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# Hybrid low voltage ride through enhancement for transient stability capability in wind farms

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ABSTRACT

Protection of a doubly fed induction generator (DFIG) implemented for both wind farm and power systems is very important for transient stability. Crowbar circuits have been used for protection of DFIGs; however, a crowbar circuit is insufficient in terms of transient stability. Therefore, in this study, the passive Low voltage Ride Through (LVRT) capability method as well as the active LVRT capability method were developed for the purpose of transient analysis of the DFIG. The performances of DFIG models with and without active LVRT were compared. Modelling was carried out in a MATLAB/SIMULINK environment. Comparisons were made between behaviours of 3-phase fault and 2-phase fault systems and between rotor dynamic systems and those without a rotor dynamic. Parameters included DFIG output voltage, active power, speed, electrical torque variations and $d$–$q$ axis stator current variations. In addition, a 34.5 kV bus voltage was examined. It was found that the system became stable in a short time when the active LVRT was incorporated into the reduced order DFIG model.



## Introduction

Due to economic, technical and environmental concerns, wind power currently plays an important role in the generation of the world's energy. It is hoped that wind energy systems will be sufficient to sustain power systems in the coming decades [1]. Doubly fed induction generators (DFIGs) are used for both the generation and the low voltage ride through (LVRT) capability of wind turbines. Wind farms connected to power systems must remain connected in the case of a voltage dip occurring on the grid side; otherwise, wind power can contribute to the voltage dip as a consequent problem [2–4]. Currently, LVRT needs to be considered for the connection of wind farms to power systems. In DFIGs, the proposed LVRT method consists of a dynamic control strategy applied to both the rotor-side and the grid-side converters. Furthermore, a DC-link voltage control has been applied for transient stability in wind farms [5–7]. A dynamic voltage restorer is used for improving the transient stability state in DFIGs. With this dynamic voltage restorer, not only the rotor current controller but also the stator current controller has been provided [8–10]. The LVRT method, as analysed in DFIGs, was developed as a negative-positive sequence during transient stability. As well as LVRT capability for the DFIG, the code requirements and the control of the grid rotor side converters have been proposed [11,12]. Yang et al. [13] presented an advanced control to the rotor and grid side converters of a DFIG-based wind turbine for LVRT capability. This control method was improved to regulate the angular speed and point of common coupling energy depending on the grid code requirement. Liang et al. [14] proposed a wind farm current control scheme for the converters to enhance the LVRT capability of a DFIG. This controller allowed the regulation of rotor current and crowbar unit activation-deactivation oscillation and reactive power control was ensured for the grid code requirements of the DFIG. Moreover, this controller aimed to decrease both oscillation and crowbar activation time variations [15,16]. The DFIG was used with a finite element method-based model by Seman et al. [17]. A model of the DFIG was coupled with a model of the crowbar-protected electrical torque, grid side and rotor side converters, transformers and the grid. In another study, power characteristics of the DFIG were obtained in order to derive the capability of the different system conditions of the proposed method. The optimal crowbar resistance values were established in order to achieve the maximum power capability from the DFIG during transient stability [18,19]. Moreover, a control strategy was developed by Abdel-Baqi and Nasiri [20] for the voltage stabilization mode for LVRT before and after the fault in the DFIG. To this end, a series compensator was connected to the stator side line In order to improve LVRT capability requirements, other researchers have used a new reference strategy for steady-state and transient operation modes in the

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DFIG [21]. Besides all control strategies of DFIG for LVRT capability, Flexible AC transmission System (FACTS) devices are used. Especially, Static Synchronous Compensator (STATCOM) and Static Var Compensator (SVC) are used widely. Not only STATCOM but also SVC has provided reactive power control and voltage control during fault [22–25]. In terms of fast time response of the system, Fuzzy Logic Controller (FLC) is used in wind farm based DFIG. FLC is applied in DC link control as well as rotor side converter and grid side converter of DFIG [26,27].

In this present study, for LVRT capability of both stator and rotor circuits in the DFIG, dynamic modelling with a base voltage source was developed. Furthermore, for transient stability conditions of the DFIG, the reference current controller was enhanced. A comparison was made with and without the reference current control developed through a stator-based voltage source during 3-phase and 2-phase faults. The results of the transient state in 34.5 kV bus voltage, DFIG output voltage, angular speed, electrical torque and $d$–$q$ axis stator current variation parameters were evaluated. It was found that the hybrid LVRT-capability reference circuit control developed in this study yielded efficient results.

## Doubly fed induction generators (DFIG)

The DFIG wind turbine consists of a crowbar unit, grid side converter and rotor side converter. The DFIG circuit model is shown in Fig. 1.

The function of the grid side converter is to balance the DC-link voltage and provide reactive power compensation, while the rotor side converter controls the real and reactive power of the DFIG. Voltage limits and over-current are regulated by a crowbar unit [28]. The voltage obtained by developing stator and rotor $d$–$q$ axis equivalence circuits in a synchronous frame is seen as the DC component. Voltage, current and flux computations of the induction generator are facilitated in this way [29]. Certain assumptions are used in the mathematical enhancement of induction generators. These are as follows:

- The stator current is assumed positive when flowing towards the induction generator.
- The equations are derived in a synchronous reference frame.
- The $q$-axis is assumed to be 90° ahead of the $d$-axis with respect to the direction of rotation.
- The $q$ component of the stator voltage is selected as the real part of the busbar voltage, and the d component as the imaginary part.

Induction generator equations are determined according to an arbitrary reference frame. However, p.u. values are used in facilitating the computations of these induction generator equations in power systems. Voltage and linkage flux computations based on p.u. values in the DFIG are shown in Eqs. (1)–(4):

$$\begin{bmatrix} v_{ds} \\ v_{qs} \end{bmatrix} = \begin{bmatrix} R_s & 0 \\ 0 & R_s \end{bmatrix}\begin{bmatrix} i_{ds} \\ i_{qs} \end{bmatrix} + w_s\begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}\begin{bmatrix} \lambda_{ds} \\ \lambda_{qs} \end{bmatrix} + \begin{bmatrix} \dot{\lambda}_{ds} \\ \dot{\lambda}_{qs} \end{bmatrix} \tag{1}$$

$$\begin{bmatrix} v_{dr} \\ v_{qr} \end{bmatrix} = \begin{bmatrix} R_r & 0 \\ 0 & R_r \end{bmatrix}\begin{bmatrix} i_{dr} \\ i_{qr} \end{bmatrix} + sw_s\begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}\begin{bmatrix} \lambda_{dr} \\ \lambda_{qr} \end{bmatrix} + \begin{bmatrix} \dot{\lambda}_{dr} \\ \dot{\lambda}_{qr} \end{bmatrix} \tag{2}$$

$$\begin{bmatrix} \lambda_{ds} \\ \lambda_{qs} \end{bmatrix} = \begin{bmatrix} L_s + L_m & 0 \\ 0 & L_s + L_m \end{bmatrix}\begin{bmatrix} i_{ds} \\ i_{qs} \end{bmatrix} + \begin{bmatrix} L_m & 0 \\ 0 & L_m \end{bmatrix}\begin{bmatrix} i_{dr} \\ i_{qr} \end{bmatrix} \tag{3}$$

$$\begin{bmatrix} \lambda_{dr} \\ \lambda_{qr} \end{bmatrix} = \begin{bmatrix} L_m & 0 \\ 0 & L_m \end{bmatrix}\begin{bmatrix} i_{ds} \\ i_{qs} \end{bmatrix} + \begin{bmatrix} L_r + L_m & 0 \\ 0 & L_r + L_m \end{bmatrix}\begin{bmatrix} i_{dr} \\ i_{qr} \end{bmatrix} \tag{4}$$

where $v_{ds}$, $v_{qs}$, $v_{dr}$, $v_{qr}$: $d$- and $q$-axes are the stator and rotor voltages; $\lambda_{ds}$, $\lambda_{qs}$, $\lambda_{dr}$, $\lambda_{qr}$: $d$- and $q$-axes are the stator and rotor magnetizing fluxes; $e_d$, $e_q$: $d$- and $q$-axes are the stator source voltages; and $w_s$: synchronous speed, $s$: slip, $r_s$, $r_r$ are the stator and rotor resistances [30,31].

In creating the rotor voltage source in the full order model (FOM), Eq. (5) is obtained primarily by incorporating Eq. (4) into Eq. (2):

$$\begin{aligned} \begin{bmatrix} v_{dr} \\ v_{qr} \end{bmatrix} = &\begin{bmatrix} R_r & 0 \\ 0 & R_r \end{bmatrix}\begin{bmatrix} i_{dr} \\ i_{qr} \end{bmatrix} + \begin{bmatrix} 0 & -sw_s \\ sw_s & 0 \end{bmatrix}\left\{\begin{bmatrix} L_r+L_m & 0 \\ 0 & L_r+L_m \end{bmatrix}\begin{bmatrix} i_{dr} \\ i_{qr} \end{bmatrix}\right. \\ &\left. + \begin{bmatrix} L_m & 0 \\ 0 & L_m \end{bmatrix}\begin{bmatrix} i_{ds} \\ i_{qs} \end{bmatrix}\right\} + \begin{bmatrix} L_r+L_m & 0 \\ 0 & L_r+L_m \end{bmatrix}\begin{bmatrix} \dot{i}_{dr} \\ \dot{i}_{qr} \end{bmatrix} \\ &+ \begin{bmatrix} L_m & 0 \\ 0 & L_m \end{bmatrix}\begin{bmatrix} \dot{i}_{ds} \\ \dot{i}_{qs} \end{bmatrix} \end{aligned} \tag{5}$$

Eq. (6) is obtained by isolating the stator $d$–$q$ current in Eq. (3):

$$\begin{bmatrix} i_{ds} \\ i_{qs} \end{bmatrix} = \begin{bmatrix} \frac{1}{L_s+L_m} & 0 \\ 0 & \frac{1}{L_s+L_m} \end{bmatrix}\begin{bmatrix} \lambda_{ds} \\ \lambda_{qs} \end{bmatrix} - \begin{bmatrix} \frac{L_m}{L_s+L_m} & 0 \\ 0 & \frac{L_m}{L_s+L_m} \end{bmatrix}\begin{bmatrix} i_{dr} \\ i_{qr} \end{bmatrix} \tag{6}$$

By taking the derivation of the stator $d$–$q$ axes current, Eq. (7) is obtained

$$\begin{bmatrix} \dot{i}_{ds} \\ \dot{i}_{qs} \end{bmatrix} = \begin{bmatrix} \frac{L_m}{L_m+L_s} & 0 \\ 0 & \frac{L_m}{L_m+L_s} \end{bmatrix}\begin{bmatrix} \dot{i}_{dr} \\ \dot{i}_{qr} \end{bmatrix} \tag{7}$$

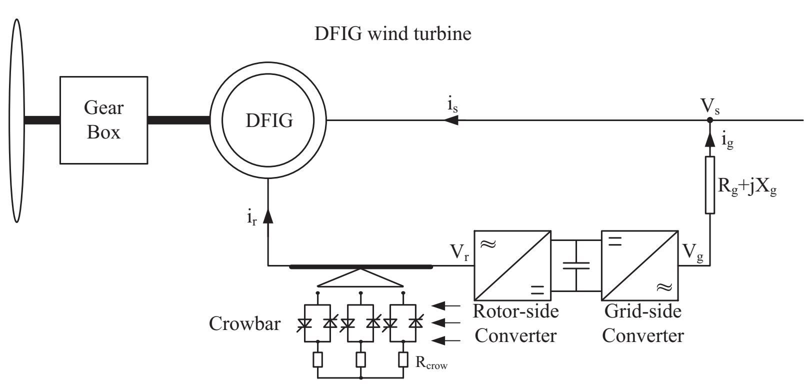


**Fig. 1.** DFIG circuit model.