Low Voltage Ride-Through Capability Enhancement of A DFIG Wind Turbine using A Dynamic Voltage Restorer with Adaptive Fuzzy PI Controller

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Abstract—This paper presents a low voltage ride-through (LVRT) capability enhancement strategy of a doubly-fed induction generator (DFIG) using a dynamic voltage restorer (DVR). The performance of the DVR depends on its controller. An Adaptive Fuzzy PI controller for the DVR is proposed to enhance the LVRT capability and fulfill the grid codes without disconnecting the turbine from the grid. Simulation results are presented for a 2 MW DFIG with a DVR system to validate the effectiveness of the proposed control technique.

Keywords—Wind energy, doubly fed induction generator, dynamic voltage restorer, fault ride-through, fuzzy control.

I. INTRODUCTION

The grid-connected DFIG must fulfill with the grid codes which include the LVRT guidelines, active/reactive power controls, frequency/voltage regulations, power quality, and system protection [1]. The disconnection of the wind turbine from the grid affects the power system stability and quality [2]. From grid codes, when a grid voltage dip occurs, the wind turbine must stay connected to the grid and continuously operates in the allowed duration as shown in Fig. 1.

To sort out this problem, crowbar circuit can be implemented in the DFIG rotor side [5]. However DFIG will absorb large amount of reactive power from grid which is not conducive for recovery during grid failure. Also it does not comply with the grid code requirements [6]. A static synchronous compensator (STATCOM) is presented in [7] to assist with the uninterrupted operation of a DFIG during LVRT. The DFIG becomes a conventional induction generator and starts to absorb reactive power during the voltage sag. The STATCOM is used to provide much reactive power which cannot be provided by the GSC.

The DVR can protect sensitive loads against grid disturbances such as voltage dip, sag, swell, and unbalance [8]. In [9]-[11], the DVR is presented to isolate the DFIG wind turbine from the grid during voltage dip as it is connected in series between the grid and the DFIG, whose voltage adds to the grid voltage in order to obtain the desired voltage [12]. However, it introduces a high cost solution. The type of controller of the DVR affects its performance. The PI controller offers simplicity and ease of implementation. However it is not adequate for systems with variable parameters and operating conditions due to its fixed gains [13]. Therefore, online tuning process should be performed. A lot of techniques have been presented to tune the PI gains [14]-[16].

In this paper, a DVR with adaptive fuzzy PI controller is proposed to improve LVRT capability of DFIG. The Simulation results show that DVR can enhance the DFIG wind turbine terminal voltage during grid voltage dips and enhance the LVRT capability.

II. DFIG CONTROL

The DFIG equivalent circuit in the synchronous rotating d-q reference frame is shown in Fig. 3. For stator flux-oriented control, the stator voltage, \( v_d \) and \( v_q \), and rotor voltage, \( v_{dr} \) and \( v_{qr} \), in the d-q reference frame:
\[
v_{dc} = R_d i_{dc} + \frac{d i_{dc}}{dt} - m_h q_v d
\]
\[
v_{qc} = R_c i_{qc} + \frac{d i_{qc}}{dt} - m_h h_{dq}
\]
\[
v_{dr} = R_r i_{dr} + \frac{d i_{dr}}{dt} - (m_e - m_r) h_{dr}
\]
\[
v_{qr} = R_r i_{qr} + \frac{d i_{qr}}{dt} + (m_e - m_r) h_{dr}
\]

where,
- \(R_c\), \(R_r\): Stator and rotor resistance.
- \(L_m\): Magnetizing inductance.
- \(L_{ds}\), \(L_{dr}\): Stator and rotor leakage inductance.
- \(i_{d*}, i_{q*}\): The \(d-q\) stator currents.
- \(i_{dr}, i_{qr}\): The \(d-q\) rotor currents.
- \(c_v\): The supply angular frequency.
- \(\omega_c\): The rotor angular frequency.
- \(h_{dq}\): The \(d-q\) stator flux linkage;
  \[
  h_{dq} = (L_{ds} + L_{m}) i_{ds} + L_{ad} i_{dr}
  \]
  \[
  h_{dq} = (L_{dr} + L_{m}) i_{qr} + L_{aq} i_{qr}
  \]
- \(h_{dqz}\): \(d-q\) rotor flux linkage;
  \[
  h_{dqz} = L_{m} i_{dr} + L_{m} i_{qr}
  \]
- \(h_{dq} = L_{ad} i_{dr} + (L_{dr} + L_{m}) i_{qr}
  \]

The vector control strategy decouples the active and reactive power. The stator active power, \(P_c\), and consequently the generator torque can be controlled by controlling the rotor \(q\)-axis current, \(i_{qr}\), as
\[
P_c = \frac{3}{2} L_c v_{qc} i_{qr}
\]

While the stator reactive power, \(Q_c\), can be controlled by controlling the \(d\)-axis current, \(i_d\), as
\[
Q_c = \frac{3}{2} L_c v_{qc} i_{qr}
\]

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Q_c = \frac{3}{2} L_c v_{qc} i_{qr}
\]

The DVR control system in the rotating \(d-q\) reference frame is shown in Fig. 4. The stator is connected directly to the grid and the rotor interfaced through the back-to-back GSC and RSC converters. The GSC is controlled to keep the dc-link voltage constant and to control the reactive power and consequence the power factor. The RSC controls independently the generator active and reactive power injected into the grid.

III. DYNAMIC VOLTAGE RESTORER(DVR)

The DVR is a three-phase voltage source converter connected in series with the power line via a coupling transformer to inject a compensation voltage. A low-pass \(LC\) filter is connected at the DVR output. The performance of the system with the DVR depends on the effectiveness of the used control technique [8].

The DVR can be used to enhance the LVRT of a DFIG in order to compensate the grid voltage dip. It is connected in series between the grid and the DFIG stator as shown in Fig. 5. During the grid voltage dip, the DVR injects voltages of controllable amplitude, phase angle and frequency in series and synchronized with the DFIG voltages via the series coupling transformer. This avoids disconnecting the wind turbine. The real power exchanged at the DVR output terminals is provided by the DVR input terminal by an external energy source or energy storage system[9].

The DVR control system is shown in Fig. 6. The measured three-phase grid voltage, \(v_g\), is transformed into the \(d-q\) synchronous reference frame voltage quantities \((v_{g\phi}\) and \(v_{g\theta}\)) rotating by the grid voltage angle \(\delta\) generated through a phase lock loop (PLL). The three-phase reference voltage is also transformed into the \(d-q\) reference frame, \(v_{dq\phi}\) and \(v_{dq\theta}\). The reference and actual grid voltages are compared and the error signal acts on the PI controller. The controller output controls the switching of the DVR inverter in order to inject the proper compensation voltage via the series coupling transformer.
During normal operation, the DVR operates in a standby mode and injects nothing. This reduces the DVR losses.

The rating of the DVR system depends on the depth of the grid voltage dip that should be compensated. The requirement of active power of the DVR is

\[ P_{DVR} = \frac{(V_1 - V_2)P_{load}}{V_1} \]  

where \( V_1 \) is the nominal voltage and \( V_2 \) is the faulty line voltage. When the DVR compensates a voltage dip, the DFIG active power is partially fed into the grid and the DVR system. The active power flowing into the DVR charges its DC-link energy storage element. The DVR should have the same rating of the wind turbine power at full voltage dip. Hence, the DVR is implemented to enhance the LVRT capability at partial voltage dip and assist during full voltage dip [18].

### A. DVR with PI Controller

The DVR with PI controller is shown in Fig. 6. The PI controller equation is

\[ u(t) = K_p e(t) + K_i \int e(t)dt \]  

where \( u(t) \) is the control output in the \( d-q \) reference to be fed to the PWM generator. \( K_p \) and \( K_i \) are the proportional and integral gains, respectively. \( e \) is the error between the reference voltage and the injected voltage by the DVR. The PI controller offers simplicity and ease of implementation. However, the fixed gains during control operation affect the system performance especially the non-linear systems with variable operating conditions and parameters in addition to the transient response [19],[20].

### B. Adaptive Fuzzy PI Controller

The fuzzy logic controller (FLC) is a non-linear controller which does not require an accurate mathematical model of the system. The design of the FLC depends on the human expertise [21],[22].

In this paper, an adaptive fuzzy PI controller is used in the DVR control system to overcome the problems of the PI controller. The online tuning of the PI gains is shown in Fig. 7. The gain is adapted at any operating condition as a function of the error and its derivative. The output gain is considered as a fuzzy variable. The rule base is constructed by collection of If-Then rules. The values of the constants \( K_p \) and \( K_i \) are changed according to the error signal, \( e \), and its derivative or rate of the error, \( oe \). The rule base is described for the parameter \( K_p \)in table 1 and for the parameter \( K_i \)in table 2 where the fuzzy variable are:

- NB = Negative Big,
- NM = Negative Medium,
- NS = Negative Small,
- Z = zero,
- PS = positive Small,
- PM = Positive Medium,
- PB = Positive Big

The rule base structure is implemented by repetitive simulation. The seven fuzzy sets are defined as shown in Fig.8. A complete fuzzy rule base consist of 49 rules can be obtained. For simplicity, assume that the fuzzy set of \( K_p \) and \( K_i \)are represented by the fuzzy set big ‘B’ and the fuzzy set small ‘S’ as shown in table 1 and table 2, respectively.
DFIG converter from increasing of the DC-link voltage as shown in Fig.13. The rise of the DC-link voltage is due to the release of the active power in the DC-link during the fault. The active power with and without the DVR are shown in Fig. 14a and Fig. 14b, respectively. The active power is almost constant when the DVR is utilized.

**CONCLUSION**

Enhancement of LVRT capability of DFIG wind turbines is important issue related to the utilization and connection of wind turbines to the electrical grid. During grid voltage dips, the system should comply with grid codes to ensure the normally operation of the wind turbine during the fault. The DVR is connected in series between the grid and the DFIG stator. It can be controlled to enhance the LVRT capability of a DFIG wind turbine. A DVR with Adaptive fuzzy PI controller has been used when grid voltage dips occur. A self-tuning technique is mandatory especially for system with variable parameters and operating conditions. A wind turbine system of 2 MW is modeled using MATLAB / Simulink software. The Simulation results have demonstrates the capability of using DVR with the proposed controller to enhance the LVRT.

**IV. SIMULATION RESULTS**

The performance of the DFIG wind turbine with and without the DVR under 10% balanced grid voltage dip from 1 to 1.5 s is investigated using a MATLAB/Simulink model. The parameters of the DFIG are listed in table 3. The results are shown in Fig.9 to Fig 14. The grid voltage dip is indicated in Fig. 9a. The DVR compensates the voltage dip resulting in DFIG stator voltage, $v_s$, of 1 pu during fault as shown in Fig. 9b. The amplitude of grid voltage, $v_g$, and the DFIG stator voltage, $v_s$, with DVR are shown in Fig. 10a and Fig 10b, respectively. The DFIG stator current, $i_s$, reaches 1.8 pu during fault as shown in Fig. 11a. This increase is almost mitigated when the DVR is activated as shown in FIG 11b. The DFIG rotor current, $i_r$, raises to 2 pu at the time instants of 1 s and 1.5 s as shown in Fig 12a. Due to the effect of the DVR, this current is limited to near 1 pu and increases only at 1.5 sto1.2puasshowninFig12b. The DVRprotects the...
Fig. 10 (a) Amplitude of grid voltage (b) DFIG stator voltage with DVR

Fig. 11 (a) DFIG stator current without DVR and (b) with DVR

Fig 12 (a) DFIG rotor current without DVR and (b) with DVR

Fig. 13 DC-link voltage (a) without DVR and (b) with DVR

Fig. 14 Active power (a) without DVR and (b) with DVR

TABLE 3: Parameters of DFIG

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated power, MW</td>
<td>2.0</td>
</tr>
<tr>
<td>Rated line voltage, V</td>
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<tr>
<td>Stator resistance, pu</td>
<td>0.0006</td>
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<tr>
<td>Rotor resistance, pu</td>
<td>0.005</td>
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<tr>
<td>Stator leakage inductance, pu</td>
<td>0.171</td>
</tr>
<tr>
<td>Rotor leakage inductance, pu</td>
<td>0.156</td>
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<tr>
<td>Mutual inductance, pu</td>
<td>209</td>
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<tr>
<td>Number of poles</td>
<td>6</td>
</tr>
<tr>
<td>Grid frequency, Hz</td>
<td>50</td>
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<tr>
<td>Inertia constant</td>
<td>5.04</td>
</tr>
<tr>
<td>Nominal DC voltage, V</td>
<td>1200</td>
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<tr>
<td>maximum DC voltage, V</td>
<td>1900</td>
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REFERENCE


