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Sliding Mode Fixed Frequency Current Controller Design for Grid-Connected NPC Inverter

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***Abstract*—In this paper, a fixed-frequency pulse width modulation (PWM) based on sliding-mode current controller (SMCC) is designed and applied to a utility interface three-phase/wire/level Neutral-Point-Clamped (NPC) inverter. The proposed design methodology of the SMC is based on a constant switching frequency operation and on Gao's reaching law that allows chattering compensation. The aim of the controller is to inject a controlled active power from renewable energy sources into the grid while controlling the power factor and minimizing supply current harmonics. Moreover, the DC-link voltages across the split capacitors are controlled with a simple proportional -integral (PI) regulator. Experimental results show the advantages of the proposed control algorithm in terms of fast dynamic response, low voltage ripple on the dc bus, low current THD, and robustness towards external perturbations from DC and AC sides, moreover a comparison with a PWM-PI current controller is presented.**

Keywords—Sliding-mode control, three-phase neutral-point-clamped inverter, active rectifier, NPC, active filters, hybrid filters.

I. INTRODUCTION

THE increasing use of multilevel inverters in renewable energy conversion applications is mainly due to their inherent harmonic reduction ability, operation at low switching frequency, and their capacity to deliver high power ratings which result in high penetration of sustainable energy resources such as wind and solar. Nowadays, power electronics devices are used as the interfacing part in sustainable power generation systems [1, 2]. The increasing request for high quality electric energy in modern and smart grids has pushed the researchers to focus more on multilevel power converter topologies and to spend great efforts in developing their structure and control circuits.

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Combination of power semi-conductor switches and DC links that generate multi-step voltage waveform is a main contribution in the multilevel topologies design [3, 4]. Many advantages of grid-connected multilevel inverters have been reported by researches [5-8].

Neutral-Point-Clamped (NPC) [9], Flying-Capacitor (FC) [10] and Cascaded H-Bridge (CHB) [11] are the most common topologies in multilevel inverters that have been built by manufacturing companies. Used as utility interface for renewable energy conversion systems, the three-level neutral-point-clamped inverter (3L-NPC) is the most attractive topology because of smaller size DC buses for the three-leg/phase topologies [12-18].

The major requirements for a current controller can be described as follows: 1) provide an ideal tracking, fast dynamic response and high utilization of the DC link voltage, 2) ensure a low current THD, and finally 3) allow a constant switching frequency for safety purposes and low switching losses. Many current control techniques were proposed for three-phase grid-connected inverters [19]. Among the proposed approaches, the nonlinear techniques show better performance against system uncertainties. Among nonlinear control techniques Sliding Mode Control (SMC) proved to be one of the most cost-effective methods due to its robustness, stability, good dynamic response and its high compatibility with the inherent switching nature of power converters [20-23]. Due to its advantages, SMC was adopted not only in electric drives systems for direct torque control [24, 25] but also in inverters interfacing renewable energy sources such as wind energy systems [25, 26] and fuel cell applications [27].

In spite of its advantageous performance, SMC suffers from chattering problem with leads to variable and high switching frequency that leads to high power losses and considered to be highly control-sensitive to noise. For this purpose solutions have proposed the introduction of constant timers in the hysteretic module of SM controller [28] or the adoption of an adaptive hysteresis band that varies the parameter changes to fix the switching frequency [29]. Lately, a combination of a variable hysteresis band and switching decision (SDA) algorithms that ensure switching spectrum concentrated around the desired switching frequency is presented in [30] . However, all these solutions requires additional control components or extra input voltage.

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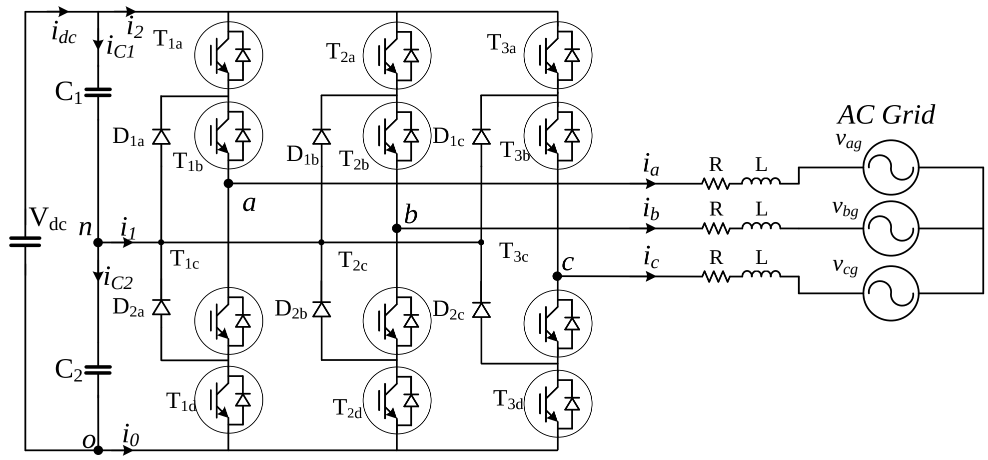

Fig. 1. Three-phase/wire/level NPC grid connected inverter as electric energy conversion system.

Another solution to operate at a constant switching frequency is by employing a pulse width modulator that uses an equivalent control law derived from the SM control. This law is used as a control signal compared to a fixed-frequency ramp in the modulator. Its main advantage is that the frequency of the output signal is kept constant regardless of the control signal variation. In literature, the design of a PWM-based SM controller was presented for buck converters [31], single phase unipolar inverters [32], DC-DC converters [33].

For grid connected inverters, studies focused on direct power (DP) based SM on two-level inverters [34, 35] and multilevel inverter [36]. Fewer attempts have adopted the SM method as a current control [30]. Besides, compliance with grid requirements in literature is not almost achieved where harmonic content of the current delivered to the grid is still relatively high. It can be concluded that even though the previous studies on the topic provide details on SM controllers for grid connected inverters, however they lack the full design and implementation of a PWM- based SM control for 3L-NPC grid connected inverter.

In this paper, we present the design of a fixed-frequency PWM-based SM current controlled NPC inverter in grid connection operation. Chattering compensation is done by the adoption of Gao's reaching law [37] . The advantages of the proposed controller are: 1) compliance with the grid requirements without the use of bulky filters at the output of NPC inverter, 2) accurate tracking response, 3) low THD and low ripple for the injected currents and synchronization with the grid voltage, and 4) stabilized DC bus voltage as well as output voltages under external perturbations. The performance and robustness of the proposed control system are tested and compared to a conventional PI-PWM regulator on a laboratory prototype of the NPC inverter. The obtained experimental results confirm the above-mentioned benefits of the proposed control technique.

The paper is divided as follows: in Section II, the mathematical model of the three-wire 3L-NPC grid connected inverter is presented; section III details the proposed sliding-mode control algorithm, while the experimental results are discussed in section IV. Finally, section V concludes the study.

II. The Three Level Neutral point Clamped Grid Connected Inverter

Renewable energy sources are harvested using appropriate power electronic converters aimed to maximize power transfer between these sources and a common regulated DC bus. The energy transfer between the multiple energy sources and the utility is assumed by the 3L-NPC grid converter which regulates the dc bus voltage at a set point ensuring efficient and well-regulated high quality power transfer between fluctuating sources and the grid. The 3L-NPC multilevel inverter has been introduced in [5] as a three-leg topology with four power switches and two clamping diode in each leg, and split DC-bus capacitors. This inverter, depicted in Fig. 1, showed lower stress on the semiconductors devices by reducing the voltage at its terminals. Its main drawback is the balancing issue between upper and lower DC-link capacitors voltages. As seen from the switching states, switches (1,3) or (2,4) in each leg are complementary. Table 1 gives the output voltage between phase *a* and the capacitors midpoint, for each combination of the switching states. The same values are obtained for the other two phases (b and c). The zero-voltage level obtained by this structure is the main factor in increasing the number of output voltage levels, which leads to a lower voltage harmonics content.

Table I
Switching States Of Phase A In 3L-NPC Inverter

Switching function	**Switching states**				**Output Voltage**
u_a	T_{1a}	T_{2a}	T_{3a}	T_{4a}	V_{an}
+1	1	1	0	0	$+V_{dc}/2$
0	0	1	1	0	0
–1	0	0	1	1	$–V_{dc}/2$

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The dynamic model of the system in Fig. 1 is given in the stationary reference frame as:

$$L \frac{d\, i_{abc}}{dt} = -Ri_{abc} + v_{abc} - v_{g,\,abc} \tag{1}$$

$$v_{abc} = \frac{V_{dc}}{3} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} u_{abc} \tag{2}$$

Where i_{abc} are the grid currents, v_{abc} represent the inverter output voltages, $v_{g,abc}$ the grid voltages, u_{abc} the switching function defined in Table I for each configuration, V_{dc} the DC-bus voltage, R and L the line resistor and inductor, respectively.

For a simpler design of the control system and for better tracking performance, the *dq*-model of the system is considered. It is obtained through a transformation from the stationary to a synchronous rotating frame using the following matrix:

$$T = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos\,\theta & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos\left(\theta + \frac{2\pi}{3}\right) \\ -\sin\,\theta & -\sin\left(\theta - \frac{2\pi}{3}\right) & -\sin\left(\theta + \frac{2\pi}{3}\right) \end{bmatrix} \tag{3}$$

Where θ denotes the angular position of (*dq*) rotating frame with respect to (*abc*) stationary frame. It yields:

$$L \frac{d\, i_{dq}}{dt} = -Ai_{dq} + v_{DC}u_{dq} - v_{g,\,dq} \tag{4}$$

$$A = \begin{bmatrix} R & -L\omega \\ L\omega & R \end{bmatrix},\ \omega = \frac{d\theta}{dt} \tag{5}$$

III. Sliding Mode Control Design

The goal of the SMC is to ensure high dynamic tracking performance for the inverter output currents. In the first stage of the control design process, the sliding surface should be chosen according to the desired dynamics in the sliding mode of operation. Once the sliding surface is defined, the reaching control law ensuring system stability on the surface is then developed. Finally, the generated SMC law is transferred as a control signal to be compared with the fixed-frequency ramp of the pulse width modulator.

A. Sliding surface design

The basic idea of a SM current control is to design a certain sliding surface in its control law that will track the desired state variables towards its desired references. For this purpose two sliding surfaces are introduced in SRF frame; S_d for controlling the direct current and S_q for the indirect one, whereas $i_{d,ref}$ and $i_{q,ref}$ are the d-axis and q-axis reference currents, respectively that should be tracked by the control system.

$$\begin{aligned} S_d &= i_d - i_{d,\,ref} \\ S_q &= i_q - i_{q,\,ref} \end{aligned} \tag{6}$$

The performance of the SMC is evaluated by the system tracking behavior and especially against disturbances. In order to obtain a sliding mode over a surface a sliding vector where σ is presented.

$$\sigma = \begin{bmatrix} s_d \\ s_q \end{bmatrix} = 0 \tag{7}$$

An equivalent control law u_{eq} that satisfies the condition $\dot{\sigma} = 0$ should be elaborated. Therefore, (8) is obtained.

$$\dot{\sigma} = \begin{bmatrix} \dot{S}_d = \dot{i}_d - \dot{i}_{d,\,ref} \\ \dot{S}_q = \dot{i}_q - \dot{i}_{q,\,ref} \end{bmatrix} = 0 \tag{8}$$

The main drawback of the SMC method is the chattering problem that is due to the discontinuity in the control law. Reducing the system chattering remains a challenge in the SMC design. Gao et al have proposed a complete definition for the reaching law that weaken system chattering [37].
In form of equation it can be written by:

$$\dot{\sigma} = \begin{bmatrix} -\varepsilon_d\ \mathrm{sgn}(S_d) - k_d S_d \\ -\varepsilon_q\ \mathrm{sgn}(S_q) - k_q S_q \end{bmatrix} \quad \varepsilon_d,\ \varepsilon_q > 0,\ k_d,\ k_q > 0 \tag{9}$$

In the presented work, the following assumptions will be considered:

$$\begin{aligned} v_{DC}u_d - v_{gd} &= -\varepsilon_d\ \mathrm{sgn}\left(s_d\right) - k_d s_d - L\omega i_q \\ v_{DC}u_q - v_{gq} &= -\varepsilon_q\ \mathrm{sgn}\left(s_q\right) - k_q s_q + L\omega i_d \end{aligned} \tag{10}$$

Where ε_d, ε_q, k_d, k_q are the SM control parameters. By computing the derivative of (6) and integrating then equations (4), (5) and (9), the following relations would be attained:

$$\begin{aligned} \dot{S}_d &= -\frac{1}{L}\left[RS_d + \varepsilon_d sgn(S_d) + k_d S_d + Ri_{d,\,ref} + L\ \dot{i}_{d,\,ref} \right] \\ \dot{S}_q &= -\frac{1}{L}\left[RS_q + \varepsilon_q sgn(S_q) + k_q S_q + Ri_{q,\,ref} + L\ \dot{i}_{q,\,ref} \right] \end{aligned} \tag{11}$$

B. Stability and reaching conditions

It is evident that the system stability is ensured by the following conditions:

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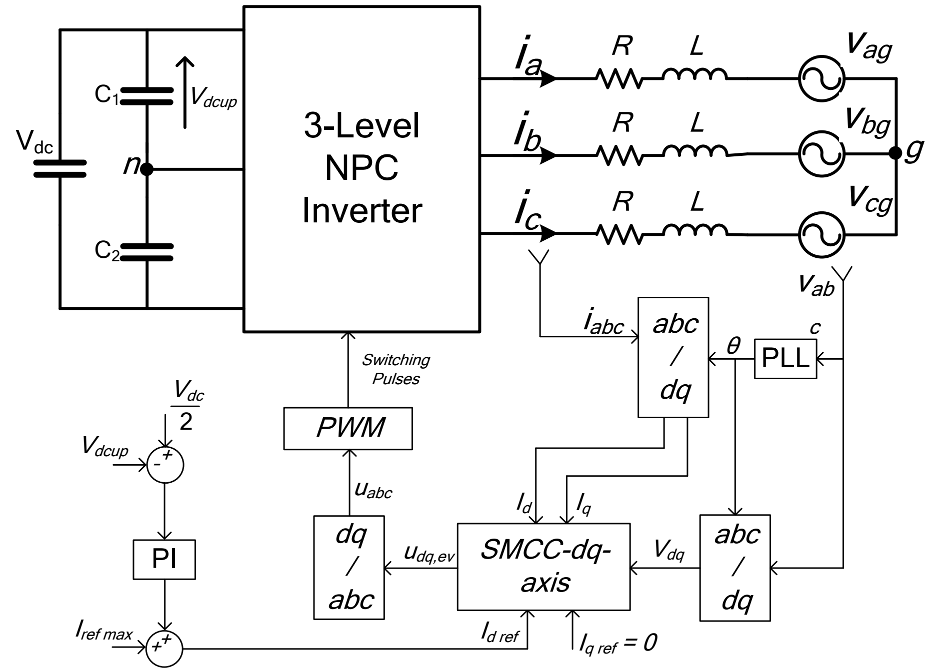

Fig. 2. Control system applied to the grid-connected three-phase/wire/level NPC inverter.

$$S_d \dot{S}_d < 0$$
$$S_q \dot{S}_q < 0 \tag{12}$$

In terms of functions it can be written as:

$$S_d \dot{S}_d = -\frac{1}{L}[(R_d + k_d)S_d^2 + S_d(\varepsilon_d \operatorname{sgn}(S_d) + Ri_{d,\,ref} + L\,\dot{i}_{d,\,ref})]$$
$$S_q \dot{S}_q = -\frac{1}{L}[(R_q + k_q)S_q^2 + S_q(\varepsilon_q \operatorname{sgn}(S_q) + Ri_{q,\,ref} + L\,\dot{i}_{q,\,ref})] \tag{13}$$

Which yields in terms of ε_d, ε_q, k_d and k_q

$$k_d > 0$$
$$k_q > 0$$
$$\varepsilon_d > \left| Ri_{d,ref} + L\dot{i}_{d,ref} \right|$$
$$\varepsilon_q > \left| Ri_{q,ref} + L\dot{i}_{q,ref} \right| \tag{14}$$

The non-positivity condition for Lyaponov function V that ensure the best reaching condition given in (15) is also ensured by the same parameters conditions given by (14).

$$V = \frac{1}{2}\left(S_d^2 + S_q^2 \right) \tag{15}$$

The choice of the parameters is very critical for this type of controller. High values of such parameters would increase the chattering problem; while lower values affect the converging process where a narrower band is obtained. A trade-off between these two selection approaches has to be considered. In order to achieve PWM-fixed switching frequency control, a relationship between the SM equivalent control law u_{eq} and the control signal of the PWM modulator should be elaborated. A detailed description about the derivation of PWM-based SM control system by mapping the equivalent control function into a duty cycle function of the PWM modulator is given in [31]. Since the SRF frame has been considered in our proposed work, two equivalent control laws are elaborated ($u_{d,eq}$, $u_{q,,eq}$) from equation (10) and therefore a transformation into natural control frame (abc) is applied.

$$u_{d,\,eq} = \frac{1}{V_{DC}}\left[-\varepsilon_d \operatorname{sgn}(s_d) - k_d s_d - L\omega i_q + v_{gd} \right]$$
$$u_{q,\,ev} = \frac{1}{V_{DC}}\left[-\varepsilon_q \operatorname{sgn}(s_q) - k_q s_q + L\omega i_d + v_{gq} \right] \tag{16}$$

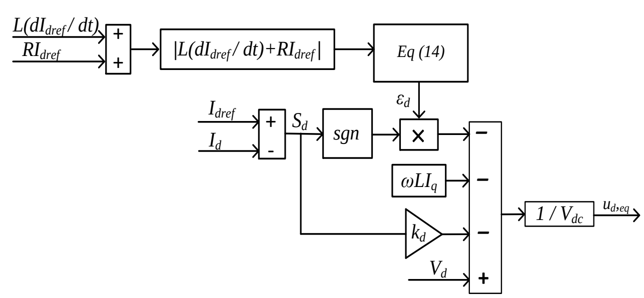

Fig. 3. Sliding Mode Current controller on the d-axis current (SMCC-d-axis)

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A block-diagram of the whole control system is shown in Fig. 2. Since the inverter is connected to the grid, the synchronization with the grid voltages is a matter of importance in the control design. The electrical grid is usually a complex dynamic system. Grid connection requires multiple features for a system to fulfill grid requirements at any time and in an accurate manner, and to respond instantaneously to grid faults. Information on the grid instantaneous state is transferred in real-time to the controller algorithm for synchronization procedure. The main goal of the converter is to inject a line current in phase with the grid voltage to get a unity power factor. So, the value of the grid phase-voltage angle is monitored continuously and used in the transformation matrix (3). Many synchronization methods were introduced for this purpose while the basic Phase-Locked Loop (PLL) technique is adopted in this proposed work. The Sliding mode current controller on d-axis is detailed in Fig. 3. It is noted that the same procedure is adopted for the current controller on q-axis.

As explained earlier, the voltage balancing process remains a drawback in this topology. So, a PI controller has been added in order to maintain the capacitor voltages at equal values which is observable in Fig. 2.

IV. Experimental Results And Discussion

A laboratory scale prototype of three-phase/wire/level grid-connected NPC has been implemented in order to validate the proposed sliding mode control scheme. Twelve 1.2 kV, 35A SiC MOSFETs of type SCT2080KE and 6 SiC fast-recovery clamping diodes of type SCS220KG are employed. The controller is implemented using the DSpace ds1103 real-time controller board with associated I/Os. The adopted sampling time is 22µs. The system parameters used for experimentation are given in Table II. Reported results cover both steady state and transient operations of the converter.

Figs. 4 and 5 show the steady operation of the NPC inverter in grid-connected mode while the SMC is controlling the injected current to be in phase with the grid voltage. Three levels phase-to neutral and five levels phase-to-phase inverter output voltages are well obtained.

The five-level symmetrical output voltage of the NPC inverter demonstrates the good dynamic performance of PWM technique leads to have fixed and low switching frequency with low power losses. Moreover, the low voltage ripple of capacitor proves the proper design of the controller in balancing the DC capacitor voltages with less deviation as it is very clear in Fig.5. The grid voltage and current waveforms (from phase a) have also been captured by AEMC power analyser, as illustrated in Fig. 6. It is clear that the power factor is almost 1. Although the source voltage has a THD 3.1% and the controller takes samples from this voltage waveform, the injected current contains low harmonics such that the THD is only 2.6% that is still below the accepted limit of IEEE standards.

TABLE II
EXPERIMENTAL SYSTEM PARAMETERS

Variable	Description	Values
V_{dc}	DC bus voltage (V)	300
f_g	Grid Frequency (Hz)	60
C_1 , C_2	DC-link Capacitance (µF)	650
L	Line inductance (mH)	5
v_{xg} $(x{:}a,b,c)$	Grid *rms* phase voltage (V)	100
i_x $(x{:}\ a,b,c)$	Grid *rms* current (A)	3.5
f_{sw}	Switching frequency (kHz)	2
Sliding Mode Current Controller Parameters		
ε_d	d-axis parameter 1	200
k_d	d-axis parameter 2	100
ε_q	q-axis parameter 1	200
k_q	q-axis parameter 2	50
Proportional Integral (PI) Controller Parameters		
K_p	Proportional gain (K_p)	0.1
K_i	Integral gain (K_i)	0.5

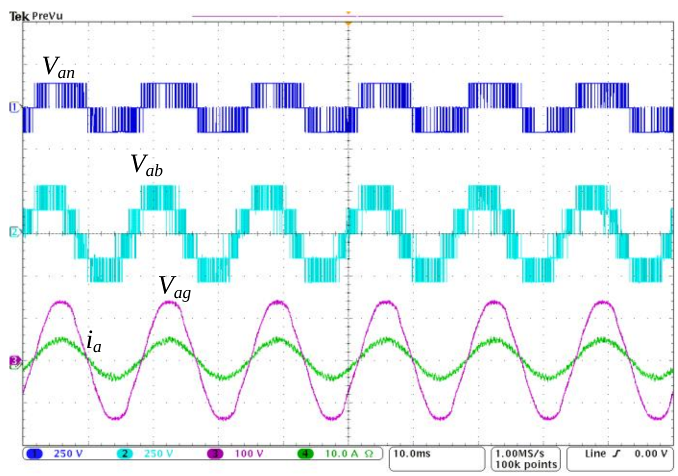

Fig. 4. Steady state voltage and current waveforms for grid connected NPC.

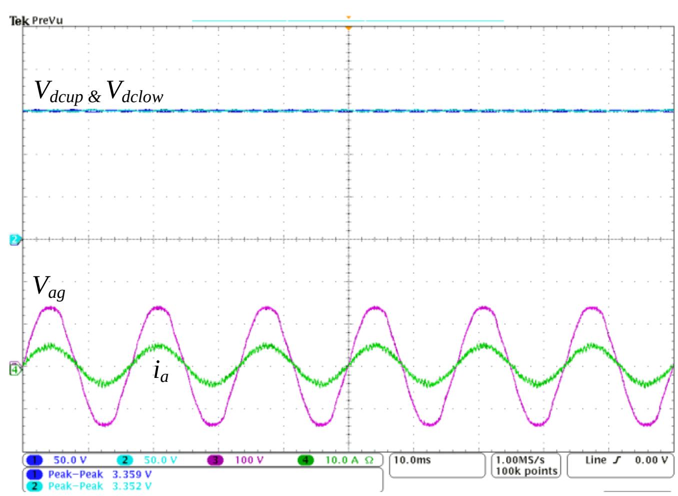

Fig. 5. DC bus voltages and grid side voltage/current waveforms.

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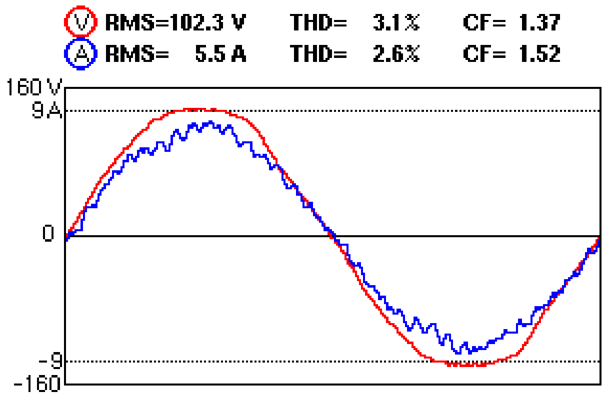


Fig. 6. Grid side voltage and current waveform, RMS values and THD.

It should be mentioned that this low THD has been achieved by firing the switches in only 2 KHz, which is significantly less than the similar works in 2-level converters. The low switching frequency makes the multilevel inverters suitable for high power applications especially in renewable energy conversion that needs high efficiency interfaces to deliver power to the grid.

In order to study more the operation of the system with the controller proposed, different tests were adopted to compare the SMC with a conventional PI regulator.

A. Test 1: operation with DC voltage variations

The main drawback of the 3L-NPC is the balancing between upper and lower capacitors. To study the behavior of the system under DC link variation a DC voltage variation of 30V has been applied to the controller as it can be seen in Fig. 7. In Fig. 7.a, the results when the proposed SMC is used are shown while Fig. 7.b shows the results of the PI regulator. The SMC shows better performance of maintaining the balancing between the DC side voltages when the DC side voltage change from 300V to 330V and returns back to 300V; lower DC voltage ripples are obtained as well as an accurate tracking to voltage variations.

B. Test 2: operation with grid voltage disturbances

A variation of 17% in the AC voltage amplitude is applied in this case. It is evident that the system operates with a unity power factor under this perturbation. Moreover, the balancing between the DC side voltages is more controlled when a SMC is used as it is shown in Fig. 8.

C. Test 3: operation with current reference variations

Moreover, to validate the fast tracking response and good dynamic performance of the designed controller, a change in the current reference value from 5A to 8A was adopted as it is shown in Fig. 9. It is evident that during the change in injected current amplitude, the controller takes action properly in making it in-phase with grid voltage as well as controlling the capacitors voltages. The change in reference current amplitude has been made during the real-time implementation.

D. Test 4: operation with reactive power variation

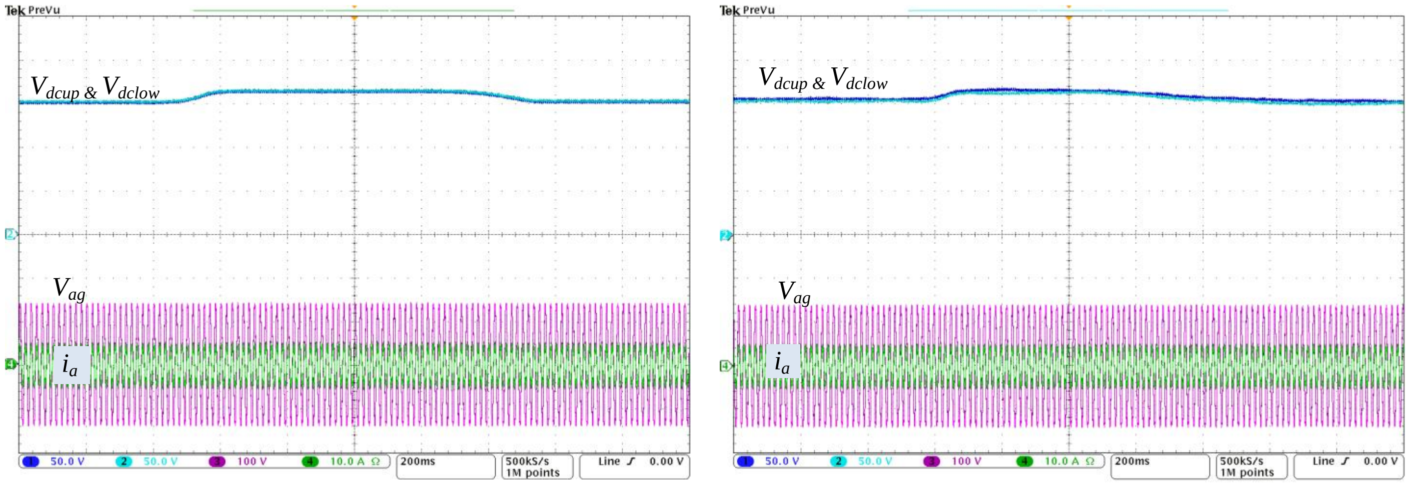
In order to investigate more the controller introduced, a reactive power test was adopted. A variation in the phase shift of 30° is applied to the controller during the real-time implementation as it is shown in Fig. 10. It is evident in the zoomed part of Fig. 10, that the controller responds and injects a shifted current to the AC side while maintaining the DC bus voltages equal. It should be noted that the same performance was obtained with the PI regulator.

E. Test 5: THD and power factor versus switching frequency and power variations.

In order to study better the performance and the robustness of this controller, the operation of the overall grid connected system has been tested for different switching frequencies with the same system parameters shown in table II. As it is presented in Fig.11 the SMC shows the same performance for higher switching frequencies. A THD current less than 5% and a high power factor were always attained. From other side, the system operates normally with a conventional PI regulator for switching frequencies less than 6 kHz. For higher switching frequencies, the system was not able to stabilize the DC voltages and inject a synchronized current to the grid. A tuning for the PI parameters is requested while the SMC shows a high robustness under switching frequencies variations. Finally, Fig. 12 depicts the results of the system tested in transmitted power variations; the SMC shows a system operation nearby the conventional one in terms of high power factor and low THD_i

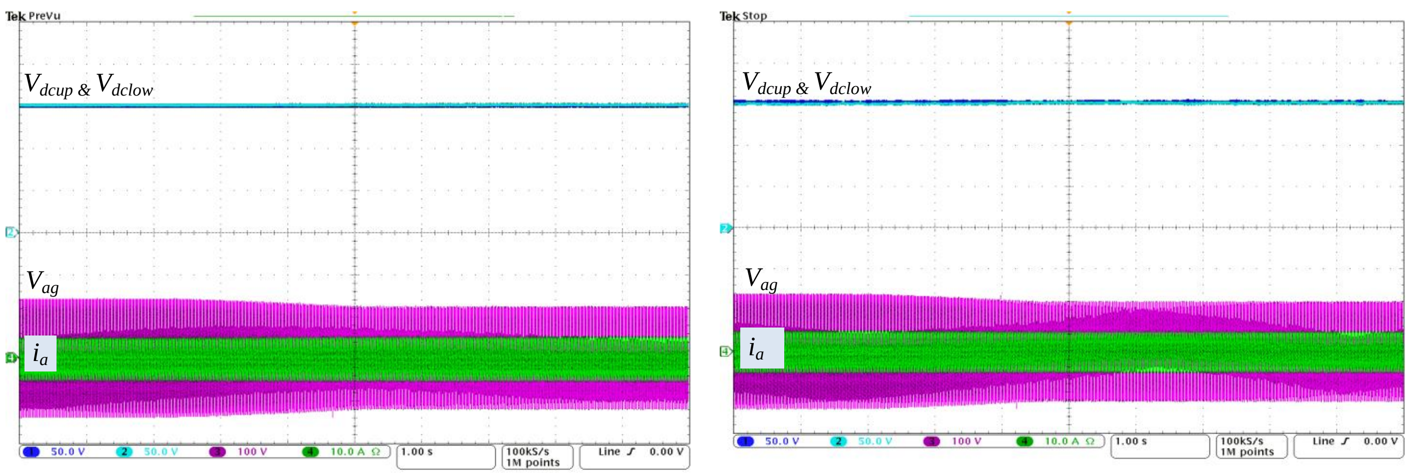
V. Conclusion

In this paper a sliding mode current control technique has been proposed and implemented on a grid connected NPC inverter as renewable energy resources interface to the grid. The main advantage of this technique is that a low THD current is given to the grid with only L filter required. Experimental results that confirm the good dynamic performance of this technique are presented. The overall system shows robustness
against external disturbances at the DC and AC sides. Moreover, it shows better performance in stabilizing the DC link voltages than a PI regulator in higher switching frequencies. Not only the robustness and the dynamic response of the system against external perturbations have been verified, but also the ability of the system to inject a synchronized current with low THD and low ripples to the grid has been proved. Eventually, it can be concluded that the presented 3 Phase/Wire/Level NPC inverter using implemented sliding mode controller can be a good candidate.



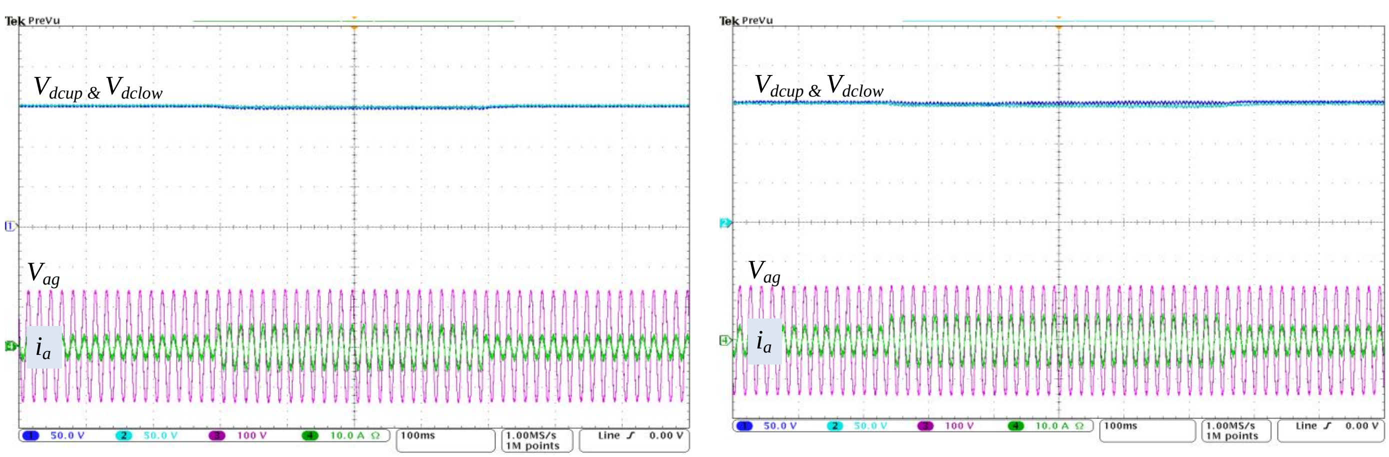
(a) (b)

Fig. 7. DC bus voltage variations between 300V and 330V (a) SMC. (b) PI



(a) (b)

Fig. 8. AC voltage variation from 100V to 83 V. (a) SMC. (b) PI



(a) (b)

Fig. 9. System respone to a sudden increase/decrease of reference current. (a) SMC . (b) PI

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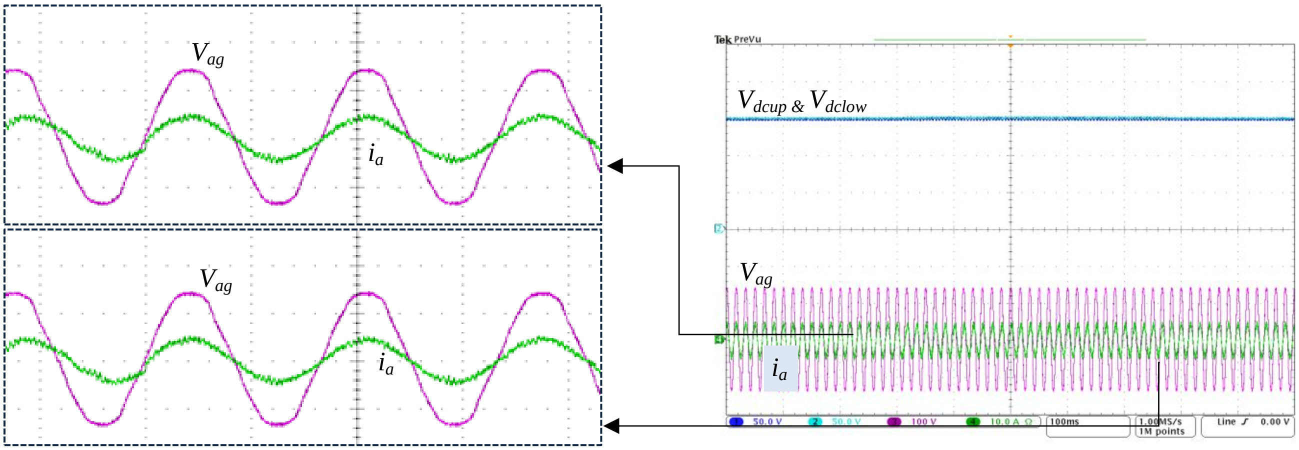


Fig. 10. Phase shift variation between 0° to 30°.

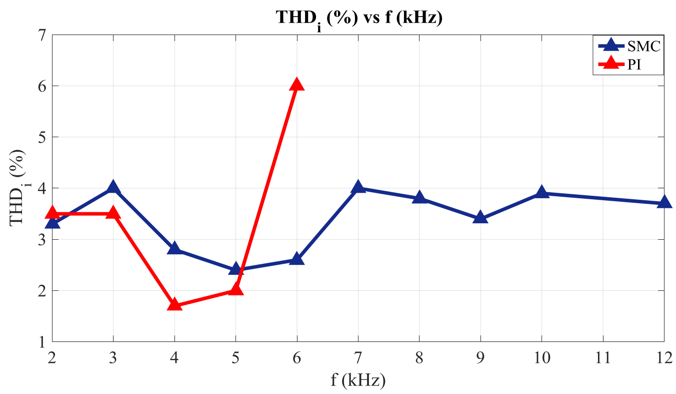
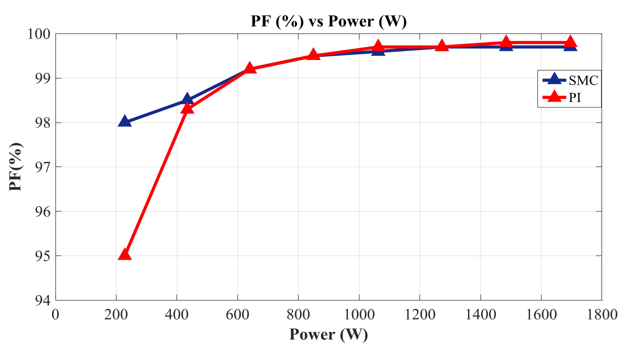


Fig. 11. System operation versus switching frequency variations; THD$_i$



(a)

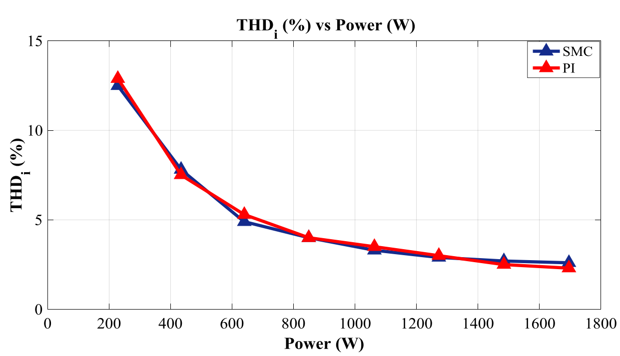


Fig. 12. System operation versus transmitted power. (a) PF (b) THD$_i$

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