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A POWER MANAGEMENT STRATEGY FOR DC MICROGRIDS OPERATING IN GRID CONNECTED MODE

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ABSTRACT

This paper presents a power management strategy to control a DC microgrid considering the operation in the grid connected mode. The analyzed system is composed of the utility grid interfaced with a voltage source converter, an energy storage system (ESS), a distributed generator and the customer loads. The proposed power management is considered as a master-slave technique, in which the VSC operates as a master grid-forming converter, while the ESS is a slave grid-supporting unity and the distributed generator works as a grid-feeding unity tracking the maximum power point. This management strategy is presented in details and its impact over the DC link voltage, the power flow and the ESS state of charge is analyzed. MATLAB/Simulink simulations are performed to obtain the results. The obtained results show that the proposed strategy is reliable and leads to better controllability over the power flow in the DC microgrid when compared with the hierarchical control.

Keywords: DC microgrid, Power management, Energy storage system, Master-slave control, Grid connected mode.

NONMENCLATURE

Abbreviations

ESS	Energy storage system
DG	Distributed generator
SOC	State of charge
VSC	Voltage source converter
PCC	Point of common couple

1. INTRODUCTION

A microgrid is considered as an autonomous cluster formed by distributed generation, energy storage systems and local customer loads [1]. This autonomous structure works connected to the utility grid, in the grid-connected mode, or in the island mode of operation when the utility grid is not available. In this sense, microgrids are presented as a reliable option for intelligent distribution systems [2].

Recently, DC microgrids have been pointed out as an alternative solution for smart grid systems due to its advantages over AC microgrids [3]. These advantages can be listed as lower losses due to reduction of conversion steps, controlling simplicity because only active power flows, and an increasing demand of DC electronic loads. In addition, many distributed generation systems, such as solar systems, provide DC power naturally. Many others, as variable speed wind systems, convert AC to DC in order to obtain better controllability.

The control and management of DC microgrids are still a challenge under study [4,5]. The researchers are mainly focused on the island mode of operation because various control challenges arise when the utility grid is not presented [4-7]. However, for an urban system, the microgrid is expected to work in the grid-connected mode for the vast majority of the time. Thus, a proper investigation of the control and management methods considering the DC microgrid in the grid-connected mode must be carried out [8].

Master-slave control is mainly criticized because it consists of a single-point of failure, which decreases system reliability [3]. Nevertheless, another point of view considers that if one wants to move towards truly smart

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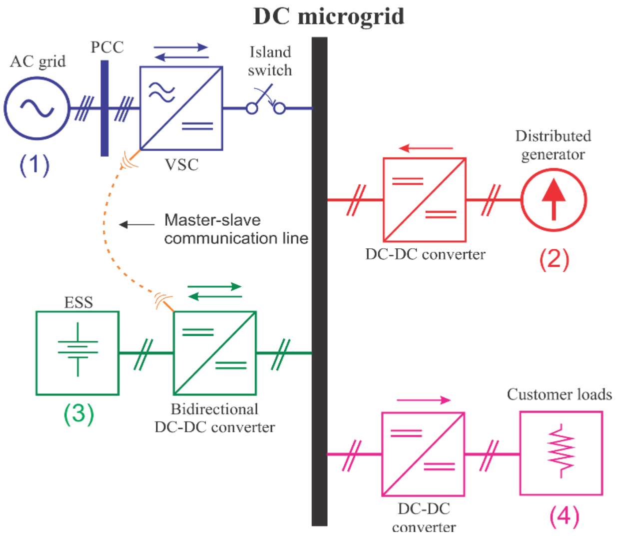


Fig 1. Grid connected DC microgrid under study

grids model, the communication system must be reliable and robust. Thus, especially for small microgrids (or nanogrids), the usage of communication lines between power electronics converters should be faced as a reality.

Considering the discussed problems, this paper presents a master-slave power management technique for DC microgrids in the grid-connected mode. The strategy under study does require communication between the converters, however, only the power information is exchanged from the master to the slave unity, which simplifies the communication procedure. In addition, ESS state of charge (SOC) is considered to obtain adaptive behavior, improving the battery life cycle.

This paper is structured as follows. Section 2 presents a description of the analyzed DC microgrid. The proposed power management strategy is detailed in Section 3. Section 4 contains the simulation results and its respective discussion. Conclusions are summarized in Section 5.

2. DC MICROGRID DESCRIPTION

The DC microgrid under study is depicted in Fig. 1. Considering future experimental implementation under development, the microgrid rated DC voltage and active power are considered to be 400 V and 2 kW, respectively. Arrows indicate the power flow direction. The system components are described in the following subsections, according to the number sequence presented in Fig. 1.

2.1 Utility Grid

The AC utility grid coupled with a voltage source converter (VSC) is employed to form the DC bus. The main goal of the VSC is to keep the DC bus voltage constant at 400 V, securing the power flow stability, which means that the VSC works mainly as an active rectifier.

2.2 Distributed generator

The distributed generator is modeled as a current source able to inject up to 2 kW of active power into the system, tracking the maximum power point as a grid-feeding unity. This modelling does not consider the particularities of any specific renewable source because only the power flow is under investigation.

2.3 Energy storage system

An energy storage system (ESS) based on battery bank is connected to the DC bus by means of a bidirectional DC-DC converter, which allows charge and discharge mode. The power management strategy used in this paper forces the AC grid to act only in the transient states, as a backup system, whilst the DG and ESS must work together to guarantee the power flow. Nonetheless, the acting of the ESS is limited by the battery bank state of charge (SOC) [8, 9].

2.4 Customer Loads

Lastly, the customer local loads are formed by a step-down DC-DC converter supplying 2 kW resistive loads at 120 V. Due to this strict voltage regulation, the customer loads are considered as constant power loads (CPL), which are the main source of instability for DC power systems [10]. This type of loads is dominant for those based on electronic converters and, because of its importance to the overall system stability, they are employed in this study.

3. PROPOSED POWER MANAGEMENT STRATEGY

The most employed control methods proposed in the literature to manage DC microgrids are the master-slave, droop, and hierarchical control [2-9]. Other methods based on consensus and multi-agent algorithm are still under development [3]. It is important to notice that droop control and its variants are decentralized, i.e. they do not require communication line between converters, being especially needed for island operation. However, droop control imposes DC bus voltage variation and current sharing mismatch depending on the droop parameter choice [3]. The hierarchical control, in its turn, aims to correct these mismatches adding a secondary and upper control layer [2,3]. The secondary control requires a low bandwidth communication line for a central control system or can be designed in a distributed fashion. Although the cited methods can be applied for the grid-connected mode, the master-slave control has advantages over them such as simple implementation and straightforward communication procedure between converters. The power management proposed in this paper is detailed in the following subsection.

3.1 General considerations

The master-slave technique is a centralized control, i.e. a high speed communication link between the converters is required. One of the converters acts as a master grid-forming unity, while the others are controlled as grid supporting or grid feeding converters. For the system considered in this paper (Fig. 1), the utility grid VSC is chosen as the master unity. As the master, the VSC active power flow should be measured and transmitted to the slave. ESS bidirectional DC-DC converter is chosen as the slave unity as it acts as a grid-supporting converter. The DG converter acts tracking the maximum power point and injecting power as a grid-feeding unity.

3.2 VSC control

The VSC control implementation is carried out through a decoupled *dq* current control using PI controllers as inner loop, as shown in Fig.2. An outer voltage loop controls the DC bus voltage and generates the reference power to the inner control loop. Sinusoidal pulse width modulation (SPWM) is applied to drive the VSC IGBT switches. More details of this implementation can be found in [11]. The dynamics of the DC Bus voltage are given by:

$$\frac{dV_{vsc}^{2}}{dt}=\frac{2}{C_b}\left\{P_{ext}-P_{loss}-\left[P_s+\left(\frac{2L_fP_s}{3V_s^2}\right)\frac{dP_s}{dt}\right]\right\} \tag{1}$$

where V_{vsc} is the DC bus voltage, P_{ext} is an external active power acting as a disturbance, P_{loss} is the VSC total losses, P_s is the power control input and V_s is the phase voltage peak.

VSC active power reference is obtained in order to keep the DC link voltage constant, while the reactive power reference is set to zero aiming to achieve a higher power factor. In the DC microgrid, the active power flowing through the VSC is the sum of each of the other unities active power. Moreover, the VSC power can also be computed by the product between voltage and current at the PCC.

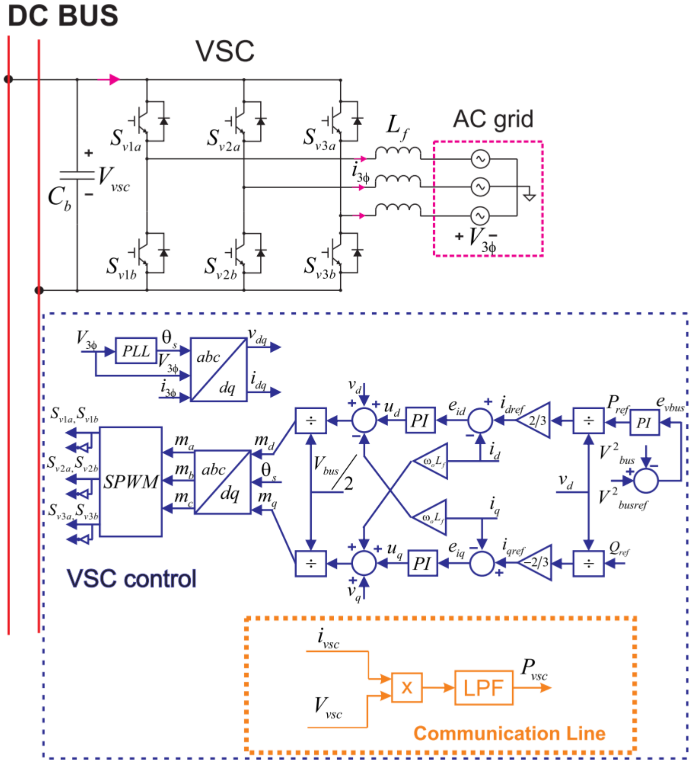


Fig 2. Master-Unity VSC scheme and control

A second order low pass filter is employed to calculate the average power injected/consumed by the VSC such as:

$$P_{vsc}=P_{ESS}+P_{DG}+P_{load}=\left(V_{vsc}\times i_{vsc}\right)\left(\frac{\omega^2}{s^2+2\zeta\omega s+\omega^2}\right) \tag{2}$$

where V_{vsc} and I_{vsc} are the VSC voltage and current at the DC bus. P_{vsc}, P_{ESS}, P_{DG} and P_{load} are the VSC, ESS, DG and load active power, respectively, and ω is the filter cutoff frequency.

Table I summarizes the parameters of the voltage source converter employed in this paper.

TABLE I – VSC parameters

Parameter	Value
Nominal Power	5 kW
Line to line AC voltage	380 V
DC bus voltage	400 V
Grid frequency	50 Hz
Switching frequency	10 kHz
Filter inductance (L_b)	6 mH
Bus Capacitance (C_b)	4 mF

Using the proposed management strategy, the VSC active power is the only information transmitted through the communication line to the ESS slave unity, as described as follows.

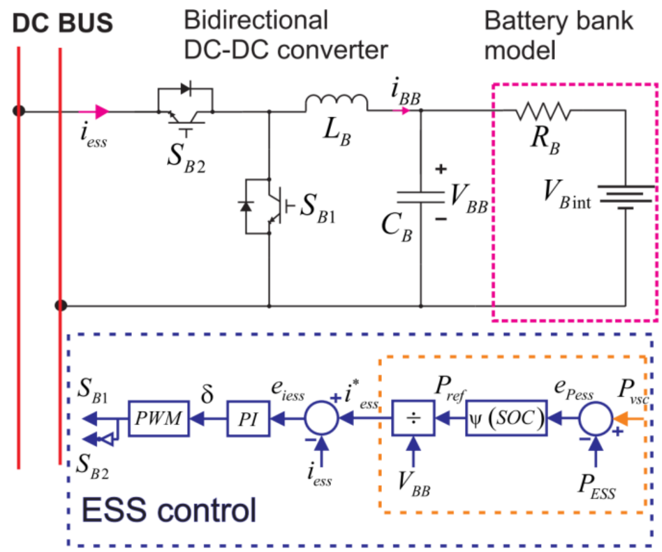


Fig 3. Slave unity ESS scheme and proposed control

3.3 ESS control

ESS bidirectional DC-DC converter works stepping the voltage up and down to match the DC 240 – 400 V requirement from one side to another. The control scheme is formed by an inner current control loop, followed by an external reference current generator (Fig. 3). The main parameters of the ESS are presented in Table II.

TABLE II – ESS parameters

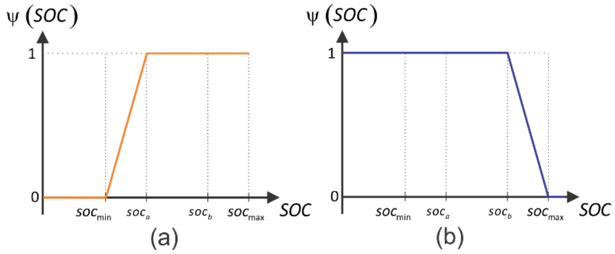
Parameter	Value
Nominal Power	2 kW
Battery side voltage	240 V
Switching frequency	30 kHz
Filter inductance (L_b)	2 mH
Bus Capacitance (C_b)	1 mF

By applying the proposed method, the utility grid only acts during transient power or when the ESS cannot support the microgrid. ESS power is feedback to close the outer loop and it can also be computed using a second order filter by:

$$P_{ESS} = (V_{ess} \times i_{ess})\left(\frac{\omega^2}{s^2 + 2\zeta\omega s + \omega^2}\right) \qquad (3)$$

where V_{ess} and i_{ess} are the ESS voltage and current at the DC bus, respectively, and ω is the filter cutoff frequency.

The ESS role is to provide the required microgrid active power. However, to improve the life cycle of the battery bank and for safety reasons, a SOC-based function ($\psi(SOC)$) is introduced. Function $\psi(SOC)$ returns the ESS power reference as a function of its state of charge. This function is differently defined for ESS discharging and charging mode as presented in Fig. 4 (a) and (b), respectively.



(a) (b)

Fig 4. State of charge based function, (a) ESS discharging mode, (b) ESS charging mode

During the charging mode, the ESS must not provide any power if the minimum SOC limit (soc_{min}) is reached. Between soc_{min} and a specified point (soc_a), the reference power increases linearly. After soc_a, the ESS is allowed to provide the maximum power required by the master unity. This process can be summarized by Eq. (4).

$$\psi(SOC) = \begin{cases} 0, & SOC \le soc_{min} \\ \dfrac{(SOC - soc_{min})}{(soc_a - soc_{min})}, & soc_{min} < SOC < soc_a \\ 1, & SOC \ge soc_a \end{cases} \qquad (4)$$

During the discharging mode, the ESS absorbs the maximum surplus power provided by the microgrid until a specified point (soc_b) is reached. Thus, the power absorbed by the ESS is linearly reduced until the maximum SOC limit is reached (soc_{max}). This action is important to avoid overcharging the battery bank. The discharge mode can be computed using Eq. (5).

$$\psi(SOC) = \begin{cases} 0, & SOC \le soc_a \\ 1 - \dfrac{(SOC - soc_b)}{(1 - soc_b)}, & soc_a < SOC < soc_b \\ 0, & SOC \ge soc_{max} \end{cases} \qquad (5)$$

Finally, the ESS reference current for the inner control loop (i_{ess}) is obtained dividing the difference (e_P) between VSC power (P_{vsc}) and ESS power (P_{ess}) by the ESS voltage (V_{BB}):

$$i_{ESS} = \left(\frac{P_{VSC} - P_{ESS}}{V_{BB}}\right) \times \psi(SOC) \qquad (6)$$

It is important to highlight that the VSC does not provide power to the ESS and vice-versa. Thus, the energy management system only sees the mismatch between the load requirements and the DG power. If the DG power is not able to attend the load demand, the grid-forming and grid-supporting unities must act to keep the power flow balanced according to the aforementioned strategy.

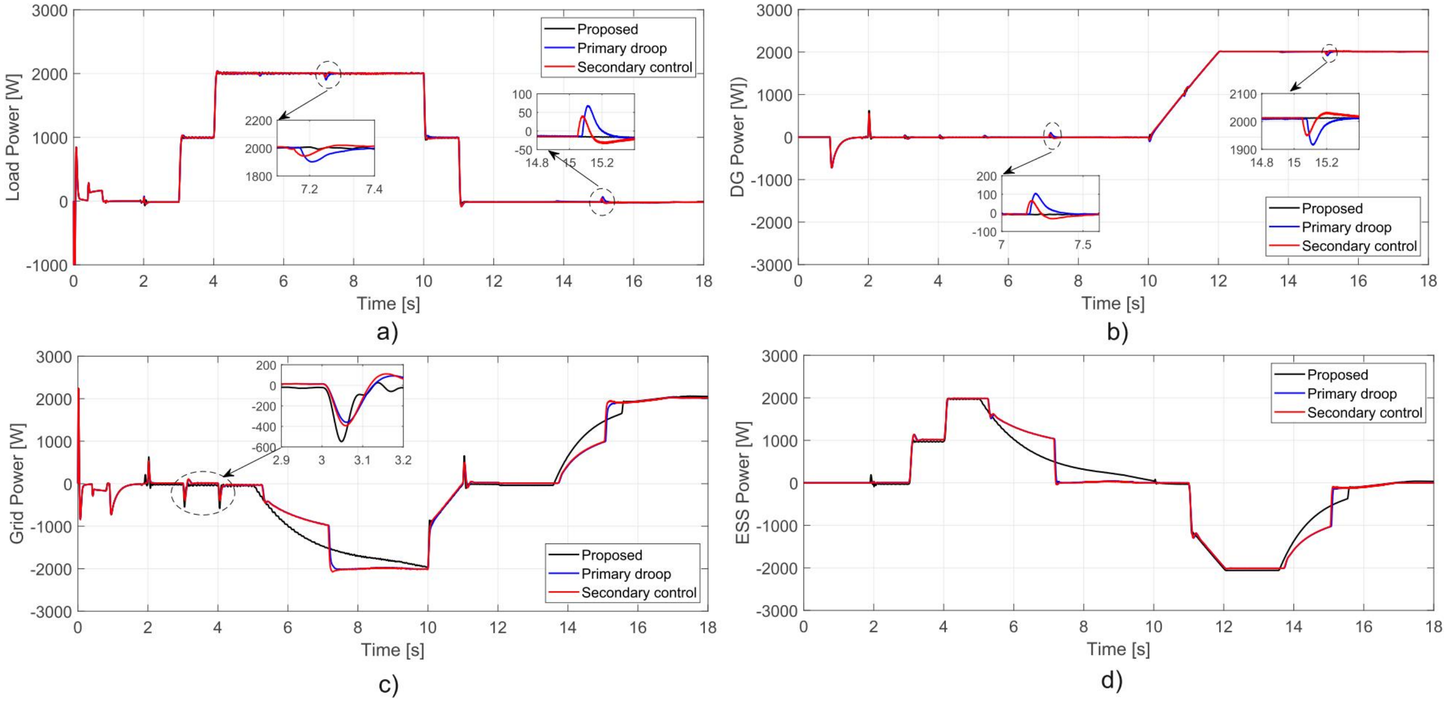


Fig 5. Comparison for the power flow results. a) Load Power, b) DG power, c) AC Grid Power, d) ESS power

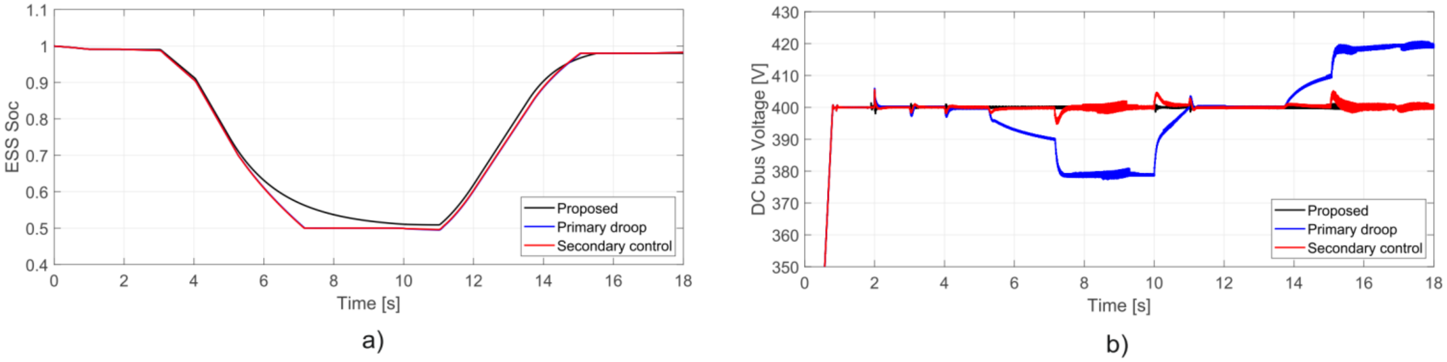


Fig 6. Comparison results. a) ESS state of charge b) DC bus Voltage

4. RESULTS AND DISCUSSION

Simulation results were obtained using MATLAB/Simulink. The proposed master-slave power management technique was implemented alongside with a hierarchical control employing only the primary droop and another one adding a centralized secondary control. All the methods were configured to the same state of charge limit conditions in order to allow comparison analyzes in the grid connected mode.

The power flow in the studied 400 V DC microgrid is presented in Fig.5. The initialization procedure occurs in the first 2 seconds, while all converters are being charged and starting to operate properly. Resistive loads with strict 120 V voltage regulation were used to simulate load variations into the microgrid, as seen in Fig.5(a). The power load is increased in steps of 1 kW to perturb the system. The DG starts to provide power into the microgrid at 10 s, in a ramp, until the power reaches its rated value, as depicted in Fig.5(b). The load and DG power flow are more affected by the hierarchical approach, as can be seen in the detailed boxes in Fig.5 (a) and (b).

The AC grid power flow is shown in Fig.5(c). As one can see, from 2 to 5 s, the AC grid injects power only during the transient, while loads are inserted to the microgrid. At the same time, the DC power is generated by the ESS, as shown in Fig.5(d). It is noticeable that the proposed method returns a smother transient period than the hierarchical approach, as the DC bus voltage is kept constant by the VSC. After 6 s, the SOC management strategy starts to act reducing the available ESS power and, in consequence, the AC grid starts to inject the required power to attend the load demand. During this period, the proposed method achieved higher controllability over the power flow, as can be noticed by a smooth power behavior.

When the DG starts to inject power into the microgrid at 10 s, the loads are turned off and, now, the ESS absorbs the surplus power. Again, the AC grid only absorbs power during the transient periods. Close to 14 s, the SOC management strategy acts to avoid critical overload to the battery bank. The proposed method achieved higher controllability over the active power during this period. The primary droop and the addition of the secondary control returned very similar results for the power flow analysis, as the main difference between them is the presence of the secondary control layer for the voltage regulation.

Fig.6 shows the comparison results for the ESS state of charge and for the DC bus voltage considering the three mentioned methods and the same power flow presented in Fig.5. Is noticeable from Fig.6(a) that all methods have accomplished the state-of-charge management control. SOC lower and higher limits were set to 50% and 95%, respectively. However, the proposed method has a better control over the ESS SOC curve, avoiding getting close to the established limits. The DC bus is kept stable, as seen in Fig.6(b). Nevertheless, the primary droop control imposes the well-known undesirable voltage variation. Although the secondary layer of the hierarchical control corrects this problem, its voltage response to power variation is not as fast as the proposed method, since low bandwidth communication is applied, which results in the undesired transient load power variations observed in Fig. 5.

5. CONCLUSION

This paper has presented a power management system for a DC microgrid operating in the grid connected mode. Simulation results have indicated that the proposed master-slave technique returns better controllability over the power flow when compared with the well-known hierarchical control with only primary droop control or the addition of the secondary control. Thus, for grid-connected mode, this method leads to promising results to be confirmed experimentally.

Finally, it is worth to highlight that both the master-slave technique and the hierarchical control with centralized secondary control suffer from a single point of failure. However, this problem can be solved by implementing local droop controller in case of communication interruption. The proposed master-slave management system only requires transmission of the AC grid power information, which makes the communication between converters straightforward.

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