Advanced Power Electronic Interface for Hybrid Energy Storage System used for Microgrids

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Abstract – Microgrids are one of the most useful and efficient ways to integrate the renewable energy technologies in order to improve security, quality, reliability and availability of electricity supply. In order to achieve these benefits when a microgrid with a substantial amount of stochastic generation operates in grid connected mode but also during islanding mode, the use of storage systems is essential. The main goal of the storage is to perform power balance during islanding mode and to avoid the effect of the renewable energy sources intermittency and load fluctuations to the grid. However, none of the currently available Energy Storage Systems (ESS) has the necessary high power and energy densities to face the effect of different disturbances coming from the load or renewable energy sources. Thus, the association of more than one storage technology in a Hybrid Energy Storage System (HESS) can be used to satisfy the above mentioned requirements. Generally, separate DC/DC converters are required to interconnect the different ESS with an inverter in order to supply the distributed system in a microgrid. The present work proposes the association of a Vanadium Redox flow battery (VRB) with supercapacitors and a Three-level Neutral Point Clamped Inverter Interface for energy management in a microgrid. The power converter control and the energy management are also detailed. The feasibility of the proposed system has been proved in Matlab/Simulink.

Keywords - Energy storage, Energy management, NPC inverter, microgrid, power control.

1. Introduction

Microgrids comprise low voltage distributed energy sources, storage systems, and controllable loads. Their main characteristic is their ability to work connected to the main grid or in islanding mode (Fig. 1).

![Fig. 1. Investigated MG architecture](image)

Because generally, a microgrid (MG) is a weak electrical grid, the use of an ESS is necessary in order to smooth the variability of the Renewable Energy Sources (RES) and loads.

The renewable energy sources power output profile and the load profile experience low frequency as well as high frequency fluctuations. In order to compensate the intermittency of the renewable energy sources and to provide a high frequency component of power and also to supply or absorb the high power transients, an energy storage system with high energy density is required. There are many different types of storage technologies [1], [2], but unfortunately none of them can cover a wide range of power and energy to satisfy the requirements of a microgrid. According with the theory of Ragone plots [3], the association of the batteries and the supercapacitors in a hybrid ESS would provide high power and energy capacities taking advantage of both technologies.

In this work, a HESS based on the association of a Vanadium Redox Battery (VRB) as energy storage device and a supercapacitor bank (SC) as a power storage device is investigated in order to improve the operation of microgrids during renewable resources and load variations. The VRB has been used in several applications, such as load levelling, power quality control, balancing of the output of RES and Uninterruptible Power Supply ride-through [4].
The VRB is a flow battery which has independent energy and power densities. It has a long life-cycle, up to 10 000 charge/discharge cycles [5]. The VRB has theoretically no depth-of-discharge limitation and a good efficiency, between 75-85% [1, 2]. Although the electrochemical response time of the VRB is under 0.5 ms [6], the response time of the VRB is limited by the flow of the electrolyte, which is controlled by pumps. As the electrochemical reaction occurs, it is necessary to introduce new active species in the stack, and therefore the flow rate must be adapted to each reaction rate.

However, the VRB is not cost effective in high power applications [4]. The use of a high power density ESS in parallel with the VRB can reduce its power rating and, therefore, also the cost.

The supercapacitor stores the energy in electrical form, without converting it into any other kind of energy in order to save it. The most important advantages of a supercapacitor are its very high efficiency (95%), very high power density 39 (up to 10 000W/kg), its tolerance to have deep discharges, and its very long life-cycle (500 000 cycles at 100% depth-of-discharge) [7]. However, its energy density is very low and it has a high self-discharge current (5% per day [1]). Thus, its use is not oriented for long-term storage applications.

The interconnection of the HESS with the microgrid can be done in different ways, but the most common solution is to use separate DC/DC converters in order to control the ESS individually [5]. With this topology, the power flow of each storage device can be controlled independently thanks to the two DC/DC converters, offering a high flexibility to manage the HESS. The biggest disadvantage of this topology is the increased number of components and consequently their associated losses.

In this paper an alternative ways of the DC/DC topology based on the association of a Vanadium-Redox flow battery (VRB) with supercapacitors and a Three-level Neutral Point Clamped Inverter Interface for the energy management in a microgrid is investigated.

The most interesting advantage of this topology is the elimination of the DC/DC converters used with the conventional solutions. Everything is integrated in one power conversion system, which is very interesting from the distributed energy resources point of view. Furthermore, the power losses can be reduced. This is due to the reduced voltage ratings of the semiconductors that this type of inverter is able to obtain.

2. ESS Modeling

This section shows the dynamic models of the two ESSs that have been used during simulations. The complexity of the dynamic models has been chosen according with the investigated phenomena.

2.1 Supercapacitor

The dynamic model that has been used to represent the SC is shown in Fig. 2.

![Fig. 2: The dynamic model of the supercapacitor.](image)

The supercapacitor is represented using a constant capacitor and a constant resistance, which represent the electronic serial resistance (ESR) in the conductors and the ionic resistance in the electrolyte. From different literature works [8], it is clear that both capacitance and the serial resistance of the SC are depending on frequency, temperature and voltage. However, taking into account the simulation time of this work (some seconds), the effect of the temperature and voltage variations can be neglected because they are almost constant. Furthermore, the frequency variations of the SC current are low enough to assume that the capacitor value is also constant. The self-discharge of the SC is also neglected.

2.2 Vanadium Redox Battery

The dynamic model used to represent the dynamics of the VRB has been presented in detail in [9], [10]. The model takes into account the physical and mathematical properties of the battery. The stack voltage is modeled as a controlled voltage source, its value depending on the SOC and the open circuit voltage or Nernst voltage. The parameters of the model are determined assuming that at the operation point where the stack current is maximum and the state-of-charge (SOC) 20%, the power losses of the VRB are of 21%. Therefore, at this operation point the overall efficiency is supposed to be 79%.

![Fig. 3: The VRB dynamic model.](image)

The transient behavior of the VRB is related to the electrode capacitance as well as to the concentration
depletion close to the electrodes. In the used dynamic model only the electrode capacitance is represented [11]. The electrical equivalent circuit of the VRB that has been used is shown in Fig. 3.

3. Three-level neutral point clamped inverter topology

The three-level neutral point clamped (3LNPC) inverters are typically used in high power applications due to their ability to reduce the voltage ratings of the semiconductors used in this topology, comparing with the ratings that are necessary with conventional two-level topologies. Another advantage of the multilevel inverters is their improved output power quality [12]. This alternative topology can be useful from the point of view of the association of two ESSs. The two ESSs can be used as the energy sources of the 3LNPC, whereas the capacitors are maintained in order to filter the effect of the switches. The inverter can be controlled to manage the power flow across the HESS.

One of the most important problems of the 3LNPC inverter is the neutral point voltage balance, i.e. to maintain an equal distribution of the DC bus voltage between the two capacitors. Several methods for maintaining this equality can be found in the literature, like the use of the redundant vectors in the Space Vector Modulation (SVM) [13] and the zero sequence component injection in the carrier based PWM modulations [14]. These methods are oriented to maintain constant the neutral point voltage changing the modulation and varying the current of the neutral point. Thus, they can be designed with a different objective and used to control the currents of the storage devices.

The topology that has been used in this work is shown in Fig. 4.

![Fig. 4: The 3LNPC inverter topology.](image)

3.1 Modulation strategy

There are several modulation methods for the multilevel applications, and they are usually divided into two main groups, space vector based algorithms and voltage level based algorithms. In this work, a high switching frequency has been selected in order to have a high bandwidth and a good output power quality. A switching frequency of 15 kHz is used for the investigated topology. Because the modulation techniques are not the object of this work, for the sake of simplicity, a carrier based PWM modulation has been used.

It must be noticed that in the 3LNPC inverter it is necessary to maintain the two voltage sources at the same voltage level in order to be able to generate the AC voltage properly. Many different methods have been proposed to maintain this equality, some of them based on the variation of the modulation method. In the SVM the redundant vectors are used to control the neutral current. Different works have proven the equivalence between the use of the redundant vectors in SVM and the addition of a zero sequence component in carrier based PWM [15] from the point of view of the neutral point current control.

In this work, a controlled offset is added as a zero sequence component in order to control the current of the VRB. At the same time, the amplitude of the carrier signals are modified as shown in [16], in order to properly generate the output voltage of the inverter when there are transitory voltage differences between the SC and the VRB.

3.2 Control algorithm

The block diagram of the NPC inverter control is shown in Fig. 5. Voltage vector representation in a rotating frame and PI controllers are used to carry out this control. The control is made using two loops, the inner current loop and the outer current loop. The outputs of the controllers are used to generate the third harmonic injection sinusoidal modulating signal. As it has been explained before, an offset is added to the modulating signal in order to control the current of the VRB battery. The reference of the current of the VRB is generated adding the measured input inverter power in the upper level with the measured power of the SC and subtracting the power signal of the neutral point power. Then the resulting value of the addition is filtered using a low pass filter to obtain only the low frequency part of the signal and use it as the reference of the VRB current.

The final modulation signal is then compared with the carrier signal to generate the switching signals. The voltages of the SC and the VRB must be the same at steady state, but may vary in transitory parts.

4. Simulation results

The power variation in a microgrid can come from the RES and also from the AC side, as load variations. The investigated topologies have been analysed independently by means of simulations during RES and load variations.
In order to analyse the capability of the investigated system to smooth the effect of the RES power variation in a microgrid, the first case study, a wind power profile generated by a wind turbine has been introduced directly to the DC side of the 3LNPC (Figure 4).

For the second case, a load power sudden increase has been simulated. The parameters of the supercapacitor bank used in the simulations have been extrapolated from the commercial unit BMOD0083 P048 of Maxwell Technologies manufacturer. The total capacity of the used SC is 0.6F, the serial resistance is 143.1mΩ, the maximum voltage is 675V and the maximum continuous charge/discharge current is 61A.

The VRB used in this work has a rated stack voltage of 450V (at 50% of SOC and open circuit), a maximum charge/discharge current of 100A and autonomy of 4 hours.

The parameters of the investigated system are resumed in Table 1.

<table>
<thead>
<tr>
<th>VRB model</th>
<th>Simulation parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameter</td>
<td>Value</td>
</tr>
<tr>
<td>N</td>
<td>322</td>
</tr>
<tr>
<td>V_{equilibrium}</td>
<td>1.4V</td>
</tr>
<tr>
<td>k</td>
<td>0.05138</td>
</tr>
<tr>
<td>K_{pump}</td>
<td>0.9877</td>
</tr>
<tr>
<td>R_{resistive}</td>
<td>0.27Ω</td>
</tr>
<tr>
<td>R_{reaction}</td>
<td>0.405Ω</td>
</tr>
<tr>
<td>R_{fixed}</td>
<td>147.62Ω</td>
</tr>
<tr>
<td>C_{electrodes}</td>
<td>0.0186F</td>
</tr>
<tr>
<td>C_{in}</td>
<td>10mF</td>
</tr>
</tbody>
</table>

The output filter of the inverter has a 3mH inductance per phase. The load used during the first case study is of 23kW. For the second case study, this load is increased to 40kW. Capacitances of 10mF have been used in parallel to the ESSs in order to filter the effect of the switches. A DC bus voltage of 900V has been selected in order to give flexibility to the control of the 3LNPC inverter and have a certain flexibility to diminish the voltage of the DC bus while being able to generate properly the AC side voltage.

The simulations have been carried out using the Matlab/Simulink software and the SimPowerSystems toolbox.

### 4.1 RES variations

As it has been mentioned before, the variability of the RES can seriously affect the stability of the microgrid. In this work the effect of a wind turbine has been simulated. A power profile generated by a wind turbine (WT) has been introduced to the DC bus in order to analyse the behaviour of proposed system.

The average value of the WT DC current is 20A (18kW). Having a load of 23kW, there is a difference of 5kW that must be supplied by the VRB. The profile includes fast power variations up to 23kW, which must be absorbed/supplied by the SC. Fig. 6 shows the results obtained by the 3LNPC topology during the first case study. From the Fig. 6(a) it can be seen that the fast power variations are mostly absorbed/supplied by the SC and that the power of the VRB does not have big variations. However, some small variations can be noticed. The same conclusion can be drawn from the Fig. 6(b). As it can be seen, only the SC answers fast power variations of the WT. Fig. 6(c) shows the evolution of the DC bus voltage. As the DC bus voltage is formed by the voltages of the SC and the VRB, it depends on the state-of-charge of both storage devices.

### 4.1 Load variations

In order to analyze the behavior of the system when a disturbance coming from the AC bus occurs, a sudden load variation has been introduced. The load power is increased from 23kW to 40kW while a constant current of 20A (18kW) is injected by the
RES in the DC bus during the entire simulation. The RES power has been assumed constant in order to analyze the effect of the load variation independently from the DC bus variation. The load increase is introduced at 0.5s.

Fig. 7(a) shows the power division between the two ESSs. During a few milliseconds, the SC supplies almost the totality of the load power increase, but a small power fast variation is visible in the VRB. However, the slope of this variation is not high and the fast power variation is small in amplitude. After a few transitory milliseconds, the entire power requested by the load is progressively supplied by the VRB. The controller tries to manage the current supplied/absorbed by the ESSs and in the same time to generate the AC side signals. Consequently a complex control algorithm is necessary to manage properly this topology.

As can be seen from the Fig. 7(b), even if the DC bus voltage varies, the used control for the 3LNPC topology is able to properly maintain the AC side voltage at the reference values (Fig. 7(c)).

5. Conclusions

From the point of view of a distributed generation system as a microgrid, it is very important to have a simplified structure of the ESS, as it is necessary to install many storage devices in different locations. This simplification will suppose a reduction of the number of power converters and of the power losses, while the same power quality can be assured.

The presented research work has proved the feasibility of the three-level neutral point clamped inverter topology to interface a HESS with the AC side in the microgrid context. The HESS is based on the association of a Vanadium-Redox flow battery (VRB) and the supercapacitors.

The use of a Three-level Neutral Point Clamped Inverter to integrate a HESS in a microgrid seems to be a feasible alternative to classical DC/DC converters.

Two kinds of typical variations that seriously affect the behavior of the microgrid have been analyzed: the effect of the renewable energy sources and the load variations. Simulations have been run, proving that the proposed topologies and control can eliminate the negative effect of renewable resources or load sudden variations.

This analysis has been tested by means of simulations using the Matlab/Simulink software and the SimPowerSystems toolbox.

6. References