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Reliability models for DFIGs considering topology change under different control strategies and components data change under adverse operation environments

Shenghu Li*

School of Electrical Engineering and Automation, Hefei University of Technology, Hefei 230009, China

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ABSTRACT

The doubly-fed induction generators (DFIGs) are widely applied for wind energy conversion. Their reliability models are important to risk analysis of wind power systems, which has not been fully investigated due to changing topology configuration and sensitive reliability data. In this paper, three reliability models are newly proposed for the DFIGs. Under the doubly-fed mode, the DFIG is logically in series configuration with low reliability. With outage of rotor-side converter, or operation of crowbar against short current, the grid-side converter or the power grid provides var support. The DFIG operates as an induction machine, avoids tripping and yields high reliability. The DFIGs' reliability is also dependent on vulnerability of the mechanical components to the strong wind, vulnerability of the electrical components to the short current, effectiveness of the fault-ride-through capability, and possibility of strong wind and severe fault. Logistic curve is applied to modify unavailabilities of the mechanical and electrical components under the adverse operation conditions. The proposed models help to quantify the lifetime and determine the key component of the DFIGs, thus improves reliability of the wind power systems.

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1. Introduction

With bulk wind power penetration, the power systems face increasing risk caused by the stochastic wind speed and forced outage of wind turbine generators (WTGs). In recent years, wind farms at the northwestern of China experience several major contingencies. In one case, more than 1000 WTGs are tripped, yielding the instantaneously voltage as low as 267 kV (rated 330 kV), and the frequency as low as 49.854 Hz (rated 50 Hz) [1]. In another case, low voltage after short circuit and high voltage after fault curtailment lead to trip of lots WTGs. Existing literature on risk analysis to the wind power systems focus on stochastic wind speed, outage of generation/transmission facilities, and dispatch/control strategy against disturbances. The Weibull function or multi-state model is used for the wind speed [2,3]. Active output of the WTGs is given by linear, quadratic, or polynomial function of wind speed. Two-state (up and down) model is used for WTGs and synchronous generators [4,5]. Random failure of the transmission facilities and relay protections is sampled, followed by active and/or reactive power dispatch. Sequential or non-sequential Monte Carlo simulation is applied [6], yielding adequacy indices of wind power systems.

Compared with the synchronous generators [7], the WTGs have lower controllability and higher failure rate. The two-state model cannot describe the mechanical and the electrical components, whose failure, repair and replacement characteristics are different. Therefore multi-state model should be used to find the contributing factors to unavailability of the WTGs [8,9]. Ref. [10] ranks availabilities of the components, i.e. the generators, the gear boxes, the converters, the wind turbines, and the electrical systems. For constant speed induction generators (IG), the wind turbine (WT), the IG, and the power grid are logically in series connection. Failure of any component will yield outage of the IG [11].

The reliability modeling of the doubly-fed induction generator (DFIG) is more complex than the IG, or a direct-drive permanent magnet synchronous generator [12]. In the doubly-fed operation mode, all components are logically in series connection. When the rotor-side converter (RSC) is forced to outage and the grid-side converter (GSC) acts as a shunt compensator, or the converter circuit is not available and the power grid provides var support, the DFIG may work as a constant speed IG [13]. This reduced mode is also realistic when the DFIG is suffered from severe grid faults with large short current activating the crowbar and blocking the control function of the RSC. If the reduced mode is allowed, the DFIG has

* Tel./fax: +86 551 290 4435.
E-mail address: shenghuli@hfut.edu.cn.

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higher reliability compared that of the doubly-fed mode only, with the expense of lower controllability and efficiency [14]. Therefore availability of the DFIGs is related to topology change according control strategies, which has not been fully investigated in the existing literature.

Furthermore, reliability of the DFIGs is also related to the operation environments. Strong wind may increase outage possibility of the mechanical components, e.g. sudden breakdown or cumulative damage to the blade and the tower [15–17]. Short current may be several times of the rated value, causing overheat of the stator/rotor windings and the RSC, and overvoltage across the dc capacitor [18]. Inclusion of the adverse environment does not change the mean value of availability notably, however provides the conditional availability under rare but severe conditions. Detailed statistics based on the operation environments is often not practical, so instinctive modification to unavailability function of the mechanical and electrical components may be applied.

In this paper, three reliability modes are proposed for the DFIGs. Under the doubly-fed mode, the DFIG is logically in series configuration and has low reliability. With outage of rotor-side converter, or operation of crowbar against short current, the grid-side converter or the power grid may provide var support. The DFIG operates as an induction machine with higher reliability. Logistic curve is used to modify unavailability of the mechanical components under strong wind, and unavailability of the electrical components under severe fault. Numerical results are provided to validate the feasibility and accuracy of the proposed model. With the components' reliability data available, the proposed models may be used to the actual DFIGs quantifying their lifetime and key component, which is important to quantify the risk level and determining the weak equipment for power systems with bulk wind power integration.

2. Reliability modeling to wind turbine generators

2.1. Reliability model of constant speed IG

Topology of an IG is shown in Fig. 1, with the wind turbine, the drive train, and the induction generator. The wind turbine and the drive train are mechanical components (*M*), while the IG is an electrical component (*E*). The wind turbine is composed of the tower (*T*), the hub (*H*), and the blade (*B*). There are two or three blades for a wind turbine, with the latter more popular. The control unit (CU1) regulates the rotating speed and the pitch angle, thus to capture the maximum power, and responds to steep change of wind speed to avoid mechanical damage. The drive train is composed of the low-speed shaft (LS), the gearbox (GB), and the high-speed shaft (HS). Since the IG absorbs reactive power, a shunt ac capacitor (AC) is installed at the stator to maintain the voltage. If there is no capacitor, or the capacitor is out of service, availability of the IG is related to the var support (VS) from the generators nearby, or from the power grid.

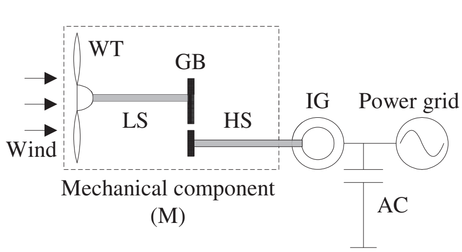

Fig. 1. Constant speed induction generator.

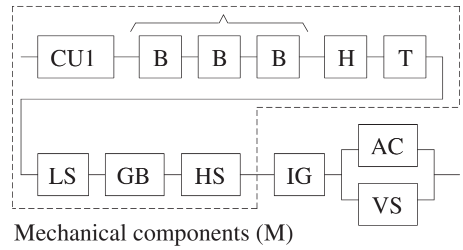

Fig. 2. Reliability model of constant speed IG.

From the viewpoint of availability, these components are in series configuration, or logically "and", while the shunt capacitor and the var support are connected in parallel, or logically "or", as shown in Fig. 2.

2.2. Reliability model to DFIG

A DFIG has the rotor winding and the stator winding connected by the back-to-back converters, as shown in Fig. 3. The converter circuit is composed of the RSC, the dc capacitor (DC), the GSC, and the transformer (TF). The control unit CU2 regulates the rotor speed, maintains the dc voltage, and produces prescribed reactive power to the stator and finally to the grid. Its control strategy is different from that of CU1.

If all the designed functions are available, the DFIG works under the doubly-fed mode. It necessitates availability of all the mechanical and the electrical components and control functions. Therefore, all the components are connected in series, as shown in Fig. 4. However, after short circuit of the power grid, the rotor winding may suffer from large current. The crowbar is triggered and the RSC losses controllability. The DFIG works as an IG, with the expense of lower efficiency and weaker controllability in energy conversion. Reliability model considering only the doubly-fed mode will yield pessimistic judgment to availability of the DFIGs.

When any component of the converter circuit is forced to outage, it is expected to be isolated by the switch. When the faulty RSC is isolated by the switch SW1, the GSC and the dc capacitor act as a shunt compensator (STATCOM) and provide reactive power. The DFIG operates as an IG, which is called reduced mode in this paper. If the dc capacitor, the GSC, or the transformer is faulty, the converter circuit is isolated by the switch SW2. Availability of the DFIG is decided by var support (VS) from the power system. If the SW2 fails to isolate the faulty elements, the DFIG is forced to outage. The reliability model for the DFIGs including the reduced mode and the switch operation is shown in Fig. 5. The control unit CU3 regulates var output and dc voltage instead of the rotor speed. Although the reduced mode is valid under certain condition and within limited time, by including it the DFIG has higher availability compared with that considering only the doubly-fed mode.

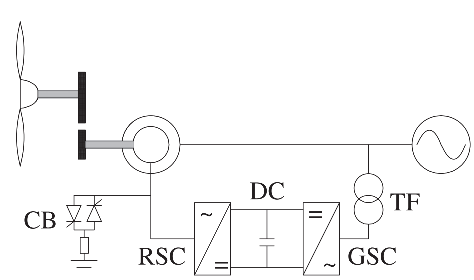

Fig. 3. Doubly-fed induction generator.

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