2014 International Joint Conference on Neural Networks (IJCNN)
July 6-11, 2014, Beijing, China

Reactive Power Control of DFIG Wind Farm Using Online Supplementary Learning Controller Based on Approximate Dynamic Programming

Wentao Guo, *Student Member, IEEE,* Feng Liu, *Member, IEEE,* Dawei He, *Student Member, IEEE,*
Jennie Si, *Fellow, IEEE,* Ronald Harley, *Fellow, IEEE,* and Shengwei Mei, *Senior Member, IEEE*

***Abstract*—Dynamic reactive power control of doubly fed induction generators (DFIGs) plays a crucially important role in maintaining transient stability of power systems with high penetration of DFIG based wind generation. Based on approximate dynamic programming (ADP), this paper proposes an optimal adaptive supplementary reactive power controller for DFIGs. By augmenting a corrective regulation signal to the reactive power command of rotor-side converter (RSC) of a DFIG, the supplementary controller is designed to reduce voltage sag at the point of common connection (PCC) during a fault, and to mitigate output active power oscillation of the wind farm after a fault. As a result, the transient stability of both DFIG and the power grid is enhanced. An action dependent cost function is introduced to provide real-time online ADP learning control. Furthermore, a policy iteration algorithm using high-efficiency least square method is employed to train the supplementary controller in an online model-free manner. By using such techniques, the supplementary reactive power controller is endowed with capability of online optimization and adaptation. Simulations carried out on a benchmark power system integrating a large DFIG wind farm show that the ADP based supplementary reactive power controller can significantly improve the transient system stability in changing operation conditions.**

I. INTRODUCTION

RECENT years have seen a tremendous growth of wind generation worldwide. As one most important category of wind power generators, doubly fed induction generators (DFIGs) are widely used due to their flexibility in active/reactive power control and high economic efficiency [1], [2].

As the penetration level of grid-connected DFIGs rapidly increases, much attention has been paid to impact of DFIG wind farms on power system stability, especially during and after a severe fault. Usually, a fault in the power system may cause voltage sag at the point of common connection (PCC) of the wind farm, further leading to temporary imbalance between the input wind power and the output electrical power of DFIGs. As a result, large current surges can occur in both stator and rotor windings of DFIGs. Furthermore, the input-output power imbalance may elicit shaft vibrations of DFIGs, and then result in low-frequency oscillations of the wind farm output power [2]. Here exist two important issues for control design of DFIGs: the first is to prevent converters of DFIG from overcurrent and to maintain uninterrupted operation of DFIGs during a fault, which is referred to as the problem of low voltage ride through (LVRT) [3]; the second is to control wind farms to support system stability during and after a fault, provided that DFIGs can successfully ride through the fault.

To address the aforementioned issues, dynamic reactive power control of wind farm is frequently used. In [2], [4], [5], [6], [7], [8], dynamic reactive compensators like static synchronous compensators (STATCOMs) and static Var compensators (SVCs) are used to supply dynamic reactive power compensation. However, due to economic concerns, many DFIG based wind farms are not equipped with dynamic reactive power compensators [9]. In such circumstances, one is obliged to make use of the dynamic reactive power regulation capability of DFIG itself through proper control. In [9], reactive power control of a DFIG based wind farm is proposed to supply reactive power to a nearby fixed speed induction generator (FSIG) wind farms during a fault. In [1], reactive power control of DFIGs in both normal operation state and on-fault state is comprehensively studied. However, the reactive power control in [1], [9] is neither designed in an optimal way nor adaptive to system changes.

As an optimal adaptive control method, approximate dynamic programming (ADP) [10] or adaptive dynamic programming [11], [12] has been introduced in power system control. ADP can obtain the optimal control policy while circumventing directly solving the associated Hamilton-Jacobi-Bellman (HJB) equation. In [2] and [8], coordinated reactive power control of DFIG and STATCOM is realized by using adaptive critic designs (ACD) [13] and direct heuristic dynamic programming (direct HDP) [14], respectively. In [7], goal representation heuristic dynamic programming (GrHDP) [15] 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 pretrain a model network. On the other hand, ACD, direct HDP, and GrHDP use gradient descent method as training

---

This work was supported in part by the National Natural Science Foundation of China (No. 51377092, No. 51321005), the Special Fund of National Basic Research Program of China (No. 2012CB215103), and the National High Technology Research and Development of China (863 Program, 2012AA050204).

W. Guo, F. Liu, and S. Mei are with State Key Laboratory of Power Systems, Department of Electrical Engineering, Tsinghua University, Beijing 100084, China (e-mail: gwt329@gmail.com, lfeng@tsinghua.edu.cn, meishengwei@tsinghua.edu.cn).

J. Si is with Department of Electrical Engineering, Arizona State University, Tempe, AZ 85287, USA (e-mail: si@asu.edu).

D. He and R. G. Harley are with School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, GA 30332, USA. R. G. Harley is also a Professor Emeritus at the University of Kwaulu-Natal in South Africa (e-mail: hedawei.david@gmail.com, rgharley@ee.gatech.edu).

978-1-4799-1484-5/14/$31.00 ©2014 IEEE

algorithm, which is less efficient in utilizing training samples, sensitive in learning parameters, and slow to converge.

In this paper, the discussion is focused on the optimal adaptive reactive power control of DFIGs when additional dynamic reactive power compensators are not available. The objectives of the dynamic reactive power control are to reduce the voltage sag at the PCC during a fault, and to damp the oscillation of wind farm output active power after a fault. A supplementary signal is added to the stator reactive power command of DFIG to realize the reactive power control. The supplementary reactive power controller is based on ADP. Different from the aforementioned ADP based approaches, a least square based policy iteration algorithm [16] is employed, which is sample-efficient, free of learning parameter, and fast in convergence. An action dependent cost function is introduced so that the learning process is independent of system model. Training proceeds along with online sample acquisition. By use of such techniques, the proposed supplementary reactive power controller can be online optimized and is adaptive to changing environment.

The rest of this paper is organized as follows. Models of a benchmark power system and the DFIG wind farm are introduced in Section II and Section III, respectively. In Section IV, both structure and training algorithm of the supplementary reactive power controller is given. Simulation results are presented in Section V to demonstrate the online optimization and adaptation capability of the proposed controller. Conclusion is given in Section VI.

II. BENCHMARK POWER SYSTEM

The 12-bus benchmark power system from [2], [17] is used for studying the reactive power control of DFIG. The single-line diagram of the test 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 governor and exciter. Area 3 is a load center with some local generation represented as a thermal generator G3, which is also modeled in detail with governor and exciter. Most of load demand in area 3 is met by the generation in area 1, through two 230 kV transmission lines and one 345 kV transmission line. Between area 1 and area 3 is area 2. Similar as [2], a 400 MW wind farm is connected to bus 12 in area 2. A part of 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.

III. MODEL AND CONTROL OF DFIG WIND FARM

The DFIG wind farm is modeled as a single equivalent DFIG wind generator by aggregation technique [2], [18]. The schematic of DFIG wind generator is shown in Fig. 2. Physically, the wind turbine drives the induction generator through a shaft system. For transient stability studies, the shaft system is modeled as a combination of a low-speed shaft, a high-speed shaft, and a gearbox between them. Details about the mechanical system model can be found in [2]. The stator of DFIG is directly connected to a power grid, while the wound-rotor of DFIG is fed to the grid through a back-to-back ac/dc/ac converter, including a rotor-side converter (RSC), a grid-side converter (GSC) and a dc-link capacitor in between. To achieve bidirectional power flow between the rotor and the grid, the RSC and the GSC are based on four-quardrant insulated-gate bipolar transistor (IGBT). To protect the RSC from overcurrent during a fault, a crow-bar circuit is used to short circuit the RSC during an on-fault state.

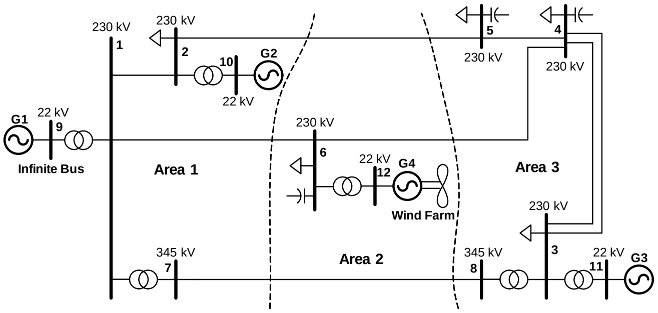

Fig. 1. Single-line diagram of the benchmark system

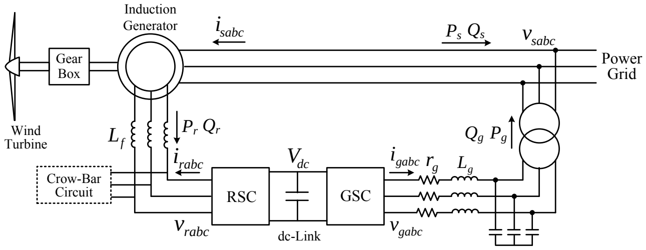

Fig. 2. Schematic of DFIG

The RSC underpins the active and the reactive power control of stator in a decoupled manner. To achieve such an objective, rotor current in abc reference frame is projected to stator-flux oriented reference frame. In the stator-flux oriented reference frame, rotor current is transformed into $d-$axis and $q-$axis component, i.e. i_{dr} and i_{qr}. The stator active power P_s is determined by the $q-$axis component, while the stator reactive power Q_s is determined by the $d-$axis component. The subscript "s" in P_s and Q_s represents "stator". Schematic of stator-flux oriented RSC control is shown in Fig. 3. It includes a very fast inner-loop for current tracking, and a relatively slow outer-loop for active and reactive power regulation. The inner-loop generates voltage commands for pulse-width modulation (PWM) converters through two proportional-integral (PI) controllers. On the other hand, the outer-loop generates reference current commands for the inner-loop through two PI controllers. Reactive power command Q_s^* is "normally" set to zero in a wind farm with adequate reactive power compensation.

The role of GSC is to maintain the dc-link voltage and to regulate the reactive power exchange between the GSC and the power grid. Different from RSC, stator-voltage oriented refer-