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Approximate dynamic programming based supplementary reactive power control for DFIG wind farm to enhance power system stability[☆], [☆☆]

Wentao Guo[a], Feng Liu[a], Jennie Si[b,*], Dawei He[c], Ronald Harley[c], Shengwei Mei[a]

[a] State Key Laboratory of Power Systems, Department of Electrical Engineering, Tsinghua University, Beijing 100084, China
[b] Department of Electrical Engineering, Arizona State University, Tempe, AZ 85287, USA
[c] School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, GA 30332, USA

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ABSTRACT

Reactive power control of doubly fed induction generators (DFIGs) has been a heated topic in transient stability control of power systems in recent years. By using a new online supplementary learning control (OSLC) approach based on the theory of approximate dynamic programming (ADP), this paper develops an optimal and adaptive design method for the supplementary reactive power control of DFIGs to improve transient stability of power systems. To augment the reactive power command of the rotor-side converter (RSC), a supplementary controller is designed to reduce voltage sag at the common coupling point during a fault, and to mitigate active power oscillation of the wind farm after a fault. As a result, the transient stability of both DFIGs and the power system is enhanced. For the supplementary controller design, an action dependent cost function is introduced to make the OSLC model-free and completely data-driven. Furthermore, a least-squares based policy iteration algorithm is employed to train the supplementary controller with convergence and stability guarantee. By using such techniques, the supplementary reactive power controller can be trained directly from data measurements, and therefore, can adapt to system or external changes without an explicit offline system identification process. Simulations carried out in Power System Computer Aided Design/ Electro Magnetic Transient in DC System (PSCAD/EMTDC) show that the OSLC based supplementary reactive power controller can significantly improve the transient performance of the wind farm and enhance the transient stability of the power system after sever faults.

1. Introduction

With rising concerns on fossil energy shortage and for environment protection, wind power generation has grown rapidly in recent years. As one of the most important types of wind generators, doubly fed induction generators (DFIGs) are widely used for their flexibility in active/reactive power control and low cost [2,3].

As the penetration level of grid-connected DFIGs increases rapidly, the issue of how the integration of DFIG based wind farm may affect overall power system stability has been brought to the forefront of wind power research. How the system behaves during and after a sever fault becomes especially critical and has drawn extensive attention. Usually, a fault in the power system may cause voltage sag at the point of common coupling (PCC) of the wind farm, and further lead to a temporary imbalance between the input wind power and the output electrical power of DFIGs. As a result, large current surges can occur in both the stator and the rotor windings of DFIGs. Furthermore, the input–output power imbalance may excite shaft vibrations of DFIGs, and then result in low-frequency oscillations of the active power output of the wind farm [3]. Here two important issues for the control design of DFIGs need to be considered: the first is how to prevent converters of DFIGs from overcurrent and to maintain an uninterrupted operation of DFIGs during a fault, which is referred to as the problem of low voltage ride through (LVRT) [4,5]; the second is how to control DFIGs to enhance system stability during and after a fault, provided that DFIGs can successfully ride through the fault [3,6].

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[*] Corresponding author.
E-mail address: si@asu.edu (J. Si).

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Transient reactive power control of wind farms is an effective method to solve the aforementioned problems. In [3,6–10], dynamic reactive compensators such as static synchronous compensators (STATCOMs) and static Var compensators (SVCs) are used to provide transient reactive power compensation. Nevertheless, due to economic concerns, many wind farms based on DFIGs are not equipped with dynamic reactive power compensators [11]. This forces the full use of the dynamic reactive power regulation capability of DFIGs themselves through proper control strategies. In [11], a reactive power control strategy for DFIG based wind farm is proposed to supply reactive power to a nearby fixed speed induction generator (FSIG) based wind farm during a fault. In [2], reactive power control of DFIGs in both normal operation condition and on-fault condition is comprehensively studied. However, the optimality and adaptability of the controller is not considered in the reactive power control strategies in [2,11].

As an optimal and adaptive control method, approximate dynamic programming (ADP) [12] or adaptive dynamic programming [13,14] is used extensively to design power system controllers. ADP can obtain the optimal control policy while circumventing the issue of solving the associated Hamilton–Jacobi–Bellman (HJB) equation directly. ADP has been proved to be effective in many power system control problems, including the turbogenerator control [15,16], the wind farm control [1,3,6,17], the dynamic stochastic optimal power flow control [18,19], and the inter-area damping control [20–22].

In [3,6,17], coordinated reactive power control of DFIG and STATCOM is realized by using adaptive critic designs (ACD) [23], direct heuristic dynamic programming (direct HDP) [24] and goal representation heuristic dynamic programming (GrHDP) [25], respectively. In [10], GrHDP is employed to coordinate the control of DFIG, STATCOM, and high-voltage direct current (HVDC) link. It should be noted that ACD is essentially an offline design approach that requires to train a model network in advance. On the other hand, direct HDP and GrHDP are model-free learning based on stochastic approximation, which do not have theoretical guarantee of deterministic stability during learning. Besides, ACD, direct HDP, and GrHDP use the gradient descent method as the training algorithm, which is less efficient in utilizing training samples, sensitive to learning parameters, and slow to converge. In summary, these existing ADP approaches cannot guarantee stability while conducting online and model-free learning. This has hindered their applications in realistic problems, since un-modeled system dynamics and uncertainties can only be handled effectively by using online learning approaches.

Different from these ADP approaches, the reactive power controller proposed in this paper is designed by using an online supplementary learning control (OSLC) [26] method based on ADP. In the OSLC, a policy iteration algorithm [27] is employed. As such, we can achieve not only stability guarantee but also fast convergence during learning. Under this problem formulation, we are able to solve the cost function by using the least square method, which is efficient in both computation time and sample utilization. We also introduce an action dependent cost function so that the learning process is independent of the system model. The training proceeds along with online sample acquisition and is completely data-driven. Therefore, our proposed OSLC is suitable for online optimal control and system adaptation to cope with ever changing environment.

In this paper, we extend the work in [1] to design an optimal adaptive reactive power controller of DFIGs when additional dynamic reactive power compensators are not available. The control objective is to reduce the voltage sag at the PCC during a fault, to damp the active power oscillation of wind farm after a fault, and ultimately to enhance the system stability and dynamic performance. Compared to [1], there are two advancements in this paper. First, we take two realistic design constraints into consideration, namely, the power rating of DFIG and the current limit of converters. These parameters are crucially important for the protection of DFIG and its converters in real applications. A limit on the reference value of the *d*-axis current in the RSC is set. Second, the contribution of the supplementary reactive power control to enhancing power system stability is comprehensively studied by simulation. Influences of the supplementary reactive power control for DFIG based wind farm on the bulk power system are shown, such as influences on conventional generators and tie lines.

To summarize, major contributions of this paper are as follows. First, different from the ADP approaches used in the literature, a new ADP approach, the OSLC, is used for online training of the reactive power controller, which is both model-free and stable. Second, since the OSLC is suitable for online implementation, we show that the reactive power controller can online re-optimize the control performance after un-modeled changes in the system. Third, impacts of the supplementary reactive power control for DFIG based wind farm on the power system stability are studied extensively.

The rest of this paper is organized as follows. Modeling of the benchmark power system and the DFIG wind farm is introduced in Section 2. In Section 3, both the structure and the training algorithm of the supplementary reactive power controller are presented. Simulation results are shown in Section 4 to demonstrate the online optimization and adaptation capability of the proposed controller. Conclusion is given in Section 5.

2. Modeling of power system and wind farm

2.1. Benchmark power system

In this paper, we use the 12-bus benchmark power system from [3,28] to study the reactive power control of DFIG based wind farm. The single-line diagram of the system is illustrated in Fig. 1. The test system contains three geographical areas. Area 1 is a generation center. Generator G1 in area 1 is modeled as an ideal voltage source, which makes bus 9 an infinite bus. The other generator in this area, G2, is modeled in detail as a hydro generator with a governor and an exciter. Area 3 is a load center with some local generation represented as a thermal generator G3, which is also modeled in detail with a governor and an exciter. Most of the load demand in area 3 is met by the generation from area 1, through two 230 kV transmission lines and one 345 kV transmission line. Between area 1 and area 3 is area 2. Similar to [3], a 400 MW wind farm is connected to bus 12 in area 2. A part of the wind generation is locally consumed, and the rest is delivered to the load center area 3. The wind farm only has some fixed-capacitor compensation at the high tension side of the step-up transformer. No dynamic reactive compensator like STATCOM or SVC is installed in or around the wind farm. As discussed above, a fault in the system, such as at the location of bus 1, can cause a voltage sag at bus 6 and an oscillation in the active power output of the wind farm. In the following context, a supplementary reactive power controller for the wind farm will be developed to reduce the voltage sag and to mitigate the active power oscillation.

2.2. DFIG based wind farm

It is not easy to mathematically model a wind farm with a large number of DFIGs. Modeling all DFIGs in detail could create a huge simulation overhead. As such, representing a wind farm by a simplified model has been the focus of modeling efforts. According to [29], when we investigate the collective response of a wind farm