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POWER MANAGEMENT AND CONTROL FOR GRID CONNECTED HYBRIDENERGY STORAGE SYSTEM UNDER DIFFERENT OPERATING MODES

1SARODAY.UDAY KIRAN, 2Sri .Dr. M.MURALI KRISHNA
1PG Student, 2Associate Professor
DEPT OF EEE
BHEEMA INSTITUTE OF TECHNOLOGY AND SCIENCE, Adoni

ABSTRACT:
Dynamic power management scheme is proposed for standalone hybrid AC/DC microgrid which constitutes photovoltaic (PV) based renewable energy source, proton exchange membrane (PEM) fuel cell (FC) as a secondary power source and battery-supercapacitor as hybrid energy storage. The power management algorithm accounts for seamless operation of microgrid under various modes and state of charge (SoC) limit conditions of hybrid energy storage, when all the sources, storages and loads are connected directly at the dc link. The power management scheme (PMS) generates current references for dc converter current controllers of fuel cell, battery and supercapacitor. The average and fluctuating power components are separated using moving average filter. The dc link voltage regulation under dynamic changes in load and source power variation is proposed. Also, PV power curtailment through control is formulated. The proposed power management is modified and extended to multiple photovoltaic generation system and batteries with all the sources and storages geographically distributed operating under multi-time scale adaptive droop based control with supervisory control for mode transition. The proposed power management scheme is validated using simulation results.

I. INTRODUCTION

The demand of Hybrid AC/DC micro grid (MG) has increased significantly with increased penetration of renewable energy sources such as photovoltaic array (PV) at low voltage ac distribution sector. Increased number of dc loads such as plug-in vehicle, telecom load, central computer center, emphasizes the need of evolving microgrid suitable for both ac and dc loads [2]. The key challenges involves regulation of voltage and frequency of ac microgrid, dc link voltage regulation for both ac/dc system, unbalanced load operation as well as dynamic power balance due to This work is partially supported by DST, Govt. of India under its project “UK India Clean Energy Research Institute” with project no. RP03413G and partially supported by Department of Electronics and Information Technology (DEITY), Govt. of India under Visvesvaraya PhD Scheme. The authors are with Department of Electrical Engineering, Indian Institute of Technology, Delhi, 110016, India. (email- rishikant.iitd@gmail.com, sukumar@iitd.ac.in) - intermittency of renewable energy sources and uncertain nature of load variation [1]. The PEM fuel cell (FC) is an electrochemical device which provides a reliable steady state power however, is unable to meet the power transients owing to its slow response of internal thermodynamic and electrochemical process [3]-[6]. The system is often subjected to sudden change in load and source powers (PV) which leads to high fluctuation at dc link voltage and may affect the MG performance [1]. To avoid such contingencies, hybrid energy storage (HES) which is combination of high energy density and high power density needs to be introduced to supply/absorb steady state and transient power components in MG [8]-[9]. Thus, hybrid power source comprising PV as a primary source and fuel cell as a secondary source along with battery-supercapacitor (SC) as HES is a promising combination to operate the system in standalone mode [7]. The dynamics of variation in ac/dc load as well PV power are reflected at dc link voltage. Thus, its control plays determined role in dynamic power management of MG. In [6], fuzzy logic controller based on flatness property for dc voltage regulation is used for PV, FC and SC standalone system.

The power reference of FC is obtained using low pass filter (LPF) and does not consider the over and under-utilization of H2. The LPF introduces lag in the reference power generation of FC so SC has to supply both transient and constant power. Due to this SC voltage will hit its high/low limit frequently. In [7], with application of PV, FC, and battery-SC for DC system, has reduced the burden on SC by using battery-SC combination. The operation of PV at off maximum power point (MPPT) based on power management scheme is the key issue which should be considered carefully. In [10], operation of PV, FC and SC is presented for islanded microgrid under unbalanced and nonlinear load condition. The paper lacks the effective energy management.

The separation of average and transient power component for battery and SC is also a key issue. In [14], wind/load power fluctuations are mitigated using battery-SC combination where the average current reference is obtained by passing load current through low pass filter (LPF). Also, in [11], dc link voltage controller generates average component of current references through LPF. This LPF introduces significant time lag and dominant pole near to origin which may hamper system stability. In [12] and [13], moving average filter (MAF) computes time average value and provides average current reference without much lag and instability. The multi-time scale control presented in [20]-[21], depends on hierarchical control solving economic dispatch problem with exchange of power from grid as well as SoC optimization. While the proposed work does not involves solving any economic dispatch problem, day ahead scheduling and power exchange from grid, nor it relies on dedicated central controller for its operation. For parallel operation and proper current sharing of multiple DC sources (DG) with converters in a distributed way, the output voltage reference of the converter operates in voltage droop mode defined by virtual resistance [17]. The multi-time scaling is categorized as (i) slow time scale DGs and (ii) fast time scale DGs. The conventional method to obtain muti-time scale droop for DGs with different dynamic responses utilizes the concept of virtual output impedances where the droop constant is multiplied with low pass filter for slow time scale DGs and multiplied by high pass filter for fast time scale DGs [15], [16] and [22].

In this paper, two dynamic power management schemes are proposed for two different hybrid AC/DC microgrid configurations. The first configuration (MG1) consist of single PV and PEM fuel cell based hybrid power sources, single battery and supercapcitor based HES with dc loads and three phase inverter fed ac loads. Here, all the sources and HES are interfaced to dc link directly through their dc-dc converters, assuming they are at same geographical location, as presented in Fig. 1. The second configuration (MG2), consist of multiple PVs, single PEM FC, multiple batteries (BES) and single SC with dc and ac loads. Here, all the sources and storages are interfaced to dc link through cable connected at their individual dc-dc converters such that they are geographically distributed, as shown in Fig.

The proposed dynamic power management scheme (PMS) plays key role in dc link voltage regulation, current references generation and reference current tracking by current controller to drive dc-dc converters of PV, FC, SC and battery. The main contributions of the proposed dynamic power management scheme for MG1 and MG2 are 1. For MG1, current reference generation for PEM FC, Battery and SC using single dc link voltage controller. 2. For MG1, separation of average and transient current references using moving average filter (MAF). 3. For MG1, allocation of different current references to input current controllers of dc converters of PEM FC and HES by mode based power management algorithm to drive the system seamlessly from load dominating condition to generation dominating condition while maintaining power supply reliability even if the battery SoC and SC voltage are in limit condition. 4. The operation of PEM FC with effective utilization of H2 is also ensured. Also, control based de-rating operation of PV boost converter is presented. 5. For MG2, muti-time scale adaptive droop based control with input current controller to operate the DGs in distributed way is proposed. A novel MAF based droop is used for time-scaling of fast and slow DGs. The SoC based adaptive droop is proposed for operation of multiple BES. 6. For

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MG2, supervisory control based mode transition signal employing low bandwidth communication (LBC) is proposed to operate the sources/storages in droop mode/ MPPT Mode/ SoC control mode/ Voltage control mode

1.2 Configuration of hybrid system

Figure shows the basic configuration of hybrid system discussed in this study. The hybrid system was consisted of reduction gear, main-motor (EM1), sub- motor (EM2), engine, power controller and battery. It was supposed that a double-motor system was prepared for the driving system discussed in this study. At first, acceleration was assisted by was applied only by main motor when the driving speed was low, while the corporation by two motors was often achieved
to drive the system.

If the SOC (state of charge) of battery was decreased below the specific threshold, the battery was charged by sub-motor. This operation was priority to over other actions. Figure 2 shows the modified configuration of hybrid system proposed in this study.

In the modified system, CVT was utilized to keep constant revolution numbers of the sub-motor when the sub-motor contributed to assist the system.

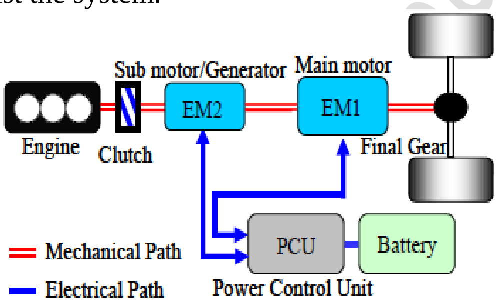

Figure 1 Schematic view of double motor hybrid system

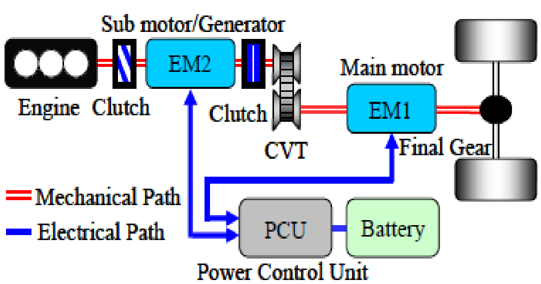

Fig 1. Schematic view of double motor hybrid system with CVT

II.FUEL CELL

A fuel cell is an electrochemical cell that converts a source fuel into an electrical current. It generates electricity inside a cell through reactions between a fuel and an oxidant, triggered in the presence of an electrolyte. The reactants flow into the cell, and the reaction products flow out of it, while the electrolyte remains within it. Fuel cells can operate continuously as long as the necessary reactant and oxidant flows are maintained.

Fuel cells are different from conventional electrochemical cell batteries in that they consume reactant from an external source, which must be replenished a thermodynamically open system. By contrast, batteries store electrical energy chemically and hence represent a thermodynamically closed system. Many combinations of fuels and oxidants are possible. A hydrogen fuel cell uses hydrogen as its fuel and oxygen (usually from air) as its oxidant. Other fuels include hydro carbons and alcohols. Other oxidants include chlorine and chlorine dioxide.

Fuel cells come in many varieties; however, they all work in the same general manner. They are made up of three segments which are sandwiched together: the anode, the electrolyte, and the cathode. Two chemical reactions occur at the interfaces of the three different segments. The net result of the two reactions is that fuel is consumed, water or carbon dioxide is created, and an electrical current is created, which can be used to power electrical devices, normally referred to as the load.

III.PHOTOVOLTAIC CELL AND ARRAY MODELING

A PV cell is a simple p-n junction diode that converts the irradiation into electricity. Fig.3.2 illustrates a simple equivalent circuit diagram of a PV cell. This model consists of a current source which represents the generated current from PV cell, a diode in parallel with the current source, a shunt resistance, and a series resistance.

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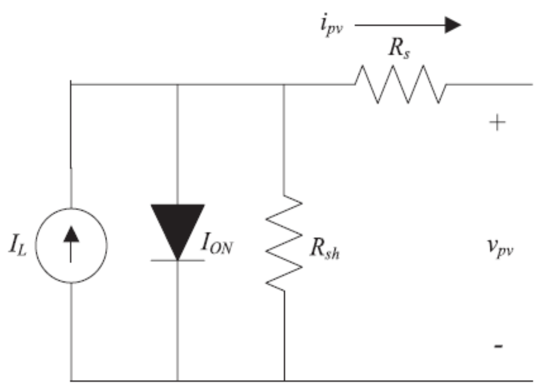

Fig.2 Equivalent circuit diagram of the PV cell

IV. PROPOSED MULTI-TIME SCALE DROOP BASED POWER MANAGEMENT SCHEME

The power management scheme for MG 2 is modified and extension of that proposed in Section III. In this scheme, the current reference generation and its tracking are executed locally in a distributed way based on individual system available measurements while mode transition signal is obtained from supervisory control using low bandwidth communication channel (LBC)[19], having access to system critical parameters responsible for mode change. To operate the microgrid (MG2) having sources with different dynamic response such as PEM FC, batteries and super capacitor, a muti-time scale adaptive droop constituting MAF is implemented for proper power sharing and generation of current references while inner current controller tracks these references to drives the dc-dc converters by generating desired duty ratio.

4.1 Reference Current Generation and Tracking

The parallel operation and proper current sharing of multiple DGs with converters in a distributed way, the output voltage reference of the converter operates in voltage droop mode. Also, multiplication of measured voltage deviation with reciprocal of virtual resistance is done for proper current sharing [15].

$$V_{oi}^{*} = V_{dcr} - R_{di} * i_{oi}$$

Where ∗ is output voltage reference, N is dc link nominal voltage, 'N is the virtual resistance or droop and \ is the output current of ith converter. The droop constant is defined as the reciprocal of virtual resistance and is given by

$$D_i = \frac{1}{R_{di}} = \frac{I_{ri}}{\delta(1-\delta)V_{ri}}$$

Where

Irl and Vrl are rated output current and voltage of ith DG while t is output voltage tolerance in percentage

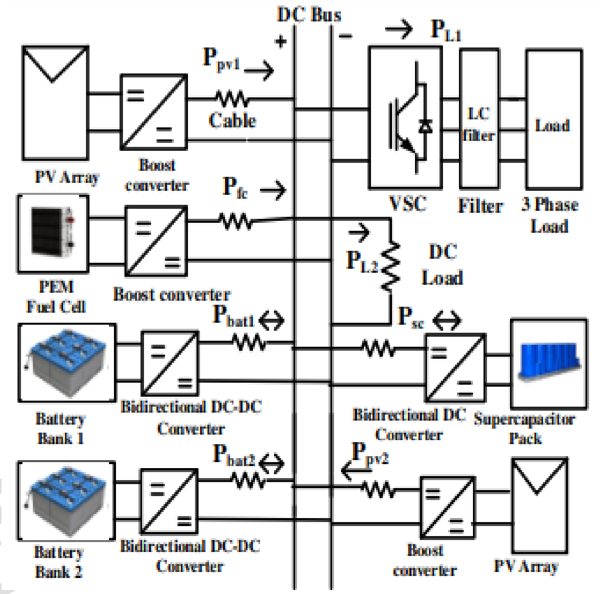

Fig 3: Hybrid AC/DC Microgrid configuration 2

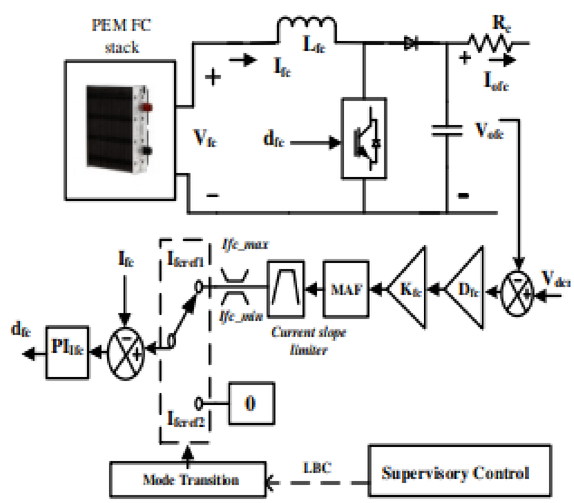

Fig.4. PEM FC time scale droop based control

The reference current for PEM fuel cell must be slow time scaled while satisfying criterion (6). The FC boost output voltage deviation is multiplied by droop constant Dfc to get desired output current sharing which is scaled by factor Kfc to obtain the corresponding input current.

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Now, the obtained input current reference is slow time scaled by passing it through MAF and current slope limiter to get the desired FC boost input current reference Ifcref1. The PI based input current controller tracks the desired current reference and generates the FC boost converter duty ratio dfc, as shown in Fig. 7. The reference dc link voltage of the DGs also considers the voltage drop due to cable resistance and is given by [18]

$$V_{dcr} = V_{dcn} + R_c * I_{oi}$$

Where Vdcn is the nominal dc link voltage, ' is cable resistance and is the output current of ith DG. And, the scale factor Ki is given by

$$K_i = V_{oi}/V_{ini}$$

Where, Voi and Vini are the output and input terminal voltage of the ith DG. The supercapacitor converter output voltage deviation is multiplied by droop constant DSC and scaled by factor KSC. Now, the obtained current reference ISC1 is passed through MAF and its error with ISC1 serves as the SC converter input current reference ISCref1. The ISCref1 is fast time scaled and shares the transient current using droop control. The obtained input current reference is tracked by PI controller to generate SC converter duty ratio ddroop, as shown in Fig. 8. The SC voltage control loop similar to (15) generates ISCref2 and inner PI current controller generates duty ratio dvsc for SC converter. The battery current reference must be slow time scaled as well as the current sharing must depend on its present SoC status, hence time scaled adaptive SoC based droop control is proposed. The adaptive SoC droop constant exhibits (i) the battery with higher SoC must be discharged at higher rate while battery with low SoC must be discharged at slow rate. (ii) The charge/discharge current shared must be proportional to their capacity (Ah). (iii) The battery with lower SoC must be charged at higher rate [18]-[19]. The proposed adaptive SoC based droop constant senses the output voltage deviation of the converter ebi, and changes the droop constant value accordingly for the charge and discharge mode

$$D_{bi,charge} = \frac{C_{bi}}{C_{bm}} \xi exp\big(\phi * (SoC_{BL} - SoC_i)\big),\ e_{bi} < 0$$

$$D_{bi,discharge} = \frac{C_{bi}}{C_{bm}} \xi exp\big(\phi * (SoC_i - SoC_{BH})\big), e_{bi} > 0$$

Where, %f is the capacity of ith battery, %f is the capacity of battery with highest Ahr. w and y are the tuning parameter. ze% is the SoC of the ith battery energy storage (BES). The obtained output current by multiplying droop constant with ebi is now scaled by factor Kbi to get input current reference Ibref2. This current reference is slow time scaled by passing through MAF to get the desired BES converter input current reference Ibref1. The inner PI based current controller tracks the desired current reference and generates the converter duty ratio ddroop. The SoC control loop for BES similar to (14) generates current reference Ibref3 and the inner controller tracks the reference current and generates duty ratio dSoC, as shown in Fig. 9. When multiple photovoltaic generation system geographically distributed are connected to dc link through cable, then they may operate either in MPPT mode or droop mode/OFF MPPT. The MPPT algorithm generates the reference PV voltage Vpv. The outer PI based voltage controller tracks the reference voltage and generates the inner current reference for boost converter Ipvref2. The PI based inner current controller tracks Ipvref2 and produces duty ratio dmmpt for boost converter [18]. For operation of PV at OFF MPPT, droop based control is adopted [19]. The output terminal dc voltage obtained using droop (27) and the error is passed to PI based voltage control loop which generates the boost converter input current reference Ipvref1. The PI based current controller tracks

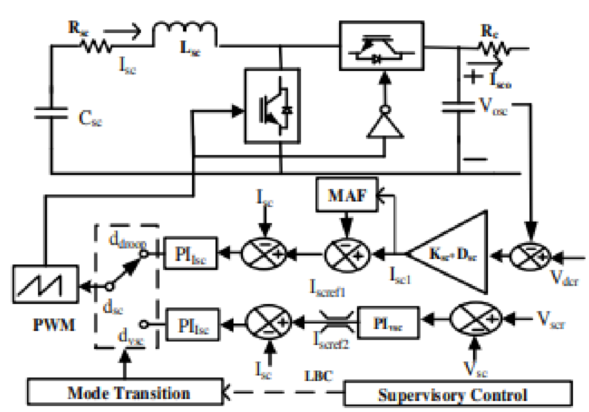

Fig. 5.SC time scale droop based control.

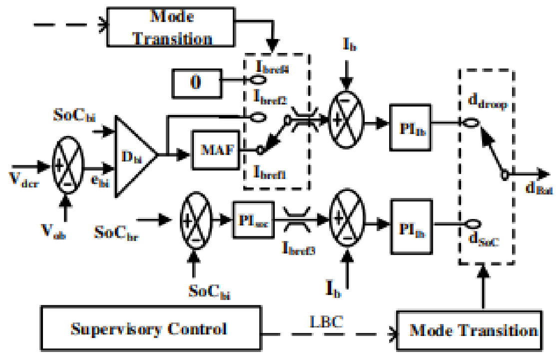

Fig. 6. BES time scaled adaptive SoC based droop control

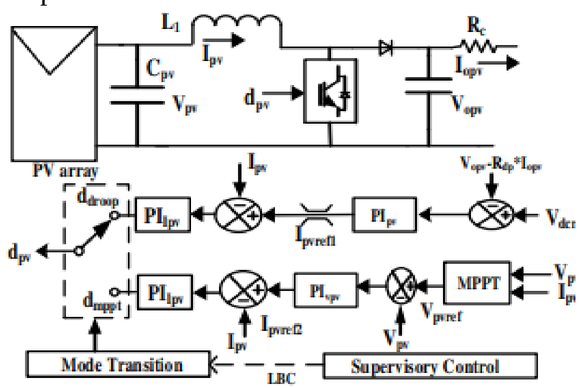

Fig 7 PV MPPT/droop control.

V.MATLAB DISCUSSION&SIMULATION RESULTS

The hybrid AC/DC microgrid configuration 1 is simulated under various modes and conditions discussed above to validate the proposed dynamic power management scheme 1 under dynamic load and source power variation. All the components are modelled in Matlab/Simulink in simpowersystem domain and parameters used for simulation..

5.1 Scenario I:

During t=0 to t=4 s, the system is working in Mode II, Condition F as the PV power is less than load power, as shown in Fig.5.1 . The deficit power is supplied by fuel cell, battery and SC, according to (22). At t= 2 s, PV power changes from 6.4 kW to 7.4 kW while at t= 4 s, load power decreases from 7.6 kW to 5.5 kW. Now, the hybrid microgrid operates in Mode I Condition A. Consequently, FC power start decreasing while SC and battery absorb power to maintain dc link voltage, as illustrated in Fig.5.2 and Fig.5.4. The battery absorbs the average power while SC compensates the oscillatory and transient power as per (17), as shown in Fig. 5.4 . At t=7 s, battery SoC reaches its maximum value SoCBH (80%), hence system experiences critical Condition B and is presented in Fig.5.5. As a result, the power management scheme generates current references based on (18) and executes PV de-rating loop to match load and PV power, as shown in Fig. 5.1. At t=8 s, the load power decreases to 4.6 kW. Again, PV de-rating loop decreases the PV boost converter duty ratio to force the SC current zero, as shown in Fig. 5.1 and Fig. 5.3. At this instant, SC supplies/absorbs a very small oscillatory power. At t =11.45 s, SC voltage reaches its maximum value VSCH, hence system enters into Mode I Condition D, as shown in Fig 5.1. Now, the dc link voltage is controlled to de-rate the PV power such that it power matches the load power, as presented in Fig. 12. At this instant, SC, battery and FC supply zero powers based on (20). Three phase line to line voltage of VSC output (380 V rms) and load current is shown in Fig.5.4.).

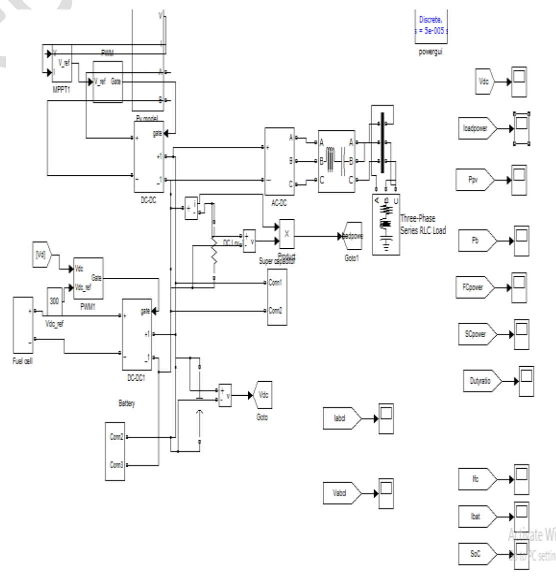

Fig 8: simulink model of proposed system

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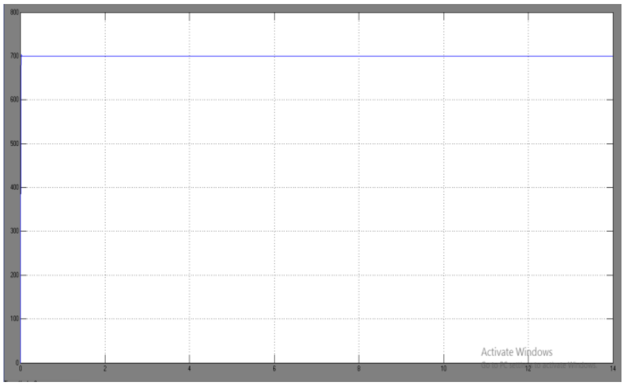

Fig 9 Vdc

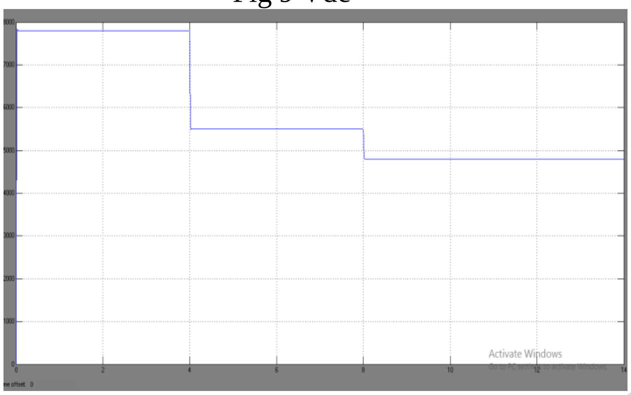

Fig 10 Load power

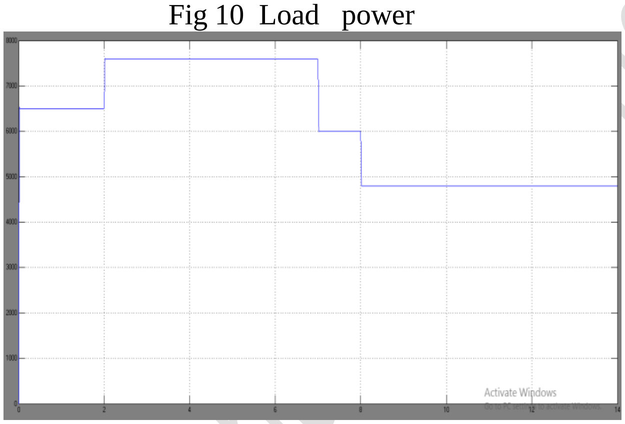

Fig 11 PV power

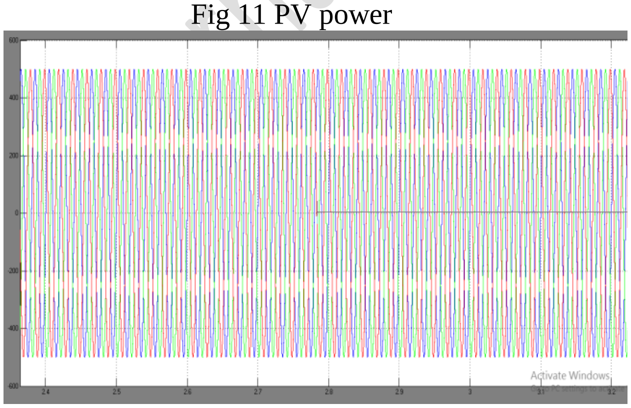

Fig 12 Load Current

5.2 Scenario II:

In this scenario, load dominating mode conditions are simulated. At t=2 s, PV power reduces from 5.5 kW to 4.5 kW and at t=4 s, again reduces to 3.4 kW, as shown in Fig. 5.8 and Fig. 5.9. During t=0 to t= 6 s, load power of 6.4 kW is more than PV power hence the system operates in Condition F. The average deficit power is supplied by the FC assisted by battery and transient/oscillatory power being supplied by SC as per (22) and is shown in Fig. 5.9. At t=6.1 s, battery reaches its lower SoC limit SoCBL (20%), as presented in Fig.5.10. Now, the power management algorithm produces current references according to (23) as system experiences Condition G. At t=9.94 s, the SC voltage reaches its lower voltage limit VSCL, therefore system experiences Condition I. Thus, PM produces zero current references for battery and SC while average current reference is supplied by FC as per (25) and the converter current controller track these references effectively

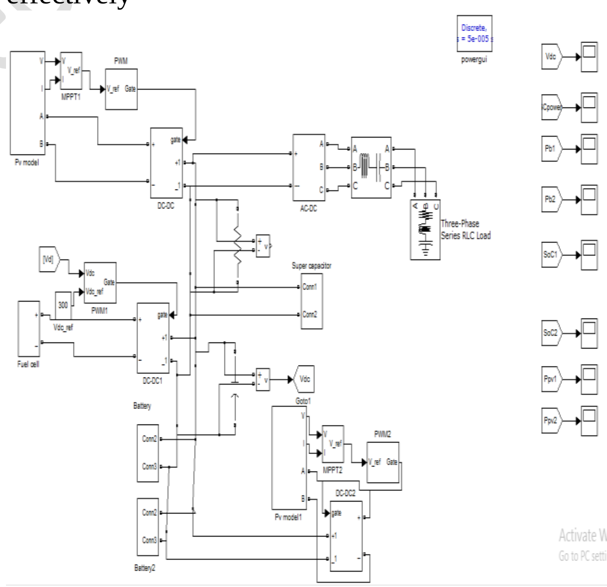

Fig 5.7 Scenario II

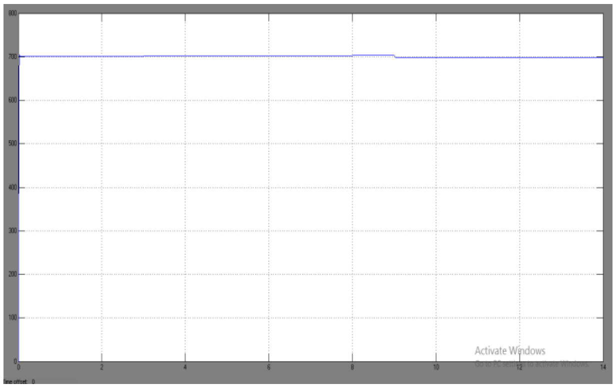

Fig 5.8 Vdc

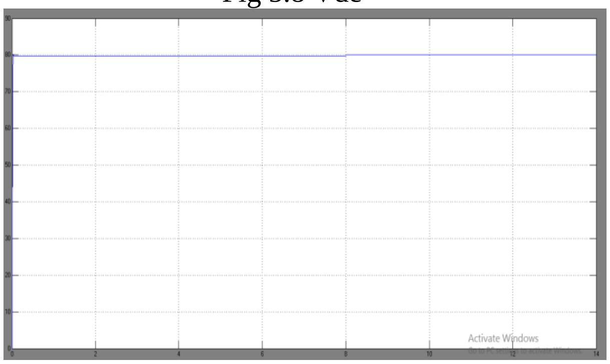

Fig 5.9 Battery SOC1

VI.CONCLUSION

The proposed PMS 1 for hybrid AC/DC MG1 successfully drives the MG1 from generation dominating mode to load dominating mode with efficient dc link voltage regulation. The presented PMS is robust to wide variation in operating point. The use of MAF efficiently separates the average current reference to be supplied by fuel cell and battery while transient and oscillatory component of power to be supplied by SC. The proposed MAF based multi-time scale adaptive droop PMS with supervisory control for MG2 offers reliable transition algorithm for operation of multiple PVs and BES in a geographically distributed location. It also considers the SoC charging and discharging rates for multiple BESs. Also, the PMS considers effective utilization of H2 in FC stack by using current slope limiter. The paper also proposes the control based PV power curtailment under critical conditions. The proposed PMS considers all the contingency conditions. The simulation results validate the proposed PMS under normal as well as critical conditions. Thus, PV-PEM fuel cell with HES and proposed PMS presents a promising scope for operation as a hybrid AC/DC microgrid.

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