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Optimized hierarchical power oscillations control for distributed generation under unbalanced conditions

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HIGHLIGHTS

- A hierarchical control structure is proposed to reduce power oscillations for DGs.
- Relationship between amplitudes of active and reactive power oscillations is deduced.
- Injected negative-sequence currents are obviously restrained by using the proposal.
- Test results show that the proposal can effectively limit the oscillations together.

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ABSTRACT

Control structures have critical influences on converter-interfaced distributed generations (DG) under unbalanced conditions. Most of previous works focus on suppressing active power oscillations and ripples of DC bus voltage. In this paper, the relationship between amplitudes of the active power oscillations and the reactive power oscillations are firstly deduced and the hierarchical control of DG is proposed to reduce power oscillations. The hierarchical control consists of primary and secondary levels. Current references are generated in primary control level and the active power oscillations can be suppressed by a dual current controller. Secondary control reduces the active power and reactive power oscillations simultaneously by optimal model aiming for minimum amplitudes of oscillations. Simulation results show that the proposed secondary control with less injecting negative-sequence current than traditional control methods can effectively limit both active power and reactive power oscillations.

1. Introduction

With the rapid development of renewable energy resources, the concept of converter-interfaced distributed generation (DG) is playing an important role in power grids [1–3]. The voltage-sourced converter (VSC) has become a key component of an energy-conversion device for DGs [4]. Due to inertialess factors of VSC, grid disturbances have adverse impact on performances of DG converters [5,6]. Most of DGs are located at the terminals of a distribution network or microgrid where unbalanced conditions exist owing to single-phase loads and asymmetrical faults [7,8]. Grid imbalance in a three-phase system leads to double working frequency power oscillations. For one thing, active power oscillations have negative effects on DC-link of converters; for another, reactive power oscillations may result in high power loss and over-current stress [9]. Consequently, various control structures have been proposed to enhance the operation performance of VSC under asymmetrical conditions in recent years.

It's known that control structures play a very important role in the DG's behavior under unbalanced conditions [10]. Notch filters are adopted to separate the components of positive- and negative-sequences from the sampling electrical quantities and the dual PI controllers in dual synchronous rotating frames (SRFs) are proposed to regulate positive- and negative-sequence components respectively [11]. The DC-link voltage ripple and active power oscillations can be suppressed by means of the dual current controllers, but reactive power oscillations are significantly amplified and system dynamics are limited by notch filters. On the contrary, to extract symmetrical components, the delay signal cancellation (DSC) is employed by combining 1/4 working frequency cycle delay and the original AC value [12]. Moreover,

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positive- and negative-sequences detection can be replaced when resonant controllers are adopted and it is demonstrated that the stationary frame resonant controllers are suitable for extracting symmetric-sequence electrical quantities. The dual SRFs can be simplified to one stationary frame and realize zero error tracking. Further, in order to promote DG performances and system dynamic tracking, controllers must be able to extract the positive- and negative-sequences components and achieve feedback control [13,14]. Therefore, all these control schemes focus on eliminating the active power oscillations and improving reference tracking, while there is seldom optimized operation strategy considering reactive power compensation and DC bus voltage oscillation simultaneously [15].

Besides control structures, it is also very important to generate current references under unbalanced conditions. Considering the constraints of DG converter, an accepted constant DC-link bus voltage should be maintained. Based on the input positive- and negative-sequence components, an unbalanced transfer matrix of input phase voltages is generally feasible [11]. However, a constant DC bus is obtained at the expense of asymmetrical currents and a sharp increase of reactive power oscillations. As discussed in [16], several schemes may improve different quality of electric energy at the point of common coupling (PCC) in terms of power oscillations and current distortions. These strategies show flexible adjustment of converters under asymmetrical voltage. However, most of them only deal with some specific distortions. It is reasonable to regulate the amplitudes of active and reactive power oscillations through an adjustable parameter of current Ref. [17]. Moreover, the relationship between active and reactive power oscillations is discussed, but it is only lagging in the qualitative analysis stage.

Previous studies mainly focus on the reduction of active power oscillations, but the analytic relationship between active and reactive power oscillations is still unclear. In addition, most work in the field of DG operation is under unbalanced grid faults, and seldom work focuses on long-term operation under a low voltage unbalance factor. However, this working condition widely exists at terminals of distribution networks or microgrids with DGs.

In this paper, a novel hierarchical control structure is proposed to suppress the power oscillations for DGs under unbalanced conditions. The contribution of this paper is twofold: the relationship between amplitudes of the active power oscillations and the reactive power oscillations is firstly deduced and a hierarchical control structure of DGs is proposed to reduce power oscillations; and significant performance improvements from applying the proposed scheme is demonstrated in detail.

The remainder of this paper is organized as follows. First, the mechanism of power oscillations is revealed from viewpoint of the positive- and negative-sequence current injection. Then, an optimization model for suppression of power oscillations is established, and a hierarchical control structure is proposed to reduce both the active and reactive power oscillations simultaneously. Application of the proposed control scheme is demonstrated using simulation tests, and finally the conclusions are made.

2. Mathematical description of converter under unbalanced conditions

An unbalanced three-phase input voltage $\{E_a, E_b, E_c\}$ at PCC without a zero sequence can be represented as the sum of positive- and negative-sequences, such that

$$E_{\alpha\beta} = e^{j\omega t}E^+_{dq+} + e^{-j\omega t}E^-_{dq-} \tag{1}$$

where $E^+_{dq+} = E^+_{d+} + jE^+_{q+}$, $E^-_{dq-} = E^-_{d-} + jE^-_{q-}$; +, – respectively denote the positive and negative-sequence component; ω is the angular frequency.

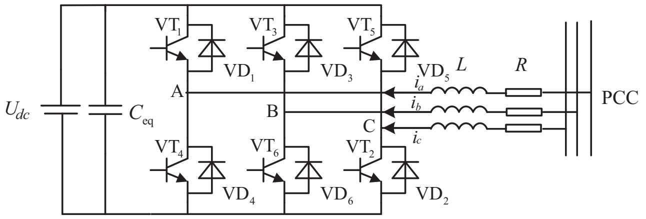

Fig. 1. Equivalent circuit of converter for DG.

The converter model of DG is described in Fig. 1 and can be decomposed as two separate parts

$$\begin{cases} E^+_{dq+} = V^+_{dq+} + L\frac{dI^+_{dq+}}{dt} + j\omega LI^+_{dq+} + RI^+_{dq+} \\ E^-_{dq-} = V^-_{dq-} + L\frac{dI^-_{dq-}}{dt} - j\omega LI^-_{dq-} + RI^-_{dq-} \end{cases} \tag{2}$$

where input current $\{I_a, I_b, I_c\}$ and output voltage of inverter $\{V_a, V_b, V_c\}$ are also expressed in forms of positive- and negative-sequence components like three-phase input voltage. With the unbalanced input voltage, apparent power is given by

$$S = \left(e^{j\omega t}E^+_{dq+} + e^{-j\omega t}E^-_{dq-}\right)\left(e^{j\omega t}I^+_{dq+} + e^{-j\omega t}I^-_{dq-}\right)^* \tag{3}$$

An unbalanced three-phase input voltage $\{E_a, E_b, E_c\}$ at the PCC causes double working frequency power oscillations, and instantaneous power of a DG can be expressed as

$$P(t) = P_0 + P_{c2}\cos(2\omega t) + P_{s2}\sin(2\omega t) \tag{4}$$

$$Q(t) = Q_0 + Q_{c2}\cos(2\omega t) + Q_{s2}\sin(2\omega t) \tag{5}$$

where P_{c2}, P_{s2}, Q_{c2}, Q_{s2} caused by unbalanced input voltage appear as the double working frequency oscillations, and they can be expressed as

$$\begin{cases} P_0 = E^+_{d+}I^+_{d+} + E^+_{q+}I^+_{q+} + E^-_{d-}I^-_{d-} + E^-_{q-}I^-_{q-} \\ P_{c2} = E^+_{d+}I^-_{d-} + E^+_{q+}I^-_{q-} + E^-_{d-}I^+_{d+} + E^-_{q-}I^+_{q+} \\ P_{s2} = E^+_{d+}I^-_{q-} - E^+_{q+}I^-_{d-} - E^-_{d-}I^+_{q+} + E^-_{q-}I^+_{d+} \end{cases} \tag{6}$$

$$\begin{cases} Q_0 = E^+_{q+}I^+_{d+} - E^+_{d+}I^+_{q+} + E^-_{q-}I^-_{d-} - E^-_{d-}I^-_{q-} \\ Q_{c2} = E^+_{q+}I^-_{d-} - E^+_{d+}I^-_{q-} + E^-_{q-}I^+_{d+} - E^-_{d-}I^+_{q+} \\ Q_{s2} = E^+_{d+}I^-_{d-} + E^+_{q+}I^-_{q-} - E^-_{d-}I^+_{d+} - E^-_{q-}I^+_{q+} \end{cases} \tag{7}$$

Instantaneous active and reactive power in (4) and (5) can be rewritten as

$$P(t) = P_0 + P_v\sin\left(2\omega t + \tan^{-1}\left(\frac{P_{c2}}{P_{s2}}\right)\right) \tag{8}$$

$$Q(t) = Q_0 + Q_v\sin\left(2\omega t + \tan^{-1}\left(\frac{Q_{c2}}{Q_{s2}}\right)\right) \tag{9}$$

where $P_v = \sqrt{P^2_{s2} + P^2_{c2}}$, $Q_v = \sqrt{Q^2_{s2} + Q^2_{c2}}$. From the Eqs. (8) and (9), the instantaneous power can be divided into AC and DC components. When a microgrid contains single-phase loads and sources, active and reactive power oscillations exist simultaneously because of unbalance voltage in PCC. Consequently, there is an urgent need to reveal the couple relationship between them.

3. Mechanism of power oscillation under unbalanced conditions

Based on (6) and (7), the relationship between active and reactive power oscillations can be derived as followed:

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