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Multilevel Single Phase Isolated Inverter with Reduced Number of Switches

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***Abstract*—This paper proposes a cascaded single phase multilevel inverter using an off-the-shelf three-phase inverter and transformer. The concept is based on a cascaded connection of two inverter legs using a typical three phase inverter in such a way that the third leg is shared between the other two phases. The cascaded connection is achieved through an integrated series transformer with a typical three-phase transformer core. Utilization of a special transformer design has been previously proposed in the Custom Power Active Transformer. However, cascaded connection of inverter legs has not been previously investigated with such a concept. In this way, a three-leg inverter and a three-phase transformer are converted into an isolated multilevel single-phase inverter based on an unique configuration and modulation technique.**

***Index Terms*—Cascaded Transformer Multilevel Inverter, Custom Power Active Transformer, Multilevel Inverters.**

I. Introduction

During the last years, multilevel inverters have become the most popular power electronics configurations, overtaking the classical two level inverter. Several applications have presented interest in utilizing such configurations in order to achieve high-power quality waveforms, lower switching losses and high-voltage capability [1]. The most remarkable multilevel topologies discussed in literature include: neutral point clamped, flying capacitors and cascaded H-bridge cells. The competitiveness between each of these approaches resides mainly in component count versus number of voltage levels. Moreover, other factors that affect the selection criteria involves utilization of separate dc sources, isolation and switching stress [2].

The insulation concern in application such as photovoltaic (PV) energy and battery storage systems has lead to the requirement of topologies with low or high frequency transformers. Converters with two conversion stages provide high frequency isolation through dc-dc converters [3]-[5], which are also able to decouple the dc from the ac side and control their variables independently. On the other hand, low frequency transformers are used in topologies with one conversion stage to provide galvanic isolation and step up the ac voltage.

Other configurations such as cascaded connection of multiple inverters through multiple isolated transformers to create multilevel output voltage levels have been presented in [6]-[10]. However, in such a configurations, the output voltage levels as well as the number of bulky isolation transformers increase with the number of levels. Although the number of switches can be reduced as claimed in [9] by utilizing different topologies, the number of isolated transformers is always greater than one.

Recently, there has been an interest in combining power electronics converters with coupled magnetic elements. Such topologies mainly benefit the system by providing isolation through injection transformers, reducing component count and achieving cascaded isolated connection. This has been presented in [11] by utilizing a cascade combining transformer. Such a configuration is promising in the sense of providing multilevel output voltages in an integrated structure. However, expansion to more output levels still requires several transformers. The concept presented in the Custom Power Active Transformer (CPAT) [12] shows the possibility of combining multiple series power converters in a single transformer core by utilizing multiple shunt magnetic paths. Based on this concept, cascaded connection of multiple inverters can be achieved in a single integrated transformer. Furthermore, in [13], this concept has been validated experimentally for three-phase applications. Thus, this concept can be utilized to achieve isolated cascaded connection of inverter legs that would provide a multilevel output voltage configuration.

In this paper, a typical three-phase inverter is employed with a three-phase transformer to generate a five levels single-phase multilevel isolated inverter. This is achieved by employing two inverter legs for generating three output voltage levels and the third leg is used as a common return point between them. The inverter legs are connected to the three-phase transformer windings through two shunt magnetic paths. A modulation technique is proposed to generate a multilevel output voltage over the third shunt magnetic path. This magnetic path is connected to the grid where the injected current is controlled through a suitable controller. Finally, a high-quality output current is supplied to the grid due to the multilevel output voltage and the inherent filtering capability of the isolated transformer provided by the leakage inductances. Based on simulation results such concept is proven viable and promising for transformer integrated multilevel inverters.

This paper is organized as follows: Section II describes the topology, its operation model and the modulation technique.

Section III describes the integrated series transformer that would facilitate the cascaded connection of inverter legs. Section IV explains the control strategy to control the grid current. Section V presents the simulation results of the proposed configuration. Finally, Section VI discusses the conclusions and practical considerations of the proposed configuration.

II. Topology Description

The multilevel single phase inverter proposed is based upon a two-level three phase inverter and a low frequency three phase transformer. The magnetic circuits theory states that each winding over a shunt core limb is equivalent to a series electrical circuit. This principle is presented in [12] where it has proved the capability of providing a cascaded connection with galvanic isolation through the magnetic circuit generated by the transformer core. Considering that all windings over the core limbs are isolated, it is possible to generate a single phase multilevel inverter with a typical three leg inverter, where the third leg operates as a common leg. In such a case, by using unipolar modulation [14], the output voltage v_{c1} between a and n is able to provide three voltage levels, likewise v_{c2} measured between b and n. The proposed configuration shown in Fig.1, presents the three phase inverter connected to the first and second limb winding of the transformer, while the grid is connected to the third limb winding. Even though, an integrated series transformer has been used, for a sake of simplicity, a classical three phase transformer can be implemented as well. However, the connection between the three phase inverter and the classical transformer has to be performed through each winding limb of the primary or secondary side. All other winding not required are left in open circuit.

This configuration provides several advantages over other topologies presented in literature such as reduced number of switches and transformer windings. Since the series connection is performed through the magnetic circuit, an inherent galvanic isolation between the ac and dc side is provided. This assists in overcoming the insulation limitation problem in dc sources such as photovoltaic panels and battery energy storage systems. In addition to this, the magnetic series connection between the voltages v_{c1} and v_{c2} increases the output voltage v_c despite using one dc source. This feature allows an ac voltage higher than the dc voltage level. Moreover, adjusting the number of turns in each limb and implementing a specific modulation technique, it is possible to increase the number of voltage levels at the grid side, thus reducing the current ripple injected to the grid.

Since the voltage v_{c1} and v_{c2} rely on the switching states and the dc source, the output voltage v_c can be mathematically modeled by:

$$v_c = \underbrace{v_{dc} \cdot (s_1 - s_3)}_{v_{c1}} + \underbrace{v_{dc} \cdot (s_2 - s_3)}_{v_{c2}} \tag{1}$$

In addition, the dynamic model on the grid side is given by:

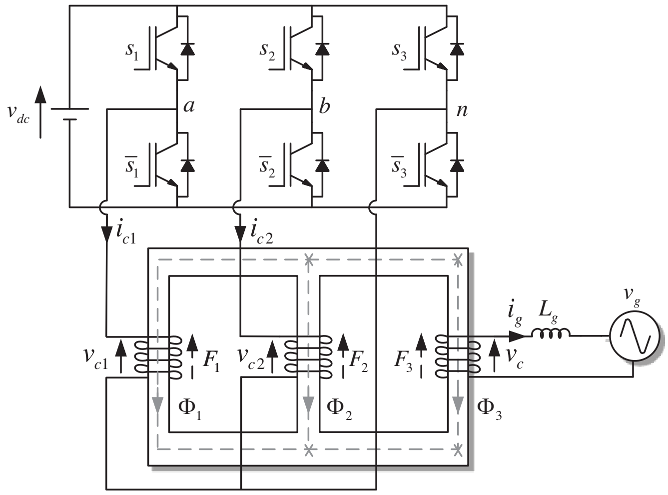

Fig. 1: Proposed configuration

$$v_c = (L_T + L_g) \cdot \frac{di_g}{dt} + R_T \cdot i_g + v_g \tag{2}$$

Where L_T represents the equivalent inductance of the transformer, which provides an inherent filter effect on the grid current, L_g is the line filter, R_T is the resistive losses of the transformer, i_g is the grid current and v_g is the grid voltage.

A. Modulation Strategy

The modulation technique used is based on the classical multilevel carrier modulation strategy presented in [15]. This strategy requires $N-1$ carrier signals to generate N output voltage levels in the grid side. Since v_{c1} and v_{c2} are able to generate three voltage levels, the output voltage v_c is able to generate until five voltage levels, unless different turn ratios are used in the limb windings. In such a case, higher voltage levels could be generated. Assuming that each limb winding has the same turn ratio, as mentioned, five voltage levels can be generated. Therefore, four carrier signal (two positive and two negative) displaced in vertical shift are required. Fig.2 shows the modulation technique proposed, where the carrier signals $\{t_{r1}, t_{r2}, t_{r3}$ and $t_{r4}\}$ are compared with the modulation index m in order to provide the switching states of the inverter legs. S_1 controls the first leg, S_2 controls the second leg and S_3 controls the third leg (common leg). The combination of these three signals provide nine possible combinations to generate the corresponding output voltage levels.

Table.I presents the nine possible states, where the output voltage levels can be simplified to $2v_{dc}$, v_{dc}, 0, $-v_{dc}$ and $-2v_{dc}$. It can be observed that $2v_{dc}$ and $-2v_{dc}$ are generated through one state, while the others voltage levels are achieved through two states. This redundancy allows to decrease the switching stress in the semiconductor devices, since the conduction time can be reduced by alternating those states. The equivalent circuit for the corresponding switching states are shown in Fig.3.

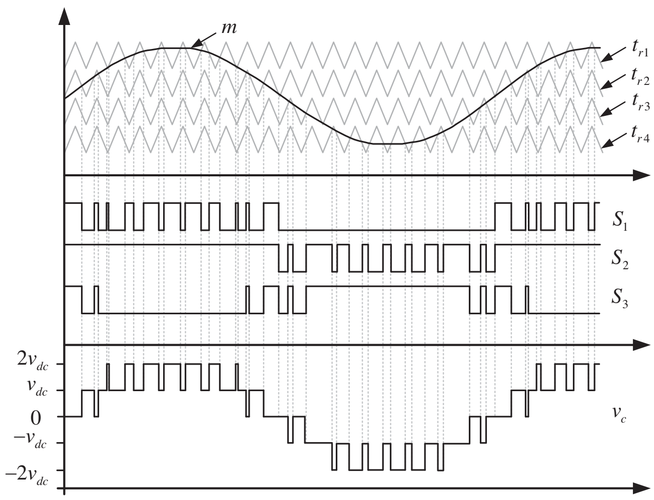

Fig. 2: Modulation technique

Following with the modulation analysis shown in Fig.2, the carrier signal t_{r1} is responsible of providing the $2v_{dc}$ level, while t_{r2} and t_{r3} determine v_{dc}, 0 and $-v_{dc}$. Finally, t_{r4} defines the $-2v_{dc}$ level.

TABLE I: Switching states and voltages levels

S_1	S_2	S_3	v_1	v_2	v_3
1	1	0	v_{dc}	v_{dc}	$2v_{dc}$
1	0	0	v_{dc}	0	v_{dc}
0	1	0	0	v_{dc}	v_{dc}
0	0	0	0	0	0
1	1	1	0	0	0
0	1	1	$-v_{dc}$	0	$-v_{dc}$
1	0	1	0	$-v_{dc}$	$-v_{dc}$
0	0	1	$-v_{dc}$	$-v_{dc}$	$-2v_{dc}$

It is worth mentioning that the configuration proposed generates symmetrical voltage levels, despite using equal or different turns ratio between each limb. This characteristic is due to the fact that one dc source is connected to all legs, therefore, v_{c1} and v_{c2} change according to the same dc voltage level. In this way, voltage changes will not create asymmetrical levels. This is an advantage over other cascaded configurations, in which modules use independent dc sources. Therefore, slight voltage differences will affect the grid current and the power quality unless voltage balancing control strategies are used.

III. Integrated Series Transformer

The electrical circuit of the integrated series transformer can be analyzed from the magnetic circuit's law [16]. As mentioned, windings wound on a common core are equivalent to a parallel connection of voltage sources, while windings wound over parallel shunt cores are equivalent to a series connection of voltage sources. This concept can be studied by considering an ideal transformer, where the coupling factor is 1 and the leakage inductance is zero. From the Faraday's law, a voltage v_k is induced in N turns of wires by changing the total magnetic flux Φ_i passing through the coils according to:

$$v_k = -N_i \frac{d\Phi_i}{dt} \tag{3}$$

Where the sub-index k represents the inverter leg and i the number of limb.

In the Ampere's law, the magneto-motive force (mmf) represented by F_i in Fig.1 across the reluctance $\Re$ in a close path can be represented by:

$$\frac{d\Phi_i}{dt} = \frac{1}{\Re}\frac{dF_i}{dt} \tag{4}$$

Moreover, the winding F_i depends on the winding effective current according to:

$$F_i = N_i i_k \tag{5}$$

The total mmf around a close path add up to zero. Therefore, assuming an ideal transformer with no leakage inductance, the relationship between the mmf in any limb of Fig.1 is equal to any of other two limbs. This can be expressed by:

$$F_1 = F_2 = F_3 \tag{6a}$$

$$N_1 i_{c1} = N_2 i_{c2} = -N_3 i_g \tag{6b}$$

In addition, according to the Ampere's law, the sum of all magnetic fluxes in the three limbs of the transformer should be equal to zero.

$$\Phi_1 + \Phi_2 + \Phi_3 = 0 \tag{7}$$

Replacing the magnetic flux equation presented above by the mmf expression of (6), the relationship between the induced voltage across each winding is mathematically expressed by:

$$\frac{v_{c1}}{N_1} + \frac{v_{c2}}{N_2} - \frac{v_c}{N_3} = 0 \tag{8}$$

Where N_1, N_2 and N_3 represents the number of winding turns.

The electric circuit of the integrated series transformer can be represented as a multiple series circuits as is shown in [12] and [13]. Each winding on a magnetic limb in Fig.4 can be considered as a voltage source v_k with a series leakage inductance L_k. Moreover, shunt non-linear inductances L_L represent the limb magnetizing inductance. Such inductance can be considered significantly large and it has a minor impact on the cascaded circuit since transformer core limb reluctances are designed to be minimal to achieve maximum coupling between windings. Furthermore, the non-linear effect of magnetizing inductance can be observed in a transformer

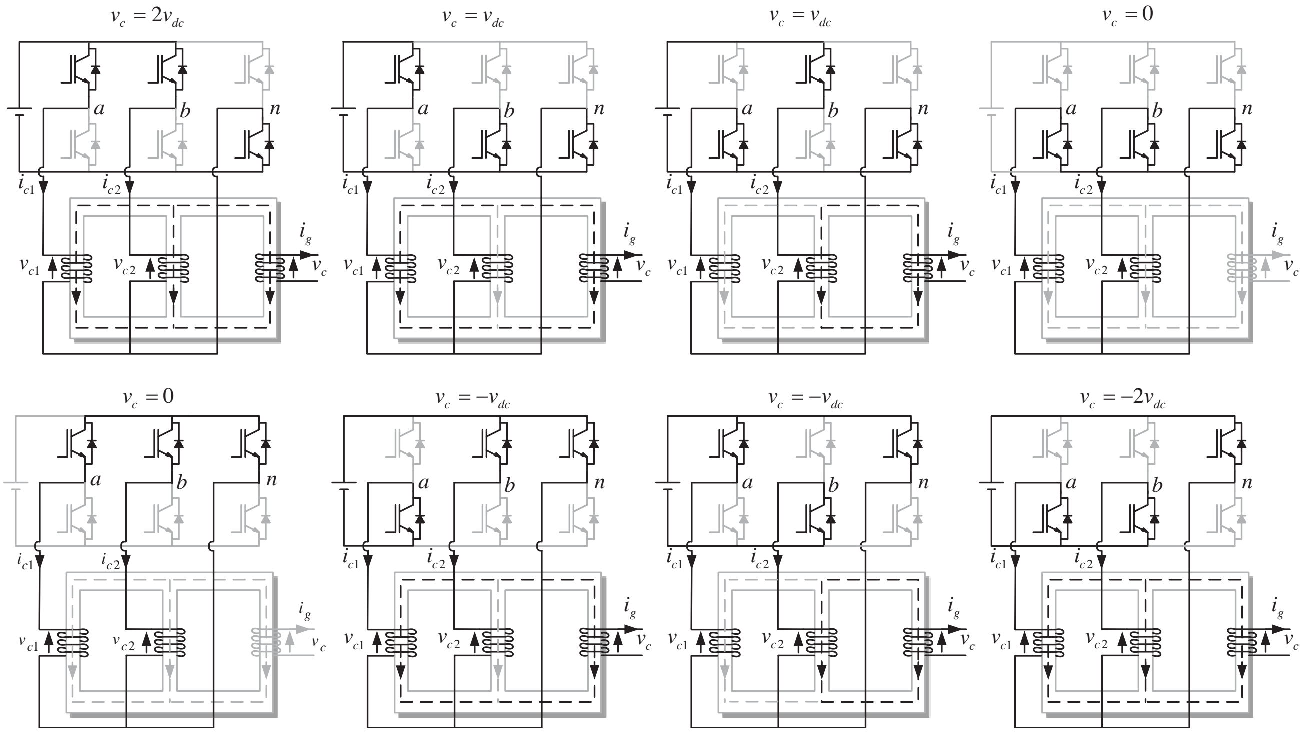

Fig. 3: Switching states

mangetizing current which is typically minimal. Another non-linear element in the equivalent circuit is the yoke inductance L_Y which has similar characteristics to L_L. As shown in [13], the magnetizing non-linear current required by such inductances to magnetize the core can be provided through the connected converters. Core leakage inductance L_0 represents the homopolar inductance of a typical three-phase transformer and it can be realized as the leakage flux from the core through the air. Such inductance can play a role in future design of the integrated series transformer since it is in series with the circuit and can affect the filtering capability of the transformer. Based on these assumptions and the mathematical analysis provided before, core magnetizing inductances can be considered negligible and the transformer circuit can be represented as in Fig.4(b) as cascaded series voltage sources with winding leakage inductances and a core leakage inductance.

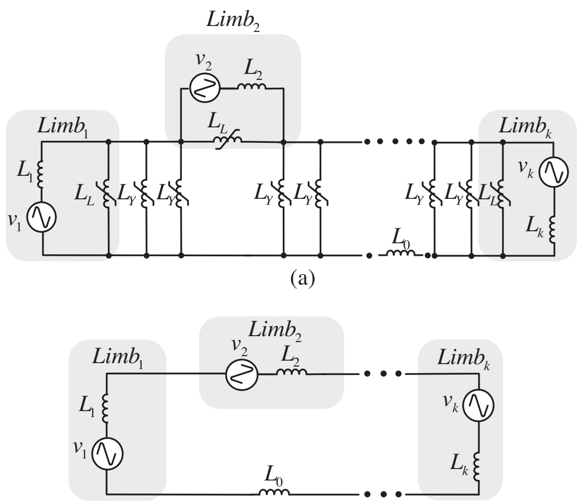

Fig. 4: Integrated series transformer. (a) Equivalent electric circuit, (b) Simplified electric circuit

IV. Control Strategy

The grid current is regulated using the single-phase voltage oriented control (VOC), which has an inner control loop to regulate the grid current and an external control loop to regulate the dc voltage. In addition, a synchronization control strategy such as Phase Locked Loop (PLL) is required to provide the synchronous grid angle and ensure unitary power factor. This control strategy is presented in Fig.5, where the voltage difference between the reference and the measured voltage v_{dc} is regulated using a PI controller which returns the power reference delivered to the grid. This reference is transformed into the grid current reference amplitude and then multiplied by a sinusoidal signal synchronized with the grid. In this way, the total power delivered by the inverter is mainly active, however different angles can be set to provide reactive power if necessary.

The dc-link voltage measurement is filtered with a notch filter to eliminate the second harmonic ripple presented in the dc voltage which is caused by the grid rectification. This

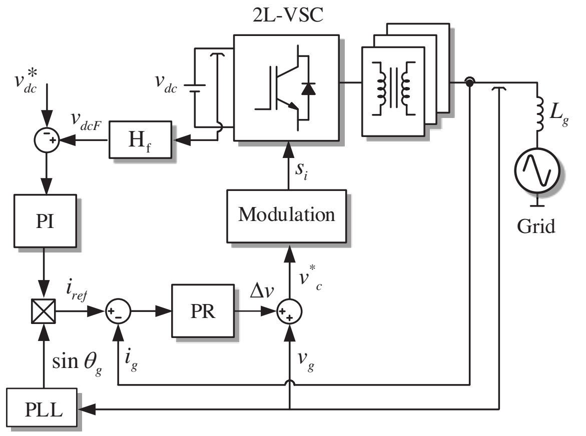

Fig. 5: Single-phase voltage oriented control scheme

TABLE II: Simulation Parameters

Parameters	Symbol	Value
Nominal power	P_o	3 kW
DC voltage	v_{dc}	300 V
Grid voltage amplitude	$\hat{v}_g$	320 V
Grid frequency	f_s	50 Hz
DC-link capacitance	C_{dc}	4700 μF
Switching frequency	f_c	2500 Hz
Line inductance	L_g	1 mH
Transformer voltage	V_T	400 V
Inductance primary winding	L_p	0.9113 mH
Inductance secondary winding	L_s	0.9113 mH
Resistance primary winding	R_p	0.2518 Ω
Resistance secondary winding	R_s	0.2518 Ω
Magnetizing inductance	L_m	2 H
Base voltage	V_B	220 V
Base power	S_B	3 kW
Base current	I_B	18.77 A

filter avoids the third harmonic component introduced in the grid current reference when the current reference amplitude is multiplied by the synchronization signal.

The grid current reference is compared to the measured current i_g and its error is regulated through a PR controller since no rotating reference frame is used. This PR controller ensures perfect tracking with zero steady state error at the grid frequency. According to the dynamic model presented in (2), the output current control defines the dynamic response of the voltage difference between v_c and v_g. Therefore, the output voltage reference v_c^* can be represented according to:

$$v_c^* = \Delta v^* + v_g \tag{9}$$

Where Δv^* is the voltage difference provided by the current control loop.

Finally, the output voltage reference is used by the modulation technique to provide the switching stages required by the inverter to generate the proper voltage level at the ac side.

V. Simulations Results

The effectiveness of the proposed configuration and its modulation technique are validated using Matlab-Simulink. In the case of study, a two level three-phase inverter is connected to a integrated series transformer such as presented in Fig.1. The inverter has a rated power of 3 kW and a grid voltage of 230/50 V/Hz. Due to the series connection provided by the magnetic circuit, the maximum output voltage level at the grid side is twice the dc voltage. The dc voltage and other parameters are listed in Table.II.

In the following analysis all results are in per unit, where the base power S_B is 3 kVA and the base voltage V_B is 230 V. The converter voltage waveforms and switching states are studied in steady state operation, meanwhile grid waveforms such as the current, grid voltage and active power are studied in dynamic state operation.

In Fig.6 the induced voltage in all limb winding terminals are shown. The middle point of the first and second leg are connected to two independent limb windings, meanwhile the third phase is used as a common leg between them. As a single-phase H-bridge inverter, the first and second winding limb generate three voltage levels. However, asymmetrical levels are observed due to the fact that the common leg does not allow another voltage pattern to generate the expected five voltage levels in the third limb winding. Fig.6(c) shows the five voltage levels of the output voltage v_c. Due to the droop voltage introduced by the leakage inductances of the transformer, the maximum amplitude achieved is $1.8v_{dc}$.

The previous results are obtained through the switching states shown in Fig.7. As presented in the modulation technique, a multilevel PWM modulation is implemented to gener-

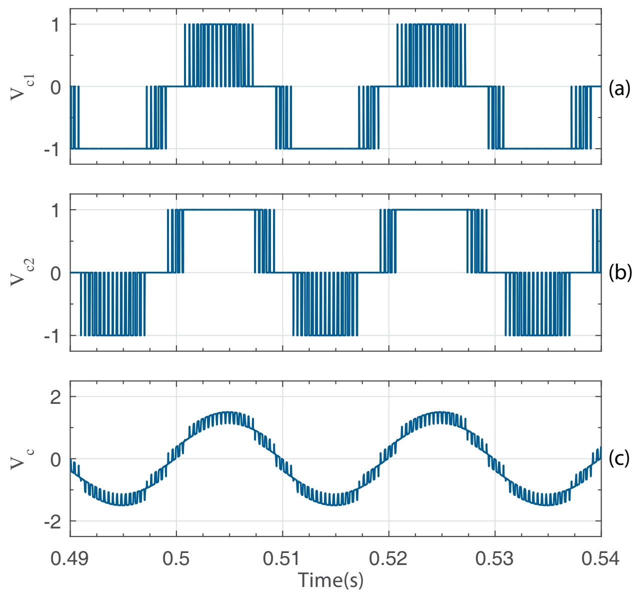

Fig. 6: Voltage waveforms. (a) Converter voltage v_{c1}, (b) Converter voltage v_{c2}, (c) Output voltage v_c

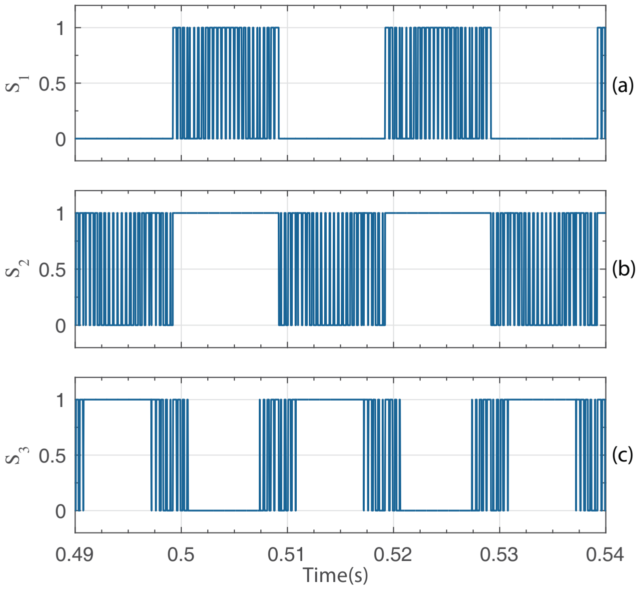

Fig. 7: Switching states. (a) S_1, (b) S_2, (c) S_3

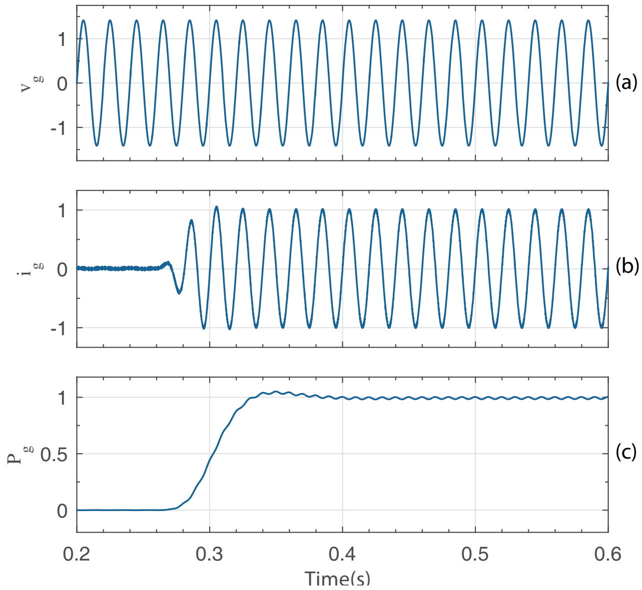

Fig. 8: Grid waveforms. (a) Voltage, (b) Current, (c) Active power

ate the switching state in each inverter leg. Since S_1 depends on the carrier signals t_{r1} and t_{r2}, its state changes when the modulation index has positive values. On the other hand, negative values of the modulation index compared with t_{r3} and t_{r4} affect the switching state S_2. In case of S_3, the carrier signals t_{r2} and t_{r3} set its pattern.

To demonstrate the performance of the proposed topology connected to the grid, Fig.8 shows the dynamic response under an active power step. The step takes place at $t = 0.27$ s, at that time, the grid current shown in Fig.8(b) increase up to its rated value. The small current ripple is due to the multilevel voltage generated in the grid side and the inherent filtering capability of the transformer leakage inductance. Furthermore, since a stiff grid is connected, the voltage shown in Fig.8(a) does not present any disturbance under the power step.

VI. Conclusion

This paper proposes a novel configuration for utilizing an off-the-shelf three-phase inverter and transformer to form an isolated multilevel single-phase inverter for grid connected applications. Based on the operation mode of an integrated series transformer, the proposed topology shows how the shunt magnetic limbs can be utilized to create a cascaded configuration by connecting two inverter legs to each terminal of two limb windings while the third leg is the common return point. A modulation technique has been proposed for this configuration to control the common leg as well as providing the five voltage levels without the requirement of auxiliary devices. Simulation analysis has shown the capability of the transformer connection to provide such voltage levels with the requirement of small passive filters, thanks to the inherent filtering capability of the transformer leakage inductances. The proposed cascaded configuration can be further expanded using multiple inverter legs and multiple shunt magnetic paths for several voltage steps and a higher quality output voltage.

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