STABLE OPERATION OF A SINGLE - PHASE CASCADED H-BRIDGE MULTILEVEL CONVERTER

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ABSTRACT

The proposed paper presents the steady state power balance in the cells of a single-phase two cell cascaded H-Bridge converter. Multilevel cascaded H-Bridge (CHB) converters fonds a good solution for high-power applications. The power balance can be achieved by supplying the active power from the grid or to deliver active power to the grid in each cell. This can be analyzed by maintaining the DC-link voltages and the desired AC output voltage value. To have a stable operation it is necessary to supply the active power to 2C-CHB between maximum and minimum limits. The circuit for 2C-CHB synchronous rectifier is designed in MATLAB and the results are obtained successfully.

KEYWORDS: *Cascaded Converters, Multilevel systems.*

I. INTRODUCTION

MULTILEVEL converters have turned into a mature technology that has increased its use in the last years. [1]-[3]. Among the multilevel converter topologies, the Cascaded H-Bridge (CHB) converters were first presented in 1975.Since then, the research works have paid attention in this topology because it presents several advantages compared with other multilevel converter topologies in terms of modularity, Simplicity, and the number of levels with a minimum number of power semiconductors [4]

The CHB has been used to develop different applications, such as synchronous rectifiers, inverters, Statcoms, active filters, renewable energy integration systems, motor drives, etc. [5]-[10]. Moreover, specific control strategies and modulation techniques, associated with those applications, have been designed for this converter topology.[11]-[13]. As each DC link is independent, when the CHB converter is used as a synchronous rectifier, it is possible to connect loads with several values to each DC link. In addition, each DC link can be controlled to a different DC voltage level providing a high degree of freedom. When two or more DC voltage values are needed, although it is possible to use independent two-level converters, the CHB converter provides some extra benefits. It has a lower input current harmonic content; thus, a lower smoothing inductor Value can be used. Therefore, the CHB provides reduction in the overall volume, weight, and economical cost. For these reasons, the CHB topology is very suitable when two or more DC voltage levels are needed. However, the converter operation has to be taken into account in the design process. Due to the fact that every cell shares the same input AC current, the loading condition of each cell affects the behavior of the overall system.

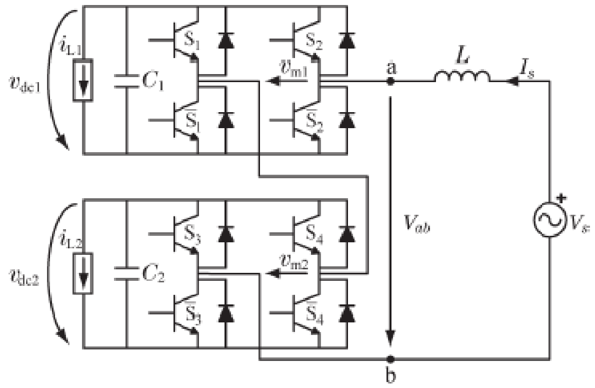

Fig. 1. Two-cell Single-Phase CHB power converter.

In this paper, the steady-state power balance in the cells of a single-phase two-cell multilevel CHB (2C-CHB) power converter and the grid is analyzed. In Section II, a brief description of the 2C-CHB topology is presented. Then, in Section III, the steady-state power balance in the cells of the 2C-CHB is studied. The capability of active power supplied from the grid or to deliver active power to the grid in each cell is analyzed according to the DC-link voltages and the desired AC output voltage value, addressing the limits of the maximum and minimum loads for a stable operation of the 2C-CHB.
In Section IV, a brief description of the system controller is introduced. Finally, in Sections V and VI, simulation results validating the presented analysis and final conclusions are stated.

II. SYSTEM DESCRIPTION

A single-phase 2C-CHB power converter is shown in Fig. 1. The system is connected to the grid through a smoothing inductor *L*. Load behavior is considered by using current sources i_{L1} and i_{L2} connected to each DC-link capacitor C_1 and C_2, respectively. The system parameters and variables are described in Table I, where the continuous control signals δ_1 and δ_2 represent the switching functions.

TABLE – I System Variable

Parameter	Description
L	Smoothing inductor
C_1,C_2	DC-link Capacitors
i_{L1},i_{L2}	Load Currents
I_S	Grid Current
V_S	Grid Voltage
v_{dc1},v_{dc2}	Dc-Link Voltages
V_{ab}	Converter output voltage
v_{m1},v_{m2}	Cell output voltages
δ_1, $\delta_2 \epsilon[-1,1]$	Control Signals
p_t	Converter input instantaneous power

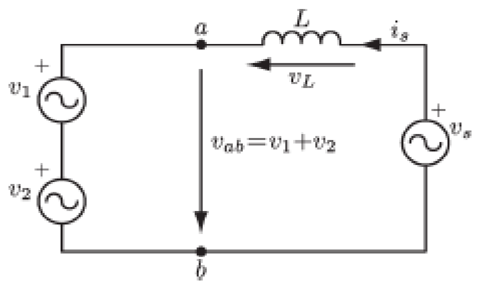

Fig. 2. 2C-CHB equivalent circuit

The equations that describe the 2C-CHB behavior are well known, and they have been reported previously.

$$v_{m1} = \delta_1 \, v_{dc1} \qquad p_1 = v_{dc1} \, i_{L1} \quad \text{(1)}$$

$$v_{m2} = \delta_2 \, v_{dc2} \qquad p_2 = v_{dc2} \, i_{L2} \quad \text{(2)}$$

$$p_t = p_1 + p_2 \quad \text{(3)}$$

$$V_s = L\frac{dI_s}{dt} + v_{m1} + v_{m2} \quad \text{(4)}$$

$$v_{m1} \, I_s = C_1 \frac{d}{dt}\left(\frac{v^2{}_{dc1}}{2}\right) + p_1 \quad \text{(5)}$$

$$v_{m2} \, I_s = C_2 \frac{d}{dt}\left(\frac{v^2{}_{dc2}}{2}\right) + p_2 \quad \text{(6)}$$

The behavior of 2C-CHB is characterized by the inductor current dynamic (4) and DC-link capacitor voltage dynamic in each cell (5) and (6). In these equations, signals V_{m1} and V_{m2} represent the output voltages of each cell. These voltages depend on the DC-link voltage and the control signal values in each cell. Moreover, signals p_1 and p_2 are the instantaneous powers demanded or delivered by the current sources connected to each cell, respectively.
To analyze the steady-state power balance in the cells of a cascaded converter, the power converter equivalent circuit shown in Fig. 2 is used. In this representation, the cells have been replaced by voltage sources with values V_1 and V_2 that are equal to the rms values of the fundamental harmonic of the voltages modulated by the cells $V_{m1,1}$ and $V_{m2,}1$, respectively. In addition, the rms values of the fundamental harmonic of the output phase voltage (V_{ab}), grid voltage (V_s), and grid current (i_s) are considered in the equivalent circuit.

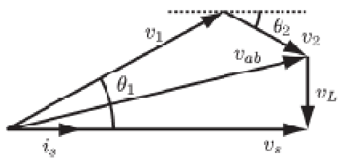

Fig. 3. 2C-CHB phasorial diagram of voltages and current

III. POWER BALANCE ANALYSIS

The sign of the active power of each cell depends on the shift angle between the current i_s and the output voltage in the cell $V_{i,i=1,2}$. This can be analyzed using the phasorial diagram of the 2C-CHB equivalent circuit shown in Fig. 3, where the rms values of the converter main magnitudes are plotted. In the analysis, it is assumed that v_{ab} is calculated in such a way that i_s is in phase with v_s. Other solutions can be considered; however, the same active power has to be supplied by the grid to the cells or delivered from the cells to the grid.
The only difference is the shift angle between the input current and the grid voltage, leading to a reactive power exchange between the grid and the converter. Therefore, the conclusions from the presented analysis are still valid. The capability to be supplied with active power from the grid or to deliver active power to the grid in each cell depends on the value of the capacitor voltage in the cell and the voltage that should be modulated by the 2C-CHB.

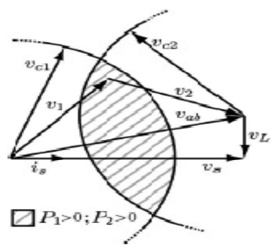

Fig. 4. Stable control area when $V_{c1} \leq V_{ab}$ and $V_{c2} \leq V_{ab}$.

In what follows, the three possible cases are described, and in all cases, it is assumed that v_{ab} can be modulated by the converter, i.e.,

$$V_{c1} + V_{c2} \geq V_{ab} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (7)$$

3.1 .$V_{c1} \leq V_{ab}$ and $V_{c2} \leq V_{ab}$

In this case, it is necessary to use both cells to generate the output voltage V_{ab}. Fig. 4 shows in a marked area the possible points to achieve the desired output voltage. Any point outside of this region makes the system unstable because the output voltage cannot be modulated with those values of the dc-link capacitor voltages. In addition, as shown in the figure, the projection of V_1 over i_s is always positive, and the same occurs for V_2; as a consequence, the active power values in both cells are positive, meaning that the grid supplies active power to both cells simultaneously.
Moreover, it is not possible to find a point where the grid supplies active power to one cell and, at the same time, the other cell delivers active power to the grid. In addition, this situation means that it is not possible to have the grid supplying active power only to one cell or to have only one cell delivering active power to the grid. On the other hand, it can be observed that the reactive power exchanged with the inductor is supplied by the cells. There is no restriction to the reactive power sign contributed by each cell. This means that the reactive power in each cell can be different; even in one cell; the reactive power can have a capacitive nature while the other has an inductive nature.
In Fig. 5, it is shown that, for a given total amount of active power supplied by the grid to the the converter, the power delivered to each cell has to be between a minimum and a maximum value to achieve a stable operation. Fig. 5(a) shows the minimum active power that has to be supplied to cell -1. This value corresponds with the minimum reachable length of the projection of $v1$ over is, represented in the figure with $V_{\min1p}$. As the total amount of active power is fixed, this value is related with the maximum active power that can be delivered to cell 2, shown in Fig. 5(a) as $V_{\max2p}$, which is the maximum reachable length of the projection of V_2 over i_s. In the same way, the values for the maximum active power that can be supplied in cell 1 $V_{\max1p}$ and the minimum active power that has to be Delivered to cell 2 $V_{\min2}p$ can be defined. These values are shown in Fig. 5(b).

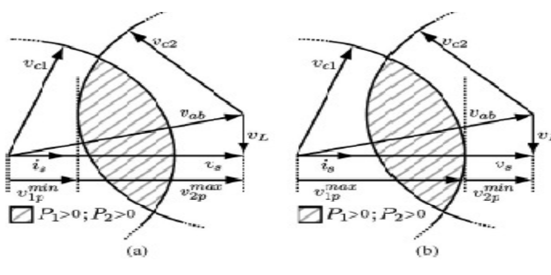

Fig. 5. Maximum and minimum active power limits when $V_{c1} \leq V_{ab}$ and $V_{c2} \leq V_{ab}$

3.2 $V_{c1} > V_{ab}$ and $V_{c2} \leq V_{ab}$

In this case, the desired output voltage can be achieved using both cells or just using the cell with the higher dc voltage. This allows two possible power balance situations in the cells. In Fig. 6, the marked area represents the points where both cells are supplied with active power from the grid, while the marked area shows the points where the first cell is supplied with active power from the grid while the second cell delivers active power to the grid. As in Section III-A, the reactive power is exchanged between the inductor and the cells without restrictions in the reactive power sign contributed by each one.

Fig. 6(a) shows a possible solution with both cells supplied with active power from the grid, and Fig. 6(b) shows a possible solution when the first cell is supplied from the grid while the second cell delivers active power to the grid. It is worth noting that, when $V_{c1} > V_{ab}$ and $V_{c2} \leq V_{ab}$, if the total active power supplied to the converter from the grid is positive, then only the second cell active power can be negative, while the first cell active power is positive; it is not possible to have a negative active power in the first cell while the second cell has a positive active power value.

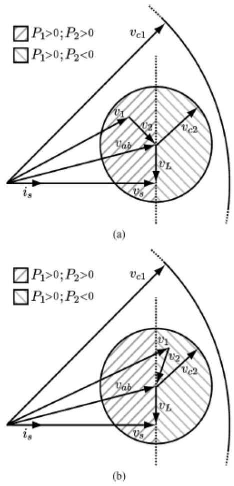

Fig. 6. Stable control area when $V_{c1} > V_{ab}$ and $V_{c2} \leq V_{ab}$. (From top to bottom) Possible solution with (a) $P_1 > 0$ and $P_2 > 0$, and (b) $P_1 > 0$ and $P_2 < 0$.

Fig. 7 shows the limits for the maximum and minimum active power values allowed in the cells to achieve a stable operation, when the total amount of active power supplied from the grid to the converter is fixed. Two different power balance situations can be clearly identified.

The first one can be considered as the conventional operation of the converter, and it is shown in Fig. 7(a). In this case, both cells are supplied from the grid, and as a consequence, a minimum active power has to be supplied to cell 1 from the grid; this value corresponds with the minimum reachable length of the projection of v_1 over i_s, represented in the figure with $V_{\min1p}$. Associated with this value is $V_{\max2p}$, which is the maximum reachable length of the projection of V_2 over i_s and represents the maximum active power that can be supplied to cell 2.

The second power balance situation, shown in Fig. 7(b), implies that the active powers in each cell have different signs. Thus, the cell with the higher dc voltage is supplied from the grid, while the other cell is delivering active power to the grid.

Under this situation, the values for the maximum active power that can be delivered to cell 1 $v\max1p$ and the minimum active power that has to be supplied to cell 2 $V_{\min2p}$ can be defined. In Fig. 7(b), it can be noticed that $V_{\min2p}$ has opposite direction than is; thus, the second cell is delivering active power.

Moreover, the maximum active power supplied to cell 1 is higher than the total amount of active powers delivered from the grid. This means that the active power delivered from the second cell is going into the first cell.

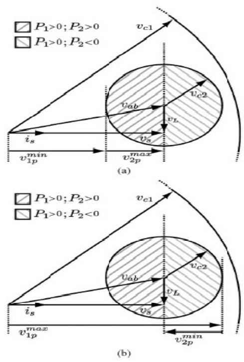

Fig. 7. Maximum and Minimum active power limits when $V_{c1} > V_{ab}$ and $V_{c2} \leq V_{ab}$.

3.3 $V_{c1} > V_{ab}$ and $V_{c2} > V_{ab}$

In this case, the output voltage can be modulated using both cells or just using one of them. As a consequence, three possible power balance situations in the cells are under concern. In the marked area of Fig. 8, both cells are supplied simultaneously with active power from the grid, whereas the marked area shows the set of points where the first cell is supplied with active power from the grid while the second cell delivers active power to the grid. On the other hand, the marked area represents the set of points where the first cell delivers active power to the grid while the second cell is supplied with active power from the grid. Again, the reactive power is exchanged between the smoothing inductor and the cells without restrictions in the sign of the reactive power of each cell.

Fig. 8 shows the three possible solutions, one for each power balance situation under concern. Fig. 8(a) shows the conventional operation, where both cells are supplied with active power from the grid. Fig. 8(b) shows the converter operation when the first cell is supplied from the grid while the second cell delivers active power to the grid. Finally, Fig. 8(c) shows a solution with the first cell delivering active power to the grid while the second cell is supplied with active power from the grid. It can be noticed that, when $V_{c1} > V_{ab}$ and $V_{c2} > V_{ab}$, although the total active power supplied to the converter from the grid is positive, it is possible that any one cell delivers active power to the grid while the other one is supplied with active power from the grid. When the maximum and minimum limits of the active power consumed or injected by the loads connected to the cells are analyzed, similar conclusions to those presented in Section III-B, when the power balance through each cell has different signs, are found.

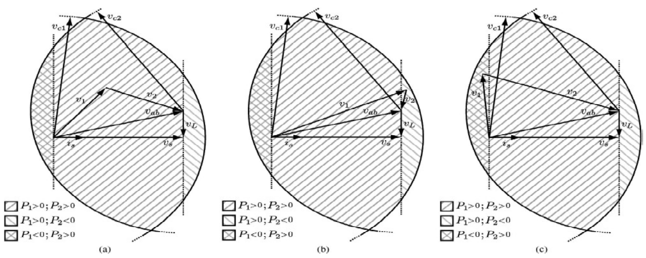

Fig. 8. Stable control area when $V_{c1} > V_{ab}$ and $V_{c2} > V_{ab}$. (From left to right) Possible solution with (a) $P_1 > 0$ and $P_2 > 0$, (b) $P_1 > 0$ and $P_2 < 0$, and (c) $P_1 < 0$ and $P_2 > 0$.

In Fig. 9, the maximum active power that can be supplied and the minimum active power values that have to be delivered to each cell to achieve a stable operation, for a given total amount of active powers consumed by the loads connected to the converter, are shown. Under this situation, the minimum active power that has to be supplied in each cell is negative; thus, the cell is delivering active power. Meanwhile, the maximum active power that can be consumed by the loads connected to the cell is higher than the total active power supplied to the converter; thus, part of the energy consumed in this cell comes from the other cell and not from the grid.

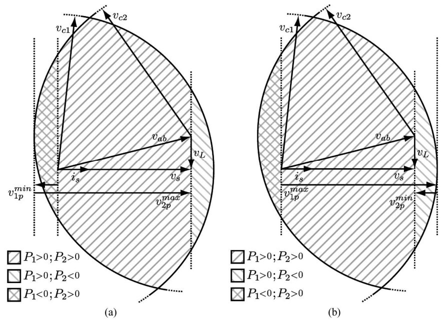

Fig. 9. Maximum and minimum active power limits when $V_{c1} > V_{ab}$ and $V_{c2} > V_{ab}$

IV. SIMULATION RESULTS

In this section, simulation results are shown to validate the analysis presented in Section III. For this purpose, a single phase 2C-CHB converter prototype has been used. The electric parameters of the prototype are summarized in Table II. To assess the presented analysis, three different experiments are described. The first one shows the converter operation in the stable region, as described in Section III-A, while the second experiment shows the prototype behavior when the loading condition leads outside this stable operation region.

TABLE II Electric Parameters

Parameter	Description
RMS Grid Voltage(v_s)	230 V
Grid Frequency(f)	50 HZ
Smoothing Inductance(L)	3 mH
DC -Link Capacitors(C_1,C_2)	2200 µF
Switching Frequency(f_{sw})	10 KHZ
Sampling Frequency(f_s)	10 KHZ

Finally, an experiment showing the stable converter operation with both cells having opposite power balance signs, as presented in Section III-B, is analyzed.

4.1 Stable Operation With $V_{c1} \leq V_{ab}$ and $V_{c2} \leq V_{ab}$

In this case, both cells have to be supplied or to deliver active power from the grid simultaneously. To illustrate this operation, a resistor of 60 Ω is connected to each dc link as a load. Several dc voltage step references are applied to show the behavior of the 2C-CHB. Initially, the dc voltage commands are set to 200 V. When the actual dc voltages achieve their references, the loads are connected. Approximately 2s later, the voltage command for the first cell is changed to 300 V, and then, after 1 s, a new reference for the second cell of 100 V is established. Fig.10. shows the real and reactive powers of stable operation.

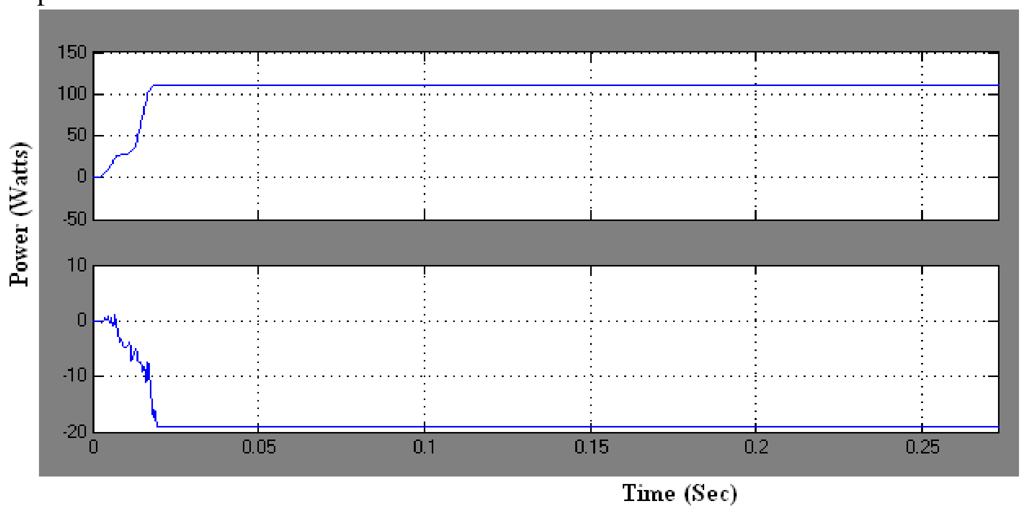

Fig.10. Real and reactive power

4.2 Unstable Operation with $V_{c1} \leq V_{ab}$ and $V_{c2} \leq V_{ab}$

In this section, the behavior of the 2C-CHB converter, when it is operated in a point outside the stable region, is shown. As has been shown in Section III-A, for a fixed total amount of active power exist the minimum active power values that have to be consumed by the loads connected in each cell and the maximum active power values that can be supplied to the cells. In this experiment, the output dc voltage commands are established to 200 V, and the total active power consumed by the converter is set to 2 kW. Fig.11. shows the real and reactive powers of unstable regions

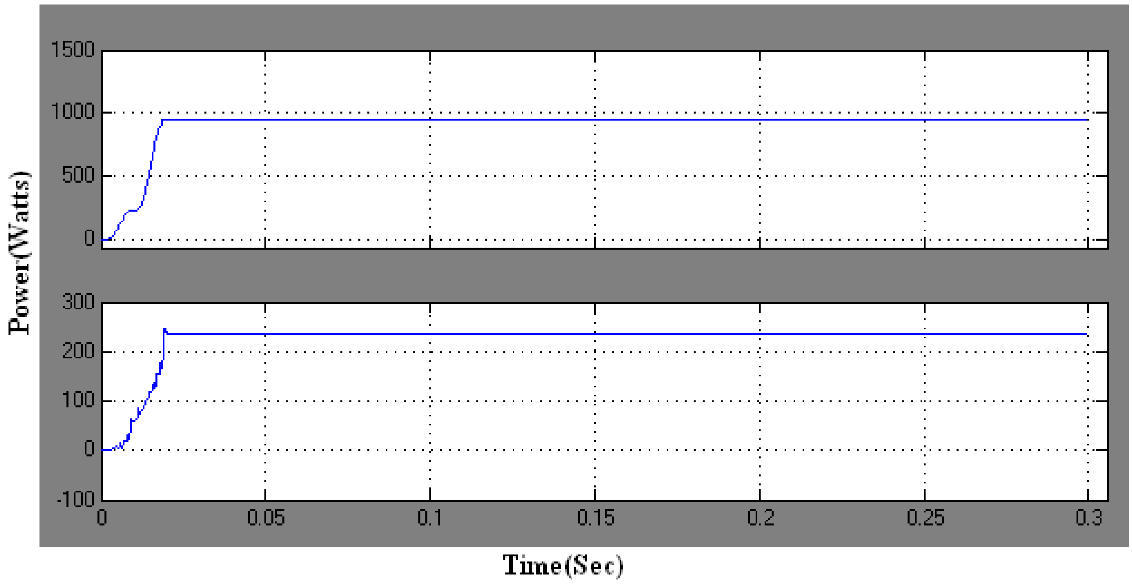

Fig. 11. Real and reactive power

It can be noticed that, for the first load configuration, the converter achieves a stable operation, the dc voltages are stable in the reference commands, and the input current is established in agreement with the output load. When the load step is applied, the converter tries to follow the references; however, as it is working outside the stable region, it is not possible to achieve the commands and the dc voltages change without control. Finally, the converter has to be stopped to avoid a malfunction caused by the input current or by a high output voltage value.

C. Stable Operation with $V_{c1} > V_{ab}$ and $V_{c2} \leq V_{ab}$

When $V_{c1} > V_{ab}$ and $V_{c2} \leq V_{ab}$, the stable region can be split into two areas, depending on the cell power balance. In this experiment, the behavior of the 2C-CHB converter working in both areas is explored. To develop the test, the following steps are applied. In the beginning, both cells are controlled to 200 V, and a resistor of 100 Ω is connected to each cell. When steady state is achieved, the first cell command is changed to 400 V. When the active power is supplied from the second cell; thus, there is an energy transfer from the second cell to the first cell.Fig.12. Shows the real and reactive powers

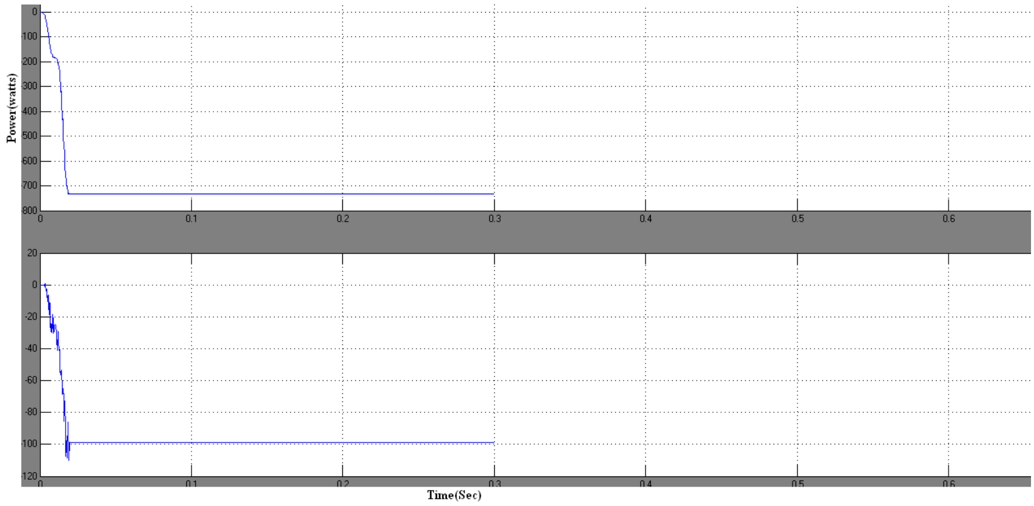

Fig. 12. Real and reactive power

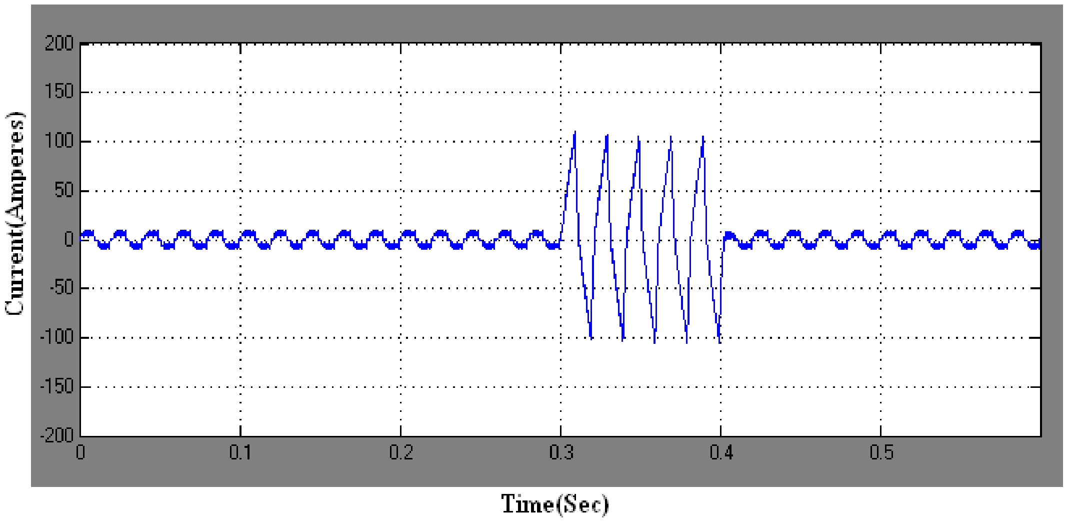

Fig.13. Current through the grid

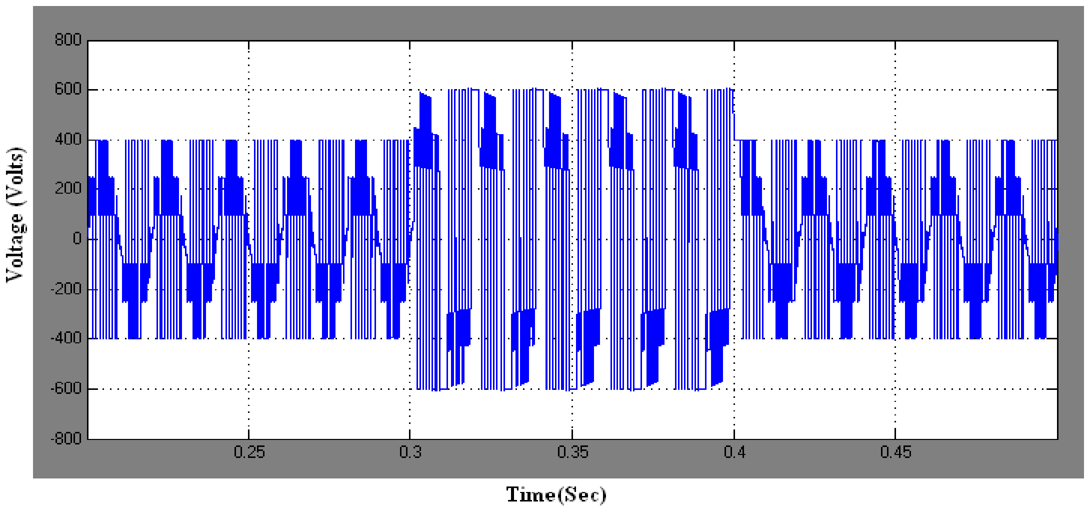

Fig.14. Multi level Inverter output voltage.

V. Conclusion

A CHB power converter is a suitable topology to be used when two or more independent dc voltage values are needed in a synchronous rectifier or back-to-back application. However, some criteria have to be taken into account to achieve a stable converter operation. In this paper, the power balance limits in the cells of a single-phase 2C-CHB power converter have been addressed.

These limits depend on the dc-link voltage values It is shown that, under certain conditions, it is possible to have opposite sign active power values simultaneously in both cells. Moreover, to have a stable operation, it is necessary to ensure that, for a total amount of active power supplied to the 2C-CHB, both cell loads are between the maximum and minimum allowed. Finally, simulation results are introduced, validating that the presented analysis is an appropriate tool to establish the design criteria for the 2C-CHB synchronous rectifier or back-to-back application.

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