Hybrid Fuzzy-Sliding Control Scheme for Bi-directional SEPIC Converter in Renewable Based DC Microgrid

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Abstract — **This paper describes a hybrid fuzzy-sliding control scheme for bi-directional SEPIC converter in renewable based DC microgrids. The performance of a DC microgrid is directly dependent on the voltage stability of the DC bus. In operation, the voltage level of the system is affected by the power injection of the power sources connected to the microgrid, in particular those dependent on environmental factors (such as sun and wind), and by the power consumption of non-constant loads. This feature of microgrids makes control a complex engineering problem. Considering this problem, we propose a hybrid control scheme for a SEPIC bi-directional converter capable of regulating the power flow and stabilizing the system's DC bus. Proposed control technique is simulated in a 48 V DC microgrid and results are provided.**

Keyword - Bi-directional converter, Fuzzy-sliding control, Microgrid, SEPIC converter

I. INTRODUCTION

Colombia has large regions without electricity service (the coverage of electricity service is only 34%), are regions isolated from the traditional power grid (about 52% of the national territory, and inhabited by about 1,800,000 people) which have been called Non-Interconnected Zones (ZNI) [1]. There are many reasons for this type of deprivation of electricity service, but the most common reason is the high cost of installing the network to power an area with low population density. The most promising solution for supplying electricity to these areas is the installation of microgrids. The global market trend indicates that microgrids are becoming consolidated as an energy solution for the end user (and not necessarily for those not connected to the traditional power grid) that can even bring economic benefits [2].

A microgrid is a localized group of different kinds of electrical energy sources, which work together to meet the energy needs of a specific area, and which can operate either in conjunction with the traditional power grid or in isolation [3]. This microgrid integrates different energy sources according to the energy availability of the area (solar energy, wind turbines, coal, liquefied petroleum gas, etc., although with a strong propensity for renewable resources, or renewable distributed energy resources - DER), and have a variable architecture according to the advantage of generating energy primarily from one or another energy source. This variable topology makes microgrid control and protection complex and an open-ended engineering research problem [4, 5], particularly when considering power flow problems, load sharing, voltage regulation and mitigation of various kinds of power quality issues [6].

A great energetic advantage of the microgrids is their greater electrical efficiency when feeding electronic type loads as variable speed drives and LED loads, because they do not need AC/DC and DC/AC converters when feeding them directly in direct current (DC) [7, 8]. The DC power supply system has other advantages over the AC (alternating current) system, for example, it has higher reliability and lower cost (disappear problems of reactive power control, skin effect and frequency synchronisation).

Among the main issues in the design and control of a DC microgrid are the selection of power converter topologies, voltage control and load sharing [9, 10]. This paper focuses on the problem of controlling the bi-directional DC/DC converter connected to the power storage system (batteries) by considering the DC bus voltage. It should be remembered that in a microgrid renewable energy sources (such as solar and wind) have fluctuating power characteristics due to environmental factors, and that in general a microgrid also operates with variable loads.

The voltage level in a DC system is a fundamental design parameter since it directly affects the performance of the microgrid. As stated in [7], an excellent DC voltage option for residential applications is a 48 V system. This voltage level is chosen considering losses in both the medium power distribution grid and the electronic power converters required in the installation. In addition, 48 V is considered a safe voltage level for humans.

The performance of a DC microgrid is determined by the voltage regulation on the system's DC bus [11]. The DC voltage regulation of the inverter must guarantee a constant voltage regardless of the conditions of the generating sources and the load [12, 13]. The voltage varies in relation to the amount of power injected into the DC bus by the power sources, and by the continuous changes in the load due to power requirements. Power converters require a good monitoring and control scheme for this voltage.

This paper proposes the use of a bi-directional SEPIC (Single-Ended Primary-Inductor) converter with a hybrid fuzzy-sliding control scheme to keep the system's DC bus voltage within a range, using a battery as a power source and sinking unit [14, 15]. The DC bus voltage is designed at 48 V, while the battery has a 24 V voltage. The control strategy establishes two control surfaces according to the energy in the converter, and establishes specific operating rules for each of them.

The following part of the paper is arranged in this way. Section 2 presents preliminary concepts and problem formulation. Section 3 illustrates the design profile and development methodology. Section 4 we present the preliminary results. And finally, in Section 5, we present our conclusions.

II. Problem Formulation

The microgrids have proven to be an excellent alternative for the supply of electrical energy to users in remote areas without access to the electrical power grid. The topology of these microgrids integrate different energy sources, different types of loads and the possibility of connection to the power grid. These characteristics make their design and control complex.

In the case of DC microgrids, a system with better electrical performance and efficiency can be obtained by feeding electronic loads directly into DC. For these systems, DC bus voltage regulation is fundamental to system performance. The DC bus voltage is affected by the injection of electrical power from electrical power sources, and the extraction of electrical power from the load, which is generally not constant. The DC microgrid topology considered in this research is shown in Fig. 1. Loads, power sources, storage elements and the AC grid are connected to the DC voltage bus through electronic power converters.

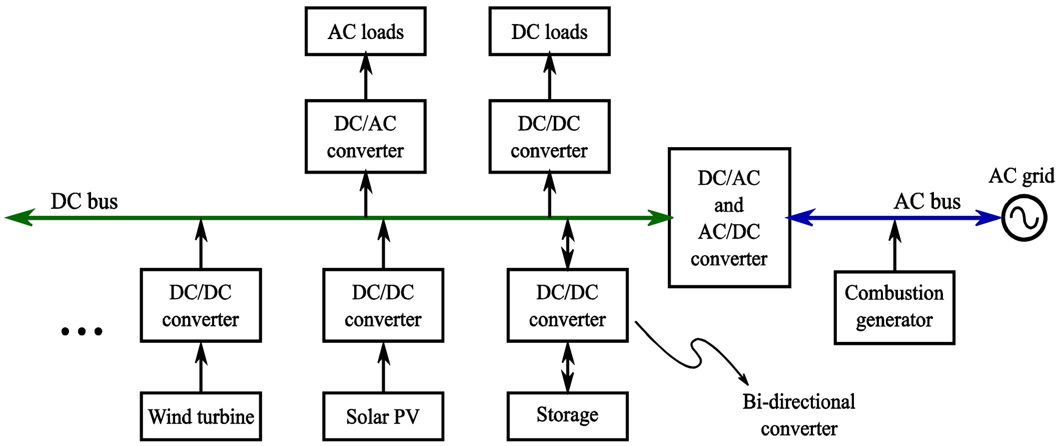

Fig. 1. Block diagram of considered DC microgrid topology

DC bus monitoring and control can be performed with a bi-directional DC/DC converter. The control of this converter must regulate the DC bus voltage by extracting and returning power to the storage unit according to the system requirements. Because the load and generation behaviour is unpredictable, converter control becomes complex. The use of the DC/DC converter has other advantages, such as the possibility to supply electronic loads directly on DC, leaving aside the active power factor correctors. However, these converters have a non-linear dynamics, which makes their design more difficult.

The control system of the bi-directional SEPIC converter must be able to maintain the DC bus voltage within a tolerance range. To do this, power must be taken/injected from the storage unit (battery) to the DC bus. The SEPIC is a DC/DC converter with a single switch/control, capable of regulating DC voltages of any value. This power topology can be modified by means of an auxiliary circuit that allows the power flow to the batteryand making it bi-directional (Fig. 2). In the circuit of Fig. 2 we have included the parasitic resistors of the DC chokes and the capacitors of the converter. In addition, the fast recovery diode has been replaced by a transistor to explicitly control its conduction time, as there are now three switches that must operate during the same T switching period.

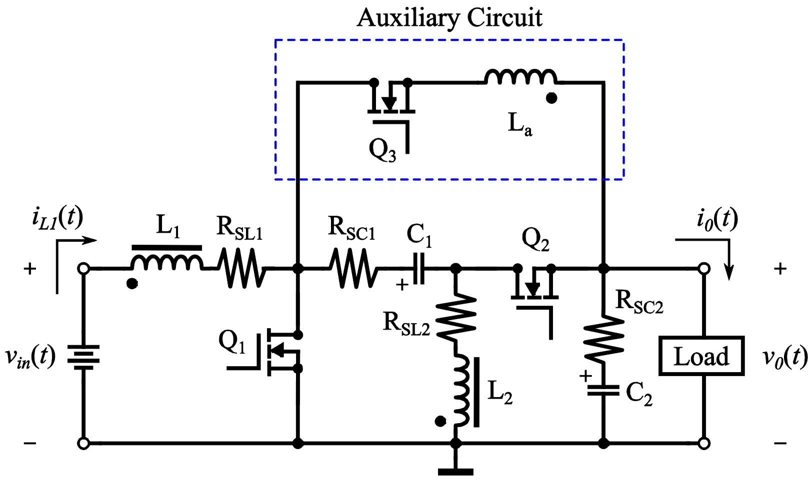

Fig. 2. Bi-directional SEPIC DC/DC converter

By controlling the duty cycle of the three semiconductor switches it is possible to increase or decrease the voltage on the DC bus of the microgrid. The transistors are working as a switch with on/off times dynamically determined according to the input energy in the converter. This energy is estimated from the input current or current in the L_1DC choke. The control scheme defines two control surfaces according to how far the input current is from the expected value: near the set point and far from the set point. This current loop also guarantees stable operation of the converter. The DC bus voltage is 48 V, and the storage battery has a nominal voltage of 24 V, besides, any number of sources or the loads can be present.

III. Methodology

The proposed scheme for DC bus regulation proposes the use of a bi-directional DC/DC converter and a DC power storage system (battery). The purpose of the control unit is to regulate the voltage and power in the DC bus, which requires controlling the power flow to and from the battery. The selected power converter is the SEPIC, but with an auxiliary circuit to allow the flow of power from output to input (Fig. 2).

The main circuit uses two switches as in the unidirectional SEPIC, but in this case both are directly controlled with control signals at their gate (two transistors, Q_1 and Q_2). The rest of the circuit is identical to the unidirectional SEPIC: two DC chokes and capacitive filters. The auxiliary circuit achieves the power flow in the opposite direction, and uses another switch (an additional transistor, Q_3) and another DC choke (L_a).

The switching of Q_1 and Q_2 controls the voltage regulation on the DC bus, sending power to the load. Q_3 switching allows power to be sent to the battery. According to these requirements the duty cycles of the three transistors (d_1, d_2 and d_3) are calculated (Fig. 3).

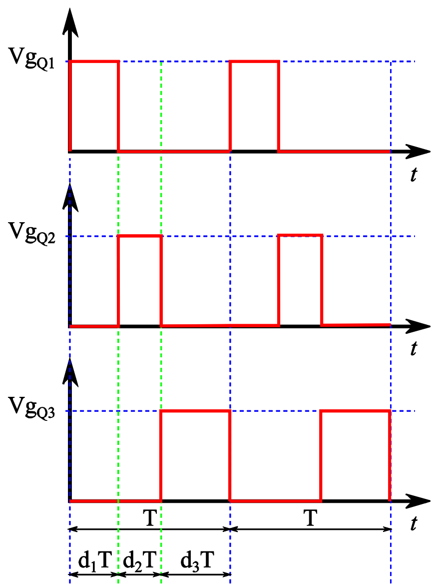

Fig. 3.Drive control signals per switching period

This bi-directional converter has three modes of operation during a T-switching period:

- Mode 1 (t_0 - t_1): This mode is similar to the t_{ON} of a unidirectional SEPIC. The flow of currents is shown in Fig. 4(a).
- Mode 2 (t_1 - t_2): This mode is similar to the t_{OFF} of a unidirectional SEPIC. The flow of currents is shown in Fig. 4(b).
- Mode 3 (t_2 - t_3): In this mode only the auxiliary circuit switch is closed, allowing power flow to the battery. The flow of currents is shown in Fig. 4(c).

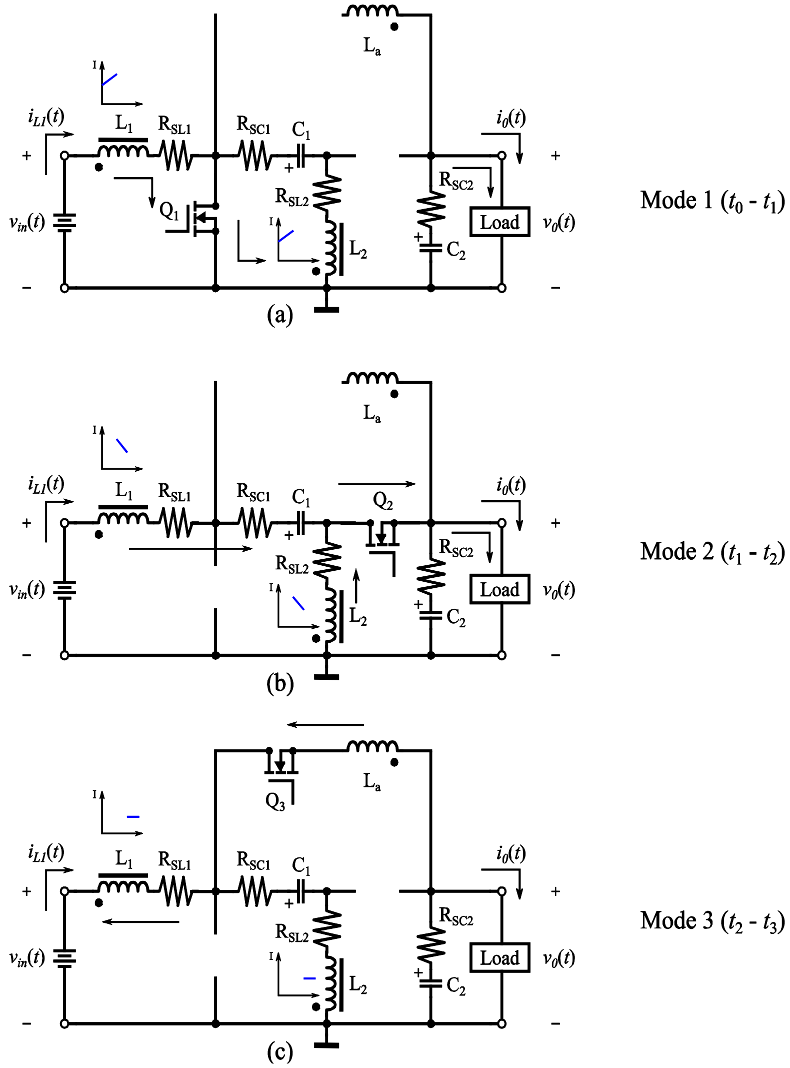

Fig. 4. The three operating modes of the bi-directional SEPIC converter

For the design of the control strategy we use the average motion of the current at the input choke L$_1$ (to estimate the system power) and the output voltage (regulation requirement) as state variables. Since the control objective is output voltage regulation, the sliding surface in state variables for steady-state control (near the set point) is given by (Ecu. 1):

$$S = \{\mathbf{X}(t) \in \mathbb{R}^2: \quad \overline{v_0(t)} = V_{ref}\} \qquad (1)$$

Where:

- $\overline{v_0(t)}$ is the average output voltage.
- V_{ref} is the desired output voltage.

However, the surface of the Ecu. 1 does not guarantee the stability of the converter. In order to guarantee the stability of the converter, it is necessary to regulate the input energy, which can be done by assuming the input current (current in the L$_1$ choke) as the control surface, which is equal to a constant depending on the output power (Ecu. 2).

$$S = \{\boldsymbol{X}(t) \in \mathbb{R}^2: \quad \overline{\iota_{L1}(t)} = K\} \qquad (2)$$

However, the primary objective of the converter remains the regulation of the output voltage, which is why it is necessary to eliminate the stationary error of the converter. This being the case, one might think of the need for two different control surfaces to solve the problem, one operating near the steady state equilibrium point, and the other operating during converter transients. The unification of these two control strategies into a single one is done by means of a fuzzy control block, hence the name given to the control strategy used. A fuzzy control scheme allows us to build a different control surface for each rule of the system, allowing us to use the most appropriate control surface at any given time.

Then, the proposed control scheme has two feedback loops: a current loop and a voltage loop. The dynamics of the current loop is much faster than that of the voltage loop, because a fast dynamic response is required depending on the energy handled by the converter, similar to the way the control is performed in current mode. The voltage loop, which is slower dynamic in order to avoid oscillations in the output voltage due to noise in the feedback signal, is in charge of establishing the current reference for the internal loop (current loop).

The reference value of the current in the choke is automatically adjusted by the converter according to the power balance condition. For the implementation, the following variables are selected as antecedents: (1) the output voltage error,E_u, and (2) the current in the converter choke i_{L1}.

For the fuzzy section, a total of seven fuzzy sets are defined for the output voltage error as shown in Fig. 5.

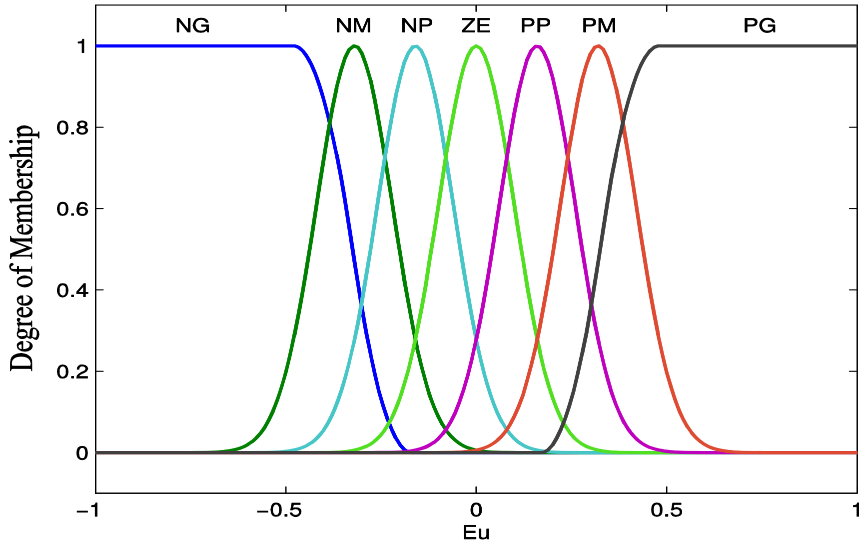

Fig. 5. Fuzzy sets for output voltage error

IV. Results and Discussion

The control scheme and the operation of the converter in the microgrid were validated by simulation in Python 2.7 on a computer Intel(R) Core(TM) i7-7700HQ @ 2.80 GHz with Linux 64 bits kernel 4.13.0-46-generic. We build the SEPIC converter model using system-level models of semiconductor switches (general behaviour, not specific devices). The parameters of the models used in the circuit were:

- MOS Field Effect Transistor (MOSFET, Q_1, Q_2 and Q_3):
  - Type: Equivalent line
  - Forward voltage: 0.8 V
  - Bulk resistance: 1mΩ
  - Reverse resistance: 100 kΩ
- L_1 and L_2:
  - Inductance: 47 uH
  - Parasitic resistance in series: 1mΩ
- L_3:
  - Inductance: 220 nH
  - Parasitic resistance in series: 1mΩ
- C_1:
  - Capacitance: 440 uF
  - Parasitic resistance in series: 1mΩ

- C_2:
    - Capacitance: 220 uF
    - Parasitic resistance in series: 1mΩ

The battery is rated to supply or absorb a power of 100 W at any source/load condition. The model used for the battery allows the input/output current to be considered as load/unload current, and to increase/reduce its nominal voltage according to the power flow.

The architecture assumed in the simulation includes at least one power source connected to the system's DC bus. In this way there is always power from the DC bus to the battery. The behaviour of this current is assumed constant in the model, but can be variable without affecting the system or the control unit. This behaviour is controlled with the d_3 duty cycle. Due to this constant behaviour, a constant charge of the battery is observed in the simulations.

The simulations include a response time of the control unit of 100 us. This time is what a digital device would require to digitize the voltage and current signals, calculate the system state variables, look up the values in a table stored in ROM with the results of off-line simulation of the hybrid fuzzy-sliding control block, and apply the corresponding duty cycle to each of the converter's switches.

The control structure could not be implemented online on an embedded device due to the time required for its calculations. For the implementation it is proposed to simulate the hybrid fuzzy-sliding control scheme for all possible combinations of values of the state variables, and the results, to store them in a table in ROM memory inside the digital device. This allows control decisions to be made very quickly, in fact, this strategy was also used in the simulations presented here.

We perform two kinds of simulations: with constant load and with variable load. These simulations allow to determine the operation of the proposed control scheme, and to observe the capacity of the battery to absorb/deliver power while regulating the DC bus voltage, and therefore the stability of the microgrid. The constant load simulation was performed with an output power of 38.4 W (a constant output current of 0.8 A, Fig. 6).

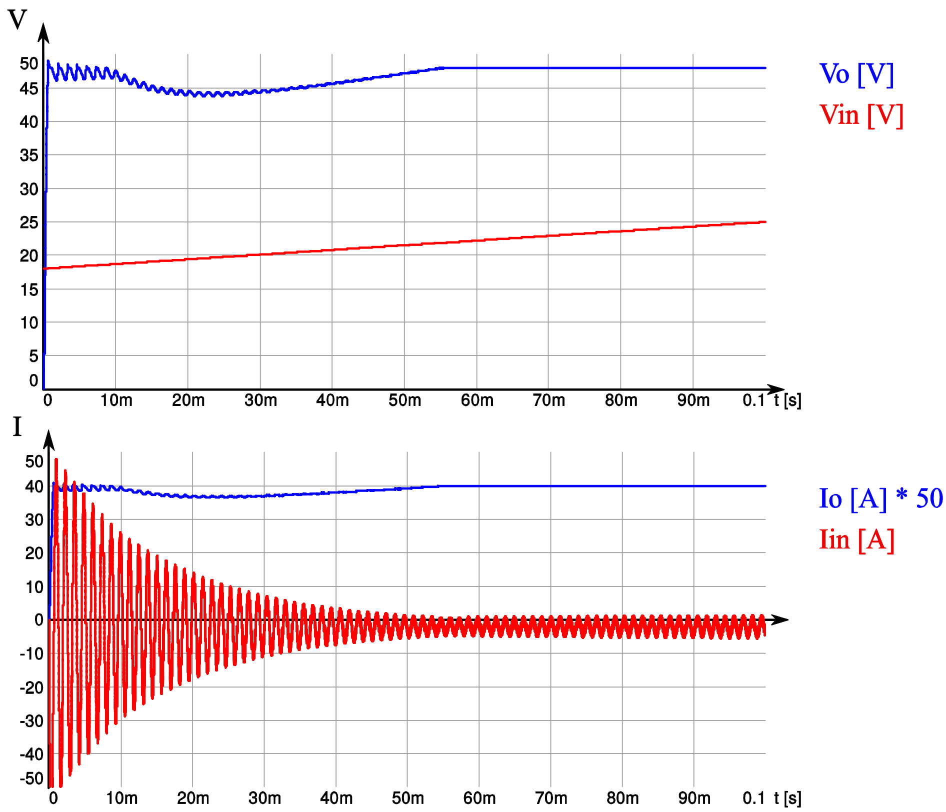

Fig. 6. Input (red) and output (blue) voltages and currents of the converter for constant load

In operation with constant load it is possible to observe the transient connection of the converter. We assume that there is a certain amount of power in the battery (initial 18 V battery voltage), and that it absorbs power while feeding the 0.8 A charge. The capacitors and DC chokes of the converter have no stored energy, so when the converter is connected a large amount of current is consumed to charge them. In addition, the voltage on the DC bus of the microgrid is not regulated (assumed to be 0 V initially) so the inverter must quickly stabilize the microgrid.

After an initial transient of about 55 ms, the power flow in the converter has reached a steady state. However, during the entire transient period the converter regulates the DC bus voltage using both the power of the battery and the power sources connected to the microgrid. Current flows tend to be high while the converter and DC bus are stabilized.Fig. 7 shows what happens when the load requirement for the converter doubles after it has reached its steady state (at 70 ms).

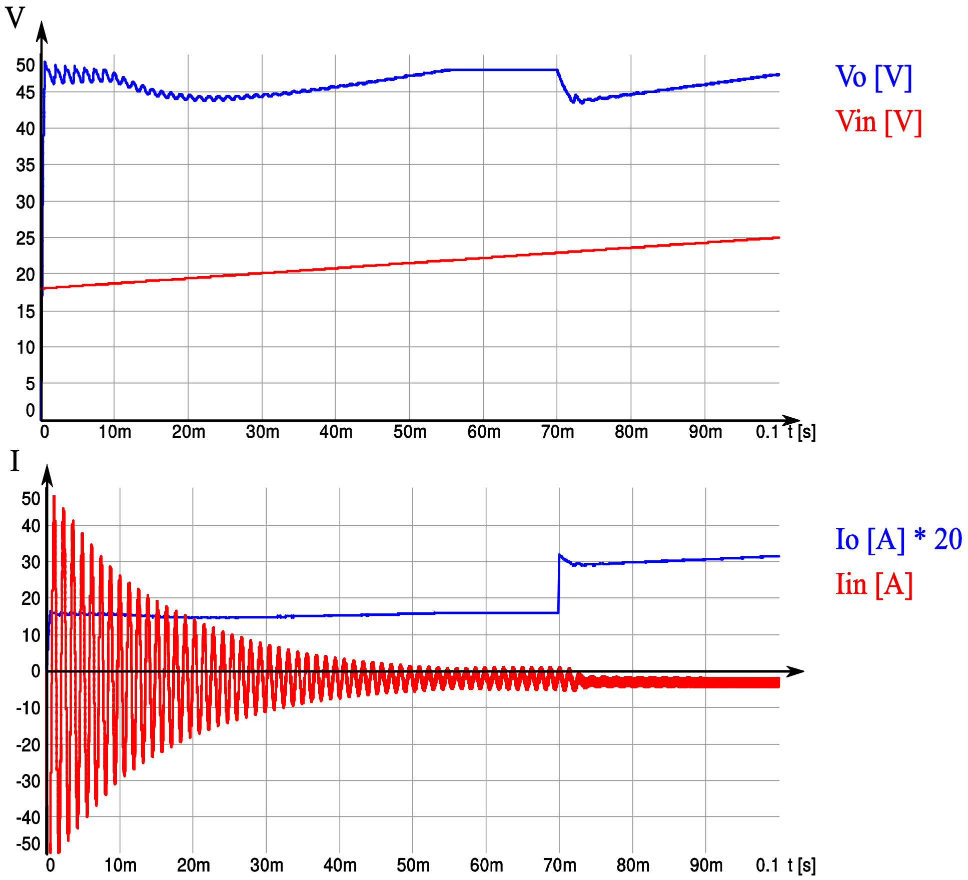

Fig. 7. Input (red) and output (blue) voltages and currents of the converter for variable load

When the load unexpectedly increases, a new transient occurs in the converter. However, this new transient is much smaller than the initial one, the current does not present large current peaks (in fact, a small 6.7% transient is observed in the output current with a duration of only 2 ms, we don't see peaks in the input current). The output voltage transient reaches a drop of 10.4% and lasts less than 30 ms.After this 30 ms the converter reaches its new stationary state point.

An additional restriction of the control unit is to limit the maximum current delivered to the battery. The limit was set at 50 A for maximum 1 ms. The voltage regulation falls mainly on the ratio of d_1 to d_2, but the control of the battery charge current depends mainly on d_3. This power limit controls the duration of the converter's initial transient.

V. Conclusion

In this paper we propose a control strategy for a bi-directional SEPIC converter that guarantees the regulation and stability of the voltage in a DC microgrid, and that also presents an excellent response to transients due to changes in the charge or storage batteries. The scheme proposes the use of a single control unit on an embedded digital system. The proposed control defines two control surfaces: one near to the converter's stability point and the other for transients, where power regulation is required. Near to the equilibrium point the main purpose is to regulate the output voltage (DC bus voltage), while during transients the amount of current in the converter is mainly controlled. By simulating the theoretical model of the system, the performance of the control strategy was observed in the event of changes in the charge and in the battery. The proposed control scheme successfully kept the DC bus voltage constant, and limited the behavior of the current transients.

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