Control design of parallel-connected PWM DC-AC converters for sustainable energy applications

E C Chang, G W Lin, Y T Lin, K C Mao and R C Wu*

Department of Electrical Engineering, I-Shou University, Taiwan
E-mail: rcwu@isu.edu.tw

Abstract. Parallel-connected PWM DC-AC converters bring lots of merits, such as, additional capacity of power, modularity ability, better thermal regulation, convenient maintenance, and redundancy that have found wide application in sustainable energies. We propose a control technology in which the strengths of rotating sliding manifold (RSM) as well as exponential grey model (EGM) are incorporated to derive a higher performance parallel-connected PWM DC-AC converter. The RSM makes sure that the sliding mode happens from the any starting status, nevertheless the fixed sliding manifold fails to achieve the robustness in the face of parametric variances and perturbations. Once occurring with high non-linear loads, the fluttering existing in the RSM potentially generates a great deal of output-voltage distortion in the parallel-connected PWM DC-AC converters, which deteriorates sustainable energy stability. With the aim of removing the fluttering, the EGM has optimized the RSM control gains to produce both good steady-state and transience behaviour of the PWM DC-AC converter. The potency of the control technology has been well proven in terms of designing procedure, theory analysis, simulation and experimental results.

1. Introduction

In terms of backup and stability, parallel-connected PWM DC-AC converters have been efficiently applied in sustainable energy systems [1-7]. That is, PWM DC-AC converters run redundantly in parallel as the (N+1) arrangement. In this way it is possible to realize the flexibility of increasing the loading, in case it is required at a later date, as well as a high level of dependability of the output loading, where (N) PWM DC-AC converters feed the loading while the additional inverter acts as the back-up. With the objective of affording the appropriate functioning of parallel single-phase converters, it is imperative to have the control loops. For example, these are voltage control loops devised to acquire the requisite magnitude and frequency of the output voltage while the current loops are constructed to drive the current dispense of the parallel modules [8-11]. There are many kinds of control options throughout the literature that can address the above requirements. But they are compromised in terms of a steady state and a transitory reaction [12-14]. The sliding mode control (SMC) basically drives the system state to a sliding manifold that is the arrival phase. Then when the system state meets the sliding manifold, the system behaviour is controlled by the manifold that is the sliding phase. However, such fixed sliding manifold may be disturbed by parameter variations and loads during the arrival phase. An advanced sliding mode control term of rotating sliding manifold (RSM) has been engineered to traverse via incipient conditions followed by the rotating for movement to a scheduled sliding manifold. With such a presented sliding-manifold, there is diminished susceptibility to loading perturbations by expediting the reaching stage, whereby there is
less fluttering phenomenon, which raises the system robustness [15-20]. Unfortunately, for severe uncertain loading, the flutter appears in the AC power regulation output which experiences acute harmonic distortion, resulting in both power loss and probably even transistors impairment, which lastly weakens the steadiness. The exponential grey model (EGM) for many areas has been used extensively, allowing for more improved prediction accuracy when compared to traditional grey prediction [21-25]. For this paper, a mathematically straightforward as well as an algorithmically effective grey prediction method is adopted as a remedy to eradicate the fluttering whenever the RSM faces an excessive upper limit of system uncertainty, permitting the proposed parallel-connected PWM DC-AC converter to hold high-level performance. The experimental results check the results of the theory analyzing and designing and simulation.

2. Statement of system and control technology design

The parallel-connected PWM DC-AC converter can be structured as depicted in the Figure 1, to extend the power and raise the dependability.

![Figure 1. Parallel-connected PWM DC-AC converter.](image)

With the use of Figure 1 and KVL as well as KCL, the dynamic equations of parallel-connected PWM DC-AC converter can be stated as

\[
\begin{align*}
    u_{in1} &= r_1i_1 + L_1\frac{di_1}{dt} + v_{ac} \\
    \vdots \\
    u_{inm} &= r_mi_m + L_m\frac{di_m}{dt} + v_{ac}
\end{align*}
\]

and

\[
\begin{align*}
    i_L + i_L + \cdots + i_L &= i_{c_a} + i_{ac} \\
    i_{ac} &= \frac{v_{ac}}{R_{LOAD}} \\
    i_{c_a} &= C_{total}\frac{dv_{ac}}{dt}
\end{align*}
\]

where \( C_{total} = \sum_{j=1}^{m} C_j \).
Then an error state variable $e_1$ is specified with respect to the output voltage $v_{ac}$ as well as the requested voltage $v_{cmd}$ as follows:

$$e_1 = v_{ac} - v_{cmd}$$  \hspace{1cm} (3)

where $v_{cmd} = \sqrt{2}V_{rms}\sin(2\pi f t)$ ($V_{rms}$ stands for root-mean-square voltage value, and $f$ indicates the frequency).

The rotating sliding manifold is available in the following, and its structure can be plotted as Figure 2.

$$s = K_1(t) \cdot e_1 + e_2$$  \hspace{1cm} (4)

where $e_2 = \dot{e}_1$, $K_1(t) = Et + F$, and $E$, $F$ signify constants.

![Figure 2. Structure of rotating sliding manifold.](image)

A power reaching law is conceived as

$$\dot{s} = -\eta_1 |s| - \eta_2 |s|^\beta \text{sign}(s)$$  \hspace{1cm} (5)

where $\eta_1 > 0$, $\eta_2 > 0$, $0 < \beta < 1$, and $\text{sign}(s) = \frac{2}{1 + e^{-s/\tau}} - 1$, here $\tau$ represents constant.

Starting from the (1) to (3), it is easy to derive the state of error equation as

$$\dot{e} = G + Hu + w$$  \hspace{1cm} (6)

where $e$ is error states, $u$ symbols control input, $G, H$ denotes state matrix, and $w$ denotes uncertainties.

The control law of the presented RSM in terms of the (4) to (6) yields

$$u(t) = -(H)^{-1}[G + (Ee_1 + K_1(t) \cdot e_2) + \eta_1 |s| + \eta_2 |s|^\beta \text{sign}(s) + \dot{v}_{cmd}]$$  \hspace{1cm} (7)

The following exponential grey model steps are then adopted to overcome the fluttering problem when the uncertain limit is overvalued:

Step 1: The primitive sequence of data can be recorded as

$$\Phi^{(0)} = \{\phi^{(0)}(j), j = 1, 2, m\}$$  \hspace{1cm} (8)

where $m$ denotes the data quantity recorded.

Step 3: By means of the accumulated generating operation (AGO), the first-order AGO sequence becomes

$$\Phi^{(1)} = \{\phi^{(1)}(j), j = 1, 2, \ldots, m\}$$  \hspace{1cm} (9)

where $\phi^{(1)}(j) = \sum_{i=1}^{n} \phi^{(0)}(i), \ n = 1, 2, \ldots, m$.

Step 4: A GM(1,1) with exponential grey model can be created as

$$\frac{d}{dt} \phi^{(1)} + \alpha \phi^{(1)} = \beta e^{-\alpha t}$$  \hspace{1cm} (10)
where \(\alpha\) and \(\beta\) stand for parameters. 

For getting the grey background values, the data sequence is specified as 

\[
Z^{(1)}(n) = 1/2(\varphi^{(1)}(n) + \varphi^{(1)}(n-1)), \quad n = 2, 3, \cdots, m
\]

(11) 

Then the differential equation is formulated as 

\[
\varphi^{(1)}(n) + \alpha Z^{(1)}(n) = -\beta(1-e^{-\alpha})e^{-\alpha n}/\alpha
\]

(12) 

The sequence of time responses for the grey differential equation will be 

\[
\dot{\varphi}^{(1)}(k) = (fk + \sum_{i=1}^{n} (\varphi^{(1)}(n)e^{-\alpha n} - \beta ne^{-2\alpha n}))e^{-\alpha k}/\sum_{i=1}^{n} e^{-2\alpha n}
\]

(13) 

where \(n = 1, 2, \cdots, m\).

Step 5: The predicted values deduced from the (13) can be written as 

\[
\dot{\varphi}^{(0)}(k) = \varphi^{(1)}(k) - \dot{\varphi}^{(1)}(k-1)
\]

(14) 

3. Results and discussions

Three PWM DC-AC converters are combined in parallel under the parameters listed below: 

\[
E_{dc1} = E_{dc2} = E_{dc3} = 200V, \quad L_1 = L_2 = L_3 = 0.18 mH, \quad C_1 = 20 \mu F, \quad r_{L1} = r_{L2} = r_{L3} = 0.020 \Omega, \quad R_{LOAD} = 12 \Omega, \quad \text{switching frequency} = 20 kHz, \quad \text{and output voltage}, \quad v_{dc} = \sqrt{2} \cdot 110 \cdot \sin(2\pi \cdot 60t).
\]

In the Figure 3, the simulated output voltage of the proposed parallel-connected PWM DC-AC converter is displayed with the changes in the inductor-capacitor parameters. The simulated output voltage of the traditional rotating sliding manifold controlled parallel-connected PWM DC-AC converter in response to the changes in inductor-capacitor parameters can be seen in the Figure 4. A traditional rotating sliding manifold has no robustness and is affected easily by the changes of the inductor-capacitor parameters, but with the proposed PWM DC-AC converter the simulated output voltage is impervious against the changes of the inductor-capacitor parameters with the virtually sinusoidal AC shape. The experimental output voltages of the proposed PWM DC-AC converters and the traditional RSM controlled PWM DC-AC converters for phase-controlled loads (changing from unloaded to rated load condition at trigger angles of 90 degrees and 270 degrees) respectively are compared as shown in Figure 5 and Figure 6. It emerges that the proposed control technology has been found to render superior output-voltage compensation, as compared to the traditional RSM especially at the ignition angle. This implies more reduced voltage dipping and accelerated restoration time. Now we know that because the exponential grey model is a more accurate predictor of system state than traditional grey model, the fluttering can be dispelled as well as transitory and steady-state reactions are also improved. Figure 7 plots the rate of state error convergence for the proposed control technology, which is clearly seen to converge quickly to the equilibrium point. On the contrary, as shown in Fig. 8, the state error convergence of the traditional RSM is slow and oscillatory.

**Figure 3.** Proposed control technology under inductor-capacitor parameters changes (vert.: 50 V/div).

**Figure 4.** Traditional RSM under inductor-capacitor parameters changes (vert.: 50 V/div).
Figure 5. Proposed control technology under phase-controlled load.

Figure 6. Traditional RSM under phase-controlled load.

Figure 7. Proposed control technology convergence rate.

Figure 8. Traditional RSM convergence rate.

4. Conclusions
In this paper, a rotating sliding manifold based on exponential grey model is described and subsequently applicable to a PWM DC-AC converter. Through the use of exponential grey model, there is the capability to minimize the fluttering in the surrounding of rotating sliding manifold. Both simulated and experimental results exhibit that the proposed converter can not only expand the power and enhance the reliability, but also sustain the satisfactory response in the presence of unexpected changes in loads or parameter variations in the inductor-capacitor filter.

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