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Control and dynamic power management of PV PEM Fuel cell based Standalone AC/DC Micro grid

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Abstract — *This is my proposed paper and, in this paper, and in this paper, we have proposed dynamic power management scheme for standalone hybrid AC/DC microgrid which Creates PV-photovoltaic based analogous source of energy, PEM - proton exchange membrane FC - fuel cell is recycled as another battery-supercapacitor and power source is used as hybrid energy storage. The algorithm of power management accounts for coherent procedure of microgrid under different modes and SOC - state of charge limit circumstances of hybrid energy storage, when all the Loads, storages and sources are associated precisely to the dc link. The PMS - power management scheme brings about current references for dc converter current controllers of fuel cell, battery and supercapacitor. The equate and rise and fall power components are disconnected using transferring average filter. The dc link voltage regulation with dynamic changes in load and also with source power variation is proposed. Also, PV power curtailment through control is formulated. The recommended power management is adjusted and enhanced to numerous photovoltaic formation system and batteries with all the storages and sources geographically shrared performing under multi-time scale flexible droop-based control with controlling for mode transition. The proposed power management scheme is checked using simulation results.*

Keywords: *PV, PEM fuel cell, power management, supercapacitor, voltage source converter, standalone AC/DC microgrid, Moving average filter, Multi-time scale, droop.*

I. INTRODUCTION

The Requirement of Hybrid AC/DC MG - microgrid has expanded undoubtedly with heightened entrance of sustainable energy sources such as PV - photovoltaic array (PV) at low voltage ac circulation sector. heightened number of dc loads for example central computer center, telecom load, plug-in vehicle, accentuate the need of participating microgrid applicable for both ac and dc loads. The key challenges involve 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 because of intermittent of sustainable energy sources and precarious nature of load variation. 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.

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. To escape such probability, HES - hybrid energy storage which is amalgamation of high-power density and high energy density needs to be imported to absorb/supply transient power components and steady state in MG. 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. 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. 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 must supply both transient and constant power. Due to this SC voltage will hit its high/low limit frequently. 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. 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. 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, 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. moving average filter (MAF) computes time average value and provides average current reference without much lag and instability. The multi-time scale control presented 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.

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. 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 supercapacitor 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.

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. 6.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 H2is 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 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.

II. HYBRID AC/DC MICROGRID CONFIGURATION 1

The hybrid AC/DC microgrid (MG1) configuration 1 includes of PV with boost converter and PEM fuel cell (FC) with boost converter, both connected directly at dc link, as shown in Fig.1. It is supported by hybrid energy storage (HES) consisting of battery and supercapacitor (SC) connected directly to dc link through bidirectional DC-DC converters (BDC). The load consists of dc load and three phase ac load with three phase voltage source converter (VSC). Fuel cell generates steady state power to meet the excess power demand if very less no of PV power is available. The HES supports the steady state as well as transient power changes in generation and loads. It also led the fuel cell to slowly ramp up its generation from zero value to the reference value. The SC supports fluctuating power changes and is insufficient to absorb constant power changes for long time duration due to its low energy density. While battery support constant power changes due to its high energy density, it may also supply transient power only under critical cases. The VSC operates in voltage control mode with fixed frequency which is obtained from voltage controlled oscillator. It supplies three phase ac load. The PV power is obtained by operating on the linear characteristic of PV curve between MPP (Vmp) point and open circuit (Voc).

Modelling and Control of PEM Fuel Cell

Some of the important equations that describes the modelling of PEM fuel cell are shown in [4]-[5]. Fuel cell stack current and hydrogen flow are related as

$$q_{h2}^{r} = N_0 I_{fc}/2F = 2K_r I_{fc} \qquad (1)$$

Where, No is the number of fuel cells in the stack, Ifc is stack current (A), F is faraday's constant (C/Kmol) and Kr is modeling constant (Kmol/(sA)-1).

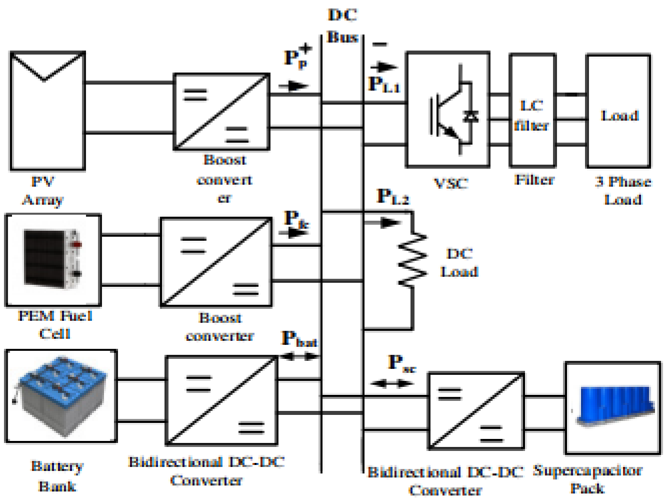

Fig. 1. Hybrid AC/DC Microgrid configuration 1

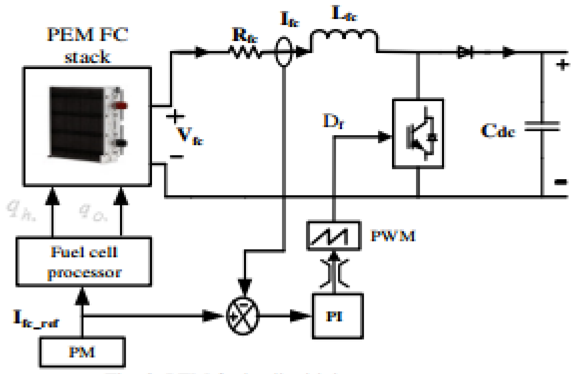

Fig. 2. PEM fuel cell with boost converter

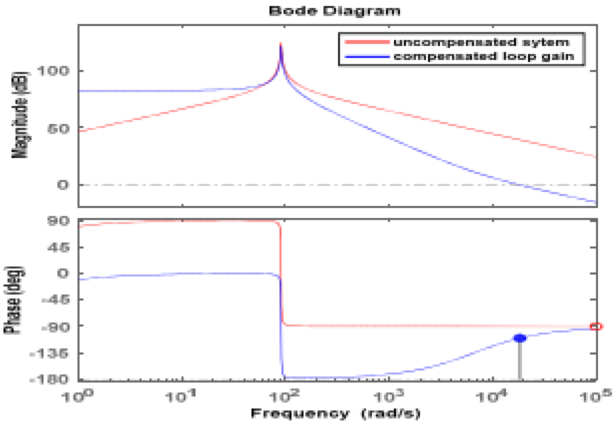

Fig. 3. Bode plot of compensated loop gain and uncompensated loop gain

The Polarization curve of fuel cell gives the fuel cell voltage which is sum of the Nernst instantaneous voltage E, activation overvoltage ***n act*** and ohmic overvoltage *n ohmic* and is expressed mathematically as follows.

$$V_{cell} = E + \eta_{act} + \eta_{ohmic} \quad (2)$$

Where, *nact* is function of oxygen concentration Co2 and *Ifc* , *n ohmic* is function of *Ifc* and and stack internal resistance Rint (Ω). Assuming constant O2 concentration and constant temperature, equation (2) can be written as

$$V_{cell} = E - B\ln(C\,I_{fc}) - R^{int} I_{fc} \quad (3)$$

Where, B=0.04777 V and C=0.0136 A-1. The Nernst voltage in terms of gas molarities is given in equation [4]

$$E = N_0\left[E_0 + \frac{RT}{2F}\log\left[\frac{\rho_{h2}\,\rho_{O2}^{0.5}}{\rho_{H2o}}\right]\right] \quad (4)$$

Where, Eo is open cell voltage (V). Hydrogen utilization factor (U) is defined as the ratio of H2 reacted inside the stack to the injected H2 into the tank and it has value between 0 and 1.

$$U = q_{h2}^{r} / q_{h2}^{in} \quad (5)$$

Values above 0.9 indicates over-utilization of hydrogen leading to fuel starvation and reduces its life and performance. On the other hand, values below 0.8 indicates underutilization of hydrogen which means there is presence of excess hydrogen, leading to sharp rise in output voltage and reduction in overall power efficiency. Thus, for optimal utilization of H2 in fuel cell stack, stack current is limited by using following criterion.

$$\frac{0.8q_{h2}^{in}}{2K_r} \le I_{fc} \le \frac{0.9q_{h2}^{in}}{2K_r} \quad (6)$$

The current reference *Ifc_ref* obtained from the power management scheme which generates the H2 reference given by

$$q_{h2}^{ref} = \frac{2K_r I_{fc\_ref}}{U_{opt}} \quad (7)$$

According to (6), the ramp rate of fuel cell reference current is controlled by current slope limiter (Ampere/sec) whose slope is based on current and power rating of PEM fuel cell [8]. Hence fuel cell avoids steep changes in load and guarantees to match the reactant delivery rate and the usage rate [9].
The PEM FC connected to dc link through boost converters operating in current mode control is shown in Fig.2.
A conventional PI controller is implemented to track the reference current signal which is obtained from power management scheme and generates duty ratio to boost fuel cell voltage to reference dc link voltage. The transfer function of fuel cell boost inductor current to converter duty ratio is given in equation [8],

$$\frac{\hat{\iota}_{FC}(s)}{\hat{d}_f(s)} = \frac{\frac{I_{FC}}{(1-D_f)}\left(1+\frac{V_{dc}C_{dc}s}{(1-D_f)}\right)}{s^2L_{FC}C_{dc}+sR_{FC}C_{dc}+(1-D_f)^2} \qquad (8)$$

Where, LFC, RFC, and IFC are the inductance, resistance and current of boost converter and inductor respectively, DF is converter duty ratio,*Vdc* and *Cdc* are dc link voltage and capacitance respectively. The transfer function in (8) is compensated using proportional integral (PI) controller to obtain stable compensated system as well as ensure zero or very less steady state tracking error. The compensated loop gain is stable with phase margin of 700 and with bandwidth around 2500 Hz, as shown in Fig.3.

III. PROPOSED POWER MANAGEMENT SCHEME

The proposed dynamic power management scheme (PMS) for MG1 is shown in Fig 4. It comprises of current references generation, mode selection power management algorithm (PM), tracking of current references by current controllers and duty ratio generation for PWM switching pulses for different converters which are interfaced to sources and HES.
The power balance in hybrid AC/DC microgrid is ensured by controlling the power at the dc link. The total dc link power is the summation of power injected by the primary and the secondary source, and the difference of power absorbed by ac and dc loads and sum/difference of power supplied/absorbed by the HES. The total power required to maintain the dc link is defined as (i) average power component (Pavg) due to slow changes in PV/FC power and load power, (ii) oscillatory power component which is caused due to instantaneous ac power (Po) of inverter fed load and (iii) transient power component (Pt) which arises due to sudden changes in PV power and ac/dc loads. Thus, the power balance equation of hybrid AC/DC Microgrid at dc link consists of above three component which is given in equation (9)

$$\begin{aligned} p_{pv}(t) + p_{fc}(t) \pm p_{sc}(t) \pm p_B(t) - p_L(t) \\ = p_{dc}(t) = v_{dc}i_{dc} \\ = p_{avg}(t) + p_o(t) + p_T(t) \end{aligned} \qquad (9)$$

Where, Ppv(t),Pfc(t),Psc(t) and Pb(t) are the PV, FC, SC and battery power respectively,PL(t) is the sum of ac and dc load power, pdc(t) is the total dc link power, vdc and idc are the dc link current and voltage respectively. An Idc is the effective reference current for PMS which is denoted by I_ref. It is the summation of the average current reference i_avg, oscillatory i_o and transient current reference i_T.

$$i_{\_ref} = i_{\_avg} + i_{\_O} + i_{\_T} = \left(K_{pvdc} + \frac{K_{ivdc}}{s}\right)(v_{dcr} - v_{dc}) \qquad (10)$$

Where, Kpvdc and Kivdc are the proportional and integral gain of the outer dc link voltage controller, vdcr is the reference value of dc link voltage. The average component of the reference current i_avg is found by filtering i_ref through moving average filter which equals to the time average of the signal and does not introduces significant time delay unlike low pass filter. The transient and oscillatory component of reference current is found by subtracting average current reference from total reference current, thus the time scaled references are obtained.

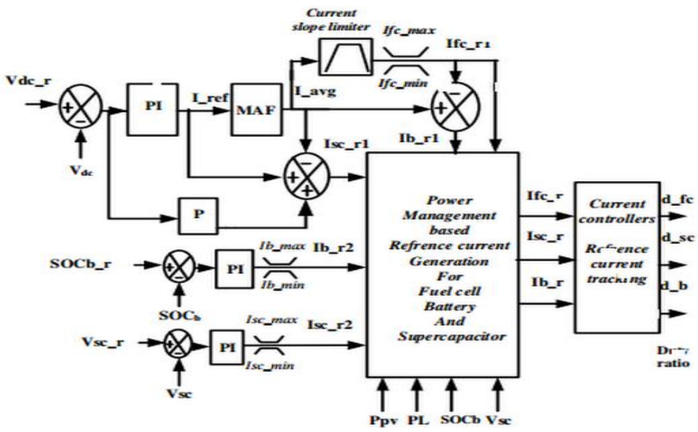

Fig.4. Proposed power management scheme for hybrid AC/DC microgrid 1.

$$i_{\_O} + i_{\_T} = i_{\_ref} - i_{\_avg} \qquad (11)$$

The fuel cell reference current is obtained by limiting the ramp rate of i_avg through current slope limiter. Also, the obtained FC current reference must be within the maximum value (Ifc_max) and minimum current limit (Ifc_min/zero) value must be based on the rating of PEM fuel cell. Thus, Ifc_r1 is the fuel cell reference current which is obtained from PMS. The Ifc_r1 varies slowly and it remains unaffected by transients caused by sudden variation in load and power generation. Now, the battery reference current is obtained to assist the fuel cell under normal operating condition. The total average reference current is obtained by secondary source FC, however it is unable to meet the demand instantaneously. Thus, the difference of the average reference current and reference fuel cell current is supplied by battery bank of HES. Hence, the battery reference current is given by

$$Ib\_r1 = I\_avg - Ifc\_r1 \qquad (12)$$

Therefore, battery supplies average power and it also assists PEM FC to meet the demand under normal operation. The transient and oscillatory component of current reference in equation (11) is added with proportional dc link voltage error (P) to improve dynamics of dc link voltage under transient. This current serves as the supercapacitor reference current (Isc_r1).

$$Isc\_r1 = I\_ref - I\_avg + P(v_{dcr} - v_{dc}) \qquad (13)$$

To maintain the state of charge (SoC) of battery when it reaches to lower SoC limit condition (SoCBL), the battery reference current is obtained from the SoC control loop which is secondary control and operation is initiated by power management algorithm (PM). The error of reference SoC and estimated SoC is minimized by using PI controller to generate battery reference current (Ib_r2) to charge the battery from the available power sources.

$$Ib\_r2 = \left(K_{ps} + \frac{K_{is}}{s}\right)(soc_{br} - soc_b) \qquad (14)$$

Where, the Kps and Kis are the proportional and integral gain of SoC control loop of battery respectively, socbr is the reference SoC value of battery to be maintained. Similarly, supercapacitor voltage control loop is to maintain the supercapacitor voltage when it reaches the minimum voltage limit (VSCL). The SC voltage control loop uses PI controller to generate SC reference current Isc_r2 to charge the SC to reference voltage.

$$Isc\_r2 = \left(K_{psc} + \frac{K_{isc}}{s}\right)(V_{SCr} - V_{SC}) \qquad (15)$$

IV. CONCLUSION

The proposed PMS 1 for hybrid AC/DC MG1 drives the MG1 from generation of dominating mode to load the dominating mode with efficient dc link voltage regulation. The presented PMS is robust to the wide variation in operating point. The use of MAF efficiently separates the average current reference which is supplied by fuel cell and battery while transient and oscillatory component of power is 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 the discharging rates for multiple BESs. Also, the PMS considers the effective utilization of H_2 in FC stack by using current slope limiter. The paper also proposes the control-based PV power curtailment under crucial conditions. The proposed PMS considers all the contingency conditions. The simulation and experimental results validate the proposed PMS under normal as well as crucial 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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