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High-Performance AC Power Source by Applying Robust Stability Control Technology for Precision Material Machining

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Abstract. This paper presents a high-performance AC power source by applying robust stability control technology for precision material machining (PMM). The proposed technology associates the benefits of finite-time convergent sliding function (FTCSF) and firefly optimization algorithm (FOA). The FTCSF maintains the robustness of conventional sliding mode, and simultaneously speeds up the convergence speed of the system state. Unfortunately, when a highly nonlinear loading is applied, the chatter will occur. The chatter results in high total harmonic distortion (THD) output voltage of AC power source, and even deteriorates the stability of PMM. The FOA is therefore used to remove the chatter, and the FTCSF still preserves finite system-state convergence time. By combining FTCSF with FOA, the AC power source of PMM can yield good steady-state and transient performance. Experimental results are performed in support of the proposed technology.

1. Introduction

The AC power sources are broadly applied in precision material machining (PMM), such as high strength aluminum alloys, brass alloys, and stainless steel alloys [1]. The requirements of a high-performance AC power source must have low THD output-voltage, fast transient response and steady-state errors as small as possible in the face of different loading. To achieve such requirements, proportional–integral–derivative (PID) controller is usually used. However, when the system using PID controller under the case of a variable load rather than the nominal ones, cannot obtain fast and stable output voltage response [2]. Numerous control technologies are also reported in literature, such as wavelet transform technique, deadbeat control, repetitive control, and so on [3], [4], [5]. But, they are difficult to implement and have complex algorithms. Sliding mode control (SMC) with insensitivity to system uncertainties was first proposed in early 1950's. The SMC of AC power sources are also frequently used, but they adopt linear sliding function with slow convergence time [6]. In order to speed up the convergence speed, a finite-time convergent sliding function (FTCSF) is employed, and the system state can be driven to the origin within finite time [7], [8]. It is worth noting that the chatter will occur around the FTCSF once a severe nonlinear loading is applied. In the AC power source output, the high THD caused by the chatter easily yields, thus worsening the stability of the PMM. Firefly optimization algorithm (FOA) is a meta-heuristic technology inspired by the sparkling behavior of fireflies, and has been broadly used for solving optimal control problems in various engineering fields [9], [10]. The FOA is thus used to remove the chatter while the FTCSF is employed to speed up the convergence speed of the system state. By the combination of FTCSF and FOA, a closed-loop AC power source of PMM will reveal excellent performance, such as low total harmonic distortion of output voltage, fast transient response, and the reduction of the chatter.

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Experimental results are given to prove the effectiveness of the proposed robust stability control technology. Because the proposed control technology is easier to realize, faster to converge, more effective to remove the chatter than prior methods, this paper will be a useful reference to correlative material researchers.

2. Proposed robust stability control technology for AC power source of PMM

Figure 1 displays the circuitry of AC power source converter of PMM, and the PWM inverter is a key unit in the controlled system. In case the output voltage v_o follows a sinusoidal reference voltage v_d exactly, the error between v_o and v_d can be converged to the origin. By defining $x_{e1} = v_o - v_d$ and $x_{e2} = \dot{x}_{e1}$, the error state-space matrix is represented as

$$\begin{bmatrix} \dot{x}_{e1} \\ \dot{x}_{e2} \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ -a_1 & -a_2 \end{bmatrix} \begin{bmatrix} x_{e1} \\ x_{e2} \end{bmatrix} + \begin{bmatrix} 0 \\ b \end{bmatrix} u + \begin{bmatrix} 0 \\ N \end{bmatrix} \tag{1}$$

where $a_1 = 1/LC$, $a_2 = 1/RC$, $b = K_{PWM}/LC$, K_{PWM} is the inverter equivalent gain, and $N = -a_1 v_d - a_2 \dot{v}_d - \ddot{v}_d$ signifies the disturbance, and u denotes the control signal that can enforce the error to the origin within finite time.

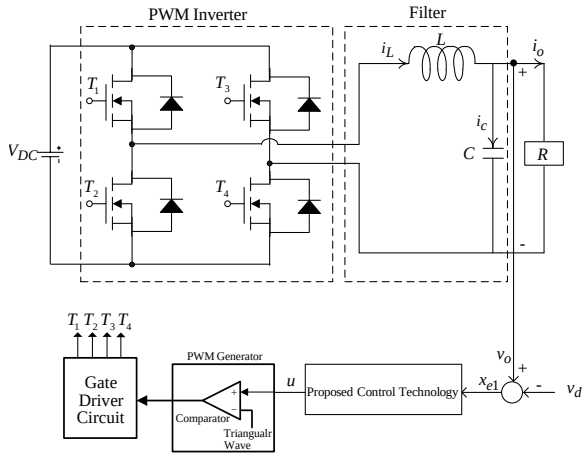


Figure 1. AC power source of PMM.

To speed up the convergence speed, a finite-time convergent sliding function $s_1(t)$ is defined due to the infinite system-state convergence time of the conventional sliding mode function $s(t) = c_1 x_{e1} + x_{e2}$ (c_1 is constant).

$$s_1(t) = x_{e1}(t) + \frac{1}{\mu} x_{e2}^{p_1/q_1}(t) \tag{2}$$

where $p_1 > q_1$, p_1 and q_1 stand for positive odd numbers ($1 < p_1/q_1 < 2$), and a sliding mode reaching term $\dot{s}_1 = -\sigma sign(s_1)$ is constructed.

Then, the control law u can be expressed as

$$u(t) = u_{eq}(t) + u_s(t) \tag{3}$$

with

$$u_{eq}(t) = b^{-1}[a_1 x_{e1} + a_2 x_{e2} - \mu \cdot \frac{q_1}{p_1} x_{e2}^{2-p_1/q_1}] \tag{4}$$

$$u_s(t) = -b^{-1}[\sigma sign(s_1)], \ \sigma > 0 \tag{5}$$

where u_{eq} is the equivalent control, and u_s displays the sliding control for compensating the perturbation influences. In practice, a smooth *approximation* of the *sign* function in (5) can be replaced by $\tanh(s_1) = \exp(s_1) - \exp(-s_1)/\exp(s_1) + \exp(-s_1)$.

Note that the chatter around the FTCSF still exists if a highly nonlinear loading is applied. Thus, to remove the chatter, the FOA is used to adjust the control gains of FTCSF. The rules of the FOA are supposed below: (1) The FOA is independent of sex; the all fireflies are unisex and one firefly can seduce other fireflies. (2) The attraction is proportioned to the firefly shine. The less bright firefly moves towards brighter firefly. If the distance is extended among fireflies, the brightness is lessened. The brightest firefly will move randomly since there are no insects to seduce it. (3) The brightness of the firefly correlates closely with the analytical form of the objective function. The brightness can proportion to the value of the objective function in a maximization problem.

While firefly j is more glamorous than firefly i, the activity is decided as

$$x_i = x_i + \phi \cdot e^{-\rho r_{ij}^2} \cdot (x_j - x_i) + \varepsilon \cdot (rand - 1/2) \tag{6}$$

where ϕ symbols the firefly attraction value, ρ represents the light absorption coefficient, $\varepsilon \in [0,1]$, and $rand$ signifies random number between 0 and 1.

The distance r_{ij} between fireflies i and j can be written by using Cartesian distance below.

$$r_{ij} = \left\| x_i - x_j \right\| \tag{7}$$

Thus, the FOA compares the attraction of the firefly i with the attraction of the firefly j. If the firefly j is more glamorous than firefly i, then the firefly i is moved to the new place; otherwise the firefly i will stay in the present place.

3. Experimental results

The proposed system parameters are given in Table 1. Under nonlinear load (full wave rectified with a parallel resistor and capacitor), the output waveforms with the proposed control technology and the conventional sliding mode are shown in Figure 2 and Figure 3, respectively. The output voltage of the proposed system has lower distortion than that of the conventional sliding mode controlled system. The good steady-state and dynamic response can be obtained by using the proposed control technology; the output voltage close to sine wave achieves a low %THD of 1.43%, with the proposed control technology while the output voltage with the conventional sliding mode yields a high %THD of 9.02%. Because the chatter is removed remarkably, Figure 4 shows that the tracking errors with the proposed control technology can be fast converged to the origin, however there is a great deal of tracking errors in the conventional sliding mode controlled system.

Table 1. System parameters

Filter inductor	L=0.1 mH
Filter capacitor	C=10 μF
DC supply voltage	V_{DC}=200 V
Nonlinear load	Electrolytic Capacitor: 120 μF; Load Resistor: 35 Ω
Output voltage and frequency	v_o=110 V_{rms}, f=60 Hz
Switching frequency	f_{sw} =18 kHz

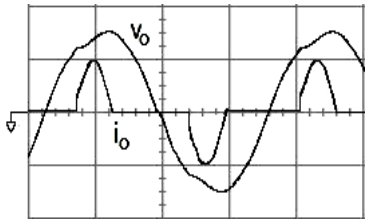


Figure 2. Proposed control technology with nonlinear load (100V/div; 25A/div; 5ms/div)

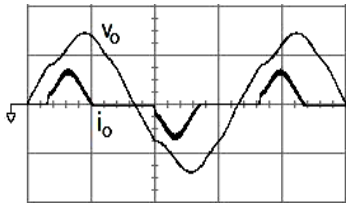


Figure 3. Conventional sliding mode with nonlinear load (100V/div; 25A/div; 5ms/div)

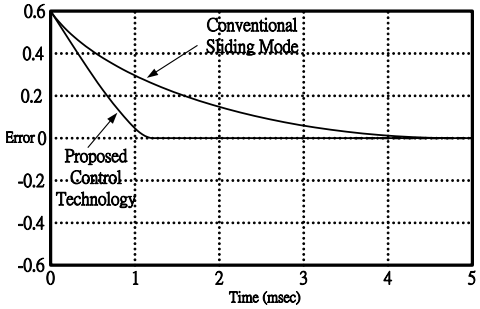


Figure 4. Tracking errors

4. Conclusions

In this paper, a FTCSF with FOA is presented for the application of AC power source of PMM. Relative to the conventional sliding mode, the proposed control technology can remove the chatter, increase the convergence speed, achieve satisfactory steady-state, and fast transience. Experimental results reveal that low THD, fast transient response, the reduction of the chatter, and the attenuation of the tracking error are obtained in the proposed controlled system even under highly nonlinear loading.

5. Acknowledgment

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