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Energy management schemes for distributed energy resources connected to power grid

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ABSTRACT

In a technically advanced world where demand is increasing very fast especially large number of non-linear loads and electric vehicles has led to energy crisis and pollution of grid power. Depleting conventional energy sources and environmental concerns has led to integration of large number of distributed energy resources (DERs) at distributional level to resolve problem of energy crisis and reduce emissions. With grid connected to different types of DERs, it is very challenging to manage the power flow, resolve energy crisis and maintain good power quality. Improper energy management may lead to inefficient operation of DERs and may build up stress on energy storage systems (ESS) impacting their life cycle. Thus, it is necessary to use energy management schemes (EMS) for efficient and reliable operation. EMS helps to enhance overall system efficiency and reduce the stress on ESS. This paper presents the analysis of different EMS applied on distribution system for efficient and economic operation of DERs and carryout stress analysis on ESS. Overall system efficiency, Hydrogen utilization in fuel cell, state of charge (SoC) of batteries and supercapacitor are the main parameters considered for performance comparison. To analyze the proposed work a simulation model is designed in MATLAB.

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1. INTRODUCTION

The economic expansion, industrial advancements and societal growth has shown that an economical and continual electric power supply is the principle concern of any country [1]. The conventional sources of power release excess pollutant gases which are blameworthy for human mortality and environmental changes like global warming, and air quality[2], [3]. The developing overall energy crisis, environmental pollution problems and depletion of fossil fuels results in increased use of alternate source of energy which is renewable in nature [4]. The reliance on the conventional power sources can be minimized by hybridization i.e., integrating various renewables and energy storage system to resolve power uncertainties [5]. In the modern power distribution system the energy storage systems (ESS) is the essential constituent [6]. ESS can enhance grid stability, improve efficiency of the system, strengthen distributed energy resources (DERs) penetration, its aids to curtail CO_2 by conserving fossil fuels [7], [8].

The significance of using fuel cell (FCs) due to its good efficiency and zero emission [9]. The by-products are directly pure H_2O and heat. FCs are classified based on the electrolyte used [10]. However, cold start of FCs is difficult and the response time of FCs is slow. Thus, it is necessary to integrate an auxiliary source of energy like battery or super capacitor to boost: peak power capability, dynamic characteristics and supply the demand at the time of cold start [11]. Most commonly lithium ion (Li-ion) batteries are used for diverse applications, especially for operations which require high power and energy density [12]. The interconnection of FCs, solar photovoltaics (PV), battery and supercapacitors (SC) takes benefits of high energy density from FC and high power density from SC in improving system performance [13], [14]. The proposed hybrid power system (HPS) results in efficient operation of FCs and solar PV systems as ESS power a part of load. Such optimization is achieved with the help of an energy management strategy (EMS), which shares the demand among the DERs and ensures that the operation of each DERs is within its limits. Furthermore, the impact of EMS on life cycle of DERs must be curtailed [15].

Extensive literature is reported on EMS for DERs integrated power system. A simple and prominent rule-based state machine control strategy is described [11], [16]; every single state is described on heuristic or empiric experience basis as in case of fuzzy logic EMS, where the distribution of power is secured by means of membership functions along with the set of IF–THEN rules [17], [18]. Classical PI controllers for EMS works by controlling the principle operational parameters, such as SoC of battery, terminal voltage of SC or voltage of dc-bus using PI controllers [9], [19], [20]. For implementing classical PI controller expert knowledge is not required, and the online tuning for advanced tracking can be easily achieved. Equivalent fuel consumption minimization strategy (ECMS) is widely used for real-time employment, power sharing problem is solved such a way to minimize an instantaneous cost function considering fuel consumption of DERs. Some of real-time EMS are based on model predictive control [21], stochastic dynamic programming [22], neural networks [23], adaptive optimal-control method [24], H-infinity control [25] Fuzzy-logic based hybrid power system and hybrid energy storage system control to improve power quality [26], [27]. Fuzzy-logic control for microgrids [28], power management of standalone DC microgrids [29], ANN based control for battery energy storage [30].

However, the response time of these EMS may be significantly affected as these are very complicated and requires lot of computations. This paper deals with the well-known and easily accomplishable EMS which are: State machine control strategy [16]; Classical PI control strategy [9], [19] and ECMS [31]-[33]. The contribution of the proposed work is to evaluate the performance of different EMS to operate DERs efficiently and economically and the work is extended to determine on the stress on battery and supercapacitor for each EMS considered. Overall system efficiency, hydrogen utilization in fuel cell, state of charge (SoC) of batteries and supercapacitor are the main parameters considered for performance comparison.

2. PROPOSED SYSTEM DESCRIPTION

The schematic diagram of the HPS simulated is shown in Figure 1. The energy from FCs, Solar PV, Batteries and SC is controlled by DC/DC converters associated with them. The EMS determines voltage and current reference signals for DC/DC converters. To protect batteries from overheating, overcharging and excess-discharging a battery management system (BMS) is implemented. To protect SC from overvoltage or input voltage of inverter a protecting resistor is adapted. The characteristic of non-linear load is fed through the converter and load curve is produced with the help of an AC/DC programmable load.

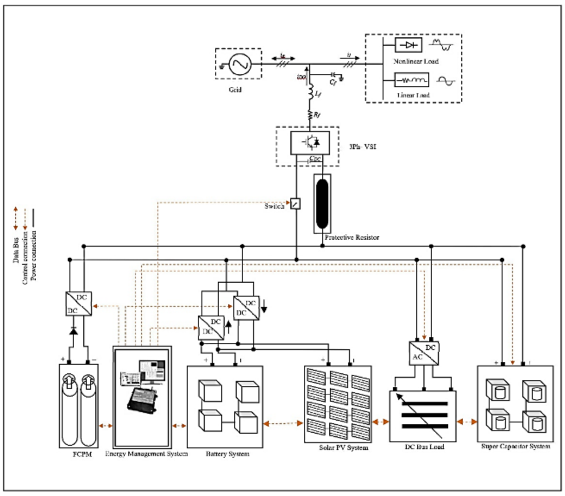


Figure 1. Schematic diagram of proposed hybrid power system

The Proposed work mainly concentrates on the analysis of different EMS therefore the designing of DERs is not explained in detail. Fundamental equations and detailed designing of Solar PV can be found in [1], [34], for designing fuel cell the details are available in [35], whereas detailed modelling of batteries and super capacitor can be found in [15], many literature are available for designing of DERs. The input variables of all the DERs considered are tabulated in Table 1.

Figure 2 shows the typical distribution generation (DG) integrated to distribution system. The system involves a 3 phase voltage source inverter (VSI), DG source (i_{DG}), LC output filter, supplying local load (i_L) and in case of surplus power generated at distribution side is transferred to utility grid (i_g). The load curve generated is as shown in Figure 3.

Table 1. DERs parameters

Input parameters of solar PV		Battery input parameters	
Parallel Strings	40	Nominal voltage (V)	48
Series-connected modules per string	10	Rated capacity (Ah)	40
module	Tata Power Solar Systems TP145SBZ	Maximum capacity (Ah)	40
Maximum power (W)	145.0008	Completely charged voltage (V)	55.88
Open circuit voltage V_{oc} (V)	22.3	Nominal discharge current (A)	17.4
Voltage at max. power point V_{mp} (V)	17.64	Internal resistance (ohms)	0.012
Temperature coefficient of V_{oc} (%/degree celsius)	-0.33	Capacity (Ah) at nominal voltage	36.17
Cells per module (N_{cell})	36	Exponential zone [voltage (V), capacity (Ah)]	[52.3, 1.96]
Short-circuit current I_{sc} (A)	8.71	Battery voltage response time (sec)	30
Current at max. power point I_{mp} (A)	8.22		
Temperature coefficient of (%/degree Celsius)	0.0638		
Fuel cell model input parameters		**Supercapacitor model input parameters**	
Voltage at 0A and 1A [V_0, V_1]	[52.5, 52.46]	Rated capacitance (F)	15.6
Nominal operating point [I_{nom}(A), V_{nom}(V)]	[250, 41.15]	Equivalent series resistance DC (Ohms)	0.15
Maximum operating point [I_{end} (A), V_{end}(V)]	[320, 39.2]	rated voltage (V)	291.6
Number of cells	65	surge voltage (V)	307
Nominal stack efficiency (%)	50	Number of series capacitor	108
Operating temperature (Celsius)	45	Number of parallel capacitor	1
Nominal air flow rate (I_{pm})	732	Number of layer*	6
Nominal supply pressure [Fuel (bar), Air (bar)]	[1.16, 1]	Molecular radius (m)*	0.4×10-9
Nominal composition (%) [H_2, O_2, H_2O(Air)]	[99.95, 21,1]	Operating temperature (Celsius)	25
fuel cell voltage response time (sec)	1		
Peak O_2 utilization (%)	60		
Voltage undershoots (V) at peak O_2 utilization	2		

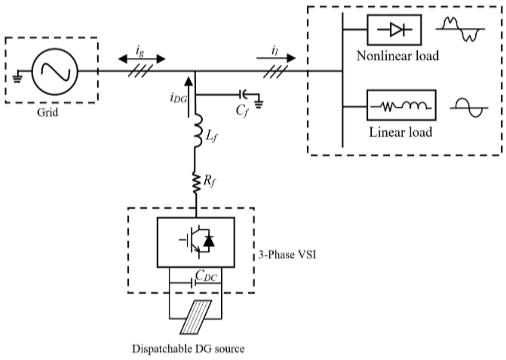


Figure 2. Typical DG connected to distribution system

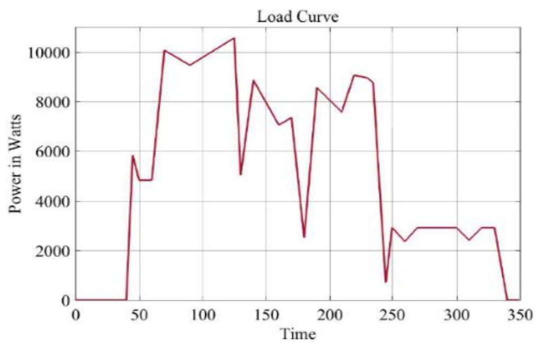


Figure 3. Load curve

3. ENERGY MANAGEMENT SCHEMES

3.1. State machine control strategy

State machine control strategy (SCMS) in the proposed work considers 8 states, as tabulated in Table 2, these states are obtained using same concept proposed in [8]. Depending upon the SOC range of battery and the demand power P_{Demand} the FC power is determined. This EMS is as shown in Figure 4. For this method hysteresis control (refer Figure 5) is necessary during switching the states, as it affects the EMS response to changes in demand power [15].

Table 2. State machine control decisions

State machine control decisions				
	If		States	
$SOC > SOC_{max}$	SOC High	$P_{Demand} < P_{FC(min)}$	1	$P_{FC}^{*} = P_{FC(min)}$
	SOC High	$P_{Demand} \in [P_{FC(min)}, P_{FC(max)}]$	2	$P_{FC}^{*} = P_{Demand}$
	SOC High	$P_{Demand} \geq P_{FC(max)}$	3	$P_{FC}^{*} = P_{FC(max)}$
SOC > [85, 65]	SOC Nominal	$P_{Demand} < P_{FC(optimal)}$	4	$P_{FC}^{*} = P_{FC(optimal)}$
	SOC Nominal	$P_{Demand} \in [P_{FC(min)}, P_{FC(max)}]$	5	$P_{FC}^{*} = P_{Demand}$
	SOC Nominal	$P_{Demand} \geq P_{FC(max)}$	6	$P_{FC}^{*} = P_{FC(max)}$
$SOC < SOC_{min}$	SOC Low	$P_{Demand} < P_{FC(max)}$	7	$P_{FC}^{*} = P_{Demand} + P_{char}$
	SOC Low	$P_{Demand} \geq P_{FC(max)}$	8	$P_{FC}^{*} = P_{FC(max)}$

Where,
$Pchar = -Pbatt_{min}$
SOC_{max} and SOC_{min} are maximum SOC and minimum SOC respectively
$P_{FC(max)}$ and $P_{FC(min)}$ are maximum FC output and Minimum FC output respectively
$P_{FC(optimal)}$ is optimal FC output.

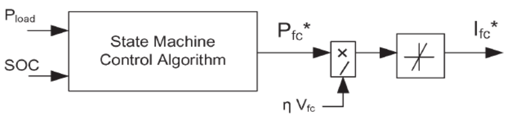


Figure 4. EMS of state machine control

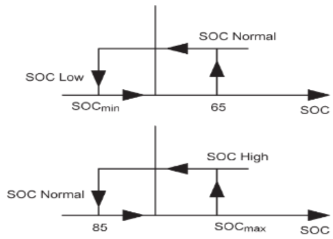


Figure 5. State machine control hysteresis

3.2. Classical PI control strategy

In this scheme whenever the SOC of battery is beyond the reference, the output of FC is minimized, and large part of demand is powered by battery. Similarly, if the SOC of battery is lesser than the reference value, the output of FC is increased to supply maximum part of load. Thus this strategy regulates the SOC of battery using PI regulator [9], as shown in Figure 6. PI gains are tuned online for an improved response.

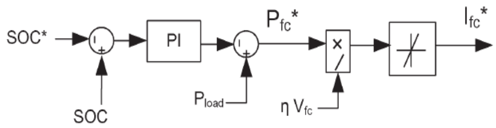


Figure 6. EMS of classical PI controller

3.2. Equivalent fuel consumption minimization strategy

The equivalent fuel consumption minimization strategy (ECMS) is widely used for optimization based on real-time cost function [31], [33]. The purpose of the optimization problem is to curtail the fuel consumed by FC and the equivalent fuel necessary to maintain the SOC of the battery. The SOC of battery is coordinated with the help of penalty coefficient of battery energy as proposed in [33]. This EMS is shown in Figure 7.

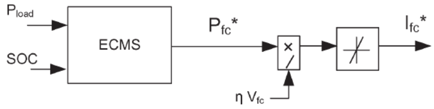


Figure 7. EMS of ECMS

The optimization Problem is expressed as.
Determine an best solution $x = [P_{FC}, \alpha, P_{battery}]$, which minimizes:

$$F = [P_{fc} + \alpha P_{batt}].\Delta T \quad (1)$$

under the equality constraints:

$$P_{Demand} = P_{fc} + P_{batt} \quad (2)$$

$$\alpha = 1 - 2\mu \frac{(SOC - 0.5\,(SOC_{max} + SOC_{min}))}{SOC_{max} + SOC_{min}} \quad (3)$$

within the boundary conditions:

$$\left.\begin{array}{c} P_{FC(min)} \leq P_{fc} \leq P_{FC(max)} \\ P_{battery(\min)} \leq P_{batt} \leq P_{battery(\min)} \\ 0 \leq \alpha \leq 100 \end{array}\right\} \quad (4)$$

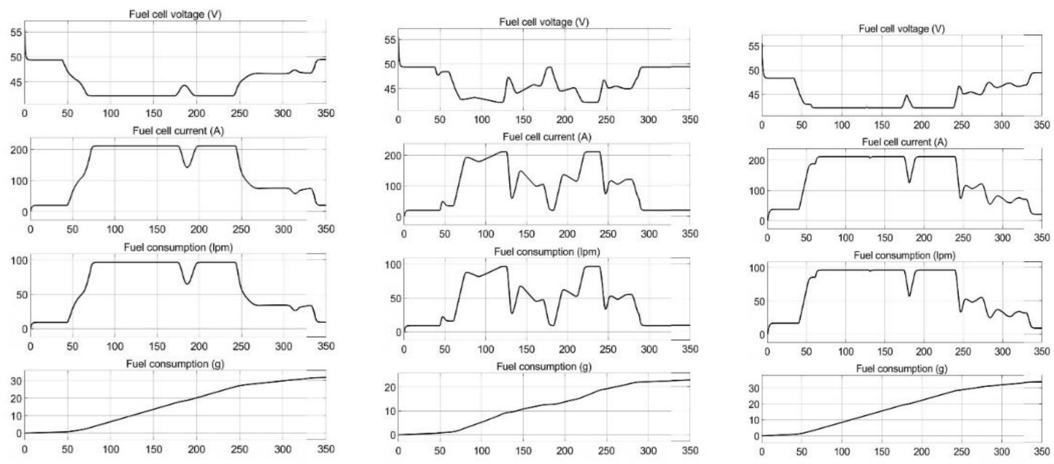
where, P_{FC}, $P_{battery}$ and P_{Demand} are the power capacity of fuel cell, battery, and the demand respectively (including the losses at converter). α is the penalty coefficient, and μ is a constant value adjusted to provide good control of the battery SOC ($\mu = 0.6$). ΔT is the sampling time.

In optimization problem the SC power is not considered because the battery converters control the DC-bus voltage i.e., immediately after discharge of SC, the equal energy from battery is used to recharge SC. In this scheme the control is over only the FC and battery to supply the total load over a given load cycle.

4. SIMULATION RESULTS AND DISCUSSION

The proposed HPS sown in Figure 1 is simulated in MATLAB to validate the analysis. The analysis is carried for two cases, in first case only linear load condition is considered whereas in second case nonlinear load condition is considered. For each case the results obtained from different EMS are analyzed and it was observed that the EMS behaves same irrespective of linear load or non-linear load, therefore the waveforms of only non-linear load condition is shown which are same as linear load condition and it was also noticed that EMS does not resolve any power quality issues.

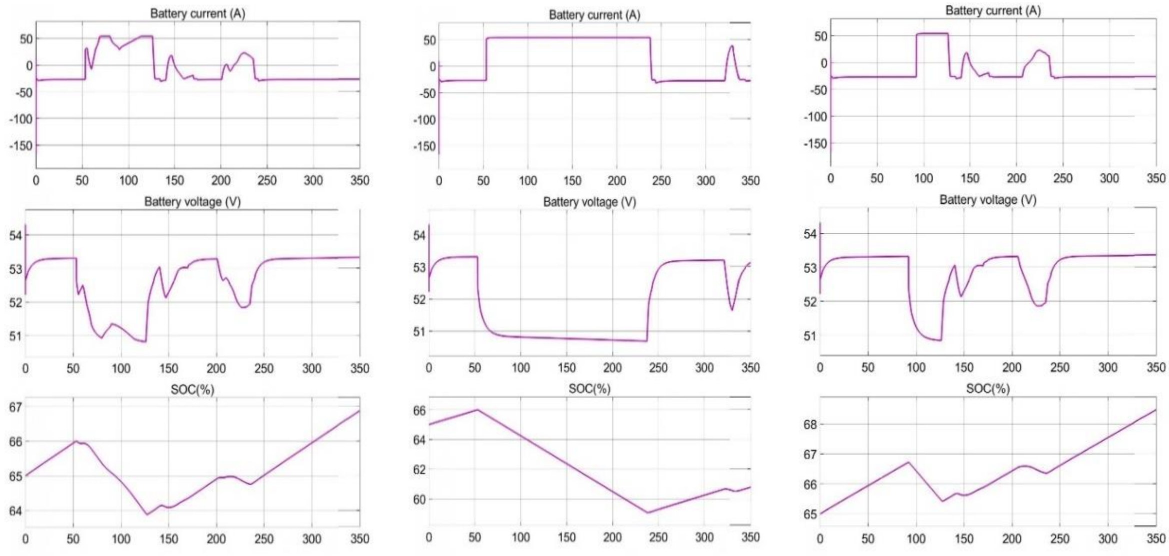
The fuel cell output voltage and current as well as fuel consumption (in grams) is plotted for all the three EMS considered as shown in Figure 8 (Figures 8(a), 8(b) and 8(c) represents outputs of fuels for SMCS, classical PI control strategy and ECMS respectively). As observed from Figure 8(b) the change in fuel cell current and voltage is more corresponding load compared to other two EMS. The fuel consumption for SMC strategy, classical PI Control and ECMS are 31.8 gm, 22.89 gm and 33.76 gm respectively.



(a) (b) (c)

Figure 8. Fuel cell (a) SMC, (b) classical PI, and (c) ECMS

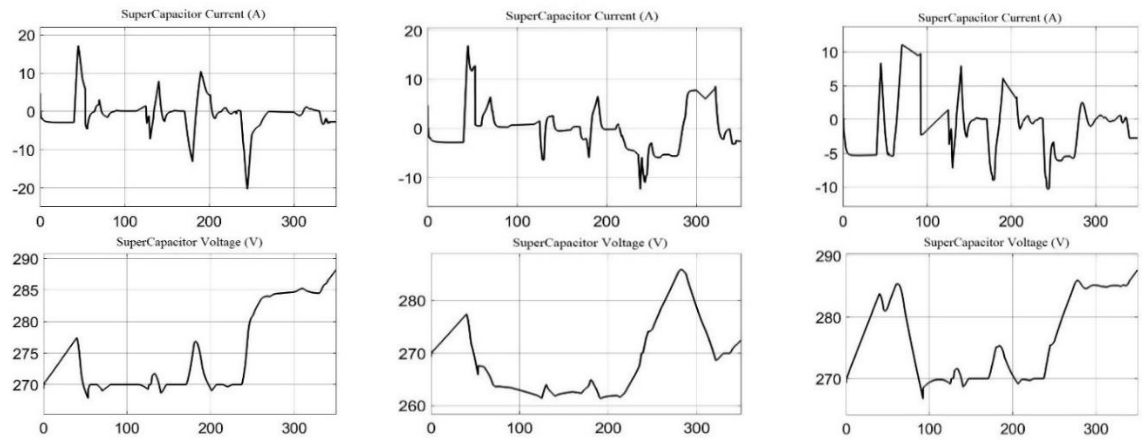
The Battery output voltage and current along with SOC (%) is plotted for all the three EMS considered as shown in Figure 9 (Figures 9(a), 9(b) and 9(c) represents outputs of battery for SMCS, classical PI control strategy and ECMS respectively). As observed from Figure 9 the variation in SOC (%) for SMC strategy, classical PI Control and ECMS are 62%-67%, 59%-66% and 63%-68% respectively. ECMS and SMCS maintains better SOC compared to that of classical PI control marginally. The response time of battery is slower than compared to that of supercapacitor which can be observed by comparing Figure 9 and Figure 10 with load curve.



(a) (a) (b)

Figure 9. Battery output (a) SMC, (b) classical PI, and (c) ECMS-NL

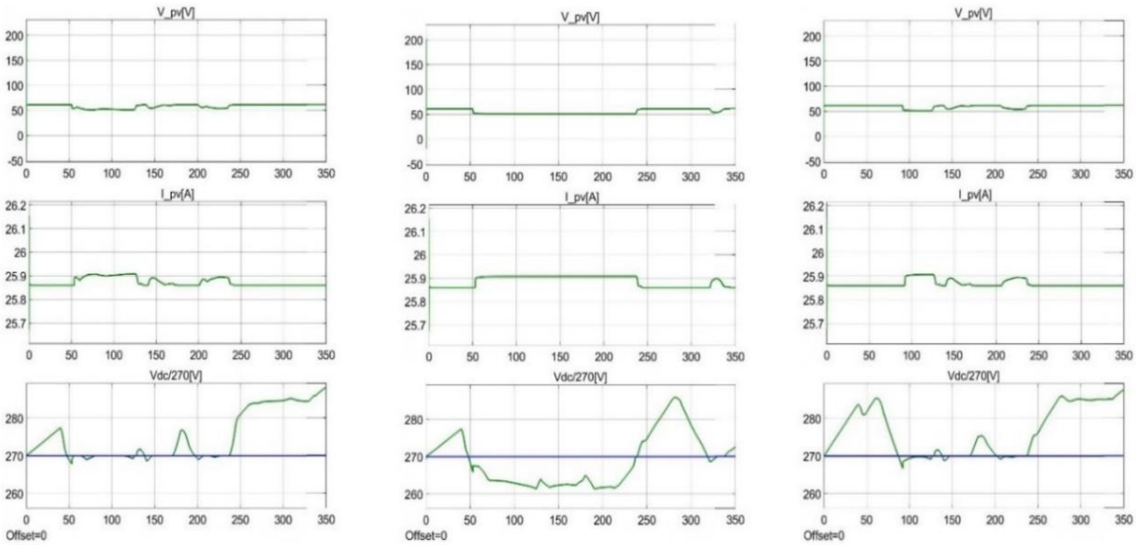
The supercapacitor output voltage and current is plotted for all the three EMS considered as shown in Figure 10 (Figures 10(a), 10(b) and 10(c) represents outputs of supercapacitor for SMCS, classical PI control strategy and ECMS respectively). As observed from Figure 10 the response of supercapacitor is fast to changing load specially for sudden rise or fall in load.



(a) (b) (c)

Figure 10. Super capacitor output, (a) SMC, (b) classical PI, and (c) ECMS-NL

The solar PV output voltage and current is plotted for all the three EMS considered as shown in Figure 11 (Figures 11(a), 11(b) and 11(c) represents outputs of supercapacitor for SMCS, classical PI control strategy and ECMS respectively). The solar output is fed to battery.

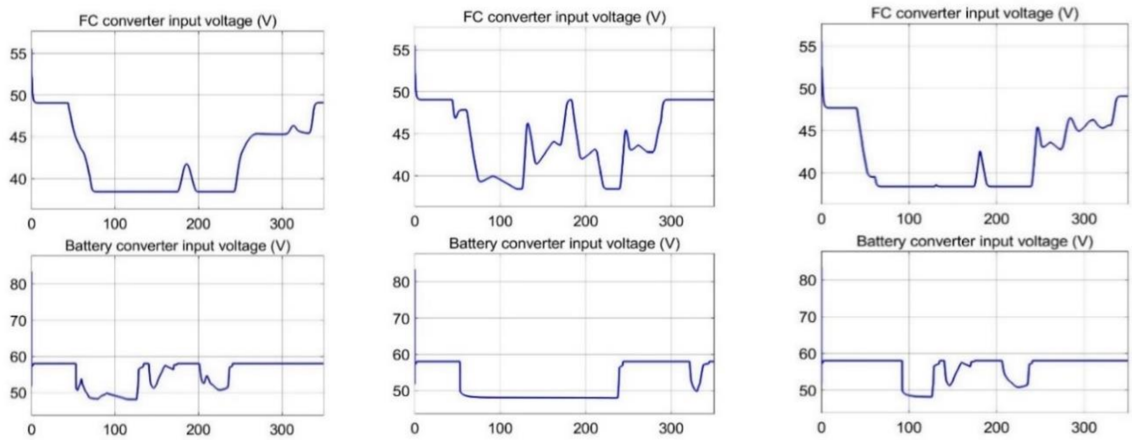


(a) (b) (c)

Figure 11. Solar PV output (a) SMC, (b) classical PI, and (c) ECMS

The input voltages of two converters used at FC and battery are as shown in Figure 12 (Figures 12(a), 12(b) and 12(c) represents for SMCS, classical PI control strategy and ECMS respectively). Thus, by observing the Figure 8 to Figure 11 all the constraints are obeyed and the stress on battery and supercapacitor is determined and tabulated in Table 3.

The supercapacitors are used mainly because if its fast dynamics compared to that of battery. As load is unpredictable and emergence of modern technology and electrical vehicles load may rise/fall suddenly. Thus, to serve such sudden peaks supercapacitors are used. The significance of supercapacitors can be observed best by comparing only the load curve and supercapacitor output curve (for SMCS) are shown in Figure 13 where it can be seen that the supercapacitor serves for suddenly peaks in load curves.



(a) (b) (c)

Figure 12. Converter output (a) SMC, (b) classical PI, and (c) ECMS

Table 3. Performance comparison

Load type	Under linear load			Under non-linear load		
EMS Criteria	SMCS	Classical PI Control	ECMS	SMCS	Classical PI control	ECMS
Battery SOC (%)	62-66	59-65	63-67	62-67	59-66	63-68
H2 consumption (g)	31.48	22.66	33.42	31.8	22.89	33.76
Fuel stress (σ)	24.1	24.5	22.71	24.1	24.49	22.71
Battery stress (σ)	12	15.1	10.61	12	15.1	10.61
Super capacitor stress (σ)	11.62	11.84	12.15	11.62	11.84	12.15
Super capacitor stress (σ) PV	1.019	1.212	0.9076	1.019	1.212	0.9076
Grid current maximum THD (%)	0.09	0.09	0.09	24.69	37.78	43.15

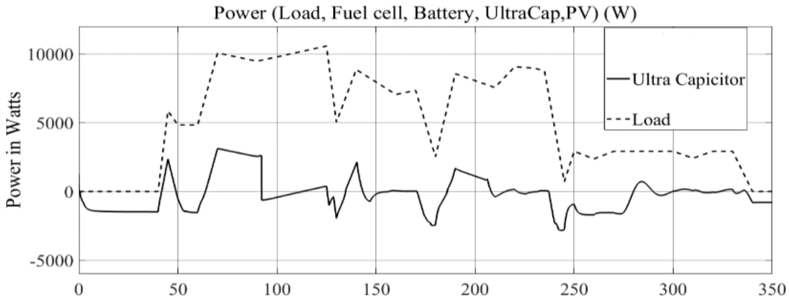
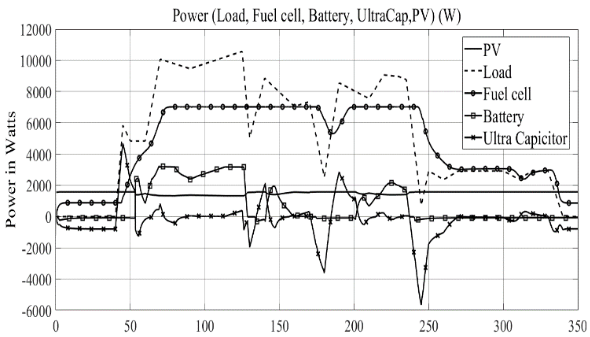
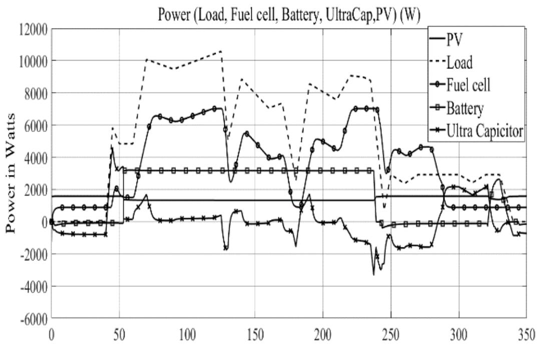


Figure 13. Load vs supercapacitor curve

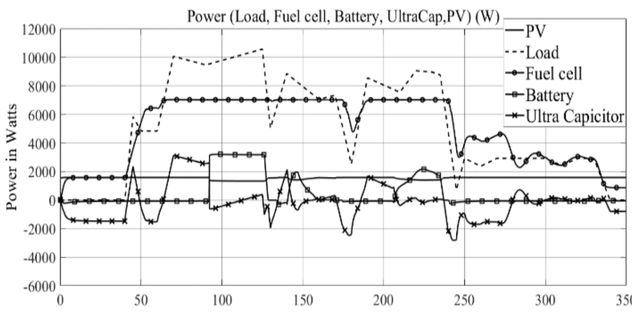
The power output of each DERs (fuel cell, solar PV, battery, and supercapacitor) in balancing the load and source by different EMS is shown in Figure 14 (Figures 14(a), 14(b) and 14(c) represents outputs of supercapacitor for SMCS, classical PI control strategy and ECMS respectively).



(a)



(b)



(c)

Figure 14. Power output of DERs (a) SMC, (b) classical PI, and (c) ECMS

The overall efficiency of the HPS for all the three EMS considered are determined for 50% load, 75% load and full load, the is tabulated in Table 4 and the same is represented in bar graph shown in Figure 15. The overall HPS efficiency is calculated as (5).

$$Efficiency = \eta\% = \frac{P_{load}}{P_{FC}^{in}+P_{solar}^{in}+P_{battery}^{in}+P_{SC}^{in}} \quad (5)$$

Where, P_{FC}^{in}, P_{solar}^{in}, $P_{battery}^{in}$ and P_{SC}^{in} are the FC input power to DC/DC converter, solar input power to DC/DC converter, battery input power to DC/DC converter and supercapacitor power respectively.

Table 4. Overall hybrid power system efficiency

Linear and nonlinear load condition			
EMS load	SMC	Classical PI	ECMS
For 50% load	77%	80%	77%
For 75% load	84%	85%	84%
For 100% load	88%	89%	88%

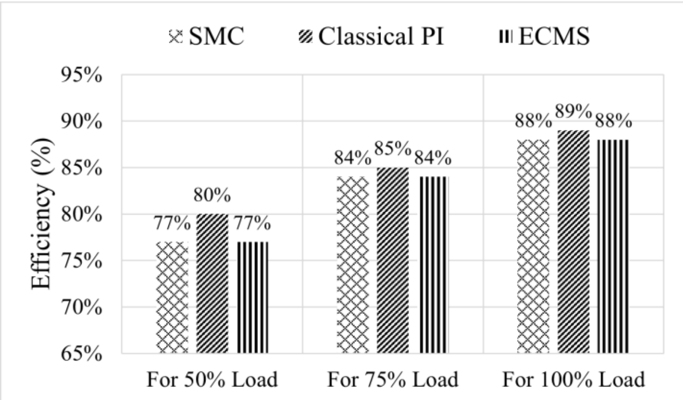


Figure 15. Overall hybrid power system efficiency

5. CONCLUSION

The proposed work analyzes different EMS to check the performance of DERs and the impact of EMS on life cycle of Energy Storage System. From results it can be clearly seen that efficiency of the Hybrid power system can be achieved up to almost 90% at full load. The power output of DERS shows the significance of use of HPS i.e., use of Fuel Cell, Solar PV and ESS as the source of energy and how ESS plays a key role in maintaining source and demand balance. The use of supercapacitors is justified where it can be clearly observed that the supercapacitor responds fast for sudden fluctuations in load. Only 34gm of Hydrogen is consumed which is zero emission source of energy.

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