Modulation Techniques to Eliminate Leakage Currents in Transformerless Three-Phase Photovoltaic Systems

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Abstract—In some photovoltaic (PV) applications, it is possible to remove the transformer of a system in order to reduce losses, cost, and size. In transformerless systems, the PV module parasitic capacitance can introduce leakage currents in which the amplitude depends on the converter topology, on the pulsedwidth modulation, and on the resonant circuit comprised by the system components. Based on the common-mode voltage model, modulation techniques are proposed to eliminate the leakage current in transformerless PV systems without requiring any modification on the converter and any additional hardware. The main drawback is that the proposed modulation technique for two-level inverters can only be used with 650-V dc link in the case of a 110-V (rms) grid phase voltage. Comparisons among the modulation techniques are discussed, and it is proven that the proposed modulation for two- and three-level inverters presents the best results. To validate the models used in the simulations, an experimental three-phase inverter is used.

Index Terms—Energy conversion, photovoltaic (PV) power systems, pulsedwidth-modulated power converters.

I. INTRODUCTION

PHOTOVOLTAIC (PV) power systems have become more widespread in the world. Most of these systems are single-phase installations [1], [2]. However, in single-phase systems, there is a pulsating ac power on the output, and large dc capacitors are required. In three-phase systems, there is a constant ac power on the output, and small dc capacitors can be used, improving the reliability and the lifetime of the systems [3]. Most of the topologies for PV systems have a transformer that adjusts the dc voltage input for the inverter and isolates the PV panels from the grid. The transformer can be used in line or high frequency, but the line-frequency transformer has large size and weight. The high-frequency transformer is used in PV systems with some stages, decreasing the efficiency and making the system more complex [3]–[5].

Topologies without a transformer generally have lower cost, size, and weight than topologies with transformers. The main disadvantage is the connection of the PV array to the grid without galvanic isolation, which rises the leakage current through the parasitic capacitance of the PV array. Due to this capacitance and depending on the inverter topology and the switching strategy, fluctuations of the potential between the PV array and the ground can appear. These fluctuations inject a capacitive leakage current, and this current can cause grid current distortion, losses in the system, and safety problems [3]. This inductance is sufficient to make the potential oscillate with high frequency and the leakage currents increase, having higher values than that recommended in standards. Without connection, high currents also appear because of the conventional pulsedwidth modulation (PWM), and three-phase inverters are not suitable for transformerless PV applications.

Based on the common-mode (CM) voltage, some techniques to reduce the CM currents in motor drives were discussed in [6] and [7]. Depending on the choice of voltage vectors, the reduced CM voltage techniques can be grouped in two types [7]: remote-state PWM (RSPWM) [6] and active zero-state PWM (AZSPWM). In RSPWM, the output voltage is synthesized from three active vectors. In AZSPWM, two active vectors are complimented with two opposing active vectors with equal time to create a zero vector.

In this paper, RSPWM techniques are proposed to eliminate the leakage current in the conventional three-phase inverter for PV applications. In RSPWM, the maximum amplitude of the phase-to-neutral voltages is reduced, but it does not require any modification on the converter and any additional hardware. Using Matlab/Simulink, comparisons of the leakage currents for three-phase PWM techniques are discussed, and it is proven that the PWM proposed for three-phase inverters presents the best results. To validate the models used in the simulations, an experimental inverter is used in a three-phase setup to evaluate the leakage currents.

On the other hand, in PV systems where series PV arrays are connected to a conventional two-level inverter, the occurrence of partial shades and the mismatching of the arrays lead to a reduction in the generated power [8], [9]. To overcome these problems, the connection of the arrays can be made using a
multilevel converter [10]–[12]. The multilevel converter maximizes the power obtained from the arrays, reduces the device voltage stress, and generates a lower output voltage harmonic distortion [10]. The CM voltage model for two-level inverters can also be applied to multilevel inverters. Using the proposed PWM (with constant CM voltage) for three-level inverters guarantees low leakage currents with a gain of 50% of the maximum amplitude of the voltages in relation to two-level inverters with the RSPWM. Therefore, the proposed PWM is specially suitable if three-level inverters are used.

II. LEAKAGE CURRENTS IN THREE-PHASE TRANSFORMERLESS PV SYSTEMS

Without a transformer, there is a galvanic connection of the grid and the dc source, and, thus, a leakage current appears. For the transformerless grid-connected system in Fig. 1(a), a resonant circuit is created if the PV array is grounded [3], [4]. This resonant circuit includes the PV array stray capacitance (\(C_{PV}\)), the filter and grid inductances (\(L\)), the inverter stray capacitances (\(C\)), and the inductance between the ground connection of the inverter and the grid (\(L_G\)). The magnitude of the PV array leakage capacitance depends on the weather conditions, changing from nanofarads up to microfarads [5]. Therefore, the leakage current can reach high values, becoming an important issue in transformerless PV systems. The model of a three-phase grid-connected PV inverter is shown in Fig. 2.

In the case of a three-phase system, the CM and differential-mode (DM) voltages are derived between each phase, resulting in three cases [3]: case 1 (CM and DM voltages for phases A and B), case 2 (CM and DM voltages for phases B and C), and case 3 (CM and DM voltages for phases C and A). Only case 1 is shown in the calculation because the other two cases are similar. The CM (\(V_{CM-AB}\)) and DM (\(V_{DM-AB}\)) voltages for phases A and B can be defined as

\[
V_{CM-AB} = \frac{V_{AN} + V_{BN}}{2} \quad (1)
\]

\[
V_{DM-AB} = V_{AN} - V_{BN} \quad (2)
\]

where \(V_{AN}\) and \(V_{BN}\) are the voltages between the inverter outputs and the negative terminal of the PV array.

Using (1) and (2), the inverter outputs can be expressed as

\[
V_{AN} = \frac{V_{DM-AB}}{2} + V_{CM-AB} \quad (3)
\]

\[
V_{BN} = -\frac{V_{DM-AB}}{2} + V_{CM-AB} \quad (4)
\]

A model for the system can be developed using (3) and (4) as shown in Fig. 3. Since the CM voltage is present in both legs, the circuit in Fig. 3(a) can be modified as shown in Fig. 3(b). The influence of the output inductors and the inverter stray capacitances can be separated as shown in Fig. 4(a). A system modeling using different output inductances was developed in [3]. In this paper, it is considered that the output inductances of the three phases are identical. Considering that the inverter stray capacitances are also identical, the model can be simplified as shown in Fig. 4(b). It can be observed in Fig. 4(b) that the leakage current can be attenuated or eliminated by the control of the CM voltage. Therefore, in a balanced system, the DM does not contribute for the leakage currents in the PV system.

To understand how to link the simplified two-phase circuit (case 1) with a final model for the three-phase system, the equivalent model shown in Fig. 5 is used. This figure can be used because the same development made for phases A and B...
TABLE I

<table>
<thead>
<tr>
<th>( S_a )</th>
<th>( S_b )</th>
<th>( S_c )</th>
<th>Vector</th>
<th>( V_{CM} )</th>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>( V_0 )</td>
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<td>1</td>
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<td>0</td>
<td>( V_1 )</td>
<td>( V_{PN}/3 )</td>
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<tr>
<td>1</td>
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<td>0</td>
<td>( V_2 )</td>
<td>( 2V_{PN}/3 )</td>
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<tr>
<td>0</td>
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<td>1</td>
<td>( V_4 )</td>
<td>( 2V_{PN}/3 )</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>0</td>
<td>( V_5 )</td>
<td>( V_{PN}/3 )</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>1</td>
<td>( V_6 )</td>
<td>( 2V_{PN}/3 )</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>( V_7 )</td>
<td>( V_{PN} )</td>
</tr>
</tbody>
</table>

Using (1) and similar equations for cases 2 and 3 in (5), it is possible to write the total CM voltage as

\[
V_{CM} = \frac{V_{CM-AB} + V_{CM-BC} + V_{CM-CA}}{3}. \tag{5}
\]

Table I presents the eight possibilities of the inverter switches and the total CM voltage for the three-phase inverter using (6). It can be seen in Table I that, using SVPWM, the CM voltage will change everytime that a different space vector is used. For example, in sector I, the SVPWM uses the vectors \( V_0, V_1, V_2 \), and \( V_7 \). Therefore, the CM voltage assumes four values: 0, \( V_{PN}/3 \), \( 2V_{PN}/3 \), and \( V_{PN} \) as shown in Fig. 7. The SVPWM has one switching in each vector change, totaling six if the switching pattern is defined in such a way to reduce the harmonic distortion. The output voltage in relation to the central point of the dc link is intentionally modulated with a third harmonic component of the fundamental to increase the voltage in the ac side. The maximum amplitude of the phase-to-neutral voltages is \( V_{PN}/\sqrt{3} \) in the linear region, where the fundamental frequency component in the output voltage varies linearly with the voltage gain.

In the AZSPWM, the active vectors are complimented with two opposing active vectors with equal time to create a zero voltage vector. Depending on the choice of the voltage vectors, the AZSPWM can be grouped in two types [7]: AZSPWM1 and AZSPWM2. The differences between the two types are illustrated in Table II for sectors I, II, and III in Fig. 6. It can be seen in Table I that, using AZSPWM1 or AZSPWM2, the CM voltage will change with high frequency.

<table>
<thead>
<tr>
<th>Techniques</th>
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<th>Sector II</th>
<th>Sector III</th>
</tr>
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<td>7430347</td>
</tr>
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<td>1234221</td>
<td>543242</td>
</tr>
<tr>
<td>AZSPWM2</td>
<td>6213126</td>
<td>4231324</td>
<td>2435342</td>
</tr>
<tr>
<td>RSPWM1</td>
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<td>315135</td>
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</tr>
<tr>
<td>RSPWM2B</td>
<td>426242</td>
<td>426242</td>
<td>24642</td>
</tr>
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</table>

III. MODULATION TECHNIQUES TO ELIMINATE LEAKAGE CURRENTS IN THREE-PHASE INVERTERS

The space-vector PWM (SVPWM) is generally used to control the three-phase inverter output voltages (Fig. 1). The eight possible combinations are composed of six active (\( V_1, V_2, V_3, V_4, V_5, \) and \( V_6 \)) and two zero (\( V_0 \) and \( V_7 \)) vectors of voltage (Fig. 6). In the SVPWM, the plane is divided in six sectors, delimited by the active vectors. The zero and active vectors that define the sector, where the reference is placed, are used to comprise, in average values, the reference voltage vector.

A. Proposed Modulation

RSPWM eliminates the high frequency components of the CM voltage. The technique consists in using only the odd active vectors or only the even active vectors to comprise the reference. Therefore, \( V_1, V_3, \) and \( V_5 \) are used in the case of choosing the odd vectors, and \( V_2, V_4, \) and \( V_6 \) are used in the
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The RSPWM presents two switchings in each vector change, and the switching pattern to reduce the harmonic distortion (eight switchings per period) is used. The maximum amplitude of the phase-to-neutral voltages is $V_{PN}/3$, which is 57.7% of the voltages that can be obtained with the SVPWM. However, applying the RSPWM is the only condition in which the leakage currents have low values.

Another pattern (RSPWM3) can be applied using odd or even active vectors depending on the place of the reference vector [7]. For example, the vectors $V_1$, $V_3$, and $V_5$ are used within $-30^\circ$ and $30^\circ$ (last $30^\circ$ of sector VI and first $30^\circ$ of sector I). The vectors $V_2$, $V_4$, and $V_6$ are used within $30^\circ$ and $90^\circ$ (last $30^\circ$ of sector I and first $30^\circ$ of sector II). Using this pattern, the maximum amplitude of the phase-to-neutral voltages is $2V_{PN}/(3\sqrt{3})$, which is 15.5% higher than the amplitude that can be obtained with the RSPWM1 or RSPWM2. For the RSPWM3 technique, the CM voltage during a fundamental period is shown in Fig. 9.

B. Simulation Results

The simulations were done in Matlab/Simulink using the three-phase setup shown in Fig. 10. The grid voltages have values of 110 V (rms), and the output inductance is $L = 1.8$ mH.

The PV array was simulated with a dc voltage source of 650 V. The leakage capacitance between the cells and the grounded one was modeled with a simple capacitance between the PV array terminals and the ground. This capacitance ($C_{PV}$) has a value of 220 nF, and the ground resistance ($R_G$) is 10.75 Ω.

The results in Figs. 11(a) and 12(b) show the leakage impedance voltage and current ($v_L$ and $i_L$ in Fig. 10) for different techniques. The SVPWM and AZSPWM techniques to reduce the CM currents in motor drives [7] are not suitable for transformerless PV applications, as shown in Fig. 11(a) and (b). The RSPWM techniques [Fig. 12(a) and (b)] present the best results for three-phase inverters because, using the SVPWM and AZSPWM techniques, the PV array terminals are varying between different levels with the switching frequency,
Fig. 12. Simulated leakage impedance voltage and current of the three-phase PV inverter: (a) RSPWM1 and (b) RSPWM3.

which would generate high leakage currents. During the transitions between the two levels of the CM voltage in RSPWM3 [Fig. 12(b)], there are some fluctuations in this voltage caused by the components of the system. Therefore, the RSPWM1 and RSPWM2 techniques are preferred in relation to eliminate the leakage currents.

The results in Fig. 13(a) and (b) show the grid currents ($i_A$, $i_B$, and $i_C$ in Fig. 10) for the SVPWM and RSPWM techniques. The switching frequency was set to 10 kHz in SVPWM and 7.5 kHz in RSPWM in such a way to keep the same switching count. The drawback of the RSPWM1 and RSPWM2 is that the space vector will rotate within the triangle described by $V_1 - V_3 - V_5$ or $V_2 - V_4 - V_6$, and this circle has a radius that is 50% of the dc-link voltage. However, it is shown in Fig. 13(b) that, using RSPWM, it is possible to inject a sinusoidal current into the three-phase grid (110 V) with 650 V in the dc link. In this case, the PV array has a $V_{MPP}$ (maximum power point voltage) of 650 V with a $V_{OC}$ (open circuit voltage) of 800 V.

The comparison results of the PWM techniques are shown in Tables III and IV. In the tables, the techniques are compared considering the following: switchings per period ($T_s$), maximum amplitude voltage, CM voltage, leakage current, and total harmonic distortion (THD) that is defined as

$$THD = \sqrt{\frac{\sum_{h=2}^{\infty} F_h^2}{F_1^2}} \times 100\%$$

where $F$ is the rms value of the inverter output voltage or current and $h$ is each frequency component. Two possibilities are shown in Tables III and IV for the THD calculation: $THD_{20}$ means that only the harmonics up to 20 were considered, and $THD_{200}$ means that harmonics up to 200 were considered. It is worthwhile to mention that the SVPWM has superior performance for $THD_{200}$, but the analysis of $THD_{20}$, which takes into account only the lower order harmonics, shows that the

<table>
<thead>
<tr>
<th>TABLE III</th>
<th>COMPARISON RESULTS FOR THE SVPWM AND AZSPWM TECHNIQUES</th>
</tr>
</thead>
<tbody>
<tr>
<td>$THD_{20}$ voltage</td>
<td>0.59</td>
</tr>
<tr>
<td>$THD_{200}$ voltage</td>
<td>63.52</td>
</tr>
<tr>
<td>$THD_{20}$ current</td>
<td>0.77</td>
</tr>
<tr>
<td>$THD_{200}$ current</td>
<td>4.43</td>
</tr>
<tr>
<td>Switchings</td>
<td>6</td>
</tr>
<tr>
<td>Amplitude</td>
<td>Variable</td>
</tr>
<tr>
<td>CM voltage</td>
<td>High</td>
</tr>
<tr>
<td>Leakage Current</td>
<td>High</td>
</tr>
</tbody>
</table>
RSPWM and SVPWM techniques have similar performance. As the modulation techniques suggested for the inverter are both linear, the low-frequency THD is expected to be low in both cases. It is the harmonic content at the switching and higher frequencies which mainly determines the current ripple and also the power efficiency of the modulation technique. The RSPWM3 presents the variable (low frequency) CM voltage resulting in low leakage current but with spikes in the transitions of the CM voltage.

C. Losses Calculation

A study of losses is presented, and the methodology is used to compare the SVPWM and RSPWM techniques for grid-connected PV systems. The losses produced in switching devices consist mainly of conduction and switching losses. The technique used in this paper is based on the following methodology: Build the loss tables from the results in the data sheets; generate the loss equations; introduce these models into a simulation program for the PWM converter; and calculate the losses for a complete cycle of operation. This methodology allows comparing the losses of the converters by simulation.

Conduction losses for a switch or a diode can be calculated by

\[ E_C = U_C \cdot I_C \cdot t_C \]  

(8)

where \( E_C \) is the conduction energy, \( U_C \) is the conduction voltage, \( I_C \) is the collector current, and \( t_C \) is the conduction time. At a given temperature, the relationship between \( U_C \) and \( I_C \) is usually characterized by a linear equation

\[ U_C = a_C + b_C \cdot I_C \]  

(9)

where \( a_C \) and \( b_C \) are coefficients from the curve fitting provided from the device data sheets.

Switching losses for turn-on and turn-off of devices can be calculated by

\[ E_{SW} = a + b \cdot I_C + c \cdot I_C^2 \]  

(10)

where \( a \), \( b \), and \( c \) are coefficients imposed by the curve fitting provided from the device data sheets and \( E_{SW} \) is the switching loss energy.

Inverter efficiencies have been calculated from the described models with the same parameters of the simulation results. The devices are insulated-gate bipolar transistors and diodes with nominal values of 1200 V and 60 A. The switching frequency was set to 10 kHz in both techniques (SVPWM and RSPWM). The SVPWM presents the best efficiency (97.4%) for the three-phase inverter when compared to the RSPWM (97%). This is expected since only one switching is used in each vector change in the SVPWM. However, only one stage is used in the conversion process when using the RSPWM. Using the SVPWM in PV systems, a two-stage topology or a line-frequency transformer is normally used. Since a line-frequency transformer has large size and weight, a two-stage topology using SVPWM is compared to a one-stage topology using the RSPWM. The differences among the efficiencies of the two-stage topologies are significant when changing the dc–dc topology. In Table V, hypothetical cases are considered with dc–dc topologies having efficiencies changing from 97% to 99%. The global efficiency (a dc–dc converter plus a three-phase inverter) would present efficiencies changing from 94.5% to 96.4%. Therefore, the transformerless PV system using only one stage (three-phase inverter) with the RSPWM has better results since it presents an efficiency of 97%. Other advantage of the RSPWM techniques is that the PV system has a minimal number of components, decreasing the cost and complexity of the system.

D. Experimental Results

For the experimental measurements, the same simulation three-phase setup (Fig. 10) was used. The grid voltages have values of 10 V (rms), and the output inductance is \( L = 1.8 \) mH. The dc voltage source is 60 V, the leakage capacitance \( \left( C_{PV} \right) \) has a value of 220 nF, and the ground resistance \( \left( R_G \right) \) is 10.75 \( \Omega \). The complete system control was executed in discrete time using the TMS320F2812 DSP from Texas Instruments with sampling and switching frequencies of 10 kHz. It can be seen in Fig. 14(a) and (b) that only the RSPWM technique makes the leakage current have low values. A good agreement can be seen between the simulation and the experiment, showing that the theoretical assumptions used in the simulations are valid. The results indicate that the RSPWM technique has potential for using in grid-connected transformerless three-phase PV systems.

IV. Modification Techniques to Eliminate Leakage Currents in Three-Level Inverters

The constant CM voltage technique for the two-level inverter can also be used for an \( N \)-level inverter. In this paper, the technique is explained for the three-level inverter (Fig. 15). The SVPWM is generally used to control the three-level inverter output voltages, and there are 27 possible combinations of voltage as shown in Fig. 16. The combinations are composed of six long vectors \( (V_1, V_2, V_3, V_4, V_5, \) and \( V_6) \), six medium vectors \( (V_8, V_9, V_{10}, V_{11}, V_{12}, \) and \( V_{13}) \), six small vectors \( (V_{14}, V_{15}, \)
Fig. 14. Experimental leakage impedance voltage and current of the three-phase PV inverter: (a) SVPWM and (b) RSPWM1.

Fig. 15. Diode-clamped three-level inverter.

Fig. 16. Space vectors in the output of a three-level inverter.

TABLE VI
CORRESPONDING SPACE VECTOR FOR THE POSSIBLE COMBINATIONS OF THE INVERTER SWITCHES FOR THE FIRST 150°

<table>
<thead>
<tr>
<th>$S_{1a}$</th>
<th>$S_{2a}$</th>
<th>$S_{1b}$</th>
<th>$S_{2b}$</th>
<th>$S_{1c}$</th>
<th>$S_{2c}$</th>
<th>Vector</th>
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<td>0</td>
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</table>

The proposed technique consists in using only the medium vectors and the zero vector $V_{14}$ to comprise the reference vector. Therefore, in the region between the vectors $V_8$ and $V_9$, the vectors $V_8$, $V_9$, and $V_{14}$ are used. Other option is to use always the three medium vectors. Considering the same region, the vectors $V_8$, $V_9$, and $V_{10}$ would be used in this case. In any option, it can be seen that the CM voltage always assumes the values $V_{PN}/2$. For the three-level inverters, the proposed PWM can be applied with the maximum amplitude of the phase-to-neutral voltages equal to $V_{PN}/2$, resulting in 86.6% of the voltages that can be obtained with the SVPWM ($V_{PN}/\sqrt{3}$). Therefore, using the proposed PWM for three-level inverters guarantees low leakage currents with a gain of 50% of the voltage amplitude in relation to two-level inverters with the RSPWM. It is important to mention that, increasing the number of levels with the proposed PWM, the maximum amplitude voltage also increases, but the best gain occurs when there is a change of two- to three-level inverter. There are other combinations that guarantee a constant CM voltage using long and small vectors, but, in this case, the amplitude of the output voltages will be lower than the amplitude of the voltages.
using the technique with medium vectors if sinusoidal phase-to-neutral voltages are desired.

The results in Fig. 17 show that, using the proposed PWM, the three-level inverters present low leakage currents in transformerless PV systems. In this figure, the proposed solution is compared to the traditional solution that uses the three-level inverter as a three-phase half-bridge structure, that is, with the neutral connected to the middle point of the PV generator. The connection between the neutral and the middle point of the dc link is not ideal, and a small inductance has to be considered [3]. This inductance is sufficient to make the leakage currents increase.

V. COMPARATIVE ANALYSIS

In this section, the transformerless three-phase inverters are compared. The comparison is based on the number of switching devices and auxiliary diodes, the voltage rating of the devices, the output voltage amplitude, the CM voltages, and the leakage currents.

The comparison is shown in Table VII. In terms of power devices, it can be said that the diode-clamped three-level inverter needs twice the switching elements and six extra diodes in relation to the two-level inverter. The advantage in this case is that the switching elements need only half of the voltage rating compared to those in the case of the two-level inverter. Using the proposed PWM for three-level inverters guarantees a gain of 50% of the output voltage amplitude in relation to two-level inverters with the RSPWM. Considering the leakage current, the two- and three-level inverters are suitable in the case of applying the proposed techniques. Using SVPWM, the PV array terminals are jumping between different levels with the switching frequency resulting in high leakage currents.

VI. CONCLUSION

In this paper, the leakage current in three-phase transformerless PV systems connected to the grid has been studied. Without the transformer, the capacitance of the PV array can allow the circulation of the leakage current above the permissible levels. Modulation techniques designed for three-phase transformerless PV systems have been proposed. The techniques guarantee a constant total CM voltage, improving the behavior of the two- and three-level inverters in terms of leakage currents without additional hardware. The behavior of the techniques has been validated on a three-phase inverter prototype. Using the proposed modulation for three-level inverters guarantees low leakage currents with a gain of 50% of the maximum amplitude of the voltages in relation to two-level inverters with the proposed modulation. Therefore, the technique is specially suitable if three-level inverters are used.

REFERENCES


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