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A Novel Sliding-Mode Current Controller in On-Grid NPC Converter

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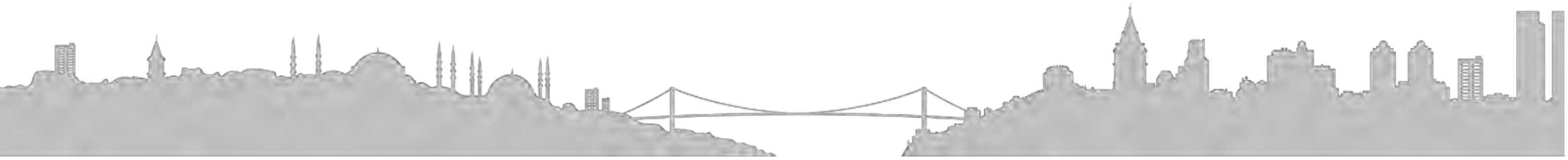
Abstract

This paper proposes a model based on robust control for three-phase three-level Neutral Point Clamped (NPC) power converters. Based on the continuous averaged model of the power system, a Sliding Mode Control (SMC) technique is applied to implement in the control system. The nonlinear SMC based on Gao's reaching law has been utilized to control the grid current in order to inject desired amount of active and reactive power to the grid. Using a single *dc* source at the NPC inverter *dc* bus, neutral point voltage is controlled through redundant switching states and instantaneous *dc* voltage feedback integrated into proposed controlling technique. There is no external voltage controller involved, since no associated fine-tuning issues are existed. Simulation results are provided to verify the fast-dynamic performance, low content of line current THD, and good voltage balancing of *dc* bus capacitors of NPC inverter.

Key words: Current Controller; Sliding Mode Control; NPC; Power factor correction.



1. Introduction

In the last decades, multi-level power electronic converters have attracted great interest in medium and high voltage applications, such as the integration of renewable energy sources, energy storage systems, etc. [1]-[2]. Multi-level converters are capable to increase the output voltage applying medium or low voltage solid state switches, have high nominal power rating, and improve output power quality [3]-[4]. Among the different multi-level converters, the Neutral Point Clamped (NPC) is one of the most popular topologies due to its low harmonic content in output voltage, fast dynamic response, low voltage power semiconductors and a good trade-off between performance and cost in high-voltage and high-power systems [5]-[6].

The challenging task in developing power converters is to meet the low cost and high efficiency, and it remains the most important question for grid connected power conversion systems [3]-[4]. For a decade, major evolution from classical inverter topologies toward multilevel topologies has been introduced [5]-[7]. Recently, neutral point clamped (NPC) topology is one of the most well-known type of multilevel converters and is widely utilized for various industrial applications. NPC inverter has a common *dc* bus for three phases, makes it suitable for stand-alone and grid-connected applications where a renewable energy resource should be applied and there are some limitation in the number of isolated *dc* suppliers [8].

The main objectives in the control of NPC converters are to adjust instantaneous active and reactive powers according to demands, regulate the *dc*-link capacitor voltage to reference voltage and *dc*-link capacitor voltage stability. These objectives should be achieved and additionally the power converter must inject minimum current harmonic distortion to the network. In this paper, a Direct Power Control (DPC) strategy is utilized to reach these goals. DPC is a well-known control method for electronic power converters [9]. The main objective of conventional DPC is to choose the best set of power semiconductors from a look up table which performs suitably in all possible states, in such a way that the regulations of instantaneous active and reactive power to their demands are achieved. The significant disadvantage of DPC is its non-constant switching frequency. Pulse Width Modulation (PWM) technique as well as Space Vector Modulation (SVM) techniques are applied to solve this problem [10]-[12].

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 to have a low current THD; and finally 3) Provide a constant switching frequency for safety purposes and low switching losses. Many current control techniques have been proposed for three-phase grid-connected inverters [13].

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 [8]-[9].

Due to its advantages, SMC was adopted not only in electric drives systems for direct torque control [14], but also in inverters interfacing renewable energy sources such as wind energy systems [12] and fuel cell applications [15].

This paper presents a method for fixed-frequency PWM based on SM current controlled NPC inverter in grid connection mode. Chattering compensation is done by the application of Gao's reaching law [16]. The advantages of the proposed controller are: 1) Matching with the grid requirements without using bulky filters at NPC inverter output; 2) Accurate tracking response; 3) Low THD and low ripple for the injected currents and synchronization with the grid voltage; and 4) Regulated *dc* bus voltage as well as output voltages under external perturbations. The performance and robustness of the proposed control system is tested and compared to a conventional PI-PWM. The results confirm the above-mentioned advantages in the proposed control technique. Modelling of NPC inverter is described in section II. Proposed SMC and SVM design are mentioned in section III and IV, respectively. Simulation results are presented and converter performance is analyzed in section V, which indicates the previously mentioned advantages of the proposed method in on-grid operation.

2. Model of The System

The power circuit of the proposed three phase three level NPC converter is shown in Fig. 1. The system is connected to the grid through smoothing inductors L_g and it is assumed that an equivalent resistive load R_L is connected at the *dc*-link capacitor. Two capacitors C_1 and C_2 are forming *dc*-link of the converter. The PV system, along with the boost converter is modelled by a constant *dc* voltage source.

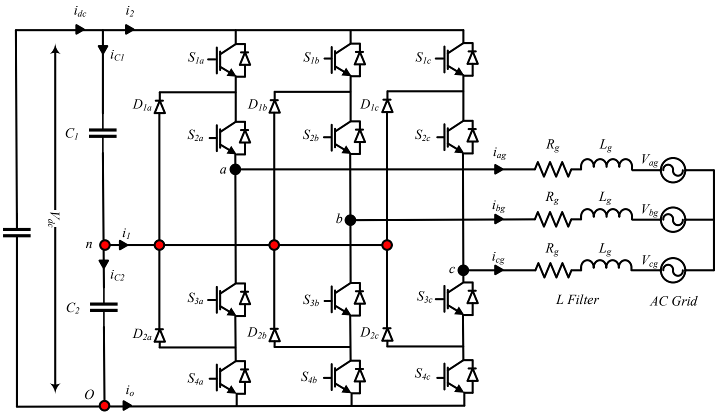


Fig. 1. Topology of grid-connected three-level neutral point clamped inverter

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \cos(\theta) & \cos(\theta-\frac{2\pi}{3}) & \cos(\theta+\frac{2\pi}{3}) \\ \sin(\theta) & \sin(\theta-\frac{2\pi}{3}) & \sin(\theta+\frac{2\pi}{3}) \end{bmatrix}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{1}$$

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

$$L\frac{di_d}{dt} = -ri_d + L\omega i_q + v_d - u_d V_{dc}$$
$$L\frac{di_q}{dt} = -ri_q - L\omega i_d + v_q - u_q V_{dc} \tag{2}$$

3. Sliding Mode Control Design

When a current controller operating in synchronous-reference frame (SRF), two sliding surfaces can be considered. In order to controlling the direct component of the grid current S_d is utilized, and S_q is applied for the quadrature component:

$$\begin{aligned} S_d &= i_d - i_d^* \\ S_q &= i_q - i_q^* \end{aligned} \tag{3}$$

the performance of the SMC can be evaluated by the system tracking behavior and especially its performance during disturbances. In order to obtain a sliding mode over a surface, a sliding vector is presented where σ is introduced:

$$\dot{S}_d = \dot{S}_q = 0 \tag{4}$$

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 and his team have proposed a complete definition for the reaching law that weakens system chattering [17]. Its mathematic expression is:

$$\begin{aligned} \dot{S}_d &= -\alpha_d \operatorname{sgn}(S_d) - k_d S_d \\ \dot{S}_q &= -\alpha_q \operatorname{sgn}(S_q) - k_q S_q \end{aligned} \tag{5}$$

Here, the following assumptions are considered:

$$\begin{aligned} V_{dc}u_d - V_d &= -\alpha_d \operatorname{sgn}(S_d) - k_d S_d - L\omega i_q \\ V_{dc}u_q - V_q &= -\alpha_q \operatorname{sgn}(S_q) - k_q S_q + L\omega i_d \end{aligned} \tag{6}$$

which are the SM control parameters.

by computing the derivative of (4) and integrating it with (2) and (6), the following relations are achieved:

$$\begin{aligned} \dot{S}_d &= -\frac{1}{L}[rS_d + \alpha_d \operatorname{sgn}(S_d) + k_d S_d + ri_d^* + L\dot{i}_d^*] \\ \dot{S}_q &= -\frac{1}{L}[rS_q + \alpha_q \operatorname{sgn}(S_q) + k_q S_q + ri_q^* + L\dot{i}_q^*] \end{aligned} \tag{7}$$

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

$$S_d \dot{S}_d < 0 \\ S_q \dot{S}_q < 0 \tag{8}$$

In terms of equations it can be written as:

$$S_d \dot{S}_d = -\frac{1}{L}[(r+k_d)S_d^2 + \alpha_d S_d \operatorname{sgn}(S_d) + ri_d^* + L\dot{i}_d^*] \\ S_q \dot{S}_q = -\frac{1}{L}[(r+k_q)S_q^2 + \alpha_q S_q \operatorname{sgn}(S_q) + ri_q^* + L\dot{i}_q^*] \tag{9}$$

which yields in terms of α_d, α_q, k_d , and k_q :

$$k_{d,q} > 0 \tag{10}$$

$$\alpha_{d,q} > \left| ri_{d,q}^* + L\dot{i}_{d,q}^* \right| \tag{11}$$

The non-positivity condition for Lyapunov function V that ensures the best reaching condition given in (11) is also ensured by the same parameters conditions given by (10):

$$V = \frac{1}{2}(S_d^2 + S_q^2) \tag{12}$$

In this type of controllers, the controller parameters selection is very critical. High values for the parameters would increase the chattering problem; while low values affect the converging process where a narrower band is needed. 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_{eqll} 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 [17]. Since an SRF frame has been considered here, two equivalent control laws are elaborated (u_d, u_q) from (13) and therefore a transformation into natural control frame (abc) is applied.

$$u_d = \frac{1}{V_{dc}}[-\alpha_d \operatorname{sgn}(S_d) - k_d S_d - L\omega i_q + v_d] \\ u_q = \frac{1}{V_{dc}}[-\alpha_q \operatorname{sgn}(S_q) - k_q S_q + L\omega i_d + v_q] \tag{13}$$

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 very important in the control system. The electrical grid is usually a complex dynamic system.

4. Simulation Results

In order to validate the proposed control schemes, they have been tested by means of numerical simulations in MATLAB® Simulink® environment. System and the control parameters are mentioned in Table I & II. The simulation circuit of NPC converters is the same as the circuit in Fig. 1. The current controller based on SMC procedure is as explained in the block diagram in Fig. 3.

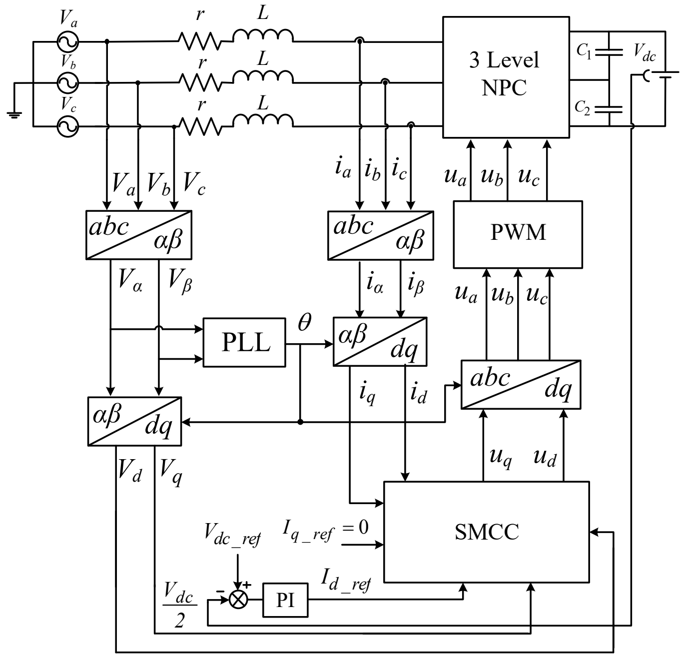


Fig. 2. Control system applied to the grid-connected three-level NPC inverter

Table 1: System Parameters

Parameter	Values
Filter Inductor L	5.4 ~ 4 mH
Normal *dc* Link Capacitor C	3.7 µF
Sampling Frequency f_s	5000 Hz
Filter Resistance r	0.005 Ω
dc Load R_L	6 ~ 9 Ω
Phase-to-Phase RMS Voltage e_a	220 V
Grid Frequency f_s	50 Hz

Table 2: Control Parameters

Parameter	Values
K_d, K_q	2000, 2000
A_d, α_q	12000, 12000

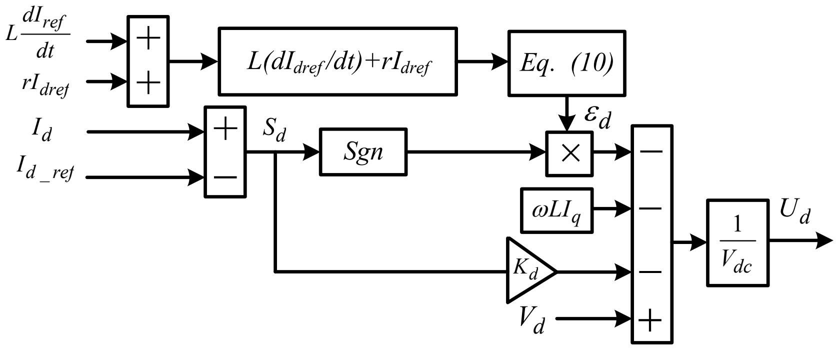


Fig. 3. Sliding Mode Current Controller on the d-axis current (SMCC-d-axis)

Fig. 4 shows the slip surface variations along the d and q axes. In the following, the control input from the grid is shown in Fig. 5.

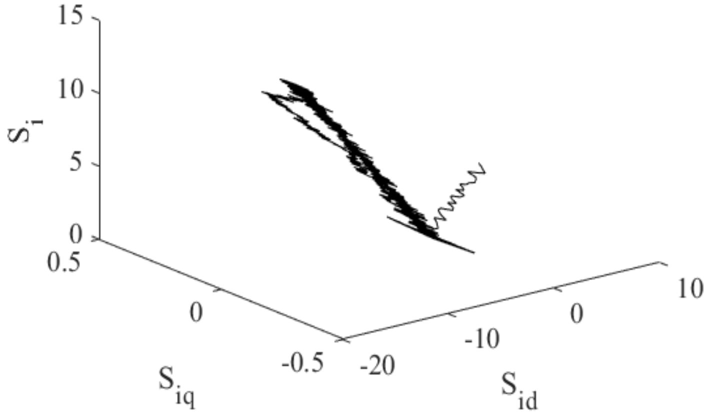


Fig. 4. Variation of sliding surfaces

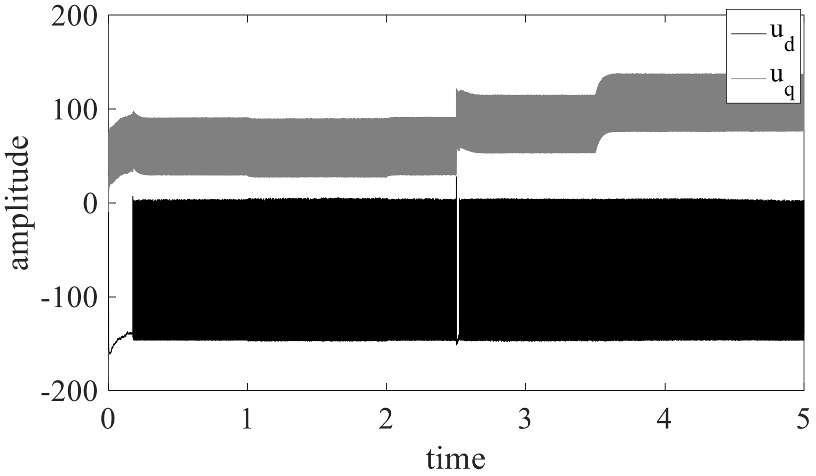


Fig. 5. Control inputs from the grid

Fig. 6 shows the input phase current (i_a) and the corresponding grid voltage (v_{an}); and Fig. 7 shows input phase current harmonic content. As it can be observed, both of the controllers make the three currents properly controlled, which are in phase with the grid voltage and low current distortion.

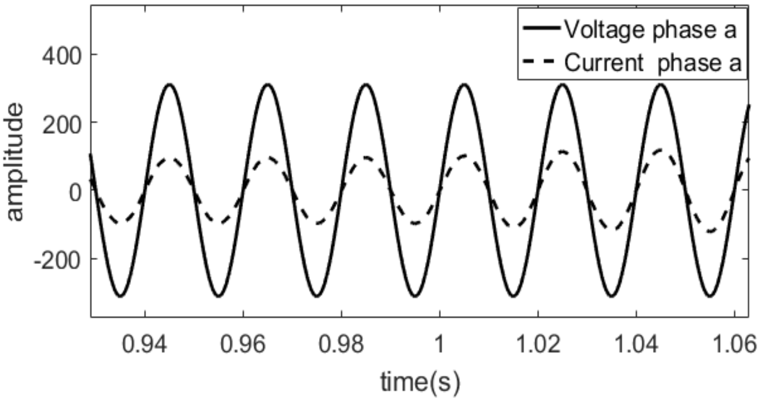


Fig. 6. Phase current (i_a) and grid voltage (V_{an}) with proposed controller

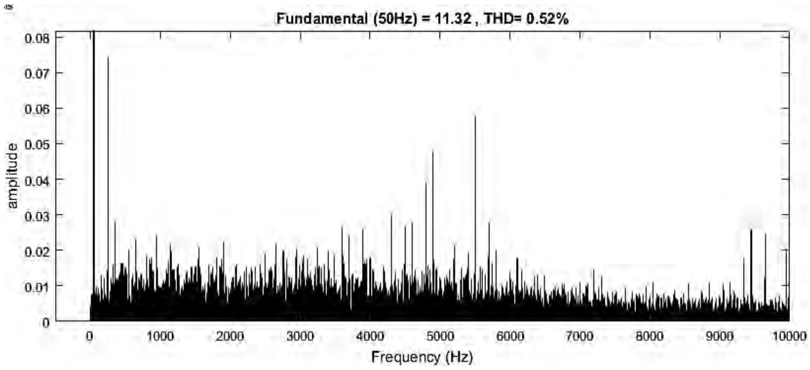


Fig. 7. Current harmonic spectrum, phase (a) with proposed controller

In Fig. 8, harmonic distortion changes are shown for different loads. Also, in Fig. 9, harmonic distortion variations for different inductances are shown. According to Fig. 9, the total harmonic distortion value (THD), is equal to 0.85%.

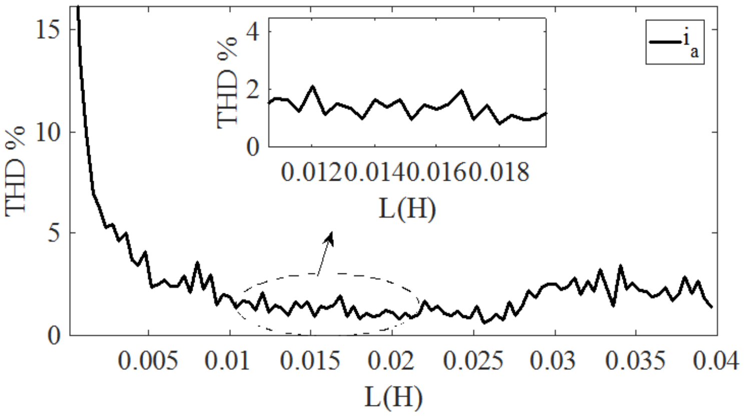


Fig. 8. Harmonic distortion changes for input inductance changes with proposed controller

In the following, with the same parameters, the simulation was performed with a linear control controller. The results are shown in Fig. 10 and Fig. 11. The results confirm the optimal performance of the proposed controller to reducing in the harmonic distortion of current compared to the linear controller.

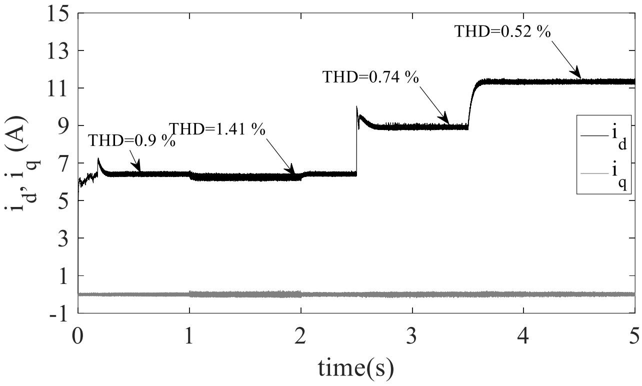


Fig. 9. Current variations and harmonic distortion in coordinates d and q with proposed controller

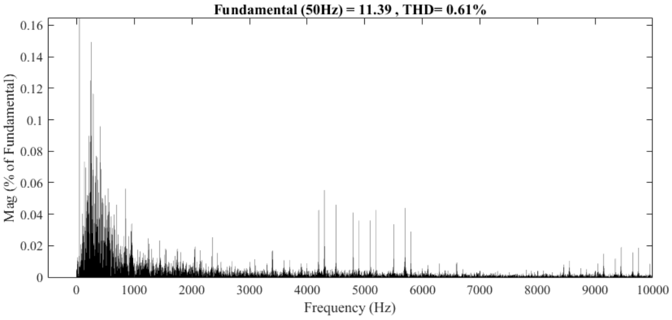


Fig. 10. Current harmonic spectrum phase (a) with PI controller.

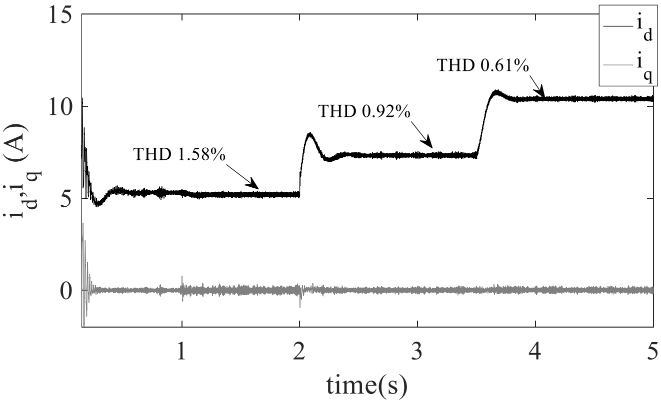


Fig. 11. Current variations and harmonic distortion in coordinates d and q with PI controller.

5. Conclusion

A nonlinear robust control using SMC technique is proposed for a three-phase three-level NPC converter. The current loop has been set to track the current references in the presence of system parameter uncertainties using SMC. The SMC task is to control the current in order to decrease its harmonics content and ensure to desired amount of active/reactive power exchange with the grid by adjusting amplitude and phase angle of converter. Results confirmed that THD of the grid current is reduced to lower than 1%, which is less than the values specified by IEEE-519 Standard. Moreover, the grid unity power factor is obtained. The simulation results impressed the effectiveness of the proposed control strategy.

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