An improved grid-connected pre-synchronization method for photovoltaic micro-grid

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Abstract. Due to the obvious steady-state error that traditional grid-connected pre-synchronization regulation, current shock may occur when photovoltaic micro-grid is connected to the grid. To solve this problem, an improved pre-synchronization method with higher steady-state adjustment accuracy is designed by using the brain emotion control algorithm in the inverter control link. This method can reduces the transient shock of current when the micro-grid is connected to the grid. MATLAB / Simulink software is used to establish a simulation model, through which the correctness and feasibility of the proposed method are verified.

Keywords: virtual synchronous generator (VSG); pre synchronization; Emotional control of brain; master-slave control

1. Introduction
With the rapid development of distributed generation, micro-grid has become an important medium for renewable energy access to the grid [1]. The virtual synchronous generator (VSG) provides a new control strategy for micro-grid operation [2]. Therefore, the parallel / off grid operation of the master-slave micro-grid based on the virtual synchronous generator control has gradually attracted the attention of the majority of researchers [3], and the pre synchronization control is the key technology to complete the micro-grid connection process. In reference [4], a single virtual synchronous generator is used for grid connection pre synchronization simulation, and a PI control pre synchronization method without PLL is used. In reference [5], the master-slave structure micro-grid based on virtual synchronous generator is used for grid connection simulation, and the PI controller is also selected as its pre synchronization control link, and there is still a certain steady-state error in the pre synchronization regulation.

In order to solve the problem of stability error in the traditional PI controller, and to reduce the transient impact in the process of micro-grid connection, this paper applies the emotion control algorithm to the pre synchronization regulation to improve the system regulation accuracy. Finally, through simulation modeling and comparison, the improved strategy is analyzed to verify the feasibility of the strategy.

2. Micro-grid structure and control strategy of inverter
Due to the wide application of the master-slave structure micro-grid, this paper takes the master-slave structure photovoltaic micro-grid as the research object. The converter in the main control unit is also
called grid connected inverter. It operates in VSG control mode in island mode and is responsible for stabilizing the voltage and frequency of the micro-grid. In grid connected mode, power is delivered to the system according to the actual load demand. In slave control unit, PQ control is always adopted to continuously deliver constant power to the system.

2.1. Grid connected inverter structure

Figure 1 is the wiring diagram of VSG and power grid connection. The grid connected inverter mainly consists of six parts: ideal constant voltage DC source, detection and calculation unit, LC filter unit, central control unit, mode switching unit and PWM modulation wave unit. In the mode switching, by controlling the current command value and the phase output of the modulation wave of the VSG control loop, the drive signal is obtained after being processed by the current loop controller, and finally the control of the inverter module is completed.

![Diagram of the VSG connection to the grid](image)

**Fig. 1** Diagram of the VSG connection to the grid

![VSG control block diagram](image)

**Fig. 2** VSG control block diagram

2.2. VSG control strategy

VSG control is shown in Figure 2. VSG control can simulate the rotor of synchronous generator to make the micro-grid have certain inertia, which can restrain the sudden change of grid frequency. The mechanical control equation of VSG can be obtained by introducing the rotor equation of synchronous generator into the control strategy of distributed inverter power supply:

\[
\begin{align*}
J \frac{d\omega}{dt} &= T_m - T_e - T_D = P_m - P_e - D\Delta\omega \\
T_D &= D\Delta\omega = D(\omega - \omega_n) \\
\theta &= \int \omega dt
\end{align*}
\]

Where, \( J \) is the moment of inertia; \( T_m, T_e \) and \( T_D \) are respectively mechanical torque, electromagnetic torque and damping torque. \( P_m, P_e \) corresponds to the mechanical power and electromagnetic power of the synchronous generator. \( D \) is the damping coefficient. \( \Delta\omega \) is the angular velocity difference, \( \omega_n \) is the rated angular velocity, \( \omega \) is the actual angular velocity; \( \theta \) is the electrical Angle.

The mechanical power of VSG consists of two parts: mechanical power instruction \( P_{m\text{ref}} \) and frequency deviation feedback instruction \( \Delta P \), namely:

\[
\begin{align*}
P_m &= P_{m\text{ref}} + \Delta P \\
\Delta P &= k_o(\omega - \omega_n)
\end{align*}
\]

Where, \( k_o \) is the active power regulation coefficient.
Through the control of the mechanical power, the frequency deviation is used as the correction signal to adjust the active power, and finally realize the adjustment response of the active power to the frequency fluctuation.

The excitation potential $E$ of VSG consists of two parts: no-load potential $E_0$ and reactive voltage regulator delta $E_Q$:

$$
\begin{align*}
E &= E_0 + \Delta E_0 \\
\Delta E_0 &= k_0(Q_0 - Q_e)
\end{align*}
$$

(3)

Where: $E_0 = 311V$; Reactive power regulation part delta $E_Q$ simulates the reactive power - voltage sag characteristic in synchronous generator, $Q_0$ is the power given by the central controller, $k_0$ is the reactive power regulation coefficient, and $Q_e$ is the instantaneous reactive power output of the inverter.

3. Realization of grid connection mode switching

3.1. Principle of pre-synchronous regulation of PI control

PI control pre-synchronization unit is composed of two parts: phase compensation and amplitude compensation. The voltage phase and amplitude of the inverter are correspondingly different from the voltage phase and amplitude of the distribution network, and then the phase and amplitude are adjusted respectively by PI controller as the compensation part to meet the grid connection conditions. The formula is as follows:

$$
\begin{align*}
\Delta \omega_s &= K_{\omega}(\theta_s - \theta) + \frac{K_{\omega}}{s}(\theta_s - \theta) \\
\Delta E_s &= K_{E}(E_s - E) + \frac{K_{E}}{s}(E_s - E)
\end{align*}
$$

(4)

In formula (4), $\Delta \omega_s$ and $\Delta E_s$ are the synchronous compensation values of rated angular frequency and rated output voltage amplitude of the inverter respectively.

In this paper, the ideal DC voltage source is used for the distributed power supply in the simulation model, and the infinite grid is used for the distribution network. Therefore, it can be considered that the difference between the output voltage amplitude $E$ of the inverter and the voltage amplitude $E_g$ of the distribution network is very small, that is, $U_{oa} \approx U_{og} = U$. However, there is usually a phase difference between the micro-grid voltage and the distribution network voltage in island mode, which leads to a large instantaneous deviation between the two voltages (the maximum peak value of the deviation is $2U$) [6]. If the micro-grid is connected to the distribution network in the case of large instantaneous voltage deviation, it may produce too much impulse current, resulting in switching failure. Take phase A as an example, the instantaneous difference $\Delta u$ between the two voltages is:

$$
\Delta u = u_{oa} - u_{ga} = U_o \sin(\omega t + \theta) - U_g \sin(\omega t + \theta_g)
$$

(5)

$$
\Delta u \approx 2U \sin\left(\frac{\omega - \omega_0}{2} + \frac{\theta - \theta_g}{2}\right) \cos\left(\frac{\omega + \omega_0}{2} + \frac{\theta + \theta_g}{2}\right)
$$

(6)

3.2. Improved principle of pre-synchronous regulation

The principle of brain emotion control is shown in FIG. 3.
The maximum value $A_{th}$ of the output $O_t$, sensory input $SI$, reward signal $REW$ and thalamus receiving sensory input signal can be expressed as:

$$O_t = A_{th} = \max SI + A_{th} + \sum O$$

In formula (7), $A$ is the output of the amygdala, $O$ is the output of the prefrontal cortex, and $m$ is the number of input signals of the sensory cortex. $k_{d1}, k_{d2}, r_1, r_2$ and $r_3$ are all adjustable parameters.

The output signal of the emotion controller can be regarded as the output signal $O_t$ of the brain, which can be obtained by adding the output of the processing signals of the amygdala and the prefrontal cortex after being weighted respectively. The prefrontal cortex and the amygdala are different in the output signal processing. The amygdala sends the weighted sum of the maximum outputs of the thalamus and the sensory cortex into the amygdala and gets output $A$, while the prefrontal cortex directly adds the weighted sum of the outputs of the sensory cortex and the amygdala to get output $O$, so $A$, $O$ and $O_t$ are expressed by the formula:

$$A = v_1 k_{oe} e + v_2 k_{oe} \int edt + v_3 A_{th},$$
$$O = \omega k_{oe} e + \omega k_{oe} \int edt,$$
$$O_t = k_{d1}(v_1 - \omega_1)e + k_{d2}(v_2 - \omega_2) \int edt + v_1 \max(k_{d3}e, k_{d4} \int edt),$$

In formula (8), $v_1, v_2$ and $v_3$ are the weights of the amygdala, and $\omega_1$ and $\omega_2$ are the weights of the prefrontal cortex. These two weights are directly related to the learning rate $\alpha$ and $\beta$, which are important adjustable parameters that are different from those of the PI controller.

The emotional learning process of amygdala or orbitofrontal cortex is realized by dynamically adjusting the weight. The output of amygdala reflects the direct tracking characteristics of reward signal, which is a positive incentive mechanism [7]. When the output is less than the reward signal, the weight value increases, and the direction is the same as the input signal, while when the output is greater than the reward signal, the weight value remains unchanged. In the VSG pre-synchronization control, the amygdala weight regulation law of the emotional controller is as follows:

Fig. 3 The principle of brain emotion control
Then, the output of the emotion controller is:

\[
\Delta \omega = k_{d1}(v_1 - \omega_1)\Delta \theta + k_{d2}(v_2 - \omega_2)\int \Delta \theta dt + v_3 \max(k_{d1}\Delta \theta, \ k_{d2}\int \Delta \theta dt)
\] (10)

It can be seen from equation (10) that the emotional controller is similar to the traditional PI controller. \(k_{d1}(v_1 - \omega_1)\) corresponds to the proportional part of the PI controller, and \(k_{d2}(v_2 - \omega_2)\) corresponds to the integral part of the PI controller. However, there is a learning rate \(\alpha\) in the emotional controller. By changing the learning rate \(\alpha\), the weights \(v_1, v_2\) and \(v_3\) can be changed, so as to change the range of PI parameter automatic adjustment, so that PI parameter adjustment has greater freedom and flexibility. In addition, the third item on the right side of equation (10) has parameter self adaptability. At the beginning of adjustment, \(k_{d1}\Delta \theta\) is greater than \(k_{d2}\int \Delta \theta dt\), which takes \(v_3k_{d1}\Delta \theta\), increasing the proportion adjustment part and shortening the adjustment time; at the later stage of adjustment, when \(k_{d2}\int \Delta \theta dt\) is greater than \(k_{d1}\Delta \theta, v_3k_{d2}\int \Delta \theta dt\) is taken, increasing the integral adjustment part and reducing the steady-state error.

3.3. Grid connection improvement pre-synchronization control

The improved pre-synchronization control structure is shown in Figure 4. The pre-synchronization regulation process is divided into the following four steps: ① when the micro-grid needs to be connected to the grid, an enabling signal is sent to the pre-synchronization control unit, and the pre-synchronization regulation switch S is closed at this time; ② the pre-synchronization regulation signal is sent to the grid controller to participate in the phase regulation process of VSG until the phase of the micro-grid is consistent with that of distribution network; ③ when the phase of the micro-grid meets the grid connection requirements, it is closed and combined The circuit breaker at the PCC point of the grid completes the switch from island to grid mode of the micro-grid; ④ after the grid operation is completed and the switch S is cut off, the pre-synchronous regulation is completed and exited.

![Fig. 4 Improved pre-synchronization control structure chart](image-url)

4. Simulation verification

In order to verify the feasibility of the proposed method, this paper builds a simulation model based on MATLAB / Simulink software platform, including two distributed power supplies, two inverters and one 12kW fixed active load. Island micro-grid and distribution network are connected by AC circuit breaker, and distribution network adopts 380V ideal three-phase power model. In order to verify the effectiveness of the improved pre-synchronization method, the micro-grid is set to transmit power to 12kW fixed active load before and after grid-connection. The effect of PI control and improved pre-synchronization is compared by simulation. See Table 1 for main electrical parameters of grid connected inverter.
Table 1. Table 1 Parameters of simulation.

| The parameter          | Parameter selection | The parameter          | Parameter selection |
|------------------------|---------------------|------------------------|---------------------|
| Dc voltage             | 650 V               | The moment of inertia  | 5 J/kgm²            |
| Rated frequency        | 50 Hz               | Damping coefficient    | 60                  |
| Rated line voltage     | 380 V               | k_f                    | 260                 |
| Filtering inductance   | 2 mH                | k_U                    | 0.002               |
| Filter capacitor       | 420 μF              | k_Q                    | 0.0001              |

Before pre-synchronization, the system is in island mode, the main control unit operates under VSG control, and the slave control unit always operates under PQ with rated power of 6.5kW. Before grid connection, the voltage phase of islanding micro-grid is 120° behind the voltage phase of distribution network, the instantaneous value of A-phase voltage of micro-grid and distribution network is difference, and the pre-synchronization operation instruction is sent out at 1.2s, when the difference is about 0V, the pre-synchronization is completed. Under the same other conditions, the effectiveness of the improved method is verified by comparing the two methods.

Fig. 5 Instantaneous voltage difference in the process of pre-synchronous regulation

Fig. 5 (a) and Fig. 5 (b) show the voltage difference tracking curve of pre-synchronous regulation with PI control and emotional control algorithm respectively. It can be seen that the pre-synchronization voltage difference of PI controller overshoot at 1.21s, and then the voltage difference is stable at ±2V at 1.26s; the pre-synchronization voltage difference of emotional control algorithm is stable at ±0.2V at 1.25s.

Although the two pre-synchronization methods can realize the grid connection, the pre-synchronization using the emotional control algorithm has two advantages compared with the traditional pre-synchronization: ① in the pre-synchronization regulation process, the pre-synchronization using the emotional control algorithm has no overshoot, and the regulation time is shorter. ② The steady-state error of pre-synchronization using emotional control algorithm is obviously smaller than that of PI pre-synchronization. Simulation results verify the effectiveness of the proposed method.

In order to further reflect the effectiveness of the improved pre-synchronization regulation, observe and compare the current changes of the grid connected inverter at the moment of 1.4s grid-connection using the two pre-synchronization methods respectively. In order to avoid the influence of load fluctuation in the process of grid-connection, the load of the system is always 12kW and the control mode of the inverter remains unchanged.
The steady-state error of pre-synchronous regulation has a direct impact on the magnitude of current and power transient impulse at the time of grid connection. During the simulation, the load of VSG is 5.5kW, so the output current is stable at about 9.8A.

The influence of the steady-state error of the pre-synchronous algorithm on the transient impact at the grid-connection time can be observed through Figure 6. Figure 6 (a) shows the current waveform of PI control pre-synchronization method, and the current impulse value reaches 4.2A at 1.4s grid-connection time; Figure 6 (b) shows the current waveform of improved control pre-synchronization method, and the current impulse value at 1.4s grid-connection time is 0.6A. By comparing the instantaneous value of the current at the time of grid-connection, it can be seen that the improved pre-synchronization control is adopted, and the impact current is very small when grid-connection, which ensures that the master-slave micro-grid system transits from island mode to grid-connection mode more smoothly. In conclusion, compared with the PI control pre-synchronization, the improved pre-synchronization method has better regulation effect, and is more conducive to the realization of micro-grid connection switching.

5. Conclusion
In order to solve the problem of current impact caused by the obvious steady-state error in the PI pre-synchronization process, this paper adopts the emotional control algorithm in the pre-synchronization process and designs an improved pre-synchronization process. The simulation results show that the method can reduce the steady-state error of the system pre-synchronization and improve the impact of grid switching.

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References
[1] ZHEN Tianwen, CHEN Laijun, CHEN Tianyi, et al. Review and prospect of virtual synchronous generator technologies [J]. Automation of Electric Power Systems, 2015, 21:026.
[2] WEN Chunxue, YANG Chunlai, CHEN Dan, et al. Power Loop Based Dual Mode Control of Virtual Synchronous Energy Storage Converter [J]. Automation of Electric Power Systems, 2019, 43(8): 56-64.
[3] Wei Yalong, Zhang Hui, Sun Kai, et al. Fault Location Method for Double circuit HVDC Transmission Lines on Same Tower Based on Single circuit Electrical Quantities [J]. Automation of Electric Power Systems, 2016, 40(12): 124-129.
[4] Qiu Lin, Xu Lie, Zheng Zedong, et al. Control method of micro-grid seamless switching [J]. Transactions of China Electrotechnical Society, 2014, 29(2): 172-176 (in Chinese).
[5] Shi Rongliang, Zhang Xing, Xu Haizhen, et al. The Active and Reactive Power Control of
Virtual Synchronous Generator Based on Adaptive Mode Switching [J]. Automation of Electric Power Systems, 2016, 40(10): 16-23.

[6] Yang Yongchao, Zhou Zhigang, et al. Control Strategy Based Seamless Switch of Grid-tied Inverter in Distributed Generation [J]. Proceedings of the CSU-EPSA, 2016, 28(8): 91-97.

[7] YANG Daliang, LU Ziguang, HANG Naishan, et al. Unified power quality conditioner using emotional intelligent controller [J]. Power System Protection and Control, 2013, 41(20): 118-124.