Electrical Power and Energy Systems 101 (2018) 75–84

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

journal homepage: www.elsevier.com/locate/ijepes

Stability analysis and energy storage-based solution of wind farm during low voltage ride through

Ju Liu[a,b], Wei Yao[a,*], Jiakun Fang[c], Jinyu Wen[a], Shijie Cheng[a]

[a] State Key Laboratory of Advanced Electromagnetic Engineering and Technology, School of Electrical and Electronic Engineering, Huazhong University of Science and Technology, Wuhan 430074, China

[b] Sate Grid Hubei Electric Power Company Limited Economic Research Institute, Wuhan 430074, China

[c] Department of Energy Technology, Aalborg University, 9220 Aalborg, Denmark

ARTICLE INFO

Keywords:
Low voltage ride through (LVRT)
phase-locked loop (PLL)
energy storage system (ESS)
Frequency
Injection current

ABSTRACT

According to most grid codes, wind farms are required to inject reactive current into the connected power grid during fault. However, this requirement may lead to the system instability and the failure of low voltage ride-through (LVRT), especially for the wind farms connected to a weak grid. In this paper, we suppose that the instability of wind farm during LVRT is mainly due to the instability of the phase-locked loop (PLL), thus a state-space model of the wind power system including the PLL under the low voltage condition is established for stability analysis. The mechanism of the system instability phenomenon during fault is investigated and revealed. To address this problem, an energy storage system (ESS)-based stability control strategy is proposed to maintain the stability of the wind power system during fault. The detailed electromagnetic model of the test system including three wind farms is installed in PSCAD/EMTDC environment for simulation studies. Simulation results verify the correctness of the obtained stability analysis results and the effectiveness of the ESS-based stability control strategy.

1. Introduction

As a kind of renewable energy sources, the increasing wind power has been integrated into power system over the past decade. The high penetration of wind power gives rise to lots of issues [1–5], for example, the instability of the power system. Unlike conventional synchronous generators, most wind turbines (WTs) are connected to a power grid through the voltage-sourced converters (VSCs) [6–9]. Thus, those VSC controlled WTs are significantly different from the conventional synchronous generators in terms of physical and electrical characteristics. In order to ensure the stable and reliable operation of the wind power system, most grid codes stipulate that wind farms must keep connecting to the power system during fault and require to inject reactive current for voltage support [10–12]. Generally, the injected reactive current is proportional to the voltage drop with a dead band about 0.1 p.u. For instance, the low voltage ride through (LVRT) requirement of China is shown in Fig. 1, the grid code states that the injected reactive current of wind farm should be 1 p.u., when the voltage at point of common coupling (PCC) bus of wind farm drops below 0.4 p.u. [11]. Additionally, those requirements are also stipulated in many other grid codes of transmission system operators, including the ENTSO-E that requires the WTs to stay connected with the grid even when the voltage of PCC bus drops down to zero [10].

As one of the main types of wind turbines, full-scale converter wind turbines (FSCWTs) have been widely applied in the power system. In accordance with the grid code requirements, the response characteristics of the WTs during LVRT have attracted much attention. In [13–17], the low voltage fault behaviors of WTs and its impact on power grid voltage and transient stability have been analyzed. The control strategies to assist the WTs for LVRT and improve voltage support to the grids are also addressed. Besides, the frequency stability is also one of the aspects to ensure the safety operation of FSCWTs during the LVRT. In [18], the loss of synchronism (LOS) of wind power plants, namely the frequency of the wind plants loses synchronism with the main power grid, under the weak grid condition for non-faulted cases has been handled. Although the frequency of the wind farm is beyond the safety operation range during LOS, it is different from the traditional frequency stability problem caused by the unbalance active power of the power system. It is well known that the frequency of the wind farm maintains synchronism with the main power grid through the phased locked loop (PLL). If the PLL could not keep stability, the wind farm will lose synchronism with the power grid, and then the

* Corresponding author.
E-mail address: w.yao@hust.edu.cn (W. Yao).

https://doi.org/10.1016/j.ijepes.2018.03.013
Received 1 November 2017; Received in revised form 11 January 2018; Accepted 10 March 2018
0142-0615/

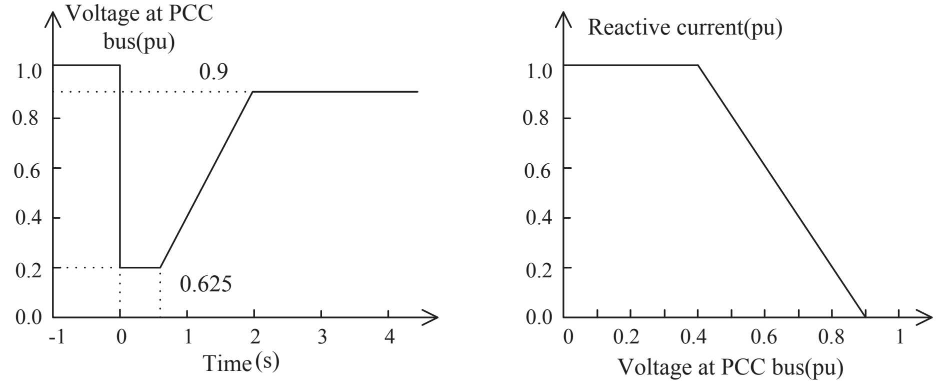

Fig. 1. LVRT requirement of China for a wind farm.

frequency of the wind farm cannot keep stable. When the occurrence of fault in the power grid makes the voltage of the PCC bus dip approach to zero, as stated by the grid codes, the reactive current is required to be injected by the WTs. Under such an operation situation, the connection between the wind farm and the main power grid also becomes very weak. Refs. [19,20] state that if the WTs' injection current characteristics (the ratio of active current to reactive current) is not in accordance with the impedance characteristics (the ratio of the resistance to the reactance) between the WTs and PCC bus, the frequency of the wind power system will deviate far away from the rated value. Consequently, WTs will also lose synchronism with the main grid, the LOS problem will also happen during the LVRT of wind farm, which is the main stability problem concerned in this paper. As will be given in the following parts, FSCWTs will lose synchronism during the severe voltage faults if one p.u. pure reactive current is injected into the power grid according to grid codes. Then the wind farm is tripped by the protection devices, which may threaten the stability of the main power grid. The phenomenon of the LOS and derivation of the stability region of the injection current are described in [19]. Also, Refs. [21,18] and try to reveal the mechanism of LOS through "frequency positive-feedback" theory. To investigate this instability issue further, Ref. [22] tries to illustrate the instability phenomenon from the viewpoint of the interaction between phase-locked loop (PLL) and the impedance characteristics of the external AC grid. However, few studies present the detailed dynamic frequency characteristics of the wind farm and mechanism of the LOS phenomenon. Since the coupling between the wind farm and the external AC power grid is very weak during the LVRT, the frequency characteristics of the wind farm are dominantly determined by the PLL of WTs. In [23–25], the PLL-based devices occur stability problem when connected to weak grid. Accordingly, the similar problem may also be observed in the wind power system during the LVRT. As reported in [26–28], the DC voltage of the WTs may oscillate during the LVRT when the detailed model of the PLL has been considered. However, those papers could not clearly give out the detailed dynamic frequency characteristics after fault through the analysis. Also, the analysis results could hardly be used to design the stability controller. Therefore, it is necessary to established a model for stability analysis from the viewpoint of control theory and analyze the impact of the PLL on the frequency characteristics of the wind power system during the LVRT.

To ensure the stability of the wind power system during the LVRT, the following two methods could be considered. One is to block the PLL to maintain the frequency of the wind power system at the rated frequency as proposed in [20]. However, this control strategy is only verified by representing the wind farm as a single WT. Since a wind farm usually contains multiple WTs, blocking the PLL will lead to circulating current among the WTs and instability of the wind power system. The other is to adjust the injected current characteristics of the WTs [19]. By feeding back the frequency of the wind power system, the controller can adjust the characteristics of the injection current and maintain the stability of the wind power system. However, when the voltage at the PCC bus becomes quite low, the reactive current injected by the wind farm is stipulated to be as large as its rated current. Since the active current of the wind farm is not adjustable, additional equipment is needed to improve the current injection characteristics of wind farm under low voltage condition. As an important part of smart grid [29], energy storage technology has been widely used to smooth output the power fluctuation of wind farm [30], restrain wind power ramp [31], provide auxiliary frequency regulation [32–35], and enhance power system damping [36–39]. Since most energy storage systems (ESSs) are capable of swiftly regulating active power, the active current injected from the wind farm side can be controlled through installing an ESS at the PCC bus. The current injection characteristics of the wind farm could be improved by controlling the ESS properly, which can maintain frequency stability of the wind farm.

Since the whole model of the wind power system is complicated, it is difficult to find the reason of the LOS phenomenon. Inspired by the research mentioned above, we suppose that the instability of the wind farm during the LVRT is mainly due to the instability of the PLL. The wind power generator units are simplified as the controlled current source. Then a state-space model of the wind power system mainly including the PLL under the low voltage condition could be established. From the viewpoint of control theory, the LOS phenomenon could be revealed and the controller could be designed. By solving this mathematic model, the detailed dynamic frequency characteristics after the fault, which has not been given out in [19,26], as well as the mechanism of the LOS phenomenon could be revealed. Then an ESS-based stability controller is adopted to improve the current injection characteristics of the wind farm. With the aid of this controller, the ESS could keep the frequency of the voltage at the PCC bus stable, avoiding the occurrence of the LOS. In order to verify the hypothesis, the detailed electromagnetic model of the wind farm has been established in PSCAD/EMTDC. Simulation results verify the correctness of the stability analysis results under the hypothesis and the effectiveness of the proposed controller.

The rest of this paper is organized as follows. Section 2 briefly presents the impact of injection current characteristic on the stability of the wind farm. In Section 3, the mathematical model of the PLL system during the LVRT is obtained and the mechanism of the LOS phenomenon is also revealed. In Section 4, the ESS-based stability control strategy is designed. In Section 5, simulation studies are conducted to verify the correctness of the stability analysis results and the effectiveness of the proposed control strategy. Conclusions are drawn in Section 6.