SLIDING MODE CONTROL FOR DC-AC CONVERTER

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To my beloved MOTHER, who have fulfilled my heart with love and brightness.

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ABSTRACT

The aim of this study is to design a sliding mode controller (SMC) for DC-AC converter to track the desired AC voltage under load variation. In order to design the controller, a set of differential equations describing the plant need to be established to obtain state-space equation of the system. The state variables of the control system are the variables which come from the energy storage elements, such as the inductor current or capacitor voltage. In converters, the level of current is a function of load and most of the time is nonlinear. The suggested controller does not need current sensors and only the desired AC voltage is used as reference. Variation of resistive load is considered as uncertainty and it causes that system to become unstable, so that output voltage has not the ability to track reference sinusoidal voltage. The effect of load changing on the system is compensated effectively by SMC. Two indices are considered for measuring the existing error between output and reference voltage which are integral of absolute error (IAE) and integral of total control power (ITCP). Also, two gains from SMC are optimized by using GA optimization technique in order to minimize the error. Finally, the results are compared with existing PID controller which is implemented to the system. From simulation, it is observed that SMC is more robust, fast and stable against perturbations in contrast to PID controller in DC-AC converter.

ABSTRAK

Tujuan kajian ini dijalankan ialah untuk merekabentuk sebuah pengawal berterusan yang dinamakan sliding mode controller (SMC). Pengawal ini digunakan untuk menjadikan penukar single-phase aras teras (DC) – aras alayalik (AC) menjejaki voltan AC yang diingini dengan perubahan beban. Untuk mereka-bentuk pengawal tersebut, satu set persamaan pembezaan yang menerangkan sistem kajian perlu diwujudkan mengikut hukum KCL dan KVL. Seterusnya, set persamaan pembezaan matematik ini digunakan untuk mendapatkan persamaan state-space sistem kajian tersebut. Sebagai satu sistem fizikal, pemboleh ubah keadaan sistem kawalan ialah elemen penyimpan tenaga seperti arus induktor atau voltan kapasitor. Projek ini membentangkan kerja pemodelan matematik dan simulasi dwikutub PWM yang diaplikasikan kepada satu DC-AC satu fase (inverter) sebagai skema suis kawalan. Seterusnya, projek ini juga membentangkan kaedah merekabentuk SMC untuk mendapatkan nilai voltan AC yang dikehendaki dalam pengeluaran dengan beban yang di variasi kan. Pengawal yang dicadangkan ini mempunyai ciri-ciri berikut: pertama, pengawal yang terhasil adalah sangat mudah untuk dilaksanakan, tidak perlu sensor semasa dan hanya voltan output yang dikehendaki digunakan sebagai rujukan. Di samping itu, ia mempunyai tindak balas yang cepat dan teguh di bawah beban yang variasi.

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LIST OF SYMBOLES

I_l	-	Inductor current
V_c	-	Capacitor voltage
V_{inv}	-	Controller output
R	-	Resistive load
$\dot{I}_l$	-	Derivative of inductor current
$\dot{V}_c$	-	Derivative of capacitor voltage
V_{dc}	-	DC voltage
s	-	Sliding surface
v_{ref}	-	Reference voltage
$e(t)$	-	Error
k_d	-	Coefficient of error
$\dot{s}$	-	Second-order sliding surface
$\dot{e}$	-	1^{st} error derivative
$\ddot{e}$	-	2^{nd} error derivative
$\ddot{v}_c$	-	2^{nd} derivative of output
u_{eq}	-	Equivalent controller signal
u_s	-	Nonlinear controller signal
U	-	Controller signal
$\hat{f}$	-	Estimate of dynamics
f	-	Real dynamics
f_s	-	Switching frequency
m_i	-	Modulation index
η	-	Strictly positive constant
K	-	Coefficient of sign function
f_i	-	Fitness function

LIST OF ABBREVIATIONS

VSS	-	Variable Structure System
SMC	-	Sliding Mode Control
SPDT	-	Single pole double throw
PWM	-	Pulse width modulation
GA	-	Genetic algorithm
IAE	-	Integral absolute error
ITCP	-	Integral of total control power
PSS	-	Power System Stabilizer
PID	-	Proportional Integral Derivative
THD	-	Total Harmonic distribution

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CHAPTER 1

INTRODUCTION

1.1 Power electronics

Power electronics is used to change the characteristics of electrical power to suit particular applications in the case of current and voltage magnitude or/and frequency. This is the technology that dealing with different branches of learning.

Some applications of power electronics are in transportation (electrical locomotives), utilities (HVDC), industrial (motor drive systems), consumer products (air conditioning) and medical equipment.

Power conversions are divided to AC-DC converter (rectifier) which converts input AC to variable magnitude DC, AC-AC converter that input AC converts to variable magnitude variable frequency AC, DC-AC converter (inverter) that converts input DC to variable magnitude variable frequency AC and DC-DC converter that input DC converts to variable magnitude DC.

1.2 DC-AC converter

Inverter is an electrical instrument which transforms direct current/voltage (DC) to alternating current/voltage (AC); the converted AC can be at any demanded voltage and frequency with the use of proper transformers, switching, and control circuits. A physical DC-AC converter is shown in Figure 1.1.

Figure 1.1: Physical DC-AC converter

Inverters can be discovered in a diversity of shapes, including full bridge or half bridge, three phase or single phases. They must control the frequency and magnitude of the output voltage. This is performed by Pulse Width Modulation of the converter switches and therefore such converters are called PWM converters.

Basically, PWM converters have a constant DC voltage in the case of magnitude. Also, magnitude and frequency are controlled by AC output voltage. The PWM is the most imperative part of a DC-AC conversion system. Furthermore, it must also have the ability to improve from transients caused by external disturbances as rapidly as possible.

There exist many types of inverters such as square wave, modified sine wave, pure sine wave, resonant, synchronous, solid state and so on. Solid-state inverters are used in a wide variety of applications, from small switching power supplies in computers, to large electric utility high-voltage direct current applications that carry bulk power. They are also used to supply AC power from DC sources like batteries or solar panels.

Some of other inverter’s applications are AC machine derive, uninterruptible power supply (UPS), machine tools, induction heating, locomotive traction, static var generation (power factor correction) and photovoltaic.

1.3 Single Phase Full Bridge Inverter

These days, with the rapid reproduction of power converters connected as loads, a PWM DC-AC converter is essential to transport non-linear output current [1]. A single phase inverter circuit and its output example is illustrated in Figure 1.2. It contains of four switching element which are labeled as S1, S2, S3 and S4. The processes of single phase full bridge converter can be separated into two states. Usually, the switches S1 and S4 are turned on and retained on for one half period and S2 and S3 are turned off at the same time. At this state, the output voltage through the load is equal to $+V_{dc}$. When S2 and S3 are turned on, the switches S1 and switches S4 are turned off, then at this stage the output voltage is equal to $-V_{dc}$. The output voltage will vary consecutively from positive half period and negative half period.

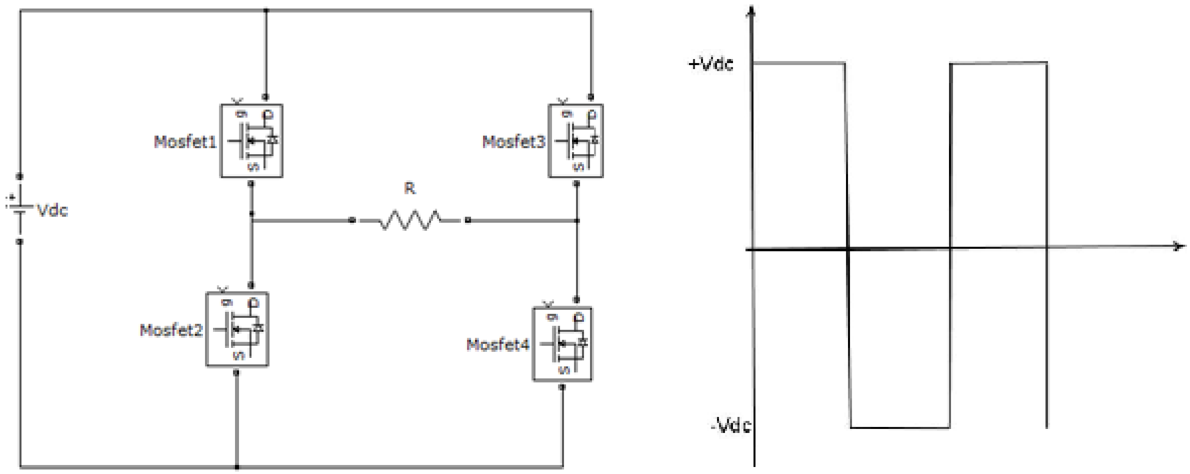

Figure 1.2: Single phase converter topology and its output example

The DC-AC converter takes power from a DC source (voltage or current) and transports to an AC load. The output variable of the inverter is a low distortion AC voltage or AC current of single-phase.

1.4 Overview on Sliding Mode Control (SMC)

Many techniques to design Variable Structure Systems (VSS) are based on sliding mode. VSS with SMC was first proposed and expanded in the early 1950's in the Soviet Union by Emelyanov and several co-researchers [1].

Nonlinear system model may come from the determined choice of a simplified demonstration of the system's dynamics or from actual uncertainty of the plant (e.g., unknown plant parameters). Control of nonlinearity is one of the main problems in control science. Stability in control is one of the most significant approaches to deal with model uncertainty where the method can resolve this problem by unidentified disturbances of the system or modeling the errors.

SMC is an important robust and stable control approach that is introduced for nominal and uncertain model. To protect the stability of the system, SMC provides a organized approach for the class of the system that it has been applied.

There are two key factors which must be considered in the SMC. The first one is sliding manifold that is used to switch between different configurations. Switching manifold which is a chosen manifold that system state is forced to move along, should be used to determine the closed loop system performance [2]. The other one is control rule which can retain and force the states remain on the manifold.

Figure 1.3 displays an example trajectory of a system under SMC. The sliding surface is described by s = 0 and the sliding mode along the surface starts after the finite time when system trajectories have reached the surface. In this figure, phase plane trajectory of a system being stabilized by a sliding mode controller. The system states "slides" along the line s = 0 after the initial reaching phase. The specific s = 0 surface is chosen because it has desired reduced-order dynamics when forced to it. In this case, $s = \dot{x}_1 + x_1 = 0$, relates to the second-order system $\dot{x}_1 = -x_1$, which has an exponentially stable source [2].

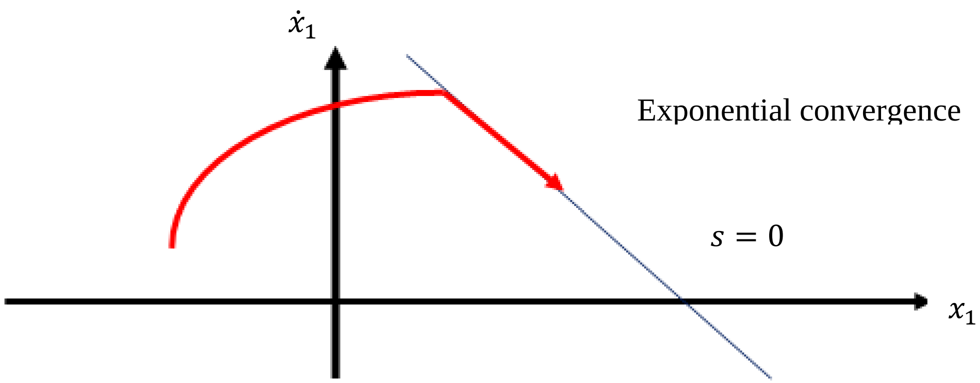

Figure 1.3: Graphical interpretation

1.5 Importance of SMC

The most attractive characteristic of SMC are robustness and invariance to uncertainties. These situations are available when the unbounded switching on the sliding surface is possible. However, this is not possible in practical conditions because of parasitic dynamics such as external disturbances. These parasitic dynamics signify the fast actuator and sensor dynamics which are frequently disregarded in the open-loop model used for control design [2]. Insensitive to a specific class of uncertainty for closed loop response, stability and good dynamic response are some advantages of SMC as reported in many established literatures [2], [7] and [19].

In this search, the procedure of control is such a way that the inverter output voltage (i.e. load voltage) will be compared at each stage with the reference voltage. The achieved error, is given as input to the SMC, and the controller output will effect on four pulses with appropriate changing of their duty cycles as can be seen in Figure 1.4. Due to this change the output voltage will be maintained constant during the loading conditions.

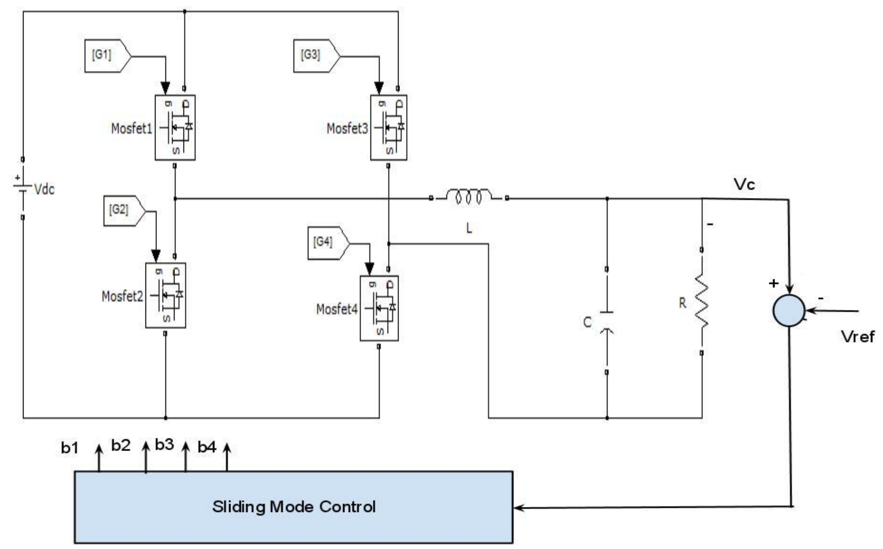

Figure 1.4: A single phase inverter with SMC

1.6 Statement of the problem

The argued problem is that with the load variation at the AC side, the amount of amplitude and frequency of output AC voltage will be changed, because output voltage is directly affected by the load variations as its uncertainty. This cause that output voltage cannot track the reference voltage and system become unstable.

There are several weaknesses to the design SMC for DC-AC converter. One of them is that, although it can be designed suitable controller parameters, but sometimes it requires time-consuming trial-and-error procedures. To remedy this problem, genetic algorithm (GA) optimization is proposed to optimize the parameters also, reduce the power of controller signal (ITCP) and integral absolute error of output signal (IAE) in this study.

1.7 Objectives of the study

The objectives of this work are listed as follows:

1. To derive the mathematical model for DC-AC converter.

2. To design a suitable SMC with the aim of tracking reference voltage beside load variation presented as uncertainty.

3. To optimize the parameters of controller with GA optimization technique in order to minimize the error between reference and output voltage.

4. To simulate the results and compare them with existing PID controller.

1.8 Scope of Study

In this project the scopes of work are given as follows:

1. Steady-state model of DC-AC converter is re-derived.
2. SMC is designed with considering load as uncertainty.
3. The controller parameters are optimized by GA optimization techniques.
4. Designed controller is verified in MATLAB simulink environment.
5. Results are compared with existing PID controller.

1.9 Chapter summary

In this chapter, a brief introduction about the power electronics and DC-AC conversion system and their applications are discussed. Also, an introduction about the importance of SMC in variable structure systems (VSS) such as converter systems is presented. Finally, the objective and scope of this project is demonstrated.

REFERENCES:

[1] Utkin, V. I. (1977). Variable structure systems with sliding modes. *IEEE Trans. Automat. Contr.*Vol. AC-22: pp. 212-222.

[2] Young, K. D., Utkin, V. I., and Ozguner, U. (1999). A control engineer's guide to sliding mode control. *IEEE Trans. Control Syst.*, Vol. 7, No. 3, pp. 328–342.

[3] Tzou, Y., Hsu, H. (1997). FPGA based SVPWM control IC for PWM inverters. *IEEE Trans. on Power Electronics*, April 10, pp. 138–143.

[4] Wong, L. K., Leung, F. H. and Tam, P. K. S (1997). A simple large-signal nonlinear modeling approach for fast simulation of zero-current-switch quasi-resonant converter. *IEEE Transactions on Power Electronics*, 12(3), pp. 437-442.

[5] Choi, C. T. and Li, C. K. (2000). Large signal modeling of quasi-resonant converter using regulated unified model. *Computer in Power Electronics IEEE*, the 7th Workshop on 16-18 July, pp. 134-138.

[6] Font, J., Martinez, L. and Fuinjoan, F. (1992). Large signal modeling of a boost converter with output filter. *Circuit and Systems ISCAS '92 Proceeding IEEE Symposium*, 3-6 May, 4, pp.1899-1902.

[7] Huspeka, J. (2009). Second order sliding mode control of the DC motor. *17th International Conference on Process Control*, June 9–12, Strbsk´e Pleso, Slovakia, pp. 340-345.

[8] Liu, Y. F. and Sen, P. C. (1994). A large-signal model for current-programmed boost converter. *Industry Application Society Annual Meeting, IEEE,* 2(2-6), pp. 1106-1112.

[9] Jawad F. and Ghazanfar S. G. (2009). Modeling and simulation of a three-phase inverter with rectifier-type nonlinear loads. *American Journal of Physics,* Vol.2, issue 4, pp. 307-316.

[10] Tajuddin, M. F. N., Ghazali, N. H., Siong, T. C. and Ghazali, N. (2009). Modeling and simulation of modified unipolar PWM scheme on a single phase DC-AC converter using PSIM. *Proceeding of 2009 student Conference on Research and Development (SCOReD 2009)*,16-18 Nov, UPM Serdang, Malaysia.

[11] Holtz, J., Lotzkat, W., Khambadkone, A. (1992). On continuous control of PWM inverters in the over modulation range including the six step mode. *Proc. of IECON'92 conference,* , San Diego, pp.307-312.

[12] Atsuo, K., Kiyoshi, I. (1988). High frequency deadbeat control of Three Phase PWM inverter used for uninterruptible power supply. *Power electronics specialists conference*. *PESC '88 Record., 19th Annual IEEE,* Japan, Vol. 2, pp. 644- 649.

[13] Kawamura, A. and Hoft, R. (1984). Instantaneous feedback controlled PWM inverter with adaptive hysteresis. *IEEE Transactions on Industry Applications*, *IA-20, 4*, pp. 769-775.

[14] Weiss, G., Zhongy, Q., Green, T. and Liang, J. (2004). H^{∞} repetitive control of DC-AC converters in micro-grids. *IEEE Transactions on Power Electronics*. Vol. 19. pp. 219-230.

[15] Leyva, R., Luis, M. S., Bruno, J., Jean, C. M. and Francisco, G. (1997). Identification and control of power converters by means of neural networks. *IEEE transactions on circuits and systems.* Vol. 44. No. 8. pp. 257-264.

[16] Rajarajeswari, N., Thanushkodi, K. (2008). Design of an intelligent bi-directional DC-DC converter with half bridge topology. *European Journal of Scientific Research ISSN 1450-216X*. Vol. 22, No. 1, pp. 90-97.

[17] Liping, G., John Y. and Nelms, R. (2011). Comparative evaluation of sliding mode fuzzy controller and PID controller for a boost converter. *Electric Power Systems Research 81*. pp. 99–106.

[18] Silva, J. F. and Paulo, S. (1993). Fixed frequency sliding modulator for current Mode PWM inverters. *Power Electronics Specialists Conference*, *PESC '93 Record., 24th Annual IEEE.* Lisbon. pp. 623- 629.

[19] Carpita, M., Farina, P. and Tenconi, S. (1993). A single phase sliding mode controlled inverter with three levels output voltage for UPS or power conditioning applications. *Proceedings of the Conference EPE*. Brighton. pp. 272-271.

[20] Perry, G., Liu, Y. and Sen, P. (2004). A new design method for PI-like Fuzzy logic controllers for DC-DC converters. *In Proc. PESC-Aachen,* Aachen, Vol. 5. pp. 3751-3757.

[21] Habetler, T. G. and Harley, R. (2001). Power electronic converter and system control. *Proc. IEEE,* Vol. 89. No. 6. pp. 913-925.

[22] Md. Ayob, S., Ahmad Azli, N. and Salam, Z. (2009). PWM DC-AC converter regulation using a multi-loop single input Fuzzy PI controller. *Journal of Power Electronics,* Vol. 9. No. 1. pp. 872-878.

[23] Utkin, V.I. (1993). Sliding mode control design principles and applications to electric drives. *IEEE Transaction on Industrial Electronics.* Vol. 40. pp. 23-36.

[24] Sabanovic, A., Ohmsh, K. and Sabanovic, N. (1993). Control of PWM three phase converters: A sliding mode approach. *Power conversion Conference,* Yokohama. pp. 188-193.

[25] Malesani, L., Rossetto, L., Spiazzi, G. and Zuccato, A. (1993). An AC power supply with sliding mode control. *Conference Record of the 1993 IEE*. Vol. 2. pp. 1115-1121.

[26] Chiarelli, C., Malesani, L., Pirondini, S. and Tomasin, P. (1993). Single-Phase, three-level, constant frequency current hysteresis control for UPS applications. *Fifth European Conference on Power Electronics and Application*. Vol. 4. pp. 180-185.

[27] Chang, E. C., Liang, T. J., Chen, J. F. and Chang, F. J. (2007). Real-time implementation of grey fuzzy terminal sliding mode control for PWM DC–AC converters. *IET Power Electronics.* Vol. 1. pp. 235-244.

[28] Sainana, A. (2005). A novel sliding mode observer applied to the three-phase voltage source inverter. *European Conference on Power Electronics and Applications.* pp. 12-17.

[29] Mattavelli, P., Rossetto, L. and Spiazzi, G. (1993). General purpose Sliding Mode Controller for DC-DC converter applications. *IEEE Power Electronics Specialists Conference* – pp. 609 615.

[30] Vazquez, N., Alvarez, J., Aguilar, C. and Arau, J. (1998). Some critical aspects in Sliding Mode Control design for the boost inverter. *Power Electronics Congress VI IEEE International.* pp.76-8.

[31] Sanchis Gurpide, P., Alonso Sadaba, O., Marroyo Palomo, L., Meynard, T. and Lefeuvre, E. (2001). A new control strategy for the boost DC-AC inverter. *Power Electronic Specialists Conference 2011 IEEE 32nd Annual.* Vol.2. pp. 974-979.

[32] Sanchis, P., Ursaea, A., Gubia, E. and Marroyo, L. (2005). Boost DC–AC inverter: A new control strategy. *IEEE Transactions on Power Electronics*. Vol. 20. NO. 2. pp. 343-353.

[33] Cortes, D., Alvarez, J. and Vazquez, N. (2006). Output feedback sliding-mode control for the boost inverter. *32nd Annual Conference on IEEE Industrial Electronics.* pp. 1890 – 1895.

[34] Moin, N. H., Zinober, A. S. I. and Harley, P. J. (1995). Sliding mode control design using Genetic Algorithm. *First International Conference on Genetic Algorithms in Engineering Systems.* pp. 238-244.

[35] Kristinsson, K. and Dumont, G. A. (1992). System identification and control using genetic algorithms. *IEEE Transaction on Systems, Man and Cybernetics*. Vol. 22. pp. 1033- 1046.

[36] Goldberg, D. E. (1989). *Genetic Algorithms in Search, Optimization and Machine Learning*. (1st ed.) Addison-Wesley Professional.

[37] Sundareswaran, K., Vadali, K. V., Nadeem, S. K. and Shyam, H. N. (2008). Robust controller identification for a boost type DC-DC converter using Genetic Algorithm. *IEEE Region 10 and Third International Conference on Industrial and information system.* pp. 1-5.

[38] Holmes, G. and Lipo, T. (2003). *Pulse width modulation for power converters: Principles and practice.* (1st ed.) Wiley-IEEE Press.

[39] Biel, D., Guinjoan, F., Fossas, E. and Chavvaria, J. (2004). Sliding mode control design of a boost-buck switching converter for AC signal generation, *IEEE Trans*. pp. 1539–1552.

[40] Nguyen, V. M., Lee, C. Q. (1996). Indirect implementation of sliding mode control law in buck-type converters. *IEEE Applied Power Electronics Conf. and Expo. (APEC)*, Vol. 1, pp. 111-115.

[41] Tan, S. C., Lai, Y. M., Cheung, M. K. H. and Tse, C. K. (2005). On the practical design of sliding mode controlled buck converter. *IEEE Trans. Power Electron*., Vol. 20. No. 2. pp. 425-437.

[42] Levant, A. (1993). Sliding order and sliding accuracy in sliding mode control. *Int. J. Control*. Vol. 58. pp. 1247–1263.

[43] Emelyanov, S., Korovin, S. and Levant, A. (1996). High-order sliding modes in control systems. *Computational mathematics and modeling Conference*, Vol. 7, No. 3, pp. 294–318.

[44] Punta, E. (2001). *Second order sliding mode control of nonlinear multivariable systems*. (1st ed.) Institute of Intelligent Systems for Automation National Research Council of Italy, ISSIA-CNR, Genoa, Italy.

[45] Fridman, L. and Levant, A. (1996). *Higher order sliding modes as a natural phenomenon in control theory, in Robust Control Via Variable Structure and Lyapunov Techniques*. London: Springer Berlin / Heidelberg. Vol. 217. pp. 107–133.

[46] Shiau, L. G., and Lin, J. L. (1997). Direct and indirect SMC control schemes for DC-DC switching converters. *36th SICE Annual Conference*. pp. 1289-1294.

[47] Jung, S. L. and Tzou, Y. Y. (1993). Sliding Mode Control of a Closed-loop Regulated PWM Inverter under Large Load Variations. *24th Annual IEEE on Power Electronics specialists Conference*. pp. 616-622.

[48] Pisano, A. (2000). *Second order Sliding Modes: Theory and Applications*. PHD Thesis. Dipartimento di Ingegneria Elettrica ed Elettronica (DIEE), Universit´a degli Studi di Cagliari.

[49] Wilfrid, P. and Barbot, J. P. (2002). *Sliding mode control in engineering*. (1st ed.) CRC Press. France.

[50] Liping, G. (2006). *Design and implementation of digital controllers for buck and boost converters using linear and nonlinear control methods*, Auburn, Alabama. pp. 69.

[51] Tokat, S., Eksin, I. and Guzelkaya, M. (2002). Sliding mode control using a nonlinear time-varying sliding surface. *10th Mediterranean conference on control and automation*. Lisbon.

[52] Jacques, J., Slotine, E. and Weiping, L. (1991). *Applied Nonlinear Control*. (1st ed.) Prentice Hall Englewood Cliffs, New Jersey.

[53] Trigg, M. C., Nayar, V. (2006). Matlab Simulink Modeling of a Single-Phase Voltage Controlled Voltage Source Inverter. *Journal of Electronic Engineering*. pp. 80-85.

[54] Wong, C. C and Chang, S. Y. (1998). Parameter Selection in the Sliding Mode Control Design Using Genetic Algorithms. *Tamkang Journal of Science and Engineering*. Vol.1, No. 2, pp. 115-122.

[55] Buckner, G. D. (2002). Intelligent Bounds on Modeling Uncertainty, Applications to Sliding Mode Control. *IEEE Transactions on Systems, Man, and Cybernetics.* Vol. 32, No. 2.

[56] Utkin, V., Lee, H. (2006). Chattering Problem in sliding mode control systems. *International workshop on variable structure systems.* pp. 346-350.