Analysis and Design of Sliding Mode Control for a Single-Phase AC-DC Converter

Winyu Sawaengsinkasikit*, Vittaya Tipsuwanporn** and Chanlit Tarasantisuk**

*Department of Electrical Engineering, Faculty of Engineering,
Kasem Bundit University, Bangkok, Thailand
(Tel:+66-2-3202777 Ext.1213)
**Department of Instrumentation Engineering, Faculty of Engineering,
King Mongkut's Institute of Technology Ladkrabang, Bangkok, Thailand.
(Tel:+ 66-2-739-2406-7 Ext. 102, E-mail: ktvittay@kmitl.ac.th, s2061165@kmitl.ac.th)

Abstract: In this paper, analysis and control design of ac-dc converter, normally nonlinear time-varying system, using sliding mode controller to achieve fast output voltage response, disturbance rejection and robust system in the presence of load variation are demonstrated. The objective of this method is to develop methodology for output voltage to be constant and input current sinusoidal that results in nearly unity power factor, respectively. In addition the converter can be also bidirectional power flow. Simulation results using Matlab/Simulink show the effectiveness of sliding mode control system compared with linear feedback controller to guarantee enhanced PF>0.98, THD<5%, and ripple output voltage is less than 1% at the maximum output power.

Keywords: Sliding mode control, ac-dc converter, power factor correction.

1. INTRODUCTION

The conventional ac-dc power converters that are connected to the line through full-wave rectifier draw sinusoidal input current. Harmonic content in a line waveform flowing through the impedances in the electric utility distribution system can create harmonic voltages. These harmonics distort the local voltage waveform, potentially interfering with other electrical equipment connected to the same electrical device [1,4]. Also, a distorted ac input current waveform prohibits the extraction of the maximum possible real power from the utility service. Unity power factor converter employ active waveshaping of the ac input current to ensure a sinusoidal current slope, while delivering a constant dc output voltage.

This paper concentrates on control of boost ac-dc converter loaded by unknown (linear or nonlinear) resistive load. Besides the linear resistive load of particular interest is the constant power load, which is often used as a simplified model for the input impedance of a converter with output voltage regulation.

Typical linear control schemes employed in the state of the art unity power factor converters have fairly low bandwidth in order to limit the impact of output voltage ripple on input power factor. In such controllers, disturbances are attended by control actions taken at most in the order of twice per line cycle.

The fast controller presented here executes control action at a much faster rate. As a result, the fast controller achieves a fast response time to disturbances. A key feature of our controller is its ability to reject feedback of the ripple on the dc-bus capacitor by actively canceling it, so that high bandwidth can be maintained without distorting the input current during steady state operation.

In past years, a wide range of nonlinear control methods for feedback control [2,3], state estimation, and parameter identification have emerged. Among them, the sliding mode control has gained wide acceptance due to the use of straightforward fixed nonlinear feedback control functions, which operate effectively over a specified magnitude range parameter variations and disturbances. The essential property of variable structure control (VSC) is that the discontinuous feedback control switches on one or more manifold in the state space. Ideally, the switching of control occurs at infinitely high frequency to eliminate deviations from sliding manifold. In practice, the frequency is not infinitely high due to the finite switching time and the effect of unmodeled dynamics causing undesired chattering of the control. That is a well-known problem, different schemes for smoothing the control discontinuity in the vicinity of the sliding manifolds to eliminate the chattering have been suggested [5,6,7]. Once in sliding mode control, the system also has reduced parameter sensitivity. Parameter variations which are in certain subspace will not affect the dynamic system behavior. This robustness against parameter variation is one of the attractive features.

In this paper, a unified control approach for output dc voltage and input current of boost converter with unity power factor on the use of the sliding mode design method is presented. Simulation results are presented to confirm the characteristics of the proposed sliding mode control system.

2. SYSTEM CONFIGURATION AND PROPOSED CONTROL SCHEME

2.1 AC-DC converter model

The proposed system configuration is shown in fig.1. The main power circuit consists of a bridge with antiparallel diode, which is connected to the single-phase supply through an inductor L. A load and capacitor C are connected to the dc side of the converter. The inductor L performs the voltage boost operation in combination with the capacitor C and, at the same time, acts as a low-pass filter for the for the ac line current. The dynamics of the single phase boost converter for the ac current control is described as:

$$\frac{d_{is}}{dt} = -\frac{R}{L}i_s + \frac{1}{L}\left(v_s - u * V_o\right) \tag{1}$$

and output voltage control as

$$\frac{dV_o}{dt} = -\frac{V_o}{R_o C} + \frac{i_s}{C} * u \tag{2}$$

$$\text{where} \quad \begin{cases} u = 1 & if\ S_1\ and\ S_4\ are\ on \\ u = -1 & if\ S_2\ and\ S_3\ are\ on \end{cases} \quad \text{and} \quad \begin{matrix} V_o > \left|v_s\right| \\ v_s = V_m \sin \omega t \end{matrix} \tag{3}$$

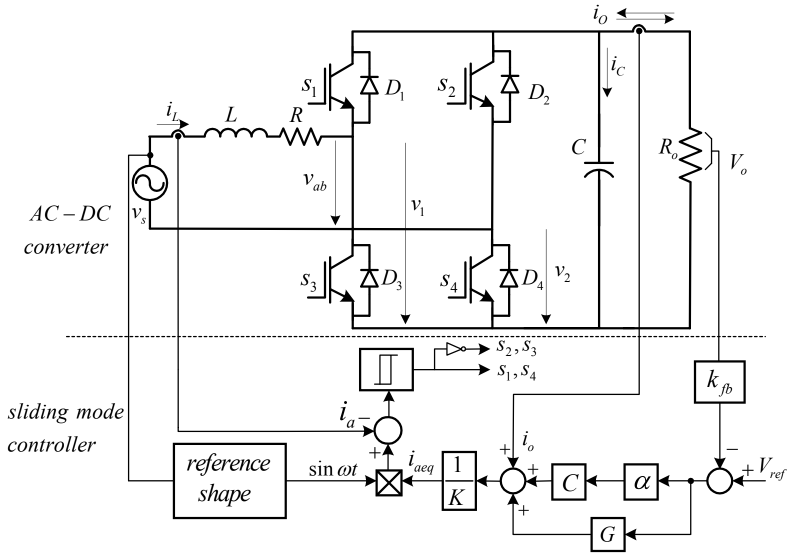

Fig.1 System configuration and proposed control scheme.

2.2 Sliding mode control scheme

The sliding mode surface gives the sequence and the duration of the ON and OFF switching state for given dynamic specifications. The converter is used as a constant voltage power supply. The sliding surface is given by

$$\sigma = \frac{de}{dt} + \alpha e \tag{4}$$

Output voltage error is

$$e = V_{ref} - V_o \tag{5}$$

and

$$\frac{de}{dt} = \frac{dV_{ref}}{dt} - \frac{dV_o}{dt} \tag{6}$$

A time-varying surface σ in sliding mode

$$\sigma = -(\frac{v_o}{R_oC} - \frac{i_o}{C} * u) - \alpha(V_{ref} - V_o) \tag{7}$$

The problem of variable structure control (VSS) is to determine u^+ and u^-, the system will reach the sliding mode and preserve it. The control is defined by the switching law:

$$u = \begin{cases} u^+(x,t); \sigma > 0 \\ u^-(x,t); \sigma < 0 \end{cases} \tag{8}$$

The control is determined from the sliding mode condition. The existence of the sliding mode requires the fulfilment of fillipov's law condition [1,3]

$$\lim_{\sigma \to 0^-} \dot{\sigma} > 0 \,, \ \lim_{\sigma \to 0^+} \dot{\sigma} < 0 \tag{9}$$

To make the treatment of inequations for the existence of the sliding mode, assume the reference voltage V_{ref} to be constant, that the derivative of reference is zero, boost operation $V_o > |v_s|$ and neglected line resistance.

$$\dot{\sigma} = \left[\frac{u}{LC}(v_s - V_o * u) + (-\frac{V_o}{R_oC} + \frac{i_s * u}{C})(\alpha - \frac{1}{R_oC}) \right] \tag{10}$$

$$\lim_{\sigma \to 0^-} \dot{\sigma} > 0, u^- = -1, = -\frac{1}{LC}(v_s + V_o) - \frac{1}{C}(i_s + \frac{V_o}{R_o})(\alpha - \frac{1}{R_oC}) > 0 \tag{11}$$

$$\lim_{\sigma \to 0^+} \dot{\sigma} < 0, u^+ = 1, = \frac{1}{LC}(v_s - V_o) - \frac{1}{C}(i_s - \frac{V_o}{R_o})(\alpha - \frac{1}{R_oC}) < 0 \tag{12}$$

The inequations that assure the existence of sliding mode, the values of control input u and the lowest values of the constant α.

$$\alpha > \frac{1}{RC} \tag{13}$$

The cascade control scheme in (14) is clearly seen in fig.1.The sliding mode control consists of the feedforward that contributes the load current compensation signal and dynamic reference voltage changes on capacitor and the feedback loop of the control error between the reference and the capacitor voltage.

$$i_{aeq} = \frac{1}{K}\left[i_o + C * (\alpha * (V_{ref} - V_o)) \right] \tag{14}$$

The output voltage V_o and the load current I_o should be measured for control signal.

3. SIMULATION RESULTS

The parameters of the simulation boost converter are listed in table 1.

Table 1 Simulation specifications

Parameter / Component	*Symbol*	*Value*
Line voltage	v_s	220 V
Output power	P_o	1 kW
Hysteresis band	Δi	0.3
Inductance	L	10 mH
Capacitance	C	2200 μF
Load resistance	R_0	106.5 Ω
Line resistance	R	1 Ω
Sliding coefficient	K	0.39

3.1 Linear feedback control

Ac-dc converter topologies are nonlinear and time-variant, because of their switching action and an alternating source. However, classical control requires linear, time-invariant representation. Therefore the modeling process can be summarized as follows: first generate the state equations for each converter mode (ON, OFF), then averaged over time; secondly, remove the time variance from the averaged equations; and finally, linearize the time variant equations to give steady state and small signal as (15).

$$\frac{\partial \tilde{v}_o}{\partial \tilde{m}} = \frac{I\cos(\Phi-\Delta)\left((sL+R_s)^2+L^2\omega^2+MV_o(sL+R_s)\right)}{2(sC+1/R_o)\left((sL+R_s)^2+L^2\omega^2\right)+M^2(sL+R_s)} \qquad (15)$$

The frequency response of the converter have been plotted as in fig.2.

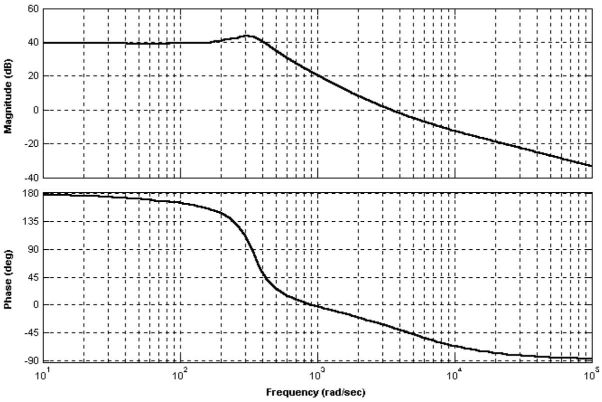

Fig.2 Frequency response of single phase ac-dc converter.

The PI controller presents lower performance as shown in fig. 3 and 4. The controller was designed by small signal frequency response in fig. 2. Fig.3, 4 illustrate the input current and output voltage when a step change in the load is applied.

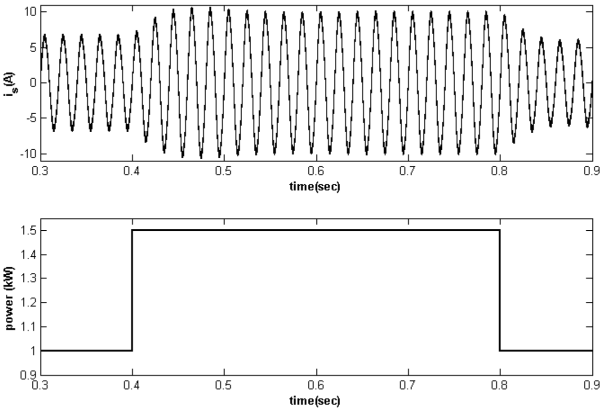

Fig.3 Input current i_s with step load 50% (PI).

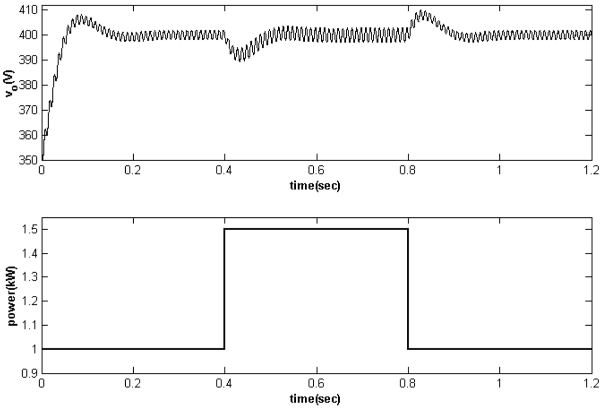

Fig.4 Output voltage V_o with step load 50% (PI).

3.2 Sliding mode control

The single-phase ac-dc converter with sliding mode control was simulated. Fig. 5 shows the low distortion input current and fast response when step load. The dynamic response of output voltage in Fig. 6 is improves, resulting in fast response and lower overshoots. The line current is exactly in phase with the input line voltage and nearly sinusoidal. Thus the input power factor approaches unity.

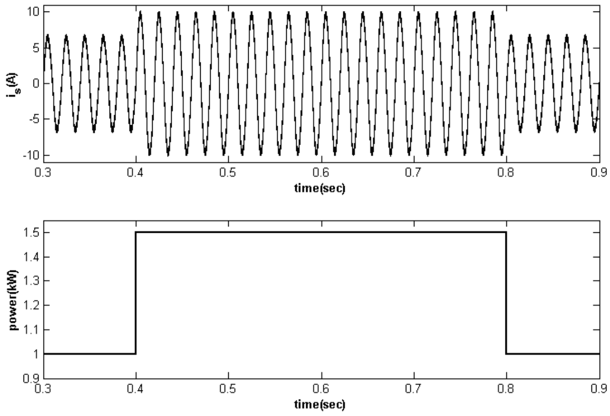

Fig.5 Input current i_s with step load 50% (SMC).

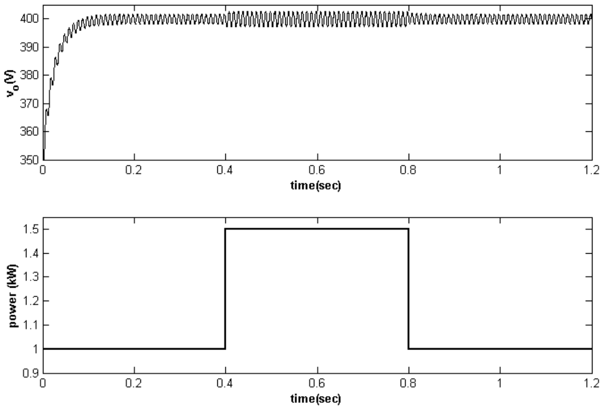

Fig.6 Output voltage V_o with step load 50% (SMC).

Fig.7 illustrates the simulation results of high power because of low distortion of an input current analysis with FFT is satisfied to IEC 61000-3-2 standard. Performance of sliding mode controller to attenuate disturbance and to robustly stabilize system with load variation.

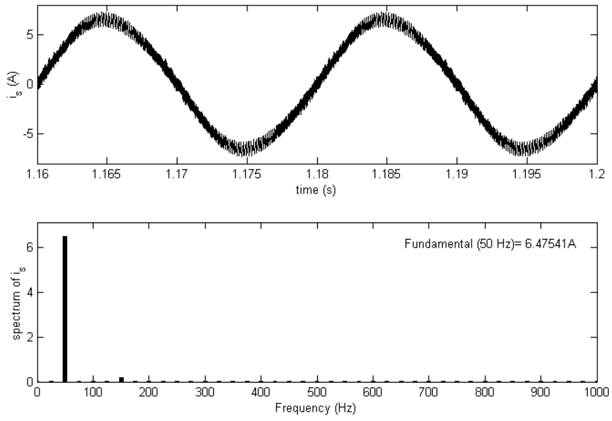

Fig.7 Harmonics spectrum of current source (i_s) at full load.

4. CONCLUSION

A sliding mode controller for ac-dc conversion with input current quality improvement and bidirectional power flow that is simple and low cost implementation compared with classical feedback controller is proposed. The results from the proposed scheme illustrated the good quality of input current and the robustness of system in the presence of load variation.

REFERENCES

[1] J. F. Silva "Control methods for power converters" in *Power electronics handbook*, M. H. Rashid, ed. NewYork,Academic, pp. 431-486, Ch. 9, 2001.

[2] R. A. DeCarlo, S. H. Zak and G. P. Matthews "Variable structure control of nonlinear multivariable systems: a tutorial" *Proceeding of IEEE,*Vol. 76, No. 3, pp 212-232, 1988.

[3] J.Y. Hung, W. Gao and J. C. Hung "Variable structure control: a survey" *IEEE Trans on Industrial Electronics,* Vol.40, pp.2-20, 1993.

[4] J. T. Boy and A.W. Green, "Current forced single phase reversible rectifier", *IEE Proceeding.* Vol. 136, Part.B, No. 5, pp. 205-211,1989.

[5] L. Rossetto, G. Spiazzi, P. Tenti, B. Fabiano and C. Licitra "Fast-response high quality rectifier with sliding-mode control" *IEEE Trans on Power Electronics*,Vol. 9, No. 2, 1994.

[6] K. Jezernik, D. Rutar and M. Milanovic "Nonlinear voltage Control of power factor boost converter" *ISIE'93*, pp. 492-497, 1993.

[7] L.G. Shiau and J. L. lin "Direct and indirect SMC control schemes for DC-DC switching converter" *SICE'97*, pp. 1289-1294, 1997.

[8] V. F. Pires and J. F. Silva, "Teaching nonlinear modeling simulation, and control of electronic power converters using Matlab/Simulink" *IEEE Trans. Education,* vol. 45, no. 3, pp. 253-261, 2002