

MAXIMUM POWER POINT TRACKING ALGORITHM AND COMPUTER AIDED DESIGN AND ANALYSIS OF DIRECT DRIVE DOUBLY FED INDUCTION GENERATOR

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Abstract— On the basis of the preliminary understanding and analysis of the dynamic performance of the permanent magnet doubly fed wind generator, a mathematical model is established by the method of mechanism modeling. The simulation model of the whole wind turbine is built under the Simulink running environment, and the system is designed by computer aided method. In this paper, the maximum power tracking algorithm is mainly studied. Based on the basic method of maximum wind energy capture, two simulation models of the maximum power tracking algorithm are built, including the tip speed ratio method and the power signal feedback method. Finally, the correctness of the wind turbine model is verified by the analysis of the simulation results. Under the condition of lower wind speed, two kinds of wind energy capture methods are compared and simulated, which can better reflect the performance of the maximum power tracking control algorithm.

Keywords— Direct drive doubly fed induction generator (DFIG); maximum power point tracking; computer aided design (CAD); simulation modeling.

I. INTRODUCTION

Wind turbine is a dynamic mechanical system that transforms wind energy resources into mechanical energy (Wu *et al.*, 2018a). The development of wind power technology is faster than that of constant frequency and constant speed to constant frequency variable speed wind turbines (Kumar *et al.*, 2017). Direct drive and doubly fed are two different ways of constant frequency variable speed wind turbine system (Ke *et al.*, 2018). In doubly fed induction generator system, because it only accounts for about 30% of the rated capacity of the system, it has great advantages in saving system cost (Daili *et al.*, 2015). In the case of different wind speeds, the maximum power tracking of the system can be achieved by adjusting the various devices in the wind power generation system. Consequently, the power emitted by the wind power generation system can be maintained in the vicinity of the rated power steadily. Additionally, it would be possible to avoid accidents caused by the wind power generation system, exceeding the speed limit or the limit of the work rate (Wu *et al.*, 2018b).

Therefore, the superior control method is designed and studied so that the output power can be kept at the rated power under the unpredictable wind speed. It is particularly important to improve the efficiency of the wind power generation system (Wu, 2015).

II. STRUCTURE AND MATHEMATICAL MODEL OF DIRECT DRIVE DOUBLY FED WIND POWER GENERATOR

A. Topological structure of direct drive double fed wind generator

(1) Doubly fed generator set

The impeller of the doubly fed wind turbine is driven by a multistage gearbox (Diop *et al.*, 2016; Caraballo *et al.*, 2017). In the sub synchronous power generation, the generator is fed by the stator to the power grid and the rotor absorbs energy to produce the braking torque, so that the motor works in the power generation state and the variable flow system is fed bi-directional, so the dual feed technology is called.

(2) Direct-drive generator sets

Wind turbines of direct-drive wind turbines directly drive generators and are mainly composed of wind turbines, transmissions, generators, converters, and control systems. In order to improve the efficiency of low-speed generators, direct-drive wind turbines adopt a large increase in the number of poles (usually the number of poles is increased to about 100) to increase the utilization of wind energy, and full-power converters are used to realize the speed regulation of wind turbines.

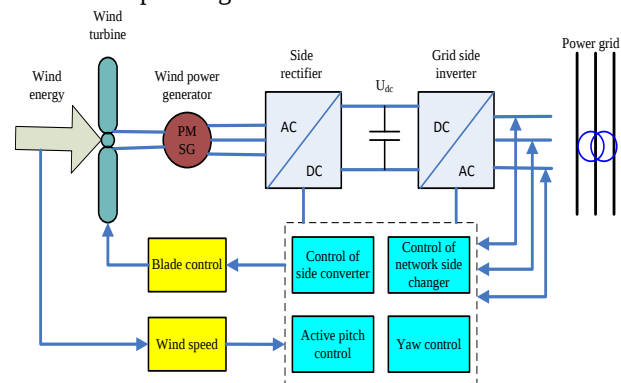


Figure 1. Model structure diagram of wind turbine.

Direct-drive generators can be classified into electric excitation and permanent magnet according to the excitation method. Permanent-magnet direct-drive is a wind-power technology developed in recent years. This technology uses permanent magnetic materials instead of complex electro-excitation systems (Garvey *et al.*, 2000). In addition, in the manufacturing process of permanent magnet direct drive wind turbines, rare earth strategic resources are needed, and the cost is high.

The converter of direct drive VSCF wind power generation system has the following functions:

- 1) Maximize the capture of wind energy;
- 2) Wider range of speed is suitable for variable speed operation of wind turbines.
- 3) The active and reactive power of the system can be flexibly adjusted.

B. Mathematical model of wind turbine generator

The commonly used PMSG mathematical model is established in synchronous rotating coordinate system. In order to deduce the mathematical model of PMSG, it is necessary to neglect some nonlinear factors of the motor itself which are less influential, so as to achieve the purpose of simplification. Assume the following:

- 1) The conductivity of the permanent magnetic material is 0.
- 2) The effect of leakage flux can be ignored.

Based on the above assumptions, the mathematical model of PMSG in DQ coordinates can be obtained from the stator flux linkage equation 1 in the coordinate system.

$$\begin{cases} \psi_d = L_d i_d + \psi_p \\ \psi_q = L_q i_q \end{cases} \quad (1)$$

The stator voltage equation (2) of the generator is as follows:

$$\begin{cases} u_d = R_s i_d + \frac{d\psi_d}{dt} - \omega_e \psi_q \\ u_q = R_s i_q + \frac{d\psi_q}{dt} + \omega_e \psi_d \end{cases} \quad (2)$$

Generator output electromagnetic torque is expressed in the next equation (3):

$$T_d = 1.5n_p(\psi_d i_q - \psi_q i_d) \quad (3)$$

Among them: ψ_d and ψ_q are the flux chain that the direct current of the stator winding and cross shaft produce, L_d is the d-axis inductance of the stator winding, the same L_q is the q-axis inductance of the stator winding; i_d and i_q are the components of the stator current vector on the d and q axes, respectively; ψ_p is the magnetic flux generated by the permanent magnet field in the stator winding; u_d and u_q are the d and q axis components of the generator stator voltage; R_s is the resistance of the stator winding; ω_e is the electrical angular velocity (rotation angle frequency); $\omega_e = n_p \omega_G$, n_p is the number of pole pairs of the rotor of the generator.

Substituting ψ_d and ψ_q into both Equations (2) and (3), respectively, eliminates the mathematical model of the generator of the flux linkage:

$$\begin{cases} u_d = R_s i_d + L_d \frac{di_d}{dt} - \omega_e L_q i_q \\ u_q = R_s i_q + L_q \frac{di_q}{dt} + \omega_e L_d i_d + \omega_e \psi_p \end{cases} \quad (4)$$

$$\begin{aligned} T_d &= 1.5n_p(\psi_d i_q - \psi_q i_d) \\ &= 1.5n_p[\psi_p i_q + (L_d - L_q)i_d i_q] \end{aligned} \quad (5)$$

The formula of the output voltage and torque of the generator further confirms that the permanent magnet generator is a multivariable and nonlinear system (as seen in both Equations 4 and 5). The current of the generator d and q axis is influenced not only by the stator and rotor voltage, but also by the coupling voltage caused by permanent magnets and stator windings.

III. WIND TURBINE MAXIMUM POWER TRACKING

A. The basic theory of maximum power tracking

Wind turbines have an optimal operating state at ever changing wind speeds, in which case the utilization of wind turbines is optimal. According to the Betz theory, the power that a wind turbine can absorb in wind energy is:

$$P = \frac{1}{2} \rho S C_p(\lambda, \beta) v^3 \quad (6)$$

In equation (6), ρ is the air density; S is the area swept by the blade; C_p is the wind energy utilization factor; λ is the tip speed ratio of the wind wheel, β is the pitch angle of the blade, and v is the wind speed. In the case where the wind wheel is fixed, and the air density and wind speed are determined by the surrounding environmental factors, only C_p is the factor that affects the power of the wind turbine. C_p is a function determined by λ and β . When the wind speed is lower than the rated wind speed, the wind wheel does not perform pitch control, that is, the blade pitch angle β is a constant value, in which case C_p is determined by λ .

For a certain wind turbine, when the wind speed and blade pitch angle received by the wind turbine are definite data, there is an optimal tip speed ratio λ_{opt} , corresponding to a maximum wind energy utilization factor C_{pmax} .

Fig. 2 shows the output power characteristics of wind turbines with different wind speeds, including v_1 , v_2 , v_3 and among which $v_1 < v_2 < v_3$. The maximum power curve P_{opt} is the connection of the maximum power point under the above three different wind speed conditions. When the wind turbine is running on the P_{opt} curve, the maximum output power is seen in Eq. 7:

$$P_{max} = \frac{1}{2} \rho S \left(\frac{R}{\lambda_{opt}} \right)^3 C_{pmax} \omega_m^3 \quad (7)$$

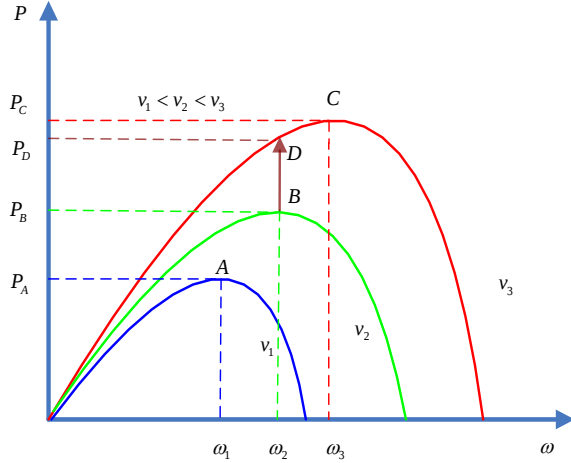


Figure 2. Power characteristics of wind turbines.

When the wind speed is the same value, the output power of the wind turbine represents different speed. In order to track the maximum power curve P_{opt} , it is necessary to ensure that the generator speed can be adjusted in time with the change of wind speed, so as to ensure the optimum ratio of blade tip speed λ_{opt} , the maximum wind energy utilization coefficient $C_{p max}$ can be obtained, so that the maximum wind energy can be captured to the maximum. The maximum power point tracking (Maximum Power Point Tracking, abbreviated as MPPT), MPPT control process is shown in Fig. 2. At this time, the speed is stable at the optimum speed v_3 when the wind speed is ω_3 , and the maximum mechanical power output by the wind turbine is P_C .

B. Algorithm classification of maximum power tracking

As the core problem of the wind turbine, the MPPT control algorithm has gradually entered people's field of vision in recent years and has become one of the hot research topics. The difficulty degree of these three control algorithms is gradually increasing, and as a result, with the improvement and innovation of the old algorithms, some new algorithms emerge, making the maximum power tracking control technology gradually perfect.

(1) Tip Speed Ratio Control (TSR)

TSR is the simplest algorithm for maximum power point tracking. Its working principle is that when the wind speed is measured, the blade tip speed ratio keeps it at the optimum value of λ_{opt} . When the pitch angle is constant λ_{opt} must correspond to an optimum wind utilization factor $C_{p max}$, which makes the wind generator run in the optimal state. Fig. 3 is the principle block diagram of the TSR control algorithm. The natural wind speed signal v and the observation value and measurement value ω of the wind turbine speed are seen as the input signal sent to the control system, and the actual blade tip speed ratio of the wind turbine is calculated at present. The difference value is used as the feedback signal of the speed of the wind turbine to control it until the best state of the wind turbine running at the best value of λ_{opt} .

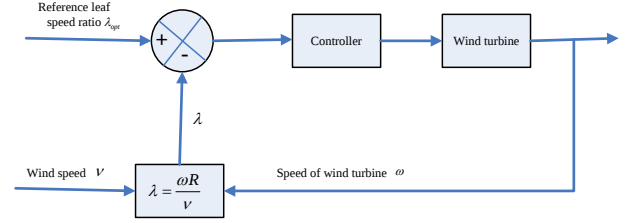


Figure 3. TSR control schematic diagram.

(2) Power Signal Feedback Control (PSF)

The basic principle of the RSF algorithm is to first detect the fan speed ω , and then compare the measured speed ω with the previously learned maximum power curve to obtain the maximum power at this speed P^* , comparing P^* with the measured output power. Fig. 4 shows the change of the operating state of the wind turbine under the control of the PSF algorithm. Fig. 5 shows the block diagram of the PSF control algorithm.

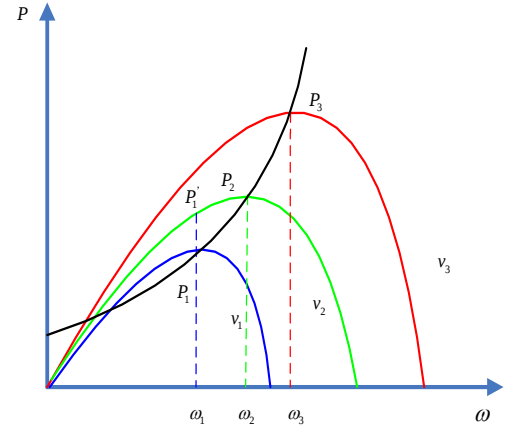


Figure 4. The change of the operating point of the wind turbine.

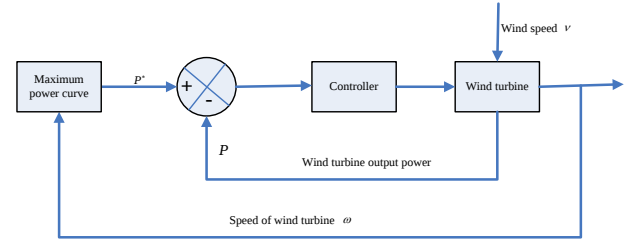


Figure 5. PSF control schematic diagram.

The wind speed information is not required for the PSF, but the best power curve inherent to the speed and wind turbine needs to be measured and calculated. Compared with the TSR, the measurement of wind speed is omitted, and it has better efficiency and better practical value. So, it is interesting to consider the next aspects:

1) Advantages: Effectively prevent the fluctuation of output power of the unit, and the control principle is relatively simple.

2) Disadvantages: The maximum power curves of different wind turbines are different, and they need to be calculated in advance using simulation or experiments. What is more important is that the unit characteristics

will change with the increase of the service life, and thus the accuracy of the control will be difficult to guarantee.

IV. DESIGN OF COMPUTER AIDED SYSTEM FOR WIND TURBINE GENERATOR

Due to the complexity of the internal electromagnetic relationship and the complexity of the electromagnetic calculation steps, and the manual hand calculation, the traditional motor design is designed by the designers to devote a lot of time and energy to the manual calculus. The C++Builder 6 software is used to compile the CAD software of a direct drive external rotor permanent magnet synchronous wind generator based on Windows operating system. The system has the characteristics of powerful function, convenient operation and maintenance, friendly interface and accurate calculation.

A. Introduction to C++Builder6.0

The Borland C++Builder6.0 introduced by the American Borland company is a good tool for rapid application and development of C++ programs. Both in the development environment and in the rapid development of Web, Internet applications and database processing, it has shown its powerful functions and simple good features. C++Builder6.0 has the following characteristics:

(1) The visual programming environment of the whole process of program design has changed the programming way of program development. Developers can achieve complex functions through very few manual programming.

(2) The C++ compiler that meets the ANSI standard.

The development environment of Borland C++Builder6.0 is divided into functional areas, such as title bar, main menu, toolbar, object tree, object observer, form design window, program code editor, and component bar. The object observer is divided into three parts:

1) Component list

The component list is a composite combo box, which contains all the components on the current form, and enumerates the components contained in all forms. Sometimes components that are not easy to select by using the mouse can be selected by using the component list combo box.

2) Property page

The properties of the currently selected component are listed in the property page. These attributes can be modified directly in the process of programming and can also be modified by code during the running of programs.

B. Processing of key technology iterations

There are usually many iterative processes in the electromagnetic computation program of motor design, and the parameters of some parameters can be approximately determined through these iterative processes. In the electromagnetic calculation program of the direct drive external rotor permanent magnet synchronous wind generator, the permanent magnet no-load working point b_{m0} and the cross axis current I_q are two parameters which need to

be determined through the iterative process. Next, take b_{m0} determination as an example to illustrate how to deal with the iterative process in the CAD system.

The key parameters in the iterative process are initial values, allowable errors and re setting values, which are detailed below:

(1) Initial set value

B is an initial value and is based on empirical statistics.

(2) Permissible error

ξ is a permissible error. In the traditional design of hand calculation motor, it is usually determined by the calculation precision and the calculation work load of the program itself. Because the speed of the computer is far faster than the hand speed, it can put forward higher requirements. Generally speaking, ξ takes 0.01 from hand counting, and the CAD system takes 0.005.

(3) Reset value

If the error between the calculated value b_{m0} and the assumed value b'_{m0} is greater than the allowable error ξ , it is necessary to set the value again and recalculate the iteration process. The setting value of the iterative process of the no-load working point of the permanent magnet is between the calculated value and the assumed value. In order to converge faster, the assumed value b'_{m0} in the CAD system is calculated as:

$$b'_{m0} = b_{m0} - \frac{|b_{m0} - b'_{m0}|}{3} \quad (8)$$

In order to accelerate the convergence speed, the following equation (9) is applied in the loop body to converge the cyclic process.

$$x_1 = x_2 - \frac{x_2 - x_1}{3} \quad (9)$$

C. The overall design of CAD system and its database technology

The traditional method of motor design is to calculate according to the given motor parameters, and check the calculation results, and adjust the parameters until the design requirements are met. Therefore, the CAD system of the direct-drive doubly-fed wind generator in this paper mainly includes data input, electromagnetic calculation, result output, database, and application assistance. The electromagnetic calculation and database are the core of the system. The CAD system architecture is shown in Fig. 6.

The CAD system of direct drive doubly fed induction generator is based on database. In the long-term motor manufacturing, the motor manufacturing industry has formed a certain industrial standard. Most of the databases used in the direct drive doubly fed wind generator CAD system are the experimental data provided by the manufacturers, some of which are found in the Handbook, which all have a certain time stability, so they appear as a backstage database in the design.

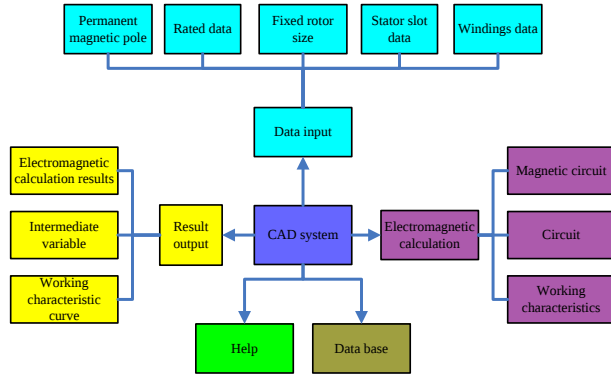


Figure 6. CAD system structure of wind turbine generator.

In Fig. 7, you can see the principles of database usage and control from left to right. The main function of the visual control component is to display the data, and the user can see all the data that is read. These components include: DBGrid, DBText, DBNavigator and so on as the user's data display interface.

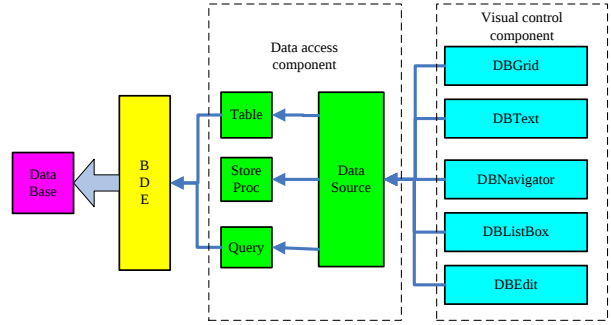


Figure 7. Database component schematic.

V. SIMULATION RESULTS AND ANALYSIS

When the wind speed is below the rated wind speed, the response curve of maximum power point tracking using tip speed ratio method and power signal feedback method is shown in Fig. 8.

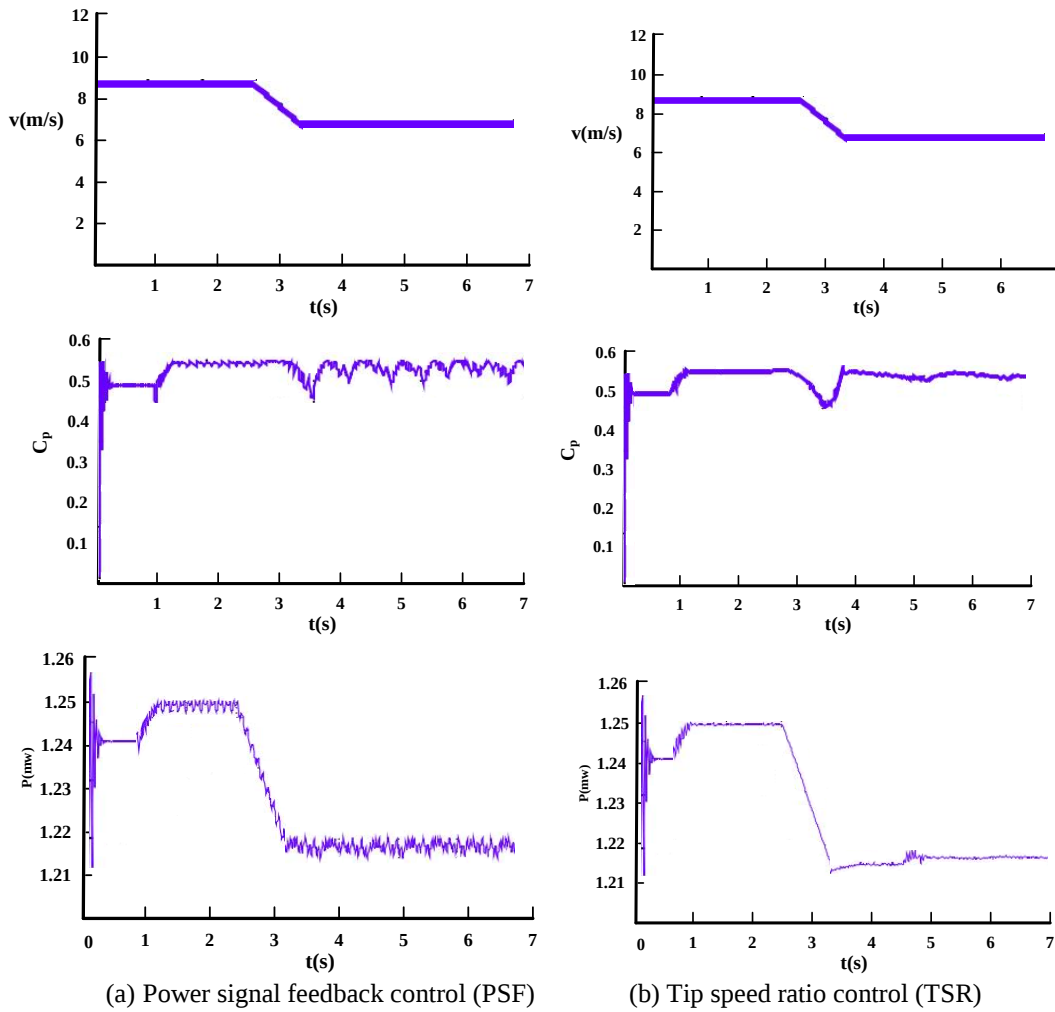


Figure 8. MPPT control response curve of wind turbine.

In Fig. 8, the left column is PSF, the MPPT control response curve is carried out, and the one on the right is TSR for MPPT control response curve. It can simultaneously take into account the speed and stability of the system and its control effect is obviously better than that of PSF. The above results are only the result obtained in the ideal condition of the laboratory, but in reality, there are many practical problems in the realization of TSR method.

VI. CONCLUSIONS

In this paper, a mathematical model is established for the mechanism modeling of a direct drive double fed wind generator, and a simulation model is built for the whole wind turbine under the operating environment of Simulink. Finally, through the analysis of the simulation results, the correctness of the wind turbine model is verified, and the performance of the maximum power tracking control algorithm can be better reflected under the condition of lower wind speed.

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