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Fixed Frequency Sliding Mode - PI Control for Single Phase Unipolar Inverters

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***Abstract* - Sliding Mode- PI controller is recognized as robust controller with a high stability in a wide range of operating conditions, although it suffers from chattering problem. In addition, it cannot be directly applied to multi switches power converters. This paper concerns a sliding controller design with the proportional-integral (PI) control form. First, a theoretical analysis of the considered sliding PI controller is provided. Our analysis reveals that the proportional control term of the sliding PI controller, i.e., sliding proportional controller, can reduce the chattering problem and thus, the robustness can be established. Second, the chattering problem is eliminated by smoothing the control law in a narrow boundary layer, and a pulse width modulator produces the fixed frequency switching law for the inverter. The smoothing procedure is based on limitation of pulse width modulator. Therefore, the chattering problem of the proportional gain is resolved and the valuable robust control property of the sliding integral controller is illustrated again. The simulation model has been developed and tested using MATLAB software.**

***Keywords:* Pulse width modulator, Sliding PI control, Unipolar single phase inverter**

I. INTRODUCTION

Now-a-days, single-phase pulse width modulation(PWM)-based inverter (see Fig. 1), which is used in uninterruptible power supply (UPS), should supply nonlinear and critical step loads. Since the inverter output impedance is not zero, these loads can deform the sinusoidal output voltage of the inverter. According to the IEEE Standard 1547, the total harmonic distortion (THD) of the output voltage must be less than 5%, especially for nonlinear load. Table I shows the standard details for maximum acceptable harmonic voltage distortion. For inverters with 50-Hz output voltage frequency and its switching frequency higher than 2 kHz, low-frequency harmonics (2nd to 13th) should be rejected by a closed-loop controller perfectly. Moreover, the controller must perform a good regulation of the output voltage against the abrupt variations of the input voltage, output current, and the reference voltage. These demands imply to use a fast controller with good dynamic response for the inverters.

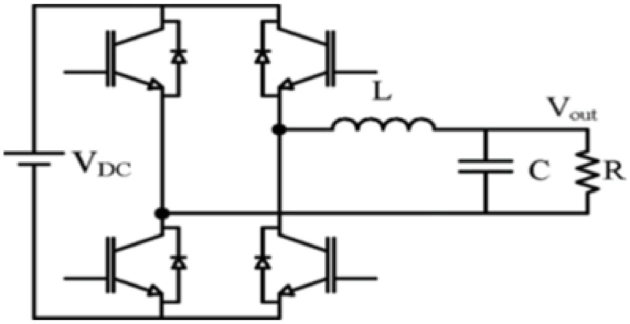

Fig. 1. PWM-based single-phase inverter.

TABLE I IEEE STANDARD 1547 FOR MAXIMUM ACCEPTABLE HARMONICVOLTAGE DISTORTION

Individual Harmonic order	h<11	11≤h<17	17≤h<23	23≤h<35	35≤h	Total Harmonic Distortion
Percent (%)	4.0	2.0	1.5	0.6	0.3	5.0

Recently, many control methods, like repetitive control, deadbeat control, multi loop feedback, hysteresis current mode control, and internal model control,have been proposed to achieve the aforementioned demands. Occasionally, nonlinear observer and harmonic elimination techniques are employed to improve the transient response. It is noticeable that these control methods are based on average model (small signal model) of the inverter, because the inverter state space equations vary when the switches state changes. In this model, discontinuous control quantity, duty ratio of switches, is approximated and modelled by a continuous variable over a number of switching cycles. Thus, it can only well describe the system behaviour close to its operating points. In fact, the instantaneous behaviours of the inverter are ignored in the average model and the model is only valid around the operating point.

II. Existing Method

The inherent switching nature of power converters is compatible with sliding mode control (SMC) feature. The SMC is well known for its robustness, stability, and good regulation properties in a wide range of operating conditions; moreover, it is not necessary to use average model of the inverter. According to the SMC theory, the main subject of the power converter control (with an inherent switching action) is the definition of a good sliding surface and switching condition to guarantee the output voltage regulation with low THD in different conditions.

In spite of the SMC excellent performance, it suffers fromchattering problem which leads to variable and high frequency switching in the converter. This phenomenon increases power losses and also produces severe electromagnetic compatibility (EMC) noise. To fix the switching frequency against line variation for step-down dc/dc converter, Tan *et al*. have introduced an adaptive feed forward control scheme that varied the hysteresis band in the hysteresis modulator of the SM controller in the event of any change of the line input voltage.

In addition to chattering problem, discontinuous control law (switching condition) that is generated by a sign function or hysteresis modulator in the SMC is only suitable for single switch converter such as buck converter due to two stable states of the sign function output. Consequently, the SMC method could not be applied to multi switch converters such as the single-phase inverters, directly. At least, four stable states are needed toobtain suitable switching pulses for unipolar single phase.

In this paper, based on SMC theory, a fixed frequency and high-performance controller is proposed to apply to unipolar single-phase inverters. A pulse width modulator is employed to fix the switching frequency and to generate the suitable switching law for the four switch inverter.

III. SMC

One effective control tool compliant with the switching nature of the inverter is represented by SMC, which is derived from the variable structure system theory. This control method has individual advantages for control of converters such as

1) Stability against severe variations of load and the line;

2) Robustness;

3) Good dynamic response;

4) Very simple implementation.

Based on SMC theory, a discrete control law can be defined for each system in which the system states X follow desired states Xd.

The discrete control law is as follows:

U= sign (S(X)) = +1 if S(X) > 0

= -1 if S(X) < 0Where$S(X)$ is a scalar function and$S(X)$=0 is called switching or sliding surface. This function is defined as

$$S(X) = \left[\frac{d}{dt} + \lambda\right]^{n-1} (X - X_d) \qquad (2)$$

where n is the system order (n _= 1) and λ is a strictly positive constant. According to Lyapunov theorem, to ensure the stability of the system, the following inequality should be established

while η is a strictly positive constant:

$$\frac{1}{2}\frac{dS^2}{dt} \le -\eta|S| \qquad (3)$$

This means that

$$\frac{lt}{S \to 0^+} S(X) > 0 \qquad \frac{lt}{S \to 0^+} \dot{S}(X) < 0 \qquad (4)$$

$$\frac{lt}{S \to 0^-} S(X) < 0 \qquad \frac{lt}{S \to 0^-} \dot{S}(X) > 0$$

If conditions (4) or sliding conditions are established, starting from any initial condition, the discontinuous control law u makes the state trajectory to reach the sliding surface in a finite time, and then slides along the surface towards

X_d exponentially. In the slidingmode, the system dynamic response is represented by $S(X) = 0$.

IV. UNIPOLAR SINGLE-PHASE INVERTER

There are two popular PWM techniques (see Fig. 2), applying to single-phase inverters, unipolar and bipolar PWM. The unipolar PWM employs + VDC and zero to provide positive outputs, and − VDC and zero to provide negative outputs, but the bipolar PWM only uses + VDC and − VDC to make either positive or negative outputs. Hence, carrier harmonic content in the bipolar scheme is twice of unipolar scheme. Notice that, in the unipolar technique, the output voltage does not contain even harmonics and also the first high-frequency harmonic appears around twice of the switching frequency and not at the switching frequency as it would have been in the case of bipolar PWM. Because of these three attractive features of the unipolar PWM, we develop unipolar PWM in this paper.

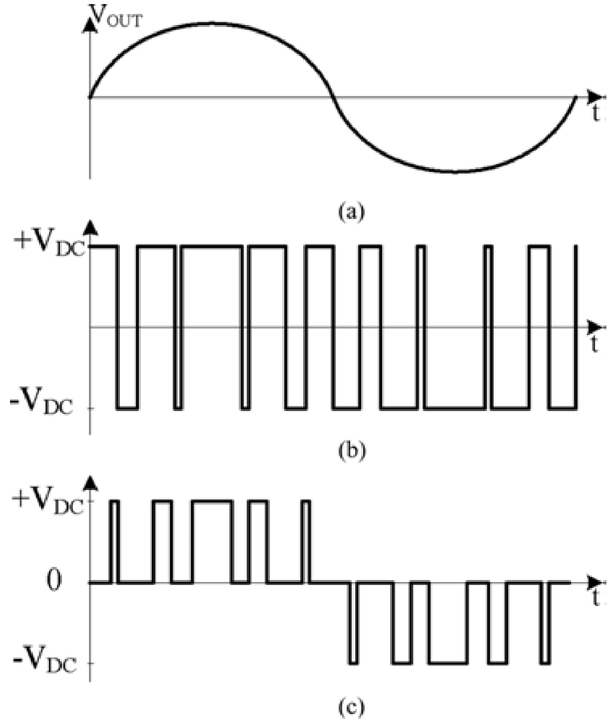

Fig. 2. (a) Inverter output voltage. (b) Bipolar PWM. (c) Unipolar PWM.

The ac output voltage of the inverter can be written as:

$$V_{out} = V_{DC} \times m \times \mathrm{Sin}\,(2\pi f_o\, t) \tag{5}$$

where V_{out}, V_{DC}, m, and f_o represent the output voltage, the input voltage, modulation factor, and output frequency, respectively.Assuming ideal elements, the state equations of the inverterare

$$\begin{aligned} L\frac{di_L}{dt} &= V_{in} * U - V_{out} \\ C\frac{dV_{out}}{dt} &= i_L - i_o = i_c \\ i_o &= \frac{V_{out}}{R} \end{aligned} \tag{6}$$

where inductor current i_L and output voltage V_{out} are selected as state variables. u is the discontinuous input of the system. It is 0 or 1 to provide positive output and, 0 or−1 to provide negative output. In addition, i_c, i_o, and R are the capacitor current, output current, and load, respectively. To implement the SMC along with PI for the inverter, it is more convenient to use a system description, which involves the output error and its derivative.

$$\begin{aligned} e &= x_1 = V_{out} - V_{ref} \\ \dot{e} &= x_2 = \dot{x}_1 = \frac{i_c}{C} \end{aligned} \tag{7}$$

where V_{ref} is the reference voltage. In the inverter, the output voltage is forced to be equal to V_{ref} by appropriate switching. Considering continuous current mode operation of the inverter and, selecting the e and $\dot{e}$ as state variables, the system equations in terms of the state variables $x1$ and $x2$ can be rewritten as follows

$$\begin{aligned} \dot{x}_1 &= x_2 \\ \dot{x}_2 &= \frac{d}{dt}\left(\frac{i_c}{C}\right) = \frac{1}{C}\frac{d}{dt}\left(i_C\right) \end{aligned} \tag{8}$$

Therefore,

$$\dot{x}_2 = -\frac{x_1}{LC} - \frac{V_{ref}}{LC} - \frac{x_2}{RC} - \frac{U * V_{in}}{LC} \tag{9}$$

The SMC for single phase unipolar inverters and the non-linear load is shown in Fig 3 and Fig 4.The values of the components are choose based on the IEC 62040-3 standard .

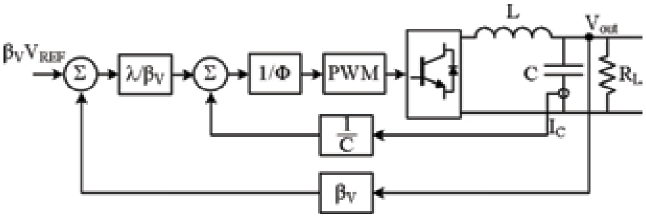

Fig 3. Existing Controller for single phase inverters

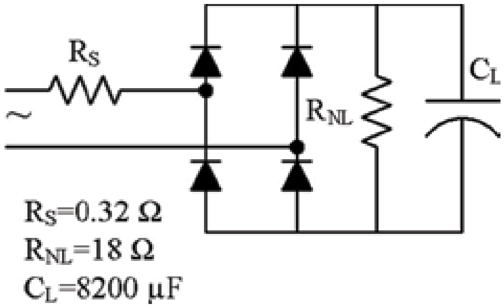

Fig 4. Nonlinear load according to IEC62040-3 standard

V. Simulation Result

The existing control method has been simulated by Simulink Toolbox in MATLAB for an inverter whose main characteristics are mentioned in Table II, in which *fs* and *fr* are switching frequency and cut-off frequency, correspondingly. Controller parameters of the simulated inverter are listed in Table III. *βV* is selected considering the electronic circuit's limitation. The simulation results is shown in fig 5 and Fig. 6.

Table II Simulated Inverter Characteristics

V_{DC}	350V
R(full load)	27.5Ω
S_{out}	6KVA
f_s	15KHZ
F	50HZ
L	357μH
C	9.4μF
f_r	2750HZ

Table III Controller Parameters

βv	0.022727
λ	15000
φ_{min}	134751
V_p	8V

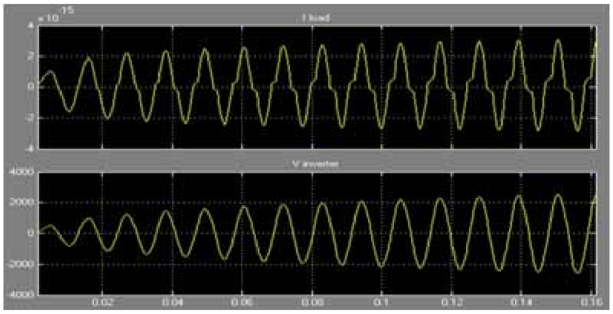

Fig.5 Simulation result. Output voltage and current at 6-kVA nonlinear load

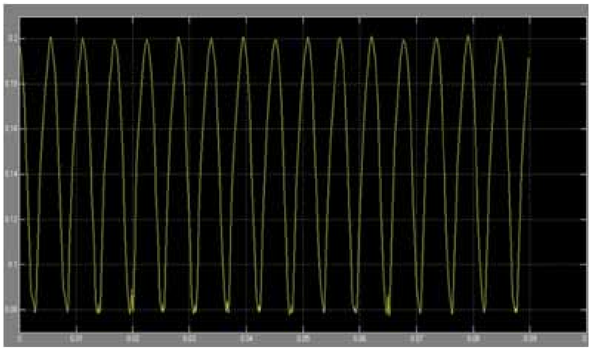

Fig 6 Total Harmonic Distortion for 6-KVA nonlinear load

V. Proposed System

Experimental results show that fixed frequency sliding mode control results in variations in dynamic responses. It leads to significant overshoot, long settling time and obnoxious oscillations before the output of interest settles down at the desired value. So in order to have a better settling time and to reduce oscillations a new control method called SlidingMode-PI Controller is introduced.

VI. PI Current Regulator Design

Conventional PI control theory is widely used in designing control systems for industrial applications. This isdue to its simplicity and low cost. PI control deals predominantlywith linear systems having constant parameters and being regulated at fixed operating points. Unfortunatelyin practical situation, however, inherent nonlinearities are unavoidable in unipolar inverters. When these nonlinearities or factors are introduced, the linear constant coefficient approximation will not always be satisfactory.

In this work we do not intend to linearize the plant since the load is inherently nonlinear. So conventional pole-placement method is not suitable in designing a PI controller of the non-linear load. For a certain operating point trialand-error method is used to find the optimum controller parameters. PWM signals are used to produce a controlled voltage to feed the single phase inverter.The duty cycle K of the PWM is proportional to controller output C(t). The controller is expressed as

$$e(t) = i(t) - i * (t) \qquad (10)$$

$$C(t) = K_d e(k)+K_i\ \Sigma^{K}{}_{J}{=}0^{e}(j) \qquad (11)$$

The controller parameters Kp, and Ki, are only optimumat a certain operating point in the sense of fast settlingtime, small overshoot and small torque ripples. When the operating point changes, Kp and Ki, should alsochange accordingly to achieve the optimum performance.

VII. Sliding Mode-PI Control Design

Controller parameters are only suitable for a certain operating point. When the operating point changes, performance deteriorates. Italso shows poor capability of tolerating disturbances. Therefore, we conclude that PI control is unacceptable forhigh performance non-linear loads.

The sliding mode control, however, has the disadvantages such as the "chattering" and steady state error,which is inferior to PI control. To integrate the advantages of the two schemes above,the sliding mode-PI control scheme can be designed as shown in Fig.7. When inverter is operating far away from the stable point, the controller is sliding mode controller, in order to acquire good dynamic characteristic. On the other hand,when the inverter is operating near to the stable point, the controller will switch to PI controller, in order to acquire good precision.

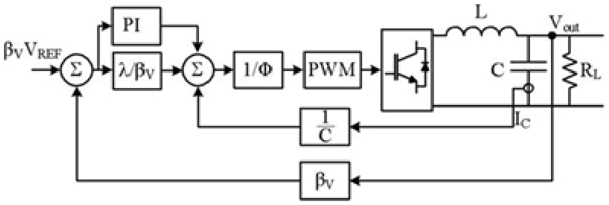

Fig. 7 Existing Controller for Single Phase Inverters

VII. Simulation Results of Proposed Work

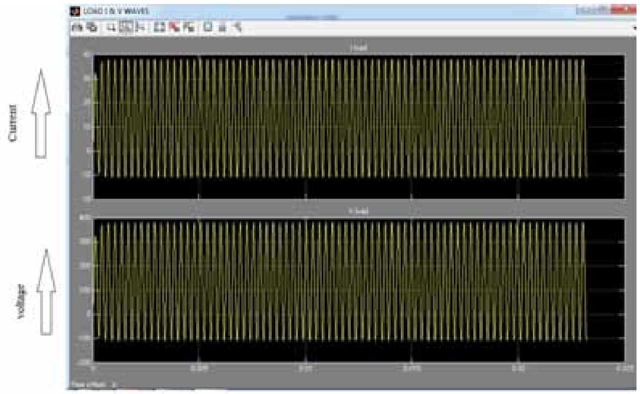

Fig. 8 Simulation result.Output voltage and current at 6- kVA nonlinear load

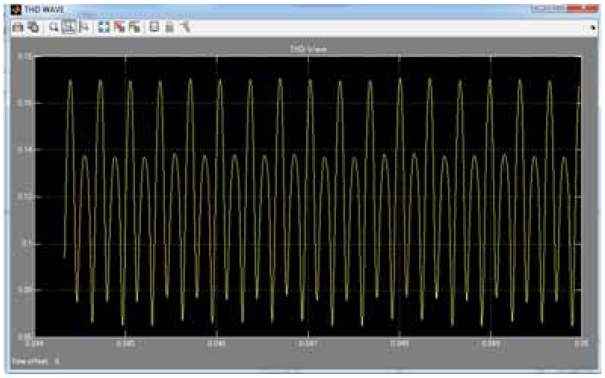

Fig .9 Total Harmonic Distortion for 6-KVA nonlinear load

VIII. Conclusion

In this work, a sliding controller design with the proportional-integral (PI) control form is presented. First, a theoretical analysis of the considered sliding PI controller and 1.7% at maximum linear and nonlinear load, respectively. The simulation and experimental results show that the load regulation is about 1% at the steady state as well. With this compensator, the load regulation was measured which has been below 0.2%. Table IV summarizes the inverter characteristics and compares them with previous works. As can be seen from Table IV, the proposed inverter shows an impressive performance that is better than or comparable to that of the previous works. Although THD of output voltage in [9] is better than this work, its switching frequency is relatively higher and it is variable from 20 to 40 kHz. Moreover, in spite of high switching frequency, it has been used a large output capacitor. Cut-off frequency of the output filter is about 520 Hz in [9], while for this work is about 2800 Hz.

Table IV Comparison of Inverter Characteristics: Published and This Work

REF	[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	THIS WORK
V_{DC}(V)	220	±110	120	300	50	±300	300	360	360
V_{AC}(V_{RMS})	140	42	50	110	28	71	210	220	220
Controller	Deadbeat	Multiple Feedback Loop Control	Virtual Resistor	Multiple Feedback Loop Control	Quasi-Sliding	Multiple Feedback Loop Control	Multiple Feedback Loop Control	Sliding	Sliding-PI Control
F_{sw}(KHZ)	6.2	2	-	8	20-40	20	5	15	15
S_{out}(KWA)	0.6	0.1	0.25	10	0.4	1	1	6	5.5
THD (NL)	2.40%	4.07%	4.20%	12.0%	0.30%	2.70%	-	1.70%	1.60%
Output Capacitor (μF)	80	100	200	120	60	-	40	9.4	9.4
Inductor (mH)	1.3	5	5	0.2	1.5	-	0.1	0.357	0.357

REFERENCES

[1] K. Zhang, Y. Kang, J. Xiong, and J. Chen, “Deadbeat control of PWM inverter with repetitive disturbance prediction,” in *Proc. 14thAnnu. Appl.Power Electron. Conf. Expo.*, 1999, pp. 1026–1031.

[2] N. M. Abdel-Rahim and J. E. Quaicoe, “Analysis and design of a multiple feedback loop control strategy for single-phase voltage-source ups inverters,” *IEEE Trans. Power Electron.*, vol. 11, no. 4, pp. 532–541, Jul. 1996.

[3] P. A. Dahono and E. Taryana, “A new control method for single-phasePWM inverters to realize zero steady-state error and fast response,” in*Proc. 15th Int. Conf. Power Electron. Drive Syst.*, 2003, pp. 888–892.

[4] Y. T.Woo and Y. C. Kim, “A digital control of a single-phase ups inverterfor robust ac-voltage tracking,” in *Proc. 30th Annu. Conf. IEEE Ind.Electron. Soc.*, Busan, Korea, Nov. 2–6, 2004, pp. 1623–1628.

[5] A. A. Ahmad, A. Abrishamifar, and S. Elahian, “Fixed frequency slidingmode controller for the buck converter,” in *Proc. 2nd Power Electron.,Drive Syst. Technol. Conf.*, Tehran, Iran, Feb. 2011, pp. 557–561.

[6] W. Guo, S. Duan, Y. Kang, and J. Chen, “A new digital multiple feedback control strategy for single-phase voltage-source PWM inverters,” in *Proc.Int. Conf. Elect. Electron. Technol.*, Aug. 2001, vol. 2, pp. 809–813.

[7] A. M. Salamah, S. J. Finney, and B. W. Williams, “Single-phase voltage source inverter with a bidirectional buck–boost stage for harmonic injectionand distributed generation,” *IEEE Trans. Power Electron.*, vol. 24, no. 2, pp. 376–387, Feb. 2009.

[8] AdibAbrishamifar, Ahmad Ale Ahmad, and Mustafa Mohamadian, “Fixed Switching Frequency Sliding Mode Control for Single-Phase Unipolar Inverters,” *IEEE Trans. on power electronics,* vol 27,no.2, May2012.

[9] Yang Haiqing, Sanjib K. Panda, Liang Yung Chii, “Performance Comparison of Sliding Mode Control with PI Control for Fourquadrant Operation of Switched Reluctance Motors,” IEEE Trans. Power Electron., vol. 14, pp. 381-387, May 1999.