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Rosa A. Mastromauro

Sante Pugliese

Domenico Ricchiuto

Silvio Stasi

Marco Liserre

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DC Multibus based on a Single-Star Bridge Cells Modular Multilevel Cascade Converter for DC Smart Grids

Rosa A. Mastromauro*, Sante Pugliese*, Domenico Ricchiuto*, Silvio Stasi* and Marco Liserre**

* Politecnico di Bari, Via Orabona, 4, 70125 Bari, Italy

** Christian-Albrechts-Universität zu Kiel, Kaiserstr. 2, D-24143 Kiel, Germany

Abstract—In the last years a growing interest towards DC Smart Grids has been registered due to high penetration of distributed generation systems with embedded storage. Trying to foresee the possible future scenarios of the power systems, it can be noticed that DC Smart Grids can be even preferable to AC Smart Grids in terms of flexibility and redundancy since they are compatible with the achievement of a DC Multibus working at different voltage levels. In this paper the Single-Star Bridge Cells Modular Multilevel Cascade Converter is used to create a DC Multibus. The performances of the system are analyzed considering different load configurations and coexistence of different voltage levels of the buses forming the DC Multibus. Results confirm the validity of the proposed solution and the robustness of the control system in case of load variations.

Index Terms-- DC Smart Grids, Single-Star Bridge Cells Modular Multilevel Cascade Converter, DC Multibus.

I. INTRODUCTION

In the actual power system DC transmission is adopted just for a limited number of applications such as electric traction and submarine transmission. As a consequence, also in the field of Distributed Power Generation Systems (DPGS), AC Smart Grids have experienced a wider spread than DC Smart Grids. However also DC Smart Grids contain a great potential to be exploited and the study of a DC Smart Grid operation can be considered the preliminary step towards the development of a future DC power system. The advantages of the High Voltage Direct Current (HVDC) transmission are well known in case of submarine or overhead lines used to cover long distances since DC lines are more competitive, from an economical point of view, than AC lines as line length increases. Different advantages are verified in case of Smart Grids applications: the first one relies on the nature of some renewable sources which are intrinsically DC sources. As a consequence, a DC/AC power conversion stage is required in order to connect the system to the main grid or to feed the loads. Differently, a lot of domestic loads require DC supply, hence the double power conversion stage implies additional losses (around 10-40%). Starting from these considerations, DC Smart Grids can provide higher efficiency reducing the number of power conversion stages [1]-[4]. A second important issue is flexibility due to coupling various DC renewable sources which operate at different voltage levels.

Connection to the main AC grid can be guaranteed by means of a bidirectional AC/DC converter, as shown in Fig.1. The third important issue is the continuous operation in case of faults on the AC side due to embedded storage systems; the last advantage is the absence of synchronization since phase control is not required. On the contrary disadvantages rely on:

1. need to create new DC lines;
2. protections circuit complexity since their action cannot be based on zero-crossing detection;
3. potential instability due to coexistence of different voltage levels.

The DC Multibus concept derives from naval applications [1], [4] and it can be successfully applied to the DC Smart Grids characterized by the coexistence of different voltage levels, different storage systems and different load supplies. The DC Multibus can contribute to the system redundancy since a single load can be supplied by a single DC bus, by more buses simultaneously or sequentially.

A DC Multibus can be achieved by means of a Modular Multilevel Cascade Converter (MMCC) (which can operate both with equal and different voltages at the DC-links of the power conversion modules), possibly combined with DC/DC converters. MMCCs have been recently classified by Hakagi [5], among them, the Single-Star Bridge Cells (SSBC) MMCC is particularly proper for battery energy storage systems based on one-converter-to-one-battery modules [6-7].

In this paper the SSBC MMCC is applied to a DC Smart Grid with the aim to create a flexible DC Multibus in order to guarantee continuous operation in presence of critical loads and varied operating conditions. The rest of the paper is structured as follows. Firstly, a short review of the main components of a DC Smart Grid is presented in Section II. The operation of the MMCC SSBC and the design of its control system is discussed in Section III, results related to different operating conditions are shown in Section IV.

II. DC SMART GRIDS AND DC MULTIBUS

The main components of a DC Smart Grid are:

- the distributed power generation sources, for example photovoltaic, fuel cells, wind turbines (after a first AC/DC power conversion stage);

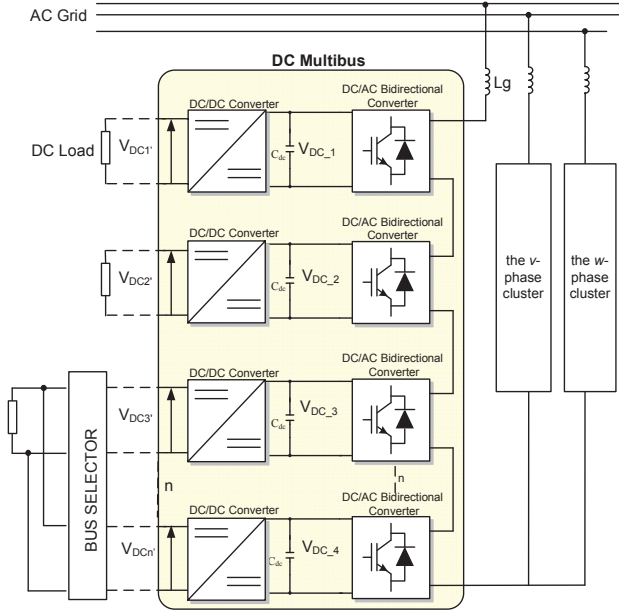


Fig. 1. DC Multibus based on the SSBC MMCC connected to the main AC power system

- the storage systems (batteries, supercapacitors), which are essential in order to get the power balance among the sources and the local loads and between the microgrid and the main power system (guaranteeing also reliability of the overall system);
- the loads (critical and not);
- one DC/AC bidirectional power converter (required in case of grid-connected operation).

In this scenario the use of a DC Multibus allows multiple options to supply the loads ensuring:

- 1) redundancy since sensitive loads can be supplied by different DC-links;
- 2) availability of various voltage levels.

With reference to Fig. 1, each power conversion cell can feed a local load or the power can be shared by a bus selector which establishes what DC bus may supply each load in order to fulfill continuous operation also in case of fault on one bus.

A possible decision strategy consists of the selection of the bus with the highest voltage. Alternatively, other strategies are based on the droop control theory in order to guarantee current sharing [8].

III. THE SSBC MMCC AND ITS CONTROL SYSTEM

The proposed system consists of a SSBC MMCC creating a DC Multibus as shown in Fig.1. The MMCCs family is one of the most famous multilevel topologies, particularly used for MV applications. The performances of a MMCC depends on the number of voltage levels denoted as M . M is defined on the basis of the power conversion cells number (H) used for each phase:

$$M = 2H + 1 \quad (1)$$

In the considered case study, the MMCC is a SSBC composed by four cells which are connected in cascade as shown in Fig.2, hence, it results: $M=9$ (the DC-links

voltages are assumed all equal).

On the AC side an inductive filter is used in order to reduce the current harmonic distortion. L_g should be designed considering the maximum power that can be delivered, the Total Harmonic Distortion (THD) of the grid current, the current ripple and the inrush current value. L_g is tuned as :

$$L_g = D_m \frac{|V_m - V_{dc_TOT}|}{2f_{sw}\Delta i} \quad (2)$$

where D_m is the converter duty-cycle, V_m is the maximum value of the AC voltage, V_{dc_TOT} is the overall DC voltage ($V_{dc_TOT} = V_{dc_1} + V_{dc_2} + V_{dc_3} + V_{dc_4}$), f_{sw} is the switching frequency and Δi denotes the current ripple.

A proper design of the capacitance C_{dc} of each DC-link is fundamental in order to get the desired DC voltage. Since C_{dc} may be chosen on the basis of the admissible voltage ripple, it can be calculated as:

$$C_{dc} = \frac{P_{max}}{(V_{dc_i}^* \Delta U \pm \frac{1}{2} \Delta U^2) f_{sw}} \quad (3)$$

where P_{max} is the maximum value of the instantaneous power, $V_{dc_i}^*$ is the reference voltage of the SSBC MMCC i -DC-link and ΔU is the voltage ripple. In the proposed application each phase of the SSBC MMCC is treated separately. For each power cell a unipolar phase-shifted Pulse Width Modulation (PWM) is adopted where the modulating signal is provided by the control system, while the phase shift angle between the carriers of two adjacent cells is:

$$\phi_{cr} = \frac{360^\circ}{(M-1)} \quad (4)$$

Hence, in the considered case study, it results: $\phi_{cr} = 45^\circ$.

The control system may guarantee synchronization with the main grid and full control of the DC voltage. Each power conversion cell is controlled as shown in Fig.2 where the voltage v_{ph} denotes the output of the multiloop control system; it is provided as voltage reference to the PWM modulator establishing the switching function of each cell ($p_{cell1}, \dots, p_{cell4}$).

The outer loop controls directly the DC voltage of every cell and indirectly the power exchanged with the main AC grid since it generates in output the current reference for the inner loop. The voltage loop operates as in the following: the DC voltages, available at each DC-link, are summed and the average value is calculated; then the average value is firstly filtered in order to cut-off the second order harmonic, typical of the single-phase H-Bridge, and later this value is compared with the voltage reference V_{dc}^* . The voltage control is based on a PI regulator, a feed-forward action is added in order to improve the dynamic performances of the system (Fig.3). A phase-locked-loop (PLL) circuit provides a single-phase sinusoidal waveform perfectly synchronized with the main grid voltage.

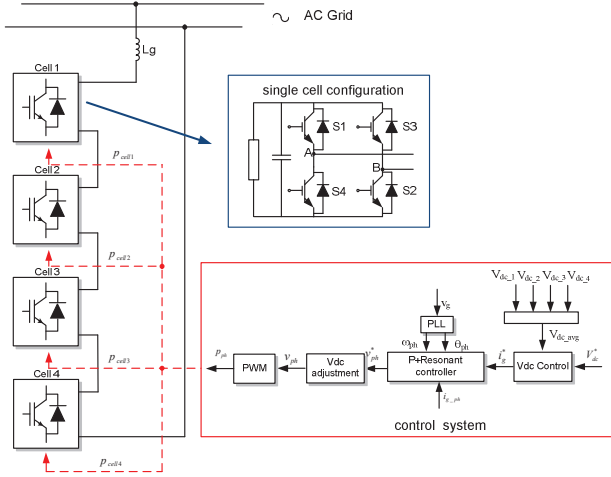


Fig. 2. u -phase of the 9 levels SSBC MMCC and its control system.

The sinusoidal current reference $i_{g,ph}^*$ is obtained multiplying the unitary sinusoidal signal by i_g^* (provided in output by the voltage control). The current loop is based on a P+Resonant controller [9] as shown in Fig.2 and in Fig.4. The output v_{ph}^* is the average voltage which may be generated by the overall power stage in order to annul the current error. The voltage reference v_{ph}^* is shared among the different units. A correction action is introduced by means of an offset calculated in order to take into account the gap between the real voltage of each cell $V_{dc,j}$ and the average value $V_{dc,avg}$. Hence v_{ph} denotes the PWM modulating signal obtained as overall output of the multiloop control system.

In order to provide flexibility to the system, DC/DC bidirectional converters can be connected to the DC-links of the SSBC MMCC. In this hypothesis DC voltages higher than the DC-links can be obtained. Among the DC/DC converters topologies, the Dual Active Bridge (DAB) converter ensures galvanic isolation avoiding the occurrence of unwanted circulating currents inside the system, which can be present in case of loads sharing among more DC/DC units [10]. In the proposed case study, four DAB converters are connected to the four DC-links of the SSBC MMCC u -phase.

The DAB converters are controlled with the aim to guarantee tracking capability of the reference voltage for each DC bus of the Multibus. Since each DAB converter consists of two Full-Bridge power conversion modules connected by a Medium Frequency Transformer (MFT), the phase-shift between the input voltage and the output voltage is used to control the power flow.

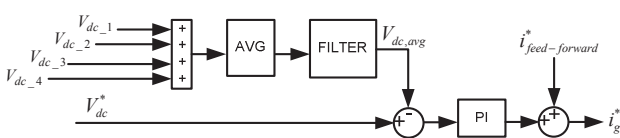


Fig. 3. V_{dc} voltage control of the SSBC MMCC u -phase.

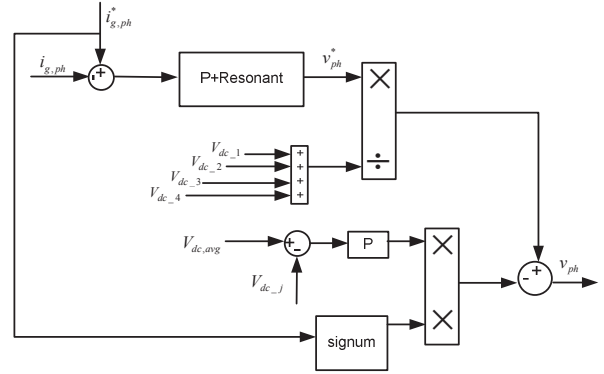


Fig. 4. Current control and DC voltage adjustment of the single power conversion cell of the SSBC MMCC.

The control system of the DAB converter is shown in Fig. 5. It is based on a PI controller, tuned on the basis of the technical optimum, but a 100 Hz resonant compensator [9] is added in order to act on the second order harmonic typical of the single-phase systems.

IV. RESULTS

The operation of a small scale DC Multibus based on a SSBC MMCC has been tested in different conditions. The behavior of the proposed system has been investigated in the following operations: 1) with the DC buses working at the same voltage and feeding independent loads; 2) in case of critical loads shared among more buses and with the buses of the DC Multibus operating at different voltage levels; 3) in case of load variations. It is supposed that the overall system is parallel connected to the main grid. In Table I there are reported the power stage parameters used for the simulation of the system shown in Fig. 1.

A. DC Multibus operation with independent loads

The voltage reference for each DC-link of the SSBC MMCC is $V_{dc}^* = 100$ V. The voltage references for the DAB converters control are chosen as: $V_{dc1}^* = V_{dc2}^* = V_{dc3}^* = V_{dc4}^* = 400$ V. Each load is connected to a single bus of the DC Multibus and it absorbs an active power: $P = 0.5$ kW. In Fig. 6 it is shown the 9-levels voltage of the MMCC SSBC compared to the grid voltage; the grid current THD is 2%. In Fig. 7, there are reported the SSBC MMCC output voltages obtained at each DC-link, while in Fig. 8 there are represented the DC Multibus voltages provided in output by the DC/DC converters and the loads currents.

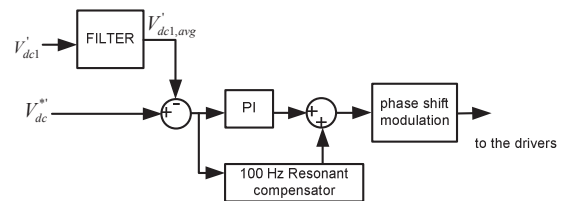


Fig. 5. Control of the DAB converter.

TABLE I
POWER STAGE PARAMETERS

Parameters	Value
Switching frequency f_{sw}	1.1 kHz
Sampling frequency f_s	4.4 kHz
Grid resistance R_g	9 m Ω
Grid Inductance L_g	0.5 mH
DC-link Capacitance C_{dc} (related to every cell of the CHB)	10 mF

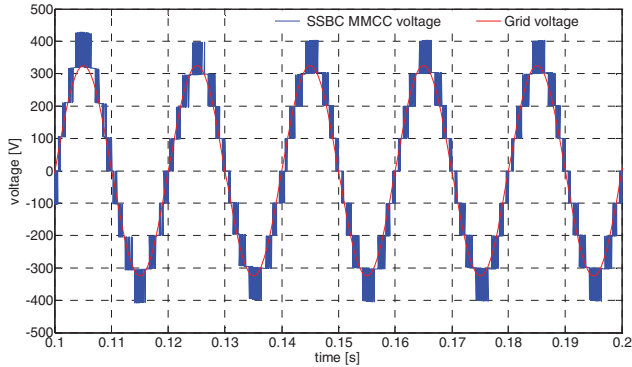


Fig. 6 AC grid voltage and 9-levels voltage of the SSBC MMCC.

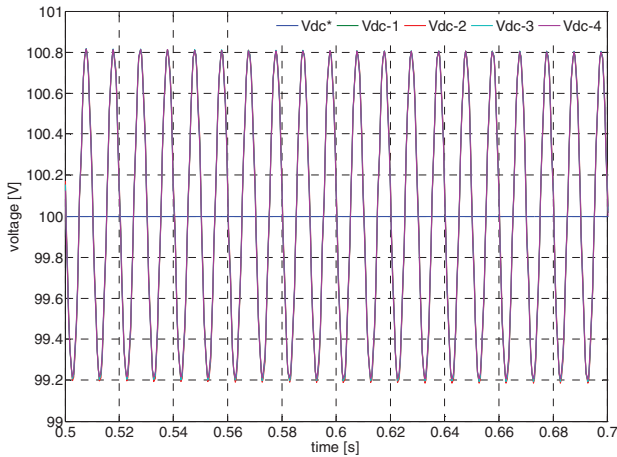


Fig. 7 SSBC MMCC DC-links voltages.

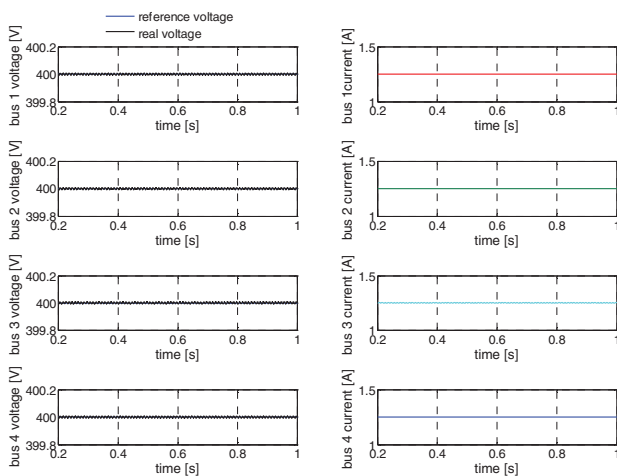


Fig. 8 DC-Multibus voltages and currents: V_{dc1} , V_{dc2} , V_{dc3} and V_{dc4} , i_{dc1} , i_{dc2} , i_{dc3} and i_{dc4} in case of independent loads operation.

B. DC Multibus operation with buses in parallel

Load sharing allows to guarantee continuous operation mode even in case of faults on one of the DC buses. Indeed, in case of failure, it is possible to isolate the damaged bus supplying the load by means of the remaining buses. In this subsection the buses denoted as bus 1 and the bus 2 (Fig.1) supply a sensitive load of 1000 W in parallel, while the bus 3 and the bus 4 share respectively another load of the same power. The peculiarity is that the buses are also operating at different voltage levels: the buses 1-2 are working at 400 V while the buses 3-4 are working at 300 V. It is verified that bus 1 and bus 2 share perfectly the load providing a half of the required power as the buses 3-4 respectively. The results are summarized in Fig.9.

C. DC Multibus operation in case of load variation

Load variations at one or more buses involves imbalance of the power absorbed by the cells of the SSBC MMCC. In order to test the robustness of the control system, the performances of the system are analyzed in case of load variations of different amount. Some selected results are reported in Fig.10-12. The DC buses operate at different voltage levels: $V_{dc1}^* = V_{dc2}^* = 400V$, $V_{dc3}^* = 300V$, $V_{dc4}^* = 250V$. One load of 1 kW is shared by the bus1 and the bus 2 while two loads of 0.5 kW are supplied by the bus 3 and the bus 4 separately. High performances are obtained due to the proper action of the DC voltage adjustment of the single power conversion cells of the SSBC MMCC. In the first case the expected behavior of the system is verified in case a load variation of 10% is applied for each load at different times (Fig.10). The DC-links voltages waveforms of the SSBC MMCC converter in the described perturbed conditions are shown in Fig.11. In the second case the effectiveness of the control system is confirmed in case of a 40% load variation applied just at one load (load 1 which is shared between the bus 1 and the bus 2). Related results are summarized in Fig.12. For load variations beyond 40% the system becomes unstable.

V. CONCLUSION

A DC Multibus operating at different voltage levels can provide flexibility and redundancy to a DC Smart Grid. In this paper the role of a SSBC MMCC converter for the creation of a DC Multibus has been investigated. The SSBC MMCC is combined with DC/DC converters in order to extend the operating voltage range. A proper control system has been designed in order to manage voltage regulation and power balance. The performances of the system have been verified in numerous operation conditions confirming the validity of the proposed solution and the robustness of the control system in a wide range of loads variations.

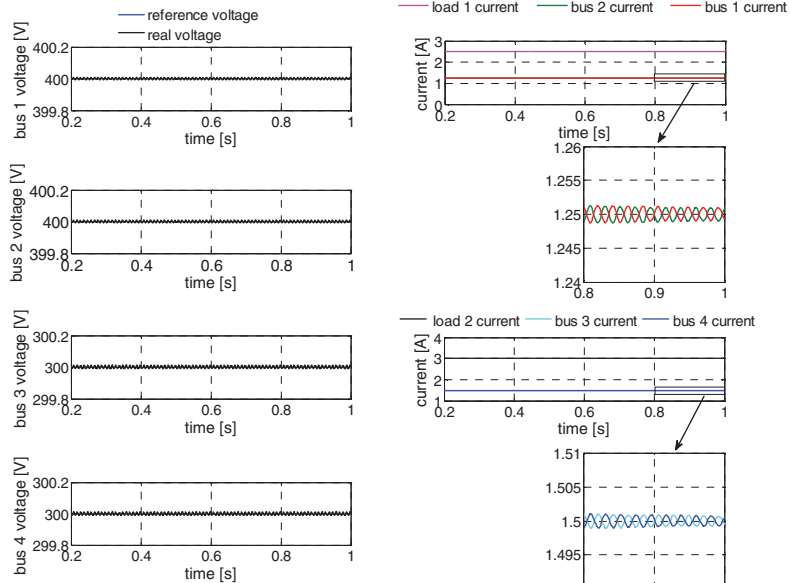


Fig. 9 DC-Multibus voltages and currents: V_{dc1}' , V_{dc2}' , V_{dc3}' and V_{dc4}' , i_{dc1} , i_{dc2} , i_{dc3} and i_{dc4} in case the bus1 and bus 2 share one sensitive load while bus 3 and bus 4 share another load respectively.

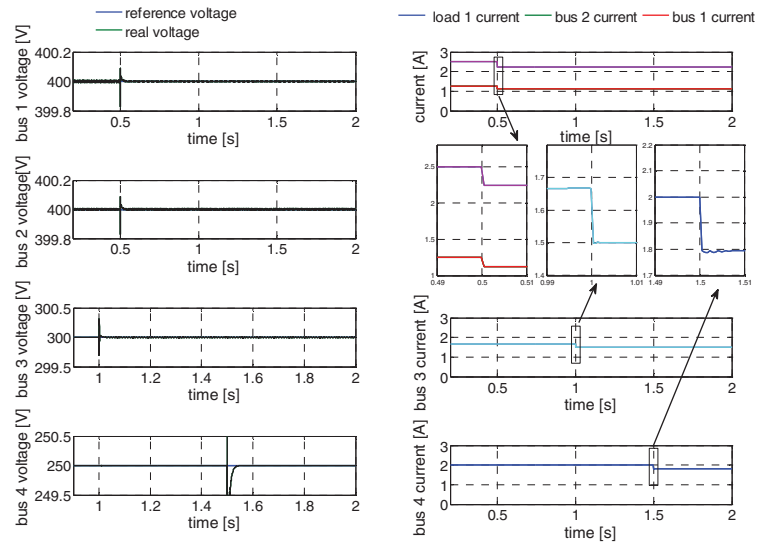


Fig. 10 V_{dc1}' , V_{dc2}' , V_{dc3}' and V_{dc4}' , i_{dc1} , i_{dc2} , i_{dc3} and i_{dc4} in case of 10% load variations applied for each bus at different times.

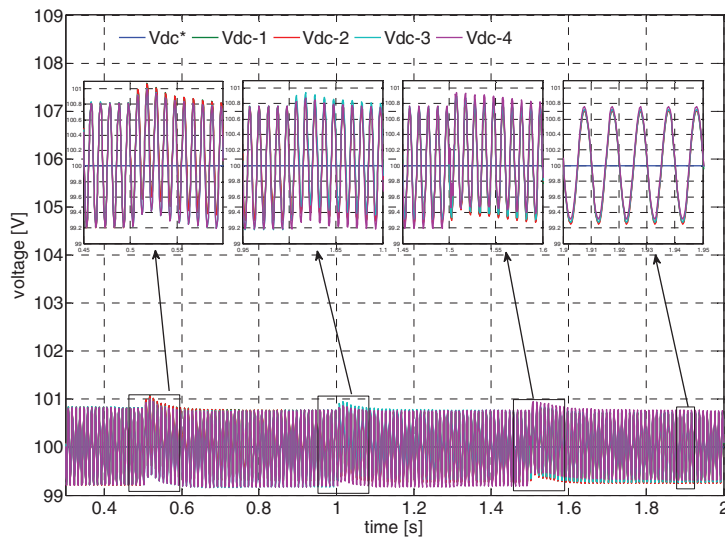


Fig. 11 SSBC MMCC DC-links voltages in case of 10% load variations applied for each bus at different times.

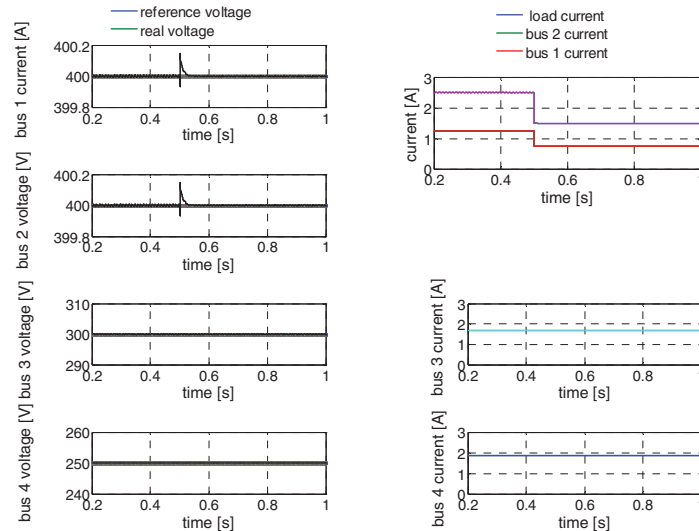


Fig. 12 V_{dc1} , V_{dc2} , V_{dc3} and V_{dc4} , i_{dc1} , i_{dc2} , i_{dc3} and i_{dc4} in case of a 40% load variation related to the load shared between the bus 1 and the bus 2.

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