ENHANCEMENT OF REACTIVE POWER CAPABILITY OF DOUBLY FED INDUCTION GENERATOR

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ABSTRACT

With the growing integration into power grids, wind power plants are very important for power system. According to the grid codes wind power plants should have the ability to perform voltage control and reactive power compensation at the Point of Common Coupling (PCC). In general, the entire wind farm operates within a power factor range of 0.95 leading and lagging. This operation drastically under utilizes the reactive output of the machine. The results offered in this paper demonstrates enhancement of reactive power capability of Doubly Fed Induction Generator (DFIG). This additional reactive power supports to improve the post fault voltage and reduces the overall system losses and also reduces the cost of the generation. The utilization of extended reactive limits in voltage control may prevent system collapse.

Keywords: Capability Curve, Reactive Power, Wind Turbine

1. INTRODUCTION

As the world embraces for a sustainable energy future, renewable power generation integration into the power grid is increasing rapidly. Among these renewable energy technologies, wind energy is the most rapidly growing one which has been exploited and integrated in large scale. As of 31 December 2013 the installed capacity of wind power in India was 20149MW [01]. According to International energy agency, the global wind power capacity exceeds 318.1 GW by the end of 2013 [02].

With the increasing integration of wind power into power grids, many requirements for wind power plants have been proposed in the grid codes. According to these grid codes, four most common requirements for the wind farms are (1) Active Power and Frequency Control, (2) Reactive Power and Voltage Control, (3) Fault Ride Through (FRT) capability and (4) Frequency and voltage operation range [03].
The precise modelling of DFIG units is important for both static and dynamic analysis of power system performance. Computation of reactive power is essential to accurately assess the stability of a system and to prevent voltage violations. The effect of wind speed variation and wind farm output variability becomes a critical factor, when studying system performance with high penetration levels [04].

Paper [03] discussed about the generation of capability curve and limitations of machine. The amount of reactive power reserves at generating stations is a measure of the degree of voltage stability [05]. Participation factor of each generator in the management scheme are predetermined based on the voltage-var (V-Q) curve methodology. In the grid impact studies of wind power integration, voltage stability is the mostly concerned problem that will affect the operation and security of wind farms and power grid [06].

This paper extends an application of the capability curve to demonstrate economic and reliability improvements in both static and dynamic power system operation. This work validates that DFIG wind farm may operate at much lower power factor without incurring additional converter cost. When we implement the full reactive capability of the DFIG farms, the excess available reactive power impacts system cost and may justify investment in DFIG generation. This surplus reactive power improves the voltage stability when faults are occurring in the system. Here, in this paper we are comparing the operation of DFIG with capability curve and without capability curve (Restricted Power Factor). Some relevant references are [8-17]. This article organized in seven sections. In section 1, we introduce the current scenario of the DFIG. The reactive power characteristics of DFIG been discussed in section 2. Section 3 deals with modelling part of DFIG. Section 4 provides information about the capability curve of DFIG. Section 5 deals with Voltage control application. Impact of capability curve on generation and the contingency analysis of the system been discussed in section 6. Paper is concluded with help of results in section 7.

2. REACTIVE CHARACTERISTICS OF DFIG

Reactive power is essential for the stable operations of the Power system. It facilitates flow of active power from generation sources to load centers and maintains bus voltages within prescribed limits. Stable operation of power systems requires the availability of sufficient reactive generation. Both static and dynamic reactive power source plays an important role in voltage stability.

Traditional wind generation units consisting of Fix Speed Induction Generators (FSIG) does not allow for reactive support, but are reactive power consumers. To mitigate this reactive demand, FSIG wind parks are typically equipped with external sources of reactive power. Static sources like shunt capacitors are relatively inexpensive compared to dynamic resources such as SVCs [04].

The wind farm applying variable speed generator enclosed with power electronics controllers like DFIG has reactive power capability. The presence of power electronics control in DFIG makes them a fast acting dynamic reactive resource as compared to direct grid connected synchronous generators.

In 2005, FERC orders 661 and 661A [04], a key requirement for plant operation is that the power factor at the point of interconnection (POI) must remain between 0.95 leading and 0.95 lagging. The reason for this ruling is that reactive power capability for a wind plant is a significant additional cost compared to conventional units which possess inherent reactive capability.

As penetration level continues to increase, the impact from the loss in performance translates into higher operating costs. Utilization of the capability curve can lead to improved system performance. This will reduce the amount of committed conventional reactive reserve.
3. MODELLING OF DFIG

The proper modeling of the machine is necessary for understanding the reactive capability of DFIG wind farm. These machines can be represented using the simplified traditional induction machine T-model shown in Fig. 1.

![Fig.1 DFIG wind turbine static model](image)

In Fig. 1, the stator and rotor voltage ($V_s$ and $V_r$) and flux ($\Phi_s$, $\Phi_r$) equations can be derived from the machine currents ($I_s$ and $I_r$), in (1)-(4), ($R_s$), ($L_s$), and ($L_m$) are the respective stator and rotor inductance and leakage inductance with $\frac{R_m}{L_m}$ defining the magnetizing induction:

\[
\begin{align*}
V_s &= (R_s + j\omega L_s)I_s + j\omega L_m(I_s + l_r) \\
V_r &= (R_r + j\omega L_r)I_r + j\omega L_m(I_s + l_r) \\
\Phi_s &= I_s L_s - L_m I_r \\
\Phi_r &= I_r L_r - L_m I_s
\end{align*}
\]  

The grid frequency is given by $f$, the machine slip is $s$, and $\frac{R_m}{L_m}$. The RSC size is computed from the ratings of the rotor side Voltage source by combining the above basic Kirchhoff voltage law (KVL) loop equations with the stator and rotor flux equations. Eliminating the stator flux from these equations, expressions for the rotor current, voltage, and converter MVA rating can be computed.

\[
\begin{align*}
I_r &= \frac{\Phi_r - L_m I_s}{L_r} \\
V_r &= \Phi_r \left(\frac{R_r}{L_r} + j\omega L_s\right) - \left[ I_s \left(\frac{L_m}{L_r}\right) R_r \right] \\
S_r &= 3|V_r I_r^*|
\end{align*}
\]

The converter that excites the DFIG machine is constructed with a back-to-back power electronic converter (PEC) that is fed from a dc voltage source. Given the highest ac voltage connected to the bi-directional converter the dc link voltage can be obtained using the following relation.

\[
V_{dc-link} = \frac{3\pi}{\sqrt{3} f_m} V_{ac}
\]

is modulation index.
4. CAPABILITY CURVE OF DFIG

The power output of a generator is usually limited to value within the MVA rating by the capability of its prime mover. When real power and terminal voltage is fixed, its armature and field winding heating limits restricts the reactive power generation from the generator. The armature heating limit is a circle with radius \( R_1 = \frac{V_t I_a}{V_{t1}^{1/2}} \), centered on the origin \( C_1 \) and given by

\[
P^2 + Q^2 \leq \left( \frac{V_t I_a}{V_{t1}} \right)^2 \tag{9}
\]

The Field heating limit is also a circle, centered at \( C_2 \left( 0, \frac{V_t^2}{X_s} \right) \), radius \( R_2 = \frac{V_t E_a f}{X_s} \) given by fig.2

\[
P^2 + \left( Q + \frac{V_t}{X_s} \right)^2 \leq \left( \frac{V_t E_a f}{X_s} \right)^2 \tag{10}
\]

\( V_t \) is the voltage at the generator terminal bus, \( I_a \) is the steady state armature current, \( E_a f \) is the excitation voltage and \( X_s \) is the synchronous reactance. \( P \) and \( Q \) are real and reactive power generation from machine, respectively. The machine rating in MVA is the point of intersection of two circles. The corresponding real power generation is denoted by \( P_R \), when \( P < P_r \) the limit on the reactive power is imposed by the generator’s field heating limit (10) while when \( P > P_r \) the armature heating limit (9) imposes restricts the generators reactive power output. There is also an under-excitation limit \( Q_{min} \), to restrict the unit operation in under-excited mode due to localized heating in the end region of the armature.

In this paper we are comparing the DFIG with fix power factor (restricted power factor) and DFIG which operate with the actual capability of the machine (based on capability curve).
Thus, by utilizing the capability curve in network analysis, additional reactive power and hence improved power system performance may be attained over a regulated power factor. It is evident from the figure that at 100% plant output, the use of the capability curve does not give much additional reactive support compared to the 0.95 leading operation. In contrast, additional reactive consumption may be realized in lagging operation. Wind parks will very seldom operate continuously at 100% output, and therefore, in the periods of operation below 100%, there is significant additional reactive power available that could aid in improved system performance.

5. VOLTAGE CONTROL APPLICATION

There are two voltage control strategies that are implemented to demonstrate a comparison between DFIG wind farm responses on system performance. The first strategy utilizes the ±0.95 power factor regulation set forth by all the DFIGs which are used now days. Where reactive limit are defined by the farms real output.

$$|Q_{\text{max}}| = P_{\text{out}} \tan(\cos^{-1}(0.95))$$  \hspace{1cm} (11)

The second strategy utilizes the reactive capability that is detailed in developed capability curve in Fig.4

Control scheme for DFIG was developed for three different areas. Here we use a three different scheme for generate the reactive power. First was wind emulator, in this scheme we set the $V_{\text{reg}}$ and $V_{\text{ref}}$ as per requirements. In second we generate the own model for another development. And third power factor regulators, in this pfa control scheme we are generate the reactive power as per the power factor. The controller design was developed using power word simulator.
For this we were use the one machine and infinite bus system. After applying the control strategy for the gaining of the extra reactive power we got the reactive power more with the use of capability curve (cc) as compare with fix power factor. In this system we have to do the transient stability analysis and for that we open the lines and then power flow is possible. In this analysis due to fault in the system, system voltage goes down. But applying the capability curve analysis we have to improve the reactive capability of the DFIG.

![Fig.6 Transient stability analysis of DFIG for CC](image)

![Fig.7 Transient stability analysis of DFIG for fixed power factor (0.95pf)](image)

### 6. IMPACT OF CAPABILITY CURVE ON GENERATION DISPATCH

The optimal power flow analysis described is used to assess impact of extended reactive capability on system operating costs. The central goal of using technique is to compare the system operation with restricted power factor (0.95pf) versus the capability curve. The described system in Fig. 8 is studied with a load of 392MW and 87 MVAr. At base case the depicted three conventional generators are online to satisfy this demand the production costs of all generators are assumed to be the same.
Additionally, to analyze the impact of increased DFIG wind penetration, various penetration levels at 15, 20, 25, and 30% are simulated. In this study, wind penetration is defined as the total capacity of wind generation compared to the total load:

\[
\text{Penetration Level} = \frac{\sum \text{Installed wind capacity}}{\sum \text{Load}}
\]  

(12)

At each penetration level, the total wind generation is simulated at 2, 15, 50, and 100% output in order to consider various production conditions from cut-in to cut-out wind speeds. Since wind is not a constant resource, this study aims to capture the effect of wind variability on system operating costs.

At 2% park output, it is considered that the wind units have just cut-in and the real power output is at a minimum. When employing the capability curve, the reactive limits of the machines are the greatest at this output as compared to the other output levels studied. As wind speeds increase, the parks real output increases and consequently the reactive capability of the DFIG wind farm reduces. In this analysis we have to compare the reactive power generation for different level of penetration for restricted power factor and capability curve. Here we are use the wind farm capacity of 100MW.

**Table 1: Generation of reactive power with different penetration level**

<table>
<thead>
<tr>
<th>Penetration Level</th>
<th>$P_{\text{gen}}$ (MW)</th>
<th>$Q_{\text{gen}}$ through Restricted Power Factor (0.95pf) MVAr</th>
<th>$Q_{\text{gen}}$ through Capability Curve MVAr</th>
</tr>
</thead>
<tbody>
<tr>
<td>100%</td>
<td>100</td>
<td>32.87</td>
<td>37</td>
</tr>
<tr>
<td>80%</td>
<td>80</td>
<td>26.29</td>
<td>46.60</td>
</tr>
<tr>
<td>60%</td>
<td>60</td>
<td>19.72</td>
<td>57.40</td>
</tr>
<tr>
<td>40%</td>
<td>40</td>
<td>13.15</td>
<td>66.60</td>
</tr>
<tr>
<td>20%</td>
<td>20</td>
<td>6.57</td>
<td>74</td>
</tr>
<tr>
<td>2%</td>
<td>2</td>
<td>0.7</td>
<td>80</td>
</tr>
</tbody>
</table>

At each penetration level, the total system operating costs are computed for each output level. The system operating costs are comprised of both the cost of generation to meet the demand and generation cost to satisfy losses. When a unit is unable to meet its local reactive load, remote
generation compensates this requirement, but the system incurs additional line losses. Since the demand is fixed the reactive dispatch of the DFIG wind farm results in reduced system losses due to DFIG generation being able to meet the local reactive requirements. In this study, the cost of system losses is minute as compared to the cost of generation. Thus, even a substantial reduction in losses will not reflect a significant savings in total operating costs. Hence, the reduction in system losses is used as a metric of comparison between the reactive control strategies. With this comparison we have to reduce the cost of the generation and also reduce the losses of the system.

![Fig. 9 Total hourly cost per MW for CC and RPF](image)

6.1 CONTINGENCY ANALYSIS

To study the effect of contingencies on system performance, a preliminary analysis of 20% wind penetration scenario was performed by removing line $X_{13}$ and $X_{23}$ from service (fig 7). At the 20% penetration level, it was observed that at 2% and 15% plant output levels, with restricted power factor, the OPF does not converge. In contrast, operation with the capability curve provides additional reactive support at these low output levels which leads to OPF convergence. At 50% and 100% outputs, both control schemes have sufficient reactive capability for OPF convergence.

At 2% plant output level, the reactive power of the capability curve is at its maximum whereas the reactive power of the restricted power factor operation is at its minimum. At 2% real output, the additional reactive power gained by employing the capability curve over the regulated power factor control is 80 MVAr. Thus, the investment in shunt capacitance for secure system operation at a restricted power factor can be avoided by utilizing the capability curve.

DFIG wind farm implementing capability curve control may substantially reduce system losses, especially at low plant output levels. This control strategy not only facilitates reductions in operating costs but also avoids the necessity of additional reactive compensation required for secure operation of the power system. The combined savings in total system costs may help justify transmission investment for future wind installations.

For the analysis point of view we have to analysis of the bus 4 that generator bus (DFIG connected). In this we have to take a result of generated MW at that bus, generated MVAr and field voltage at that bus.
**Fig. 10** Bus-1 restricted power factor through generation of MW, MVAr, and Field voltage for penetration level 20%
Fig. 11 Bus-1 Improved result with CC for generation of MW, MVAr, Field voltage for penetration of 20%
7. CONCLUSION

The operation of DFIG wind farm implementing a capability curve paves the way for regulatory changes. In general guidelines for interconnecting wind farm are used a restricted power factor. When DFIG work with capability curve, fully utilizing the potential of DFIG wind farm may be obtain at no extra cost to the wind farm owner, which not only facilities reduced system losses but also improves the post fault voltage recovery following a disturbance. As the levels of wind penetration continues to increase the reactive power the certain point it should be in limit. At the 100% penetration the limit of reactive power in both CC and RPF are almost same.

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