An Optimal Reactive Power Control Scheme in DFIG based Wind Power Generation with Reduction in Losses

Sinchana.B.K, Student,
4th Sem, M.Tech (EPS),
Ghousia College of Engineering,
Ramanagaram, Karnatakata, India

Dr. Mohd .Z.A. Anasari,
Professor & HOD,
Ghousia College of Engineering,
Ramanagaram, Karnatakata, India

Abstract- **Power relations of doubly fed induction generator (DFIG) wind power generation system are analyzed. Based on this, a method is proposed to calculate the reactive power limit. The control strategy used at the wind generator level exploits a combination of pitch control and control of the static converters to adjust the rotor speed for the required operation points. This paper proposes an optimal reactive power dispatching strategy in order to minimize the total losses in a DFIG based wind farm, including the copper loss of the generators, the losses of converters, filters, transformers and the losses of cables. With the increasing penetration of wind turbines (WTs) grid utilities require extended reactive power supply capability not only during voltage dips but also in steady-state operation. A reactive power compensation strategy for the local user using DFIG wind farm is given. Simulation results are provided to verify the proposed theory.**

Index Terms- Doubly fed induction generator, Wind turbines, Grid side converter, rotor side converter

I. INTRODUCTION

Wind power has established itself as one of the most important renewable energy source over the past decades. With the priority status accorded to it in many countries, the share of wind power in relation to the overall installed capacity has increased significantly and this trend is in all likelihood set to continue. In some countries, the share of wind in relation to the overall installed capacity is already approaching the 50% mark. The increased prominence of wind in the generation mix inevitably leads to the question of its role in the provision of ancillary services, the most important of which being reactive power supply in support of grid voltage.

The Doubly fed induction generator (DFIG) has many advantages such as good controllability, reduced power converter rating, etc., so it has been widely used in wind turbines. DFIG wind generation systems can provide or absorb reactive power from both the stator and the Grid Side Converter (GSC). Nowadays, the DFIG wind generation system is mostly required to operate at unity power factor status, which is a waste of its reactive power regulation ability, especially at low wind speed conditions. Due to the increased integration of wind energy into the power system, the wind farm are required more by the grid operator, and the reactive power control has become a major issue faced by wind farm operators.

The most commonly used dispatch strategy is proportional dispatch, which spreads the required reactive power among all WTs proportional to their available reactive power. This method is easy to implement and is unlikely to exceed the reactive power limit of each WT. However, it does not consider active power loss in the WF. Another dispatch method proposed in considers the active power losses along the transmission cables and the transformers of WTs. However, this method does not consider the active power losses in the energy conversion system of WTs, which are responsible for a great part of the total loss in the WFs. Actually, the attempt to minimize active power losses along the transmission cables and the transformers may cause more losses in the energy conversion systems.

An optimal dispatch strategy proposed in considered the losses from wind energy conversion systems, transformers and transmission cables, and found an optimal dispatch of reactive power for loss minimization. However, the strategy only used a simple WT control strategy and did not considered the influence of reactive power dispatch inside the Doubly Fed Induction Generator (DFIG) based wind energy generation systems. Since the DFIG energy generation system can regulate reactive power between the stator and the grid side converter (GSC), the reactive power flow inside the system will influence the losses of the system. Therefore the reactive power control method of the DFIG energy generation system should be studied. The most common method is to provide the reactive power only from the stator side by the rotor side converter (RSC). This method can reach good efficiency operating near Unity power factor, but the copper losses of the generator will increase significantly when the power factor increases. The second method is to regulate reactive power using both the RSC and the GSC to minimize copper losses. This method does not consider the losses from the converters and filters. It can reach a lower loss in certain choices of reactive power reference, but will increase the total loss in other cases. The method of splits the reactive power burden over the RSC and the GSC to reach minimum losses for the generator and converters. The splitting ratio is iteratively calculated, forming a set of look-up tables. In the control process, the controller should look up the tables to decide the optimal reactive power currents.

In this paper, an optimal reactive power dispatch strategy is proposed for total loss minimization, which includes not only losses in the transmission cables and WT transformers, but also the losses inside wind energy generation system. The reactive power control of the WT uses optimal splitting strategy over the RSC and the GSC, which is implemented by solving an optimization problem that aims to minimize the total loss from the generator, the converters and the filter. Consequently, reactive power dispatch between the WTs is integrated with the optimal reactive power control strategy of the WTs. The proposed strategy is then compared with traditional dispatch strategies in different cases.

II. WIND FARM LOSS MODELS

The WTs and the cables are the main devices that cause losses in a WF. The power losses of a WT consist of friction losses in the mechanical part, core losses and copper losses in the DFIG, losses in the converters and the filter, and the losses in the transformer of the turbine. The friction losses and core losses can be considered constant under a certain operation point; therefore they are not considered in this paper. In the following paragraphs, the loss models of each component are derived.

1. *Loss Model of DFIG*

For a DFIG operating in a stator voltage oriented reference frame, the steady-state voltage equations are as follows. All variables in the equations are in per unit (pu) system.

$$\begin{bmatrix} V_s \\ 0 \\ V'_{rd} \\ V'_{rq} \end{bmatrix} = \begin{bmatrix} R_s & -X_s & 0 & -X_m \\ X_s & R_s & X_m & 0 \\ 0 & -sX_m & R'_r & -sX'_r \\ sX_m & 0 & sX'_r & R'_r \end{bmatrix} \begin{bmatrix} I_{sd} \\ I_{sq} \\ I'_{rd} \\ I'_{rq} \end{bmatrix} \quad (1)$$

Where stator inductance *Xs* equals *Xls* + *Xm*, rotor inductance X'_r equals X'_{lr}+ *Xm*, *Xls* is stator leakage inductance, *Xm* is mutual inductance, X'_{lr} is rotor leakage inductance, *s* is rotor slip. The subscripts are *s*, *r* and *g* for stator, rotor and grid converter circuits; *l* and *m* for leakage and mutual inductances; *d* and *q* for direct and quadrature axes. The superscript' is used for rotor value referred to the stator. At a fixed wind speed, the rotor d-axis current is constant, and can be calculated as

$$I'_{rd} = -\frac{X_s}{V_s X_m}\frac{\omega_s}{\omega_r} P_{mec} \quad (2)$$

$$I_{rd} = ụ\, I'_{rd} \quad (3)$$

where *Pmec* is the power extracted from the wind, *ωr* is the angular frequency of the voltages and currents of the rotor windings, *ωs* is the angular frequency of the voltages and currents of the stator windings, *u* is the turns ratio. The stator q-axis current can be calculated as:

$$Isq = Qs/Vs \quad (4)$$

where *Qs* is the reactive power of the stator. Deriving from (1), the rotor d-axis current and stator d-axis current can be calculated:

$$I'_{eq} = -\,AI'_{rd} - \frac{1}{BX_m} I_{sq} - \frac{V_s}{X_m} \quad (5)$$

$$I_{rq} = ụ\, I'_{rq} \quad (6)$$

$$I_{sd} = B\left[-X_m I'_{rd} + A\,X_m I'_{rq} + A\,V_s\right] \quad (7)$$

where $A = Rs/Xs$, $B = Xs/(X_s^2 + R_s^2)$
The copper losses in the DFIG can be calculated using:

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

2. *Loss Model of Converters and the Filter*

The losses in the converter, which consists of transistors and reverse diodes, can be divided into switching losses and conducting losses. The losses in a converter can be expressed as

$$P_{con}^{loss} = a_1 I_{rms} + b_1 I_{rms}^2 \quad (9)$$

where *Irms* is the rms value of the sinusoidal current at the converter ac terminal, and *al* and *bl* are the power module constants and can be expressed as

$$a_1 = \frac{6\sqrt{2}}{\pi}\left(V_{IGBT} + \frac{E_{ON} + E_{OFF}}{I_{C.nom}}\right) f_{sw} \frac{E_{rr}}{I_{C.nom}} f_{sw} \quad (10)$$

$$b_1 = 3r_{IGBT} \quad (11)$$

where *VIGBT* is the voltage across the collector and emitter of the IGBT, *EON* + *EOFF* is the total turn-on and turn-off losses of the IGBTs, *IC,nom* is the nominal collector current of the IGBT, fswis the switching frequency, *Err* is the turnoff (reverse recovery) loss of the diodes, *rIGBT* is the lead resistance of the IGBT.
The current flows through Rotor Side Converter (RSC) and GSC can be calculated as:

$$I_{rms}^{RSC} = \sqrt{\left(I_{rd}^2 + I_{rq}^2\right)}$$
$$I_{rms}^{GSC} = \sqrt{\left(I_{gd}^2 + I_{gq}^2\right)} \quad (12)$$

The grid side converter d-axis current *Igd* can be calculated:

$$I_{gd} = \left(I_{rd}V_{rd} + I_{rq}V_{rq}\right)/V_s \quad (13)$$

The grid side converter q-axis current *Igq* can be calculated:

$$I_{gq} = \frac{Q_g}{V_s} \quad (14)$$

$Q_g = Q_{WT} - Q_s$ (15)

where Qg is the reactive power provided by the GSC and QWT is the total reactive power from/to the WT. With the grid side converter currents, the loss in the grid side filter can be calculated using:

$$P_{filter}^{loss} = R_{filter}\left(I_{gd}^2 + I_{gq}^2\right) \quad (16)$$

So, the total loss from a WT P_{WT}^{loss} is :

$$P_{WT}^{loss} = P_{Cu} + P_{filter}^{loss} + P_{RSC}^{loss} + P_{GSC}^{loss} \quad (17)$$

3. Loss Model of Transformers

The active power loss in transformers P_{trans}^{loss} can be calculated as

$$P_{trans}^{loss} = P_o + \beta^2 P_k \quad (18)$$

where β is the load ratio, $P0$ is the no-load loss, and Pk is the load loss.

4. Loss Model of Cables

Consider the cable connecting the two buses i and j in Fig. 1, where y and I mean the admittance and current of each cable, and V means the voltage on each bus. The cable current, Iij , measured at bus i and j defined positive in the direction $i \rightarrow j$ is given by

$$Iij = Il + Ii0 = yij\,(Vi - Vj) + yi0Vi. \quad (19)$$

Similarly, the cable current Iji is given by

$$Iji = -Il + Ij0 = yij\,(Vj - Vi) + yj0Vj\,. \quad (20)$$

The power loss in cable ij is the algebraic sum of the complex powers Sij from bus i and j and Sji from bus j and i,

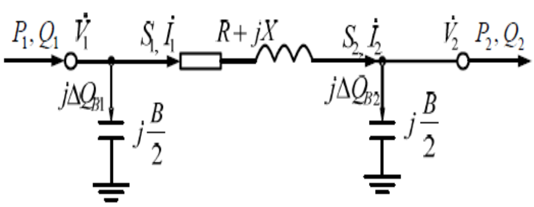

Fig. 1: The model circuit of a Cable

The losses of cables in a wind farm are calculated after power flow computation using Newton-Raphson method in this paper.

III. OPTIMIZATION PROBLEM FORMULATION

Proportional dispatching method is a traditional strategy for reactive power dispatching. It is compared with the proposed loss minimization dispatching strategy in this paper. The formulas of both strategies are presented in the section.

Strategy 1(S1): Traditional Proportional Dispatching Strategy

The strategy dispatches the required reactive power proportionally among all operative generators based on their available reactive power which can be expressed in

$$Q_{ref}^{WT\,i} = \frac{Q_{max}^{WT\,i}}{\sum_{i=1}^{n} Q_{max}^{WT\,i}}\, Q_{ref}^{Total} \quad (21)$$

where $Q_{ref}^{WT\,i}$ is the reactive power that wind turbine i must generate; $Q_{max}^{WT\,i}$ the maximum reactive power that wind turbine i can generate in one specific moment; n is the number of wind turbines and Q_{ref}^{Total} is the total reactive power required by the wind farm operator. The wind turbines are controlled by setting reactive power of the GSC equals to zero, so the reactive power is generated by the RSC. Therefore the maximum reactive power that can be provided is limited by the maximum current of the RSC. The total reactive power required by the wind farm operator Q_{ref}^{Total} of Strategy 1 must include the reactive power requirement of the Point of Common Coupling (PCC) Q_{ref}^{PCC} and the reactive power loss on the cables.

Strategy 2(S2): *Loss minimization dispatching strategy*

The proposed strategy aims to minimize the total losses of the whole system in the wind farm. The objective function is:

$$\min \sum_{i=1}^{n} P_{WT}^{loss} + \sum_{i=1}^{n} P_{cable}^{loss} \quad (22)$$

where P_{WT}^{loss} is the active power loss of wind turbine i , n is the total number of wind turbines,
P_{cable}^{loss} is the active power loss of cable k, m is the total number of cables.

The main constraint is the maximum available reactive power constraint, which is limited by the maximum current of the RSC, so it can be expressed as:

$$I_{rms}^{RSC} \leq I_{rms}^{Rated} \quad (23)$$

Where I_{rms}^{RSC} can be calculated using (12), I_{rms}^{Rated} is the rated collector current of RSC.
Another constraint is the voltage limit at each bus, as expressed as follows:

$$V_{min}^{K} \leq V^{k} \leq V_{max}^{k} \quad (24)$$

where k is the number of the bus. Also, the output reactive power should follow reactive power requirement at PCC. So the constraint can be expressed as:

$$\sum_{i=1}^{n} Q_{ref}^{WT} - \sum_{i=1}^{n} Q_{cable}^{loss} = Q_{ref}^{Pcc} \quad (25)$$

where Q_{ref}^{WT} is the reactive power set point of wind turbine i, Q_{cable}^{loss} is the reactive power loss on cable k , Q_{ref}^{Pcc} is the reactive power requirement of the PCC. So, Strategy 2 can be modelled as an optimization problem with the objective (22) and the constraints (23), (24), (25).

Strategy 3(S3): *Optimization Methods*

Sequential quadratic programming method is used in the paper to solve the optimization problem under constraints. This method makes a lot of iterations in order to find the optimization results under the constraints. At all iteration, an approximation is made of the Hessian matrix of the Lagrangian function using a Quasi-Newton updating method. This is then used to generate a quadratic programming subproblem whose solution is used to form a search direction for a line search procedure.

IV. SIMULATION MOODEL OF DFIG

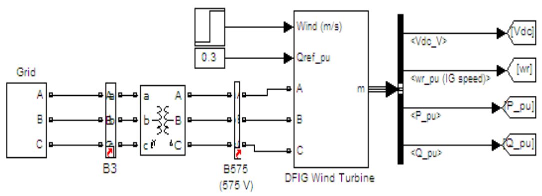

Fig 2: Simulation model of DFIG system connected to Grid

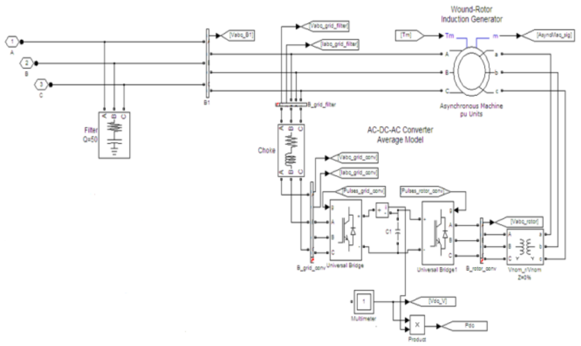

Fig 3: The DFIG system which is connected to back-to-back converters

A schematic diagram of a wind energy conversion system of DFIG is shown in Fig. 2 and Fig 3. The stator of the DFIG is directly connected to the grid through buses to supply the active and reactive power. In the rotor circuit, there are back-to-back converters (grid side converter, rotor side converter, filters) inserted between rotor and gird. The grid converter is used to regulate DC bus voltage speed. This simulation model is done by using MATLAB Simulink software.

The doubly fed induction generator provides reactive power to grid and initially reactive power reference is taken as zero. When more reactive power is required to the consumers or when the inductive loads are high, then the DFIG generates reactive power. Similarly, When the inductive loads are low, the DFIG absorbs reactive power the balances the system. Filter produces constant reactive power.

V. SIMULATION RESULTS

The simulation results of the doubly fed induction generator are shown in the below fig 4 and fig 5. With the theoretically basics of loss models and with the help of simulation results, the least power loss is produced by the machine than compare to rotor side converter, grid side converter and filters. Hence the machine with fed the reactive power to the gird for further utilization by consumers. This is shown is the graphs below.

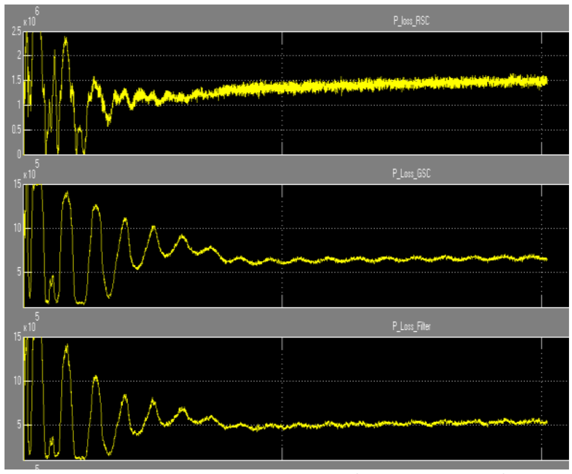

Fig 4: the power loss resuts of RSC, GSC and filter

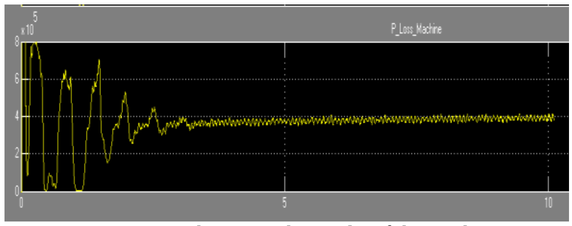

Fig 5: the power the results of the machine.

The figure 6 shows the real and reactive power feeding to the gird. The results are in per unit value. The graph shown below is generating reactive power with constant real power. At starting the waves are more oscillating because the machine needs few second to change its operating mode.

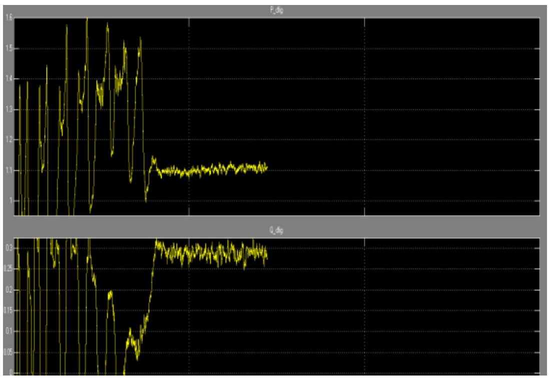

Fig 6: Real and reactive power results

CONCLUSION

This paper introduces an optimal reactive power dispatching strategy to minimize the total losses in a wind farm. On the basis of the loss model, an optimization problem is built considering the operating constraints. Proposed strategy is compared with traditional proportional dispatching strategy. It can be concluded from the simulation results that the proposed strategy is effective in minimizing operating loss of the whole system. The DFIG-based WT systems can adjust active and reactive power output independently. The implementation of this optimized strategy requires a modification on the WT control level, i.e., each WT should be able to follow two reactive power references by controlling the RSC and the GSC.

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