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Solar Energy Storage System Microgrids Integration For Power Quality Improvement Using Four Leg Three Level NPC Inverter and Second Order Sliding Mode

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***Abstract*—** Rising demand for distributed generation based on Renewable Energy Sources (RES) has led to several issues in the operation of utility grids. The microgrid is a promising solution to solve these problems. A dedicated energy storage system could contribute to a better integration of RES into the microgrid by smoothing the renewable resource's intermittency, improving the quality of the injected power and enabling additional services like voltage and frequency regulation. However, due to energy/power technological limitations, it is often necessary to use Hybrid Energy Storage Systems (HESS).In this paper, a second order sliding mode controller is proposed for the power flow control of a HESS, using a Four Leg Three Level Neutral Point Clamped (4-Leg 3LNPC) inverter as the only interface between the RES/HESS and the microgrid. A three-dimensional space vector modulation and a sequence decomposition based AC side control allows the inverter to work in unbalanced load conditions while maintaining a balanced AC voltage at the point of common coupling. DC current harmonics caused by unbalanced load and the NPC floating middle point voltage, together with the power division limits are carefully addressed in this paper. The effectiveness of the proposed technique for the HESS power flow control is compared to a classical PI control scheme and is proven through simulations and experimentally using a 4 Leg 3LNPC .

***Keywords* --** DC-AC power converters, Energy storage,Microgrids, Power quality, Sliding mode control.

I. INTRODUCTION

The increasing penetration of DG is changingmanagementof the grid from centralized to decentralized schemes,creating several challenges that must be carefullyaddressed in order to keep the electrical grid's properoperation. High penetration of renewable energy can lead tostability and power quality issues due to the stochastic natureof RES, such as wind and solar energy. The microgridconcept, which can be defined as a small scale weak electricalgrid that is able to operate both in connected and islandedmode, has been extensively studied as a solution for RESintegration. The weak nature of a microgrid implies the use ofan Energy Storage System (ESS) to increase RES penetrationand insure its stability [1]–[3].

The use of an ESS integrates constraints such as admissiblebandwidth, maximum ratings, current/power maximumgradient and the number of cycles. If these constraints are notrespected it can lead to a dramatic lifetime reduction of theESS, or in certain cases, to its destruction. [4], [5]. The use ofa Hybrid Energy Storage System (HESS) offers the necessary trade-off for increasing the lifetime of each ESS while also increasing the global specific energy and power of the wholesystem [6], [7]

Fig. 1 shows the main structures currently found in theliterature to integrate a HESS into a grid. The passive topologya) shows a lack of control of the power flow as well as theESSs State of Charge (SOC) [8], [9]. The floating b) andparallel c) topologies are active topologies that use DC/DCconverters to manage energy flows directly. They arealreadybeing used within the industry and fulfill a high standard(stress reduction and specific power/energy enhancement [7],[10]–[12]). Parallel topology offers the best flexibility but theuse of several DC/DC converters affects the global efficiency[13]. Finally, despite a lower flexibility when compared to theparallel topology, the 3L-NPC topology d) can be used as asingle power converter able to manage the power flow of aHESS, acting as an interface between the RES and the grid.

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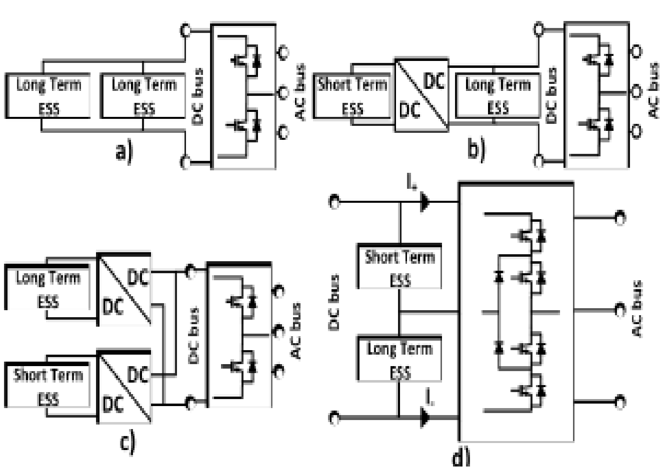

Fig. 1 Power converter topologies for microgrid ESS hybridization

(a) passive (b) floating (c) parallel (d) 3L-NPC topology

Due to the reduced voltage applied on the switches and an increased number of voltage levels, the 3L-NPC topology becomes more efficient while showing a lower current Total Harmonic Distortion (THD) [13] than an equivalent two levelinverter.Several works have been carried out on ESS hybridizationusing multilevel topologies, including the 3 Leg 3L-NPC[13]–[15]. In [13], a PI controller is designed to control thepower flow of a Vanadium Redox Flow Battery (VRB)whereas a SuperCapacitor (SC) provides the fast variation of power with both parallel and 3 Leg 3L-NPC inverters. It isshown that, beyond the limits of the 3L-NPC topology, theefficiency and THD improvement make this topology suitablefor ESS hybridization. Another particularity of this topology is the floating DClink middle point voltage which involves voltage ripples atthree time the fundamental frequency (i.e. 150 Hz) [16]–[20].

The harmonic magnitudes are directly linked to theModulation technique used, as well as the DC link filtercharacteristics [21], [22]. These voltage ripples coupled tohighly unbalanced AC loads may cause large DC currentharmonics which may increase electromagnetic interference(EMI) and impact ESSs lifetime due to increased thermallosses [23], [24]. This effect could be exacerbated by a Degraded DC link filter. The 4-Leg 3L-NPC used as an active power filter is alsoextensively studied in the literature [19], [25]–[28]. Thanks tothe 4th leg this inverter is able to produce zero sequencecurrents in addition to direct and negative ones. Thischaracteristic enables compensation for the increasing numberof unbalanced loads (monophasic customers, electricVehicles…) and single phase generators (small wind/PVunits).

In [19], [27], [29] several modulation techniques andredundant vector selection methods are used to balance thecapacitor voltages in power filter application. In [27], the ACside predictive control of a 4 Leg 3L-NPC inverter in isolatedmode improves the performance and the power quality. In [30]a non-linear control strategy is developed for a 4 Leg 3L-NPCinverter used as an active power filter. However, the 4-Leg3L-NPC inverter used both as a power filter and a HESS

Interface for a RES integration into the grid is not addressed inthe literature.The use of the 4-Leg 3L-NPC topology when associatedwith an adapted control strategy in a microgrid contextpresents itself as a promising solution due to its ability tocombine the following characteristics• Increase the efficiency of RES and HESS integration tothe microgrid through a unique power electronicsinterface acting as an active power compensator able tosmooth the RES by acting on the HESS [13]

`• Reduce AC side current harmonics (for the sameswitching frequency and AC filter components whencompared to a 2 level inverter) [31]

• Reduce HESS current harmonics caused by the floatingmiddle point inherent to the NPC topology and move theripples involved by unbalanced AC loads to the high

Specific power ESS [32]

• Compensation of AC side microgrid disturbancesproduced by unbalanced/nonlinear loads thanks to thefourth leg [19]

In this paper, the power flow management of a HESScomposed of a Li-Ion battery and a Vanadium Redox Battery(VRB) is investigated in a microgridcontext. The 4 Leg 3LNPCinverter has been chosen to interface the HESS with themicrogrid due to its low THD, high efficiency and its ability tomanage unbalanced AC loads through the 4th leg.The objective of the paper is to prove that by adding the fourth leg to a 3L-NPC converter and using a new DC sidecontrol strategy it is possible to reach both fast and efficientDC power sharing between the two ESSs and the RES, and atthe same time improve the AC side power quality. The maincontribution of this paper lays in the DC power flow controllerwhich allows HESS power flow control and DC currentharmonics suppression. The new model for 4-Leg 3L-NPCstructural limits proposed in [33] is assessed. The effectivenessof the proposed system has been tested through simulationsand experimental tests using a laboratory prototype.The paper is organized as follows: in Section II the ESSsand 4-Leg 3L -NPC inverter are modelled. In Section III thedesign and tuning process of a Second Order Sliding Mode

Controller (2-SMC) and a PI classical scheme are developedfor the DC power flow control. The AC side control whichallows working in unbalance load conditions is also exposed in this section. Section IV features simulations andExperiments which aim to prove the effectiveness of thetopology and the ability of the 2-SMC to control the HESSpower flow in various conditions.

proposed feedforward calculation algorithm based on vector analysis improves the system dynamics conspicuously. To demonstrate the complete verification of the proposed method, a mathematical proof is included.

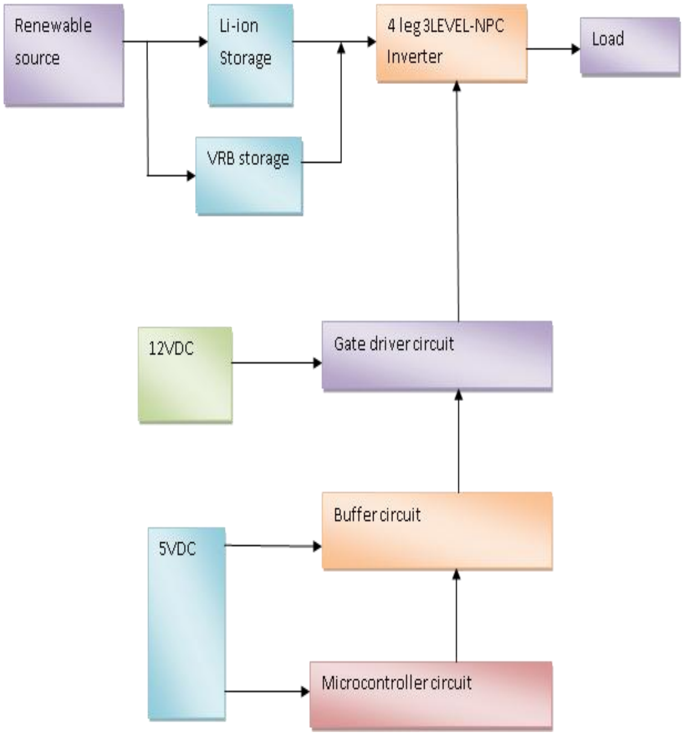

Fig.2 Block Diagram for Proposed System

Fig.1 is a block diagram of proposed system. It consists of blocks following as below;

- Nonlinear load
- NPC converter
- superCapacitor bank
- Battery bank
- IGBT switch
- Gate driver circuit
- PWM Generator
- Microcontroller circuit
- Renewable energy source

The above Fig. 1 is the overall functions are following as, the generation station power is generated that power is transferred to the load side through the grid. That power is transfer in the middle of the time such faults are occur in the grid lines so, the quality of the grid power is reduced by that faults. If voltage sags is occur how to compensate that faults so, this method is proposed.

The PID controller has some set of reference values for simultaneously monitoring or measuring the capacitor bank values. If capacitor bank is suddenly down that compared with set of reference values the PID controller is disenabled to the capacitor bank and enabled to the battery bank to the CHB inverter through the IGBT switch.The PID controller has two inputs one is set of reference values and another one is DC capacitor bank values.Then next is space vector modulation (SVM) control technique is used. It has taken the two inputs one is ac grid voltage and another one is capacitor bank reference voltage and the PID controller is monitoring the DC capacitor voltages if any errors are available that errors are given to the input for SVM. This SVM is taken that inputs that produces a space vector pulse width modulations for cascaded h-bridge inverter. The SVM produces a gate pulses for given to the input in cascaded h-bridge switches and CHB inverter has two inputs one is gate pulse and another one is capacitor bank is discharged energy to the CHB inverter. That CHB inverter has inverting the dc voltage to the ac voltages. Those voltages are injected to the grid lines used in the STATCOM. Finally, the voltage sags are compensated using this control technique.

HESS AND 4-LEG 3L-NPC MODELING

In order to design and assess in simulation a control strategy able to manage the DC power flow withinthe HESS and at thesame time improve the AC power quality, the investigatedsystem has first been modeled, taking into account theobjective of the study, i.e. the transient behavior.

A. Modelling of the ESSs

The investigated HESS is formed of a Li-Ion battery and VRB. The VRB technology benefits from the decoupledspecific power (which depends on the stack characteristics)and its specific energy(which depends volume ofelectrolyte tanks). Along with the flexibility offered by thisspecificity, the technology is also suited to long term energystorage as there is nearly no self-discharge with a good round trip efficiency of 78%-88% [34]. The Li-Ion battery benefitsfrom a high specific power and moderate self-discharge (1-5%per day). This technology has also been developed for highpower standalone applications in recent years [35].Consequently; the use of the set work technologies iscomplementary and realizes a high specific energy and highspecific power HESS.

1) VRB model

The VRB used in this work has a rated voltage of 450V (at50% of SOC and open circuit), a maximum charge/discharge Current of 60A and a rated power of 25kW. The model of theVRB is based on the dynamic model introduced in [36], [37]And has been validated on a 1.25kW experimental device in[38]. as only the transient behavior is under investigation, forthe sake of simplicity only the capacitance of the electrode istaken into account. Fig. 2 shows the equivalent circuit of theVRB whose parameters are summed up in Table I .

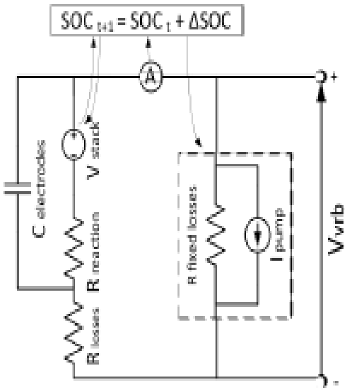

TABLE I
VRB UNIT PARAMETERS

Parameter	Value
Cells in series	322
Vequilibrium (V)	1.4
Rreaction (Ω)	0.81
Rresistive (Ω)	0.54
Rfixed (Ω)	295.2
Celectrode (F)	0.0186

Fig. 3. Model of the VRB

2) Li-Ion model

The Li-Ion model used in this work is based on the modulePresented in [39]. This model is already implemented in theMATLAB/Simulink within the SimPowerSystems library.TheBattery is realized with strings of seriesmodules connected inParallel to build an ESS of 825V/30Ah (at 80% of SOC andopen circuit). Both charge anddischarge voltage easer given in(1) and (2) respectively. The parameters of the LiIon batteryare summed up in Table II.

$$E_{Li-Ion}^{charge} = E_0 - K\frac{Q}{Q-it}.i_{LP} - K.\frac{Q}{Q-it} + A\,exp(-B.it) \tag{1}$$

$$E_{Li-Ion}^{dischare} = E_0 - K\frac{Q}{it+0.1Q}.i_{LP} - K.\frac{Q}{Q-it} + A\,exp(-B.it) \tag{2}$$

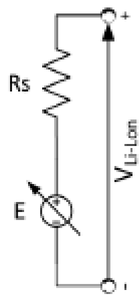

TABLE II
LI-ION UNIT PARAMETERS

Parameter	Value
Cells in parallel	20
Cells in series	550
E_0 (V)	3.73
K (V)	0.00876
A (V)	0.468
B $(Ah)^{-1}$	3.53
R_s (Ω)	0.09

Fig. 4. Model of a Li-Ion cell

B. Modelling of the 4-Leg 3L-NPC

Fig. 4 shows the schematic representation of the 4-Leg3LNPC.

Inverter used as a HESS interface for RES and HESSintegration to a microgrid. This topology requires the RES tobe a current source and in particular, could be adapted ifplaced either after a Maximum Power Point Tracking (MPPT)converter for a solar plant, or instead of the grid-side converterof a back to back set up for wind turbines. For this study theRES is considered as a current source injecting into the DCbus.

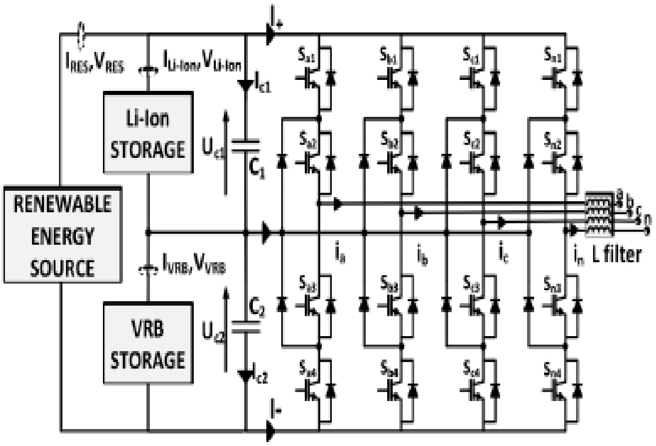

Fig. 5. 4-Leg 3L-NPC topology used as a HESS/RES interface

The 4-Leg 3L NPC inverter has 34 = 81 different switchingstates that produce different voltage vectors defined by (3).The vectors generated by more than one switching state arecalled redundant vectors and allow power flow sharing controlamong the HESS [15].

The strategy adopted for the 4th leg modulation signalgeneration is based on the Three Dimension Space VectorModulation (3D-SVM) in ABC coordinates [40] and thepractical development of this scheme is based on [41]. The3D-SVM scheme is used to operate a transform from three tofour phases and only generates the modulation signal for theFourth leg of the inverter but is not detailed further as it is outof the scope of this paper. After 3D-SVM, a zero sequencesignal Zs is added to the modulation signals for redundantvector selection and therefore for the power flow control [14],[15] and DC link harmonic suppression [42]. In addition themodulation signal is processed using (5) with A1 and A2expressed in (4) in order to keep AC voltage balanced eventhough the ESSs voltages are unbalanced [22]. Finally, themodulating signals are split into their positives and negativesusing (6) to feed a single synchronous carrier PWM scheme which leads to the expressions in (7).

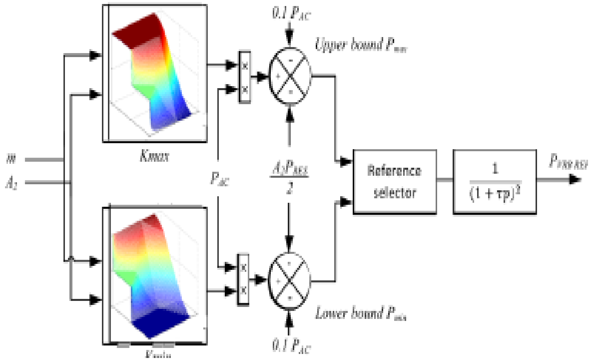

Fig. 6. VRB power reference definer

$$\begin{cases} A_1 = \dfrac{2V_{Li-Ion}}{V_{Li-Ion} + V_{vrb}} \\ A_2 = \dfrac{2V_{vrb}}{V_{vrb} + V_{Li-Ion}} \end{cases} \tag{4}$$

$$\begin{cases} d_k^{Li-Ion} = \dfrac{A_1 - 1 + d_k^{Zs}}{A_1} \\ d_k^{VRB} = \dfrac{A_1 - 1 + d_k^{Zs}}{A_2} \end{cases} \qquad k = a, b, c, n \tag{5}$$

$$\begin{cases} d_k^{+} = d_k^{Li-Ion} \dfrac{1 + sign\left(d_k^{Li-Ion}\right)}{2} \\ d_k^{-} = d_k^{VRB} \dfrac{1 - sign\left(d_k^{VRB}\right)}{2} + 1 \end{cases} \qquad k = a, b, c, n \tag{6}$$

$$\begin{aligned} d_k^{+} &= \frac{A_1 - 1 + d_k^{SVM} + Z_s}{A_1} P_k \\ & \quad with\ P_k = \frac{1 + sign\left(\dfrac{A_1 - 1 + d_k^{SVM} + Z_s}{A_1}\right)}{2} \\ d_k^{-} &= \frac{A_1 - 1 + d_k^{SVM} + Z_s}{A_2} M_k + 1 \\ & \quad with\ M_k = \frac{1 - sign\left(\dfrac{A_1 - 1 + d_k^{SVM} + Z_s}{A_2}\right)}{2} \end{aligned} \tag{7}$$

Considering the assumption that the carrier frequency ismuch higher than the fundamental one (i.e. more than 10times), the current in the bottom branch of the inverter *I*+linking the AC side variables to the DC ones is expressed in(8). The relation between the current of the top branch *I*E andthe current of the Li-Ion battery can be obtained Symmetrically.

$$\begin{aligned} I_{-} &= i_a d_a^{-} + i_b d_b^{-} + i_c d_c^{-} + i_n d_n^{-} \\ &= i_{res} + i_{vrb} + R_{svrb} C_2 \frac{di_{vrb}}{dt} - C_2 \frac{dE_{vrb}}{dt} \end{aligned} \tag{8}$$

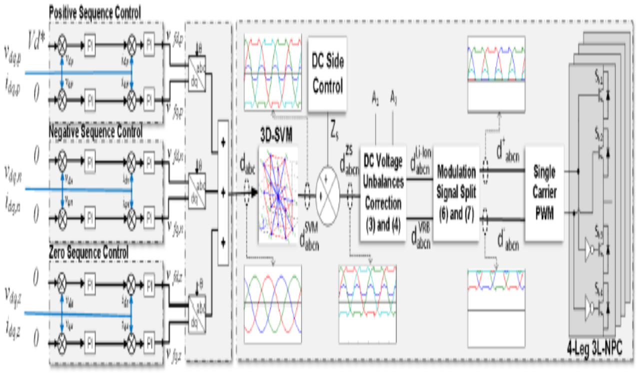

Fig. 7. Block representation of the modulation scheme

3) HESS harmonics suppression

The control algorithm designed for the HESS power flowmanagement is also able to tackle the DC link voltage rippleissue of the NPC topology that involve HESS harmonics. Fig.11 presents the HESS currents for different zero sequenceinjection controls and for the same conditions as the previoussimulations. As it can be seen in Table IV, the 2-SMC schemeallow a significant improvement of the current harmonicssuppression compared to the PI control. Also, the better resultof the VRB harmonic suppression compared to the Li-Ion oneare due to the fact that only the VRB current is controlledthrough zero sequence injection. It could be possible to reducethese harmonics even more using as miller settling time, butthe AC side harmonics wouldincrease as a consequence.

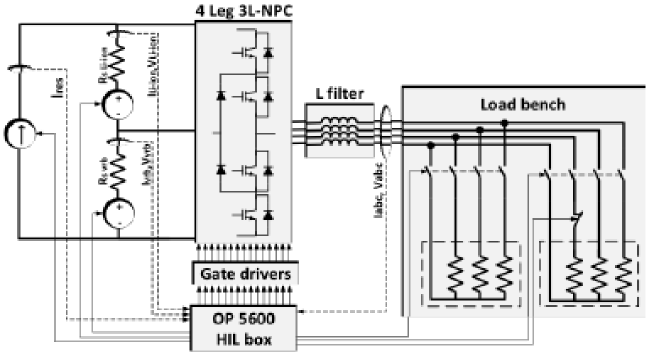

Fig. 8. Experimental test bench schematic

II. SIMULATION CIRCUIT AND RESULTS

To verify the validity of the proposed method, the simulation has been developed using MATLAB software. The simplified schematic of the simulated system is illustrated as Fig. 4.

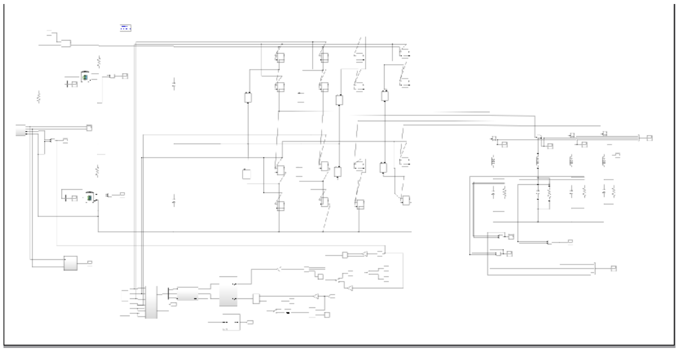

Fig.1.Overall simulation circuit diagram

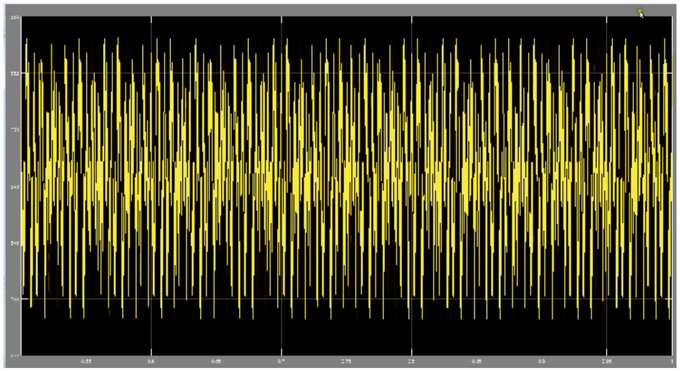

Fig.2. solar off battery operated waveform

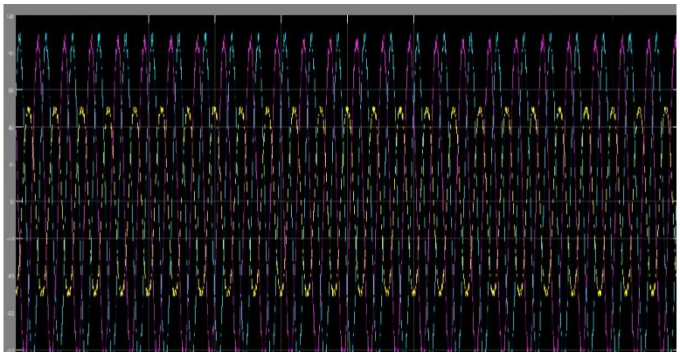

Fig. 3.Solar on battery operated waveform

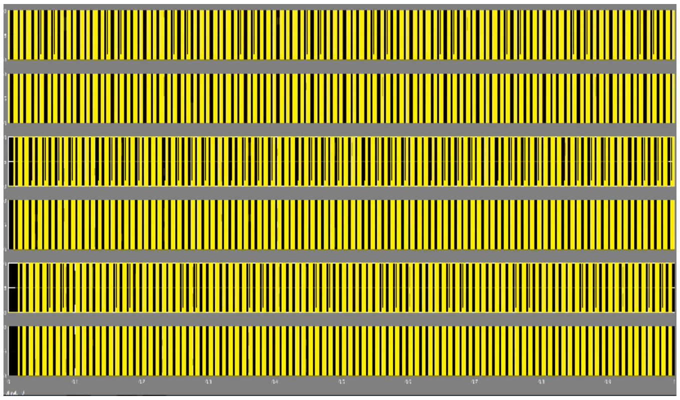

Fig.4. Gate pulse generator waveform

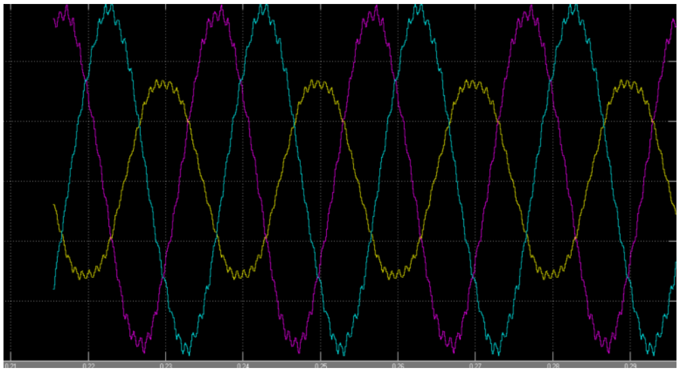

Fig.5. Waveform of input

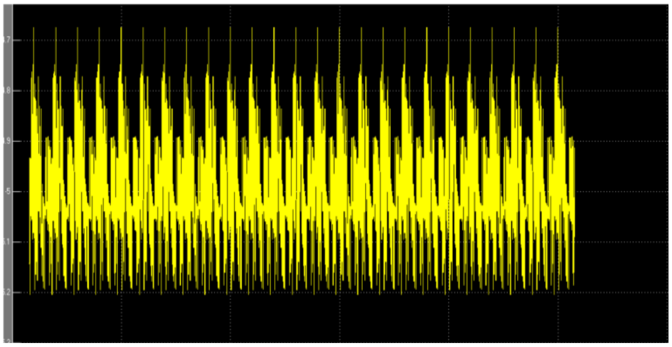

Fig.6. Waveform of output

TABLE I: CIRCUIT PARAMETERS VALUES

Quantity	*Values*
Switching frequency Fsw	10KHZ
AC RMS voltage L-N Vac	230V
AC filter Lf	3Mh
DC filter C	3.3Mf
VRB power setting time	0.25s

III. CONCLUSION

In this paper the use of a 4-Leg 3L-NPC power convertertopology to interface a RES with a HESS (formed by a VRBand a Li-Ion battery) in a microgrid context has beeninvestigated. A new model of the structural limits is presentedand implemented to exploit the entire capability of the 4-Leg3L-NPC converter to insure a maximum power divisionbetween the two ESS. A non-linear 2-SMC scheme has beendesigned and tuned to control the zero sequence injection inthe modulating signals in order to control the power flow ofthe HESS. Furthermore, the fourth leg of the converter allowsactive power filter capabilities. The investigation of the limitso of the topology showed a power exchange capability amongthe HESS. Simulation and experimental results proved thecapacity of the proposed control strategy to manage a HESS in order to improve the power quality and stability as wellas tocontrol the renewable energy injected into a microgrid.

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