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Parameter design and hot seamless transfer of single-phase synchronverter☆

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ABSTRACT

This paper reveals the parameter design of single-phase synchronverter (SPSV) and proposes a hot seamless transfer method for SPSV. The design challenge of SPSV lies in its necessary for single-phase power calculation to generate an average value of active/reactive power and the high order system feature caused by the virtual inertia element. The small signal analysis shows that the low-pass filter time constant and SPSV active power loop time constant determine the system damping ratio together. Then we proposed a SPSV parameter design method to provide a proper damping ratio and guarantee system small signal stability. Based on the SPSV parameter design method, a hot seamless-transfer is proposed. During the disconnection and reconnection processes, SPSV can maintain a non-zero power output, which is essential for the critical local loads when the SPSV serves as an uninterrupted power source. The SPSV parameter design method and hot seamless transfer are investigated by simulation. Finally, a 500 W SPSV prototype is built for further demonstration.

1. Introduction

As the increasing renewable energy penetration, the research on distributed generations (DGs) and microgrids have a fast-growing significance [1–5]. Grid-connected converters are used as the power electronic interfaces between DGs (such as energy-storage device, photovoltaic panels, fuel cells and wind turbines) and the grid [6,7]. Voltage source converter (VSC) research is of vital importance to ensure that distributed generations can offer high-reliability electrical power supply [8].

Synchronverter is one way to control VSC, which mimics both the dynamic and steady character of the synchronous generator (SG) [9–11]. It can synchronize without phase-locked loops (PLLs), realize frequency- and voltage-droop using only the local information. Nowadays, the investigation of synchronverter has extended into STATCOM [12], photovoltaic power generation [13], wind turbines, high voltage direct current (HVDC) transmission [14] and static VAR compensator (SVC) [15] and so on. One of the remained problems of synchronverter is the dynamic stability and performance improvement, especially when considering the low-pass filter.

Single-phase converters are widely used in distributed energy conversion [16–20]. Along with the development of power electronic transformer (or solid state transformer) [21–23], single-phase converters will play an important part in railway power supply. Single-phase synchronverter (SPSV) is an essential element for power-electronics-enabled autonomous power Systems [24,13,25,26]. Two issues are essential for SPSV application: parameter design and hot seamless transfer.

The design challenge of SPSV lies in two aspects. Firstly, unlike its three-phase counterpart, SPSV needs single-phase power calculation to generate average torque and reactive power [6], which bring a challenge to the design of SPSV. Single-phase power calculation methods introduce delay element into the power measure loop and reduce the bandwidth of the close loop system [18,27–29]. In this paper, we choose the first order low-pass filter to investigate in detail, which is accurate enough to show the challenge of SPSV design and explain the solution because it can demonstrate time delay feature of other single-phase power calculation methods as well. Secondly, unlike conventional droop control, the active power loop of synchronverter is a high order control system because it has a virtual inertia element, which makes the design process much more complicated than the design of conventional droop control [29,30]. However, no reference, in the research field of synchronverter, investigated the SPSV parameter design focus on the influence of low-pass filter and obtained the formula for SPSV parameter design. In this paper, we will discuss the SPSV small sig-

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nal modeling with regard to its specificity and reveal guidance for its parameter design.

A seamless transfer indicates the swap process between the grid-connected mode and stand-alone mode [16,31,32,20]. Several studies have been conducted to solve the seamless transfer issue of the three-phase synchronverter [33,34]. In references [33,35], researchers proposed a control strategy based on the PLL essence of a synchronverter to realize the self-synchronization for synchronverters. However, this control method cannot provide hot seamless transfer: prior to reconnection, synchronverter output current should decrease to zero at first. Reference [34] proposes a three-phase synchronverter seamless transfer method based on PLL. However, PLL is a notably complex system, in particular, the the single-phase PLL commonly includes a $\alpha\beta$/dq0 transformation block and a quadrature signal generation block or nonlinear calculation block and a low-pass filter [6]. Thus, it is extremely complicated and time-consuming to tune the PLL parameters to achieve satisfactory performance [35]. To resolve the aforementioned problems, in this paper, we propose a hot seamless transfer for SPSV, and without PLL inside the control strategy.

There are two contributions in this paper. Firstly, this paper demonstrates the essential difference between the SPSV and three-phase synchronverter; furthermore, it reveals the design of SPSV. Secondly, derived from the quasi-synchronization principle, this paper proposes a hot seamless transfer in the single-phase system. Only an RMS value calculation block is added to the basic SPSV control strategy. Thus, the proposed seamless transfer control strategy is PLL-free. Most importantly, the entire seamless transfer process is hot seamless transfer, i.e., seamless transfer without power cut-off from the local load, which is critical when the local load is sensitive or uninterrupted. The remainder of this paper is organized as follows. Section 2 explains the design challenges of SPSV is in detail. Section 3 introduces the hot seamless transfer strategy in the SPSV. Section 4 presents the simulation results. Section 5 is the experimental results of a 500 W prototype.

2. Parameter design of single-phase synchronverter

2.1. It is necessary to use single-phase power calculation in SPSV

Ref. [9] shows that the conventional three-phase synchronverter model is based on Eqs. (1)–(3).

$$T_e = M_f i_f \langle i, \tilde{\sin}\theta \rangle \tag{1}$$

$$e = \omega M_f i_f \tilde{\sin}\theta \tag{2}$$

$$Q = -\omega M_f i_f \tilde{\cos}\theta \tag{3}$$

In the steady state, the three-phase instantaneous active power $p(t)$ and instantaneous reactive power $q(t)$ are:

$$\begin{cases} p(t) = \dfrac{3}{2}\omega M_f i_f \hat{I}\cos(\omega t - \varphi) \\ q(t) = \dfrac{3}{2}\omega M_f i_f \hat{I}\sin(\omega t - \varphi) \end{cases} \tag{4}$$

where $\hat{I}$ and φ are the peak value and phase of i. Note that the angular speed can be treated as a constant in the steady state. Under this condition, the right side of Eq. (4) is the conventional definitions for the active power and reactive power which are essentially the average active power P (proportional to torque T_e) and reactive power Q. The coincidence between the instantaneous and conven-

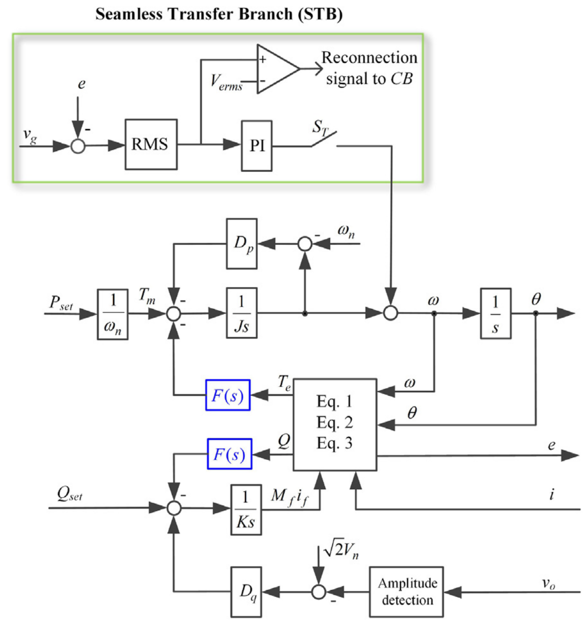

Fig. 1. Low-pass filter $F(s)$ and seamless transfer branch (STB) in single-phase synchronverter control strategy.

tional power definitions in the three-phase synchronous generator can be expressed as:

$$\begin{cases} p(t) = P \\ q(t) = Q \end{cases} \tag{5}$$

The drooping characteristic of the synchronous generator is based on the average value of active/reactive power. It is because of this coincidence shown in Eq. (5), the previous Eq. (4) for $p(t)$ (proportional to torque) and $q(t)$ can be used for calculation to mimic the drooping characteristic of the synchronous generator.

However, this coincidence only exists in three-phase synchronverters. Unlike the three-phase synchronous synchronverter, the instantaneous active power and reactive power in the single-phase synchronverter do not coincide with the conventional definitions of active power and reactive power. The results of Eqs. (1) and (3) have oscillation at twice the line frequency when the system is stable. As a result, the conventional three-phase control strategy should introduce low-pass filters, shown as $F(s)$ in Fig. 1, to calculate the average value of active/reactive power, and then mimic synchronous generator drooping character.

2.2. Parameter design to provide enough damping ratio

The low-pass filter is essential for single-phase synchronverter. However, the low-pass filter time constant will influence system stability by slowing down the system respond speed and reducing the system bandwidth. This part will investigate the interaction between low-pass filter time constant and other parameters and find out the rule for single-phase synchronverter parameter design.

The regulation mechanism of the active power (torque) shown in the upper part of Fig. 1 has a nested structure, where the inner loop is the frequency loop and the outer loop is the more complex active power loop. The active power loop has a feedback coming from the virtual torque T_e, which is calculated by the SV output current i, shown in Fig. 2.

Because the inner frequency loop is faster than the outer active power loop, the change of T_e and P_{set} are so small that can be ignored