Particle Swarm Method-Based Hyperbolic Sliding Mode Control Strategy for the Optimal Design of Parallel-Connected UPS Systems

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***Abstract*—In this paper, the optimal design of parallel-connected UPS systems using particle swarm method-based hyperbolic sliding mode control strategy is developed. By the use of the Hyperbolic Sliding Mode Control (HSMC), the AC output voltage regulation and balanced current-sharing among the parallel modules can be achieved. However, the chattering phenomenon still exists in HSMC and will cause heat losses and high voltage harmonics in UPS systems. To remarkably attenuate the chattering, a particle swarm method is used to optimally design the HSMC system. With the proposed strategy, the robustness of the UPS system is enhanced, and a high-quality UPS sinusoidal output voltage with low voltage harmonics and fast dynamic response can be obtained even under large parameter variations. Experiments are performed to testify the proposed strategy.**

***Index Terms*—Hyperbolic Sliding Mode Control (HSMC), chattering, particle swarm method, UPS system, voltage harmonics**

I. INTRODUCTION

Due to the design ease in thermal management and the remarkable improvement in redundancy, modularity, and maintainability, the parallel-connected Uninterruptible Power Supply (UPS) system is popularly used in energy conversion systems, such as photovoltaic systems, wind energy systems, and fuel cell systems [1], [2]. The parallel-connected UPS system must provide high-quality AC output voltage with low Total Harmonic Distortion (THD), fast dynamic response, and zero steady-state errors; these requirements can be obtained by employing feedback control methods. To provide the operation of the parallel-connected UPS systems well, it is essential to employ a voltage control loop and a current control loop. The voltage control loop is designed to obtain the output voltage with the desired amplitude and frequency while the current control loop is designed to control the current-sharing among the parallel modules. Generally, a Proportional Integral (PI) controller can be used for parallel-connected UPS system design. However, the performance of the parallel-connected UPS with the PI controller is disappointing under rectified load conditions [3]-[5]. Advanced nonlinear control methods are thus adopted to ensure good performance of parallel-connected UPS systems, such as deadbeat control, wavelet transform technique, repetitive control, and so on. However, these methods need complicated mathematical models or large computation time [6]-[8]. Many literatures have shown that Sliding Mode Control (SMC) is capable of making a control system robust with regards to plant parameter variations and external load disturbances [9]-[11]. The SMC have also been applied to the control of parallel-connected UPS systems. However, these SMC methods use linear sliding surface, and the system states converge to the origin in infinite time [12]-[14]. For fast convergence rate, and high-accuracy tracking, a Hyperbolic Sliding Mode Control (HSMC) with nonlinear sliding surface can be used, thus achieving parallel-connected UPS output-voltage with low THD and fast dynamic response, and balanced current sharing [15], [16]. But, the HSMC still has chattering phenomenon, and may cause heat losses, excite unmodelled high-frequency and incur high voltage harmonics. To remarkably attenuate the chattering, the particle swarm method is adopted to tune HSMC's control gains optimally [17]-[19]. Once the parallel-connected UPS using this proposed strategy is established, its good performance compared to classic SMC can be obtained, such as low voltage harmonics, fast dynamic response, and remarkably lessened chattering. Experiments are provided to demonstrate the robust control performance of the proposed strategy. The beginning of this paper represents the dynamic modeling of the parallel-connected UPS. Secondly, particle swarm method-based HSMC strategy is derived, and applied for parallel-connected UPS systems. Experimental results are finally shown to validate the performance of the proposed strategy.

II. DYNAMIC MODEL OF PARALLEL-CONNECTED UPS

Fig. 1 and Fig. 2 show the parallel-connected static UPS and the equivalent circuit, respectively. According to Fig. 2, the dynamics of the system can be written as:

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$$\begin{cases} u_1 = R_1 i_{L_1} + L_1 \dfrac{di_{L_1}}{dt} + v_o \\ \quad\vdots \\ u_n = R_{N1} i_{L_N} + L_N \dfrac{di_{L_{N1}}}{dt} + v_o \\ i_{L_1} + i_{L_2} + \cdots + i_{L_N} = i_{c_1} + i_o \\ i_{c_1} = C_T \dfrac{dv_o}{dt} \end{cases} \tag{1}$$

where $C_T = \sum_{i=1}^{N} C_i$.

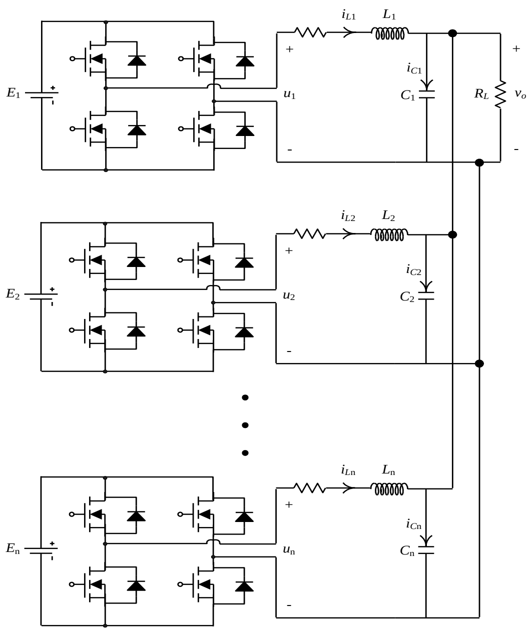

Figure 1. Structure of parallel-connected UPS system.

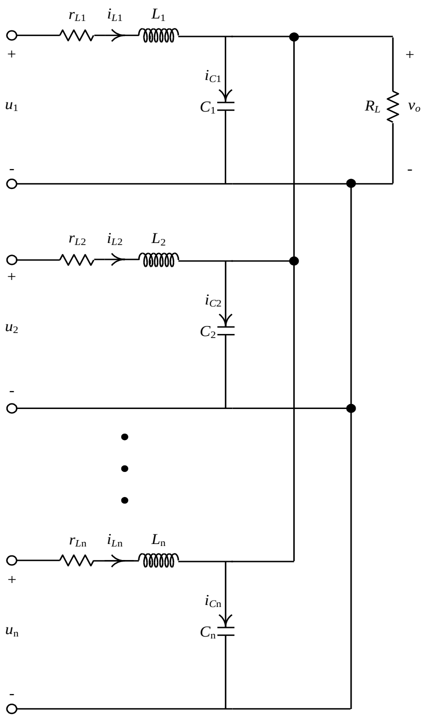

Figure 2. Equivalent circuit of parallel-connected UPS system.

III. Control Design

Letting the state error e_v be the difference between the output voltage and the reference voltage as:

$$e_v = v_o - v_{ref} \tag{2}$$

where v_o is the output voltage, and $v_{ref} = V_m \sin(\omega t)$ is the reference voltage.

Then, define the state error e_i be the difference between the output current of each UPS module and the reference current.

$$e_{im} = i_{L_m} - i_{ref} \tag{3}$$

where i_{L_m} is the output current of each module, and i_{ref} is the reference current.

Our objective is to well design the control law, $u_m = u_{em} + u_{hm}$ so that output voltage regulation and balanced current-sharing among the modules can be obtained.

For the purpose of digital realization, a hyperbolic sliding mode control with the tangent function is selected as:

$$\sigma_m(k) = \frac{1}{C_m} i_{cm}(k) + k_v \tanh(\mu e_v(k)) + k_i e_{im}(k) \tag{4}$$

where k_v , k_i and μ are constants.

From (4), one yields:

$$\begin{aligned} \sigma_m(k+1) = \frac{1}{C_m} i_{cm}(k+1) + k_v \tanh(\mu e_v(k+1)) \\ + k_i e_{im}(k+1) \end{aligned} \tag{5}$$

The equivalent control, u_{em} by the use of the invariance condition can be obtained as:

$$\Delta\sigma_m(k+1)\big|_{u=u_{em}} = \sigma_m(k+1) - \sigma_m(k) = 0 \tag{6}$$

The existence of the switching mode can be expressed in the following and then the hyperbolic sliding control, u_{hm} is obtained.

$$\sigma_m(k) \cdot \sigma_m(k+1)\big|_{u_m = u_{em} + u_{hm}} < 0 \tag{7}$$

Notice that even though the chattering in the (7) has been reduced, but the chattering still happens. Thus, to effectively attenuate the chattering, the particle swarm method expressed in (8) and (9) is employed to optimally tune the control gains of the HSMC.

The (8) and (9) show the evolution models of a particle and then the speed and position of each particle can be updated when flying toward destination.

$$\begin{aligned} V_{i+1} = c_0 V_i + c_1 r_1 (X_i^{pbest} - X_i) \\ + c_2 r_2 (X_i^{gbest} - X_i) \end{aligned} \tag{8}$$

$$X_{i+1} = X_i + V_{i+1} \tag{9}$$

where c_0, c_1 and c_2 are variables, r_1 and r_2 are random numbers, V_i indicates present flying speed, X_i shows present position, X_i^{pbest} is local best position, X_i^{gbest} is global best position. The operation of the particle swarm method is described in the following.

Step 1: Defining the number of particles, and initializing their initial speeds and positions.

Step 2: Calculate the fitness of each particle.

Step 3: For each particle, comparing its fitness with its present best fitness. When the former is better than the later, its present best fitness and best position are updated by its fitness and present position, respectively.

Step 4: For each particle, comparing its fitness with the global best fitness of the swarm. When the former is better than the later, the global best fitness and global best position are updated by the former and the best position of the being compared particle, respectively.

Step 5: Updating the position and speed of each particle.

Step 6: Doing step 2 to step 6 until terminal condition is finished.

IV. Experimental Results

The system is tested for three UPS modules connected in parallel using the following parameters: $E_1 = E_2 = E_3 = 220V$, $L_1 \cong L_2 \cong L_3 \cong 2mH$, $C_1 = 50\mu F$, $r_1 \cong r_2 \cong r_3 \cong 0.1\Omega$, $R_L = 12\Omega$, output voltage, v_o=110 V_{rms}, 60Hz. The dynamics of the UPS under phase-controlled load is tested. Fig. 3 and Fig. 4 show the waveforms obtained using the proposed strategy and the classic SMC, respectively. Inspection of the waveforms displays that the output voltage of the classic sliding mode controlled UPS has not only unsatisfactory steady-state response but also larger oscillation than that of the proposed controlled UPS. The values of *L* and *C* filter parameters are assumed in suffering from 10%~500% of nominal values while the UPS system is under 12Ω resistive loading. Fig. 5 and Fig. 6 reveal output-voltage waveforms of the UPS controlled by the proposed strategy and the classic SMC. Clearly, because the chattering is attenuated, the proposed strategy is very insensitive to large parameter variations than the classic SMC. The output-voltage %THD under phase-controlled load and LC parameter variations are given in Table I.

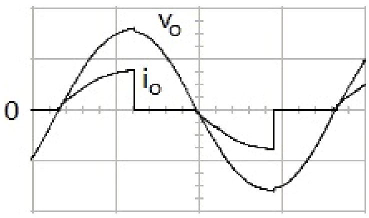

Figure 3. Output waveforms of parallel-connected UPS system under phase-controlled load with the proposed strategy (100V/div; 20A/div; 5ms/div)

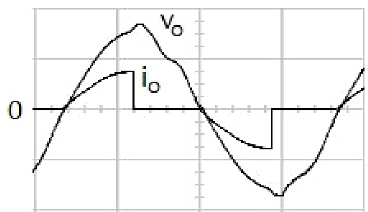

Figure 4. Output waveforms of parallel-connected UPS system under phase-controlled load with the classic SMC (100V/div; 20A/div; 5ms/div)

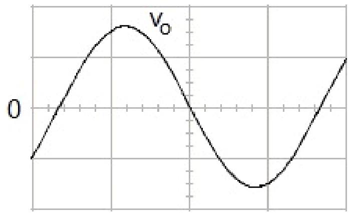

Figure 5. Output waveforms of parallel-connected UPS system under LC parameter variations with the proposed strategy (100V/div; 5ms/div)

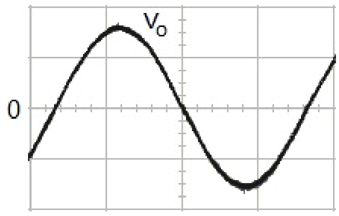

Figure 6. Output waveforms of parallel-connected UPS system under LC parameter variations with the classic SMC (100V/div; 5ms/div)

TABLE I. Experimental Output-Voltage %THD under Phase-Controlled Load and LC Parameter Variations

	Proposed Strategy		Classic SMC	
Loads	Phase-Controlled Load	LC Variation	Phase-Controlled Load	LC Variation
%THD	1.07%	1.35%	8.92%	11.46%

V. Conclusions

By the use of the HSMC, the output regulation of the parallel-connected UPS and the current-sharing among the parallel modules, have been obtained. Also, the particle swarm method remarkably attenuates the chattering which is produced by HSMC. Experiments are given to verify good performance of the proposed strategy even under large parameter variations.

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