Study on power oscillations suppression strategy of experimental microgrid based on power optimal control

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Abstract. The experimental microgrid could provide a platform for operation and testing of the tested microgrid, so that the performance of the tested microgrid could be obtained before it was put into use. The microgrid had different structures, configurations, distributed generations and three-phase unbalanced load, so the voltage, current and power of the experimental microgrid would inevitably oscillate. First, the power oscillations mechanism of multi-source microgrid was deeply analysed, that was, the analytical relationship between active power pulsation and reactive power pulsation was derived and the influence of positive and negative sequence electrical quantities on power pulsation was revealed. Then, a power oscillations suppression strategy based on power optimal control was proposed. Finally, we built a multi-source microgrid simulation model and a power oscillations control system simulation model on MATLAB. The results showed that the control strategy proposed in this paper could significantly reduce the amplitude of power oscillations caused by unbalanced voltage and current. It could be verified that the control strategy was correct and effective.

1. Introduction

The development of low-carbon clean energy was an effective way to solve the energy crisis and environmental problems. Compared with large power grid, the micro-grid which combined wind power, photovoltaic, energy storage and other distributed energy sources had several of advantages, such as high efficiency, small environmental pollution, strong flexibility of power supply, low input cost. Experimental microgrid could develop and utilize distributed generation technology, which was efficient, economical, flexible and reliable[1].

The microgrid contained a certain proportion of nonlinear load and single-phase load, which could cause three-phase unbalanced current and voltage, and then cause power oscillations[2-3]. Active power oscillations could directly affect bus voltage, and voltage fluctuation would affect the power quality. While reactive power oscillations could produce serious power loss[4-6].

For the power oscillations problem, many scholars at home and abroad had done a lot of research work. The phenomenon of microgrid power oscillations in the case of power grid failure was analysed by Wang F[7]. It was pointed out that the current value could be continuously adjusted by a given compensation parameter in order to obtain the oscillatory amplitude relation between active power and reactive power. However, this paper only gave qualitative rather than quantitative analysis of power oscillations, and failed to give an accurate expression.
Jouanne A \cite{8} designed an unbalanced phase-locked loop based on second-order generalized integrator was for three-phase unbalanced current. The inverter control strategy based on negative sequence voltage feed-forward was designed. However, the aim of this paper was to suppress the negative sequence current of the network side, and not to restrain the oscillations of the active power and reactive power.

In this paper, a power oscillations suppression strategy based on power optimal control was proposed, which successfully solved the problem for the first time \cite{7, 8}. First, the reason of power oscillations which was the existence of negative sequence voltage and current component was analysed. Second, the oscillatory amplitude relation of active power and reactive power was given quantitatively. Then, the positive and negative sequence voltage and current were separated through notch filter. Finally, a power oscillations suppression strategy based on power optimal control for positive and negative sequence voltage and current was proposed and the active and reactive power control was carried out according to the given value of current at the same time.

The simulation model of microgrid and power oscillations control system was built by using MATLAB. The conclusion was drawn that the proposed control strategy made the power system more stable.

2. Study on mechanism of power oscillations

2.1. Operation analysis of micro-source under unbalanced voltage and current

The topology of microgrid is shown in figure 1:

![Figure 1. Equivalent circuit of grid connected inverter.](image)

The mathematical model of grid-connected inverter in synchronous rotating coordinate system was shown in formula 2:

\[
E_{\alpha\beta} = e^{+\omega t} E_{\alpha}^+ + e^{-\omega t} E_{\alpha}^- + e^{+\omega t} E_{\beta}^+ + e^{-\omega t} E_{\beta}^-
\]

Where, \( E_{\alpha\beta}^+ \) and \( E_{\alpha\beta}^- \) respectively denoted the positive and negative-sequence component; \( \alpha, \beta \) represented components in dq rotating coordinate system.

The mathematical model of grid-connected inverter in synchronous rotating coordinate system was shown in formula 2:
Among them: $E$ was PCC point voltage; $V$ was the output voltage of inverter, where, $V_{+dq}$ and $I_{+dq}$ were the amplitude of positive sequence voltage and current respectively; and $V_{-dq}$ and $I_{-dq}$ were negative sequence voltage and current amplitudes respectively; $L, R$ were output inductors and resistors of distributed generation respectively; $U_{dc}$ was DC generation; $C_{eq}$ was power side filter capacitor; $\omega$ was power network frequency.

2.2. Principle analysis

When voltage and current were balanced, the phase voltage and phase current were symmetrical and the angle difference was $\phi$. $\alpha$ was the initial phase. The amplitude of three-phase voltage and current was the same. The expression of the three phase instantaneous power at the PCC point was as follows:

$$
\begin{align*}
E_a &= EI \cos \phi - EI \cos(2\omega + 2\alpha - \phi) \\
E_b &= EI \cos \phi - EI \cos(2\omega t + 2\alpha - \phi + 120^\circ) \\
E_c &= EI \cos \phi - EI \cos(2\omega t + 2\alpha - \phi - 120^\circ)
\end{align*}
$$

The expression of the total three-phase power was as follows:

$$
P = P_a + P_b + P_c = 3EI \cos \phi
$$

It could be concluded that in a three-phase symmetric AC system, the single-phase power varied with time. The sum of the double frequency components in the total three-phase power was constant, so the equipment could keep stable all the time. When asymmetric fault occurred or voltage and current were unbalanced, the sum of double frequency components in the total three-phase power varied with time and did not reach zero. In this case, the equipment would produce vibration and affect the stability of the whole power system.

For unbalanced systems, the asymmetric components were uniquely decomposed into three symmetric components by using the symmetric component method. When zero sequence components were not included, the voltage positive and the negative sequence could be decomposed into the following expressions:

$$
E_{dq} = e^{j\omega t} E_{dq}^+ + e^{-j\omega t} E_{dq}^- = \frac{2}{3}(a e_a + a e_b + a^2 e_c)
$$

Where $a = e^{2 \pi / 3}$, the amplitude of positive and negative sequence voltage could be obtained by notch filter.

The apparent power was:

$$
S = E_{dq} I_{dq}^*
$$

When the voltage asymmetry caused by single-phase fault or other causes occurred in the microgrid, the active power output of the DG was formula (7), and the reactive power was the formula (8):

$$
\begin{align*}
P(t) &= P_0 + P_{c2} \cos(2\omega t) + P_{s2} \sin(2\omega t) \\
Q(t) &= Q_0 + Q_{c2} \cos(2\omega t) + Q_{s2} \sin(2\omega t)
\end{align*}
$$

Where

$P_0$: instantaneous average component of active power;

$P_{c2}$: the cosine component of active power instantaneous oscillations of double frequency;

$P_{s2}$: the Sinusoidal component of active power instantaneous oscillations of double frequency;

$Q_0$: instantaneous average component of reactive power;

$Q_{c2}$: the cosine component of instantaneous oscillations of double frequency reactive power;

$Q_{s2}$: the sinusoidal component of instantaneous oscillations of double frequency reactive power.
3. Study on the strategy of power optimal control

3.1. Principle of power optimal control strategy

According to Jin P’s work [11], the relationship between P, Q and positive, negative sequence voltage, current, a control strategy for suppressing active power oscillations of microsource was proposed. The expression was as shown in formula (9):

\[
\begin{bmatrix}
I_{d+}^+ & I_{d+}^- & I_{q+}^+ & I_{q+}^-
\end{bmatrix} = \begin{bmatrix}
E_{d+}^+ & E_{q+}^+ & E_{d-}^- & E_{q-}^-
E_{q+}^- & -E_{d+}^- & E_{q-}^+ & -E_{d-}^-
E_{d-}^- & -E_{q-}^- & E_{d+}^+ & E_{q+}^+
E_{q-}^+ & -E_{d-}^+ & -E_{q+}^- & E_{d+}^-
\end{bmatrix}^{-1} \begin{bmatrix}
\frac{2}{3}P_0
0
0
0
\end{bmatrix}
\]

(9)

The positive and negative sequence current could be obtained by formula (9). Since there were only four positive and negative sequence currents, this method could only control \(P_0, P_{c2}, P_{c3}\) and \(Q_0\), which made \(P_{c2}=P_{c3}=0\).

3.2. Control Strategy of Microgrid

In order to solve the above problem, the feed-forward controller was employed according to the given current value and combined with feedback to get the voltage desired value. Output voltage of grid-connected inverter was controlled to follow the given value.

\[
\begin{align*}
V^+_{d+} &= E^+_{d+} - (K_p + \frac{K_i}{s})(i^+_{d+} - i^{+}_{dm+}) + \alpha_i L_i^+ \quad \text{for positive sequence} \\
V^+_{q+} &= E^+_{q+} - (K_p + \frac{K_i}{s})(i^+_{q+} - i^{+}_{qm+}) - \alpha_i L_i^+ \\
V^-_{d-} &= E^-_{d-} - (K_p + \frac{K_i}{s})(i^-_{d-} - i^{-}_{dm-}) - \alpha_i L_i^- \\
V^-_{q-} &= E^-_{q-} - (K_p + \frac{K_i}{s})(i^-_{q-} - i^{-}_{qm-}) + \alpha_i L_i^- \\
\end{align*}
\]

(10)

\(K_p, K_i\) were the proportion and integral coefficient of the PI feed-back controller respectively.

It was known that there was coupling when the inverter model performs d-q transformation from formula (10), so it was necessary to compensate for this to reduce the influence. In order to improve the system speed and reduce the coupling, the positive and negative sequence voltage amplitudes of
parallel dots could be introduced into the control loop as feedforward. The given values of positive and negative sequence voltages were obtained by feedforward algorithm, and the corresponding voltage quantities were obtained by transforming d-q coordinate system to a-b-c coordinate system. Finally, the inverter control was realized by using SPWM modulation method.

4. Simulation analysis and verification
The feasibility of the control strategy was verified by the simulation model of multi-source microgrid and the simulation model of power oscillations control system based on MATLAB.

When there were unbalanced loads, the voltage and current would be asymmetrical, then oscillations of active and reactive power appeared.

Figure 3. showed the process of suppressing active power and reactive power oscillations. The (a), (b), (c) were the waveform diagrams of active power and reactive power and microgrid current $I_{abc}$ in the first second, the last 0.5 seconds and the whole 20 seconds, respectively.

Figure 4. showed the first second, the last 0.5 second and the whole 20 seconds waveform of current measurement of the microgrid decomposed by notch filter obtained.
Figure 4. Notch Filtered d-q Current.

Under power optimal control, the current recovered to three-phase symmetric current in about 20s, and the oscillations amplitude of active power and reactive power decreased by about 50%.

5. Conclusion
The simulation results showed that the power oscillations suppression strategy based on power optimal control could restrain the active and reactive power oscillations. When generating the power oscillations, the unbalanced current could be symmetrical by controlled the positive and negative sequence current separately. Then the oscillations of the active and reactive power could be restrained, which lead to an improvement in the stability of experimental microgrid.

Acknowledgment
Project Supported by Science and technology project of state grid corporation of China (2019yf-01)

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