitigate for the high voltages developed at those places..

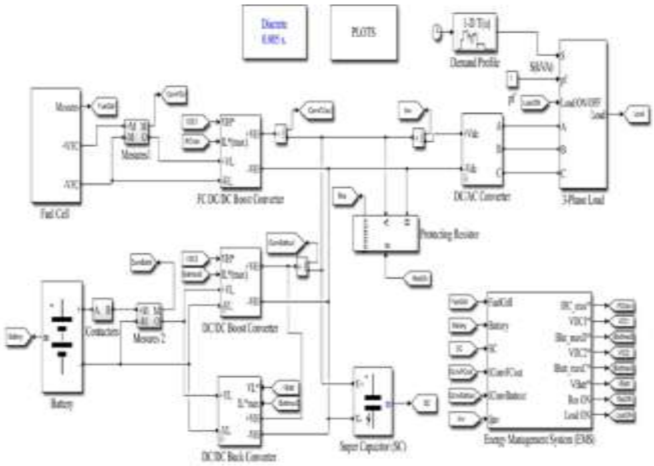

Fig. 6 MATLAB/Simulink Model of Proposed Hybrid Microgrid System

From Fig 1 it is seen that the fuel cell and battery energies are controlled via their individual DC/DC converter interfaces in microgrid arrangement. The DC/DC converter is controlled using preset input voltage set points and input and output current limits developed by the energy management system that exists in the supervisory controller. In this work, two converter units are attached to the battery because of time constraint in acquiring the required bi-directional DC/DC converter as there was no such system during the time of development. A battery management system is employed in order to safe guard the battery pack under over charging, high temperature rises and over discharge conditions. A resistance is also connected across the Supercapacitor bank or the input to inverter to suppress large voltage values across them during a transient. The load demand of the microgrid is developed by an AC/DC programmable load unit.

Responses like Fuel cell voltage, battery voltage, supercapacitor voltage, inverter input voltage, Fuel consumption rate, Load power demand, Load line voltage and Load line current are observed and displayed. These response characteristics have also been verified against their respective appropriate ranges to confirm the proper working of the proportional-integral controller and in order to establish good robustness, stability and control over the entire microgrid system..

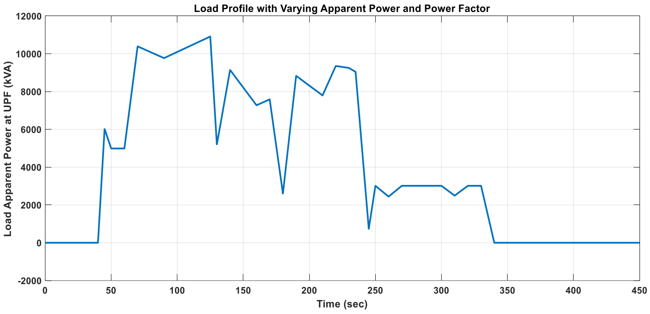

Fig. 7 Load Profile

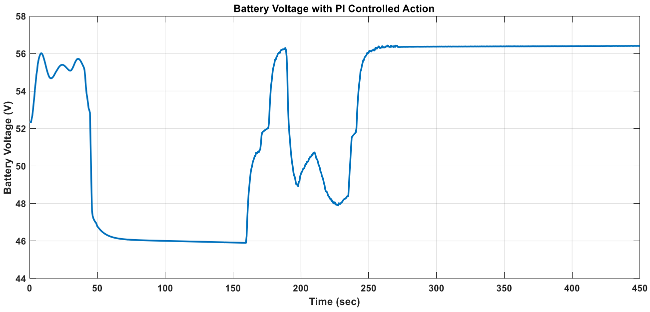

Fig. 8 Battery Voltage

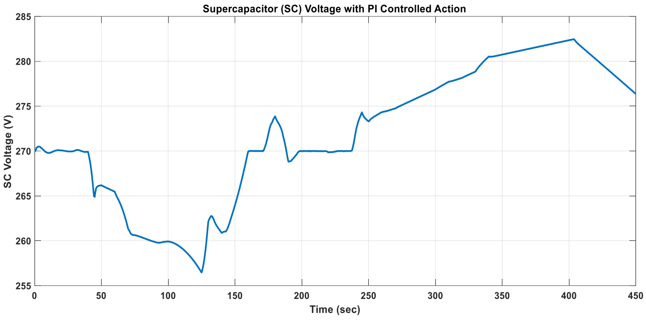

Fig. 9 Supercapacitor Voltage

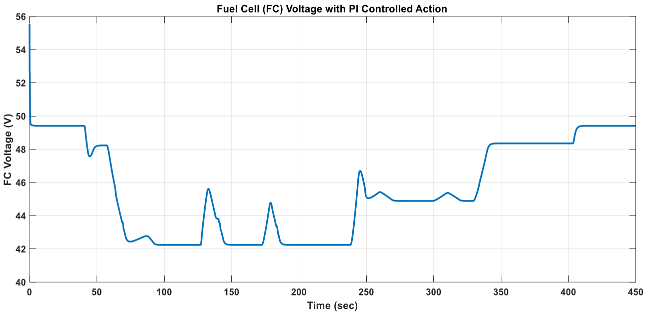

Fig. 10 Fuel Cell Voltage

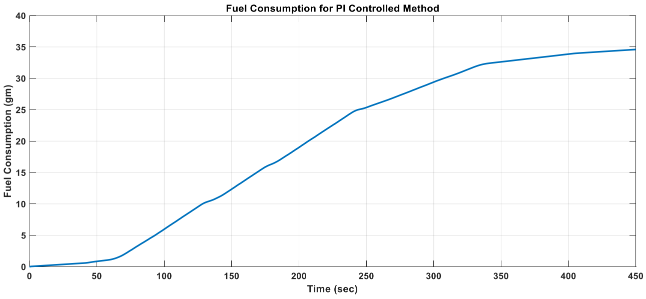

Fig. 11 Fuel Consumption by FC

Regulation of individual source output is achieved by the centrally controlled system using reference commands defining allowable voltage and current boundary values assigned separately to fuel cell and battery DC/DC converter modules.

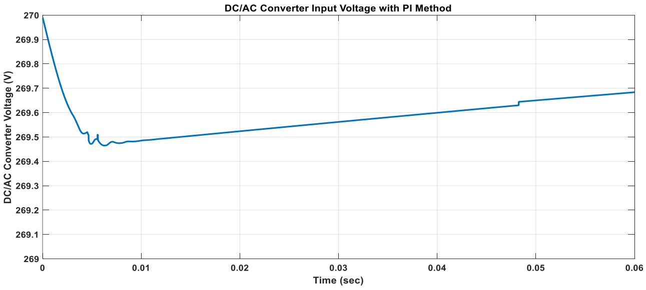

Fig. 12 DC/AC Converter Input Voltage

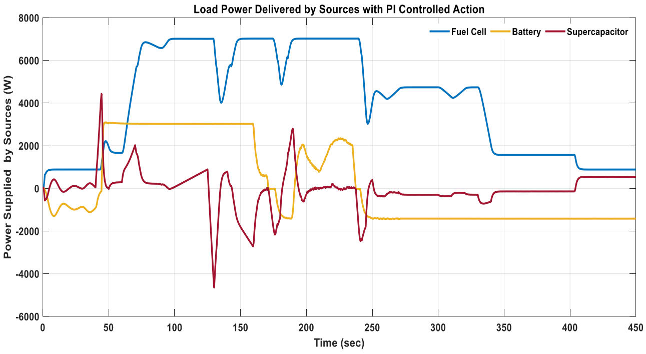

Fig. 13 Power Delivered by Various Sources

The overall sequence of events of the hybrid power system under various operating conditions throughout the simulation can be analysed from the displayed figures below. At start, essential loads are taken by main generators and the fuel cell hybrid system stands by ready for unforeseen disturbances. In 6 sec, fuel cell charges the battery with an optimum output power of around 1.2 kW. In 40 sec, generators are switched off, hybrid fuel cell system takes charge of supplying the essential loads, extra instantaneous power demand is supplied instantaneously by supercapacitor, which has much higher dynamic response compared to the gradual increase of fuel cell output.

In 44 sec, supercapacitor is in discharging state since the DC bus voltage has been kept around 269 V and the battery is in discharging mode, too in order to maintain the DC bus voltage at required level. At 49 sec, DC bus voltage or the supercapacitor voltage has reached 269 V. The battery power is switched to zero gradually and then fuel cell would be taking whole load requirement and recharge supercapacitor. At 58 sec, the second transient load is generated due to the activating of emergency hydraulic pump and the power of the extra transient load is mainly taken by the supercapacitor until fuel cell power increased. Soon after at 62 sec, the battery has again discharged to regulate the DC bus voltage at 269 V, and takes partial part of the load together with fuel cell.

In later operating stage, fuel cell output power is reached at maximum level of around 8.9 kW at 69 sec according to its input voltage constraint range of corresponding DC/DC converter. The battery is still in discharging state to satisfy another load requirement. At 109 sec, battery output power is up to maximum limit of around 3.9 kW, another load is satisfied by supercapacitor. When load demand becomes less than fuel cell maximum capacity after 124 sec, extra transient energy during operating at transient load will be charged to supercapacitor because the slow dynamic characteristics of fuel cell power generation.

In 125 sec, the DC bus voltage is stabilized at 270V. Battery power is gradually decreased to zero. Similar operation is conducted at 132 sec as the second emergency hydraulic pump is activating at that moment with similar operation as above. In later stage at 171 sec, after reducing load demand below fuel cell maximum capacity, excess power is charged to both battery and supercapacitor. Abrupt load demand increases at 179 sec, it is immediately taken by supercapacitor, then battery is in discharging at 184 sec for regulation purpose to maintain DC bus voltage constant until fuel cell power is increased.

At 233 sec, the demand of load decreased sharply, surplus fuel cell power would be charged into battery and supercapacitor. Fuel cell output power reached almost whole of load demand after 248 sec. Load demand decrease gradually to zero at 328 sec and the fuel cell power decreased toward its optimum working point, as well as battery is charging. Finally, after about 390 sec, there is negligible load demand. A decimation factor of 100 is adopted for all monitoring scopes in order to obtain better calculation efficiency and save memory; meanwhile, average value models of DC/DC and DC/AC converter are employed.

VI. CONCLUSIONS

This paper has proposed a design and control of hybrid microgrid, which is a combination of PEMFC, battery and supercapacitor. The designed control is designed to maintain steady and stable performance under the various load conditions. A cascade-based control strategy based on proportional and proportional integral controllers is designed to co-ordinate power sharing between the sources and maintain battery state of charge, as well as regulate DC bus voltage. From the simulation results performed on a MATLAB/Simulink model, it is clearly seen that the designed control can manage the interaction of different energy sources, with PEMFC maintaining the average load, and supercapacitor and battery providing for rapid, high or low current transients. Due to supercapacitor's fast dynamic characteristics, it covers short, fast dynamic loads, whereas the battery controls voltage and ensures stable operation, covers relatively slow and moderate peaks. All the results also indicate that DC bus voltage is well regulated within acceptable limits under step variations of load and emergency conditions. Compared to optimized control or intelligence-based control approaches the proposed control system has a simple structure and needs very low computation, which makes it more suitable for on line implementation. Also, by the cascade control strategy a better coordinated action is achieved maintaining a stable system. It can be summarized that an optimal combination of the control accuracy and the computation requirements of control implementation is attained.

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