Circulating Current Produced in a System of Two Inverters Connected in Parallel

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Abstract—This paper analyzes the imbalances that produce circulating current in a system of two three-phase Voltage Source Inverters (VSI) with Space Vector Pulse Width Modulation (SVPWM) that, sharing the same DC link, is connected to a balanced three-phase load without galvanic isolation. This analysis has identified two principal imbalances: the difference between the dead times of the two inverters, and the difference between the zero-vector parameters of the two inverters. The first imbalance studied in this paper is generic and can occur in any system of parallel connected inverters. The second imbalance studied in this paper is specific to the space-vector modulation. The study proposes the correction of the imbalances by measurement algorithms and Proportional Integral Control (using the Ziegler Nichols method to tune the controller), in order to reduce or eliminate the circulation current and increase system performance, when the imbalances act independently. It provides a method that does not use an equivalent circuit or a model, determining the value of the imbalance directly and through a system output signal.

Keywords—Inverter, Voltage-Source Inverter (VSI), Space Vector Pulse Width Modulation (SVPWM), Isolated-Gated Bipolar Transistor (IGBT), Circulating Current, Dead-Time, Zero-Vector Parameter, Proportional-Integral (PI), Digital Signal Processor (DSP).

I. INTRODUCTION

The performance improvement in energy conversion from renewable sources for domestic and industrial uses has focused the efforts of numerous research papers. [1-5]. The parallel connection of inverters allows the most efficient generation profile of each inverter throughout the day to be taken advantage of. The non-isolated connection to the grid or to a load is yet another of the more encouraging points to achieve such an improvement [6-9].

The simplest way to connect inverters in parallel is by using transformers whose outputs are connected together to a load or the electric grid [2]. But this type of connection has such disadvantages as the cost and size of the transformers. It also causes some losses. In order to avoid these drawbacks, the inverters are connected directly, without transformers [21].

When two parallel inverters are attached without galvanic isolation, an internal circulation current may appear [10]. This current means a loss in the system performance, the appearance of DC currents in the inverters and, consequently, a malfunction of the entire system. These phenomena appear when there are differences that cause imbalances between the homologous output voltages of the two inverters [23-31].

II. SYSTEM MODELING

The study has been carried out on a system consisting of two three-phase inverters sharing the same DC input link and connected in parallel to a balanced three-phase resistive load without galvanic isolation, as shown in Fig. 1. The inverters are VSI [2,17], with SVPWM modulation [9,15,21,28,32-33]. It is usually possible to connect different power inverters, so each one can operate at its maximum power performance. In our study, both inverters have the same power performance, and the output voltage of the system is regulated to a constant value.

Fig.1 : System formed by two VSI inverters under study with SVPWM modulation.

Fig.2 : Representation of IGBTs and antiparallel diodes of the phase “a”.

Table I and Table II list the characteristic analyzed variables for the circuit of Fig. 1 and in Table II, the values of the magnitudes and the components used in the subsequent experimental analysis are specified.
TABLE I
CHARACTERISTIC ANALYZED VARIABLES IN THE STUDY

<table>
<thead>
<tr>
<th>Magnitude (unit)</th>
<th>Description</th>
<th>Value (unit)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Va1, Vb1, Vc1 (V)</td>
<td>Output voltages of phases &quot;a&quot;, &quot;b&quot; and &quot;c&quot; of the inverter 1.</td>
<td></td>
</tr>
<tr>
<td>Va2, Vb2, Vc2 (V)</td>
<td>Output voltages of phases &quot;a&quot;, &quot;b&quot; and &quot;c&quot; of the inverter 2.</td>
<td></td>
</tr>
<tr>
<td>Va, Vb, Vc (V)</td>
<td>Load voltages of the phases &quot;a&quot;, &quot;b&quot; and &quot;c&quot;</td>
<td></td>
</tr>
<tr>
<td>Ia1, Ib1, Ic1 (A)</td>
<td>Output currents of phases &quot;a&quot;, &quot;b&quot; and &quot;c&quot; of the inverter 1.</td>
<td></td>
</tr>
<tr>
<td>Ia2, Ib2, Ic2 (A)</td>
<td>Output currents of phases &quot;a&quot;, &quot;b&quot; and &quot;c&quot; of the inverter 2.</td>
<td></td>
</tr>
<tr>
<td>Ia, Ib, Ic (A)</td>
<td>Load currents of phases &quot;a&quot;, &quot;b&quot; and &quot;c&quot;.</td>
<td></td>
</tr>
<tr>
<td>ICIR (A)</td>
<td>Circulating current of the system</td>
<td></td>
</tr>
<tr>
<td>Td1 (µsec)</td>
<td>Dead-time applied to the inverter 1.</td>
<td></td>
</tr>
<tr>
<td>Td2 (µsec)</td>
<td>Dead-time applied to the inverter 2.</td>
<td></td>
</tr>
<tr>
<td>ΔTd (µsec)</td>
<td>Difference between dead-times (Td1-Td2)</td>
<td></td>
</tr>
<tr>
<td>K1</td>
<td>Zero-vector parameter of the inverter 1.</td>
<td></td>
</tr>
<tr>
<td>K2</td>
<td>Zero-vector parameter of the inverter 2.</td>
<td></td>
</tr>
<tr>
<td>ΔK</td>
<td>Difference between the zero-vector parameters (K1-K2)</td>
<td>0.1 Ω</td>
</tr>
</tbody>
</table>

TABLE II
VALUES OF THE MAGNITUDES AND COMPONENTS USED IN THE EXPERIMENTAL ANALYSIS

<table>
<thead>
<tr>
<th>Magnitude (unit)</th>
<th>Description</th>
<th>Value (unit)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vdc</td>
<td>DC-Link</td>
<td>250 V</td>
</tr>
<tr>
<td>L_Link</td>
<td>Common Input link inductance of the system</td>
<td>500 µH</td>
</tr>
<tr>
<td>L_Link1</td>
<td>Link inductance of the inverter 1.</td>
<td>20 µH</td>
</tr>
<tr>
<td>L_Link2</td>
<td>Link inductance of the inverter 2.</td>
<td>20 µH</td>
</tr>
<tr>
<td>C_Link1</td>
<td>Link capacitor of the inverter 1.</td>
<td>600 µF</td>
</tr>
<tr>
<td>C_Link2</td>
<td>Link capacitor of the inverter 2.</td>
<td>600 µF</td>
</tr>
<tr>
<td>Ra1, Rb1, Rc1</td>
<td>Parasitic line resistor for phases &quot;a&quot;, &quot;b&quot; and &quot;c&quot; of the inverter 1.</td>
<td>0.5 Ω</td>
</tr>
<tr>
<td>Ra2, Rb2, Rc2</td>
<td>Parasitic line resistor for phases &quot;a&quot;, &quot;b&quot; and &quot;c&quot; of the inverter 2.</td>
<td>0.5 Ω</td>
</tr>
<tr>
<td>La1, Lb1, Lc1</td>
<td>Line inductance for phases &quot;a&quot;, &quot;b&quot; and &quot;c&quot; of the inverter 1.</td>
<td>1.0 mH</td>
</tr>
<tr>
<td>La2, Lb2, Lc2</td>
<td>Line inductance for phases &quot;a&quot;, &quot;b&quot; and &quot;c&quot; of the inverter 2.</td>
<td>1.0 mH</td>
</tr>
<tr>
<td>C</td>
<td>Output capacitor phases &quot;a&quot;, &quot;b&quot; and &quot;c&quot;.</td>
<td>25 µF</td>
</tr>
<tr>
<td>RL</td>
<td>Load resistor for phases &quot;a&quot;, &quot;b&quot; and &quot;c&quot;.</td>
<td>2 Ω</td>
</tr>
<tr>
<td>VCESAT</td>
<td>IGBT collector-emitter saturation voltage</td>
<td>2.5 V</td>
</tr>
<tr>
<td>Vth</td>
<td>Threshold voltage of the antiparallel diodes</td>
<td>0.7 V</td>
</tr>
<tr>
<td>RON,IGBT</td>
<td>IGBT ON-Resistor</td>
<td>0.1 Ω</td>
</tr>
<tr>
<td>RON,OD</td>
<td>Antiparallel diodes ON-Resistor</td>
<td>0.1 Ω</td>
</tr>
<tr>
<td>Fs</td>
<td>Carrier frequency</td>
<td>10 KHz</td>
</tr>
<tr>
<td>Ts</td>
<td>Period of the carrier component</td>
<td>10² sec</td>
</tr>
<tr>
<td>Fc</td>
<td>Fundamental frequency</td>
<td>50 Hz</td>
</tr>
<tr>
<td>Tc</td>
<td>Period of the fundamental component</td>
<td>2 x 10² sec</td>
</tr>
<tr>
<td>V0_reg</td>
<td>RMS output voltage</td>
<td>65 V</td>
</tr>
</tbody>
</table>

III. ORIGIN OF THE CIRCULATING CURRENT

In Fig. 1, one of the paths of phase "a" that connects the output of the inverters with the input DC link is marked. Similarly, it is possible to identify all the paths of the circuit. These paths allow the circulation of internal currents, which supposes power losses in each of the inverters connected in parallel. These currents are defined as "circulating currents" [10,23-29,31]. A difference between the voltages of the homologous outputs is also necessary to produce circulating current inside in the path of the current flow.

In the three-phase system of Fig. 1, the equation defining the circulating current is ICIR (1):

\[
ICIR = \frac{(Ia_1 - Ia_2) + (Ib_1 - Ib_2) + (Ic_1 - Ic_2)}{2}
\]  

There are two ways to eliminate the circulation current. The first is by breaking the return paths, using, for example, transformers (which is not the case of the present study). The second is by eliminating the voltage differences between homologous outputs.

It has been examined two phenomena that cause imbalances between homologous outputs of the inverters, which in turn cause the appearance of circulating currents:

- The difference between the dead-times of the two inverters [11-20,37].
- The difference between the zero-vector parameters of the two inverters [26-28].

The first phenomenon affects every system consisting of two or more parallel connected inverters without galvanic isolation, regardless of the type of modulation used. The second one is specific to the SVPWM modulation. The study proposes methods to monitor and correct imbalances, and also to eliminate the caused circulating current.

IV. EFFECT OF THE DIFFERENCE BETWEEN THE DEAD-TIMES

The non-ideal nature of the power electronic devices, such as the IGBTs and the diodes, the poles of the inverters, need the presence of small delays in the activation of the control signals to prevent short circuits in the input DC link. These time delays applied on the rising edge of the control signals are defined as "dead-times" [11-20,37].

Generally, the difference between the dead-times of the two inverters connected in parallel without galvanic isolation is due mainly to the different power ratings which inverters operate with, so they both have different dead-time references. Even when the two inverters operate at the same nominal power, the lack of synchronization or manufacturing tolerances of the components causes differences in the dead-times of each inverter.

There are many studies and bibliography on the effects of the dead-times on the imbalances and distortions in the output currents for both single-phase and three-phase inverters, working independently or connected to another inverters [12, 14, 16, 18, 19].

The present paper provides a method that does not use an equivalent circuit or a model, and determines how to obtain the value of the current imbalance which causes circulation current directly and through a system output signal.

In order to study the system shown in Fig. 1, we suppose it has applied different dead-times, i.e.: Td1≠ Td2. Analyzing one of the phases (phase "a"), and following the diagram of Fig. 2, in Fig. 3, and for the case of Td1<Td2, the activation signals and the difference between the voltages "Va1" and "Va2", when the direction of the
current "I_a" is negative (Fig. 3-a) or positive (Fig. 3-b) has been represented. Similarly, Fig. 4 shows the same signals for the case of Td1<Td2, when the direction of the current "I_a" is negative (Fig. 4-a) or positive (Fig. 4-b). In all figures, six "conduction zones" (numbered from 0 to 5) are identified. Table III identifies the corresponding devices that conduct current through each zone, for the case of Td1<Td2. Table IV identifies the corresponding devices that conduct current through each zone, for the case of Td1>Td2. For Td1<Td2, as for Td1>Td2, (Va1-Va2) are both a square pulse signal whose pulses are repeated "h" times in the period of the fundamental frequency (Ts = 1/Fs).

The pulses have an amplitude equal to "Vdc", so that, in one half cycle, they will have a sign, and, in the other half cycle, they will have the opposite sign. The value "h" is calculated according to (2):

\[ h = \frac{F_s}{F_c} \]  

The root-mean-square of (Va1-Va2) is (3):

\[ \text{rms}(\text{Va1}(t) - \text{Va2}(t)) = \sqrt{\frac{1}{T_c} \int_{0}^{T_c} (\text{Va1}(t) - \text{Va2}(t))^2 dt} = \frac{1}{T_c} \left( \frac{F_s}{F_c} \right) Vdc^2 |\Delta Td| = Vdc \cdot \sqrt{\frac{F_s}{F_c} |\Delta Td|} \]

where \( \Delta Td = (Td1 - Td2) \). Therefore, the value of \( |\Delta Td| \) is (4):

\[ |\Delta Td| = \left| Td1 - Td2 \right| = \frac{\text{rms}(\text{Va1}(t) - \text{Va2}(t))^2}{Vdc \cdot F_s} \]

That is, if we calculate the RMS value of (Va1-Va2), it is possible to calculate the absolute value of the difference between the dead-times of the two inverters. Regarding the sign of the difference of the dead times, we can observe:

- For Td1<Td2, the first harmonic of "I_a" is always delayed with respect to the first harmonic of the difference of the homologous output voltage.
- For Td1>Td2, the first harmonic of "I_a" is always forwarded with respect to the first harmonic of the difference of the homologous output voltage.

To calculate the sign of \( \Delta Td \) and for the phase "a", the proposed method analyzes the difference between the first harmonic of "I_a" and the first harmonic of the difference between "Va1" and "Va2". "I_a" is considered to be the reference signal. When "I_a" passes through zero it analyzes, on the one hand, if its slope is positive or negative, and, on the other, if the value of (Va1-Va2) is above or below zero.

![Fig. 3: Activation signal and difference (Va1-Va2) for Td1<Td2.](image)

![Fig. 4: Activation signal and difference (Va1-Va2) for Td1>Td2.](image)

**Table III**

<table>
<thead>
<tr>
<th>Zone</th>
<th>Negative direction of &quot;I_a&quot;</th>
<th>Positive direction of &quot;I_a&quot;</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Inverter 1</td>
<td>Inverter 2</td>
</tr>
<tr>
<td>0</td>
<td>SC</td>
<td>SC1</td>
</tr>
<tr>
<td>1</td>
<td>DS</td>
<td>DS1</td>
</tr>
<tr>
<td>2</td>
<td>DS</td>
<td>DS1</td>
</tr>
<tr>
<td>3</td>
<td>DS</td>
<td>DS1</td>
</tr>
<tr>
<td>4</td>
<td>SC</td>
<td>DS1</td>
</tr>
</tbody>
</table>

**Table IV**

<table>
<thead>
<tr>
<th>Zone</th>
<th>Negative direction of &quot;I_a&quot;</th>
<th>Positive direction of &quot;I_a&quot;</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Inverter 1</td>
<td>Inverter 2</td>
</tr>
<tr>
<td>0</td>
<td>SC</td>
<td>SC1</td>
</tr>
<tr>
<td>1</td>
<td>DS</td>
<td>DS1</td>
</tr>
<tr>
<td>2</td>
<td>DS</td>
<td>DS1</td>
</tr>
<tr>
<td>3</td>
<td>DS</td>
<td>DS1</td>
</tr>
<tr>
<td>4</td>
<td>DS</td>
<td>SC1</td>
</tr>
</tbody>
</table>

![Fig. 5: Block diagram and proposed control for a difference between of the dead-times of two inverters.](image)
With this information, we can know if "Ia" is delayed or forwarded with reference to the signal (Va1-Va2), and consequently, the sign of ΔTd. Now we know the absolute value and the sign of ΔTd, the PI control is applied [22-23,25,37-38] acting on a module that establishes the dead-time value of the second inverter (Td2). Thus, the difference between the dead-times is eliminated, and consequently the imbalance which causes the appearance of the circulating current is also eliminated. Fig.5 shows the block diagram of the system analyzed.

V. EFFECT OF THE DIFFERENCE BETWEEN THE ZERO-VECTOR PARAMETERS

When SVPWM modulation is used for generating control signals in a three-phase inverter, it is a common practice to apply a factor or parameter that distributes the width of the zero vectors. This method, defined as "alternating zero-vectors", maintains the properties of the modulation and eliminates disturbances in SVPWM sequence generation. The parameter that allows the sequence of zero-vectors to be distributed is defined as "K" [21-22, 26-28,32-34].

Fig. 6 shows the diagram of control signals for the upper poles of the phases "a", "b" and "c" of an inverter with SVPWM modulation when the parameter "K" is applied.

The values of the parameters "d_1", "d_2", "d_0" and "k" shown in Fig.6 are defined in (5), (6), (7) and (8).

\[
d_1 = M \frac{\sqrt{3}}{2} \sin\left(\frac{n\pi}{3} - \theta(t)\right)
\]

\[
d_2 = M \frac{\sqrt{3}}{2} \sin(\theta(t) - (n-1)\frac{\pi}{3})
\]

\[
d_0 = 1 - M \frac{\sqrt{3}}{2} \left[\sin\left(\frac{n\pi}{3} - \theta(t)\right) + \sin(\theta(t) - (n-1)\frac{\pi}{3})\right]
\]

\[
k = K * d_0 = K \left\{1 - M \frac{\sqrt{3}}{2} \left[\sin\left(\frac{n\pi}{3} - \theta(t)\right) + \sin(\theta(t) - (n-1)\frac{\pi}{3})\right]\right\}
\]

where "K" is the zero-vector parameter (which varies between 0 and 1, and its typical value is 0.5), "n" represents the sector, "\theta(t)" the angle that the modulating signal describes, and "M" the modulation index.

In the same way as in the previous case, the difference between the zero-vector parameters of two inverters connected in parallel without galvanic isolation is often due to the different nominal power of each inverter. Even when the two inverters operate at the same power rating, the overall impossible similarity between the two systems results in differences in effective K values of these inverters. There have been many studies on the effects of the zero-vector parameter on the emergence of imbalances and the appearance of internal circulating current phenomena [26-28].

For the circuit of Fig. 1, we suppose that the zero-vector parameter K1 for the inverter 1, and the zero-vector parameter K2 for the inverter 2 are applied, where K1 ≠ K2. Fig. 7 shows the activation signals and the difference voltage (Va1-Va2) for K1<K2 (Fig. 7-a) and for K1> K2 (Fig. 7-b). In these figures, we have identified three "conduction zones" (numbered from 0 to 2). Table V identifies the devices that conduct current for K1<K2, also with negative or positive direction of the load current, in each of the zones. Table VI identifies the devices that conduct current for K1> K2, also with negative or positive direction of the load current, in each of the zones. For the case K1<K2, also for the case K1> K2, the difference of voltages (Va1-Va2) is independent of the direction of the carrier signal, having a width defined in (9):

\[
\Delta w = |\Delta K*T_s*d_0|
\]

where \(\Delta K = (K1-K2)\). Therefore, the signal (Va1-Va2) is a pulsed signal.

The pulse height value is named “Vdc” and the width value is directly proportional to the signal d_0 (7), which is not a constant value. However, if the approximation that d_0 is constant and equal to its mean value (\(\overline{d_0}\)) is performed, we can accept that:

\[
\frac{(\overline{Va1(t)}-Va2(t))}{T_c} = \frac{1}{T_s} * Vdc * \Delta K * \overline{d_0} * \frac{T_c}{T_s} = Vdc * \overline{d_0} * \Delta K
\]

Therefore, the value of \(\Delta K\) is (11):

\[
\Delta K = \frac{(\overline{Va1(t)}-Va2(t))}{d_0 * Vdc}
\]

With this \(\Delta K\) definition, and applying the PI control [22-23,25,38], the value of K2 can be corrected and, consequently, we can eliminate the imbalance which causes the appearance of the circulating current. Fig. 8 shows the analyzed circuit, with the applied PI control and the correction system over K2.
VI. SIMULATION RESULTS

We have performed the simulation using the formulation explained before. The models have been implemented in “PSIM” (Professional Version 9.0.3.400). Considerations included are that both inverters work ideally and simultaneously, and there are not tolerances in the passive components. The imbalances have been introduced in the inverter 2 so control signals have been fed into inverter 2. The output voltage of the system has been regulated (“V0_reg”) and, in addition, we use this value as a reference of the SVPWM signal generation of the two inverters. The PI controller tuning has been performed using the Ziegler-Nichols method, verifying the system’s stability with the corresponding Bode analysis. The simulation is performed in the sampling period of 1 μsec, with an analysis time horizon of 0.2 sec.

A. Experimental Results for the case “Difference Between Dead-Times”.

The results displayed below have been obtained for two different cases: for Td1<Td2 (Fig. 9) and Td1>Td2 (Fig. 10). For the first case, the simulation was performed with Td1=2 μsec and Td2=6 μsec. For the second case, the simulation was performed considering Td1=4 μsec and Td2=2 μsec. Figs. 9-a, 9-b, 10-a, and 10-b show the graphs of “ICIR”, “Ia1”, and “Ia2”, when the system works freely. Figs. 9-c, 9-d, 10-c, and 10-d show the same magnitudes when the proposed control and correction is applied.
B. Experimental Results for the Case of a Difference Between the Zero-Vector Parameters.

The results displayed below have been obtained for two different cases: for \( K_1 > K_2 \) (Fig. 11) and \( K_1 < K_2 \) (Fig. 12). Specifically, for the first case, the simulation was performed with \( K_1 = 0.5 \) and \( K_2 = 0.3 \). For the second case, the simulation was performed for \( K_1 = 0.5 \) and \( K_2 = 0.8 \). Figs. 11-a, 11-b, 12-a, and 12-b show the graphs of "ICIR", "Ia1", and "Ia2", when the system works freely. Figs. 11-c, 11-d, 12-c, and 12-d show the same magnitudes when applying the proposed control and correction. The method proposed in the present paper obtains the imbalance directly from the system and through the difference of the homologous output voltages of the two inverters, without using an equivalent model. This is a simple method which requires little processing power and obtains controlled signals rapidly.

Table VIII collects the data input and the output power, and the performance of the system, for the two cases analyzed. It should be noted that the reduction of the circulating current increases the system performance. For the first case, in which the initial difference between the zero-vector parameters was 0.2, a performance improvement of 5.36% has been obtained. For the second case, in which the difference between the zero-vector parameters was 0.3, a performance improvement of 10.80% has been obtained. These enhancement values are very significant because any slight variation between the zero vector parameters of both inverters generates not only harmonic components at multiples of the fundamental frequency, but also continuous components in the output currents and in the circulation current, with non-negligible values. The use of control eliminates them and substantially increases the performance.

VII. CONCLUSION

This paper has proposed methods to allow a correction action on one inverter, connected in parallel to another, in order to eliminate the circulation current and thereby increase system performance to the maximum possible value, in case of an imbalance in the dead-times, or in the zero-vector parameters. The proposed procedures are not excessively complex and do not need a high processing capacity. The proposed methods have been validated by quasi-functional simulation, based on a simulator already validated with prototypes of previous inverters.

REFERENCES


