

Transient analysis of low-voltage ride-through in three-phase grid-connected converter with LCL filter using the nonlinear modal series method



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ABSTRACT

From a theoretical perspective, this paper develops a systematic approach to analyze the transient characteristics of the low-voltage ride-through (LVRT) in three-phase grid-connected converter with LCL filter by using the nonlinear modal series method. Firstly, the mathematical model and the corresponding second order modal series model of the system are described. And then, the simulation results and the theoretical analysis manifest that there are abundant modal interactions, particularly the stronger second order modal interaction, in the LVRT transient process. The revised expressions considering the nonlinear terms for the state variables are subsequently obtained. By selecting the appropriate parameters to weaken second order modal interaction, we can effectively reduce the amplitude and the duration of the oscillation to satisfy the requirements of the system tolerance during LVRT process. Additionally, the dominant oscillation modes of each state variable are also studied. Finally, the second order quasi-resonance boundaries are defined to facilitate the selection of practical parameters for maintaining normal transient behavior.

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1. Introduction

The three-phase power electronic converters with LCL filter are now used in many renewable energy generation systems as a grid-connected interface (e.g., wind energy, solar etc.) [1,2]. Power regeneration, adjustable power factor and significantly less line current harmonic distortion are the most important advantages of this converter with respect to other types of converters [3]. As the scale of renewable energy generations becomes larger and larger nowadays [4,5], the huge penetration of these new power to the grid has led the grid codes to require the low-voltage ride-through (LVRT) capability of the grid-connected converter in these generation systems during the grid disturbances to avoid the shutdown phenomenon of large renewable energy generations [6,7]. As an example, a diagram of the LVRT requirements, in which wind turbines should be still connected for voltage sags, is shown in Fig. 1 [8,9]. Practically speaking, these renewable energy generation systems has been faced with serious problems during the LVRT process and the grid code requirements about LVRT present a significant challenge to the well-established renewable energy technologies [10,11]. In the power system where the renewable energy generation is of a major portion, the system variables such as the grid

voltage and the grid current are much fluctuated in comparison with the normal operation state during voltage dip [12], which has an important effect on the transient stability and applications in many areas of these power generations.

For the issues of LVRT, the previous work is mainly focused on a suitable ride-through control method or an additional hardware circuit to enhance the LVRT capability of the grid-connected converter in the power generation system, which will allow the operation of the renewable energy generation system to meet the requirement of the set of grid codes [13–16]. Unfortunately, since power system faults are often characterized by a momentary decrease in the RMS voltage magnitude [17], these works ignore the various transient phenomenon existing in the LVRT process and does not further analyze the transient behavior of the LVRT which might be of a powerful impact on the grid and or even destroy the system circuit. The investigation into transient behavior allows an essential understanding of the system dynamical operations and may give some useful information for practical design and control applications [18,19].

Recently, some works detailing the transient state of voltage sags on the grid-connected converter in the renewable energy generation system have appeared, and the transient phenomenon has been used to assess the oscillations at external grid voltage sag [20]. For example, Muyeen et al. have carried out extensive time-domain simulation analyses on the transient behavior of wind turbine system considering both symmetrical and

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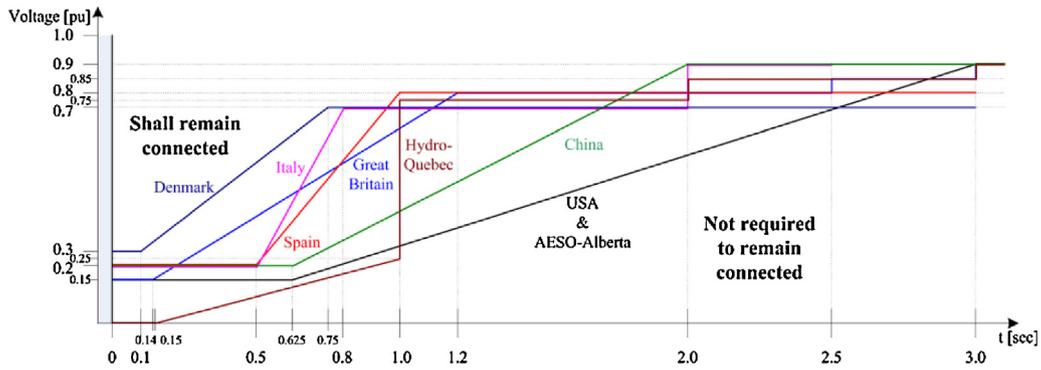


Fig. 1. National grid codes.

unsymmetrical faults occurring at several locations to analyze the LVRT characteristics of the system [21]. And the simulation waves of PV converter in LVRT process are also investigated in relative literatures [22]. Although the traditional time-domain simulation method can get some nonlinear transient information by observing the time-domain simulation phenomena, it is difficult to identify the nature of system oscillations, and the relationship between the interactive modes and the state variables, as well as system parameters and disturbances. Essentially, the existing works have not dealt with the effects of nonlinear modal interactions on the dynamic behavior of the grid-connected converter in LVRT process, and the consequent relationship between the system behavior and the control strategies. Moreover, traditional modeling methods use a linear model and the validity of linear analysis method such as Routh–Hurwitz stability criterion is restricted to a small neighborhood of the operating point which is not suitable to the case of large disturbance [23], so that the mechanism of LVRT transient behavior can not be accurately revealed. Therefore, an analysis of LVRT transient behavior for the grid-connected converter with LCL filter in renewable energy generation system is absent from a theoretical perspective.

In this paper, the nonlinear modal series method, by which the linear system theory concepts can be extended to facilitate the understanding and analysis of nonlinear system [24] through considering the nonlinear high-order polynomial in high-order modes space, is used to investigate the LVRT transient dynamic characteristics of the grid-connected converter with LCL filter during voltage sag so as to transfer the transient characteristics research from the qualitative analysis to the quantitative analysis. The intrinsic mechanism of the way by which the nonlinear modal interaction affects the LVRT transient behavior is revealed, and more appropriate functions for representing system behavior can be obtained. Based on the relationship between the modal interaction and the parameters, the oscillation amplitude and duration of the state variable during LVRT transient process can be reduced to satisfy the requirements of the system tolerance by adjusting certain of the parameters. Furthermore, the second order quasi-resonance boundaries with regard to some key parameters are analyzed, in order to facilitate the optimal design of the grid-connected converter with LCL filter.

This paper is organized as follows. In Section 2, the mathematical model of a interface system constituted by grid-connected converter with LCL filter and its control scheme are developed. In Section 3, the second order modal approximate solution of the system is established by using the nonlinear modal series method. In Section 4, more nonlinear modes are found using the second order modal method, and the simulation is also carried out to illustrate the efficiency of the nonlinear modal series method in the analysis of the LVRT transient behavior. Then, a quantitative measure is used to find out the dominant nonlinear interactive modes for the

state variable and the appropriate formulations of the main state variables are presented by selecting the stronger modal interaction. The relationship between the nonlinear modal interactions and the system parameters are newly performed to assess the parameter's impacts on the LVRT transient behavior. Subsequently, the dominant oscillation modal of the system state variables are also studied. In order to avoid the occurrence of resonance, the second order quasi-resonance boundaries are given in this subsection. Finally, Section 5 concludes the paper.

2. System modeling

2.1. Description and mathematical model

The grid-connected converter is commonly based on a voltage source inverter (VSI) connected to the supply network [25]. These converters are always used to maintain a constant DC-link voltage and to control the power factor of the generation system. The DC-link is created by a capacitor which isolates the operation of the grid-connected converter from renewable energy sources, so that the control and the operation of the converter allow being individual. In practice, the renewable energy generation system only needs to take countermeasures for the grid-connected converter and the DC-link in the case of LVRT process which will not affect the normal operations of the renewable energy source. In order to deeply investigate the transient behavior, these generation systems should be simplified. Here, the equivalent circuit of the system is shown in Fig. 2. In this paper, a grid-connected interface system constituted by a three-phase converter with LCL filter as a research model will be discussed.

In most of these studies, the power source of the system is considered as a DC voltage source [26]. However, this equivalent treatment is not adaptable to the control principles of the grid-connected converter in the renewable energy generation system such as PMSG-type wind turbine. In addition, the input current of the converter is not predictable. In order to establish a reasonably alternative model, the basic principles of a simplified treatment should ensure that both the voltage and the current characteristics of the simplified model are as same as the prototype, and the control method of the grid-connected converter remains unchanged. Based on these preconditions, a controlled current source is used to replace the renewable energy source and its related power

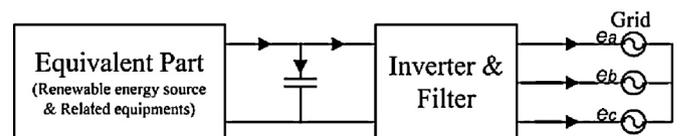


Fig. 2. Equivalent circuit of grid-connected renewable energy generation system.

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