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High-order sliding mode control of DFIG under unbalanced grid voltage conditions

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ABSTRACT

This paper proposes a novel high-order sliding mode (HOSM) based control methodology for direct power control (DPC) of doubly-fed induction generator (DFIG) wind turbine which is operating under unbalanced grid voltage conditions. Firstly, a set power quality enhancement strategies are presented, incorporating six power compensation schemes corresponding to six selective control targets in both steady and variable speed conditions. Meanwhile, the DFIG output powers are regulated with the proposed HOSM-DPC scheme, wherein a super-twisting algorithm is employed to cope with the chattering phenomenon and simplify the controller structure. The Lyapunov function method is utilized to decide the stability region of the controller parameters. Experiments and simulations are conducted to prove the validity and the performance of HOSM-DPC, where the DPC method with lookup table and the first order sliding mode based DPC are incorporated for comparison purpose. The experimental tests fully reveal the effectiveness of HOSM-DPC in power quality improvement subjected to unbalanced grid voltage conditions, and the superior performance of HOSM-DPC in dynamic response, chattering phenomenon elimination and variable wind speed operation are also validated.

1. Introduction

The upcoming global energy crisis has stimulated power community to seek for more reliable, sustainable and green energy resources, including the solar energy, wind energy, biomass energy and nuclear energy. Among them, the wind energy aroused an increasing attention of electrical researchers. A growing number of wind turbines (WT) are being installed in rural grids across the world. The employment of modern power electronic devices largely promoted the reliability, applicability and stability of WECS under operation scenarios including islanding operation, nonideal grid voltage condition and variable speed operation [1,2].

Among all the existing commercial wind turbines, the DFIG based WT is playing a dominant role in the market due to its outstanding performance in variable speed operation, low converter cost and independent control of active and reactive power. Currently, the mainstream control strategies of DFIG based WECSs are vector control (VC) and the direct torque/power control (DTC/DPC) [3–6]. The VC approach is capable of decomposing the rotor current into active and reactive components in order to achieve remarkable steady state performance with proportional-integral (PI) controller. However, the lag effect of the integral part of the controller compromises the controller's dynamic performance. Meanwhile, the phase locked loop (PLL) is required to change the system model into the synchronous reference frame [7]. Another control approach, the DPC method, which is based on the principles of DTC for motor drives with the selection of a space vector to control the instantaneous active/reactive power or electromagnetic torque, proves to have fast dynamic response and is easy to be implemented with the help of the loop up table (LUT). The drawbacks of LUT based DPC lie in that it requires variable switching frequency and large power ripples exist caused by the hysteresis comparator [8].

One of the major challenges confronting electrical engineers is how to regulate the active and reactive power of DFIG based WECS when it is connected to the grid. However, conventional control strategies generally fail to consider the grid voltage unbalance which happens frequently in isolated power grid that is far away from the main power system and is prone to unbalanced faults. The LUT based DPC approaches, for example, is proposed based on the premise that the stator voltages and currents are synchronized with the power grid. Hence, these approaches assume that the grid voltage is symmetrical and sinusoidal. As a matter of fact, majority wind turbines are installed in rural areas and connected to weak grids where heavy unsymmetrical loads, transformer windings as well as voltage dips happen frequently [9]. These unbalanced operation modes will result in fatigues on the

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mechanical components caused by non sinusoidal output currents, power and torque pulsations and unequal power losses.

Thus, the problem of grid connected wind turbine under unbalanced grid voltage condition has aroused an increasing concern in the globe, and a growing number of theories and new control techniques were proposed [10–15]. The appearance of unbalanced grid voltage will result in the appearance of negative sequence voltage and current, which will further lead to variations of stator active, reactive powers and generator torque [10,11]. Hence, different control missions are required when the grid voltage is unbalanced or distorted, such as power pulsations minimization, stator current unbalance suppression and torque ripple elimination [11]. Possible ways of achieving these control missions are: redesigning the inner current controller and the outer reactive power loop to compensate for the torque pulsation and reactive power pulsations [12]; providing compensation active power from the grid side converter and implementing a current control strategy with a main controller and an auxiliary controller [13]; installing an additional feedback compensators with resonant regulators to avoid decompositions of positive and negative sequence currents [14]; treating the rotor side converter and the grid side converter as two independent modules to improve the performance [15].

Although there are various works about novel control techniques for mitigating the impact of unbalanced grid voltage, the DPC approach still serves as one of the main stream DFIG control methods, due to its advantages in decoupled control of the active and reactive powers of wind turbine. And some advanced researches are being reported to improve the performance of conventional DPC method under unbalanced grid voltage condition [16–18]. In [16], the DPC+ approach which is based on the conventional DPC scheme is presented. This control scheme is capable of accomplishing only the goal of obtaining sinusoidal stator current when the grid voltage condition is unbalanced. However, this approach requires coordinate transformation and the information of the switching table. Hence, literature [17] presented a model predictive based DPC approach, where the instantaneous active and reactive powers are controlled without coordinate transformation and the switching table, and the power quality under unbalanced grid voltage condition is improved with a power compensation strategy. The predictive control applies three voltage vectors in each of the control period to get constant switching frequency. However, the model predictive based DPC approach requires every voltage vector to be evaluated such that the cost function can find the optimal switching modes, thus increasing the computational burden. Hence, a low complexity model predictive based DPC scheme is proposed in [18] to control the DFIG under grid voltage unbalance condition. In this literature, a unified power compensation strategy is presented to accomplish multiple control objectives.

The aforementioned DPC approaches are mostly based on linear control techniques or structural redesigns. However, most of the electrical dynamics of DFIG wind turbines are nonlinear and the parameters of DFIG are subjected to external disturbances and variations. Hence, nonlinear and robust control approaches are attracting growing interests, including sliding mode control (SMC). SMC based DPC methods are being employed in DFIG based WECSs [19–21]. The SMC technique has high robustness performances and it is insensitive to parametric perturbations [19]. Hence, SMC has some inherent capability of countering the negative impacts of unbalanced grid voltage [20]. As has been mentioned previously, in the advent of grid voltage unbalance, the main issues to be resolved are stator current asymmetry, active and reactive power ripples. Hence, the power compensation strategy based SMC approaches are being reported to resolve different issues caused by grid voltage unbalance [20,22,23]. The SMC approach presented in [22] introduced the concept of the extended active power which is capable of acquiring the sinusoidal stator currents, as well as restraining the electromagnetic torque ripples when the grid condition is unbalanced. In [23], a second-order generalized integrator (SOGI) based SMC approach for DPC of DFIG under grid voltage unbalance is proposed. However, the drawback of SMC lies in that it will cause high frequency chatters which sabotage the electronic devices and cause high frequency harmonics in the output currents and active power.

This paper aims to propose a high order sliding mode (HOSM) based DPC (HOSM-DPC) approach for DFIG based WECS subjected to grid voltage unbalance. The main contributions of this paper are: (1) we proposed a novel HOSM-DPC approach incorporating six compensation strategies to yield better output power quality of DFIG under grid voltage condition; (2) a modified power compensation strategy is introduced combing the HOSM-DPC method to cope with different operational scenarios, including the steady state wind speed scenarios and the variable wind speed scenarios, whereas the power compensation strategy will guarantee both the fulfilling of the six control targets and maintaining the optimal power output of the DFIG wind turbine; (3) a Lyapunov function based parameter selection range determination method is presented to decide the range of HOSM-DPC parameters in order to maintain the asymptotic convergence of the controllers, and the gravitational search algorithm (GSA) is employed to obtain the optimal value of the controller parameters. The main importance of applying the HOSMC method is that it resolves the chattering phenomenon of conventional SMC by taking advantage of the higher order derivative of the state variables in the control input. Moreover, different from HOSMC approaches constructed in other literatures, the HOSMC scheme proposed in this paper has simpler structure and it is more practical to be implemented in real platforms. Compared with the conventional DPC based approaches for tackling grid unbalance as given in literature [16–18], the proposed HOSM-DPC based method provides more alternatives for the operation of DFIG based WTs, and it has better robust performance. Meanwhile, most of the recent SMC based DPC approaches as presented in [19–21] and [22,23] are based on first order sliding mode control (FOSMC) which is vulnerable to the chattering issue. The chattering phenomenon is detrimental to the system stability and the safety of the WT facilities. However, the HOSMC approach is free from the chattering phenomenon, making it applicable and appropriate to be implemented in real world DFIG based WTs. The remaining of this paper will be organized as follows: in Section 2, the grid-connected DFIG model with grid voltage unbalance will be presented; in Section 3, the power compensation and stator current smoothing strategies for selective control targets will be proposed and the HOSM-DPC scheme will be provided; in Section 4, experimental tests will be conducted to validate the effectiveness and performance of this proposed method; in Section 5, a conclusion will be drawn.

2. Modeling of DFIG during grid voltage unbalance

One of the systematic structures of a DFIG based WECS subjected to unbalanced grid voltage is shown in Fig. 1(a), where the unbalanced load mainly contributes to the grid voltage unbalance. The DFIG equivalent circuit in the stator stationary $\alpha\beta$ frame is depicted in Fig. 1(b) [16]. The relationship between the flux linkage and the turbine current can be expressed as

$$\begin{cases}\psi_{s\alpha\beta}=L_sI_{s\alpha\beta}+L_mI_{r\alpha\beta}\\ \psi_{r\alpha\beta}=L_rI_{r\alpha\beta}+L_mI_{s\alpha\beta}\end{cases}\tag{1}$$

where $I_{s\alpha\beta}$ and $I_{r\alpha\beta}$ represents the stator and rotor currents in the $\alpha\beta$ frame, respectively; L_s and L_r represents the stator and rotor inductance, respectively; R_r and R_s are the rotor and stator resistance, respectively. The list of all the symbols is given in Table 5. The relationship between stator voltages and currents is shown as

$$\begin{cases}U_{s\alpha\beta}=R_sI_{s\alpha\beta}+\frac{d\psi_{s\alpha\beta}}{dt}\\ V_{r\alpha\beta}=R_rI_{r\alpha\beta}+\frac{d\psi_{r\alpha\beta}}{dt}-j\omega_{r\alpha\beta}\end{cases}\tag{2}$$

The stator instantaneous active and reactive powers are shown as