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Design and Performance Analysis of Standalone PV System with multilevel battery-supercapacitor Hybrid Energy Storage using fuzzy logic controller for electrification in Madagascar

Santatra Fiorenantsoa S.F,[1] Ramanantsihoarana Harisoa Nathalie R.H.N,[2] Rastefano Elisée R.E,[3]

[1]*PhD student, SE-I-MSDE laboratory, ED-STII, University of Antananarivo, Madagascar*
[2]*Thesis co director, SE-I-MSDE laboratory, ED-STII, University of Antananarivo, Madagascar*
[3]*Thesis director, SE-I-MSDE, ED-STII laboratory, University of Antananarivo, Madagascar*

ABSTRACT: *The standalone photovoltaic power system is one of the promising solutions in rural electrification and self-consumption contributing to the production of green energy and avoiding to depend on the local grid which is not stable and not enough for the population in Madagascar. The operation of this kind of system is mostly dependent on energy storage system (ESS) due to weather changing conditions and the intermittent nature of solar energy. Mainly Lead-acid battery ESS are used to compensate the supply-demand mismatch due to the nature of solar energy. However, the short cycle life of Lead-acid battery increases the operating cost of photovoltaic power systems. This paper proposes a domestic standalone PV system with Hybrid Energy Storage System (HESS) that is a combination of batteries and supercapacitor with a fuzzy logic control strategy as energy management system (EMS). Case study using real data collected from Antananarivo is simulated in MATLAB Simulink to analyze the effectiveness of the system. The results show that the proposed fuzzy logic control strategy successfully controls the power flow of HESS components to increase the system efficiency. The developed system is validated to provide an effective alternative that would enhance the battery life span and reduce the system maintenance cost.*

Keywords: *Battery; supercapacitor; fuzzy logic; PV; hybrid energy storage.*

I. INTRODUCTION

Electricity is one of the essential elements in the development of modern society and economy. The availability of reliable and affordable electricity supply is of crucial importance to people's daily life and economic activities. The Malagasy government is now concentrating on energy generation using renewable energy sources. Solar power plants are setup, and many projects are in progress under government-initiated schemes. Many steps are also taken to make people aware about the attributes of domestic renewable energy systems. However, the production of stable and enough electric energy is still a big challenge and load shedding is practiced in the city [1]. A promising solution to address these constraints for access to electricity is distributed autonomous power system based on renewable energy sources and sustainable technologies. Typical renewable energy sources include solar photovoltaic (PV), solar thermal, wind, hydro, biomass, geothermal, ocean waves, and tides, but in recent decades, PV has become one of the most prominent

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renewable energy technologies attributable to its modularity, easy installation, mature technology and low operating cost [2]. Typical standalone PV-battery power system is shown on Figure 1.

On the other side, the requirement of large battery storage and its expensive maintenance makes it a burdensome option for Malagasy consumers [3]. Its performance deterioration could be accelerated when subjected to deep discharged, overcharging, high C-rate and fluctuating power exchange [4]. Lithium-ion (Li-ion) and Lead-acid (LA) battery are the two most commonly used ESS technologies in residential energy systems [5]. Li-ion batteries have a higher energy density, better round-trip efficiency, and longer cycle life than LA batteries, but are relatively more expensive and immature in large-scale packaging. In contrast, LA battery bank is more suitable for standalone PV power system due to its low cost and better thermal stability [6]. Battery is one of the main cost components in typical standalone PV-based residential energy systems [7]. Therefore, it is important to address the problem of short life expectancy of LA batteries and design optimal system to increase its lifetime that ensures financial sustainability of the system.

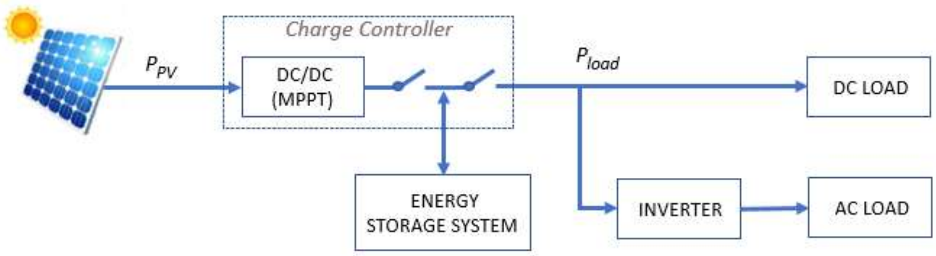


Figure 1: Typical standalone PV-battery power system

Hybridization of different ESS technologies turns out to be one of the promising ways to mitigate the battery charge-discharge stress by directing the short-term power fluctuation to another form of ESS such as the supercapacitor (SC) [8]. The SC stores electricity via electrons in static electric field and possesses high power density, has short charging-discharging time, and nearly unlimited cycle life [9]. A parallel active three level HESS topology composed by LA battery as the principal storage capacity, Li-ion battery as a secondary storage and supercapacitor to absorb the high frequency power exchange is studied in this paper.

A control strategy is essential to optimize the standalone PV system performance and to exploit the advantages of HESS [10]. Two basic control strategy are the most proposed in the literature. The Rule Based Control (RBC), which is simple and easy to implement but lacks the ability to adopt real time weather conditions, since it has a pre-defined set of rules and threshold values for operations [11,12]. The Filtration Based Control (FBC) decomposes the dynamic power demand into high and low frequency components while using filters [2,13]. The performance of FBC based controller is good in smoothing the system output curent, but it neglects the HESS state of charge (SoC) parameters. The SoC of HESS is also a trivial parameter in the control strategy, so it is not effective in minimizing the dynamic stress of the battery. In this paper, a Fuzzy Logic based HESS Control Strategy (FHCS) coupled with FBC is proposed to control the power flow of battery/supercapacitor. This proposed control strategy uses supercapacitor during high change in power demand and during the fluctuation of the irradiance to prevent unnecessary battery charge/discharge. Battery is utilized to feed the smoothed part of the power demand. This technique reduces the unnecessary charging/discharging of the battery, prevents the battery to deepen discharge and, consequently, reduces the maintenance cost of stand-alone PV system and enhances the battery life.

The remaining of this paper is organized as follows: Section 2 presents the battery-supercapacitor proposed HESS topology with a general description of its control strategy. The fuzzy logic based EMS is addressed in Section 3. To demonstrate the effectiveness of the proposed HESS topology and EMS, simulation results are presented in Section 4; and finally, in Section 5, conclusions are given.

II. TOPOLOGY OF THE SYSTEM

Battery-SC HESS can be configured in passive, active or the combination of both either in parallel or in series. For passive connection, the terminals of ESS are directly connected to the DC bus. The advantages for this configuration are simplicity, and low cost and the inconvenient is the low volumetric efficiency of the supercapacitor as well as a limited flexibility in HESS design [1,14]. On the other hand, active HESS topologies employ active components such as bi-directional DC/DC power converter to interface each element of the ESS from DC bus and to actively control their power flow. The fully active topology can achieve the best control effect, while adding more complexity. But this complexity is now easier to manage in the physical implementation because of the development of programmable numeric circuits like FPGA and the VHDL material description language [15].

The proposed multilevel HESS topology in this paper is composed of three elements. The LA battery is used as the main storage ensuring the principal capacity of the HESS to take advantage of its low cost, temperature stability and technology maturity. The second element of the HESS is a supercapacitor to absorb the high frequency exchange of power between the HESS and the DC bus to preserve batteries for unnecessary charge-discharge as it is known to have high power density, long life cycle and a very low time constant. The third element of HESS is a Li-ion battery which has higher life cycle and power density than LA battery and has very high energy density and much lower price than supercapacitor. It suits very good to absorb the middle frequency in the exchange of the power so that the supercapacitor size could be at a reasonable level. As we want to be able to have a full control of the power exchange to enhance the battery life expectancy, three bidirectional DC-DC converter buck-boost is used to interface each element of the HESS to the DC bus. The figure 2 shows the proposed topology of the HESS with a general description of the energy management system used to control the power flow and exchange in the overall system. The EMS uses as inputs the power to be exchanged with the HESS and the SoCs of batteries and supercapacitor to be computed and gives as output the duty cycle of the three bidirectional DC/DC converter which interface the batteries and supercapacitor with the DC bus.

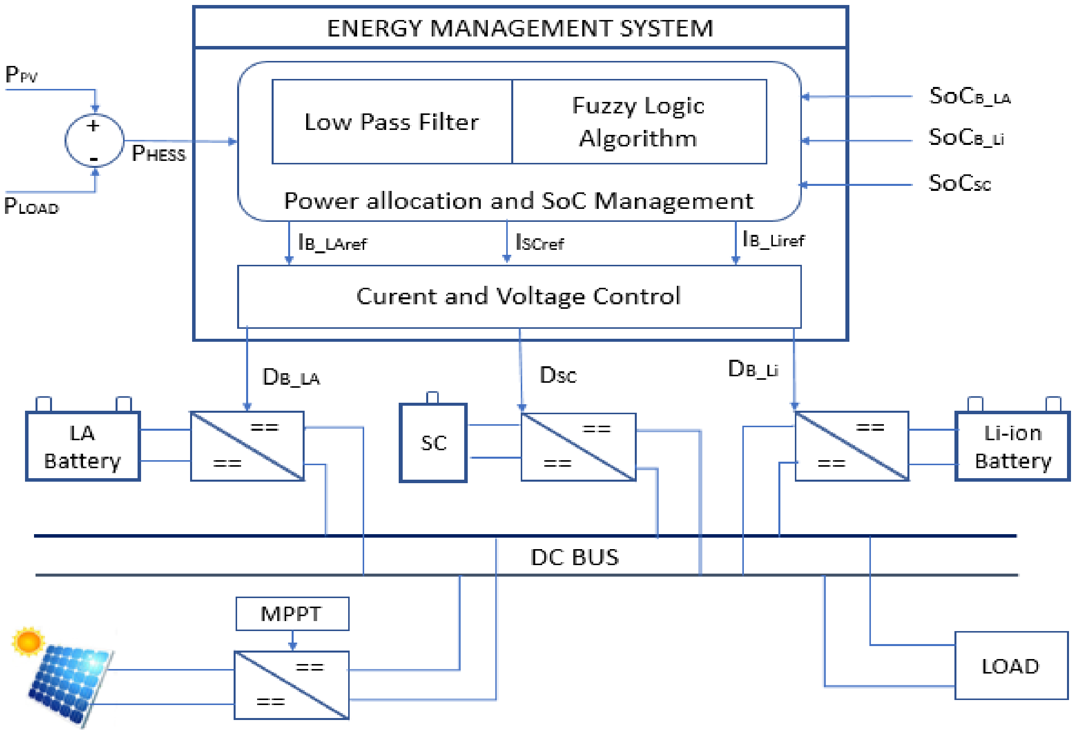


Figure 2: Proposed new topology for standalone PV power system with multilevel parallel active HESS and its EMS.

III. ENERGY MANAGEMENT SYSTEM FOR HESS

3.1 Review on HESS control strategy

Rule Based Controller (RBC) and Filtration Based Controller (FBC) are used in many researches to control HESS. RBC uses a set of rules to decide the power flow between the battery/DC Bus or Supercapacitor/DC Bus. Due to the simplicity of this technique, it does not require high processing, however it is very sensitive to system parameter variations. A detailed study of RBC can be found in [16]. Conversely, the FBC uses a filter to extract the dynamic components of the power as high-frequency and low-frequency components. Due to simplicity, this technique requires less complication. Figure 3 illustrates two low-pass filter (LPF) based FBC. The lowest frequency component is the output of the primary, the middle frequency component is the output of the secondary LPF and the high frequency component is the remaining power not filtered by the two LPF. Low, middle and high frequency components describe the power demand to be supplied by the HESS.

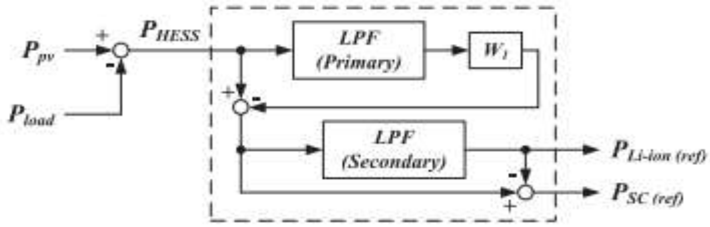


Figure 3: Filtration Based Controller (FBC)

3.2 Proposed energy management system

The proposed management system combines a Filter Based Controller and fuzzy logic control strategy. The FBC presented in Figure 3 is proved to be efficient to manage the exchange of power from the HESS, the PV and the DC bus especially in smoothing the curent int the battery [17]. However, it is not considering the SoCs of the HESS elements. Fuzzy logic based controller is then used to manage the power exchange while considering the state of charge of each elements of the HESS to keep it at a safe level so that durability can be increased [18,19].

The Figure 4 shows a diagram with SIMULINK model explaining the principle of the proposed EMS. The FLC uses four input variables which are SoC_{bat_la}, SoC_{bat_li}, SoC_{sc} and I_{DCref} and four output variables which are I_{SCref_s}, $I_{Bat\_LAref\_s}$ and $I_{Bat\_LAref\_s}$. Theses outputs values are used to control three switches to select directly the components of the power from the FBC in case the SoC of all HESS element are in an acceptable level and to keep the elements having too low or too high SoC on standby until the condition is safe to charge or discharge it. The curent in the batteries and SC are controlled by PI regulator to follow the curent reference generated by the Fuzzy logic controller. The DC bus voltage also is controlled by PI regulator to be stabilized on the desired voltage reference set to $V_{DCref} = 55\ V$. The final outputs of the EMS are six duty cycle ($Q_{1\_Bat\_LA}$, $Q_{2\_Bat\_LA}$, $Q_{1\_Bat\_Li}$, $Q_{2\_Bat\_Li}$, Q_{1_SC} and Q_{2_SC}) to command six MOSFET of the three bidirectional buck/boost converters interfacing the batteries and the supercapacitor with the DC bus.

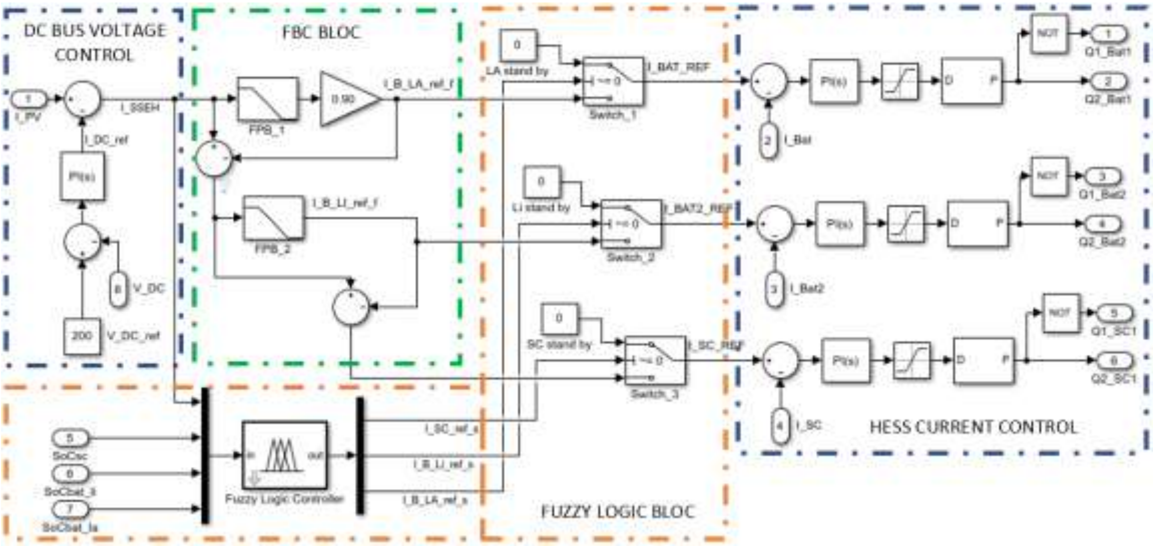


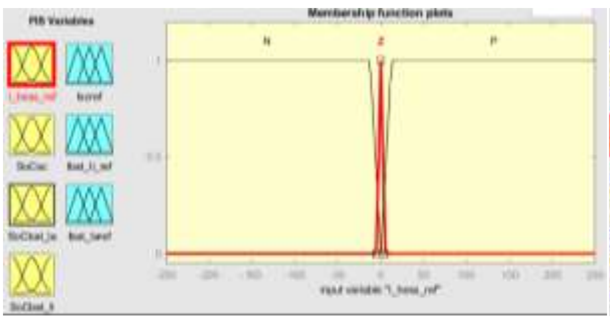
Figure 4: Simulink model of the EMS with FBC and Fuzzy Logic Controller

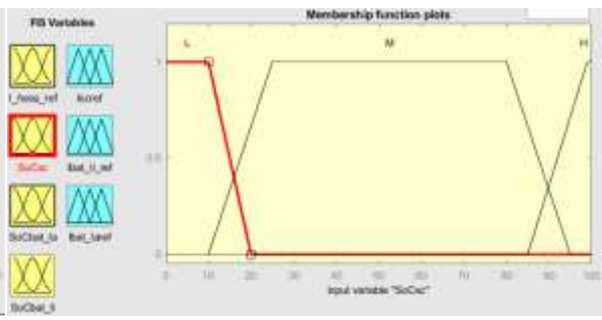
The fuzzy logic controller has been designed following three steps: the fuzzification, the inference and the defuzzification. The first step and second step consist respectively to transform the crisp input to fuzzy variables and fuzzy output variable to crisp output where we define the membership function for each input and output. The Table 1 shows the characteristics of input and output parameters. The second step is where we define the fuzzy logic rules which link the output to the input variables as described in Table 2, Table 3, Table 4, and Table 5. The values of curent are tagged as Positive (P), Zero (0) and Negative (N). The negative values mean the HESS will be charged because the PV produces more power than the load power. The positives values of curent mean the HESS will contribute to supply the load. And the zero values mean the production of PV is nearly equal to the load demand so the HESS is almost not contributing to power the load. The States of charge are qualified as Low (L), Medium (M) and High (H). The range are different for each element of the HESS as described in the Table 1. Finally, the defuzzification step is done to have the outputs with crisp values.

Table 1: Determination input-output variables and membership functions for the FLC

	$I_{HESSref}$	SoC_{sc}	SoC_{bat_LA}	SoC_{bat_Li}	I_{scref}	I_{bat_LAref}	I_{bat_Liref}
mf1	P (0 – 100 A)	L (< 20 %)	L (< 45%)	L (< 25%)	P (0 – 100 A)	P (0 – 100 A)	P (0 – 100 A)
mf2	Z (-2 – 2 A)	M (10-95%)	M (35-95%)	M (20-95%)	Z (-2 – 2A)	Z (-2 – 2A)	Z (-2 – 2A)
mf3	N (-100 – 0 A)	H (> 90%)	H (> 90%)	H (> 95%)	N (-100 – 0 A)	N (-100 – 0 A)	N (-100 – 0 A)

The Figure 5 and Figure 6 show respectively the graphical representation on MATLAB of the input variables and output variables membership function using trapezoidal function.





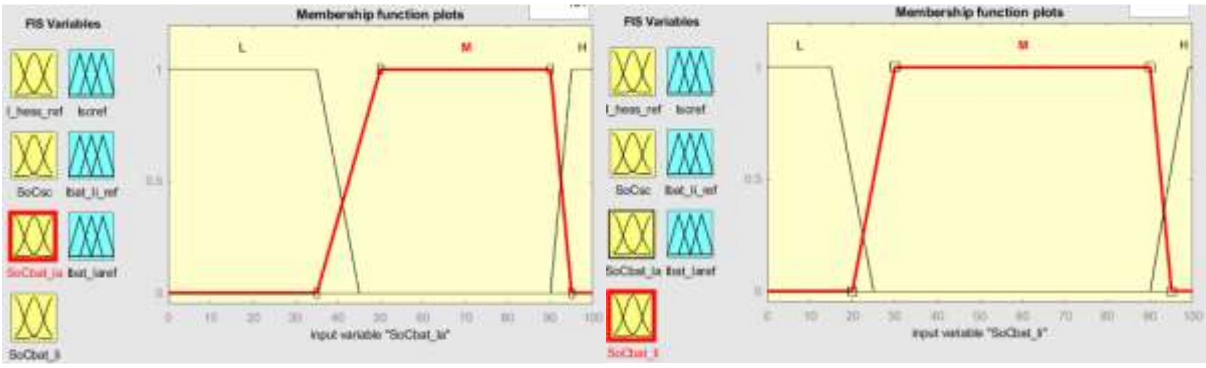


Figure 5: Membership functions of input variables designed on MATLAB environment

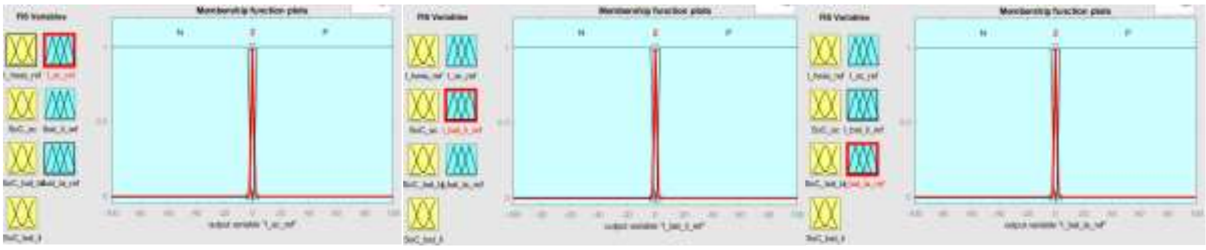


Figure 6: FLC Membership functions of output variables designed on MATLAB environment

The Fuzzy supervisor rules are designed so that, if all HESS elements are in a safe SoC level, the power flow of the system follows the power decomposed as set in the FBC. Conversely, if that is not the case for one or more elements, the fuzzy logic controller will choose which element should be used and which one should be on stand-by according to the SoC level.

The first case is when the PV produce more power than required by the load. That is to say if Idcref < 0. In that case if the state of charge of the LA battery is checked as Low or medium (SoC_{bat_LA} = Low or Medium), the outputs of the FLC could be seen on the Table 2. Then, the LA battery will be charged.

Table 2: Fuzzy rules outputs if PV produce more power and LA battery is on low or medium SoC

I_{SCref} / I_{bat_Liref} / I_{bat_LAref}		SoC_{bat_Li}		
		L	**M**	**H**
SoC_{SC}	**L**	N / N / N	N / N / N	N / Z / N
	M	N / N / N	N / N / N	N / Z / N
	H	Z / N / N	Z / N / N	Z / Z / N

Another case is, if $I_{dcref} < 0$ and $SoC_{bat\_LA} = High$. It means we have more power from the PV but the LA battery is already full so we stop charging it. The complete outputs values of FLC are given on the Table 3.

Table 3: Fuzzy rules outputs if PV produce more power and LA battery is on high SoC

I_{SCref} / I_{bat_Liref} / I_{bat_LAref}		SoC_{bat_Li}		
		L	**M**	**H**
SoC_{SC}	**L**	N / N / Z	N / N / Z	N / Z / Z
	M	N / N / Z	N / N / Z	N / Z / Z
	H	Z / N / Z	Z / N / Z	Z / Z / Z

The second case is during the time when the PV do not produce enough power or no power at all, the HESS will contribute to supply the load or produce all the power demand. Considering $I_{dcref} > 0$ and $SoC_{bat\_LA} = Low$, we can see on Table 4 the output from the FLC. As our main objective is to extend the life cycle of the LA batterie, it will not participate in supplying the load when its state of charge is at a low level. The supercapacitor and the Li-ion Battery will be used to supply the power demand.

Table 4: Fuzzy rules outputs if no PV production and LA battery is on low SoC

I_{SCref} / I_{bat_Liref} / I_{bat_LAref}		SoC_{bat_Li}		
		L	**M**	**H**
SoC_{SC}	**L**	P / P / Z	Z / P / Z	Z / P / Z
	M	P / P / Z	P / P / Z	P / P / Z
	H	P / P / Z	P / P / Z	P / P / Z

For the case in which the PV power is not enough to supply the load and the LA battery have a good state of charge, the table 5 describes the outputs of FLC ($I_{dcref} > 0$ *and* SoC_{bat_LA} *= Medium or High*).

Table 5: Fuzzy rules outputs if no PV production and LA battery is on low SoC

I_{SCref} / I_{bat_Liref} / I_{bat_LAref}		SoC_{bat_Li}		
		L	**M**	**H**
SoC_{SC}	**L**	Z / Z / P	P / Z / P	Z / P / P
	M	P / Z / P	P / P / P	P / P / P
	H	P / Z / P	P / P / P	P / P / P

The Figure 7 depicts the surface plot of the fuzzy rules in 3D when implemented on MATLAB. Each output is plotted in function of all inputs of the FLC.

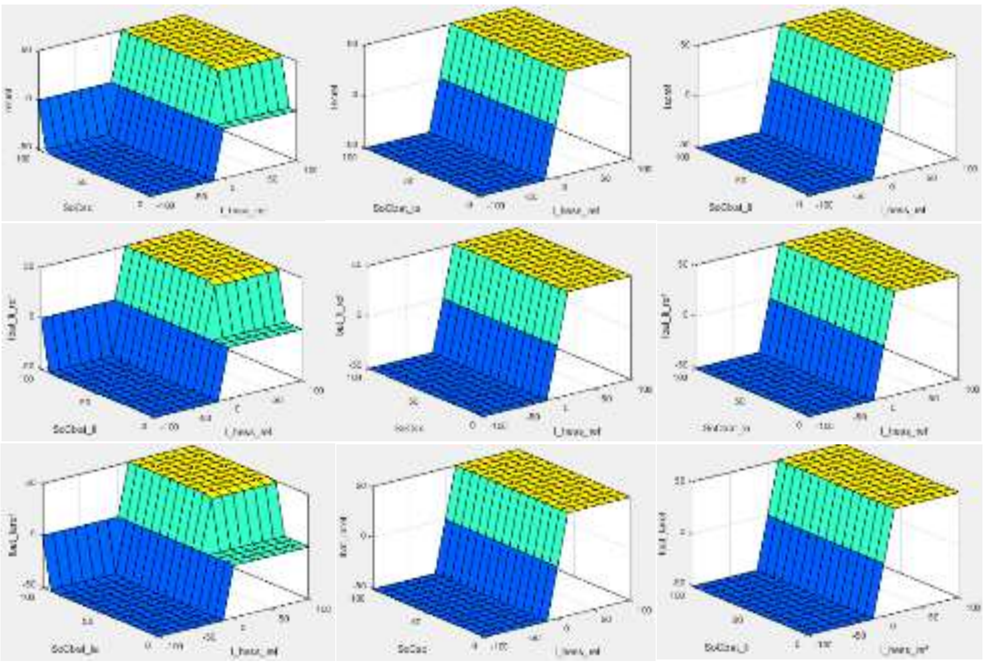


Figure 7: Surface plot of the fuzzy rules for the 3 outputs

IV. CASE STUDY

4.1 Size calculation

The size of HESS affects the performance of standalone PV system and its overall cost. The basic size of battery and supercapacitor is formulated, as follows.

The battery capacity is considered in amperes hours (Ah).

$$P = I * V_b \quad (1)$$

where, P is power, I is curent in amperes, and V_b is battery voltage in volts.

$$P * h = I * h * V_b \tag{2}$$

where h is time in hours.

$$I * h = C_b \text{ is the capacity of the battery in } Ah \tag{3}$$

Replacing these values in Equation (1), we get

$$P * h = C_b * V_b \tag{4}$$

Now, rearranging the equation gives

$$C_b = \frac{P * h}{V_b} \tag{5}$$

where C_b is the required battery capacity and it is represented in terms of P, rated power of PV system. Supercapacitor size is considered in Farad (F).

$$q = V_{SC} * C_{SC} \tag{6}$$

$$q/t = I_{SC} \tag{7}$$

where q is charge, V_{SC} is voltage, C_{SC} is capacitance, I_{SC} is curent, and t is time.
From Equations (6) and (7), it can be derived

$$I_{SC} = (V_{SC} * C_{SC})/t \tag{8}$$

$$P = I_{SC} * V_{SC} \tag{9}$$

$$P = \frac{{V_{SC}}^2}{t} * C_{SC} \tag{10}$$

$$C_{SC} = \frac{P * t}{{V_{SC}}^2} \tag{11}$$

where C_{sc} is supercapacitor size in Farad, V_{sc} is supercapacitor voltage, and P is PV system power.

In the studied model, a standalone PV system consists of a PV array, a MPPT, a battery bank, and an inverter. Trina Solar 315 W PV module is used to simulate the PV system. Eighteen PV modules in total are connected for a 5.5 kW standalone PV system having two strings and each string consists of 9 modules. A classical DC-DC boost converter is used to boost up the voltage of PV array and track the MPP. Three bidirectional DC-DC buck-boost converter is used to charge and discharge the batteries and supercapacitor. Table 6 lists the components and their ratings. Battery and supercapacitor ratings are calculated while using Equations (7) & (11).

Table 6: Characteristics of the system components

Components	Rating
PV Module	5.5 kW
LA Battery	550 Ah / 48 V
Li Battery	50 Ah / 48 V
Supercapacitor	32 F / 32 V

4.2 Data for the simulation

Irradiance of a cloudy day of June in Antananarivo will be used for the simulation to demonstrate if the build system PV-Supercapacitor will provide enough energy to supply the estimated load during a day. The month of June is the cloudiest period of the year except the period of cyclone in January and February in Madagascar. The Figure 8 shows the irradiance of a typical sunny day and cloudy day in June.

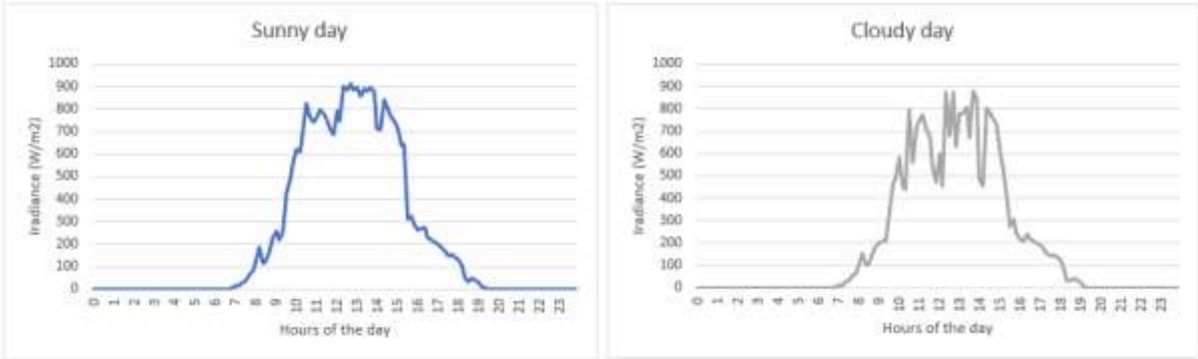


Figure 8: Typical day Solar irradiance of the zone in Antananarivo Madagascar [Meteorology Madagascar]

Investigation has been carried out in many villages in Antananarivo, and it has been determined that there are many families composed by three to five households living in the same location, wanting to have a standalone power system. After evaluation of their needs, the load profile in the Figure 9 has been established in daily normal situation and also in some special event in the family.

Figure 9: Estimated load profile during a normal day and special day

4.3 Simulation Result

The simulation of the designed HESS based PV system is carried out in MATLAB/SIMULINK environment. This PV system is simulated during a complete day using real irradiance input data for a particular cloudy day in June. The generated PV power, the load power, the output power, the LA battery power, the Li-ion battery power and the Supercapacitor power are shown on Figure 10.

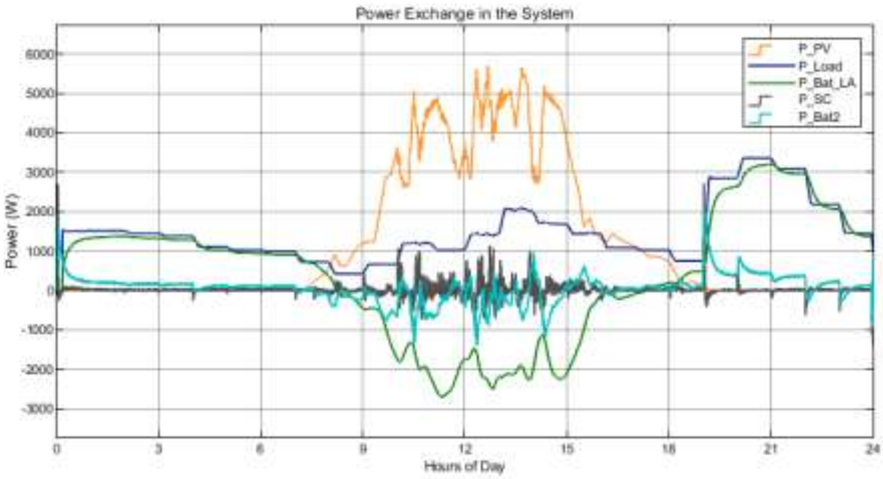


Figure 10: Power exchange in the HESS based PV system with Fuzzy Logic Control

The PV is supplying the load and charging the batteries and SC during the day while there is high irradiance. The LA battery is supplying 90 % of the load already smoothed power, 10 % remaining of the load power having a middle frequency is supplied by the Li-ion battery while the supercapacitor is only used to absorb the high frequency power remaining caused by the fluctuation of irradiance and the sudden change of the load power demand.

The voltage of the DC Bus is regulated to a voltage reference $V_{DCref} = 55\ V$. The Figure 11 depicts the PV MPP voltage and the DC Bus voltage. As the irradiance is fluctuating, the PV voltage also is changing while following the MPP. Conversely, the DC bus voltage is maintained at 55 V with under 5 % ripple and minimal spike by the algorithm regardless of the irradiance fluctuation and the changing load power demand.

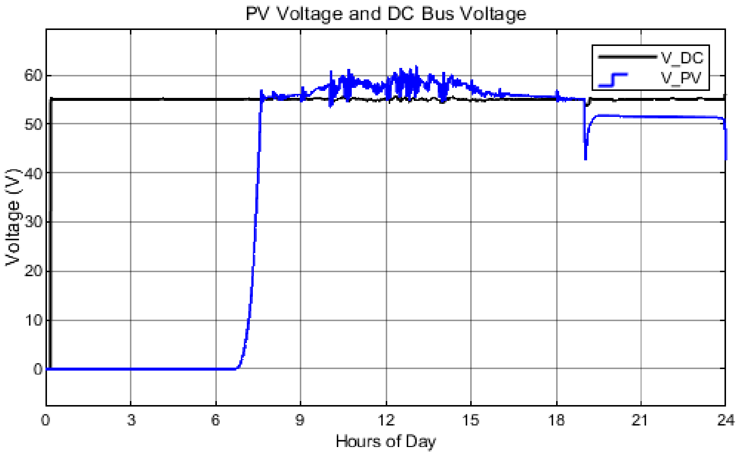


Figure 11: PV voltage and DC bus voltage variation

The batteries voltage is shown on the Figure 12 (a) respectively the supercapacitor voltage in the Figure 12 (b). The curve of the voltage variation of LA battery shows a trend far smoother than the Li-ion battery voltage variation. Conversely, the supercapacitor voltage is changing a lot and very quickly with the time particularly during the changing irradiance time. That means the charge discharge rate of supercapacitor is very high which suits very well its ability to exchange power at high rate and its very long-life cycle. The Li-ion battery is charged and discharge at a middle frequency which contributes a lot in reducing the charge/discharge stress of the LA batteries and to reduce the size of the supercapacitor needed.

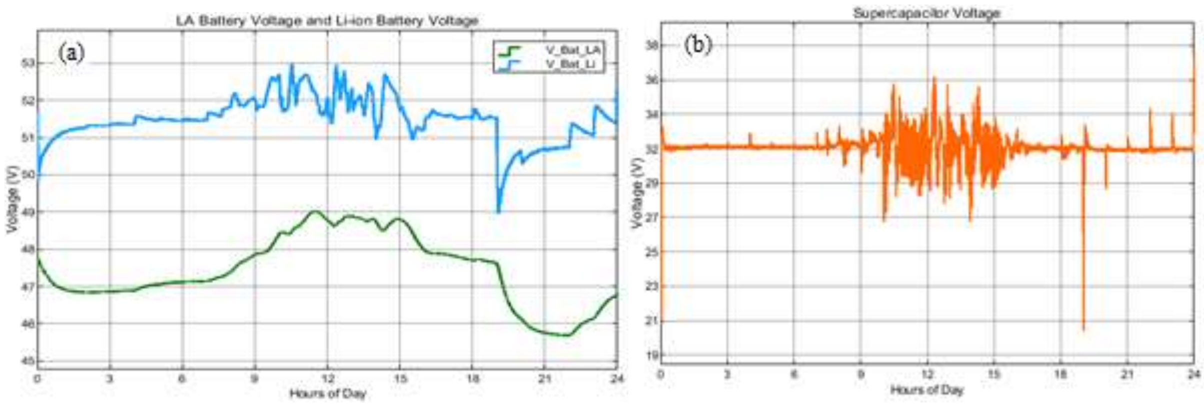


Figure 12:(a) LA battery voltage and Li-ion battery voltage variation ;(b) Supercapacitor voltage variation

The LA battery curent, the Li-ion curent and the supercapacitor curent are shown respectively in Figure 13 (a), (b), (c). The curent in the LA battery is smooth in the proposed topology because the high frequency part is absorbed by the supercapacitor and the middle frequency part is supplied by the Li-ion battery. In the traditional scenario is which these curents are all supplied by only the LA battery, the dynamicity of the curent will cause a lot of stress of high charge/discharge rate and shorten the life cycle of the battery which is already the lowest in the standalone PV system.

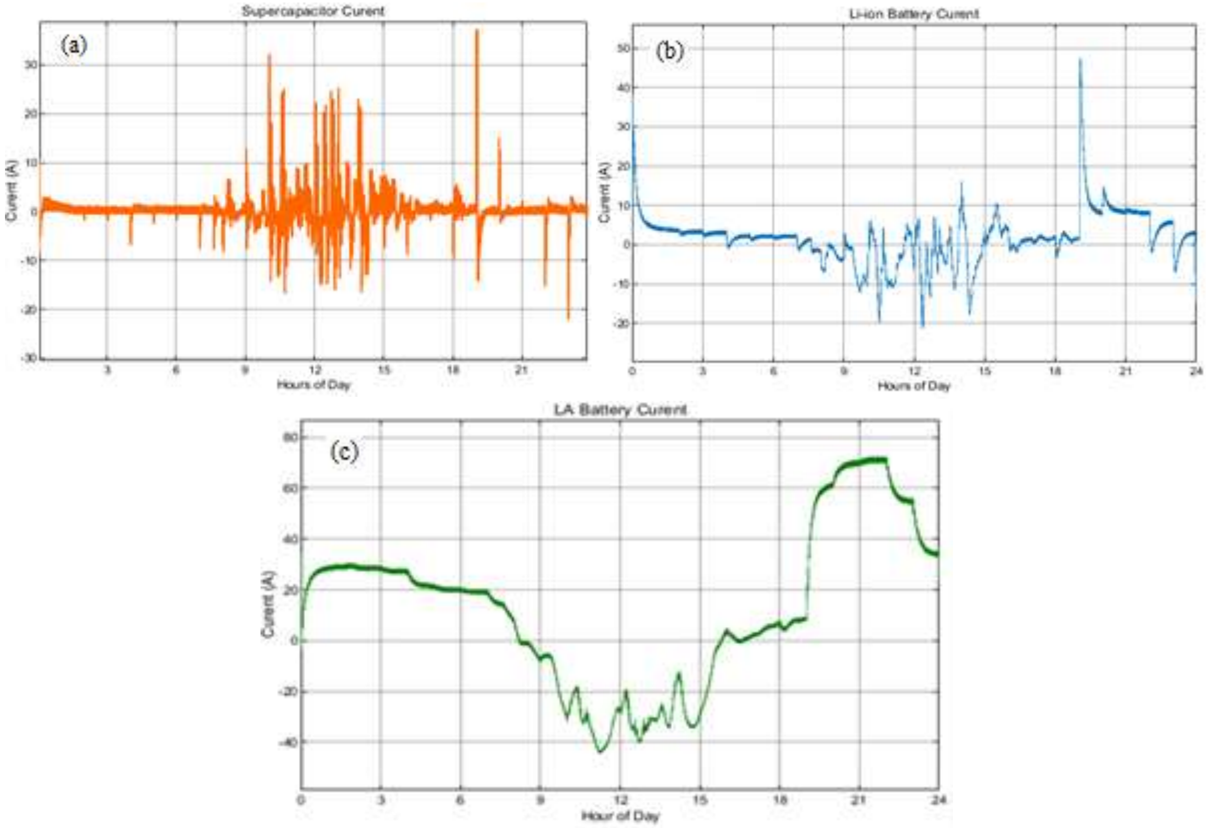


Figure 13: (a) Supercapacitor curent variation; (b) Li-ion battery curent variation; (c) LA battery curent

In normal condition the standalone PV system has been designed so that the state of charge of the batteries and the supercapacitor stay at acceptable level. The state of charge variation of the supercapacitor, the LA battery and the Li-ion battery are show respectively on Figure 14 (a), (b), (c). In normal condition the simulation was running at an initial condition that the state of charge of the LA battery and supercapacitor is at 70 % and Li-ion battery begin at 60 %. During 24 hours in this scenario, the LA battery state of charge never decreased under 50 % and never charged over 92 % which means that there is no deep discharge nor overcharge. The supercapacitor SoC variation is between 87 % to 21 % with very frequent change of the SoC in very small-time interval which can show that the SC is fully used. The Li-ion battery SoC is always limited between 94 % to 27 %. The EMS with fuzzy logic algorithm is showing efficiency to use the three elements of the HESS in their best conditions while supplying the load in permanence.

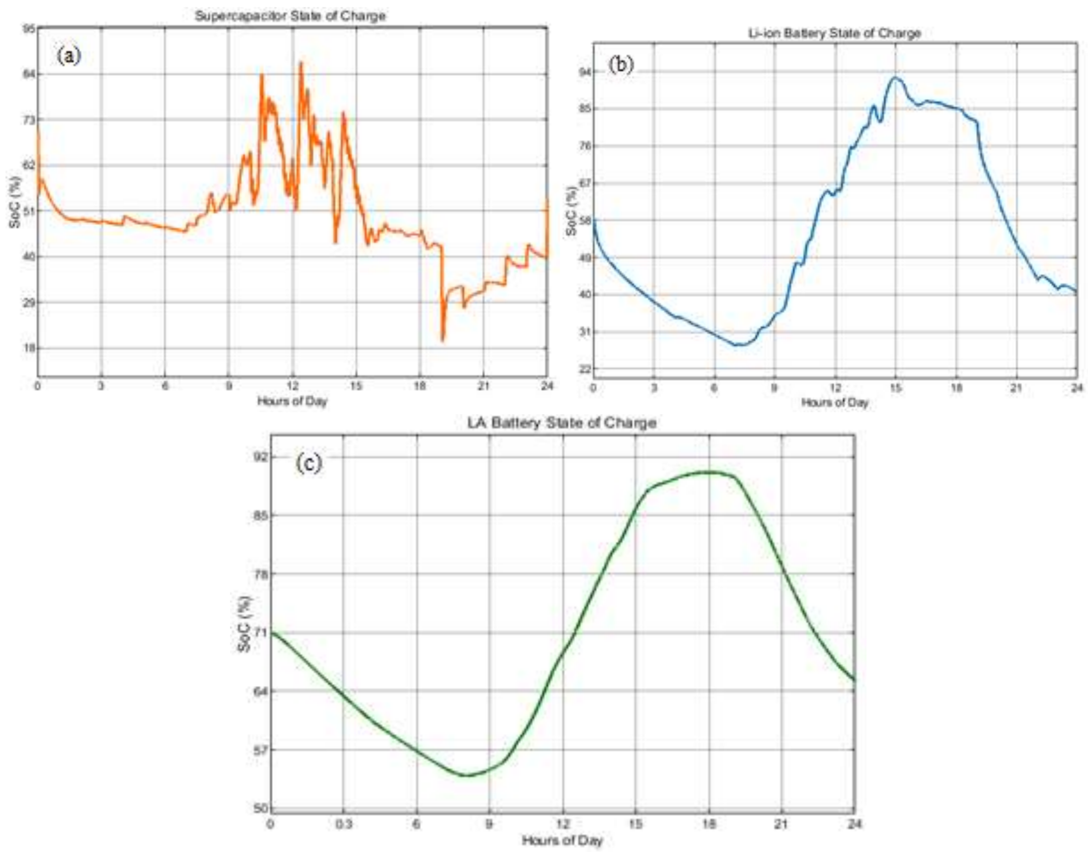


Figure 14: (a) Supercapacitor state of charge; (b) LA battery state of charge; (c) Li-ion battery state of charge

V. CONCLUSION

In this work, a HESS based stand-alone PV system and a fuzzy logic control strategy is developed for residential applications. MATLAB/Simulink model of the selected hybrid energy storage systems are developed and simulated with actual solar irradiance data and estimated load profile to evaluate the effectiveness in reducing battery stress and managing the state of charge of the HESS elements. Simulation results suggest that the combination of actively controlled LA battery energy storage with the Li-ion battery and supercapacitor with a fuzzy logic control strategy could be a very interesting setting for standalone PV power system applications because it can take advantages of all the benefits of each storage technology.

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