Modeling and Linearization of DFIG Based Wind Turbine

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Abstract

Usage level of wind units in power systems is increasing rapidly. There are different kinds of wind turbine generator. The Doubly-Fed Induction Generator (DFIG), is one of the most widely used electrical machines in the megawatt-class wind turbines. In a DFIG-based wind turbine, the stator is connected to grid directly while the rotor is connected a back-to-back converter via slip rings. Current sensor fault diagnosis for renewable power of wind turbine based on DFIG has gained serious importance. In this work, mathematical modeling of DFIG is presented. Nonlinear state equations are linearized with Takagi-Sugeno (T-S) Local Models for current sensor fault diagnosis. Modelling error between linear and nonlinear model is minimized by heuristic approach on membership functions. A bank of observer-based residual generator system for fault diagnosis is created, so additive and gain faults of stator current sensors can be detected and isolated.

Keywords: Doubly Fed Induction Generator, Modeling, Linearization, Fault Diagnosis

Introduction

In recent years, considerable concernment is given to renewable energy sources and number of power generation plants which depends on renewable energy source is increasing rapidly. Wind energy is a one of the renewable energy sources obtained with wind turbines which is the highest growth in modern power systems, has minimum negative effect on environment. This is why reliability of wind turbines becomes an important topic in research and industry.

Usage level of wind units in power systems is increasing rapidly. There are different kinds of wind turbine generator. The Doubly-Fed Induction Generator (DFIG), is one of the most widely used electrical machines in the megawatt-class wind turbines (Hansen et al.,2007). In a DFIG-based wind turbine, the stator is connected to grid directly while the rotor is connected a back-to-back converter via slip rings, so both stator and rotor are connected to the grid (Leonhard,2001). The preferred configuration for wind turbine generator is DFIG which can be seen in Figure.1.

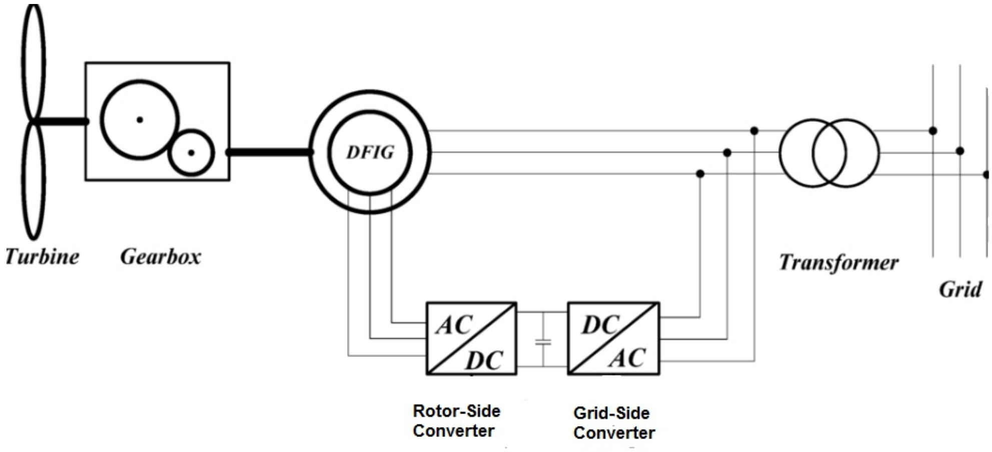

Figure 1: Schematic of DFIG Wind Power Generation System

Many wind farms use doubly-fed induction generator (DFIG)-based on wind turbine to allow variable rotor speed. Because of its various advantages over the other generators, DFIG has gained more interest (Shilpi, 2013). These advantages can be listed as follows: first, as the rotor circuit is controlled by a power electronics converter, the induction generator is able to import and export reactive power, in situations such as low voltage allows the machine to support the grid. Second, when the wind turbine speed varies, in order to remain synchronized with the grid frequency, rotor currents and voltages of DFIG can be controlled. Third, the cost of the inverter is cheaper than other generator and efficiency of DFIG is more competitive with respect to its counterparts.

The safety and reliability of DFIG is a critical issue for recent literature, fault diagnosis of these machines very essential to improve power quality, reduce the down time, and minimize the maintenance cost. There are several types of fault such as current sensor faults, voltage sensor faults and speed sensor faults which may be occurred in DFIG (Chen et al.,2010). When these faults occur in a sensor, it reduces the overall system performance, may cause uncertainty and can cause serious damage to the generator (Najafabadi et al.,2011)

In a DFIG, varied fault diagnosis approaches were proposed in recent literature. The researchers have presented: a novel scheme for current sensor faults diagnosis in the stator of a DFIG described by a T-S fuzzy model in

(Samir et al.,2016), the problem of fault detection and isolation (FDI) design for nonlinear Takagi-Sugeno (T-S) models with measurable premise variables that is easily formulated in terms of Linear Matrix Inequalities (LMI) problem, based on Lyapunov theory in (Ouyessaad et al.,2013), a Fuzzy Dedicated Observers (FDOS) method using a Nonlinear Unknown Input Fuzzy Observer (UIFO) with a Fuzzy Scheduler in (Kamal et al.,2012), an online monitoring system based on mathematical logic algorithms for fast fault diagnosis in power generators in (Ramirez-Nino et al.,2009), a new simple algorithm was developed based on an improved current observer to detect both soft and hard faults in current sensors for a DFIG in (H.Li et al.,2014), classifying the condition of small fault like sensor offset or drift in a DFIG accounting for parameter variations in (Manuel Gálvez-Carrillo et al.,2010), using the methods based on artificial neural networks (ANNs), process the massive data and automatically provide accurate diagnosis result in (Feng Jia et al.,2015), the main purpose was to analysis the current sensors faults in the stator, fault diagnosis for a Self-Excited Induction Generator (SEIG) based on in (Attoui et al.,2014), to isolate the detected faults in the stator and the rotor, an algorithm for fault identification has been designed in (Rothenhagen et al.,2009). A considerable research also has been done on the modelling, control and diagnosis of wind turbines with DFIG (Chitti et al.,2010, Odgaard et al.,2009).

The rest of paper is organized as follows: the modeling of DFIG-based wind turbine is presented, nonlinear model and proposed linearized model are introduced, an Ackermann based observer for residue generation is proposed. The proposed linearized model and bank of observer system results are shown in simulation section. Finally, conclusion section concludes the proposed work.

Modeling of DFIG-based Wind Turbine

Wind Turbine Basics

The maximum power extracted from wind turbine is limited to 59.3% of the available wind power which called as Betz Limit (Betz A,1966). The power extracted by wind turbine P_a is expressed as

$$P_a = C_p(\lambda,\beta)P_w = \frac{1}{2}\rho\pi R^2 C_p(\lambda,\beta)v^3 \quad (1)$$

where $C_p(\lambda,\beta)$ is aerodynamic efficiency, λ and β are tip-speed-ration and blade pitch angle respectively, ρ denotes air density, R is the rotor radius and v represents wind speed (before interacting with turbine).

The tip-speed-ratio is defined

$$\lambda = \frac{\Omega R}{v} \quad (2)$$

where Ω and v denotes rotor angular speed and incoming wind speed respectively.

The DFIG Model

The electrical model of DFIG can be considered as wound rotor induction machine in synchronous reference frame. The modelling equation can be expressed as;

$$V_{ds} = R_s i_{ds} + \frac{d_{\emptyset_{ds}}}{d_t} - w_s \emptyset_{qs} \quad (3)$$

$$V_{qs} = R_s i_{qs} + \frac{d_{\emptyset_{qs}}}{d_t} + w_s \emptyset_{ds} \quad (4)$$

$$V_{dr} = R_r i_{dr} + \frac{d_{\emptyset_{dr}}}{d_t} - w_r \emptyset_{qr} \quad (5)$$

$$V_{qr} = R_r i_{qr} + \frac{d_{\emptyset_{qr}}}{d_t} + w_r \emptyset_{dr} \quad (6)$$

with

$$\emptyset_{ds} = X_s i_{ds} + X_m i_{dr} \quad (7)$$

$$\emptyset_{qs} = X_s i_{qs} + X_m i_{qr} \quad (8)$$

$$\emptyset_{dr} = X_r i_{dr} + X_m i_{ds} \quad (9)$$

$$\emptyset_{qr} = X_r i_{qr} + X_m i_{qs} \quad (10)$$

where V stands for voltages (V), *i* stands for currents (A), R stands for resistors (Ω), ∅ stands for flux linkages (V.s). Indices *d* and *q* indicate direct and quadrature axis components, respectively, while *s* and *r* denotes stator and rotor quantities respectively, w_s and w_r are the stator and rotor speed of the generator, Xr, Xs and Xm are the rotor inductance, the stator inductance and the magnetization inductance respectively (M.G.Simoesand et al.,2007)

The relationship between stator and rotor angular velocities and the electromagnetic torque (T_{em}) for P number of poles machine, are expressed by;

$$w_r = w_s - \text{P}\Omega_m \quad (11)$$

$$T_{em} = \frac{PX_m}{L_s} (\emptyset_{qs} i_{dr} - \emptyset_{ds} i_{qr}) \quad (12)$$

Linearization of a nonlinear DFIG Model

Since the back EMF (electromotive force) depends on the rotational speed of the generator, induction generator has a nonlinear dynamic model. This leads to a state matrix A that depends on rotational speed of generator (A is the nonlinear matrix).

Nonlinear state-space model of DFIG

The nonlinear state-space model of the DFIG obtained from both the stator and rotor voltage equations according to following assumptions:

Inductance saturation, skin effect, iron losses and bearing friction are neglected.

$$\frac{dx(t)}{dt} = A\big(w_m(t)\big) + Bu(t) \tag{13}$$

$$y(t) = Cx(t) \tag{14}$$

where;

$$x(t) = [i_{ds}(t)\ \ i_{qs}(t)\ \ i_{dr}(t)\ \ i_{qr}(t)]^T \tag{15}$$

$$u(t) = [v_{ds}(t)\ \ v_{qs}(t)\ \ v_{dr}(t)\ \ v_{qr}(t)]^T \tag{16}$$

$$y(t) = [y_1(t)\ \ y_2(t)]^T = [i_{ds}(t)\ \ i_{qs}(t)]^T \tag{17}$$

where x(t) is the state vector with stator currents and rotor currents components, u(t) is the input vector which consists of the stator and rotor voltage components, y(t) is the output vector.

$$A(w_m) = \frac{1}{\sigma}\begin{bmatrix} -(RsXrwb) & -(X_m\delta + XrXsws) & RrXmwb & -(Xr\delta + XmXrws) \\ X_m\delta + XrXsws & -(RsXrwb) & XmXrws - X_r\delta & RrXmwb \\ RsXmwb & X_s\delta + XmXsws & -(RrXswb) & \frac{XrXs\delta}{Xm} + Xm^2ws \\ X_s\delta - XmXsws & RsXmwb & \frac{XrXs\delta}{Xm} - Xm^2ws & -(RrXswb) \end{bmatrix}$$

(18)

$$B = \frac{wb}{\sigma}\begin{bmatrix} Xr & 0 & -Xm & 0 \\ 0 & Xr & 0 & -Xm \\ -Xm & 0 & Xs & 0 \\ 0 & -Xm & 0 & Xs \end{bmatrix}$$

(19)

where $\boldsymbol{\sigma} = -Xm^2 + XrXs$, $\boldsymbol{\delta} = Xm\,(wm - ws)$, w_b is the base angular frequency, R_s and R_r are the stator and rotor resistance respectively.

The given state-space model of DFIG is nonlinear and time-variant because of generator speed. So, we need to linearization of nonlinear model of DFIG to approximate its behavior.

Proposed model for linearization of DFIG

Linear models are easier to understand and are necessary for most control system design methods. Induction generator nonlinear model can be linearized using various approaches such as Kalman Filter and Takagi-Sugeno (T-S) fuzzy model (Eric A et al.,2000, Johansen et al.,2000).

With nonlinear membership functions, the T-S fuzzy model approximates nonlinear model and gives satisfactory results. In figure 3 simulink implementation of DFIG modeled with T-S fuzzy can be seen. In this section, we focus on a region (region 2) which has variable wind speed between minimum and maximum wind speed thus generated power is variable, this is because when the wind speed is lower than required wind speed (region 1), there is no generated power in this region, likewise when the wind speed is higher than required wind speed (region 3), it is max wind speed and variable power isn't generated, see in figure 2. Using membership functions, nonlinear model of DFIG is linearized in region 2 (Varzaneh et al.,2014).

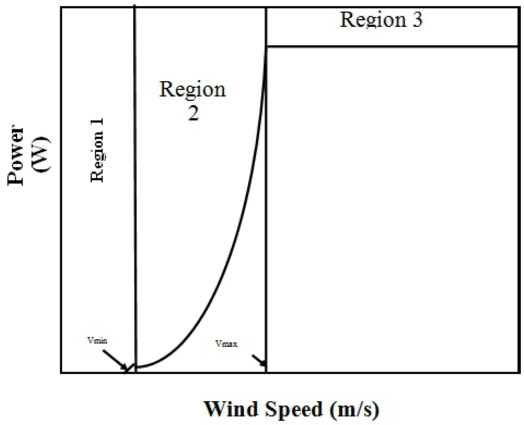

Figure 2: Operation Regions of DFIG

Simulation Result

Nonlinear modeling, linearization and observer design are performed Matlab Simulink software. The states of output equations (i_{ds}, i_{qs}) are obtained for each simulation. Firstly, nonlinear system is constructed with T-S local linear models, comparison of stator current in three phase, i_{abc}, is shown in Figure 5 where solid line shows nonlinear model output while dotted line shows T-S local linear model output. According to result, it can be concluded that output of local linear model was completely identical with output of nonlinear model.

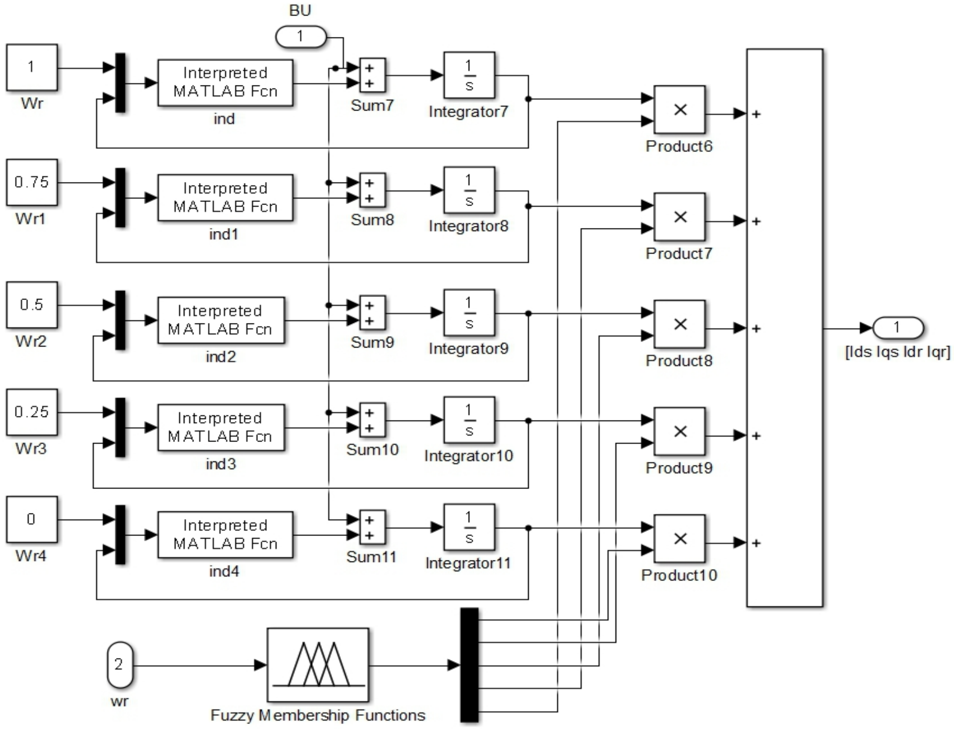

Figure 3: Simulink implementation of DFIG modeled with T-S Linearization

Ackermann Observer Design

The dynamics of the state estimation error

$$\tilde{x}(k) = x(k) - \hat{x}(k) \quad (20)$$

$$\tilde{x}(k+1) = Ax(k) + Bu(k) - A\hat{x}(k) - Bu(k) - K[y(k) - C\hat{x}(k)]$$
$$= (A - KC)\tilde{x}(k) \quad (21)$$

and then

$$\tilde{x}(k) = (A - KC)^k(x(0) - \hat{x}(0)) \quad (22)$$

The dynamics of the state estimation error:

$$\frac{d\tilde{x}(t)}{dt} = (A - KC)\tilde{x}(t) \quad (23)$$

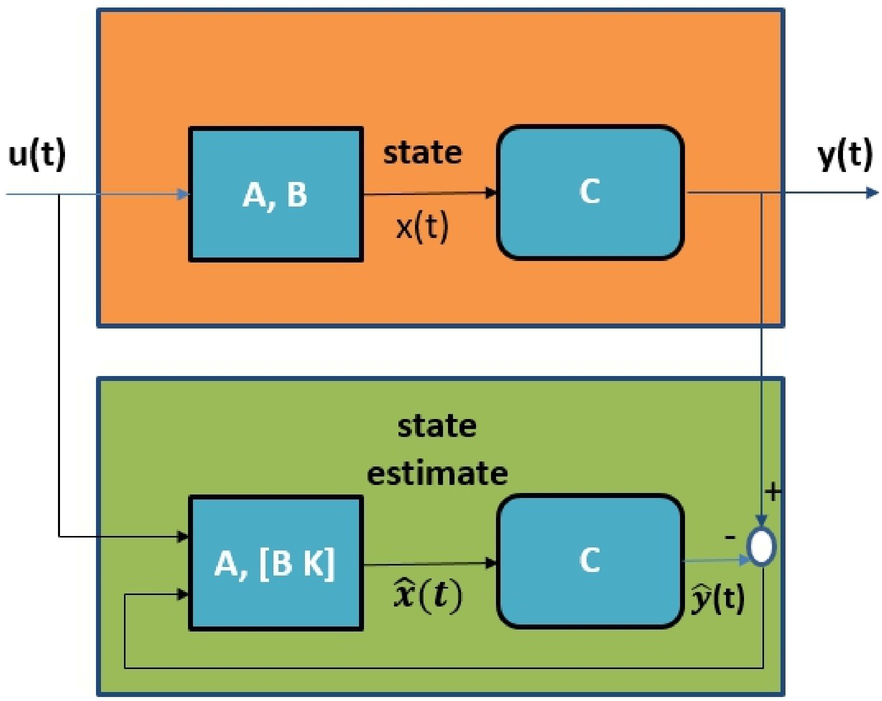

Figure 4: Block scheme of observer

In order to detect abnormalities in linear model with in any fault situation, states of system can be observed via an observer block. The difference between observer and local model outputs is called as residual. In fault free case, the residue approaches to zero as shown in Figure 6.

Conclusion

In this paper, the mathematical modelling of doubly-fed induction generator based wind turbine has been presented. Nonlinear state equations are linearized with Takagi-Sugeno (T-S) Local Model for current sensor in the stator of a DFIG based wind turbine. Using a heuristic approach on membership functions, error between nonlinear and linear model is minimized. A bank of observer based residual generator system is created for fault diagnosis, therefore additive and gain faults in the stator current sensor of DFIG can be detected and isolated for feature works.

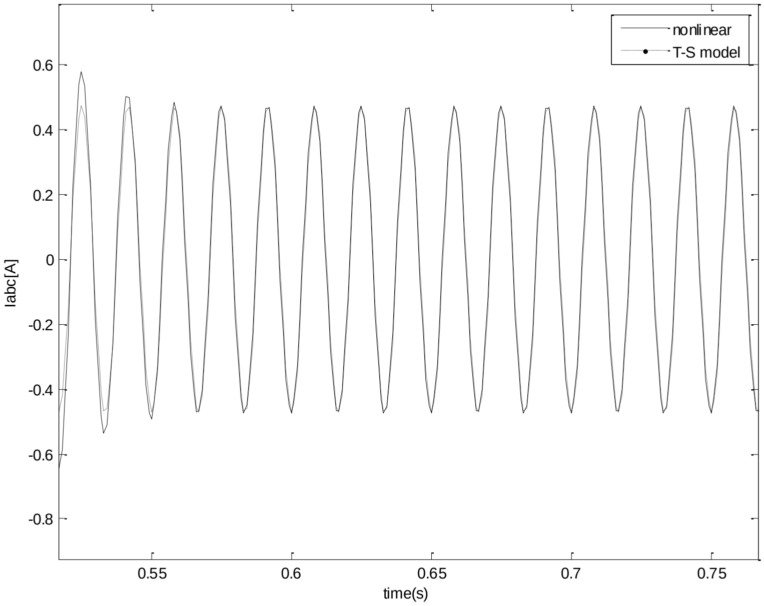

Figure 5: Comparison between the 3-phase stator current of the nonlinear system and T-S linear model

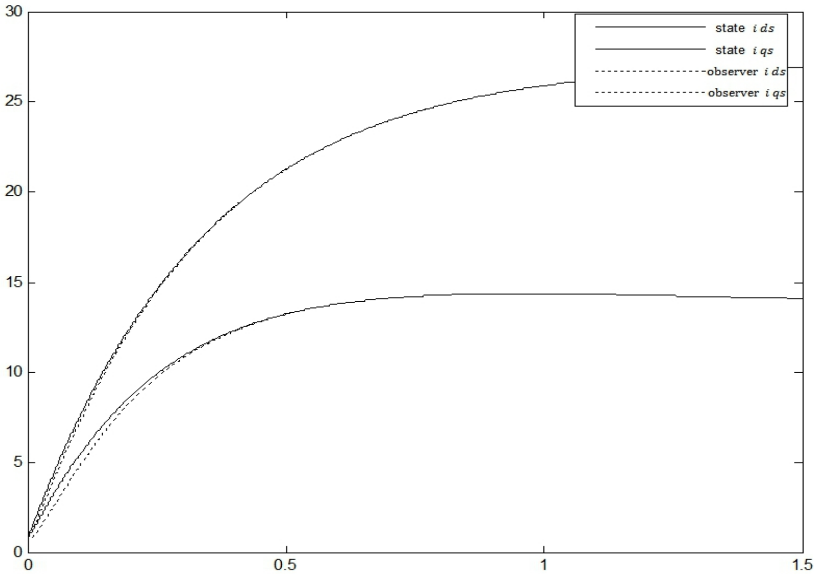

Figure 6: Comparison between the states of the linear system and observer

References:

Alberto Bemporad. State estimation and linear observers. Toronto, 2010
Betz A. Introduction to the Theory of Flow Machines. Oxford, 1966

B. Chitti, K. Mohanty. Doubly-Fed Induction Generator for Variable Speed Wind Energy Conversion, Systems- Modeling & Simulation. International Journal of Computer and Electrical Engineering, 2010

C. Gálvez, M. Kinnaert. Sensor fault detection and isolation in doubly-fed induction generators accounting for parameter variations. Belgium, 2010

E. Kamal, A. Aitouche. Robust fault tolerant control of DFIG wind energy systems with unknown inputs. France, 2012

Eric A. Wan, Rudolph van der Merwe. The Unscented Kalman Filter for Nonlinear Estimation. Oregon Graduate Institute of Science & Technology, 2000

Feng Jia, Yaguo Lei, Jing Lin, Xin Zhou, Na Lu. Deep neural networks: A promising tool for fault characteristic mining and intelligent diagnosis of rotating machinery with massive data. China, 2015

Hansen AD, Michalke G, Sørensen P, Lund T, Iov F. Co-ordinated voltage control of DFIG wind turbines in uninterrupted operation during grid faults. Denmark, 2007

H. Li, C. Yang, Y.G. Hu, B. Zhao, M. Zhao, Z. Chen. Fault-tolerant control for current sensors of doubly fed induction generators based on an improved fault detection method. China, 2014

H. Ouyessaad, H. Chafouk, and D. Lefebvre. Doubly-fed induction generator fault diagnosis using unknown input Takagi-Sugeno observer. Tunisia, 2013

H. Ouyessaad, H. Chafouk, Fault Sensor Diagnosis with Takagi-Sugeno Approach Design Applied for DFIG Wind Energy systems. France, 2013

I. Attoui, A. Omeiri. Modeling, control and fault diagnosis of an isolated wind energy conversion system with a self-excited induction generator subject to electrical faults. Algeria, 2014

J. Ramirez-Nino, A. Pascacio, J. Carrillo, O. de la Torre. Monitoring network for online diagnosis of power generators. Mexico, 2009

K. Rothenhagen, F.W. Fuchs. Current sensor fault detection, isolation, and reconfiguration for doubly fed induction generators. Germany, 2009

Leonhard W. Control of electrical drives. 3rd ed. Springer-Verlag, 2001

M.G. Simõesand, A. Farret. Alternative Energy Systems: Design and Analysis with Induction Generators. Second ed., 2007

P. Odgaard, F. Thogersen and J. Stoustrup. Fault isolation in parallel coupled wind turbine converters. France, 2009

R. J. Lee, P. Pillay and R. G. Harley, D-Q Reference Frames for the Simulation of Induction Motors. South Africa, 1984

Samir Abdelmalek, Linda Barazane, Abdelkader Larabi, Maamar Bettayeb. A novel scheme for current sensor faults diagnosis in the stator of a DFIG described by a T-S fuzzy model. Algeria, 2016

Shilpi Saini. Review of Doubly Fed Induction Generator Used in Wind Power Generation. India, 2013

S. Chen, R. Zivanovic. Estimation of frequency components in stator current for the detection of broken rotor bars in induction machines. Australia, 2010

S.G. Varzaneh, H. Rastegar, G.B. Gharehpetian. A new three-mode maximum power point tracking algorithm for doubly fed induction generator based wind energy conversion system. Iran, 2014

T.A. Najafabadi, F.R. Falmasi, P. Jabehdar-Maralani. Detection and isolation of speed, DC-link voltage and current-sensor faults based on an adaptive observer in induction-motor drives. Iran, 2011

Tor A. Johansen, Robert Shorten, Roderick Murray-Smith. On the Interpretation and Identification of Dynamic Takagi–Sugeno Fuzzy Models. Norway, 2000

Y. Ling, X. Ling and X. Cai. Rotor current dynamics of doubly fed induction generators during grid voltage dip and rise. China, 2013