Robust Control of an Uninterruptible Power System (UPS) Using a Discrete Fuzzy Logic Sliding Mode Controller Approach

Ntapat Worapongpat[1]* and Phongsak Phakamach[2]

[1] ศูนย์ถ่ายทอดองค์ความรู้ เทคโนโลยี นวัตกรรมชุมชน ผู้ประกอบการ การท่องเที่ยว และการบริหารการศึกษา

[1] Center for Knowledge Transfer, Technology, Community Innovation, Entrepreneurship, Tourism and Educational Administration.

[2]วิทยาลัยนวัตกรรมการจัดการ มหาวิทยาลัยเทคโนโลยีราชมงคลรัตนโกสินทร์

[2] College of Innovation Management Rajamangala University of Technology Rattanakosin, Nakhon

* Corresponding Author E-mail: dr.thiwat@gmail.com

ABSTRACT

A Discrete Fuzzy Logic Sliding Mode Control or DFLSMC for the uninterruptible power system (UPS) is presented, which is tracking a sinusoidal ac voltage with specified frequency and amplitude. The control function is derived to guarantee the existence of a sliding mode. The rules of the proposed DFLSMC are independent of the number of system state variables because the input of the suggested controller is fuzzy quantity sliding surface value. Hence the rules of the proposed DFLSMC can be reduced. The application of DFLSMC to the UPS at sinusoidal frequency has show that the proposed approach can improved the tracking performance and the output waveform of the controlled PWM inverter is much more smooth that that of the previous study methods, like the VSC and PI strategies. Furthermore, its can achieve the requirements of robustness and can supply a high-quality voltage power source in the presence of plant parameter variations, external load disturbances and nonlinear dynamic interactions.

Keywords: Fuzzy Logic Control, Sliding Mode Control, Uninterruptible Power System.

1. Introduction

An uninterruptible power system (UPS) have been used widely of computer network, instrumentation equipment and factory automation systems. The proposed scheme of the UPS, as shown in Fig. 1, consists of a rectifier, battery charger, booster, pulse width modulations (PWM) inverter, LC filter, current controlled loop and voltage controlled loop. The current controlled loop is designed to control the capacitor charge current quickly and effectively, especially when a sudden load occurs. The voltage controlled loop is designed to achieve accurate voltage tracking and minimize the total harmonic distortion in the presence of load disturbance and plant parameter variation. Such performances are usually difficult to achieve by using a simple linear controller.

In certain cases, a variable structure control or VSC approach is invariant to system parameter variations and disturbances when the sliding mode occurs [1-2]. In the sliding mode the dynamic behavior of the system becomes equivalent to that of an unforced system of lower order and the closed-loop response becomes insensitive to those changes in plant parameters which act within channels implicit in the nominal control input. The idea of VSC is to force the system to slide along a predetermined switching plane and is a variable high speed switching feedback control.

This variable structure control law provides an effective and robust means of controlling nonlinear plants. The sliding mode operation results in a control system that is robust to model certainties, parameter variations and disturbances. The VSC attains the conventional goals of control such as stabilization, tracking and regulation. Although the conventional VSC approach has been applied successfully in many applications, but it may result in a steady state error when there is load disturbance in it. In order to improve the problem, the integral variable structure control or IVSC approach is presented in [3], combines and integral controller with the variable structure control for achieving a zero steady state error under step command input. However, its performance when changing,e.g., ramp and sinusoidal command input, the IVSC gives a steady state error. The Feedforward Integral Variable Structure Control or FIVSC approach, proposed in [4-5], uses a double integral action to solve this problem. Although, the FIVSC method can give a better tracking performance than the IVSC method does at steady state, its performance during transient period needs to be improved.

Fuzzy control is a practical control method which imitates human being fuzzy reasoning and decision making processes. Fuzzy logic control is derived from the fuzzy logic and fuzzy set theory that were introduced in 1965 by Professor Lotfi A. Zadeh of the University of California at Berkeley. Fuzzy logic control can be applied in many disciplines such as economics, data analysis, engineering and other areas that involve a high level of uncertainty, complexity or nonlinearity. In engineering, engineers can use the fundamentals of fuzzy logic and fuzzy set theory to create the pattern and the rules, then design the fuzzy controllers, Finally, the output response of many systems can be improved by using a fuzzy controller[6]. The method is applicable to conduct robustness control over target for which a mode is hard to be established. The final program form of the method is simple and easy to achieve. Therefore, combining fuzzy control with the VSC would maintain the insensitivity of sliding mode control to parameter perturbation and external disturbances while in the mean time effectively eliminate the chattering phenomenon.

In this paper, the discrete Fuzzy Logic Sliding Mode Control or DFLSMC approach is presented. This approach, which is the extension of FIVSC approach, incorporates fuzzy logic control to improved the dynamics response for command tracking and strong robustness. The proposed approach is more suitable for the UPS which is tracking a sinusoidal ac voltage with specified frequency and amplitude.

The design and implementation of an UPS, which is tracking a sinusoidal command input using the DFLSMC approach is described. As a experimental results, the tracking performance can be remarkably improved and is fairly robust to plant parameter variations and external load disturbances.

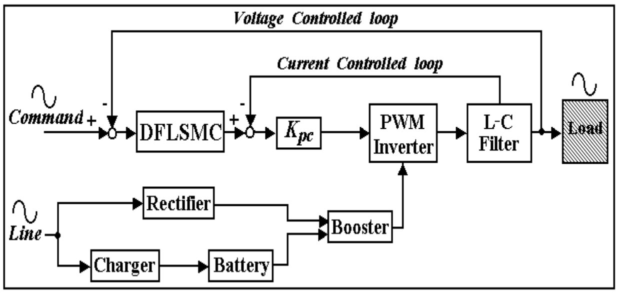


Figure 1. The functional configuration of the UPS.

2. Dynamic Modeling of The PWM Inverter With Output Filter

The block diagram of the proposed L-C output filter is show in Fig. 2, the current loop for the UPS which consists of PWM inverter circuit and power MOS as the switching device. In the PWM circuit, let sinusoidal input be e_a=$A_m$sin(ωt), then its approximate output voltage is

$$V_m = \frac{V_{DC}A_m}{2A_d}\sin(\omega t) \tag{1}$$

where V_{DC} is the dc supply voltage from booster and A_d is the triangular peak value. Thus, the mode of the PWM inverter can be synthesized to be and amplifier with constant gain

$$K_A = \frac{V_m}{e_a} = \frac{V_{DC}}{2A_d} \tag{2}$$

The current-controlled loop is designed so that the current of the capacitor can respond quickly and effectively. The mathematical model of the current-controlled loop for the UPS is shown in Fig. 3, where KA is the equivalent gain of the PWM inverter and Kpc is the compensated gain of the current loop.

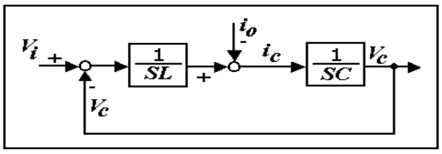


Figure 2. The block diagram of the L-C output filter.

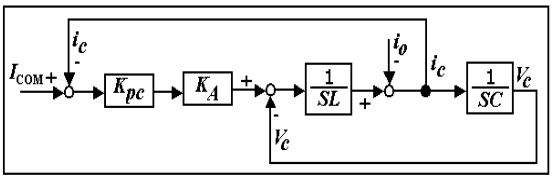


Figure 3. The block diagram of the current loop for the UPS.

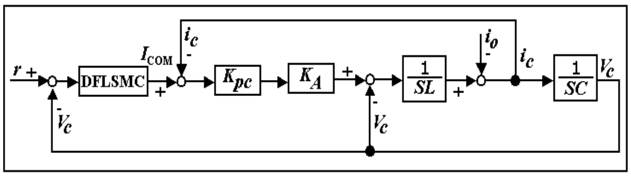


Figure 4. System configuration of the UPS with DFLSMC.

Note that the reason split inductor is used at the output filter instead of a single inductor is to lessen the effect of EMI source. The relevant equations of the filter are derived as follows:

$$V_i = L\dot{i}_L + V_c$$

$$\dot{V}_c = \frac{i_c}{C}$$

$$i_c = i_L + i_o.$$

Then, the state dynamics can be expressed as

$$\dot{i}_L = \frac{-V_c}{L} + \frac{V_i}{L} \qquad (3a)$$

$$\dot{V}_c = \frac{i_L}{C} - \frac{i_c}{C} \qquad (3b)$$

where L is the inductance; C is the capacitance; i_L is the current through inductor; V_C is the voltage across capacitor; i_o is the load current and V_i is the equivalent output voltage of PWM.

The dynamic model of the UPS with a SMFC as shown in Fig. 4, is derived as

$$\dot{z} = -e_1 \qquad (4a)$$

$$\dot{e}_1 = \dot{r} - \dot{V}_c = e_2 \qquad (4b)$$

$$\begin{aligned}
\dot{e}_2 &= \ddot{r} - \ddot{V}_c \\
&= \ddot{r} - \frac{1}{C}\left\{\frac{1}{L}\left[(U - C\dot{V}_c)K_{pc}K_A - V_c\right] - \dot{i}_o\right\} \\
&= \ddot{r} - \left\{\frac{1}{LC}\left[(U - C\dot{V}_c)K_{pc}K_A - V_c\right] - \frac{1}{C}\dot{i}_o\right\} \\
&= \ddot{r} - \frac{1}{LC}K_{pc}K_A(U - C\dot{V}_c) + \frac{1}{LC}K_{pc}K_A - V_c + \frac{1}{C}\dot{i}_o \\
&= \ddot{r} - \frac{1}{LC}K_{pc}K_A U + \frac{1}{L}K_{pc}K_A(\dot{r} - e_2) + \frac{1}{LC}V_c + \frac{1}{C}\dot{i}_o \qquad (4c)
\end{aligned}$$

where r is the input command, V_C represents output voltage, $z = -\int c_1 dt$ and $e_1 = r - V_C$.

The simplified dynamic model of the UPS control system with the FLSMC can be described as

$$\dot{z} = z - e_1 \qquad (5a)$$

$$\dot{e}_1 = e_1 + e_2 \qquad (5b)$$

$$\dot{e}_2 = e_2 + \left(\ddot{r} + bU(k) + a_1(\dot{r} - e_2) + a_2(r - e_1) + f\right). \quad (5c)$$

where

$a_1 = \frac{K_{pc}K_A}{L}$, $a_2 = \frac{1}{LC}$, $b = \frac{K_{pc}K_A}{LC}$ and $f = \frac{i_o}{C}$.

Note that the input command r in the above equation, as previously stated, is a sinusoidal ac voltage with specified frequency and amplitude, that is,

$$r = R_m \sin(\omega t).$$

The first and second time derivative of this input command are, respectively,

$$\dot{r} = R_m \omega \cos(\omega t) \text{ and } \ddot{r} = -R_m \omega^2 \sin(\omega t).$$

3. Design of DFLSMC System

The structure of FLSMC is shown in Fig. 5 can be described by the following equation of state

$$\dot{x}_i = x_{i+1}, i=1,\ldots,n-1 \quad (6a)$$

$$\dot{x}_n = -\sum_{i=1}^{n} a_i x_i + bU - f(t) \quad (6b)$$

$$\dot{x}_0 = (r - x_1) \quad (6c)$$

Figure 5. The structure of DFLSMC system.

The switching function, σ is given by

$$\sigma = c_1(x_1 - Tx_0 - rK_F) + \sum_{i=2}^{n} c_i x_i \quad (7)$$

where $C_i > 0$=constant, C_n=1 and T=integral time.

The control signal, U can be determined as follows, from (6) and (7), we have

$$\dot{\sigma} = -c_1 T(r - x_1) + \sum_{i=2}^{n} c_{i-1} x_i - \sum_{i=1}^{n} a_i x_i + bU - f(t). \quad (8)$$

Let $a_i = a_i^0 + \Delta a_i$; $i = 1,\ldots,n$ and $b = b^0 + \Delta b$; $b^0 > 0$, $\Delta b \succ b^0$.

The control signal can be separated into

$$U = U_{eq} + U_{fu}. \quad (9)$$

This condition results in

$$U_{eq} = \{c_1 T(r - x_1) - \sum_{i-2}^{n-1} c_{i-1} x_i + \sum_{i=1}^{n-1} a_i^0 x_i\} / b^0. \quad (10)$$

The transfer function when the system is on the sliding surface can be shown as

$$H(s) = \frac{X_1(s)}{R(s)} = \frac{\alpha_n}{s^n + \alpha_1 s^{n-1} + \ldots + \alpha_{n-1} s + \alpha_n}. \quad (11)$$

The transient response of the system can be determined by suitably selecting the poles of the transfer function.

Let $s^n + \alpha_1 s^{n-1} + \ldots + \alpha_{n-1} s + \alpha_n = 0$ (12)

be the desired characteristic equation(closed-loop poles), the coefficient C_1 and T can be obtained by

$C_{n-1} = \alpha_1$, $C_1 = \alpha_{n-1}$ and $T = \dfrac{\alpha_n}{\alpha_{n-1}}$.

4. Design of Fuzzy Logic Controller

By the definition

$$U_{fu} = k_1(x_1 - Tx_0 - rK_F) + \sum_{i=2}^{n} k_i x_i + k_{n+1} + K[\Delta k_1(x_1 - Tx_0 - rK_F)] + \sum_{i=2}^{n} k_i x_i \quad (13)$$

U_{fu} is required to guarantee the existence of the sliding mode under the plant parameter variations in Δa_i and Δb and the disturbances $f(t)$. Among them,

$$k_1 = \begin{cases} \alpha_1 & \text{if } (x_1 - Tx_0 - rK_F)\sigma > 0 \\ \beta_1 & \text{if } (x_1 - Tx_0 - rK_F)\sigma < 0 \end{cases},$$

$$k_i = \begin{cases} \alpha_i & \text{if } x_i\sigma > 0 \\ \beta_i & \text{if } x_i\sigma < 0 \end{cases}, i = 2, \ldots, n$$

and $k_{n+1} = \begin{cases} \alpha_{n+1} & \text{if } \sigma > 0 \\ \beta_{n+1} & \text{if } \sigma < 0 \end{cases}$.

According to (8), we know

$$\dot{\sigma} = -c_1 T(r - x_1) + \sum_{i=2}^{n} c_{i-1} x_i - \sum_{i=1}^{n} a_i x_i + bU - f(t)$$

and

$$U = U_{eq} + k_1 T(r - x_1) - \sum_{i-2}^{n-1} k_i x_i \cdot \quad (14)$$

The condition for the existence of a sliding mode is known to be

$$\sigma\dot{\sigma} < 0 . \quad (15)$$

In order for (15) to be satisfied, the following conditions must be met,

$$k_i = \begin{cases} \alpha_i < \text{Inf } [\Delta a_i - a_i^0 \Delta b / b^0 + c_{i-1} \Delta b / b^0 \\ - c_i(c_{n-1} - a_n^0)(1 + \Delta b / b^0)] / b \\ \beta_i > \text{Sup } [\Delta a_i - a_i^0 \Delta b / b^0 + c_{i-1} \Delta b / b^0 \\ - c_i(c_{n-1} - a_n^0)(1 + \Delta b / b^0)] / b \end{cases} \quad (16a)$$

where $i = 1, \ldots, n-1$, $c_0 = 0$

$$k_n = \begin{cases} \alpha_n < \text{Inf } [\Delta a_n + a_n^0 - c_{n-1}] / b \\ \beta_n > \text{Sup} [\Delta a_n + a_n^0 - c_{n-1}] / b \end{cases}$$

and where $k_{n+1} = \begin{cases} \alpha_{n+1} < \text{Inf } [-N] / b \\ \beta_{n+1} > \text{Sup}[-N] / b \end{cases}$ (16b)

Now we consider the effect of Δk_i(i=1,...n), Δk_i is the function is to eliminate the chattering phenomenon of the control system and find out Δk_i by making use of fuzzy set theory. Firstly take positive constants α and β, normalize switching function σ and its rate of change against time.

Suppose $\sigma_n = \alpha.\sigma$, (17)

$\sigma_n = \beta.\sigma$ (18)

The input variable of the fuzzy controller is

$$\sigma_n sign(x_1 - Tx_0 - rK_F),$$

$$\dot{\sigma}_n sign(x_1 - Tx_0 - rK_F),$$

$$\sigma_n sign(x_i)$$

and $\dot{\sigma}_n sign(x_i)$ (i=2,...n), the output of the controller is Δk_i.

Secondly, define the language value of σ_n and $\dot{\sigma}_n$ as P, Z, N: Δk_i is language value as PB, PM, PS, ZE, NS, NM, NB; as well as their subordinate functions as in Figs. 6~8:

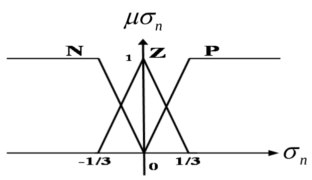


Figure 6. The subordinate function of σ_n.

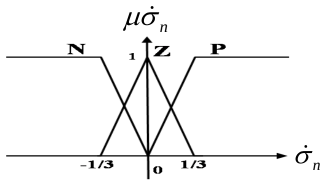


Figure 7. The subordinate function of $\dot{\sigma}_n$.

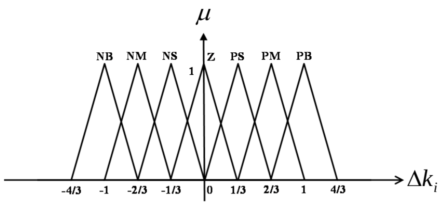


Figure 8. The subordinate function of Δk_i.

Define the following fuzzy control regularity Table 1.

Table 1. Fuzzy control regularity.

	N	Z	P
N	PB	PM	PS
Z	PS	ZE	NS
P	NS	NM	NB

According to the above form, use the fuzzy calculation method introduced in [7] and gravity method to turn fuzzy output into precise control quantity

$$\Delta k_i = \left(\int \Delta k_i \tilde{\mu}_{\Delta k_i} d\Delta k_i\right) / \left(\int \tilde{\mu}_{\Delta k_i} d\Delta k_i\right) \qquad (19)$$

When

(1) $\sigma_n \leq -\frac{1}{3}, \dot{\sigma}_n \leq -\frac{1}{3}$; it is easy to get Δk_i=1,

and when

(2) $\sigma_n \leq -\frac{1}{3}, -\frac{1}{3} \langle \dot{\sigma}_n \leq 0$; σ_n (N), $\dot{\sigma}_n$ (N,Z).

The following conditions must be met in (20).

The subordinate function of Δk_i(PB, PM) corresponding to is shown in [8-9].

Thus, points P1 and P2's abscissa are $\dot{\sigma}_n + \frac{2}{3}, \dot{\sigma}_n + 1$;

P3 and P4's abscissas are $-\dot{\sigma}_n + \frac{2}{3}, \dot{\sigma}_n + \frac{4}{3}$; then

$$\Delta k_i = \frac{-\frac{5}{2}\dot{\sigma}_n^2 - \frac{7}{6}\dot{\sigma}_n + \frac{2}{9}}{-3\dot{\sigma}_n^2 - \dot{\sigma}_n + \frac{1}{3}}$$

Using the same method we get the precise output Δk_i under other circumstances to be for i=1, σ_n is $\sigma_n sign(x_1 - Tx_0 - rK_F)$ and $\dot{\sigma}_n$ is $\dot{\sigma}_n sign(x_1 - Tx_0 - rK_F)$; for i=1, σ_n is $\sigma_n sign(x_i)$ and $\dot{\sigma}_n$ is $\dot{\sigma}_n sign(x_i)$. Finally, the control function of DFLVSC approach for simulate is obtained as

$$U = U_{eq} + k_1(x_1 - Tx_0 - rK_F) + \sum_{i=2}^{n} k_i x_i + K\left[\Delta k_i(x_1 - Tx_0 - rK_F) + \sum_{i=2}^{n} \Delta k_i x_i\right]. \quad (21)$$

Among them, U_{eq} is given by (10), k_i is given by inequality (16), Δk_i is given by (19), therefore U is a continuous function.

$$
\Delta k_i = \begin{cases}
1 & \sigma_n \le \frac{1}{3} & \dot{\sigma}_n \le \frac{1}{3} \\
\dfrac{-\frac{5}{2}\dot{\sigma}_n^2 - \frac{7}{6}\dot{\sigma}_n + \frac{2}{9}}{-3\dot{\sigma}_n^2 - \dot{\sigma}_n + \frac{1}{3}} & \sigma_n \le \frac{1}{3} & -\frac{1}{3} < \dot{\sigma}_n \le 0 \\
\dfrac{-\frac{3}{2}\dot{\sigma}_n^2 + \frac{1}{6}\dot{\sigma}_n + \frac{2}{9}}{-3\dot{\sigma}_n^2 - \dot{\sigma}_n + \frac{1}{3}} & \sigma_n \le \frac{1}{3} & 0 < \dot{\sigma}_n \le \frac{1}{3} \\
\dfrac{1}{3} & \sigma_n \le \frac{1}{3} & \dot{\sigma}_n > \frac{1}{3} \\
\dfrac{-4\dot{\sigma}_n^2 - 2\dot{\sigma}_n + \frac{1}{9}}{-6\dot{\sigma}_n^2 - 2\dot{\sigma}_n + \frac{1}{3}} & -\frac{1}{3} < \sigma_n \le 0 & \dot{\sigma}_n \le \frac{1}{3} \\
\dfrac{-3\dot{\sigma}_n^2 - 2\sigma_n - \frac{1}{2}\dot{\sigma}_n^2 - \frac{1}{2}\dot{\sigma}_n}{-3\dot{\sigma}_n^2 - 2\sigma_n - 3\dot{\sigma}_n^2 - \dot{\sigma}_n + \frac{1}{3}} & -\frac{1}{3} < \sigma_n \le 0 & -\frac{1}{3} < \dot{\sigma}_n \le 0 \\
\dfrac{-2\dot{\sigma}_n^2 - \frac{4}{3}\sigma_n + \frac{1}{2}\dot{\sigma}_n^2 - \frac{1}{2}\dot{\sigma}_n}{-3\dot{\sigma}_n^2 - 2\sigma_n - 3\dot{\sigma}_n^2 - \dot{\sigma}_n + \frac{1}{3}} & -\frac{1}{3} < \sigma_n \le 0 & 0 < \dot{\sigma}_n \le \frac{1}{3} \\
\dfrac{-\frac{2}{3}\sigma_n - \frac{1}{9}}{-6\dot{\sigma}_n^2 - 2\sigma_n + \frac{1}{3}} & -\frac{1}{3} < \sigma_n \le 0 & \dot{\sigma}_n > \frac{1}{3} \\
\dfrac{-\frac{2}{3}\sigma_n - \frac{1}{9}}{-6\dot{\sigma}_n^2 + 2\sigma_n + \frac{1}{3}} & 0 < \sigma_n \le \frac{1}{3} & \dot{\sigma}_n \le \frac{1}{3} \\
\dfrac{-\dot{\sigma}_n^2 + \frac{3}{2}\dot{\sigma}_n^2 + \frac{1}{6}\dot{\sigma}_n - \frac{1}{9}}{-3\sigma_n^2 - 3\dot{\sigma}_n^2 - \dot{\sigma}_n + \frac{2}{3}} & 0 < \sigma_n \le \frac{1}{3} & -\frac{1}{3} < \dot{\sigma}_n \le 0 \\
\dfrac{\frac{5}{2}\dot{\sigma}_n^2 - \frac{7}{6}\dot{\sigma}_n - \frac{2}{9}}{-3\sigma_n^2 - 3\dot{\sigma}_n^2 - \dot{\sigma}_n + \frac{2}{3}} & 0 < \sigma_n \le \frac{1}{3} & 0 < \dot{\sigma}_n \le \frac{1}{3} \\
\dfrac{4\dot{\sigma}_n^2 - 2\dot{\sigma}_n - \frac{1}{9}}{-6\sigma_n^2 + 2\sigma_n + \frac{1}{3}} & 0 < \sigma_n \le \frac{1}{3} & \dot{\sigma}_n > \frac{1}{3} \\
-\dfrac{1}{3} & \sigma_n \le \frac{1}{3} & \dot{\sigma}_n \le \frac{1}{3} \\
\dfrac{\frac{3}{2}\dot{\sigma}_n^2 + \frac{1}{6}\dot{\sigma}_n - \frac{2}{9}}{-3\dot{\sigma}_n^2 - \dot{\sigma}_n + \frac{1}{3}} & \sigma_n \le \frac{1}{3} & -\frac{1}{3} < \dot{\sigma}_n \le 0 \\
\dfrac{\frac{5}{2}\dot{\sigma}_n^2 - \frac{7}{6}\dot{\sigma}_n - \frac{2}{9}}{-3\dot{\sigma}_n^2 + \dot{\sigma}_n + \frac{1}{3}} & \sigma_n \le \frac{1}{3} & 0 < \dot{\sigma}_n \le \frac{1}{3} \\
-1 & \sigma_n \le \frac{1}{3} & \dot{\sigma}_n \le \frac{1}{3}
\end{cases}
\tag{20}
$$

5. The DFLSMC System for an UPS

The block diagram of DFLSMC system is shown in Fig. 9. The nominal values of the UPS parameters and the DFLSMC controller are listed in Table. 2 and Table. 3, respectively. The DFLSMC algorithm is demonstrated on a digital signal processor with the control law

$$\begin{aligned} U &= U_{eq} + \Delta U \\ &= \{(c_1 a_1^0 - a_2^0 + c_1 K_I - c_1^2)[x_1 - K_I z - rK_F] \\ &\quad + (c_1 K_I - a_2^0) K_I z + \ddot{r} + a_1^0 \dot{r} + a_2^0 r\} / b^0 \\ &\quad + (\varphi_1 |x_1 - K_I z - rK_F| + \varphi_2 |x_2| + \varphi_3) M_\delta(\sigma) \end{aligned} \tag{22}$$

where $r = \theta_c$ is desired position

$$\varphi_1 \langle -\mathrm{Sup}\left|[\Delta a_1 - a_1^0 \Delta b / b^0 - c_1(c_2 - a_3^0)(1 + \Delta b / b^0)] / b\right|$$

$$\varphi_2 \langle -\mathrm{Sup}\left|[\Delta a_2 - a_2^0 \Delta b / b^0 + c_1 \Delta b / b^0 - c_2(c_2 - a_3^0)(1 + \Delta b / b^0)] / b\right|$$

$$\varphi_3 \langle -\mathrm{Sup}\left|[\Delta a_3 + a_3^0 - c_2] / b\right|$$

$$\varphi_4 \langle -\mathrm{Sup}\left|[N] / b\right|$$

with the switching function,

$$\sigma = c_1(x_1 - K_I z - rK_F) + x_2 . \tag{23}$$

The robustness of the proposed DFLSMC approach against large variations of plant parameters and external load disturbances has been simulated for demonstration.

By considering operating points, one assumes the range of the plant parameter variations to be

$$|\Delta a_1| < 50\ \%\ a_1^0,\ |\Delta a_2| < 50\ \%\ a_2^0$$

$$|\Delta b| < 50\ \%\ b^0 \text{ and } |N| < 1200.$$

Thus, from (22), the gain φ_1, φ_2 and φ_3 must be chosen to satisfy the following inequalities :

$$\varphi_1 < -0.05,\ \varphi_2 < -0.0015 \text{ and } \varphi_3 < -0.005.$$

And, based on demonstrations, one possible set of the switching gains can be chosen as

$$\varphi_1 < -0.05,\ \varphi_2 < -0.00055 \text{ and } \varphi_3 < -0.0001.$$

Table 2. Parameters of the UPS.

Parameter	Symbol	Value	Dimension
Capacitance	C	20	μF
Inductance	L	4.5	mH
Gain of Current loop	K_{pc}	2.7	Dimensionless
Gain of PWM	K_A	12.5	Dimensionless
DC-bus	V_{dc}	300	Volt

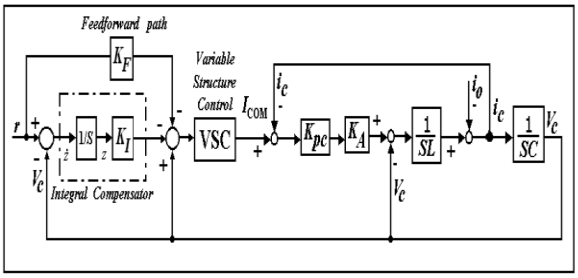


Figure 9. The block diagram of DFLSMC system for an UPS.

Table 3. Parameters of DFLSMC controller.

Symbol	**Value**
λ_1 , λ_2	$-1200.55\pm2352.84i$
λ_3	-815.93
C_1	2300
K_I	4587
K_F	18.64
φ_1	-0.05

φ_2	-0.00055
φ_3	-0.001
a_1^0	43460
a_2^0	14357
b^0	1090843
δ_0	0.1
δ_1	0.001

6. EXPERIMENTAL RESULTS AND DISCUSSIONS

The experimental results of the dynamic response are shown in Fig. 10 and Fig. 11. Fig. 10, shows the trajectory of the output voltage. Where a sinusoidal command [150sin(120πt)] is introduced and the UPS is applied with a random variation of filter parameters L and C, respectively, from 50% to 400% and 50% to 400% of the nominal value under resistive load 100Ω. These curves illustrate the robustness of the DFLSMC for the UPS under various loads and abrupt disturbance.

Fig. 11, shows the comparison of tracking errors under the same testing conditions. It is clear from the figures that DFLSMC can track the sinusoidal command input very fast and extremely. Among others, the DFLSMC approach gives the minimum tracking error.

7. Conclusions

A DFLSMC design methodology for the UPS is presented. The system combines the nonlinear sliding mode control with additional the Fuzzy Logic controller. Procedures are developed for choosing the control function for determining the coefficients of the switching plane and the integral control gain such that the system has desired properties. Also, by using a continuous function, the chattering can be effectively suppressed. The application of DFLSMC to an UPS at sinusoidal frequency has show that the proposed approach can improved the tracking performance and the output waveform of the controlled PWM inverter is much more smooth that that of the previous study methods, like the FIVSC and PI strategies. Furthermore, the experimental results demonstrated that the proposed approach can achieve the requirements of robustness and high-quality power supply. It is a practical law for the UPS control systems.

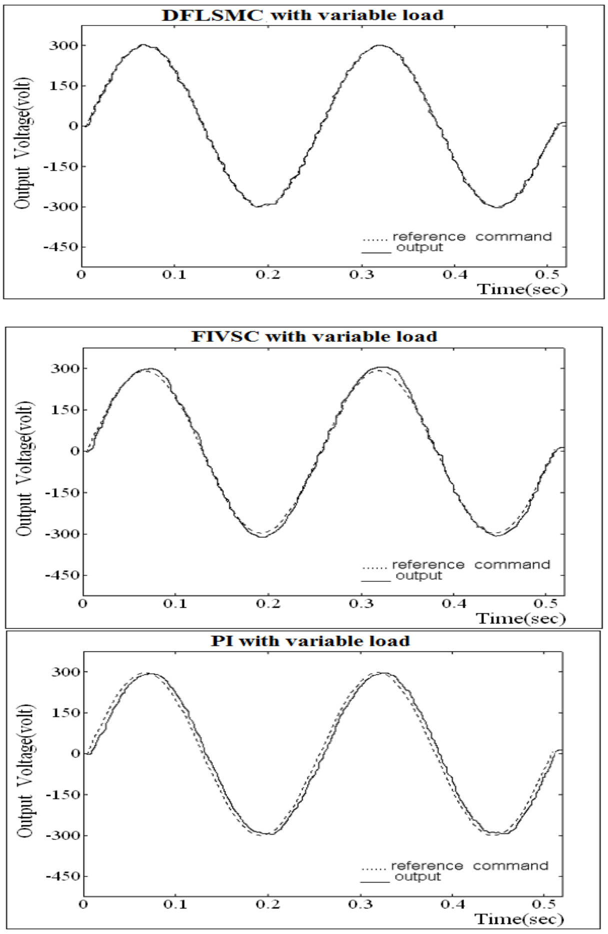
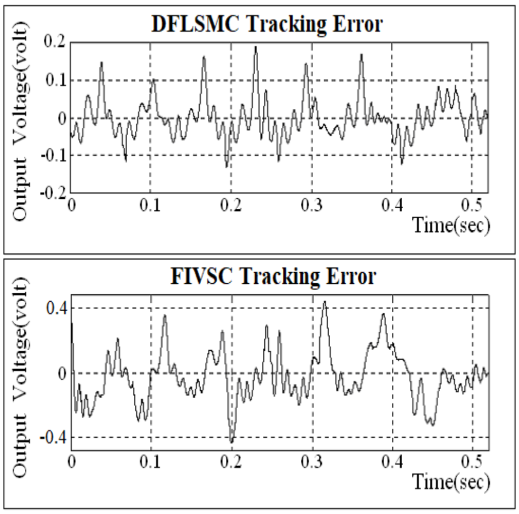


Figure 10. Comparison of sinusoidal tracking performance (output voltage)under random deviation of *L* 50 to 400%, *C* from 50 to 400%, and with resistive load = 100 Ω.



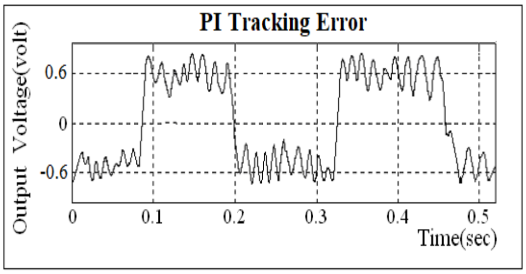


Figure 11. Comparison of tracking errors under random deviation of *L* 50 to 400%, *C* from 50 to 400%, and with resistive load = 100 Ω.

8. References

[1] U. Itkis. Control Systems of Variable Structure. New York: Wiley; 1976.

[2] V.I. Utkin, J. Guldner and J. Shi. Sliding Mode Control in Electromechanical Systems. Oxford: Taylor & Francis; 1999.

[3] T.L. Chern and J. Chang. DSP-Based Induction Motor Drives using Integral Variable Structure Model Following Control approach. IEEE International Electric Machines and Drives Conference Record. 1997. pp.9.1-9.3.

[4] S. Nungam and P. Phakamach. Design of a Feedforward Integral Variable Structure Control Systems and Application to a Brushless DC Motor Control. IEEE International Symposium on Intelligent Signal Processing and Communication Systems, Thailand. Dec. 1999. pp.390-393.

[5] P. Phakamach and C. Akkaraphong. Microcontroller-Based Discrete Feedforward Integral Variable Structure Control for an Uninterruptible Power System. The International Conference on Power Electronics and Drive Systems, Singapore, Nov. 2003. pp.1422-1427.

[6] P. Phakamach. A Variable Structure Control Based on Fuzzy Logic Algorithm with an Integral Compensation for a DC Servomotor Drives. The International MultiConference of Engineers and Computer Scientists, HongKong, Jan. 2007. pp.1510-1516.

[7] S. Thongchai. Behavior-based learning fuzzy rules for mobile robots", American Control Conference. Alaska, USA. May. 2002.

[8] L. Shiyong. Fuzzy Control. Ha Gong Da Publication Co., 1996.

[9] N. Worapongpat, P. Phakamach and U. Chaisakulkiat. UTK Journal. Rajamangala University of Technology Krungthep. 14(1). (January-June) 202