Design and Analysis of Uninterruptible Power Supply Control Technology for Manufacturing Automation Applications

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***Abstract*—In this paper, an Uninterruptible Power Supply (UPS) with a robust control technology is proposed for the application of the Manufacturing Automation (MA). The proposed control technology is composed of a Fast Sliding Mode Control (FSMC) and a Glowworm Swarm Optimization (GSO). Although the FSMC guarantees finite system-state convergence time of the UPS, the distorted and unstable UPS output-voltage degrades the unreliability of MA. This is because the inappropriate control parameters exist in UPS system. The GSO is thus employed to tune FSMC control gains optimally, yielding high performance UPS in the use of the MA. Experimental results show that the proposed control technology can lead to high-quality AC output voltage and fast dynamic response. Because the proposed control technology is simpler to implement than previous methods and has higher convergence accuracy, this paper will be of interest to investigators of related MA.**

***Index Terms*—Uninterruptible Power Supply (UPS), Manufacturing Automation (MA), Fast Sliding Mode Control (FSMC), finite system-state convergence time, Glowworm Swarm Optimization (GSO)**

I. Introduction

Uninterruptible power supply (UPS) has been applied for providing emergency power [1], [2] and is necessary to maintain industrial productivity in manufacturing environments because it defends essential factory automation equipment against damage, data loss and downtime [3], [4]. In UPS systems, the whole performance is dependent upon the static inverter-filter arrangement, which is employed to convert a direct current to a sinusoidal alternating current. A high-performance UPS should provide low distorted output-voltage, fast dynamic response and nearly zero steady-state errors. To achieve these requirements, a PI/PID controller is frequently used for the improvement of UPS performance; however it is sensitive to uncertain disturbances [5]-[8]. Several existing control techniques have been considered in the literature such as deadbeat control, mu-synthesis, and H-infinity method [9]-[11]. The high quality output-voltage can be produced using deadbeat control; nevertheless, such a method depends strongly on precision parameters [9]. Though mu-synthesis and H-infinity method solve the problem of system uncertainties, they have high control complexities and take more complex calculations [10], [11]. Sliding Mode Control (SMC) is insensitive to the plant parameter variations and external load disturbances [12], [13]. The SMC system employs a switching control law to enforce the system state to reach and stay on the predefined sliding surface [14], [15]. In the design process of a SMC, the following two steps have to be fulfilled: (i) The system state is driven towards the sliding surface [16], [17]. (ii) Once the system state arrives at the surface, thereafter, it will slide along the surface to the origin point [18], [19]. The controller of the UPS is quite popularly designed via SMC [20]. A single sliding function is presented to perform all control objectives; the steady-state response is acceptable, however there is poor transience [21]. The single sliding function can be improved using multi-loop control, but the steady-state error is seen [22]. A discrete sliding mode is proposed to design a servo system. Though good transience can be obtained, the chatter still exists [23]. Based on the concept of discrete SMC, a modified methodology is developed. The chatter can be reduced, but steady-state performance is unsatisfactory [24]. The combination of an optimal theory and a feed-forward scheme is integrated into discrete SMC, so as to achieve high-accuracy tracking. The system trajectory cannot meet the sliding surface completely, yielding a visible distortion under nonlinear disturbances [25]. By the addition of an integral compensation, the improved SMC can be obtained, but the chatter around sliding surface exists [26], [27]. A SMC with simple structure and easy calculation is proposed. The good response in transience can be obtained, however the steady-state performance is unsatisfactory [28]. A fixed switching frequency used in SMC is employed. Although the system performance is satisfactory, this method has complicated hardware design [29]. Above-mentioned these sliding surfaces are linear and have infinite system-state convergence time. For the sake of high accuracy control, a FSMC with nonlinear sliding surface has been presented [30]-[33] and it possesses system states converged to the origin within finite time [34]-[37]. However, owing to the lack of suitably designing FSMC parameters, the UPS output will yield high harmonic distortion, deteriorating the

Manuscript received February 21, 2018; revised July 23, 2018.

doi: 10.18178/ijoee.6.2.52-56

reliability and stability of the MA. Glowworm Swarm Optimization (GSO) is a nature-inspired optimization algorithm and has been used in various fields [38]. The GSO emulates the light behavior of the glow-worms to tempt comrades, finding global optimization efficiently [39], [40]. Therefore, the FSMC control gains can be optimally determined by GSO; a low distorted UPS output-voltage used in MA can be obtained. By combining GSO and FSMC, the presented system has improved the steady-state and transient response of the UPS that is capable of providing a high-quality AC output for MA. Finally, experimental results demonstrate the feasibility and advantages of the proposed control technology.

II. System Modelling

Fig. 1 shows the circuit diagram of a static UPS. It consists of an LC filter and a full-bridge inverter, which is the core of the system, chopping the DC input into a series of PWM pulses by the modulation signal. The output voltage v_o of the UPS can be driven to track a sinusoidal reference voltage, v_r by employing the proposed control technology. Let $\tilde{x}_1 = v_o - v_r$ and $\tilde{x}_2 = \dot{\tilde{x}}_1$, the error state matrix can be stated as

$$\begin{bmatrix} \dot{\tilde{x}}_1 \\ \dot{\tilde{x}}_2 \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ -a_1 & -a_2 \end{bmatrix} \begin{bmatrix} \tilde{x}_1 \\ \tilde{x}_2 \end{bmatrix} + \begin{bmatrix} 0 \\ b \end{bmatrix} u + \begin{bmatrix} 0 \\ -a_1 v_r - a_2 \dot{v}_r - \ddot{v}_r \end{bmatrix} \quad (1)$$

where a_1 denotes $1/LC$, a_2 stands for $1/RC$, $b = K_{pwm}/LC$, K_{pwm} symbols inverter equivalent gain, the perturbation is $-a_1 v_r - a_2 \dot{v}_r - \ddot{v}_r$, and u represents the control signal. The u needs to be designed well, yielding almost zero tracking error.

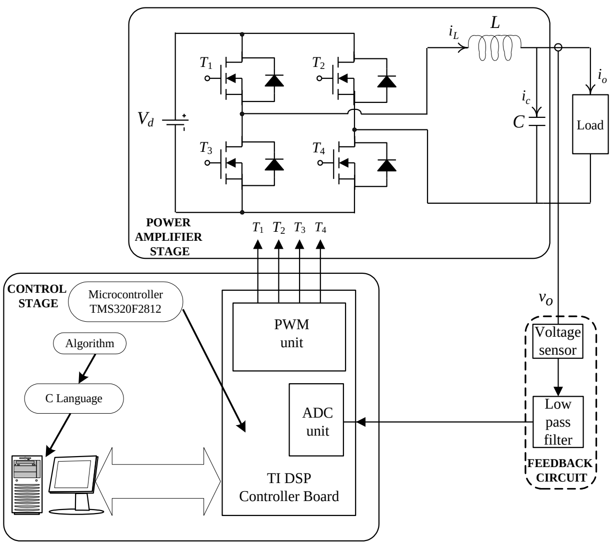

Figure 1. UPS used in MA.

III. Propsoed Control Technology

For the error dynamics (1), the FSMC with finite time convergence is written as

$$\sigma = \tilde{x}_1 + \frac{1}{\kappa}\tilde{x}_2^{\gamma} \quad (2)$$

where $\kappa > 0$, $1 < \gamma < 2$, and a sliding mode reaching equation $\dot{\sigma} = -\phi|\sigma|^{\beta} sign(\sigma)$ is constructed.

Then, the control law u becomes

$$u = u_e + u_s \quad (3)$$

with

$$u_e = b^{-1}[a_1\tilde{x}_1 + a_2\tilde{x}_2 - \frac{\kappa}{\gamma}\tilde{x}_2^{2-\gamma}] \quad (4)$$

$$u_s = -b^{-1}[\phi|\sigma|^{\beta} sign(\sigma)],\ \phi > 0,\ 0 < \beta < 1 \quad (5)$$

where u_e is the equivalent control and u_s represents the sliding control for the compensation of the perturbation influences. In practice, the *sign* function in (5) must be substituted for a saturation function $sat(\sigma/\varepsilon) = \sigma/\varepsilon, sign(\sigma)$ for $|\sigma| \le \varepsilon, |\sigma| > \varepsilon$ ($\varepsilon > 0$), respectively.

Note that the UPS output waveform is seriously distorted due to the unsuitable choice of FSMC parameters, causing unreliable and unstable MA. Thereby, the GSO is adopted to tune optimal control gains of the FSMC. The main steps of the optimization process using GSO algorithm are described in the following.

Step 1: Initialize the parameters.

Step 2: Randomly put glowworm population in the search space of the objective function.

Step 3: The luciferin level with glowworm i can be expressed as

$$\ell_i(k) = (1-\xi)\ell_i(k-1) + \varepsilon J(x_i(k)) \quad (6)$$

where ξ ($0 < \xi < 1$) stands for luciferin decay constant, ε represents luciferin enhancement constant, the position of the glowworm i denotes $x_i(k)$ and the value of the objective function is $J(x_i(k))$.

Step 4: There is a probability in each glowworm i moving toward a neighbour j.

$$p_{ij}(k) = \frac{\ell_j(k) - \ell_i(k)}{\sum_{n \in N_i} \ell_n(k) - \ell_i(k)} \quad (7)$$

where N_i indicates the set of neighbours of glowworm i.

Step 5: By the use of the (8), the position of glowworm i is updated as

$$x_i(k+1) = x_i(k) + (\text{step - size}) \cdot \frac{x_j(k) - x_i(k)}{\left\| x_j(k) - x_i(k) \right\|} \quad (8)$$

Step 6: The neighborhood range can be updated by using the (9).

$$r_{d_i}(k+1) = \min\{r_s, \max\{0, r_{d_i}(k) + \psi(n_k - |N_i(k)|)\}\} \quad (9)$$

where r_s denotes a sensor range, which restricts the size of the neighborhood range, ψ indicates a constant, and the desired number of neighbours is controlled by n_k.

IV. Experiments

The proposed system parameters are listed in Table I. Fig. 2 and Fig. 3 represent the output voltage and the output current obtained using the proposed control technology and the traditional SMC under sudden load change from no load to full load, respectively. The output-voltage waveform displays a smaller voltage sag in the Fig. 2, as compared with the Fig. 3. It is obvious that the proposed control technology provides good robustness and fast transience when an external disturbance is suddenly applied to UPS. Fig. 4 shows that the tracking error convergence rate with the proposed control technology is rapidly converged to the origin, however there is an unsatisfactory convergence behavior with visible oscillation in the traditional sliding mode controlled system as shown in Fig. 5. From Fig. 2 and 4, we observe that the proposed control technology can compensate UPS output-voltage sag very quickly and the waveform distortion in the presence of sudden load change is lower than the traditional SMC. The proposed control technology has achieved a high performance UPS and is therefore more suitable for the use of the MA. In the closing summary, both by theoretical analysis and experiments, the proposed control technology always has small voltage sag, the reduction of steady-state error and fast convergence to equilibrium in finite time. (Table II)

TABLE I. System Parameters

DC-link voltage	V_d = 200 V
Filter inductor	L = 0.2 mH
Filter capacitor	C = 4 μF
Resistive load	R_{full} =12 Ω
Output voltage and frequency	v_o = 110 V_{rms}, f = 60 Hz
Switching frequency	f_s = 12 kHz

TABLE II. Voltage Sag

Proposed Control Technology	
Experiment	Voltage Sag
	Step Load Change
	13 V_{rms}
Traditional SMC	
Experiment	Voltage Sag
	Step Load Change
	25 V_{rms}

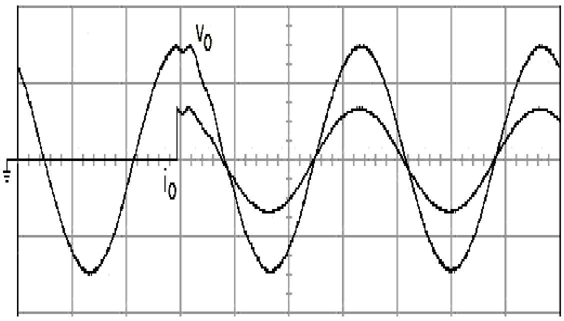

Figure 2. Proposed control technology with sudden load change (100V/div; 20A/div; 5ms/div).

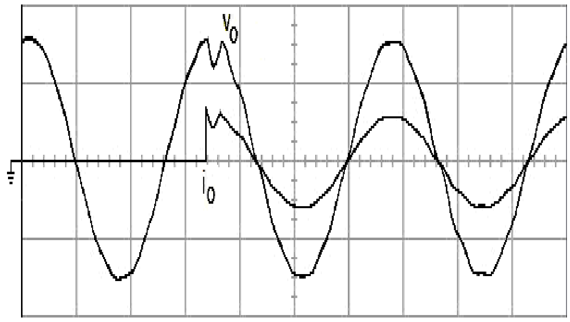

Figure 3. Traditional SMC with sudden load change (100V/div; 20A/div; 5ms/div).

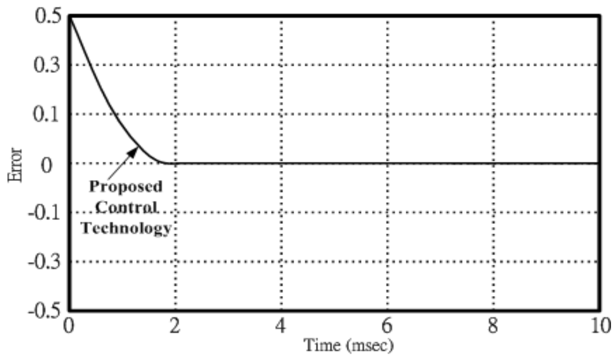

Figure 4. Tracking error convergence rate with proposed control technology.

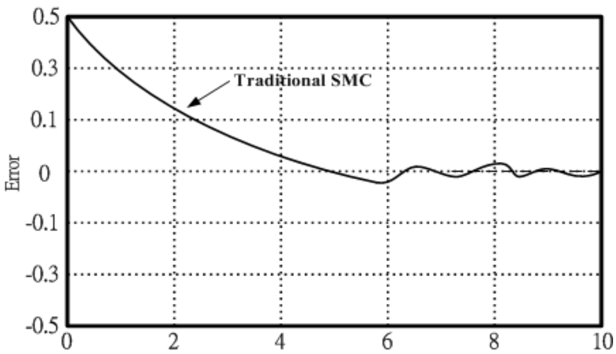

Figure 5. Tracking error convergence rate with traditional SMC.

V. Conclusions

This paper proposes a combination of FSMC and GSO for UPS used in MA. The FSMC can shorten long convergence time of the traditional SMC, but fast sliding mode controlled UPS output-voltage still produces high distorted waveform because the control parameters is without designing well. Such problem causes the unreliability and instability of the MA, too. The GSO is used to optimally tune the control gains of the FSMC, thus providing robust performance of the UPS. The improvement of the system performance has been demonstrated by experimental tests on a laboratory UPS prototype, confirming the theoretical analysis. Compared to traditional SMC, the proposed control technology yields good stead-state and transience, like the reduction of steady-state error, high disturbance rejection capability and fast finite-time convergence speed. It can be expected that the proposed control technology can be introduced to more widespread applications, such as embedded systems in factory automation, Internet of Things (IoT) in production automation, and Human-Machine Interfaces (HMI) in industrial automation. These related applications will provide our further research directions in the future.

ACKNOWLEDGMENT

This work was supported by the Ministry of Science and Technology of Taiwan, R.O.C., under contract number MOST106-2221-E-214-031.

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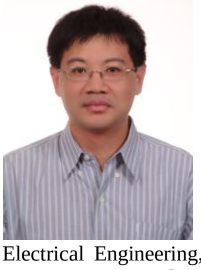

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