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Loss Minimizing Operation of Doubly Fed Induction Generator Based Wind Generation Systems Considering Reactive Power Provision

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***Abstract*—The paper deals with control techniques for minimizing the operating loss of doubly fed induction generator based wind generation systems when providing reactive power. The proposed method achieves its goal through controlling the rotor side q-axis current in the synchronous reference frame. The formula for the control reference is explicitly deduced in this paper considering the losses of the generator, the power electronic devices and the filter. Three control strategies are compared with the proposed method under different wind speeds and different reactive power references. The simulation results validate the effectiveness of the proposed method.**

Keywords—wind power generation; energy efficiency; reactive power control; doubly fed induction genertaor

I. Introduction

Due to the increased integration of wind energy into the power system, reactive power control has emerged as one of the main control issues faced by wind farm operators. One solution would be to commission additional reactive power compensation sources to supply the reactive power demand in the system. However, from the utility and the wind farm developers' perspective, it is more economical to optimize wind generation systems in order to deliver enhanced reactive power performance [1]. Moreover, some grid codes already require wind turbines to provide reactive power ability, such as Danish Grid Code Technical Regulations TF 3.2.6 [2].

Doubly fed induction generator (DFIG) based Wind generation systems is one of the wind generation systems that can provide and absorb reactive power. Because of its advantages such as high energy controllability, reduced power converter rating, etc., DFIG has been widely used in wind farms [3]. However, the efficiency of the whole system would change under different operating conditions. Therefore, it is important to minimize the overall system losses under different wind speed and reactive power conditions in order to provide more power to the grid.

In order to improve the overall efficiency, regulating reactive power flow for minimizing the electrical losses of the generator and the converters has been proposed in previous works. The optimal rotor reactive current value was derived for minimal copper losses in [4-8]. These methods only consider copper loss minimization, but the reactive power from the stator is not zero, so the required power factor at the generator terminals is regulated by the grid-side converter, which will cause loss on the converter. Therefore, these methods cannot reach an optimal efficiency for the whole system. In [9, 10], the losses of converters are taken into account and the optimal splitting of the reactive power burden over the rotor and grid side converters is iteratively calculated, which forms a set of look-up tables. In the control process, the controller should look up the tables to decide the optimal reactive power currents, which would be time consuming. The optimal rotor reactive current formula was derived in [11]. The loss of converters is piecewise linearized in order to derive the optimal rotor reactive current. However, it only analyzed the condition when DFIGs is close to the rated operation and the condition when DFIGs are required to provide reactive power to support the grid was not considered.

In this paper, an optimal control strategy is proposed to minimize the losses of the whole system (the generator, converters and the filter) when providing reactive power to the grid. The formulas of the whole system are modeled first and the optimal rotor reactive current formula is derived later considering reactive power reference provided by the grid or the wind farm controller. The currents and losses in every part of the system are calculated and their characteristics are analyzed in detail. The proposed strategy is compared with three other strategies under different wind speed and reactive power reference. Comparative simulation results validate the effectiveness of the proposed method.

This paper is organized as follows: Section II describes the analytical formulas for loss calculation. Optimal reactive current control strategy considering reactive power provision was proposed in Section III. The effect of the new strategy is illustrated in Section V, and finally conclusions are drawn in Section VI.

II. Analytical Formulas For Loss Calculation

The power losses of a DFIG wind generation system are composed of friction loss of the mechanical part, core loss and

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copper loss of the DIFG, switching loss and conducting loss of converters, and resistant loss of the filter. The friction loss and core loss can be considered constant under a certain operation point [8], therefore they are not considered in this paper.

A. Wind Turbine Characteristics

The mechanical power extracted from the wind can be expressed as follows [4],

$$P_{mec} = \frac{1}{2}\rho\pi R^2 v^3 C_p(\theta,\lambda) \tag{1}$$

where P_{mec} is the power extracted from the wind, ρ is air density (kg/m^3), R is the blade radius (m), v is the wind speed(m/s) and C_P is the power coefficient which is a function of the pitch angle θ (deg) and the tip speed ratio λ.

The term λ is defined as

$$\lambda = \omega_t R / v \tag{2}$$

where ω_t is the wind turbine speed (rad/s).

B. Loss Model of DFIG

Based on the current directions shown in Fig. 1, the steady-state stator and rotor voltages are presented in the following formula [5, 11]. Note that all of variables are in per unit (pu) system in the following expression.

$$\begin{bmatrix} V_{sd} \\ 0 \\ V'_{rd} \\ V'_{rq} \end{bmatrix} = \begin{bmatrix} -R_s & -X_s & 0 & X_m \\ X_s & -R_s & -X_m & 0 \\ 0 & -sX_m & R'_r & sX'_r \\ sX_m & 0 & -sX'_r & R'_r \end{bmatrix} \begin{bmatrix} I_{sd} \\ I_{sq} \\ I'_{rd} \\ I'_{rq} \end{bmatrix} \tag{3}$$

Where: $X_s = X_{ls} + X_m$, $X_r = X_{lr} + X_m$, X_{ls} : stator leakage inductance, X_m : mutual inductance, X_{lr} : rotor leakage inductance; s: rotor slip. Subscripts: s, r and g for stator, rotor and grid-converter circuits; l, m for leakage and mutual inductances; d, q for direct and quadrature axes; ' for rotor value referred to the stator.

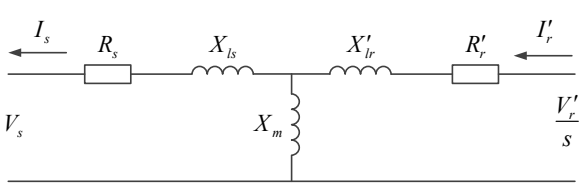

Fig. 1. Equivalent circuit for steady state operation of DFIG [11]

The stator and grid converter currents should be expressed as functions of rotor currents. Based on (3), stator currents are presented as follows:

$$\begin{aligned} I_{sd} &= B\left[A\left(X_m I'_{rq} - V_s\right) + X_m I'_{rd}\right] \\ I_{sq} &= B\left[\left(X_m I'_{rq} - V_s\right) - AX_m I'_{rd}\right] \end{aligned} \tag{4}$$

Where $A = R_s / X_s$, $B = X_s / \left(X_s^2 + R_s^2\right)$

Under stable operation, rotor d-axis current can be calculated as [13]:

$$I'_{rd} = \frac{X_s}{V_s X_m}\frac{\omega_s}{\omega_r} P_{mec} \tag{5}$$

$$I_{rd} = I'_{rd} / u \tag{6}$$

Where ω_r is the angular frequency of the voltages and currents of the rotor windings, ω_s is the angular frequency of the voltages and currents of the stator windings, u is the turns ratio.

The electric powers on the stator side and on the rotor side are calculated as follows:

$$\begin{aligned} P_r &= I_{rd}V_{rd} + I_{rq}V_{rq} \\ Q_r &= I_{rq}V_{rd} - I_{rd}V_{rq} \\ P_s &= V_s I_{sd} \\ Q_s &= V_s I_{sq} \end{aligned} \tag{7}$$

The copper losses in the generator winding, P_{Cu} , can be expressed as:

$$P_{Cu} = R_s\left(I_{sd}^2 + I_{sq}^2\right) + R_r\left(I_{rd}^2 + I_{rq}^2\right) \tag{8}$$

C. Loss Model of Converters and Filter

Each switch of a converter consists of a transistor (T) and a reverse diode (D). The losses of the converter can be divided into switching losses and conducting losses.

The conduction and switching losses can be expressed as [14].

$$P_c = V_{IGBT}\frac{2\sqrt{2}}{\pi} I_{rms} + r_{IGBT} I_{rms}^2 \tag{9}$$

$$P_{s,T} = \left(E_{ON} + E_{OFF}\right)\frac{2\sqrt{2}}{\pi}\frac{I_{rms}}{I_{C,\mathrm{nom}}} f_{sw} \tag{10}$$

$$P_{s,D} = E_{rr}\frac{2\sqrt{2}}{\pi}\frac{I_{rms}}{I_{C,nom}} f_{sw} \tag{11}$$

where P_c is the conduction losses in Ts and Ds, $P_{s,\mathrm{T}}$ is the switching losses in Ts, $P_{s,D}$ is the switching losses in Ds, I_{rms} is the rms value of the sinusoidal current to the grid or the machine, V_{IGBT} is the voltage across the collector and emitter of the IGBT, r_{IGBT} is the lead resistance of IGBT, $E_{ON} + E_{OFF}$ is the turn-on and turn-off losses of the IGBTs, $I_{C,\mathrm{nom}}$ is the nominal collector current of the IGBT, f_{sw} is the switching frequency, E_{rr} is the turn-off (reverse recovery) losses of the Ds.

Now, the total losses become

$$P_{con}^{loss} = 3\left(P_c + P_{s,T} + P_{s,D}\right) \tag{12}$$

Equation (12) can be expressed as

$$P_{con}^{loss} = a_l I_{rms} + b_l I_{rms}^2 \tag{13}$$

Where a_l and b_l are the power module constants and can be expressed as

$$a_l = \frac{6\sqrt{2}}{\pi}\left(V_{IGBT} + \frac{E_{ON}+E_{OFF}}{I_{C,nom}} f_{sw} + \frac{E_{rr}}{I_{C,nom}} f_{sw}\right) \tag{14}$$

$$b_l = 3r_{IGBT} \tag{15}$$

Given the converter characteristic data for the IGBT module (ABB 5SND 0800M170100) [15], the converter loss is estimated as:

$$P_{con}^{loss} = 7.0252 I_{rms} + 0.0087 I_{rms}^2 \tag{16}$$

Where f_{sw} is chosen as 1.2kHz.

Fig. 2 depicts the converter loss variation with the square of the rms converter current. Typically, the relation in Fig. 2 can be represented by piecewise linearization, as illustrated by linearization curves.

The linearization curves can be expressed as follows:

$$P_{con}^{loss} = P_0 + R_{con}\left(I_{rms}^2 - x_0^2\right) \tag{17}$$

All the values in this equation are pu values, the parameters are selected as:

$$\begin{cases} P_0 = 0,\ R_{con} = 0.038,\ x_0 = 0 & I_{rms} \le 0.17 \\ P_0 = 0.0013,\ R_{con} = 0.014,\ x_0 = 0.17 & 0.17 < I_{rms} \le 0.52 \\ P_0 = 0.0055,\ R_{con} = 0.0106,\ x_0 = 0.52 & 0.52 < I_{rms} \le 1 \end{cases} \tag{18}$$

So, the losses of Rotor Side Converter (RSC) and Grid Side Converter (GSC) can be calculated as:

$$\begin{aligned} P_{RSC}^{loss} &= P_0 + R_{con}\left(I_{rd}^2 + I_{rq}^2 - x_0^2\right) \\ P_{GSC}^{loss} &= P_0 + R_{con}\left(I_{gd}^2 + I_{gq}^2 - x_0^2\right) \end{aligned} \tag{19}$$

The loss of the filter can be calculated as:

$$P_{filter}^{loss} = R_{filter}\left(I_{gd}^2 + I_{gq}^2\right) \tag{20}$$

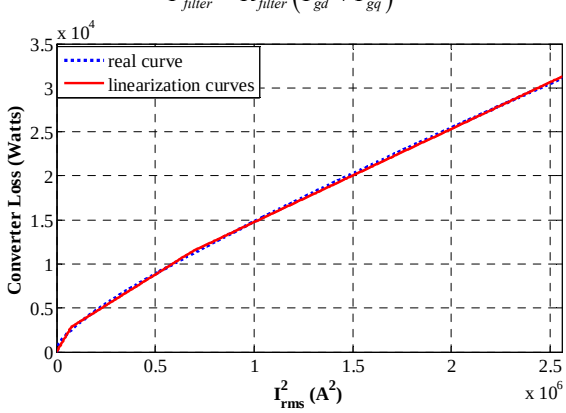

Fig. 2. Piecewise linearization for P_{con} with I_{rms}^2.

D. Calculation of grid side currents

The power flow of DFIG wind system is shown in Fig. 3, from which we can get:

$$P_g = P_r + P_{RSC}^{loss} + P_{GSC}^{loss} + P_{filter}^{loss} \tag{21}$$

$$Q_{ref} = Q_g + Q_s \tag{22}$$

where P_g is the active power absorbed from the grid, Q_g is the reactive power produced by grid side converter, Q_{ref} is the reactive power reference given by the grid or wind farm controller.

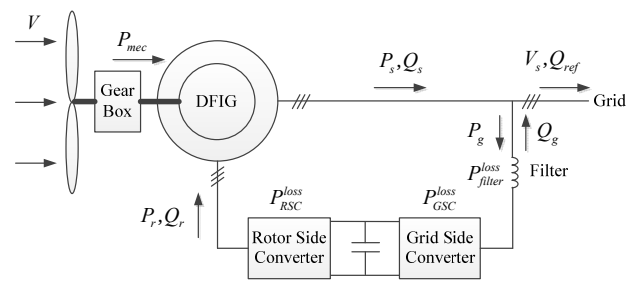

Fig. 3. Power flow of DFIG wind system

The correlation of grid side d-axis current I_{gd} and rotor side q-axis current I_{rq} is very small, so it is neglected in this paper when deriving (26).

Grid side q-axis current is:

$$I_{gq} = Q_{ref} / V_s - I_{sq} \tag{23}$$

So, the total loss, P_{tl}, can be expressed as follows:

$$\begin{aligned} P_{tl} &= P_{Cu} + P_{RSC}^{loss} + P_{GSC}^{loss} + P_{filter}^{loss} \\ &= R_s\left(I_{sd}^2 + I_{sq}^2\right) + R_r\left(I_{rd}^2 + I_{rq}^2\right) + R_{filter}\left(I_{gd}^2 + I_{gq}^2\right) \\ &\quad + 2P_0 + R_{con}\left(I_{rd}^2 + I_{rq}^2 + I_{gd}^2 + I_{gq}^2 - 2x_0^2\right) \end{aligned} \tag{24}$$

III. Loss Minimizing Operation Strategy

Previous papers [4-8] propose a control strategy to minimize the generator copper loss. The optimal reactive current contribution (I_{rqopt}) of the rotor-side converter can be found by making the derivative of the generator copper loss with respect to I_{rq} equals to zero, $\partial P_{Cu} / \partial I_{rq} = 0$, the optimal reactive current contribution I_{rqopt} can be expressed as:

$$I_{rqopt} = \frac{\left(A^2+1\right)B^2 R_s X_m}{R_r' + \left(A^2+1\right)B^2 X_m^2 R_s} V_s \tag{25}$$

However, this strategy does not consider the losses of converters and filter, which is a significant part of the total loss and could not be neglected. Therefore, an optimal control strategy considering the losses of the whole system is proposed hereafter.

The derivative of the total losses, expressed in (24), with respect to I_{rq} should be zero, $\partial P_{tl} / \partial I_{rq} = 0$. After simplification, the optimal rotor reactive current is given by

$$I_{rqopt}^{total} = \frac{1}{R_r^* u^2 + R_s B^2 \left(A^2+1\right) X_m^2 + R_g^* B^2 X_m^2} \bullet \left\{ \begin{array}{l} \left[R_s B^2 X_m \left(A^2+1\right) + B^2 X_m R_g^* \right] u V_s \\ + A B^2 X_m^2 R_g^* I_{rd} + R_g^* B X_m u Q_{ref} / V_s \end{array} \right\} \quad (26)$$

where $R_r^* = R_r + R_{RSC}$, $R_g^* = R_{GSC} + R_{filter}$.

The optimal rotor reactive current I_{rqopt}^{total} can be calculated in every control step and will be set as the control reference of the rotor reactive current.

IV. Case Studies

To testify the proposed optimal control strategy, an example was used to calculate the values of the system. The parameters are shown in Table I.

TABLE I. PARAMETERS OF DIFG WIND GENERATION SYSTEM [13]

Parameters	Value
Base wind speed (m/s)	12
Maximal output power (pu) at the base wind speed	0.73
Generator rotational speed (pu) at base wind speed	1.2
Rated power (kW)	2000
Rated frequency (Hz)	50
Rated line-to-line stator voltage (V_{rms})	690
Rated stator current (A_{rms})	1760
Rotor/stator turns ratio	0.34
V_{base} (V)	398.4
I_{base} (A_{rms})	1760
Stator resistance (pu)	0.011
Stator leakage inductance (pu)	0.1207
Rotor resistance (pu)	0.0128
Rotor leakage inductance (pu)	0.1207
Mutual inductance (pu)	3.4696
Filter resistance (pu)	0.003

A. Change of I_{rq}

Currents and losses were calculated in the condition when wind speed v=12 m/s, reactive power reference Q_{ref}=0 and the results were presented in Fig. 4 and Fig. 5.

The copper loss takes a large portion of the total loss. The copper loss (the black line in Fig. 5) reaches the minimum value (at point A1) when I_{rq} is 0.0436 pu, which is exactly the same value calculated from (25). Note that I_{rq} is the real value of the rotor side current. When referred to the stator side, it should be divided by the turns ratio u , which is 0.34 in this paper. So, I'_{rq} is 0.1282 pu, which is close to the absolute value of I_{sq} (the yellow line in Fig. 4) at point A (0.0436,-0.1569). Actually, when $X_s \approx X_m$, $R_s \approx R'_r$, it can be derived from (4) and (25) that $I'_{rqopt} = I_{sq}$, which means that the copper loss is minimum when magnetizing current is equally shared by stator side q-axis current I_{sq} and rotor side q-axis current I'_{rq} (referred to the stator side I'_{rq}). This is the same with the result from [16].

The loss of the grid side converter (the green line in Fig. 5) reaches the minimum value (at point B1) when I_{rq} is 0.0988 pu, where the loss of the filter (the red line in Fig. 5) and grid side current I_g (the black line marked with circle in Fig. 4) are also the minimum.

The total loss (the cyan line in Fig. 5) of the control strategy using (25) is reached at point D1, while the total loss of the proposed strategy using (26) is reached at point C1. It is obvious that the proposed strategy can minimize the total loss.

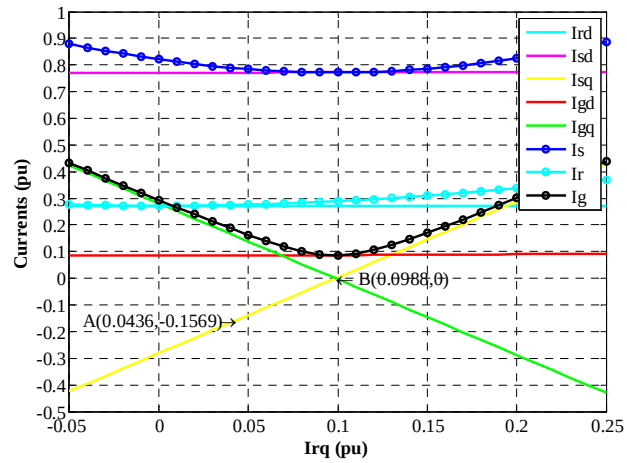

Fig.4. Currents trends with the change of I_{rq} when v=12, Q_{ref}=0

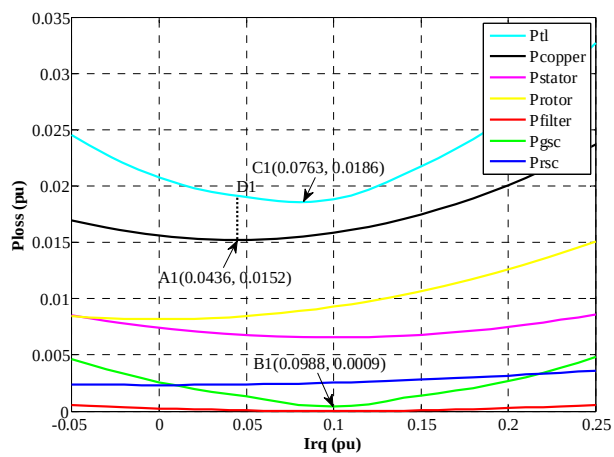

Fig.5. Losses with the change of I_{rq} when v=12, Q_{ref}=0

The losses were also calculated in the condition when v=12 m/s and Q_{ref} =0.3 pu. Results were presented in Fig. 6, from which one can see that the total loss (the cyan line in Fig. 6) of the control strategy using (25) is reached at point D2, while the total loss of the proposed strategy using (26) is reached at point C2. The total loss difference of the two strategies becomes more obvious while Q_{ref} increases.

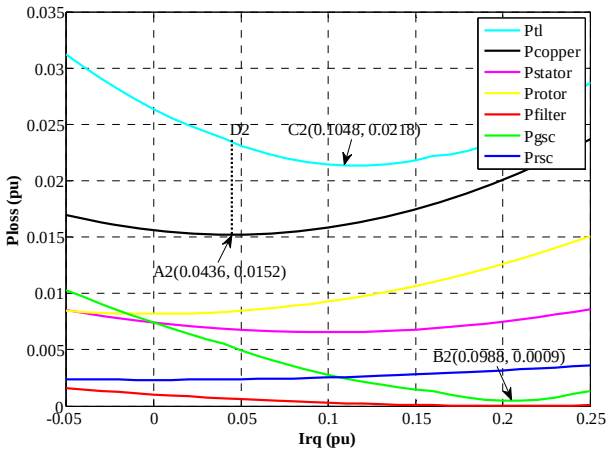

Fig.6. Losses with the change of I_{rq} when v=12, Q_{ref}=0.3

The copper loss (the black line in Fig. 6) reaches the minimum value at point A2, where I_{rq} is 0.0436 pu, which is exactly the same value as the result in Fig. 5. This means no matter what value Q_{ref} is, the optimal I_{rq} of control strategy using (25) is constant. This conclusion can also be seen from (25), when the parameter of the generator is fixed, the optimal current I_{rqopt} is constant.

The loss of the grid side converter (the green line in Fig. 6) reaches the minimum value (at point B2) when I_{rq} is 0.2089 pu, where the loss of the filter (the red line in Fig. 6) is also the minimum.

It can be seen from Fig. 5 and Fig. 6 that the value of I_{rq} for minimum copper loss and the value of I_{rq} for minimum loss of the grid side converter and the filter are quite different, and when Q_{ref} increases, the difference becomes greater. This is the reason that the value of I_{rq} for minimum total loss increases from 0.0763 to 0.1048. Therefore, it can be concluded that the optimal I_{rq} is a compromise value between the attempt to minimizing the copper loss and the attempt to minimizing the losses of converters and filter.

B. *Change of wind speed*

Fig. 7 and Fig. 8 show the overall losses for Q_{ref} =0 and Q_{ref} =0.3 respectively when wind speed ranges from 7m/s to 13.33 m/s, which is the normal operation region under the rated wind speed. The reason for this choice is that when wind power is greater than rated power, the wind turbine can capture more energy to compensate the losses.

The blue curve is the total loss of the whole system when the generator is operating under a normal control strategy, where no magnetization reactive power is provided by the rotor circuit (I_{rq}=0). The red curve shows the situation in which magnetization reactive power is solely provided by the rotor circuit (I_{sq}=0). The total loss under MinCopperLoss control strategy using (25) which only considered the copper loss minimization is depicted in black curve while the total loss under proposed MinTotalLoss control strategy is shown in cyan curve marked with circles.

It can be seen from Fig. 7 and Fig. 8, as wind speed increases, the total loss gradually rises and the slope increases. Also, at every wind speed, the MinTotalLoss strategy always gets the lowest total loss.

It also can be seen from Fig. 7 that, when Q_{ref} =0, MinCopperLoss control strategy is better than I_{sq}=0 control strategy when wind speed is below 10.5 m/s, while when wind speed is above 10.5 m/s, I_{sq}=0 control strategy is better than MinCopperLoss control strategy. However, the MinTotalLoss strategy is always the best.

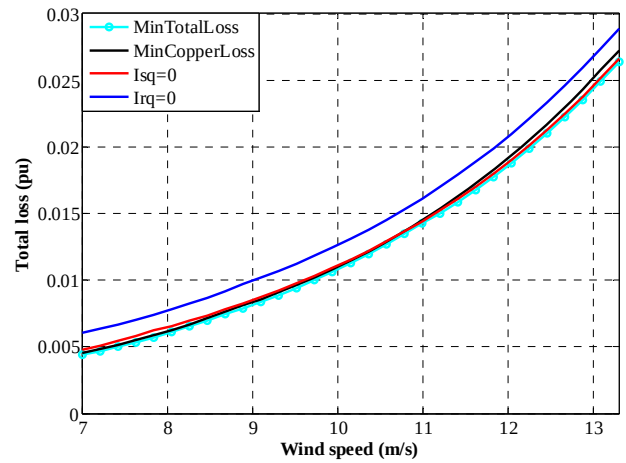

Fig.7. Total Loss with the change of wind speed when Q_{ref}=0

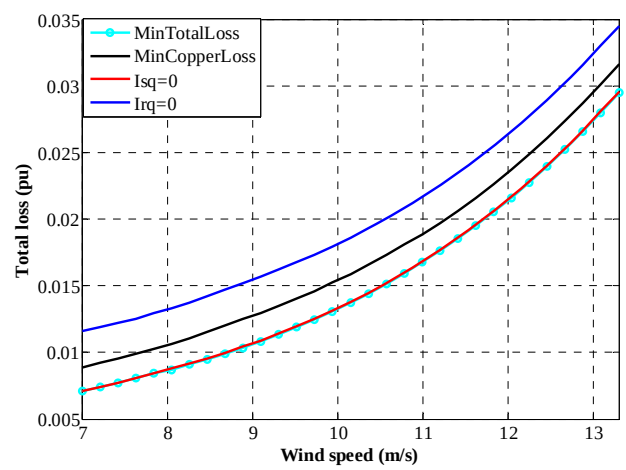

Fig.8. Total Loss with the change of wind speed when Q_{ref}=0.3

C. *Change of Q_{ref}*

Fig. 9 and Fig. 10 show the overall losses for v=7 and v=12 respectively at different reactive power reference, ranges from

-0.33 to 0.33, which is the reactive power operating range for wind power plants with a power output greater than 25 MW in Danish Grid Code [17].

It obviously can be seen in these two figures that MinTotalLoss control strategy is optimal under every Q_{ref}, while the other three only close to the optimal in certain regions. The lowest total loss reaches when Q_{ref} is about -0.15, which means when DFIG absorb a certain reactive power from the grid for magnetization, the total loss of the system will be the least.

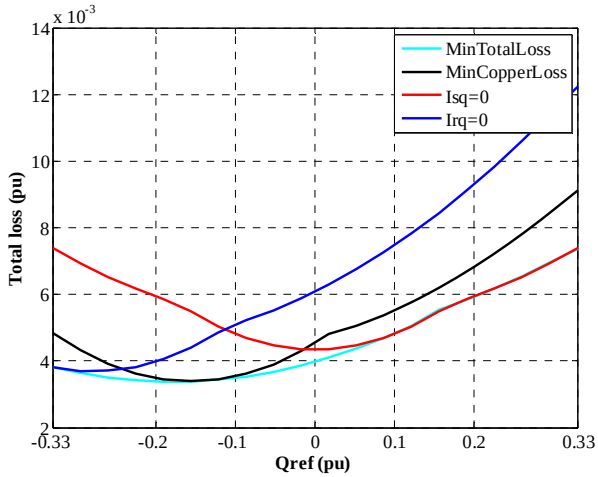

Fig.9. Total Loss with the change of Q_{ref} when v=7

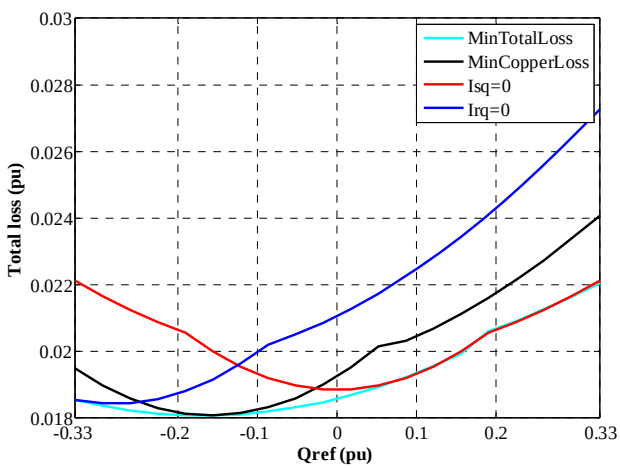

Fig.10. Total Loss with the change of Q_{ref} when v=12

D. Change of wind speed and Q_{ref}

Table II shows the relative loss decrease between proposed strategy and MinCopperLoss strategy with the change of wind speed and Q_{ref}.

As can be seen, the total loss of proposed strategy is always lower than the loss of MinCopperLoss strategy in every operating condition. At fixed Q_{ref} condition, as the wind speed increases, the relative loss decrease percentage goes down. At fixed wind speed condition, as the Q_{ref} increases, the relative loss decrease percentage firstly goes down when Q_{ref} is less than -0.1 pu, then the relative loss decrease percentage goes up continually. The largest relative loss decrease is 19.6% when Q_{ref} is 0.3 pu and wind speed is 7 m/s.

TABLE II. RELATIVE LOSS DECREASE PERCENTAGE BETWEEN PROPOSED STRATEGY AND MINCOPPERLOSS STRATEGY

v (m/s) / Q_{ref} (pu)	7	8	9	10	11	12	13
-0.3	10.4%	5.3%	2.9%	2.4%	3.0%	3.6%	3.5%
-0.2	3.5%	2.4%	1.3%	0.9%	0.7%	0.5%	0.4%
-0.1	1.6%	1.1%	0.6%	1.0%	0.7%	0.6%	0.4%
0	3.1%	2.3%	2.6%	2.0%	1.5%	3.0%	3.2%
0.1	8.6%	6.6%	6.7%	5.2%	4.1%	3.1%	2.4%
0.2	14.5%	11.7%	11.6%	9.3%	7.4%	5.8%	4.6%
0.3	19.6%	18.2%	16.8%	14.0%	11.1%	8.9%	7.2%

Fig. 11 shows the loss reduction of proposed strategy against MinCopperLoss strategy with the change of wind speed and Q_{ref}. The loss reduction is increasing with the increase of wind speed. The largest loss reduction is 0.003 pu when Q_{ref} is 0.33 pu and wind speed is 13.3 m/s.

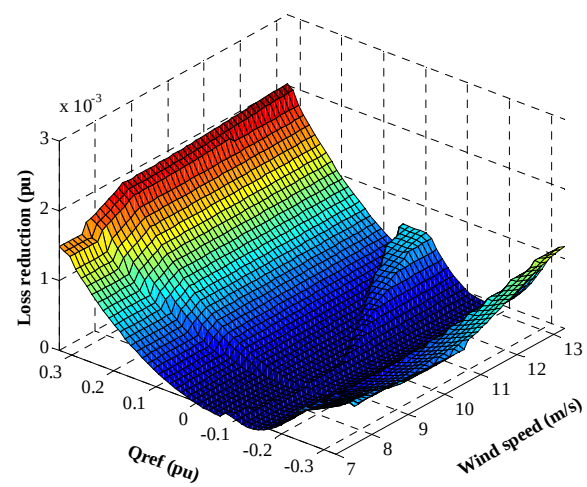

Fig. 11 Loss reduction between proposed strategy and MinCopperLoss strategy

V. CONCLUSION

This paper introduces an optimal reactive power control strategy to minimize the loss of the whole DFIG based wind system when providing reactive power to the grid. The modeling of the whole system is carried out in per unit system. On the basis of the presented model, currents and losses in every part are analyzed in detail. Different strategies for reactive power control are compared under different wind speed and reactive power reference. It can be concluded from the simulation results that the proposed strategy is effective in minimizing operating loss of wind generation systems. In the future, loss minimization operation of a wind farm may be developed by regulating reactive power between wind turbines.

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