Energy Management Strategy for Supercapacitor Storage using a Nonlinear Virtual Impedance

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***Abstract* - This paper proposes a new energy management strategy (EMS) used for charging and discharging a supercapacitor (SC). The method is based on a nonlinear impedance and resembles the droop control applied in microgrid structures. The droop control has the advantage of being decentralized so the proposed EMS also benefits this characteristic. Usually a tradeoff must be made between voltage regulation and load sharing for the droop control and a nonlinear resistor is often used to minimize this tradeoff. For charging and discharging a SC in droop controlled microgrids, a virtual impedance with an RC characteristic is usually used. The proposed method was created by merging together the two strategies, the nonlinear resistor and the virtual capacitive impedance, in order to benefit from the advantages provided by both methods. An overview of the most common strategies is also presented in this paper.**

I. INTRODUCTION

With the increase of distributed energy generation, microgrid structures are being widely used [1-3], and they tend to be more intelligent, decentralized and redundant. As more energy sources, loads and storage solutions [4-6] are becoming increasingly used, strategies for sharing the energy among them are widely required. These energy management strategies (EMS) make the decision on when and where to produce, store or use the energy in a microgrid structure, to have lower costs, higher efficiency, or increased reliability [7,8].

With the increased use of storage solutions, it is important to have better control of the energy flow, to or from the storage systems, in order to obtain maximum performances from them.

The structure considered in this paper is a DC microgrid with the topology presented in Fig. 1, with various energy sources, loads, SC and battery storage unit. When using wind energy in microgrids, it is important to smooth the energy fluctuations [9]. This can be done by using a SC to take the peak power of the wind generator, as it has a high power density. SC storage is also useful for a good voltage regulation in the DC grid because it has a fast response time. Battery storage can be used for slower variations of power and together with the SC can form a hybrid storage system that uses the advantages of both.

This paper proposes a decentralized EMS strategy for SC charge control, a strategy based on the conventional virtual impedance strategies and the nonlinear droop method. Comparisons with the conventional EMS are performed as well as the mathematical description.

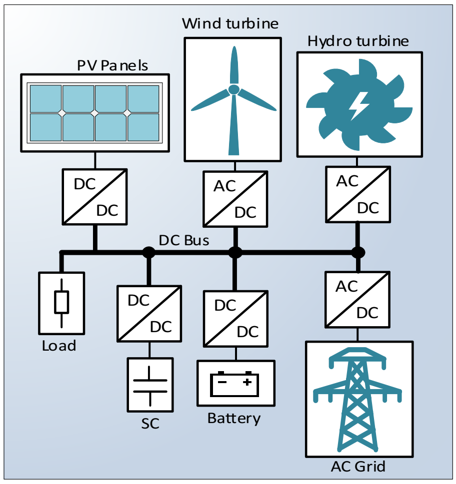

Fig. 1. Microgrid structure.

II. CENTRALIZED AND DECENTRALIZED EMS

In general, the EMS can be classified considering two categories: centralized and decentralized (Fig. 2).

A. Centralized

Centralized strategies have the advantage of better control, regulation and improved performances with the possibility to use more powerful control strategies [8]. Centralized systems, as their name suggests, have a central control unit which monitors and controls the power flow for each element of the grid [10].

B. Decentralized

Decentralized strategies have the advantage of being autonomous and easily expandable, without needing a communication network between microgrid elements [11]. For this case, each element of the grid has its own controller which does not communicate to other controllers from the grid, and it has more options with regards to compatibilities between different strategies applied in the same grid.

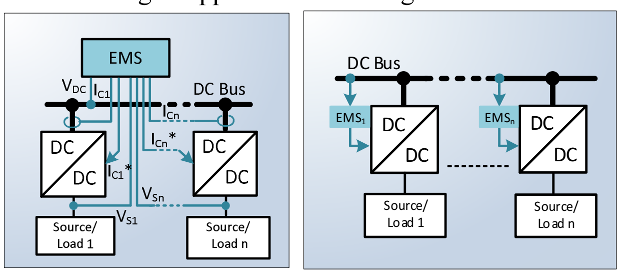

Fig. 2. Centralized EMS (left) and Decentralized EMS (right).

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Hybrid structures are also possible, being combinations between both, centralized and decentralized strategies. They still use a communication bus between elements, but the possibility to operate in a decentralized manner is taken into account in case of failure of the central control system [12, 13].

III. DROOP CONTROL AS EMS

A. *Conventional droop control*

The most common decentralized EMS used in microgrid is the droop control. Each converter acts like a voltage source (Fig. 3.a) with a virtual resistor in series to the output (R_1- R_n).

The method was proposed as a load-sharing method in multiple module converter systems, for paralleled converters, and was also used to improve stability and voltage regulation of single converter as well.

The resistor is implemented in the control algorithm, so that the output voltage of the converter drops with a value proportional to the output current of that converter. This way multiple converters can be connected in parallel to a grid and all of them can inject energy to the grid or they can draw energy from the grid. If one converter is acting as an energy source, such as solar panels, wind generator, or others, the voltage of the virtual voltage source (V_{d1} to V_{dn}) will change according to the available energy from that source [14] so that the virtual voltage source will start to inject current into the grid.

B. *Improved droop control*

The conventional droop method is a decentralized EMS but in order to have a better energy sharing, this method can be translated in a centralized system (Fig. 3.b), using a single EMS controller which provides references to all virtual sources (or virtual resistors) from the grid [13]. This way the grid can still operate in a decentralized manner if the central control unit fails, as a back-up solution, and a slower communication speed is needed for adjusting the voltage (ΔV_{OUT1} to ΔV_{OUTn}) or resistor values.

In order to keep the decentralized characteristic of the microgrid, but still have good load sharing, voltage regulation, or even lower power losses some papers propose the use of a nonlinear droop characteristic [15 - 18].

Because the cables that interconnect the elements of the grid have parasitic resistances, and because all sensors used for controlling each individual converter are affected by limited accuracy, the conventional droop method might have some issues in terms of voltage regulation or load sharing. For this reason, by using a nonlinear virtual resistor in the control loop, the performance of the microgrid could be improved.

The nonlinear resistor (Fig. 3.c) can be characterized by various mathematical dependencies between current and voltage, such as: parabola, inverse parabola, ellipse, cubic, inverse cubic, or it can model nonlinear components such as Zener diodes.

IV. THE CHARGE/DISCHARGE CONTROL OF THE SC

Charging and discharging of storage elements represent an important part of the EMS in a microgrid. In microgrid systems where wind power is used, or where a good voltage regulation under heavy load variations is required, a fast way to store and use energy is necessary. As storage elements have different power capabilities (power and energy densities), they also have different response times, so a way to share the energy between them is necessary.

Usually, EMS strategies make use of power filtering methods in order to separate the high frequency power components from the lower frequency power components and distribute them among different storage elements [19].

Conventionally, supercapacitors are used for the higher frequency power components because of their high power density, and batteries are used for the lower frequencies because of their high energy density. By using this hybrid system, the battery lifespan is prolonged while keeping a relatively low cost for the overall storage system.

The total power exchanged in the microgrid can be filtered and then the high and low frequencies are shared between SC and battery as in Fig. 4. This method is centralized, as it requires a central unit to monitor and filter the total power from the microgrid.

Decentralized strategies are also possible, and they are mostly based on local controllers that filter the voltage of the DC bus [20, 21]. The filtering can be done by using a virtual impedance (Fig. 6 - left) composed by a resistor and a capacitor which form a high pass filter for the current flowing through the voltage source. This method can be well used in a droop controlled microgrid so that the rest of the elements, such as battery storage systems, will draw the low frequency current by default. This method works well when a fixed filtering frequency is required for all operating regimes.

V. PROPOSED SC CHARGE/DISCHARGE METHOD

The proposed EMS method is based on the conventional droop filtering method and uses nonlinear virtual impedance in series to the ideal voltage source. The nonlinear characteristic of this method is given by the resistor, which has a characteristic similar to that of the varistor, or it can use an arctangent dependency for a faster implementation in a processor (Fig. 5).

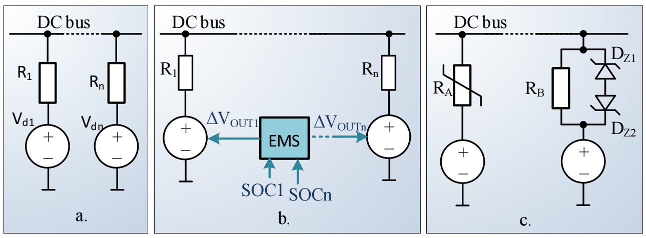

Fig. 3. Droop based control: a. Conventional; b. Centralized; c. Nonlinear.

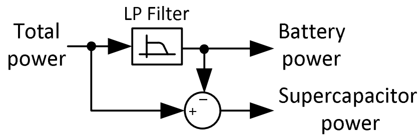

Fig. 4. Conventional filtering method used in centralized EMS.

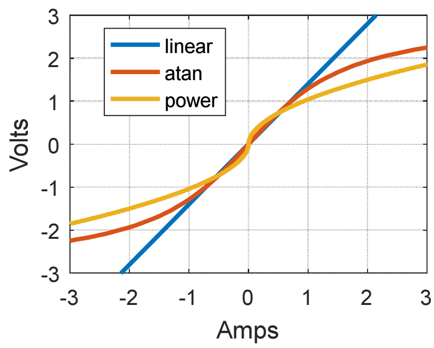

Fig. 5. Linear vs nonlinear resistor dependencies.

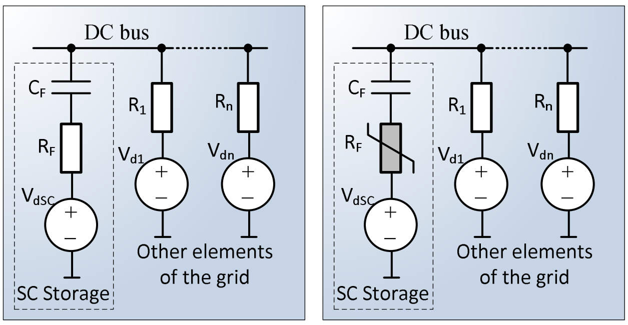

Fig. 6. Conventional EMS for SC charge (left) VS Proposed EMS (right).

By using the nonlinear characteristic for the resistor (Fig. 6 - right), the filtering frequency varies with the change of the voltage amplitude. Smaller cutoff frequencies of the filter correspond to higher variations of the voltage bus, therefore more energy is transferred to or from the SC. Higher cutoff frequencies of the filter correspond to smaller variations of the voltage bus, therefore less energy is transferred between the SC and the microgrid.

For the conventional filtering method (Fig. 6 - left), the relationship between voltages and currents is:

$$V_{DCbus} = \frac{1}{s \cdot C_F} \cdot I + R_F \cdot I + V_{dSC} \quad (1)$$

For the proposed method (Fig. 6 - right), if the arctangent function is used, the relationship between voltages and currents is:

$$V_{DCbus} = \frac{1}{s \cdot C_F} \cdot I + k_1 \cdot \mathrm{atan}(k_2 \cdot I) + V_{dSC} \quad (2)$$

Where, k_1 and k_2 are two factors which simplify the tuning of the current-voltage characteristic.

The cutoff frequency (f) can be approximated with (3), by using a dynamic resistor model, which can be calculated as the derivative of the nonlinear function.

$$f = \frac{1}{2 \cdot \pi \cdot R_F \cdot C_F} \quad (3)$$

The simulation results of the EMS containing a virtual impedance show the variable cutoff frequency of this method. In Fig. 7 a square signal was applied over the 350V of V_{d1} source. Both, the linear and nonlinear waveforms for currents (I_chg_lin, and I_chg_nonlin) and DC bus voltages (Vbus_lin and Vbus_nonlin) are identical for smaller signals (Fig. 7 - right) but for higher signals, the currents are also increasing (Fig. 7 - left).

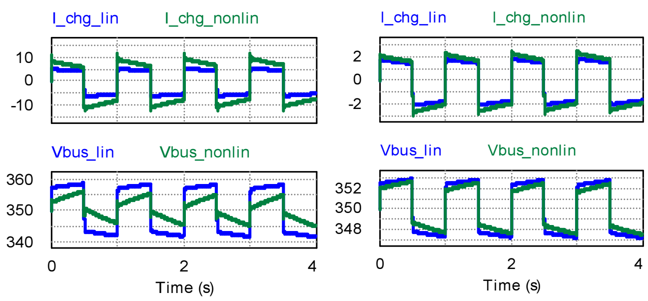

Fig. 7. Linear vs proposed EMS filtering method f = 1Hz (dV=30V - left; dV=10V - right).

VI. Method Implementation

In order to test the method, the control loop (Fig. 8) was implemented in a bidirectional hybrid high ratio converter (Fig. 9), which was thoroughly studied in the literature for SC storage applications [22].

The control is done in a conventional manner, with two cascaded control loops: a fast one for current control, and a slower one for voltage control. In addition, in series to the voltage reference of the converter, the nonlinear impedance voltage is added (ΔV_{RC}). This voltage is calculated from the output current of the converter, obtained from I_{L2} current. The virtual capacitor voltage is calculated in a conventional manner, but the nonlinear resistor uses the arctangent function to obtain the desired characteristics.

The bi-directional converter achieves higher conversion ratios by using the switched capacitive cell (C_1 - C_2, Q_3 – Q_2) and the energy stored in the SC can be used more efficiently as the V_S voltage can be decreased to lower values.

The converter resembles a boost converter when viewed from the SC to the V_O voltage, or a buck converter if viewed from the other side. The switched capacitive cell is used to either double or to halve the voltage from one or the other side respectively.

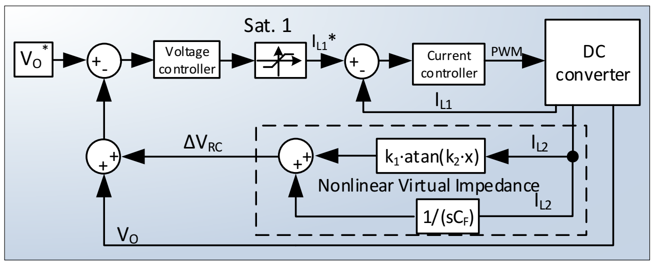

Fig. 8. Control Implementation.

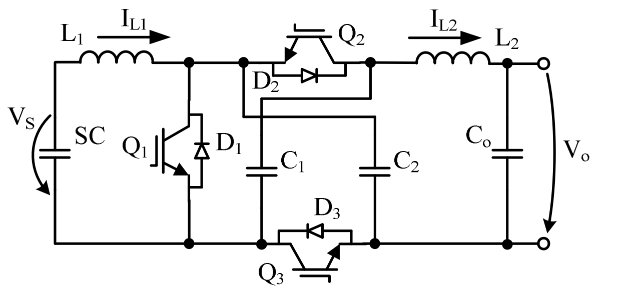

Fig. 9. DC Converter topology used for SC charging.

The driving signal is applied to Q_2 and Q_3, and is inverted and for Q_1. Considering this aspect, the duty cycle (D) can be defined relative to Q_2 and Q_3, or D' for Q_1 (D'=1-D). The conversion ratio between the SC voltage and the output voltage is:

$$\begin{cases} V_S = \frac{D}{2-D} \cdot V_O \\ V_O = \frac{1+D'}{1-D'} \cdot V_S \end{cases} \quad (4)$$

VII. Simulation and Experimental results

In order to test the proposed strategy, the setup from Fig. 10 was built. The bidirectional converter ("DC Converter") is used to charge and discharge the SC by using the conventional and the proposed EMS strategies.

A voltage source and an electronic load were used together with a real resistor to emulate the droop controlled microgrid. The load was programed as a constant voltage load and the DC source was programed at a higher voltage. The supply and the load were turned on and off respectively, and vice-versa, so that the voltage created resembles a square wave voltage with a ΔV variation. The capacitance of the bus is emulated by Cbus.

Experimental and simulation waveforms were acquired for comparison purposes. Transitions between both operating modes, buck and boost, at various voltage variations (ΔV) were analyzed.

The stability of the converter with the proposed EMS can be observed in Fig. 11, where a ±30V signal was applied over the nominal 350V. The converter has a rapid transition between boost and buck mode and only small oscillations are present in the inductor currents.

The proposed EMS was compared to the conventional EMS using the parameters from Table I, and the results are shown in Fig. 12 to Fig. 15. Voltage variations (ΔV) of ±30V and ±10V are applied by the source and load and the following waveforms are compared: SC current and voltage (I_S and V_S), bus current and voltage (I_O and V_O),

The results show that the proposed method has a much smaller intervention if the voltage variations are small (Fig. 12 and Fig. 14), therefore the converter losses are limited. When ΔV is increased the proposed EMS has the same functionality as the conventional EMS (Fig. 13 and Fig. 15). With this feature the proposed EMS can be programed to have an influence proportional to the voltage variation at the bus.

The currents were compared at one second after the voltage step was applied (at -3s and 1s). It can be observed that, with small voltage variations, the currents for the proposed EMS are almost half of the conventional EMS currents. At large voltage variations both methods have almost identical current values.

In addition, at 0 s, a large variation (-50V) was added for a short period of time in order to force the converter in current limit mode to analyze any instability that might occur.

Steady state results show that the converter is operating properly, in both step-down (Fig. 16) and step-up (Fig. 17) operating regimes. A photo of the converter is shown in Fig. 18.

All parameters which are used for the test setup are available in Table I.

TABLE I
TEST SETUP PARAMETERS

Parameter	Value	Parameter	Value
Proposed EMS		*DC Converter*	
k_1	1.7	Power	5 kW
k_2	8.59	L_1	200 µH
C_F	1 F	L_2	1410 µH
Standard EMS		C_1, C_2	705 µF
R_F	3 Ω	C_O, C_{IN}	470 µF
C_F	1 F	Switching freq.	20 kHz
Test setup		V_S	30-200 V
SC	31.5 F	V_O	320-380 V
Cbus	10 mF	V_O^*	350 V
Rdroop	4.4 Ω	DSP	TMS320F28335
Controllers		*Other Equipment*	
Current	$H(z) = \frac{1.586 \cdot z^2 + 0.166 \cdot z - 1.42}{z^2 - 0.72 \cdot z - 0.278}$	DC Source	TC.P.10.400.400.S
Voltage	$H(z) = \frac{0.11 \cdot z - 0.1}{z-1}$	Electronic Load	EA-EL 9400-50

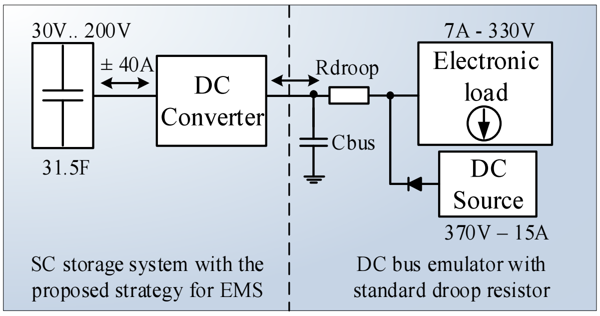

Fig. 10. Test setup diagram.

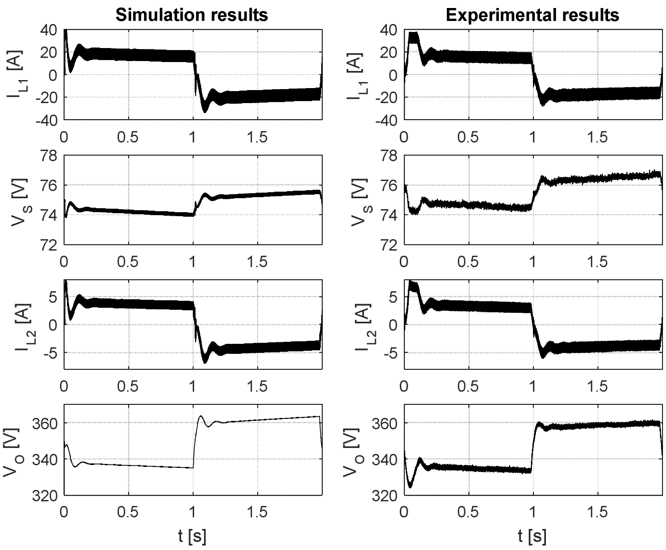

Fig. 11. SC discharge to SC charge transition (ΔV = ± 30 V).

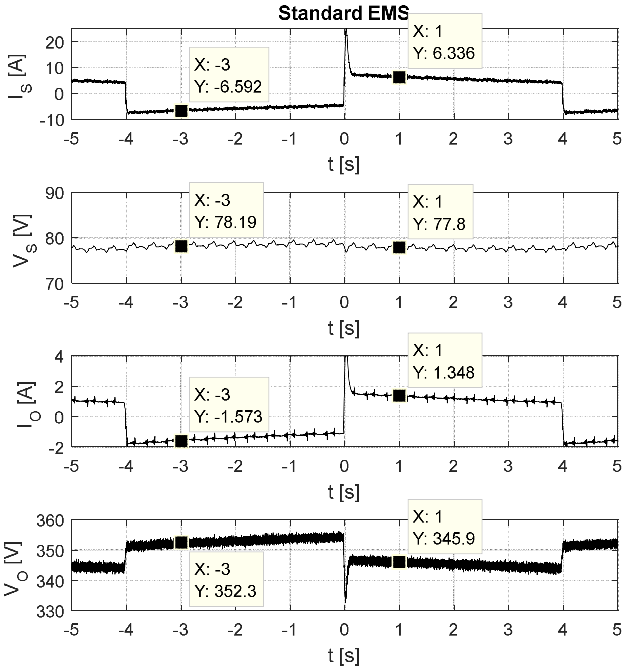

Fig. 12. Conventional EMS; Step voltage change (ΔV = ± 10 V).

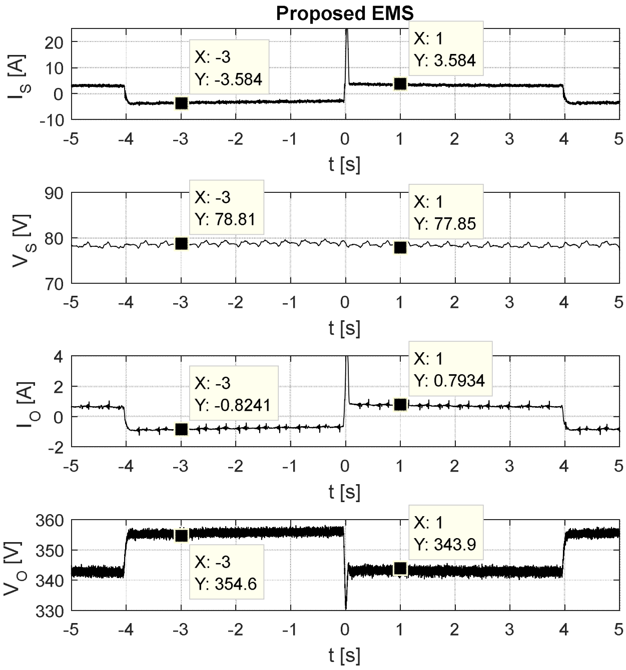

Fig. 14. Proposed EMS; Step voltage change (ΔV = ± 10 V).

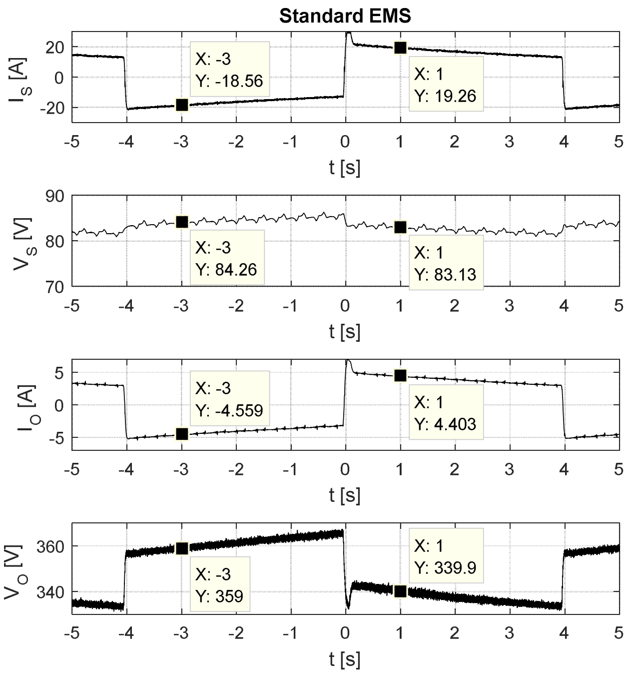

Fig. 13. Conventional EMS; Step voltage change (ΔV = ± 30 V).

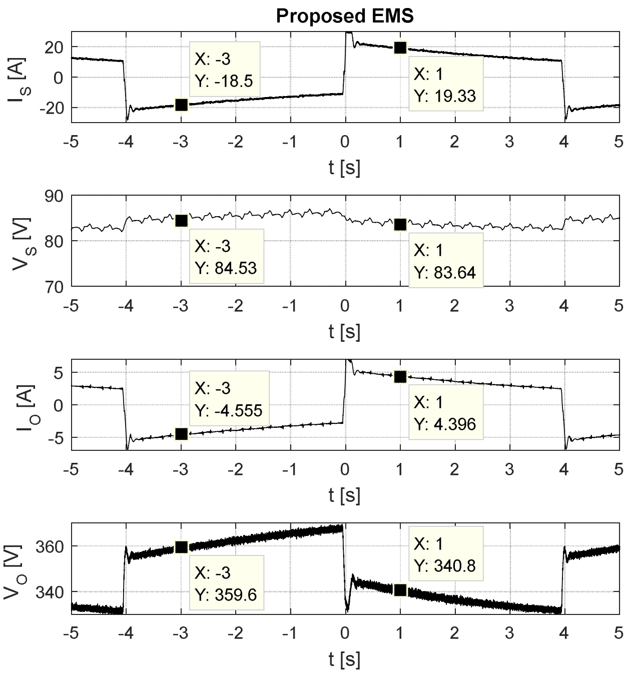

Fig. 15. Proposed EMS; Step voltage change (ΔV = ± 30 V).

CONCLUSIONS

This paper proposed a new energy management strategy used for supercapacitor storage systems, which is based on the nonlinear droop control and virtual impedance. The advantage of this method, having a variable cutoff frequency, makes it appropriate for a better energy management through strong reaction at high DC bus voltage changes and lighter reaction at smaller voltage changes.

The theoretical aspects were validated using experimental and simulation results which are in good correspondence

Stability analysis and parameter tuning possibilities will be examined in future work, together with the implications of the method utilization upon costs and maintenance of the system.

ACKNOWLEDGMENT

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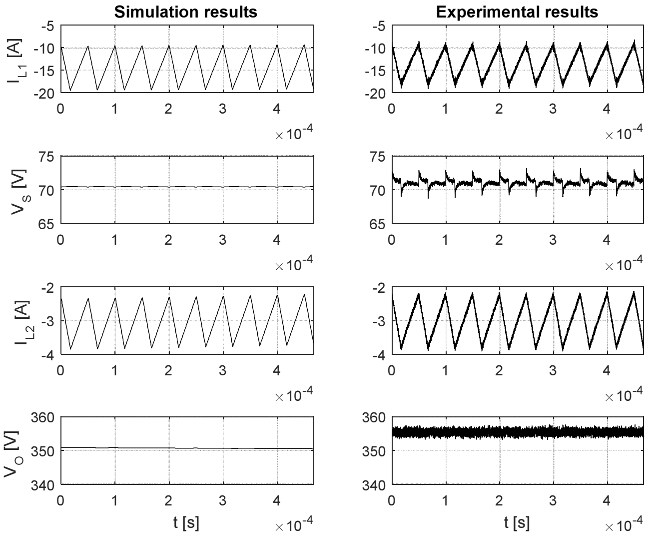

Fig. 16.Steady state waveforms for step down mode (I_{L1}= - 15A).

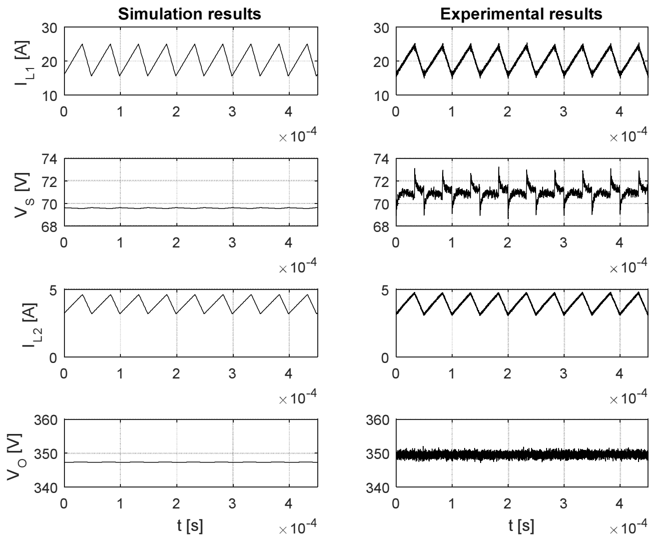

Fig. 17. Steady state waveforms for step up mode (I_{L1}= 20 A).

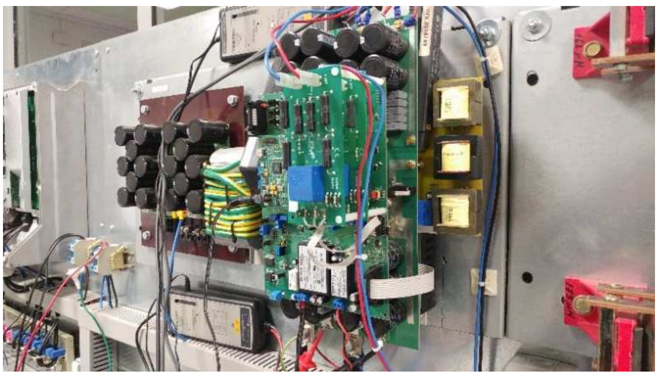

Fig. 18. High ratio converter connected to DC grid.

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