Comparative Study of Different Switching Surfaces for Sliding Mode Control of a 40 kVA Single-phase UPS Inverter

Shiva Darvishzadeh, AbdolReza Rahmati, and Adib Abrishamifar

Abstract—In this paper, the effect of switching surface on sliding mode control of a single phase inverter is studied. Capabilities of three switching surfaces in chattering elimination, THD reduction and steady state error improvement are compared. The performance of these switching surfaces has been investigated through simulation. Simulation results show that after chattering improvement by adding first integral term, adding second integral term is not advisable.

Index Terms—Chattering, sliding mode control, switching surface.

I. INTRODUCTION

Uninterruptible power supplies are essential parts in interfacing critical loads such as computers, communication systems, medical equipments, and data processing systems to the utility power grid. Problems like power failure, spike/transient, under voltage, over voltage, noise and etc, may cause problems such as electrical equipments destroying or data missing.

UPS systems provide clean and continuous power to load under normal or abnormal power conditions. The output voltage waveform of a good UPS must be sinusoidal, with fixed frequency, fixed amplitude, and low total harmonic distortion (THD) for any type of loads.

Up to now many control methods have been proposed for UPS control. Many years control methods like space vector modulation [1], deadbeat control [2], repetitive-based control [2], and sliding mode control [3]-[5] have been used for this purpose. In recent years intelligent control algorithms like neural networks [6], fuzzy control [7], and neuro-fuzzy [8] have been proposed.

Each of these methods has some advantages and disadvantages but because of the importance of UPS, choice of the best control method is so significant.

Among them, sliding mode control (SMC) has been considerable every time. This is because this method obtains fast response to different distortions and also is robust against parameters variations and distortions. SMC is especially suitable for power converters, which are variable structure systems [4].

The main problem of SMC is called chattering, which is

result of switching frequency limits. This phenomenon enforces system to oscillate around switching surface. In the inverter applications, it causes undesirable high frequency voltage harmonics in UPS inverters [5].

So far, many methods have been proposed for chattering elimination. In this paper, we studied the effect of switching surface on chattering elimination. Here we use sliding mode control for a 40 kVA single phase UPS inverter. Capabilities of three switching surfaces are compared. These switching surfaces are different in an additional integral term.

II. SLIDING MODE CONTROL FOR SINGLE PHASE INVERTER

The main structure of a single phase inverter (as shown in figure 1) consists of inverter stage, output filter (LC) and load. r_L and r_C are equivalent series resistors (ESR) of inductor and ESR of capacitor respectively (r_C assumed to be negligible).

Fig. 1. PWM inverter used in UPS

Assuming ideal components, the system equations are:

$$uV_{dc} = L \frac{di_L}{dt} + r_L i_L + v_C \quad (1)$$

$$i_C = i_L - i_O \quad (2)$$

$$i_C = C \frac{dv_C}{dt} \quad (3)$$

The aim of control is that $v_O(t)$ track $v_{ref}(t)$. Where $v_{ref} = V_m \sin(\omega t)$.

Consider $X = [x_1 \ x_2 \ \dots \ x_{n-1}]^T = \begin{bmatrix} \tilde{x} & \dot{\tilde{x}} & \dots & \tilde{x}^{(n-1)} \end{bmatrix}^T$ as state

vector, the sliding surface is defined as [9]:

$$S = \left(\frac{d}{dt} + \lambda \right)^{(n-1)} \tilde{x} \quad (4)$$

Manuscript received October 18, 2012; revised November 24, 2012.

The authors are with the Electrical Engineering Department of Iran University of Science and Technology (IUST), Tehran, Iran (e-mail: shiva.darvishzadeh@gmail.com, rahmati@iust.ac.ir, abrishamifar@iust.ac.ir).

Equivalent control (u_{eq}) can be obtained by solving $\dot{S}(x)=0$. Employing $u=u_{eq}$ can maintain the system at $\dot{S}(x)=0$ if the system dynamics is certain. But because of uncertainties in model, a discontinuous term is added to u_{eq} :

$$u = u_{eq} - k \text{sign}(S) \quad (5)$$

This term guarantees reaching and existence conditions of sliding mode ($S \dot{S} < 0$). Although this discontinuous term overcomes model uncertainties but causes chattering in practice that is an undesired phenomenon.

First we choose output-voltage error and its derivative as state variables.

$$X_1 = [x_1 \ x_2]^T = \left[(v_o - v_{ref}) \left(\frac{dv_o}{dt} - \frac{dv_{ref}}{dt} \right) \right]^T \quad (6)$$

$$x_1 = v_o - v_{ref} \quad (7)$$

$$x_2 = \dot{x}_1 = \dot{v}_o - \dot{v}_{ref} = \frac{i_C}{C} - \dot{v}_{ref} \quad (8)$$

So the sliding surface is defined as:

$$S_1(x) = x_2 + \lambda x_1 = \dot{x}_1 + \lambda x_1, \lambda > 0 \quad (9)$$

$S_1(x) = 0$ defines a straight line with gradient equal to λ in state space. λ value must satisfy reaching and existence conditions of sliding mode. It also determines the transient response, bigger λ causes faster response.

At second step we add integral terms to sliding surface. The integral terms improves steady state error of output voltage. So two other sliding surfaces are defined in (10) and (11).

$$S_2(x) = 2\lambda x_1 + x_2 + \lambda^2 x_3, \lambda > 0 \quad (10)$$

where $x_3 = \int (v_o - v_{ref}) dt$.

$$S_3(x) = 3\lambda x_1 + x_2 + 3\lambda^2 x_3 + \lambda^3 x_4, \lambda > 0 \quad (11)$$

where $x_4 = \int \int \{ (v_o - v_{ref}) dt \} dt$.

Now these three sliding surfaces must be compared to understand which one is the best in control of single phase inverter. For this reason we consider $\lambda=1000$ in all three switching surfaces.

Fig. 2. Simulink model of UPS inverter with sliding mode control

III. SIMULATION RESULTS

In order to compare capabilities of various switching surfaces mentioned in this paper, a 40 kVA single phase inverter is simulated using Matlab/Simulink. The block diagram of control system is shown in Figure 2.

The inverter parameters used in simulation are $V_{dc}=250$ V, $L=280$ μ H, $C=1.7$ mF, $r_L=0.3$ m Ω , $f_{sw}=1500$ Hz, and $v_{ref} = 110\sqrt{2}\sin(100\pi t)$.

We use a PWM generator unit, which modulates control signal (output of sliding mode controller) to control pulses of IGBT gates. This means fixed switching frequency. Because we use the perfect model of inverter in simulation, the results are near to real condition.

The simulation was done for three switching surfaces and three loads (no load, resistive, parallel RC with 0.8 Power Factor).

Fig. 3-6 show output voltages and currents of controllers with various switching surfaces in step change of load (from no load to full load).

Fig. 3. Output voltage and current of inverter under step change of load from no load to full load (controller with $S_1(x)$).

Fig. 4. Output voltage and current of inverter under step change of load from no load to full load (controller with $S_2(x)$).

Fig. 5. Output voltage and current of inverter under step change of load from no load to full load (controller with $S_3(x)$).

These figures shown that waveform of output voltage in full load are better than no load. By adding integral terms in switching surface, steady state error of output voltage was improved and the waveforms became much cleaner.

Table I and II compare measured THD and fundamental harmonic amplitude of output voltage in all conditions, which improve by adding integral terms in switching surface.

TABLE I: MEASURED THD(%) OF OUTPUT VOLTAGE IN VARIOUS CONDITIONS

Load Switching surfaces	No load	Resistive load (0.3025 Ω)	parallel RC with 0.8 Power Factor
$S_1(x)$	2.5	1.7	0.5
$S_2(x)$	2	1.6	0.3
$S_3(x)$	1.7	1.4	0.3

TABLE II: MEASURED FUNDAMENTAL HARMONIC AMPLITUDE OF OUTPUT VOLTAGE (VOLTS) IN VARIOUS CONDITIONS

Load Switching surfaces	No load	Resistive load (0.3025 Ω)	parallel RC with 0.8 Power Factor
$S_1(x)$	143.1	144.2	151.7
$S_2(x)$	152.3	153.3	154.5
$S_3(x)$	155	155.1	154.4

Fig. 6. Phase trajectory of controller with $S_1(x)$ under parallel RC load

Fig. 7. Phase trajectory of controller with $S_2(x)$ under parallel RC load

Fig. 8. Phase trajectory of controller with $S_3(x)$ under parallel RC load

Fig. 6-8 show phase trajectories of controllers with various switching surfaces under parallel RC load. It is obvious that chattering is reduced by adding integral terms to switching surfaces because of amplitude error reduction. But with comparison look between figures 7 and 8, it will be denoted that chattering in second controller is less than third one. So after adding first integral term (x_3) to switching surface, adding second integral term (x_4) has a low (or reverse) effect on chattering elimination.

IV. CONCLUSIONS

In this paper a comparison between some switching surfaces of a sliding mode controller has been done. Simulation results show that adding integral of voltage error to state variables causes reduction in steady state error and THD of output voltage and improvement of chattering.

Also it was denoted that adding second integral of voltage error to switching surface is not a good idea because by hardware addition, no sufficient improvement is obtained.

REFERENCES

- [1] J. I. Leon, R. Portillo, L. G. Franquelo, S. Vazquez, J. M. Carrasco, and E. Dominguez, "New Space Vector Modulation Technique for Single-Phase Multilevel Converters," *IEEE International Symposium on Industrial Electronics*, 2007, pp. 617 – 622.
- [2] G. Kecun and D. Yuxing, "DSP Control Method of Single-phase Inverters for UPS Applications," in *Proceedings of the 26th Chinese Control Conference*, 2007, pp. 670-672.
- [3] O. Krker, H. Kmrrgil, and A. Doganalp, "Sliding Mode Control of Single-Phase UPS Inverters Using a Three-Level Hysteresis Switching Function," in *Proc. of 32nd Annual Conference on Industrial Electronics*, 2006, pp. 331 – 335.
- [4] S. Chen, Y. M. Lai, S. C. Tan, and C. K. Tse, "Fast response low harmonic distortion control scheme for voltage source inverters," *IET Power Electronics*, 2009, vol. 2, no. 5, pp. 574–584.
- [5] S. J. Chiang, T. L. Tai, and T. S. Lee, "Variable structure control of UPS inverters," *IEE Proc.-Electr. Power Appl.*, November 1998, vol. 145, no. 6, pp. 559–567.
- [6] H. Deng, R. Oruganti, and D. Srinivasan, "Neural Controller for UPS Inverters Based on B-Spline Network," *IEEE Trans. on Industrial Electronics*, vol. 55, no. 2, pp. 899 – 909, Feb. 2008.
- [7] E. D. Bolat, "DSP Based Implementation of Current Mode Fuzzy Gain Scheduling of PI Controller for Single Phase UPS Inverter," Springer-Verlag Berlin Heidelberg, *KES 2006*, Part I, pp. 841-849.
- [8] . F. Bay and . Atacak, "Realization of a Single Phase DSP Based Neuro-Fuzzy Controlled Uninterruptible Power Supply," *IEEE International Symposium on Industrial Electronics*, 2007.
- [9] J. Jacques, E. Slotine, and W. Li, *Applied Nonlinear Control*, 1991.
- [10] A. R. Husain, M. N. Ahmad, and A. H. M. Yatim, "Chattering-free Sliding Mode Control for an Active Magnetic Bearing System," *World Academy of Science, Engineering and Technology*, vol. 39, 2008, pp. 385-391.

Shiva Darvishzadeh was born in Dezfoul, Iran, in 1986. She received the B.Sc. and M.Sc. degrees in Electronics Engineering from Iran University of Science and Technology (IUST) in 2008 and 2010 respectively.

Her fields of interest are power electronics and microcontroller-based system design.

Abdolreza Rahmati was born in Abadeh, Iran, in 1951. He received the B.Sc. degree in electronics engineering from Iran University of Science and Technology (IUST), Tehran in 1979, and the M.Sc. and Ph.D. degrees in power electronics from Bradford University, West Yorkshire, U.K. in 1987 and 1990, respectively.

He has been a member of the faculty at IUST where he is currently an Associate Professor. He was Deputy for Educational Affairs and Postgraduate Studies in the Department (1992 to 2003), and a Visiting Professor at the Illinois Institute of Technology (IIT), Chicago, USA (September 2004 to May 2005). His fields of interest are microprocessors and microcontroller-based system design, motor drives and control, HVDC transmissions, modulation strategies for power electronic systems, multilevel inverters, and power devices. Dr. Rahmati is a member of the Institution of Engineering and Technology (IET), and Engineering Council, U.K.

Adib Abrishamifar received the B.Sc., M.Sc. and Ph.D. degrees in Electronics Engineering from Iran University of Science and Technology (IUST) in 1989, 1992 and 2001, respectively. He has been with the Department of Electrical Engineering, IUST, since 1993.

His current research activities include analog integrated circuit design and power electronics.