Chapter 2
Calculation Method of Losses and Efficiency of Wind Generators

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Abstract In the recent years, many wind turbine generation systems (WTGS) have been installed in many countries. However the electric power obtained from wind generators is not constant due to wind speed variations. The generated electric power and the loss in WTGS change corresponding to the wind speed variations, and consequently the efficiency and the capacity factor of the system also change. In this chapter, methods to evaluate the losses and output power of wind generator systems with Squirrel-Cage Induction Generator (IG), Permanent Magnet Synchronous Generator (PMSG), and Doubly-fed Induction Generator (DFIG) are explained. By using the presented methods, it is possible to calculate the generated power, the losses, total energy efficiency, and capacity factor of wind farms quickly.

2.1 Introduction

Wind energy is a clean and renewable energy source. In the recent years, many wind turbine generation systems (WTGS) have been installed in many countries from the viewpoints of global warming and depletion of fossil fuels. In addition, WTGS is of low cost in comparison with other generation systems using renewable energy. However the electric power obtained from wind generators (WG) is not constant due to wind speed variations. The generated electric power and the loss in WTGS change corresponding to the wind speed variations, and consequently the efficiency and the capacity factor of the system also change. In addition, the wind characteristic of each

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area is different and thus the optimal WTGS for each area is different. Therefore, it is necessary to analyze the optimal WTGS in each area. In the determination of optimal WTGS, annual energy production and capacity factor are very important factors.

In order to capture more energy from wind, it is essential to analyze the loss characteristics of WG, which can be determined from wind speed. Furthermore, since many non-linear losses occur in WG, making prediction profit by using average wind speed may cause many errors. This chapter presents a method to represent various losses in WG as a function of wind speed, which is based on the steady-state analysis. By using the presented method, wind turbine power, generated power, copper loss, iron loss, stray load loss, mechanical losses, converter loss, and energy efficiency can be calculated quickly.

First, a calculation method of the efficiency for constant speed WGs using Squirrel-Cage Induction Generator (IG) is presented, in which, using the wind turbine characteristics and IG steady-state equivalent circuit, wind turbine output, generator output, and various losses in the system can be calculated. Next, a calculation method of the efficiency for variable speed WGs using permanent magnet synchronous generator (PMSG) is presented. PMSG has some advantages over constant speed IG; i.e., PMSG can operate at the speed corresponding to the maximum power coefficient of wind turbine; noise can be decreased because PMSG WG does not need slip ring, brush, and gear system. However, since it needs power electronics devices for being connected to the power grid, loss evaluation of the power electronics devices is also needed in order to calculate the total efficiency of the wind generation system. Finally, a method to calculate loss, power, and efficiency of WTGS with Doubly-fed Induction Generator (DFIG) is presented. In recent years, the number of wind farms with large size DFIGs has increased all over the world. This type of system has power converters in the rotor circuit, and thus it can be operated at variable speed. The power rating of the power converter can be lower in this system than those in other types of systems, for example, WTGS with a synchronous generator with a field winding or permanent magnet. Thus, the power converter cost becomes lower than those of other systems.

In the methods presented in this chapter, wind speed is used as the input data, and then all state variables and conditions of the WG system, for example, wind turbine output, generator output, output power to the power grid, and various losses in the system etc., can be obtained. Generator state variables are calculated using the d-q axis equivalent circuit.

As one application of the presented methods, annual energy production and capacity factor of the wind farm can easily be evaluated by using wind speed characteristics expressed by Weibull distribution function. Weibull distribution function is commonly used to express the annual wind speed characteristics. Coefficients of Weibull distribution function can be determined by the geography and climate data of each area. Using the data of Weibull distribution function of different areas, capacity factor is calculated and compared among three types of WTGS, i.e., Squirrel-Cage IG, PMSG, and DFIG.

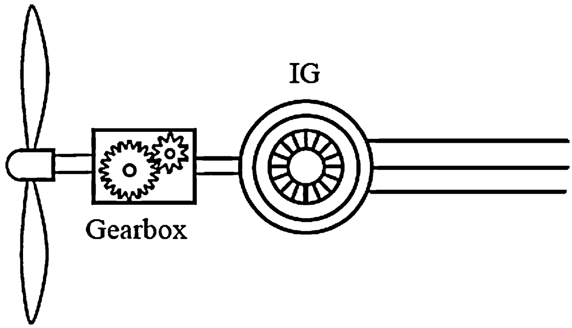


Fig. 2.1 System configuration with IG

Table 2.1 Losses of wind generator

Mechanical loss	Gear box losses
	Windage loss
	Ball bearing loss
Copper loss	Primary winding copper loss
	Secondary winding copper loss
Iron loss	Eddy current loss
	Hysteresis loss
Stray load loss	

2.2 Calculation Method for Squirrel-Cage Induction Generator

2.2.1 Outline of the Calculation Method

Induction generator is widely used as WG due to its low cost, low maintenance, and direct grid connection. However, there are several problems regarding the induction generator as given below.

- Usually the input, output, and loss conditions of induction generator can be determined from rotational speed (slip). However, it is difficult to determine slip from wind turbine input torque.
- Generator input torque is reduced by mechanical losses, but mechanical losses are a function of rotational speed (slip). It is difficult to determine mechanical losses and slip at the same time.
- It is hard to measure stray load loss and iron loss.
- It is difficult to evaluate gear loss analytically as a function of rotational speed.

In this section, a method of calculating the efficiency of WG correctly is presented, taking into account the points mentioned above. Figure 2.1 shows the system configuration for the analysis in this section. Table 2.1 shows the losses of this type of WG. The equivalent circuit of the induction generator used in the

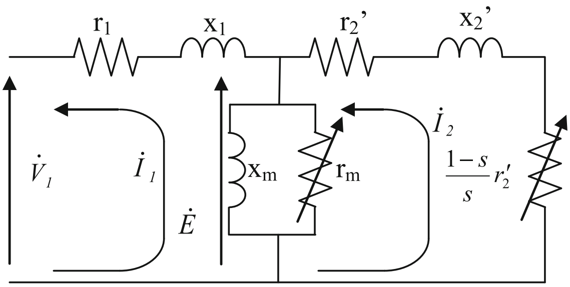


Fig. 2.2 Equivalent circuit of induction generator r_1 = stator resistance, r_2' = rotor resistance, x_1 = stator leakage reactance, x_2' = rotor leakage reactance, r_m = iron loss resistance, x_m = magnetizing reactance, s(slip) = (Ns-N)/Ns, N = rotor speed, Ns = synchronous speed

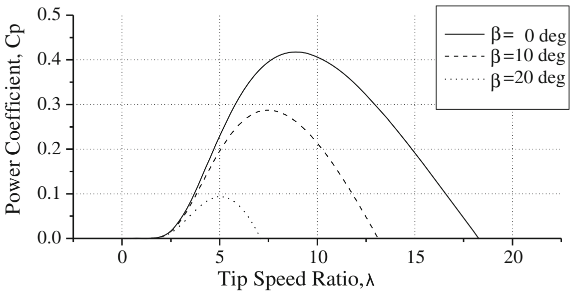


Fig. 2.3 Power coefficient versus tip speed ratio characteristics

method is shown in Fig. 2.2. The input torque and copper losses are calculated by solving the circuit Eq. 2.1.

$$\left.\begin{aligned} \dot{V}_1 &= -\left(r_1 + jx_1 + \frac{jr_m x_m}{r_m + jx_m}\right)\dot{I}_1 + \frac{jr_m x_m}{r_m + jx_m}\dot{I}_2 \\ 0 &= -\frac{jr_m x_m}{r_m + jx_m}\dot{I}_1 + \left(\frac{jr_m x_m}{r_m + jx_m} + \frac{r_2'}{s} + jx_2\right)\dot{I}_2 \end{aligned}\right\} \tag{2.1}$$

2.2.2 Models and Equations Necessary in the Calculations

2.2.2.1 Wind Turbine Power

The MOD-2 [1] model is used as a wind turbine model in this chapter. The power captured from the wind can be expressed as Eq. 2.2, tip speed ratio as Eq. 2.3, and power coefficient C_P as Eq. 2.4. As shown in Fig. 2.3, this turbine characteristic is non-linear, and it has a characteristic similar to those of actual wind turbines.

$$P_{wtb} = \frac{1}{2}\rho C_p(\lambda, \beta)\pi R^2 V_w^3 (\mathrm{W}) \tag{2.2}$$

$$\lambda = \frac{\omega_{\mathrm{wtb}} R}{Vw} \tag{2.3}$$

$$C_{\mathrm{P}}(\lambda, \beta) = 0.5(\Gamma - 0.022\beta^2 - 5.6)e^{-0.17\Gamma}\left(\Gamma = \frac{R}{\lambda}\cdot\frac{3600}{1609}\right) \tag{2.4}$$

In Eqs. 2.2–2.4, P_{wtb} = turbine output power (W), ρ = air density (kg/m^3), C_{p} = Power coefficient, λ = Tip speed ratio, R = Radius of the blade (m), V_{w} = wind speed (m/s), ω_{wtb} = Wind turbine angular speed (rad/s), and β = blade pitch angle (deg).

2.2.2.2 Several Losses in the Generator System

Generator input power can be calculated from the equivalent circuit of Fig. 2.2 as shown below:

$$I_2^2\left(\frac{1-s}{s}\times r_2'\right) \quad (\mathrm{W}) \tag{2.5}$$

Copper losses are resistance losses occurring in the winding coils and can be calculated using the equivalent circuit resistances r_1 and $r_2{}'$ as

$$w_{\mathrm{copper}} = r_1 \times I_1^2 + r_2' \times I_2^2(\mathrm{W}) \tag{2.6}$$

Generally, iron loss is expressed by the parallel resistance in the equivalent circuit. However, iron loss is the loss produced by the flux change, and it consists of eddy current loss and hysteresis loss. In the calculation method here, the iron loss per unit volume, $w_{\mathrm{f},}$ is calculated first using the flux density, as shown below [5].

$$w_{\mathrm{f}} = B^2\left\{\sigma_{\mathrm{H}}\left(\frac{f}{100}\right) + \sigma_{\mathrm{E}}d^2\left(\frac{f}{100}\right)^2\right\} \ (\mathrm{W/kg}) \tag{2.7}$$

where B: flux density (T), σ_{H}: hysteresis loss coefficient, σ_{E}: eddy current loss coefficient, f: frequency (Hz), and d: thickness of iron core steel plate (mm). Generally, flux φ and the internal voltage E can be related to Eq. 2.8. Therefore, if the number of turns of a coil is fixed, proportionality holds between the flux density and the internal voltage as shown in Eq. 2.9.

$$E = 4.44 \times f \times k_{\mathrm{w}} \times w \times \phi(\mathrm{V}) \tag{2.8}$$

$$B = B_0 \times \frac{E}{E_0}(\mathrm{T}) \tag{2.9}$$

where k_{w} : winding coefficient, w : number of turns, φ : flux, E_0 : nominal internal voltage. Then the iron loss resistance can be obtained with respect to the internal voltage E determined by the flux density as shown below, where W_{f} is the total iron loss which is determined using Eq. 2.7 and the iron core weight.

$$r_{\mathrm{m}} = \frac{E^2}{W_{\mathrm{f}}/3} \tag{2.10}$$

Bearing loss is a mechanical friction loss due to the rotation of the rotor, which can be expressed as below.

$$W_{\mathrm{b}} = K_{\mathrm{B}}\omega_{\mathrm{m}}\,(\mathrm{W}) \tag{2.11}$$

where K_{B} is a parameter concerning the rotor weight, the diameter of an axis, and the rotational speed of the axis.

Windage loss is a friction loss that occurs between the rotor and the air, and is expressed as follows.

$$W_{\mathrm{m}} = K_{\mathrm{W}}\omega_{\mathrm{m}}^2\;(\mathrm{W}) \tag{2.12}$$

where K_{w} is a parameter determined by the rotor shape, its length, and the rotational speed. Stray load loss is expressed as follows.

$$W_{\mathrm{s}} = 0.005\frac{P^2}{P_{\mathrm{n}}}(\mathrm{W}) \tag{2.13}$$

where P is generated power (W) and P_{n} is the rated power (W).

Gear box losses [6, 2], are primarily due to tooth contact losses and viscous oil losses. In general, these losses are difficult to predict. However, tooth contact losses are very small compared with viscous losses, and at fixed rotational speed, viscous losses do not vary strongly with transmitted torque. Therefore, simple approximation of gearbox efficiency can be obtained by neglecting the tooth losses and assuming that the viscous losses are constant (a fixed percentage of the rated power). A viscous loss of 1% of rated power per step is a reasonable assumption. Thus the efficiency of a gearbox with "q" steps can be computed using Eq. 2.14. Generally, the maximum gear ratio per step is approximately 6:1, hence two or three steps of gears are typically required.

$$\eta_{\mathrm{gear}} = \frac{P_{\mathrm{t}}}{P_{\mathrm{m}}} = \frac{P_{\mathrm{m}} - (0.01)qP_{\mathrm{mR}}}{P_{\mathrm{m}}} \times 100(\%) \tag{2.14}$$

where P_{t} is gear box output power, P_{m} is turbine power, and P_{mR} is the rated turbine power. Figure 2.4 shows the gear box efficiency for three gear steps. In this chapter, three steps are assumed, according to a large-sized WG in recent years.

2.2.2.3 Calculation Method

The efficiency of a generator is determined using the loss expressions described above. The input, output, and loss conditions of induction generator can be determined from rotational speed (slip). However, it is difficult to determine slip from wind turbine input torque. Therefore, an iterative process is needed to obtain

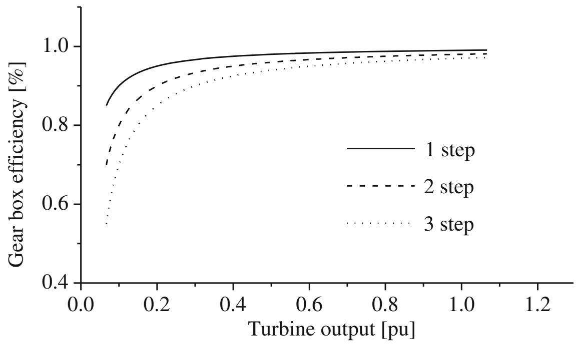


Fig. 2.4 Gear box efficiency

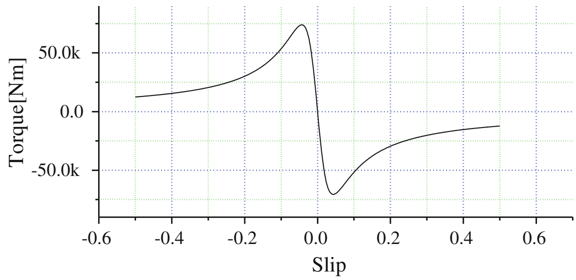


Fig. 2.5 Slip-torque curve

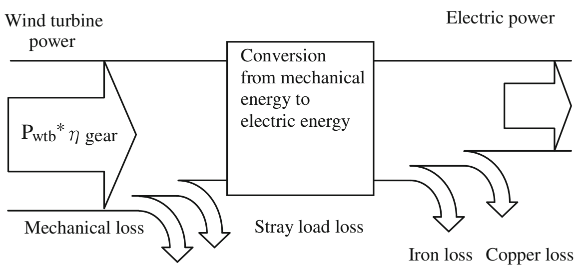


Fig. 2.6 Expression of power flow in the proposed method

a slip, which produces torque equal to the wind turbine torque, from a slip-torque curve as shown in Fig. 2.5. Furthermore, it is difficult to determine mechanical losses and slip at the same time, because mechanical losses are a function of rotational speed (slip). Mechanical loss can also be obtained in the iterative calculation. The power transfer relation in the WG is shown in Fig. 2.6.

Since mechanical losses and stray load loss cannot be expressed in a generator equivalent circuit, they are deducted from the wind turbine output. Figure 2.7 shows the flowchart of the calculation method, which is described below.

1. Wind velocity is taken as the input value, and from this wind velocity all states of WG are calculated.

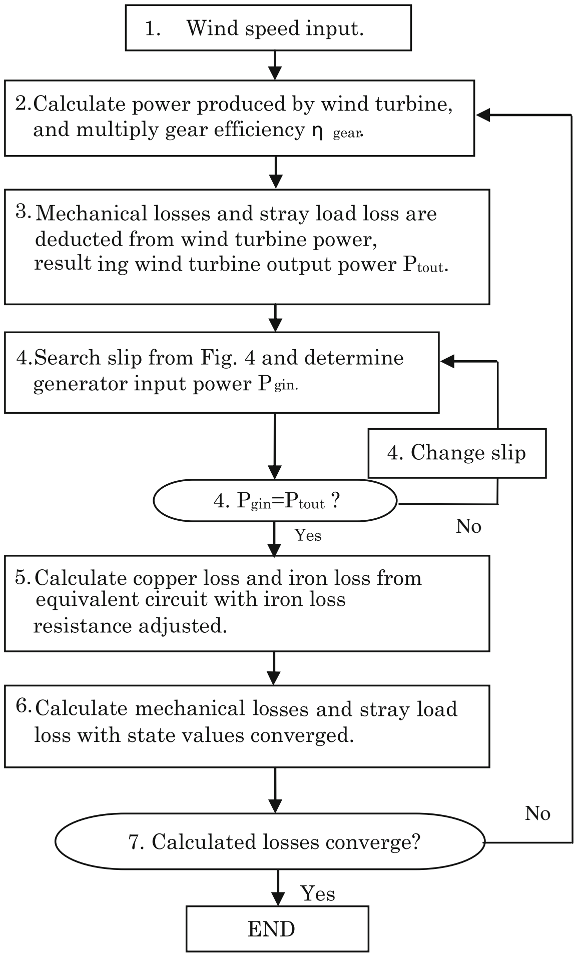


Fig. 2.7 Flowchart of the proposed method

2. Wind turbine output is calculated from Eq. 2.2. The synchronous angular velocity is taken as the initial value of the angular velocity and wind turbine power is multiplied by the gear efficiency, η_{gear}.
3. Ball bearing loss and windage loss which are mechanical losses are deducted from the wind turbine output calculated in step 2, and stray load loss is also deducted. These losses are assumed to be zero in the initial calculation.
4. At this step the slip is changed using the characteristic of Fig. 2.5 until giving the same generated power as the power calculated in step 3.
5. By using the slip calculated in step 4 and using Eq. 2.1, the currents in the equivalent circuit can be determined, and consequently the output power, copper loss, and iron loss can be calculated. Next, loss W_f is calculated from the flux density using the iron loss calculation method mentioned above, and the iron loss resistance, r_m, which produces the same loss as W_f, is also determined.

Table 2.2 Induction generator parameters

Rated power	5 MVA	Rated voltage	6,600 V
Rated frequency	60 Hz	Pole number	6
Stator resistance	0.0052 pu	Stator leakage reactance	0.089 pu
Rotor resistance	0.0092 pu	Rotor leakage reactance	0.13 pu
Iron loss resistance (Initial value)	135 pu	Magnetizing reactance	4.8 pu

6. Ball bearing loss and windage loss are calculated by using Eqs. 2.11 and 2.12, and the rotational slip of the generator determined in step 5. And stray load loss is calculated from Eq. 2.13.
7. If the calculated losses converge, the calculation will stop, otherwise it will return to step 2.

2.2.3 Calculated Results

The parameters of the WG used in this section are shown in Table 2.2. A 5 MVA induction generator is used. The cut-in and rated wind speeds are 5.8 and 12.0 m/s respectively. Moreover, it is assumed that the generated power of the induction generator is controlled by pitch controller when the wind speed is over the rated wind speed. Figure 2.8 shows the calculated results of power and various losses of the generator, in which the curves for the windage loss, bearing loss, and iron loss are enlarged for clear and easy understanding. From the Figures, it is clear that all losses are non-linear with respect to the wind speed. Iron loss decreases with the increase of wind speed. When wind speed increases, the generator real power increases, and thus the generator draws more reactive power and the internal voltage of the generator decreases. As a result, flux density and iron loss decrease.

2.3 Calculation Method for Permanent Magnet Synchronous Generator

2.3.1 System Configuration

In this section, a calculation method of the efficiency for variable speed WGs using PMSG is explained. In the method, wind speed is used as the input data in a similar way as in the previous section, and then all state variables and conditions of the WG system, for example, wind turbine output, generator output, output power to the grid, and various losses in the system etc. can be obtained.

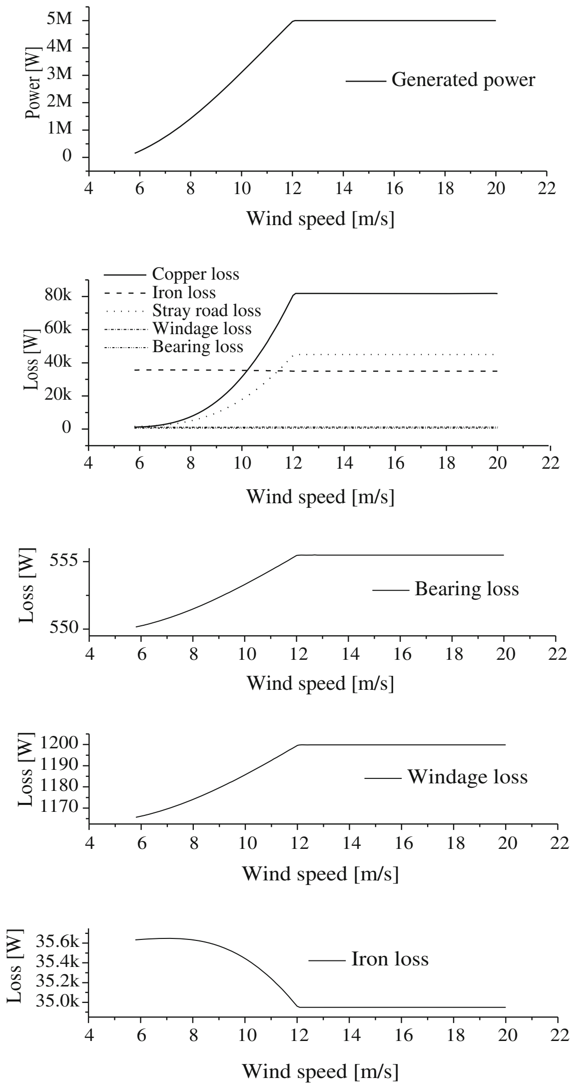


Fig. 2.8 Power and various losses of induction generator

Figure 2.9 shows the system configuration for the analysis in this section. The same model (MOD-2) as shown in Eqs. 2.2–2.4 is used as a wind turbine model. Figure 2.10 shows the wind turbine characteristic in a different manner from Fig. 2.3. Because this system can be operated in variable speed condition with the range of 0.4–1.0 pu where 1 pu is the synchronous speed, the turbine power can follow the maximum power point tracking (MPPT) line as shown in the figure. The rotor speed is controlled by the pitch controller in the high wind speed area and then kept at the rated level.

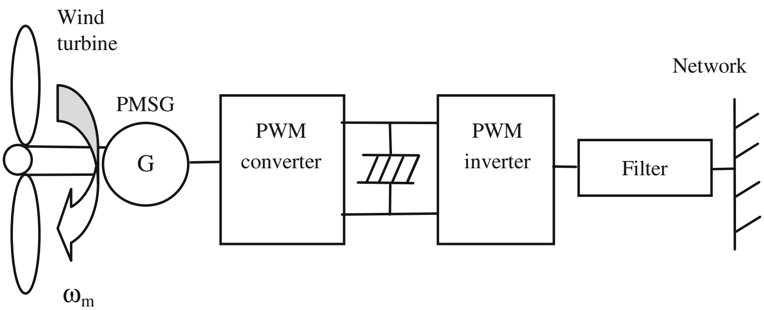


Fig. 2.9 System configuration with PMSG

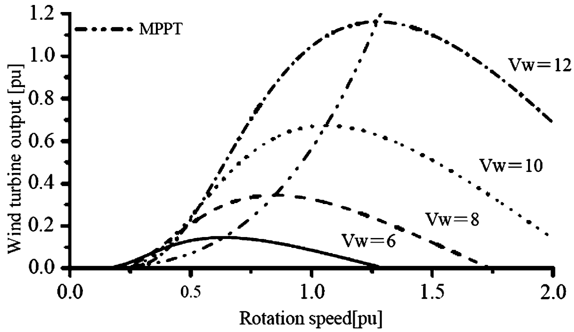


Fig. 2.10 Wind turbine characteristics

2.3.2 Models and Equations Necessary in the Calculations

2.3.2.1 Several Losses in the Generator System

Table 2.3 shows the various losses occurring in PMSG WG. Wind turbine output power is calculated by using the model equations presented above, and then generator input power can be calculated using the d-q axis equivalent circuit of Fig. 2.11 and Eqs. 2.15–2.22, where reactive power output of the generator is assumed to be controlled to zero.

$$v_d = -r_a i_d + r_m i_{di} \tag{2.15}$$

$$0 = r_m i_{di} + \omega_m \Phi_q \tag{2.16}$$

$$v_q = -r_a i_q + r_m i_{qi} \tag{2.17}$$

$$0 = r_m i_{qi} + \omega_m \Phi_d \tag{2.18}$$

$$\Phi_d = -L_d(i_d + i_{di}) + \Phi_{f0} \tag{2.19}$$

Table 2.3 Losses of permanent magnet synchronous generator

Mechanical loss	Windage loss
	Ball bearing loss
Stray load loss	
Copper loss	
Iron loss	
Converter loss	
Inverter loss	
Filter loss	

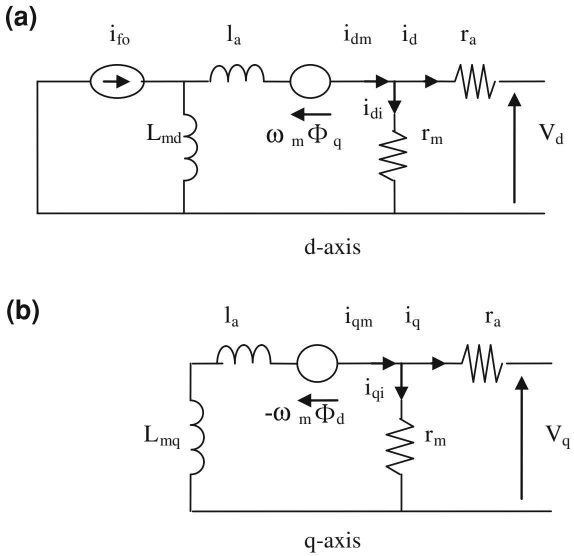


Fig. 2.11 d-q axis equivalent circuit. **a** d axis. **b** q axis r_a = Stator winding resistance, r_m = Iron loss resistance, l_a = Leakage inductance, L_{md} = d axis magnetizing inductance, L_{mq} = q axis magnetizing inductance, Φ_d = d axis flux linkage, Φ_q = q axis flux linkage, ω_m = Mechanical angular speed

$$\Phi_q = -L_q(i_q + i_{qi}) \tag{2.20}$$

$$\Phi_{f0} = L_{md} i_{f0} \tag{2.21}$$

$$P_{MG} = -\omega_m(L_d - L_q) i_d i_q + \omega_m \Phi_{f0} i_q \tag{2.22}$$

where, $L_d = l_a + L_{md}, L_q = l_a + L_{mq}$; L_d: d axis inductance; L_q: q axis inductance; P_{MG}: internal active power (W). Copper losses occur in the stator coil, and are calculated using stator winding resistance, r_a, in the equivalent circuit as below.

$$W_c = r_a(i_d^2 + i_q^2)(\mathrm{W}) \tag{2.23}$$

Mechanical losses, ball bearing loss W_b and windage loss W_m, are friction losses due to the rotation of the rotor. In general, bearing has two types, that is, plain bearing and ball-and-roller bearing. The bearing loss can be, in general, expressed as Eq. 2.24, where K_B is a parameter concerning the rotor weight, the diameter of the axis, and the rotational speed of the axis. Windage loss is a friction loss that occurs between the rotor and the air. Since it is difficult to calculate windage loss correctly, it is approximately expressed as Eq. 2.25 in this section, where K_w is a parameter determined by the rotor shape, its length, and the rotational speed. In general, bearing loss and windage loss in the case of PMSG WG are very small because its rotational speed is very low.

$$W_b = K_B \omega_m (\mathrm{W}) \tag{2.24}$$

$$W_w = K_w \omega_m^2 (\mathrm{W}) \tag{2.25}$$

Stray load loss is the electric machine loss produced under loading condition, and it is difficult to calculate accurately. The main factors for the stray load loss are the eddy current losses in conductors, iron core, and adjoining metallic parts produced by leakage flux. Stray load loss can be expressed approximately as Eq. 2.26 due to IEEE standard expression.

$$W_s = 0.005 \times \frac{P^2}{P_n} (\mathrm{W}) \tag{2.26}$$

where, P: generated power (W); P_n: rated output (W).

Power electronic converter/inverter devices are necessary to connect PMSG WG with the power grid. Since the converter/inverter circuits include switching operations of IGBT devices, in general, it is difficult to calculate the losses in the devices accurately. In this section, power electronics device (PED) loss Eqs. 2.27 and 2.28 are used which is obtained from the semiconductor device catalogs [5]. PED loss is calculated by the combination of Eqs. 2.27 and 2.28.

$$P_{IGBT} = \sqrt{2} \cdot \frac{I_0}{\pi} \cdot (k_{ton} + k_{toff}) \cdot f_c + D \cdot \left(b \cdot \frac{I_0^2}{2} + \frac{\sqrt{2}}{\pi} \cdot a \cdot I_0 \right) \tag{2.27}$$

$$P_{FWD} = \sqrt{2} \cdot \frac{I_0}{\pi} \cdot k_{rr} \cdot f_c + (1 - D) \cdot \left(d \cdot \frac{I_0^2}{2} + \frac{\sqrt{2}}{\pi} \cdot c \cdot I_0 \right) \tag{2.28}$$

where, I_0: Phase current (A); f_c: Carrier frequency; D: IGBT duty ratio; k_{ton}: IGBT turn on switching energy (mJ/A); k_{toff}: IGBT turn off switching energy (mJ/A); k_{rr}: FWD recovery switching energy (mJ/A); a,b: IGBT on voltage approximation coefficient; $V_{CE} = a + b*I$; c,d: FWD forward voltage approximation coefficient; $V_F = c + d*I$. Figure 2.12 shows an example of loss characteristics of IGBT and FWD [7].

Filter is, in general, used to reduce the high harmonic components resulted from the inverter. Filter efficiency is assumed to be 98% here.

Iron loss mainly occurs in the stator iron core. Iron loss is expressed by using the varying iron loss resistance, r_m, in the equivalent circuit as shown in Fig. 2.11. However, real iron loss varies depending on the magnetic flux density in the core

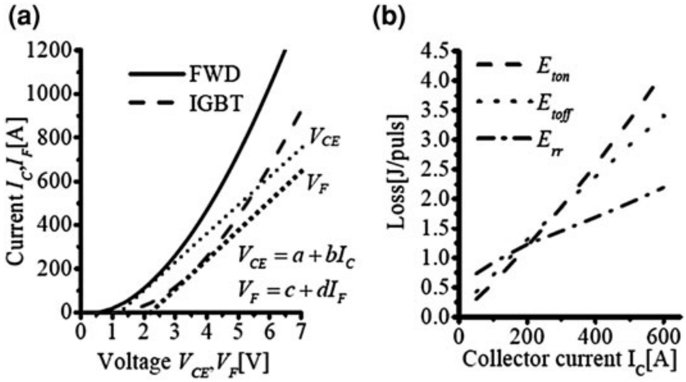


Fig. 2.12 Loss characteristics of IGBT and FWD. **a** Output characteristics. **b** Dependence of switching loss on I_C

which varies depending on the load condition. Therefore, if the iron loss is calculated using constant iron loss resistance, the result can have some error. Moreover, it should be noted that magnetic flux densities in heel piece and teeth in the stator core differ from each other.

Generally, iron loss consists of eddy current loss and hysteresis loss, both of which are proportional to the square of the magnetic flux density. In addition, eddy current loss is proportional to the square of the frequency and hysteresis loss is proportional to the frequency of alternating magnetic flux. In this section, iron loss is expressed as Eq. 2.29 in the same way as Eq. 2.7 for each of heel piece and teeth, which denotes the loss per 1 kg core. Therefore, the total iron loss W_f for each of heel piece and teeth is obtained by multiplying Eq. 2.29 by the core weight of each part. Then, the value of iron loss resistance, r_m, in the equivalent circuit is changed in order for the iron loss calculated from the equivalent circuit, W_r, to be equal to the iron loss, W_f.

$$w_f = B^2 \left\{ \sigma_H \left(\frac{f}{100} \right) + \sigma_E d^2 \left(\frac{f}{100} \right)^2 \right\} (\mathrm{W/kg}) \tag{2.29}$$

where, B: Magnetic flux density (T); σ_H: Hysteresis loss coefficient; σ_E: Eddy current loss coefficient; f: Frequency (Hz); d: Thickness of iron core steel plate (mm).

Calculation method of the iron loss is described below. Generally, magnetic flux and internal voltage can be related to each other as Eq. 2.30. Therefore, the magnetic flux density can be calculated from Eq. 2.31 and then the iron loss is calculated from Eq. 2.29, where magnetic flux density and internal voltage for the rated operating condition are expressed as nominal values, B_0 and E_0.

$$E = 4.44 f k_w w \phi (\mathrm{W}) \tag{2.30}$$

where, k_w: Winding coefficient; w: Number of turns; f: frequency.

$$B = B_0 \frac{E}{E_0} (\mathrm{T}) \tag{2.31}$$

where, E_0: Nominal internal voltage. Magnetic flux density is determined using the above equation, and then the total iron loss W_f is calculated. The iron loss resistance r_m can be obtained with respect to the internal voltage E and the total iron loss W_f as follows.

$$r_m = \frac{E^2}{W_f/3} \tag{2.32}$$

By continuing the above calculations until W_f to be equal to W_r, converged results can be obtained for the iron loss and iron loss resistance in the equivalent circuit. For the calculation of iron loss, initial value of iron loss is assumed to be 2.5% of the rated power.

2.3.2.2 Calculation Method

Figure 2.13 shows the flowchart of the calculation method, which is described below.

1. Wind speed V_w m/s is taken as the input value, and then all state variables of WG will be calculated.
2. Wind turbine output power is calculated from Eq. 2.2. Then, MPP(Maximum Power Point) produced by wind turbine is searched, resulting in the maximum wind turbine output power and the corresponding rotor speed. However, if the obtained power is greater than the rated power, the power is changed to 1 pu.
3. Bearing loss, windage loss, and also stray load loss are deducted from the wind turbine power calculated in step 2, yielding the input power to the generator. However, generator rotor speed is the value calculated in step 2.
4. Assuming generator reactive power to be 0, d and q axis currents are calculated from the d-q axis equivalent circuits, and then internal active power is calculated from Eq. 2.22.
5. Comparing the generator input power with the internal active power, if they are not equal to each other, calculation returns to step 4 with changing d-q axis currents, which will be continued until the generator input power is equal to the internal active power.
6. Using generator frequency and d-q axis currents calculated in step 5, internal voltage E, and then, W_f, W_r, and r_m, are calculated.

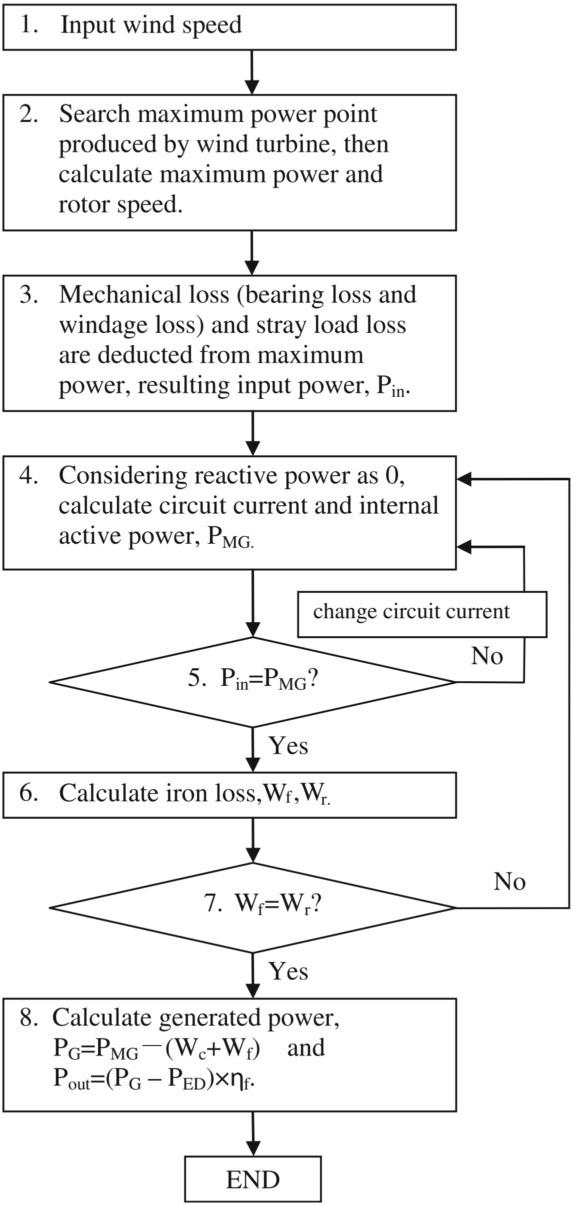


Fig. 2.13 Flowchart of calculation for PMSG wind generator

7. Comparing W_f with W_r, if W_f is not equal to W_r, calculation returns to step 4, with replacing the value of r_m by the new value calculated in step 6.
8. Generator active power P_G and AC/DC/AC converter loss, P_{ED}, are calculated. And then, deducting P_{ED} from P_G and multiplying the result by the filter efficiency, η_f, yields the final output power, P_{out}.

Table 2.4 PMSG wind generator parameters

Rated power	5 MVA	Rated voltage	6,600 pu
D axis reactance	0.88 pu	Q axis reactance	0.97 pu
Stator resistance	0.012 pu	Field flux	1.4 pu
Iron loss resistance (rated condition)	116 pu	Number of poles	96

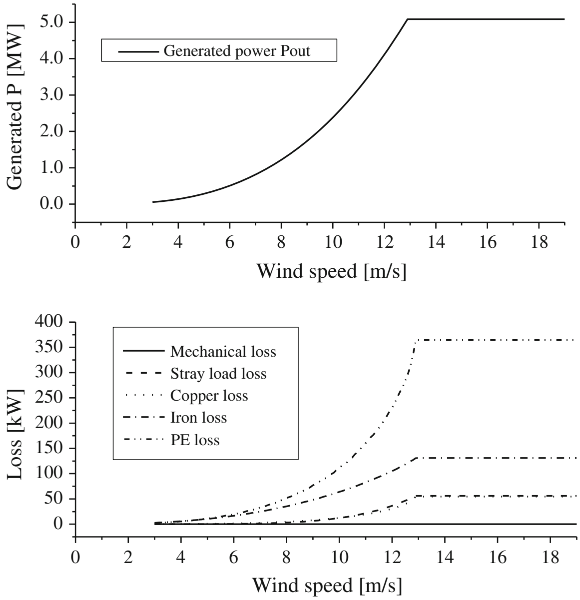


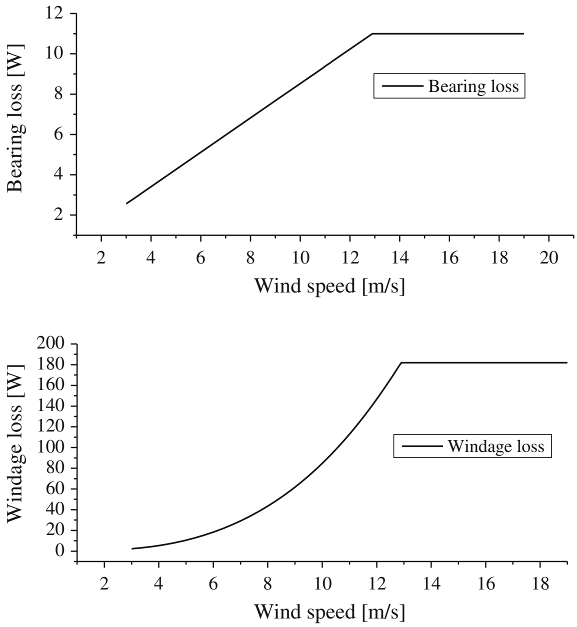
Fig. 2.14 Output and losses of PMSG wind generator

2.3.3 Calculated Results

The parameters of the PMSG WG used in the calculation are shown in Table 2.4.

Figure 2.14 shows the results of output power and various losses of PMSG. Bearing loss and windage loss characteristics are shown in Fig. 2.15. Figure 2.16 shows the characteristics of the iron loss, generator frequency, and the internal voltage. It is seen from Fig. 2.14 that output power and each loss increase with the increase in wind speed. Bearing loss and windage loss are small as shown in Fig. 2.15, because rotor speed of PMSG WG is very low. It is seen from Fig. 2.16 that the iron loss, the generator frequency, and the internal voltage increase with the wind speed. It is also seen from Fig. 2.17 that the iron loss resistance decreases with the wind speed, which can be thought to be due to the increases in generator frequency and internal voltage.

Fig. 2.15 Bearing loss and windage loss of PMSG wind generator



2.4 Calculation Method for Doubly-Fed Induction Generator

2.4.1 System Configuration

Figure 2.18 shows the system configuration of DFIG WG analyzed in this section. Wind speed is used as an input data, and then all state variables and conditions of the WG system can be obtained. This system can be operated in variable speed with the range of 0.7–1.3 pu, where 1 pu is the synchronous speed. Rated power of DFIG is set at 5 MVA.

The same model (MOD-2) as shown in Eqs. 2.2–2.4 is used as a wind turbine model. Because this system can also be operated in variable speed condition, the turbine power can follow the maximum power point tracking (MPPT) line as shown in Fig. 2.10. The rotor speed is controlled by the pitch controller within 1.3 pu.

2.4.2 Models and Equations Necessary in the Calculations

2.4.2.1 Several Losses in the Generator System

Various state values in the generator can be calculated using the equivalent circuit of Fig. 2.19, in which reactive power output of the generator is assumed to be controlled zero. Each internal voltage, E_1, E_2, is expressed as Eq. 2.33. Table 2.5 shows the various losses considered in DFIG WG.

Fig. 2.16 Iron loss, frequency, and internal voltage of PMSG wind generator

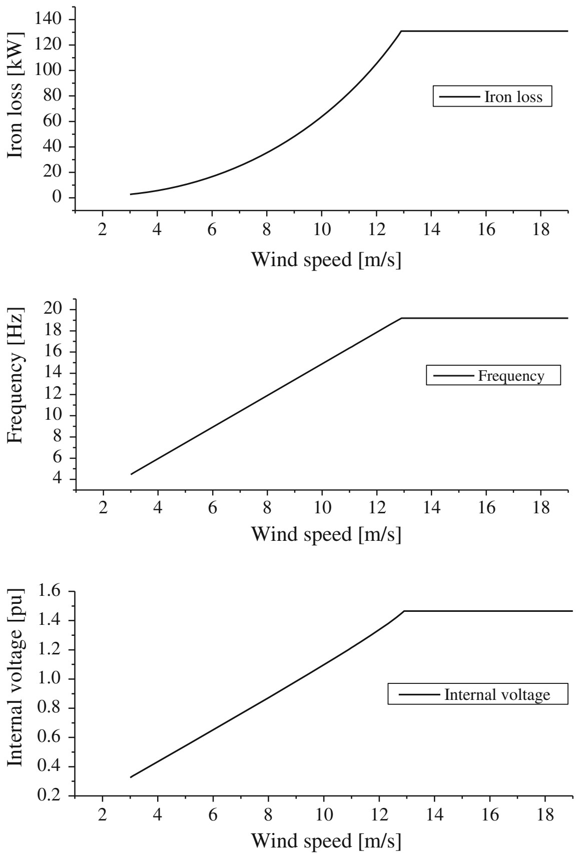
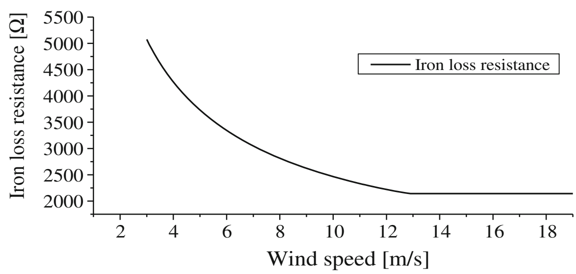


Fig. 2.17 Iron loss resistance of PMSG wind generator



$$\left.\begin{aligned} \dot{E}_1 &= jx_{\mathrm{m}}\dot{I}_{2\mathrm{a}} \\ \dot{E}_2 &= jsx_{\mathrm{m}}\dot{I}_{1\mathrm{a}} \end{aligned}\right\} \tag{2.33}$$

Gear loss, W_{gear}, among mechanical losses [3] is generated in speed-up gear between wind turbine and generator. Bearing loss, W_{b}, is a mechanical friction loss due to the rotation of the rotor. Windage loss, W_{w}, is a friction loss between the rotor surface and the surrounding air. Although it is difficult, in general, to

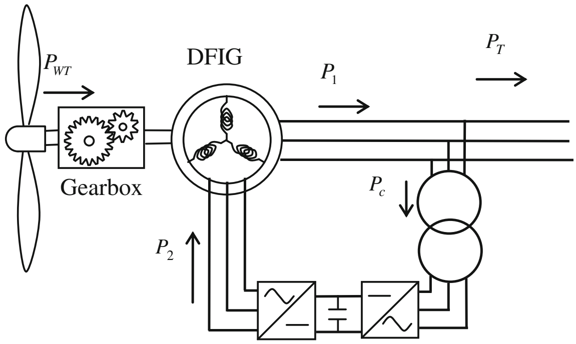


Fig. 2.18 System configuration with DFIG

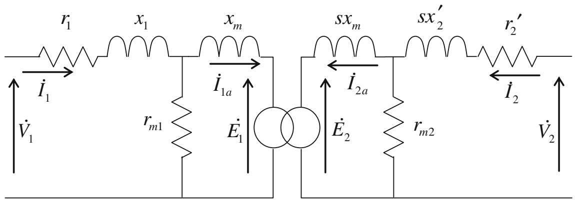


Fig. 2.19 Equivalent circuit of DFIG r_1 : stator winding resistance, r_2' : rotor winding resistance, x_1 : stator leakage reactance, x_2' : rotor leakage reactance, r_{m1} : stator iron loss resistance, r_{m2} : rotor iron loss resistance

Table 2.5 Losses in DFIG wind generator

Mechanical loss	Gear loss
	Bearing loss
	Windage loss
Iron loss	
Copper loss	
Stray load loss	
Power converter loss	
Transformer loss	

calculate these mechanical losses accurately, approximate expressions for the losses shown by Eqs. 2.34–2.36 are used in this section, where coefficients of bearing loss and windage loss, K_B, K_W, are determined by using generator structure and dimensions. Input power to the generator can be calculated by subtracting these mechanical losses from the wind turbine output.

$$W_{\mathrm{gear}} = 0.01qP_{\mathrm{mR}} \tag{2.34}$$

$$W_{\mathrm{b}} = K_{\mathrm{b}}\omega_{\mathrm{m}} \tag{2.35}$$

$$W_{\mathrm{w}} = K_{\mathrm{w}}\omega_{\mathrm{m}}^2 \tag{2.36}$$

In the equations above, P_{mR} is the rated turbine power and ω_m is angular speed.

Iron loss varies dependent on the flux density and frequency. In this section, iron loss is expressed by using variable iron loss resistances, r_{m1}, r_{m2}, as shown in Fig. 2.19. On the other hand, since the iron loss consists of hysteresis loss and eddy-current loss, it can be expressed as Eq. 2.37. Moreover, it should be noted that magnetic flux densities in yoke core and teeth core differ from each other. Therefore, iron loss of each core is calculated separately using Eq. 2.37 for each part of the stator and rotor, and then the total iron loss is obtained by summing them. Flux density can be expressed to vary in proportion to the internal voltage as shown in Eq. 2.38. Iron loss resistance in the equivalent circuit can be determined by Eq. 2.39. In these equations, K_1 and K_2 are coefficients of hysteresis and eddy-current losses, E_0 is the reference internal voltage, E' is the internal voltage, B_0 is the reference flux density, and W is iron core weight.

$$W_i = W_h + W_e = K_1 f B^{1.6} + K_2 f^2 B^2 (\mathrm{W/kg}) \tag{2.37}$$

$$B = B_0 \frac{E'}{E_0} \tag{2.38}$$

$$r_m = \frac{E'^2}{W_i \cdot W/3} \tag{2.39}$$

Copper losses in the stator coil P_{co1} and the rotor coil P_{co2} can be calculated using winding resistances, r_1 and r_2', in the equivalent circuit as follows.

$$P_{co1} = r_1 I_1^2 \tag{2.40}$$

$$P_{co2} = r_2' I_2^2 \tag{2.41}$$

Stray load loss can be expressed approximately as Eq. 2.42.

$$W_S = 0.005 \times \frac{P^2}{P_R} \tag{2.42}$$

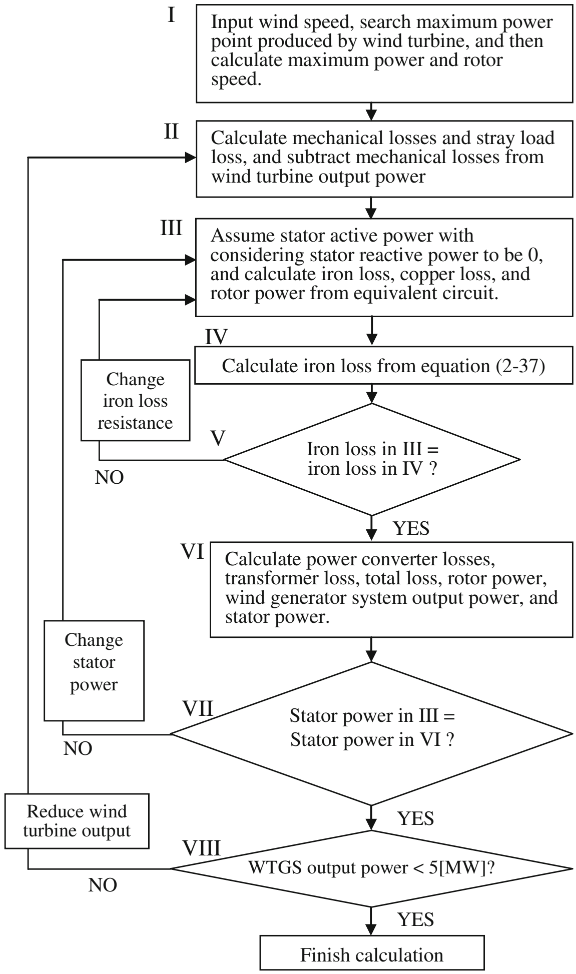
where P_R is the rated power of the generator and P is generator output.

The Power converter is composed of IGBT and FWD. Therefore, power converter loss is calculated as a summation of IGBT switching loss, reverse recovery loss of FWD, and steady-state losses of IGBT and FWD [5]. It is expressed as Eq. 2.43.

$$\begin{aligned} P_{PC} = {} & \frac{1}{2} DT \left[\frac{2\sqrt{2}}{\pi} I_0 a + I_0^2 b \right] + \frac{1}{2}(1 - DT) \left[\frac{2\sqrt{2}}{\pi} I_0 c + I_0^2 d \right] \\ & + \frac{1}{2} f_C (E_{on} + E_{off}) + \frac{1}{2} f_C E_r \end{aligned} \tag{2.43}$$

where, I_0: Phase current (A); f_c: Carrier frequency (Hz); DT: IGBT duty ratio; k_{ton}: IGBT turn on switching energy (mJ/A); k_{toff}: IGBT turn off switching energy

Fig. 2.20 Flowchart of calculation for DFIG wind generator



(mJ/A); k_{rr}: FWD recovery switching energy (mJ/A); a,b: IGBT on-voltage approximation coefficient, $V_{CE} = a + b*I$; c,d: FWD forward voltage approximation coefficient, $V_F = c + d*I$.

For simplicity, transformer is expressed by leakage impedance, and its loss is calculated as a resistance loss. The iron loss of the transformer is not considered.

2.4.2.2 Calculation Method and Results

The flowchart for the entire calculation using each loss expression explained above is shown in Fig. 2.20, which is described below.

Table 2.6 DFIG wind generator parameters

Rated output	5 MVA	Rated voltage	6,600 V
Frequency	60 Hz		
r_1	0.0053 pu	r_2	0.0052 pu
x_1	0.076 pu	x_2	0.14 pu
x_m	4.4 pu		
r_{m1}	287 pu	r_{m2}	166 pu

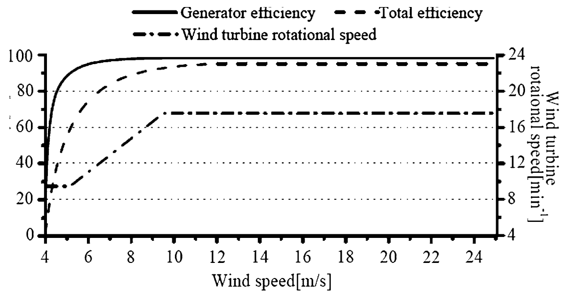


Fig. 2.21 Calculated results of efficiencies and rotational speed of DFIG wind generator

1. Wind speed V_w m/s is taken as the input value, and then all state variables of WG will be calculated. Wind turbine output power is calculated from Eq. 2.2. Then, MPPT(Maximum Power Point) power produced by wind turbine is searched, resulting the maximum wind turbine output power and the corresponding rotor speed.
2. Gear loss, bearing loss, windage loss, and also stray load loss are calculated and deducted from the wind turbine power calculated in step 1, yielding the input power to the generator. Generator rotor speed is the value calculated in step 1.
3. Assuming generator reactive power to be 0 and stator active power to be an appropriate value, iron loss, copper loss, and rotor power are calculated from the equivalent circuit, in which the stator voltage is set to be 1 pu.
4. Iron loss is calculated using Eq. 2.37 and iron core weight.
5. The above calculation is repeated until the iron loss in step 3 is equal to that in step 4 with changing the iron loss resistance.
6. Power converter losses, transformer loss, total loss, rotor power, WG system output power, and stator power are calculated.
7. Above calculation is repeated until the stator power in step 3 is equal to that in step 6 with changing the assumed stator power.
8. If the WG system output is greater than 1 pu, wind turbine output is reduced by the pitch controller and go to step 2.

The parameters of the DFIG WG used in the calculation are shown in Table 2.6. Figures 2.21, 2.22 and 2.23 show the obtained results of efficiency and losses of DFIG WG with respect to wind velocity. The cut-in wind speed, cut-out wind speed, and rated wind speed are 4.0 m/s, 25.0 m/s, and 12.1 m/s, respectively. Figure 2.21 shows that the generator efficiency becomes highest when wind

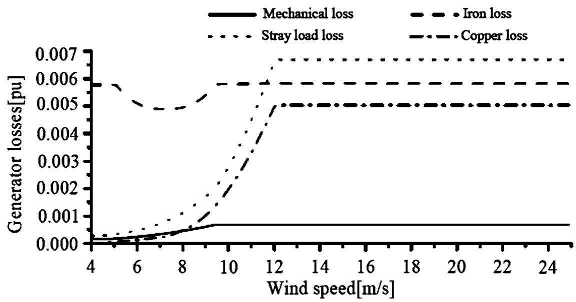


Fig. 2.22 Calculated results of losses in DFIG wind generator

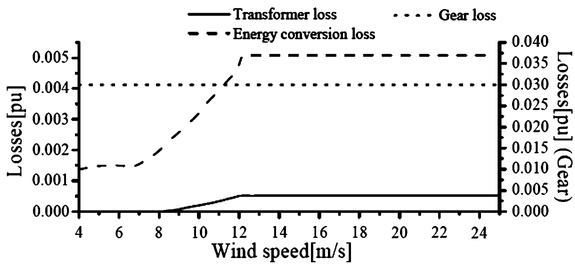


Fig. 2.23 Calculated results of other system losses in DFIG wind generator

speed is about 10 m/s but the total system efficiency becomes highest when the wind speed is over the rated speed. From Figs. 2.22 and 2.23, it can be understood that the stray load loss is greater than other generator losses and the gear loss is very large among all losses.

2.5 Comparative Study About Capacity Factor Among Three WGs (IG, PMSG and DFIG)

2.5.1 Weibull Distribution Function

If real wind speed data is available as a function of time, the efficiency calculation of WG can be precisely performed. However, it is difficult to calculate the annual generated energy and capacity factor by using the real wind data for one year expressed as a function of time. If the Weibull distribution function of wind speed for a specific area is available, it is possible to calculate the amount of annual generated energy and capacity factor for that area by using the method described above. The Weibull function can be expressed as Eq. 2.44, where k is shape factor and c is scale factor. $f(V_w)$ denotes a probability density distribution function that wind speed V_w appears. The annual generated energy can be calculated from Eq. 2.45, where $P_g(V_w)$ is generated power, E_{total} is annual energy production, V_{max} is cut-out wind speed (m/s), and V_{min} is cut-in wind speed (m/s). Capacity factor is calculated from Eq. 2.46.

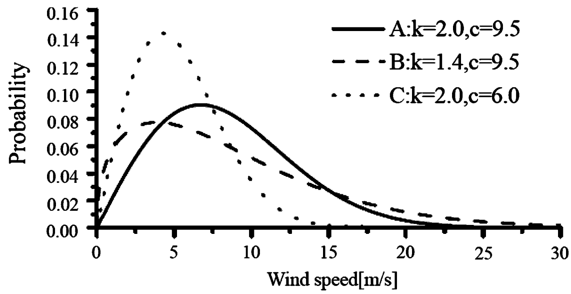


Fig. 2.24 Weibull distribution of wind speed

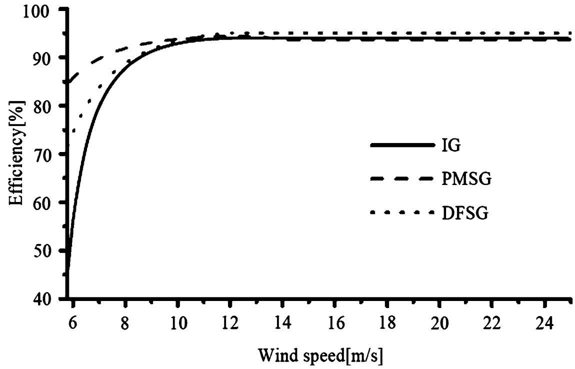


Fig. 2.25 Efficiency of each wind generator system

$$f(V_{\mathrm{w}}) = \frac{k}{c}\left(\frac{V_{\mathrm{w}}}{c}\right)^{\mathrm{k}-1} \exp\left[-\left(\frac{V_{\mathrm{w}}}{c}\right)^{\mathrm{k}}\right] \tag{2.44}$$

$$E_{\mathrm{total}} = \int_{V\,\mathrm{min}}^{V\,\mathrm{max}} P_{\mathrm{g}}(V_{\mathrm{w}}) \times f(V_{\mathrm{w}}) \times 8760dv \tag{2.45}$$

$$\text{Capacity Factor} = \frac{E_{\mathrm{total}}}{P_{\mathrm{R}} \times 365 \times 24(\mathrm{h})} \tag{2.46}$$

2.5.2 Calculated Results of Capacity Factor

Capacity factor of WG systems with Squirrel-Cage Induction Generator (IG), PMSG, and DFIG is calculated and compared to each other. Although a power converter is needed, the latter two systems can be operated in variable speed condition. On the other hand, the first system is operated in fixed speed. In the comparison analysis, 5.8 m/s is used for the fixed speed WG (IG) as the cut-in wind speed, but both 5.8 and 4.0 m/s are used for the variable speed WGs (PMSG and DFIG). Coefficients of Weibull distribution function have been determined as shown in Fig. 2.24. Figure 2.25 shows the system efficiency of

Table 2.7 Calculated results of capacity factor

Area	IG capacity factor (%)	PMSG capacity factor (%)		DFIG capacity factor (%)	
		4.0 m/s	5.8 m/s	4.0 m/s	5.8 m/s
A	40.36	43.20	42.14	42.48	41.64
B	37.40	39.74	38.79	39.12	38.37
C	12.81	16.28	14.56	15.58	14.22

each WG system with respect to wind speed. Table 2.7 shows the result of capacity factor of each WTGS for each Weibull distribution function. It is clear that capacity factors of variable speed WGs (PMSG and DFIG) are higher than that of the fixed speed one (IG).

2.6 Conclusions

In this chapter, methods to evaluate the losses and output power of WG systems with Squirrel-Cage Induction Generator (IG), PMSG and DFIG are explained, in which values of losses and state variables in each system can be calculated with respect to wind speed. By using the presented methods, it is possible to calculate the generated power, losses, total energy efficiency and capacity factor of WG system quickly.

In addition, if the Weibull distribution function of annual wind speed condition at a certain area is available,the annual generated energy and capacity factor of WG system for that area can easily be obtained. Using the method, capacity factors of three WG systems (IG, PMSG, and DFIG) for three wind conditions expressed by Weibull distribution function data have been evaluated, and then, it has been clearly shown that capacity factors of variable speed WGs (PMSG and DFIG) are higher than that of the fixed speed one (IG). The presented method can be used effectively for improving WG design, construction planning, and economic conditions of wind farms for specific areas.

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