Stability analysis of microgrid inverter off-grid mode considering nonlinear load

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Abstract—With the large-scale utilization of distributed generation in microgrid, inverter as the connection hub of new energy grid connection, directly affects the operation performance of microgrid. In order to improve the output voltage quality and load capacity of the inverter in the off-grid mode of distributed energy, the stability region of the inverter with load is analyzed by using the impedance analysis method of cascade converter and control theory. The quasi proportional resonant (QPR) double loop control is adopted to realize no static error tracking voltage while increasing bandwidth, and the influence of control parameters on performance is analyzed. At the same time, in order to improve the capacity of inverter with nonlinear load, odd harmonics are introduced into the controller to suppress the influence of low harmonics of load current on output voltage. Finally, the influence of inverter output impedance change, load level, controller parameters and filter parameters on system stability is analyzed through impedance ratio Nyquist curve, which provides corresponding theoretical support and parameter optimization reference for the design of actual system.

1. Introduction

Nowadays, facing the dual crisis of fossil energy depletion and environmental degradation, all countries are targeting renewable energy to seek to establish a safer, efficient and green energy system[1]. As a new and flexible energy architecture, microgrid cooperates with photovoltaic, wind power energy, various new energy, energy storage equipment and various loads to conduct two-way energy flow with the power grid through the grid connection interface[2]. The operation mode of microgrid are divided into grid connection mode and island mode. It not only needs to give full play to the advantages of resource integration and friendly interaction with large power grid, but also promotes the local consumption of new energy and independent power supply to local loads. As a necessary energy buffer link of microgrid system, energy storage system is the key to the safe and reliable operation of microgrid[3]. Especially in off-grid mode, the output characteristics of microgrid inverter directly determine the load power supply quality. Therefore, the stability analysis of inverter is of great significance to the selection of microgrid control strategy, the design of control parameters and the switching and optimal control of microgrid operation mode[4].

For the stability analysis of microgrid inverter, most studies are based on the establishment of small signal model, using root locus analysis method, frequency domain analysis and other methods, but these methods have high order, many parameters and cumbersome calculation[5]. In microgrid operation, the existence of a large number of power electronic devices have an impact on the equivalent impedance of the power grid that can not be ignored. In off-grid mode, the loaded operation of energy storage inverter can be regarded as a cascade system included source module composed of
energy storage inverter and load module composed of load and line impedance. The impedance analysis method proposed by Middlebrook et al has become an effective tool to analyze the performance of inverter. This method can improve the performance of the system by establishing the input and output impedance of the inverter to match and improving the stability margin of the system without modeling and knowing the specific parameters. Therefore, it has attracted the attention of many scholars and put forward some improved impedance analysis criteria. In reference[8] the stability criterion of grid connected inverter for impedance analysis have been presented, and pointed out that the grid connected system can be stable only when the ratio of grid impedance to inverter output impedance met the Nyquist stability criterion. In reference[9], the effects of PLL, current controller parameters and filter parameters on the output impedance characteristics of grid connected inverter were analyzed in detail. In reference[10] the small signal model, influencing factors and optimization design method of buck DC-DC converter output impedance were studied, which provided a reference basis for formulating the impedance standard of converter in distributed power system. In reference[11] from the perspective of impedance matching, the instability of distributed generation grid connected inverter in large power grid with high impedance characteristics was studied. At the same time, the detailed analysis method and the stability prohibition region of equivalent loop gain corresponding to the traditional impedance stability analysis method were also given.

Based on the above research, aiming at the operation condition of energy storage inverter in off grid mode, the system output impedance is derived according to the system structure, and the impedance ratio forbidden zone is used to analyze the stability of the system. Double closed-loop control strategy is adopted, and odd harmonics are introduced into the controller to ensure high gain, increase system bandwidth, reduce the influence of low harmonic current on voltage, and realize zero error tracking of voltage. Finally, through impedance ratio Nyquist curves, the influence of inverter output impedance change, load level, controller parameters and filter parameters on system stability is analyzed, and the correctness and effectiveness of the proposed stability criterion are verified, which provides corresponding theoretical support and parameter optimization reference for the design of practical system.

2. Main circuit of microgrid inverter level connection system

A large number of distributed generators are connected to the microgrid through power electronic equipment, which makes the system have the problems of low inertia, easy interference and instability. The energy storage unit adopts droop control, which can provide voltage and frequency support for the microgrid system, realize peak shaving and suppress the power fluctuation of new energy. The off-grid mode structure of the distributed energy storage system is shown in Fig.1. The energy storage inverter adopts voltage current double loop control, introduces virtual impedance and QPR control, realizes voltage zero static error tracking in a wide frequency band, and reduces the circulating current caused by voltage deviation between inverters. Where \( u_{abc} \) is the output voltage of the inverter and \( i_{abc} \) is the three-phase current on the filter inductor.

Fig.1 The structure diagram and control block diagram of the microgrids
The structure diagram and control block diagram of the microgrids composed of the inverter controlled by droop control. $L_f$ is the filter inductance, $C_f$ is the filter capacitor. The control system mainly includes $PQ$ power outer loop and voltage and current double loop tracking link. According to the collected output voltage and current signals at the grid connected terminal, the voltage reference command $E$ and angular frequency $\omega$ are generated through $PQ$ calculation and control module. The virtual impedance link is introduced to compensate the voltage to achieve accurate power distribution, and then the voltage and current double loop tracking $E$ modulates the SPWM drive signal required by the grid connected inverter components. Finally, the power is controlled and adjusted by the inverter to ensure the stability of voltage and frequency.

In the actual distributed power system, the front end of load converter usually needs to be equipped with input filter, and their overall input impedance characteristics are undoubtedly more complex, which makes it difficult to establish and analyze the input impedance model. Since the concept of impedance ratio forbidden region was put forward, the stability analysis process of power supply system has been simplified, and the stability of the system can be analyzed and determined\cite{12}. The distributed energy storage power supply module, inverter and $LC$ filter form the source module in the cascade system, and the line impedance and load form the load module in the system. The equivalent impedances of the original module and load module are $Z_o$ and $Z_i$ respectively.

3. Control strategy of inverter system

3.1. Double loop control structure

The inverter system controller adopts double loop control structure, which can increase the anti-interference of the system and improve the dynamic performance of the system. In the selection of control strategy, although the parameter setting of PI controller is convenient and easy to realize, there is steady-state error in tracking AC signal. The proportional resonance (PR) control can eliminate the steady-state error at the specified frequency, and its narrow bandwidth makes it impossible to track the signal when it deviates from the given frequency of the system.

The voltage outer loop adopts QPR controller $G_{pq}(s)$ to improve the voltage tracking performance of the inverter, while the current inner loop adopts inductive current proportional controller $G_i(s)$ to improve the response speed and anti-interference ability of the system. In the case of nonlinear load, the output voltage waveform is seriously distorted, and the load current is introduced into the inner loop, which transfer function is $H(s)$. Thus, the block diagram of double closed-loop control strategy based on QPR control can be obtained, as shown in Fig.2.

$$\begin{align*}
\text{Fig.2 Double loop control structure of inverter}
\end{align*}$$

In Fig.2, $U$ is the output voltage of inverter; $I_i$ is the output current of the inverter, $I_c$ is filter capacitor current, $k_{pc}$ is the proportional coefficient of current loop, $k_{PWM}$ is the inverter gain, $C$ is the filter capacitance. $U_{ref}$ and $U_o$ are the voltage reference load side voltage.

3.2. Principle of QPR controller

In order to reasonably configure the parameters of the QPR controller, it is necessary to understand the influence of each parameter on the performance of the controller. A zero point is added to the PR controller to transform the proportional resonance controller into a QPR controller. The transfer function of the QPR controller is as following:
\[ G_{pp} = k_p + \frac{2k_r \omega_r s}{s^2 + 2 \omega r s + \omega^2} \]  \hspace{1cm} (1)

Where: \( k_p \) is the proportional coefficient and \( k_r \) is the integral coefficient, \( \omega_r \) is the cut-off angle frequency; \( \omega \) is the fundamental angular frequency.

Comparing PR control and QPR control, it can be found that PR is at the resonance point the gain at \( \omega_0 \) is almost infinite, which can realize closed-loop static error free tracking of ac signal. However, it has large gain at the resonance point, narrow bandwidth and poor anti disturbance ability, which can easily lead to system instability. It is difficult to accurately adjust the resonance point in practical control. While the QPR has high gain at the resonance point, it increases the bandwidth of the controller and reduces the sensitivity of the system, but it still maintains high gain, has good tracking performance, increases the steady-state margin and improves the dynamic performance.

3.3 Parameter analysis of QPR controller
In order to reasonably configure the parameters of the QPR controller, then the influence of each parameter on the performance of the controller is analyzed.

3.3.1 Influence of \( \omega_r \) on controller characteristics

The bandwidth of QPR controller is mainly determined by \( \omega_c \), which is independent of the resonant point. The selection of frequency \( \omega_c \) is generally between 5-20 rad/s.
3.3.2. Influence of $k_r$ on controller characteristics

As can be seen from Fig.5, $k_r$ does not affect the bandwidth of the controller, but only the gain. When $k_r$ increases, the gain of QPR controller increases too.

3.3.3. Influence of $k_{pr}$ on controller characteristics

As can be seen from Fig.6, when $k_{pr}$ is small, the bandwidth of the QPR controller and the gain of the full frequency band are affected. When $k_{pr}$ is large, the QPR controller is approximately equal to the proportional controller.

3.4. QPR controller with harmonic resonator

When the inverter is loaded with nonlinear load, the load current contains a large number of harmonics. It is necessary to implant the internal model of fundamental wave and all harmonics into the controller to make the voltage ring obtain large enough gain, so as to improve the output voltage accuracy of the inverter and the capacity with nonlinear load. After the 1,3,5,7 harmonics are implanted into the control, there are:

$$G_{pr}(s) = k_{pr} + \sum_{h=1,3,5,7} \frac{2k_h\omega_0s}{s^2 + 2\omega_0s + \omega_h^2}$$  \hspace{1cm} (2)

Due to $k_h$, $\omega_0$ affects the gain and bandwidth of the resonance point respectively, so the design of QPR needs to determine $k_{pr}$ and fundamental resonance parameters first. The harmonic resonance part increases the gain at the harmonic of the controller, reduces the output impedance at the harmonic, and realizes no static error tracking of the output current harmonic. The gain of the resonant point can be designed from the point of view of reducing the output impedance and eliminating harmonics. Fig.7 shows the voltage outer loop open-loop Bode diagram after adding 1,3,5,7 harmonic resonators. After adding harmonic resonance, the open-loop cut-off frequency increases and the phase angle margin decreases, but the system stability can still be guaranteed. The open-loop Bode diagram has large gain at the fundamental and harmonic frequency points, and can well track the signal at the specified frequency points.
3.5. Inverter output impedance analysis

Based on the parameter design of QPR controller, the outer loop voltage transfer function is decomposed into impedance form according to the structure diagram through impedance stability analysis:

\[ U_i = G(s)U_{ref} - Z(s)I_r \]  

(3)

If \( H(s) = 1 \), then the output impedance of the inverter is:

\[ Z(s) = \frac{Ls^3 + (R + 2Lo) s^2 + (2Lo + Ro)s + Ro^2}{as^4 + bs^3 + cs^2 + ds + e} \]  

(4)

Where the coefficients are:

\[
\begin{align*}
    a &= LC \\
    b &= (k_p k_{PWM} + R + 2Lo)C \\
    c &= 1 + 2(k_p k_{PWM} + R)\omega_0C + L\omega_0^2C + k_i k_p \\
    d &= (k_p k_{PWM} + R)\omega_0^2C + 2(k_p k_p + k_i k_p)\omega + 2\omega \\
    e &= (k_p + 1)\omega^2 
\end{align*}
\]

The characteristic equation of the system is:

\[ D(s) = as^4 + bs^3 + cs^2 + ds + e \]  

(5)

The parameter conditions required for system stability can be determined according to Rouse criterion, so as to solve the value range of control parameters \( k_p \) and \( k_i \) in QPR controller.

3.6. Impedance ratio forbidden zone

Since the concept of impedance ratio forbidden region has put forward, the stability of the system can be analyzed and determined only by the impedance ratio of source and load converter. The stability criterion proposed by Middlebrook considered the relative stability of the system on the basis of absolute stability, that is, the dynamic performance must meet a certain stability margin, including amplitude margin \( GM \) and phase margin \( \gamma \). Among the many proposed impedance ratio prohibition areas, \( GM(\text{dB}) \geq 6 \text{dB} \) and \( \gamma \geq 60^\circ \) are selected.
Fig. 8 Forbidden domain of system stability

Through conversion, it is obtained that the impedance Nyquist curve meets \( \text{re}(Z_0/Z_i) \geq -1/2 \), that is, it is unstable when it crosses the red region in Fig.8. In practical engineering application, the criteria for judging system stability can be appropriately relaxed according to the actual situation, so as to avoid unnecessary trouble to system design and research due to over conservatism on the premise of ensuring system stability.

4. Analysis of the system stability

| Table 1 System parameters |
|---------------------------|
| parameters | value |
| DC voltage/V | 800 |
| L/mH | 1 |
| R/Ω | 0.01 |
| C/F | \( 40 \times 10^{-6} \) |
| \( k_p \) | 0.02 |
| \( \omega \) | \( 100\pi \) |
| \( k_p \) | 0.4 |
| \( k_i \) | 120 |
| \( \omega_n \) | 3.2 |
| \( k_{PWM} \) | 200 |

4.1. Influence of changing control parameters on system stability

4.1.1. Influence of \( \omega_r \)

The influence of control parameters and filter parameters on system stability is verified. Only change \( \omega_r \) value and other parameters remain unchanged. When \( \omega_r = 13 \), Nyquist curve of impedance \( Z_0/Z_i \) is shown in the Fig. 9. It can be seen that the curve has crossed the stable prohibition region. When the load impedance is certain, with \( \omega_r \) increased, the Nyquist curve will gradually approach the rejection region, making the system stability worse.

\[
\omega(\omega - 1/2) \leq 0
\]
4.1.2. Influence of $k_r$

It can be seen that with the increase of $k_r$, the area surrounded by the Nyquist curve of system impedance becomes larger and closer to the prohibition domain. Therefore, too large $k_r$ will make the Nyquist curve of system impedance enter the prohibition domain, resulting in system instability. However, it should be noted that the larger the $k_r$, the higher the steady-state accuracy of the system and the faster the response speed. Therefore, a larger $k_r$ value can be selected on the premise of ensuring that the system has sufficient stability margin.

4.1.3. Influence of $C$

In the process of increasing $C$, the small signal stability of the main energy storage power supply becomes better. When the filter capacitance increases, the small signal stability of the main energy storage power supply becomes better. The larger the $C$, the smaller the impact on the small signal stability of the main energy storage power supply.
4.2. Influence of load variation on system stability

The impedance ratio analysis method is used to analyze the impact on system stability by changing the load. The load parameters are: \( Z_L = 1 + 0.005s \)

By changing the load parameters, the Nyquist curve of impedance \( Z_o/Z_i \) is obtained, as shown in Fig.12.

As can be seen from Fig.12, with the increase of load level, the impedance Nyquist curve keeps approaching the rejection region. Therefore, when the energy storage system operates with load in off-grid mode, the change of load level will have a great impact on the control stability. When the load level exceeds the system power level limit, the system will not operate stably.

5. Conclusion

The stability of microgrid inverter in off-grid mode is analyzed by impedance analysis method. The double closed-loop structure with QPR control can increase the bandwidth and realize no static error tracking voltage. The change of control parameters and load will affect the output impedance of the inverter. When the impedance Nyquist curve crosses the prohibition domain, it will cause the instability of the system. Based on the results and discussions presented above, the conclusions are obtained as below:

1. In the off-grid mode, the microgrid energy storage inverter does not need to know the internal specific parameters of the subsystem, and the stability of the system can still be analyzed by the impedance ratio method of the cascade system.
(2) The double closed-loop QPR control can increase the bandwidth and gain of the controller, improve the tracking performance of the system, increase the steady-state margin and improve the dynamic performance.

(3) The controller parameters and filter parameters will affect the output impedance of the inverter. When the impedance Nyquist curve crosses the prohibition domain, it will cause the instability of the system.

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