Addressing Grid Integration Challenges in Doubly-Fed Wind Turbines: Modeling, Optimization, And Control

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Abstract. As an important means of obtaining clean energy, the doubly-fed wind turbine has undergone significant development and progress. To date, the doubly-fed wind turbine remains a prominent subject of research. This paper investigates and summarizes the maximum power capture of the doubly-fed fan, enhancements to the doubly-fed fan simulation model, and the low-pressure crossing phenomenon in doubly-fed fans. Drawing from the derivation of the maximum power control model of the Doubly Fed Induction Generator (DFIG), the study delves into the maximum power capture of the DFIG, and elucidates the basic model for grid-connected modeling of the doubly-fed wind turbine. Subsequently, an analysis is conducted on the disparity between the DIgSILENT and PSASP models in capturing the maximum power point, and an optimization model for doubly-fed wind turbines is presented based on existing literature. Through a comparison with traditional doubly-fed wind turbine models, the paper highlights the advantages and disadvantages of the optimized model. Finally, an optimization scheme for addressing low-pressure crossing in doubly-fed fans is described, along with a comparative evaluation.

Keywords: DFIG, MPPT, Modeling optimization, low voltage ride through.

1. Introduction

As advancements in clean energy technology continue at a swift pace and public demand for uncontaminated energy sources grows, harnessing wind power has emerged as a crucial option for nations globally. Furthermore, technological progress has broadened the scope of wind energy exploitation; currently, the vigorous expansion of offshore wind energy generation is underway. Nevertheless, within wind energy systems integrated with the grid, stringent grid regulations necessitate the enforcement of rigorous criteria for the consistency of wind electricity production. This requires better performance of doubly fed fans. This increase in installed wind power generation capacity has led to more apparent characteristics in grid electricity electronic systems both domestically and internationally. Electric field three-phase oscillation, off-grid, and other emerging stability issues related to power electronics are prominent, resulting in equipment damage and power generation disruptions. The serious consequences such as torsional vibration and large-scale power outages are key factors limiting the development of wind energy. This necessitates improved performance from doubly fed wind turbines.

Despite its simpler architecture, advanced maturity, and extensive operational scope, the Doubly-Fed Induction Generator (DFIG) retains significant untapped potential for application. However, owing to the erratic nature of wind currents supplying kinetic energy, the turbine's output is subject to considerable variation. This, in turn, leads to fluctuations in grid-side voltage, resulting in a three-phase voltage output that can deviate from the electrical grid's regulated standards, potentially leading to serious consequences. When wind turbines are connected to the grid, synchronous control strategies such as the phase-locked loop (PLL) are usually employed to obtain grid frequency and phase. However, these synchronous control strategies profoundly affect the steady-state and transient characteristics of the high-proportion new energy power system, making wind power systems face instability risks different from traditional power systems. On one hand, wind power resources and power load are inversely distributed, and wind turbines are usually connected to grids with low short-circuit ratios, resulting in frequent broadband oscillation problems. When the sub-synchronous/supersynchronous oscillation frequency is within the controller bandwidth, it can be significantly affected by the synchronous control strategy. On the other hand, wind turbines should have a certain grid fault tolerance time to maintain the continuity of output power. However, under the influence of large disturbances such as voltage drops, the synchronous control strategy of the doubly fed fan may not accurately track the phase of the network, and the risk of transient instability may occur, resulting in fan chain failure and unplanned downtime. Dealing with such a complex situation necessitates improvements to the DFIG.

This paper introduces the maximum power control model of the doubly fed wind turbine and the basic modeling of DFIG connected to the grid. Then, based on the literature, the optimal model of DFIG is presented. The advantages of the optimized model compared to the traditional model are expounded. Additionally, the optimal scheme for low-pressure crossing of the doubly fed fan is proposed.

2. Maximum power control of doubly-fed wind turbineTitle

The windmill harnesses the force of the wind from the foliage to generate electrical power. From the hydrodynamics, the kinetic energy of the air is given by:

$$E = \frac{1}{2} m {v_{wind}}^2 \tag{1}$$

If the area through which gas passes every second is denoted as S, then the corresponding volume would be expressed as V, where:

$$V = S v_{wind} \tag{2}$$

In addition,

$$m = \rho V = \rho S v_{wind} \tag{3}$$

The energy of the wind is:

$$E_{wind} = \frac{1}{2} \rho S v_{wind}^3 = P_{wind} \tag{4}$$

which represents instantaneous wind energy.

One may observe that the magnitude of wind power is directly linked to air density and the swept area and is proportional to the cube of the wind speed. Considering that it's impossible for wind velocity to drop to nil subsequent to its interaction with the wind turbine, it's unfeasible for the turbine vanes to fully transform kinetic wind power into mechanical energy. The Bates theorem prescribes an upper limit for the efficiency of wind power conversion, with the corresponding mathematical expression being:

$$C_p = \frac{P_m}{P_{wind}} < 59.3\% \tag{5}$$

where P_m represents actually converted mechanical energy:

$$P_m = \frac{1}{2} \rho S v_{wind}^3 C_p \tag{6}$$

Thus, according to [1], the genuine kinetic energy transformed from the wind turbine, denoted by λ, is given by:

$$\lambda = \frac{\omega_m R}{v_{wind}} \tag{7}$$

The relation between it and the electric angular velocity of the generator rotor is:

$$\omega_m = \frac{\omega_r}{N n_p} \tag{8}$$

where N is the gearbox ratio.

According to [2], the formula for maximum efficiency utilization of wind energy is given by:

$$C_p(\lambda,\beta) = C_1(\frac{C_2}{\lambda_i} - C_3\beta - C_4)e^{\frac{-C_5}{\lambda_i}} + C_6\lambda \tag{9}$$

where:

$$\frac{1}{\lambda_i} = \frac{1}{\lambda+0.08\beta} - \frac{0.035}{\beta^3+1} \tag{10}$$

The equation demonstrates that with a constant torque angle for the paddle, by precisely regulating the wind function to maintain the optimal blade tip speed ratio across varying wind velocities, optimal wind energy utilization and the highest power extraction from the variable-speed wind turbine can be guaranteed. In this way, the power control of doubly fed fan can be realized.

3. Grid-connected doubly-fed fan

Figure 1 depicts the schematic arrangement of a grid-integrated bi-directional wind energy setup, where a solitary bi-directional turbine is pitching angle modulated via its own control systems, while the doubly fed induction generator (DFIG) is tasked with transforming kinetic energy into electric power. This setup includes components such as the DFIG, Rotor Side Converter (RSC), Grid Side Converter (GSC), among others. The direct current linkage of the dual-supply wind turbine's static coil is established with the electrical network, while its rotating coil interfaces with the electrical network via a converter featuring a back-to-back configuration. The DFIG speed is obtained by the encoder, and the GSC adopts an L-type or LCL type filter. Typically, the aim of the RSC is to pursue Maximum Power Point Tracking (MPPT) with the prevailing wind conditions, while the GSC focuses on maintaining steady voltage levels within the DC bus. After the 0.69/35kV transformer, multiple doubly fed wind turbines are connected to the AC bus in parallel, and then to the 110kV AC bus through the 35/110kV transformer.

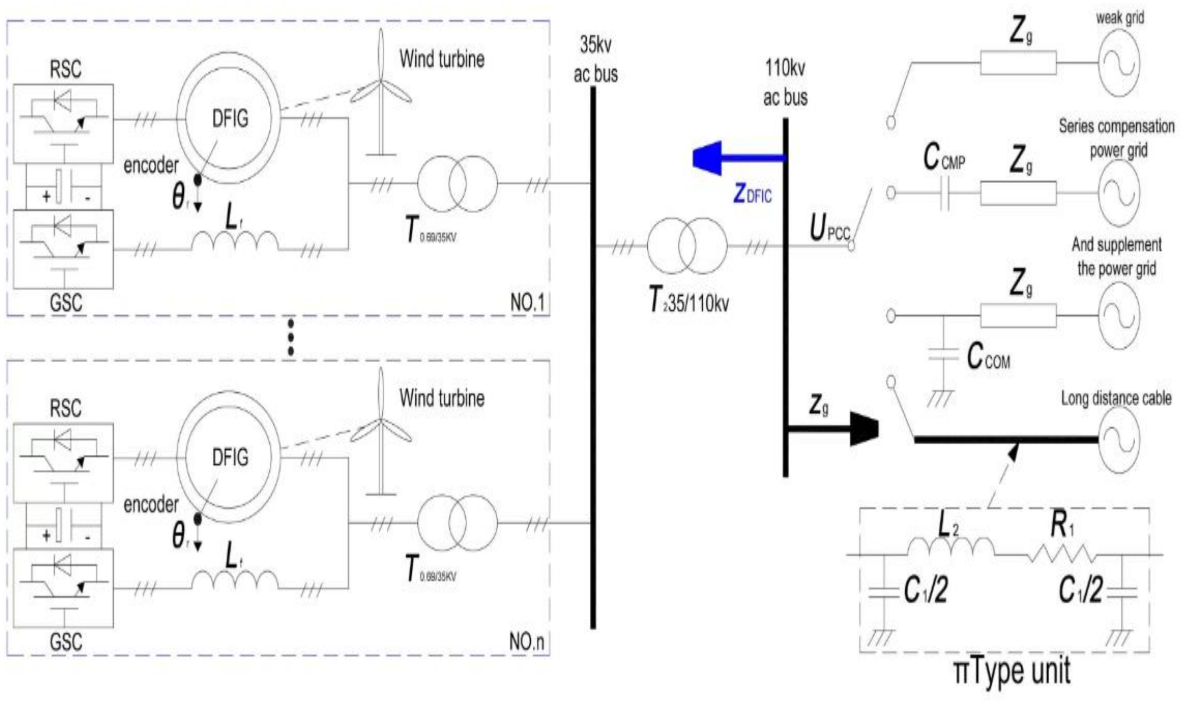

Figure 1. Grid-connected topology of doubly fed wind turbines [1].

4. Simplified modeling of doubly-fed fan output response

According to Figure 2, UPCC and IPCC represent the three-phase voltages and currents at common coupling points. UGCP represents the three-phase voltage at the remote AC network connection point.

Assuming that the DC bus voltage Vdc is constant, Zg=Rg+jωgLg represents the grid impedance, where Rg is the grid resistance, Lg is the grid inductance, and ωg=100πrad/s is the fundamental angular frequency of the grid. Lf stands for filter inductance. Kpp and Kip are the PLL ratio and integral gain, respectively, and θPLL and ωPLL are the PLL output angle and output angular frequency.

Figure 3 shows the traditional model diagram. The simplified model of DFIG based on Figure 3 greatly simplifies the grid-connected model and reduces the calculation cost. Moreover, with the proportional and integral gains of Kp and Kip in the PLL, the output angle and output angular frequency of the PLL can be obtained as θPLL and ωPLL, respectively. This achieves stable grid connection.

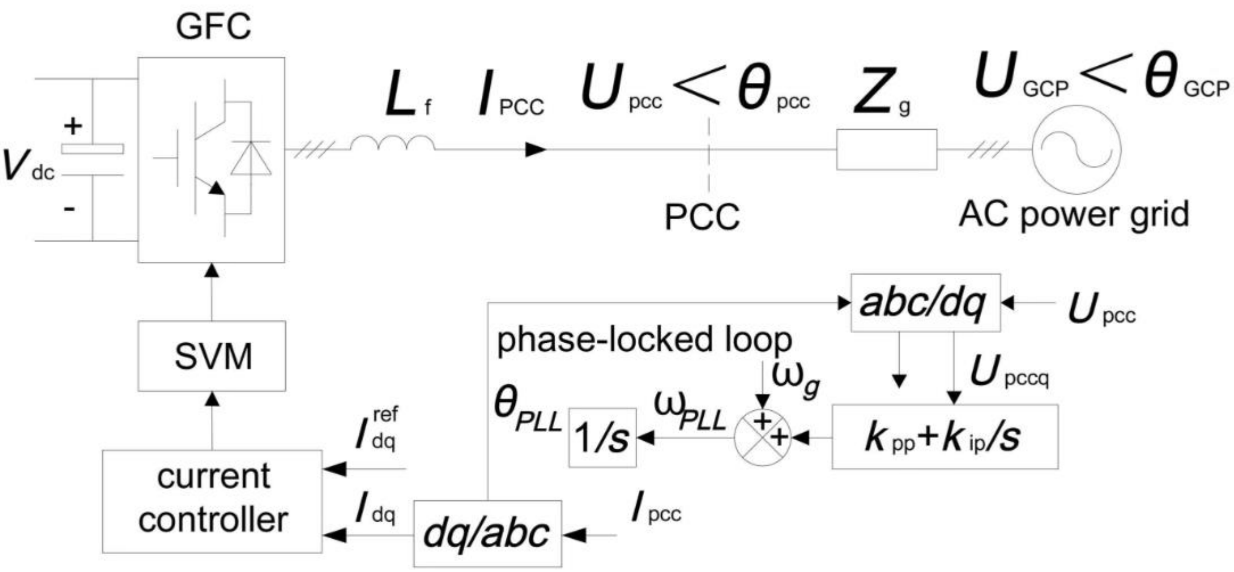

Figure 2. Modeling optimization diagram of DFIG [1].

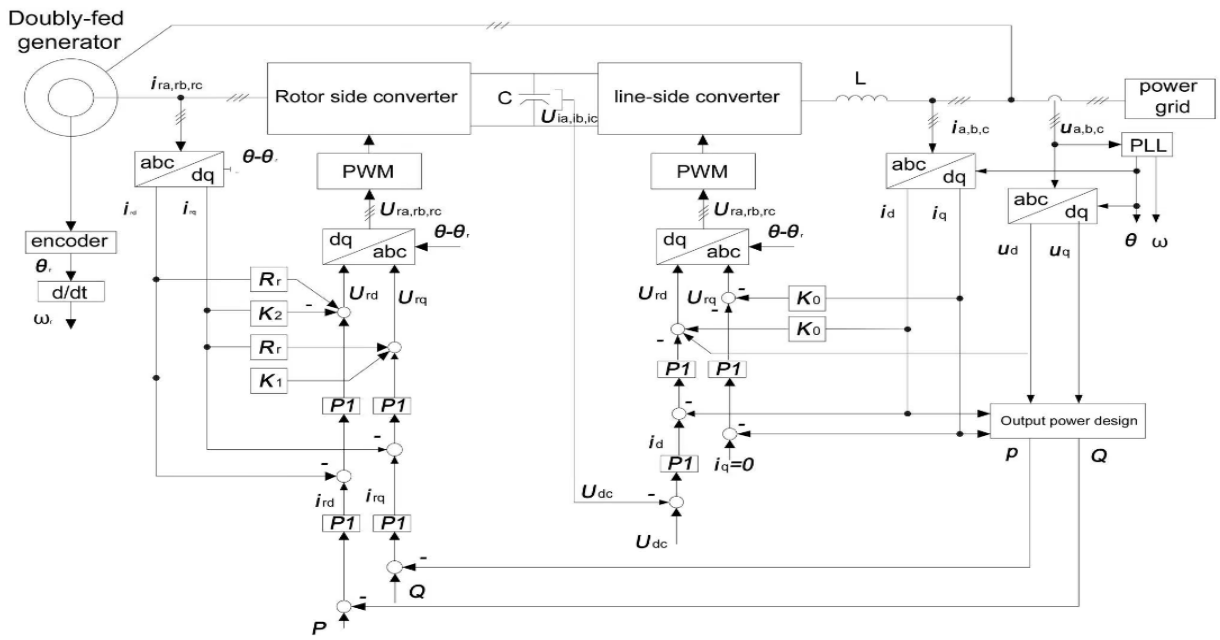

Figure 3. Modeling of DFIG [4].

5. Comparison between DIgSILENT and PSASP's doubly-fed fan model

The PSASP model document is divided into three parts: the wind turbine and control model, the generator/RSC model, and the RSC control model, as shown in Figure 4.

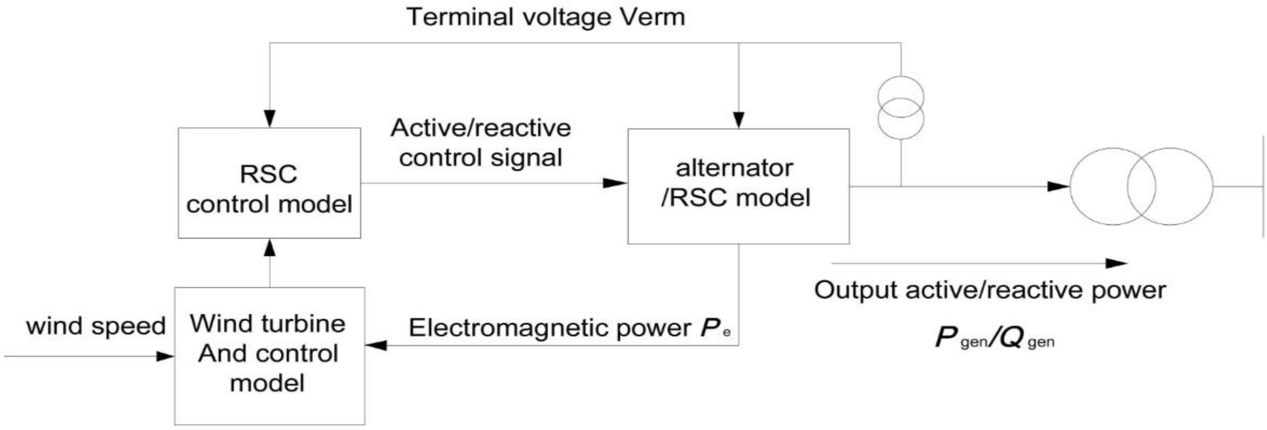

Figure 4. Flow chart of traditional doubly fed fan [5].

In PSASP, when the full load power is not reached, the power compensation control and speed control are 0, then the pitch Angle is 0, and the speed command value is obtained according to the output active power and maximum power tracking characteristics. The speed control is mainly achieved by torque control. When the full load or power command value is reached, the output of the speed control and power compensation control will be greater than 0, that is, the pitch Angle command value is increased to reduce the input mechanical power. It can be seen that DIgSILENT turbine and control model are very different from PSASP, mainly reflected in the control strategy [5]. The overall architecture of DIgSILENT's doubly fed fan model is similar to PSASP and can be divided into the same three parts. The difference is that the protection system model is also included, as shown in Figure 5.

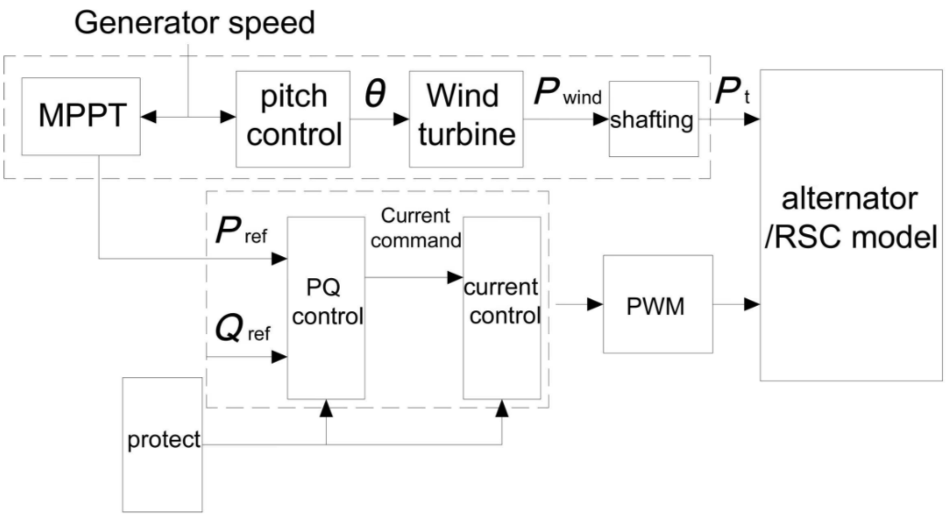

Figure 5. Improved flow chart of doubly fed fan [5].

The model in DIgSILENT ensures that the wind turbine power reaches the maximum by controlling the torque angle of the paddle in the maximum power control link. Additionally, it applies PQ control to ensure that voltage, current, frequency, and other parameters in the power system remain stable within the specified range. Furthermore, a protection link is added to both the PQ control link and the current control link to enhance generator safety. Figure 6 presents a statistical comparison of the two strategies.

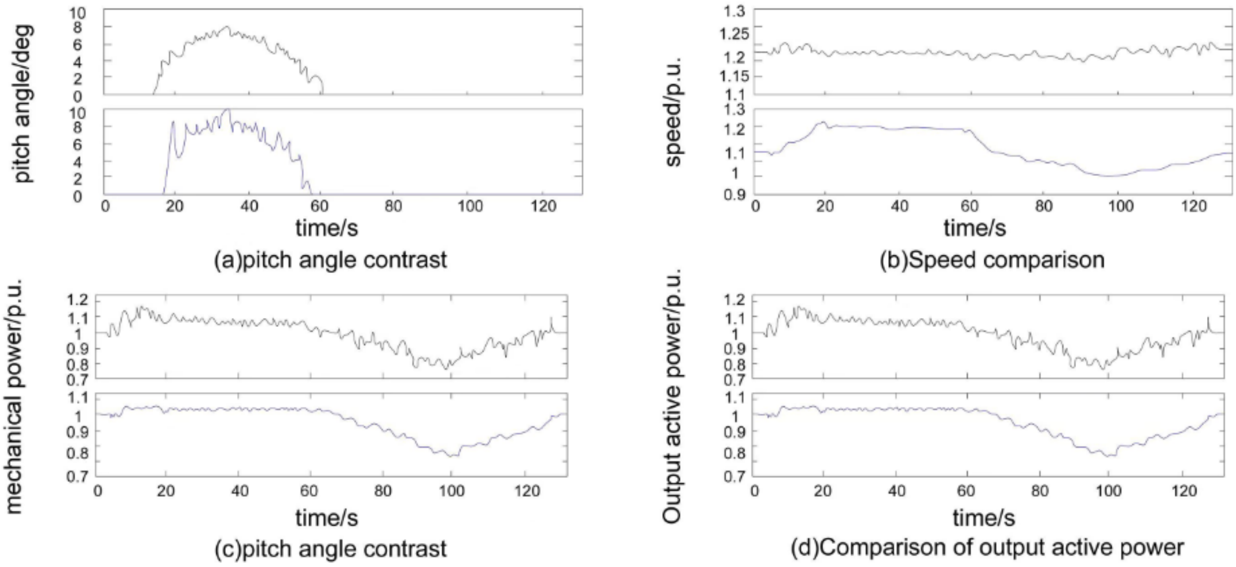

Figure 6. Comparison diagram [5].

Through the four comparison charts, it can be observed that the torque angle of the paddle fluctuates less between 20 seconds and 60 seconds, and the mechanical frequency, active power output frequency, and rotational speed are smoother, indicating that this strategy has good responsiveness. However, it has a disadvantage in terms of speed. After 60 seconds, the speed drops sharply, and the output power is also low.

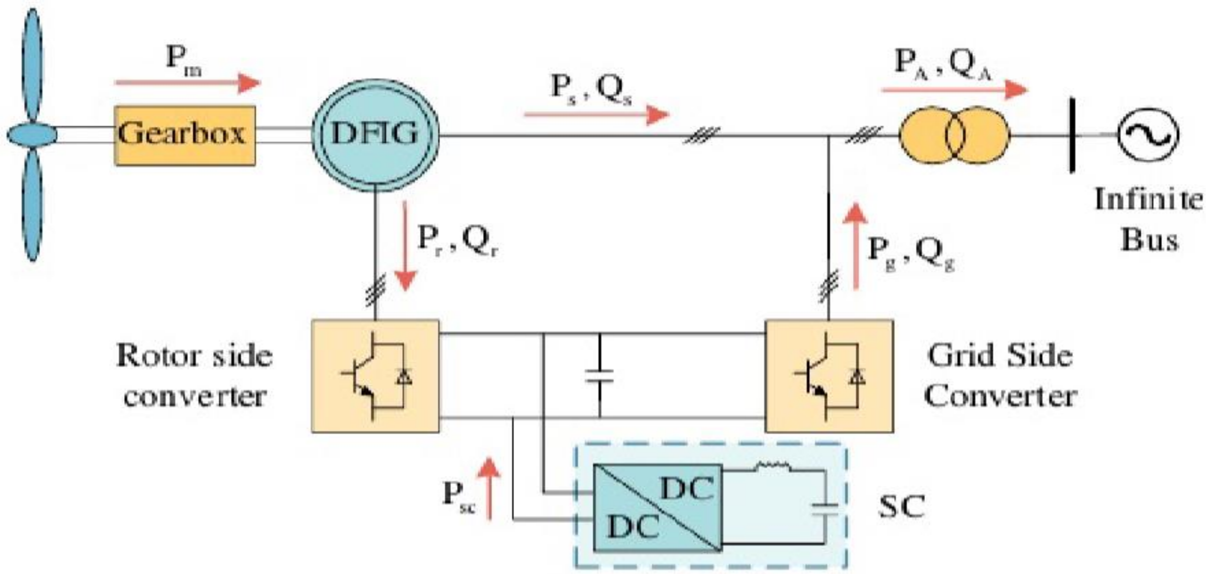

Figure 7. Doubly fed fan topology 错误!未找到引用源。.

As shown in Figure 7, the traditional DFIG lacks a protection circuit and PQ control system compared to Figure 5. Therefore, the traditional DFIG system has a poorer ability to stabilize various parameters of the power system and lower generator safety. In short, PSASP can balance the difference between supply and demand in the power system, providing energy storage and peak load balancing capabilities. Although DFIG and PSASP differ in terms of technology and application, they can both play an important role in the power system. DFIG can provide adjustable wind power capacity, while PSASP can provide energy storage and peak load capacity to balance supply and demand differences in the power system. Therefore, in some cases, a combination of DFIG and PSASP can be considered to achieve a more efficient, reliable and sustainable power system operation.

6. HESS-DFIG optimization

Ref. [7] proposes a novel low-voltage crossing scheme to improve the low-voltage crossing capability of DFIG through the cooperation of HESS and crowbar circuits. During a fault, HESS works with the crowbar circuit to stabilize DFIG's DC-link bus voltage, avoid overcurrent from damaging DFIG's stator-side converters, and reduce voltage and power oscillations after the fault is cleared, thereby enhancing DFIG's low-voltage traversal capability. After the fault is cleared, this scheme can promote the voltage and power recovery of the power grid. Under normal conditions, HESS can assist the GSC of DFIG in managing the output power of DFIG. The crowbar circuit in this scheme is used to protect the DFIG from current damage when it fails. Simultaneously, HESS can stabilize DFIG's DC-link bus voltage by cooperating with the crowbar circuit to avoid overcurrent. During a fault, the grid-side converter provides reactive power to the grid and facilitates the recovery of the PCC fault voltage. The circuit topology diagram of HESS DFIG is shown in Figure 8.

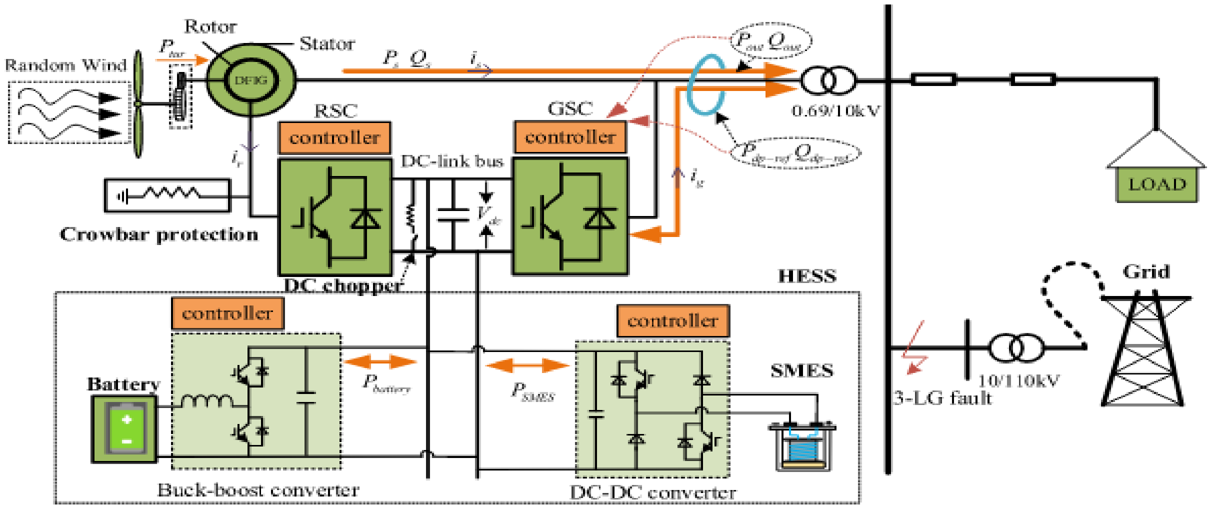

Figure 8. HESS DFIG Circuit topology diagram [6].

From the Figure 8, it can be observed that the following aspects of connecting HESS (Hybrid Energy Storage System) to DFIG's DC-link bus. During the fault period, HESS can collaborate with the crowbar circuit to stabilize DFIG's DC-link bus, thereby avoiding overcurrent that could potentially damage DFIG's RSC. This enhancement improves DFIG's low-voltage traversal capability and facilitates grid recovery after faults are cleared. Under typical circumstances, HESS is capable of collaborating with the GSC to regulate the power output from the DFIG. This synergistic strategy enables the efficient orchestration of power production from the DFIG, even amidst unpredictable wind scenarios. This approach fully realizes the application potential of HESS in normal operation, thus enhancing the overall economy of the system. However, it is essential to avoid overcharging/overdischarging of HESS to ensure its safety [8]. In comparison with the traditional DFIG system, as shown in Figure 9.

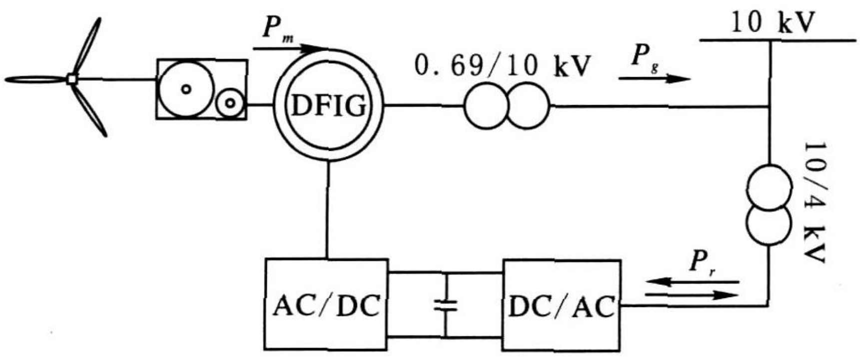

Figure 9. Sketch of doubly fed fan model [9].

HESS can be used with a crowbar circuit to stabilize DFIG. Therefore, the DC bus voltage of DFIG and HESS systems is more stable during a fault than that of traditional single DFIG systems. During a fault, the overcurrent of the DFIG can cause the DC-link bus voltage to become too high, and the traditional single DFIG system shown in Figure 9 cannot cope with the overcurrent [10]. When transient disturbances occur in the power grid, the overcurrent in the transient process can easily burn out the DFIG. In DFIG and HESS systems, HESS can absorb the excess power of DFIG, prevent overcurrent from damaging the RSC. Therefore, DFIG and HESS systems have a more stable DC-link bus voltage during failures. Compared with the traditional single DFIG system or DFIG and SMES system, the cooperative DFIG and HESS system has advantages in voltage stability, and its DC-link bus voltage is more stable during grid failures.

7. Conclusion

In conclusion, this study underscores the significance of maintaining optimal blade tip ratios for maximizing wind energy utilization. By leveraging parameters such as Kp and Kip for the proportion and integral gain of the PLL and utilizing θPLL and ωPLL to achieve stable grid connection through SVM-modulated data, advancements in grid stability are realized. While the DIgSILENT model demonstrates reduced torque angle fluctuations and enhanced system stability, there is a corresponding reduction in power output. This paper also mentions the comparison between DIgSILENT and PSASP and traditional DFIG. It can be seen from the comparison that the optimized doubly fed wind turbine system is safer and more reliable, and more in line with the needs of current doubly fed wind turbines. Moreover, the implementation of the HESS-DFIG low-pressure crossing strategy stands out for its ability to bolster system safety and economic efficiency compared to traditional models. The DC bus voltage stability of a doubly fed induction generator during failure can be improved by cooperating with a hybrid energy storage system and Crowbar circuit. Compared with the traditional single doubly fed induction generator system or doubly fed induction generator and superconducting magnetic energy storage system, the proposed scheme has better low voltage crossing ability. In addition, during normal operation, the hybrid energy storage system can also flexibly manage the output power of the doubly fed induction generator to meet different wind energy needs, thus improving the efficiency of wind energy utilization. This scheme can effectively improve the economy and reliability of the doubly fed induction generator.

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