A Novel Sliding-Mode Controller Design for a Matrix Converter Drive System

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***Abstract*—In ac/ac converter applications, the matrix converter has become increasingly attractive in recent years. The matrix converter is a single stage converter. It does not require any dc-link energy storage component. So, the structure only requires small mounting place because the braking resistance or regeneration converter is unnecessary. In addition, it has a high-power-factor sinusoidal input current with a bi-directional power flow for the whole matrix converter control system. In this paper, the matrix converter is used to drive a PMSM servo motor. A sliding mode with a neural network controller design is proposed to improve the performance of the matrix converter-PMSM drive system. By using this scheme, the chattering of the speed is improved. In addition, the drive system has a better disturbance rejection capability and a fast speed response. All the control loops, including the switching strategy, current-loop, and control law, are implemented by TMS320LF2407A digital signal processor. The hardware circuit is very simple. Several experimental results are shown to validate the theoretical analysis.**

Keywords- matrix converter; sliding mode; neural network; PMSM.

I. INTRODUCTION

The matrix converter is a single stage converter. It does not require any dc-link energy storage component. So, a large capacitor as an energy storage element is not required in the dc-link. The capacitor is large and expensive and can be a critical component. Furthermore, a braking resistance is not required to absorb the energy during braking of the drive system. In addition, the matrix converter has a high-power-factor sinusoidal input current with a bi-directional power flow for the whole matrix converter drive system. In the past, the matrix converter was developed in research laboratory only and could not be popularly used in industrial area. The situation has been changed. A new technology for integrating the whole matrix converter power devices in a single package has been developed recently. It requires small mounting place because the braking resistance or regeneration converter is unnecessary. Therefore, this type of packaging can minimize the stray inductance and the size of the power devices. Compared with the rectifier/dc-link/ inverter, the matrix converter has lesser total current harmonic distortion and higher power factor at the input side. Moreover, it has longer life because no capacitance is used. As a result, the applications of matrix converters will become more popular in the near future.

Several schemes have been proposed to achieve sinusoidal input and output current waveforms and to improve the performance of the matrix converter. For example, the space vector modulating method and input power factor correction were applied in a matrix converter. But, most of these previous publications on matrix converters have dealt with modulation strategies [1]-[3]. Very few publications have considered the controller design for the matrix converter-fed ac drive system. In this paper a sliding mode with neural network control of the matrix converter-PMSM drive system is proposed.

The theory of the sliding mode controller was proposed during the late 1950s. Compared with other controllers, the sliding mode controller has a good disturbance rejection capability, a low sensitivity to system parameters' variation, and a fast speed response. Due to the advantages mentioned above and to be implemented easily, the sliding mode controller can be used in many industrial control applications properly.

In conventional sliding mode control, the control input usually possesses high frequency chattering [4]. In this paper, a sliding mode with a neural network controller design is proposed to improve the performance of the matrix converter-PMSM drive system. The neural network controller is used to determine the sliding line of the sliding mode control. The slope of the sliding line is adjusted according to the state variables of the PMSM drive system. By suitably adjusting the slope of the sliding line, the rise time and the disturbance rejection capability of the drive system are improved, and the chattering of the speed is effectively reduced.

II. SYSTEM DESCRIPTION

Figure 1 shows the configuration of matrix converter PMSM drive system to be considered in this paper. The hardware part of the system consists of a three-phase PMSM with load, a current-regulated matrix converter, and a digital signal processor system. An encoder is mounted on the motor shaft for position sensing. Two Hall-effect current sensors are used to detect the stator currents of the motor. The digital signal processor reads the shaft angle and stator currents of the motor to execute the relative control algorithms. Finally, the digital signal processor outputs the nine signals to trigger the solid-state power switches to determine the switching patterns of the matrix converter. By using the switching strategy proposed in this paper, the ac-dc and dc-ac

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conversion signals are generated separately. Then, all of the switching patterns of the matrix converter can be obtained by synthesizing the signals of the ac/dc and dc/ac stages.

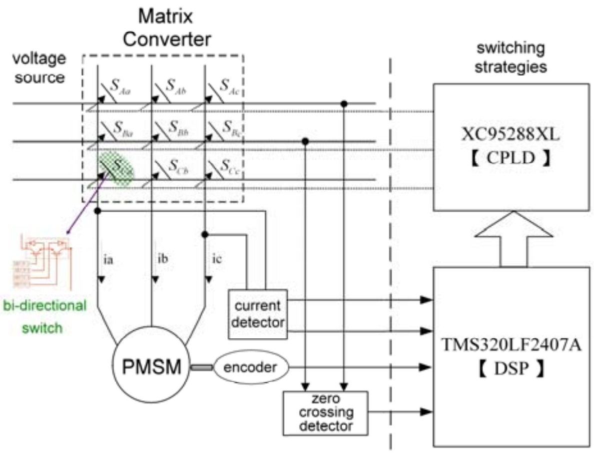

Figure 1. Configuration of matrix converter PMSM drive system.

In Figure 1, the switching of the nine switches of the matrix converter should satisfy the basic requirements. For example, the switching of the matrix converter can not short circuit the input voltage sources. In addition, it cannot open circuit the output currents of the matrix converter because the load is an inductive load. In order to achieve the safe commutating procedure, a three-stepped switching strategy is used [5]. The control circuit embedded in the CPLD for the implementation of the three-stepped switching strategy is shown in Figure 2.

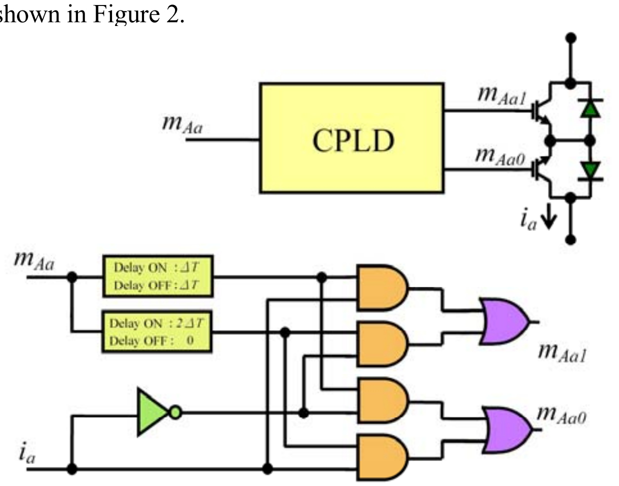

Figure 2. The control circuit of executing the three-stepped switching strategy.

III. SLIDING MODE CONTROLLER

The sliding mode controller has been widely applied to industrial area in recent years. The first step in the design of the sliding mode control is to define the sliding surface. If the initial state is not on the sliding surface, the controller must be designed such that it can attract the system state trajectory to move toward the sliding surface. The two-dimension phase plane with system state trajectory and sliding surface (line) is shown in Figure 3. The second step of the control design is to find a control law such that the state trajectory on the sliding surface can approach and keep at zero point.

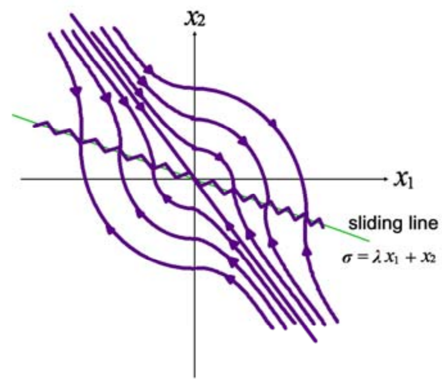

Figure 3. System state trajectory and sliding line.

The uncontrolled model of a PMSM with a current-regulated inverter can be described by the following differential equations: [6]

$$\dot{\omega}_m = -\frac{B}{J}\omega_m + \frac{1}{J}(k_t u_c - T_L) \tag{1}$$

$$\dot{\theta}_m = \omega_m \tag{2}$$

where J is the motor shaft inertia, B is the motor viscous coefficient, k_t is the torque constant, u_c is the control input, T_L is the equivalent load disturbance, ω_m is the speed of the motor, and θ_m is the shaft angle of the motor.

The block diagram of the sliding mode closed-loop control system is shown in Figure 4. To design a sliding mode controller, the state variable $x_1(t)$ is chosen as the speed tracking error $\Delta\omega_m$, $x_2(t)$ as negative acceleration, and can be expressed as

$$x_1 = \omega_m^* - \omega_m \tag{3}$$

$$x_2 = -\dot{\omega}_m \tag{4}$$

And the output of the system $y(t)$can be defined as

$$y = x_1 + \omega_m^* \tag{5}$$

where ω_m^* is the speed command.

The sliding line is chosen as [7]

$$\sigma = \lambda x_1(t) + x_2(t) = 0 \tag{6}$$

where λ is the slope of the sliding line and can be chosen by the designer. The state trajectories of the system are finally determined according the sliding line. Then, the control low $u_c(t)$ can be designed as

$$u_c(t) = \psi\ x_1(t) \tag{7}$$

where ψ is a variable scalar. If $\sigma x_1(t)$ is greater than or equal to zero, ψ is set as α, however, if $\sigma x_1(t)$ is less than zero, ψ is set as β. Therefore, ψ can be expressed as

$$\psi = \begin{cases} \alpha & \sigma x_1 \geq 0 \\ \beta & \sigma x_1 < 0 \end{cases} \tag{8}$$

where α and β are gain parameters.

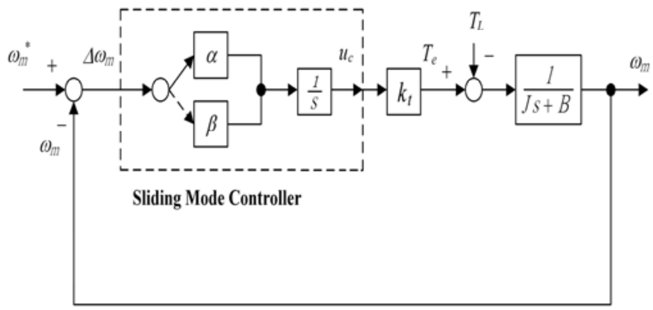

Figure 4. The block diagram of the sliding mode control system.

According to the derivation of Lyapunov function, the necessary and sufficient condition for the existence of the sliding regime is limited to

$$\lim_{\sigma \to 0} \sigma\dot{\sigma} \leq 0 \tag{9}$$

Finally, the gain parameters should be suitably chosen to achieve control objective. By substituting equations (1)-(6) into (9), one can obtain that the gain parameters α and β must satisfy the following inequality.

$$\beta \leq \frac{(\lambda B - \lambda^2 J)}{k_t} \leq \alpha \tag{10}$$

In conventional sliding mode control, the control input usually possesses high frequency chattering. In order to reduce the high frequency chattering of the control input and the motor speed, an integral compensation, therefore, is inserted behind the gain constants. Furthermore, the speed of the drive system is obtained from an encoder, therefore, the acceleration, a derivative of the speed with measuring noise, is not easily measured. If the acceleration signal is acquired by calculating the speed difference with time, the signal will consist of a lot of high frequency noise. The signal with this noise will seriously affect the servo system performance. In order to solve this problem, a sliding-mode controller with an acceleration estimator is proposed here. The estimation of the acceleration signal is measured from the speed of the motor and can be derived as

$$\hat{\dot{\omega}}_m(k) = \frac{1}{\tau_{LP}} \Delta\omega_m(k) \tag{11}$$

where

$$\Delta\omega_m(k) = \omega_m(k) - \hat{\omega}_m(k) \tag{12}$$

and

$$\hat{\omega}_m(k) = \hat{\dot{\omega}}_m(k) T_s + \hat{\dot{\omega}}_m(k-1) \tag{13}$$

T_s is the sampling time and τ_{LP} is the time constant of the acceleration estimator.

Generally speaking, it is easy to realize the sliding mode controller. Unfortunately, the states which move toward the sliding line produce a very high switching frequency chattering phenomenon and pulsate around the sliding line. In this paper, a scheme which uses a neural network controller to adjust the slope of the sliding line is proposed. By using this scheme, the chattering phenomenon can be effectively reduced. Figure 5 shows the structure of the proposed multi-layer neural network, which includes an input layer, a hidden layer, and an output layer [8]. The input state variables are the state variables x_1 and x_2 because they are related to the state response and the slope of the sliding line.

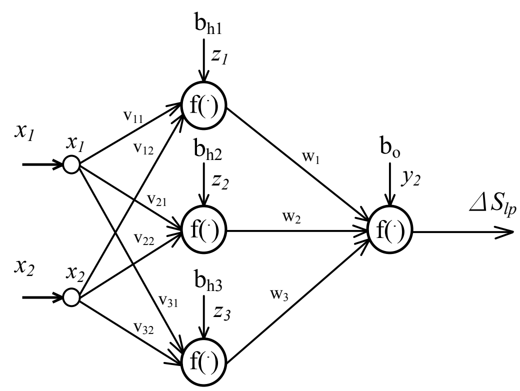

Figure 5. The structure of the multi-layer neural network.

According to the physical property of the motor drive system, the control input during transient response and steady-state conditions are different and thus require different slope of moving trajectory to reduce the fluctuation. During the motor starting, the slope of the sliding line should be adjusted to a large value to obtain a faster response. However, when the speed of the motor is under steady-state condition, the slope of the sliding line has to be set as a small value to avoid state oscillation occurring. The parameters of the neural network, w_{ik}, v_{kj}, b_{hk}, and b_{oi}, are obtained from the off-line learning processes. First, we obtain some desired training data from experimental results. After that, we were able to execute the training process to obtain the required parameters w_{ik}, v_{kj}, b_{hk}, and b_{oi}. Finally, the neural network determines the variation of the slope ΔS_{lp} of the sliding mode controller.

IV. EXPERIMENTAL RESULTS

. In this paper, the DSP TMS320LF2407A serves as the controller. Figure 6 shows the prototype of the PMSM drive system. Figure 7 is the photograph of the control board. Several experimental results are shown here. The triggering signals of the switches under the three-stepped switching commutating procedure are shown in Figure 8. Figure 9(a) shows the transient speed responses at a speed command of 600 r/min. Figure 9(b) shows the speed response when an external load of 2 N.m is added. The measured result shows the proposed sliding mode control system has satisfactory speed response ability.

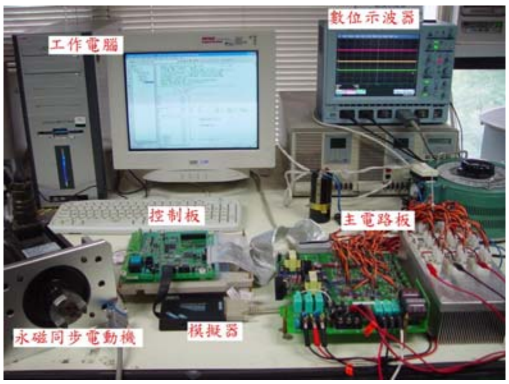

Figure 6. The prototype of the PMSM drive system.

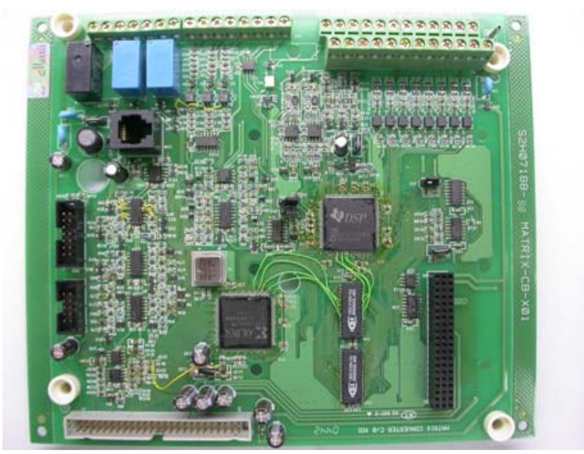

Figure 7. The photograph of the control board.

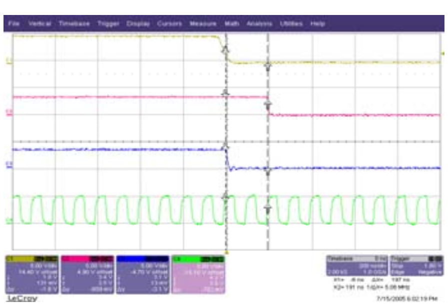

Figure 8. The triggering signals of the switches under the three-stepped switching commutating procedure.

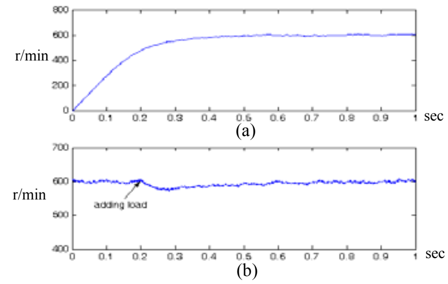

Figure 9. The speed responses of the PMSM drive system (a) transient response (b) load disturbance response.

V. CONCLUSIONS.

In this paper, the design and implementation of a sliding mode controller for a PMSM control system has been investigated. All the control algorithms, which include the switching strategy and the control law, are executed by a digital signal processor. A neural network is used to tune the slope of the sliding line to improve the performance of the matrix converter fed PMSM drive system. As a result, the system can achieve both a good transient response and a good load disturbance response. Consequently, this paper provides a novel scheme for designing a sliding mode control of PMSM drive system.

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