Stator Inter-Turn Short Circuit Fault Estimation for a DFIG-based Wind Turbine

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ABSTRACT

This paper presents an Inter-Turn Short-Circuit (ITSC) fault detection and isolation method based on the Proportional-Integral observer (PIO) design. ITSC fault is one of the most common electrical faults in electrical machines, the early detection of which can significantly reduce maintenance costs and prevent wind turbine damage. Therefore, a fault detection and isolation method is proposed to evaluate the ITSC fault level affecting the stator windings of a Double-Fed Induction Generator (DFIG). First, a state-space model of the generator with an ITSC fault in the d-q reference frame is introduced. Based on this fault model, an unknown input observer described by a Takagi-Sugeno (TS) model is also used to detect and isolate the ITSC fault. This observer provides a good estimation of the unknown inputs despite the abrupt changes in wind speed and parameter variations in the DFIG. Finally, the effectiveness of the proposed ITSC fault estimation is highlighted through simulation on a 3-kW wind turbine system.

Keywords-Inter-Turn Short-Circuit (ITSC); Doubly-Fed Induction Generator (DFIG); Proportional Integral Observer (PIO); TS fuzzy model; Unknown Input Observer (UIO)

I. INTRODUCTION

Wind power is one of the fastest growing renewable energy sources and has the potential for further usage in the future [1]. The development of a reliable and efficient fault diagnosis system is necessary for the reduction of maintenance costs and the assurance of efficient turbine operation. Due to the random nature of the wind, the turbulence around the rotor, and the complexity of the turbine aerodynamics, wind turbine fault diagnosis is very difficult and results in significant variations in the power output of wind turbines and a reduction in the efficiency of their electrical generators [2]. To address these issues, diagnostic and monitoring systems that rely on current analysis, vibration detection, and temperature measurement have been developed [3]. Among these methods, the generator current analysis offers several advantages, including affordability, installation ease, and optimal adaptation to the wind turbine environments of the employed sensors [4, 5]. Several methods have been proposed in the literature for diagnosis and fault detection in wind turbine systems [2]. The former can be divided into two main categories: analytical model-based methods and signature analysis methods. The analytical model-based methods utilize a model that characterizes the dynamic behavior of the wind turbine under normal operation and/or under fault conditions. Signature analysis methods are techniques deployed to diagnose faults in wind turbines by examining the signatures that emerge from sensor data. Authors in [2, 5, 6] showed that the shaft or coupling (3%), rotor (7%), stator windings (21%), and bearings (69%) are the most frequently failing components. The ITSC fault in the stator windings can be caused by a number of factors, including mechanical vibration and overload. This type of fault is initially considered harmless because it does not require immediate machine shutdown. As the severity of the fault increases, a significant fault current will flow in the shorted winding, resulting in a localized thermal overload in the faulty area, and consequently a shutdown of the wind turbine. Most research on ITSC faults focuses on the use of model-based FDI methods [7-9]. These methods aim to identify faults in real time and determine their exact nature in order to minimize downtime. Authors in [9] presented a three-step ITSC fault diagnosis strategy for a DFIG generator, which is based on the use of an adaptive observer to estimate the ITSC short-circuit level and to locate the faulty phase. A single Kalman observer was employed to perform the three stages of diagnosing the ITSC fault of the stator winding (an ITSC fault of 5% level in phase c is applied), but it was not quantified. Authors in [7] utilized a Lissajous diagram, which takes into account the d-q symmetry of the stator current, to detect deviations from the normal operating state. Authors in [10, 11] proposed the usage of a multi-model TS approach for the diagnosis and tolerant control of faults affecting the wind turbine system. Authors in [12] introduced a Dedicated Observer Scheme (DOS) and Generalized Observer Scheme (GOS) bank using Luenberger observers in an attempt to generate a set of residuals for sensor fault detection and isolation. The current study proposes a multi-model observer-based fault diagnosis method established on PIO to detect and estimate the ITSC in DFIG-based wind turbines. Despite the numerous generator speed changes and DFIG parameter variations, the introduced approach is able to simultaneously estimate the system state $x(t)$ and the ITSC fault level $\mu(t)$. In the wind turbine modeling frameworks, the recovered wind power at the low-speed shaft is proportional to the cube of the wind speed [1, 11]:

$$P_t = \frac{1}{2} C_p(\lambda, \beta) \rho \pi R^2 V_w^3 \qquad (1)$$

where ρ is the air density, R is the rotor radius, V_w is the wind speed, and $C_p(\lambda, \beta)$ is the power coefficient defined as:

$$C_p(\lambda, \beta) = 0.5176 \left[\frac{116}{\lambda_i} - 0.4\beta - 5\right] exp\left(\frac{-21}{\lambda_i}\right) + 0.0068\lambda_i \qquad (2)$$

with $\lambda_i = \left(\frac{1}{\lambda + 0.08\beta} - \frac{0.055}{\beta^3 + 1}\right)$. The power coefficient depends on the orientation of the blades defined by the pitch angle β and the tip speed ratio λ:

$$\lambda = \frac{\Omega_t R}{V_w} \qquad (3)$$

where Ω_t is the mechanical angular rotor speed of the wind turbine. For a variable speed turbine, the goal is to ensure that the turbine operates at an optimal tip speed ratio λ_{opt} = 6.9 while maintaining turbine power at the maximum power coefficient C_{pmax} = 0.47. The result is the extraction of the maximum available power at the wind turbine shaft. If the wind turbine system is forced to operate in optimal conditions, corresponding to λ_{opt} = 6.9, the torque developed in the low-speed shaft side of the turbine, resulting in maximum power transfer, is:

$$C_{t\_ref} = 0.5\pi\rho C \left(\frac{R^5}{\lambda_{opt}^3}\right)^2_{t\_opt_{p_{max}}} \qquad (4)$$

A. DFIG Model in d-q Reference Frame with Inter-Turn Short-Circuit Fault

In order to obtain a DFIG analytical model that adequately describes the ITSC fault generator, two parameters, μ and f_x, are defined to indicate the fault level and the fault position, respectively. Figure 1 shows the configuration of the DFIG with stator ITSC fault in phase b.

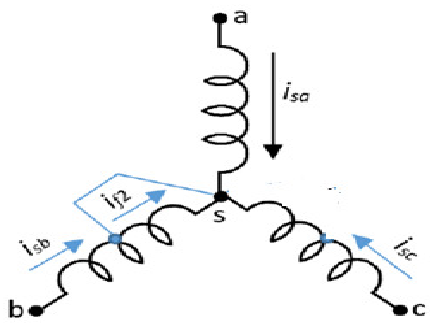

Fig. 1. Stator winding with ITSC fault in phase b.

Parameter μ is the fraction of the winding short-circuit phase in the stator winding, which is defined as the ratio of the shorted turn number in the stator winding divided by the total number of turns in the same phase. In addition, f_x indicates the phase in which the fault occurred, where x denotes the phase a, b or c. In the (d-q) reference frame, the f_x matrices are [7, 8]:

$$f_a = [1 \quad 0], f_b = \left[-\frac{1}{2} \quad \frac{\sqrt{3}}{2}\right], f_c = \left[-\frac{1}{2} \quad -\frac{\sqrt{3}}{2}\right] \qquad (5)$$

The modeling of the DFIG in the d-q reference frame with the presence of a stator ITSC fault is [8, 9]:

$$\begin{bmatrix} V_{dqs} \\ V_{dqr} \\ V_f \end{bmatrix} = \begin{bmatrix} R_s & 0_{2\times2} & -\frac{2}{3}\mu r_s f_x \\ 0_{2\times2} & R_r & 0_{2\times1} \\ \mu r_s f_x^T & 0_{1\times2} & -\mu rs \end{bmatrix} \begin{bmatrix} I_{dqs} \\ I_{dqR} \\ i_f \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} \phi_{dqs} \\ \phi_{dqr} \\ \phi_f \end{bmatrix} + [\Omega] \begin{bmatrix} \phi_{dqs} \\ \phi_{dqr} \\ \phi_f \end{bmatrix} \qquad (6)$$

$$\begin{bmatrix} \phi_{dqs} \\ \phi_{dqr} \\ \phi_f \end{bmatrix} = \begin{bmatrix} L_{ss} & L_{sr} & -\frac{2}{3}\mu L_{ss} f_x \\ L_{rs} & L_{r_r} & -\frac{2}{3}\mu L_{rs} f_x \\ \mu L_{ss} f_x^T & \mu L_{sr} f_x^T & -\mu L_f \end{bmatrix} \begin{bmatrix} I_{dqs} \\ I_{dqR} \\ i_f \end{bmatrix}, [\Omega] = \begin{bmatrix} -J\omega_s & 0_{2\times2} & 0 \\ 0_{2\times2} & -J\omega_r & 0 \\ 0 & 0 & 0 \end{bmatrix}, J = \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix} \qquad (7)$$

where ω_s is the synchronous speed of the generator, ω_r is the rotor angular frequency, and ω_m is the electrical rotor speed. The resistance and inductance matrices are given as:

$$R_s = \begin{bmatrix} r_s & 0 \\ 0 & r_s \end{bmatrix}, R_r = \begin{bmatrix} r_r & 0 \\ 0 & r_r \end{bmatrix}, L_{ss} = \begin{bmatrix} L_s & 0 \\ 0 & L_s \end{bmatrix}, L_{rr} = \begin{bmatrix} L_r & 0 \\ 0 & L_r \end{bmatrix}, L_{sr} = \begin{bmatrix} L_m & 0 \\ 0 & L_m \end{bmatrix} \quad (8)$$

The self-inductances of the stator and rotor windings including the ITSC are:

$$L_s = \left(L_m + L_{fs}\right) \ L_r = \left(L_m + L_{fr}\right), L_f = \left(L_{fs} + \frac{2}{3}\mu L_m\right) \quad (9)$$

where L_{fs} and L_{fr} are the leakage inductances of the stator and the rotor windings, and L_m is the mutual inductance. The electromagnetic torque frame is defined as [8, 9]:

$$C_{em} = PL_m\left(\frac{3}{2}I_{dqs} \times I_{dqr} + \mu i_f f_x I_{dqr}\right) \quad (10)$$

To simplify the notation, we define:

$$\theta = \frac{2\mu}{2\mu - 3} \quad (11)$$

B. *State Space Model of the Double-Fed Induction Generator with Inter-Turn Short-Circuit Fault*

This research proposes the design of an unknown input observer in state space form for the fault detection and estimation of the DFIG. The advantage of this modeling type is that it allows both healthy ($\mu = 0$) and faulty ($\mu \neq 0$) DFIG systems. Taking the currents as state variables, (5) can be written as [8, 9]:

$$\begin{cases} \dot{x}(t) = Ax(t) + B_c u(t) + B_\theta \theta u(t) \\ y = C\ x(t) \end{cases} \quad (12)$$

where $A=(A_c+A_\omega.\omega_m)$ is the state matrix, $x(t)$ is the state space vector, $u(t)$ is the input control, and ω_m is the electrical angular speed in rad/s of the rotor shaft and are defined as:

$$x(t) = [i_{sd} \quad i_{sq} \quad i_{rd} \quad i_{rq} \quad \mu i_f]^T,\ u(t) = \left[u_{sd}\ \mathrm{u}_{sq}\ \mathrm{u}_{rd}\ \mathrm{u}_{rq}\right]^T, \omega_m = p\Omega_m \quad (13)$$

where Ω_m is the mechanical angular speed of the generator and p is the number of pole-pairs. The matrices A_c, A_ω, B_c, B_θ, and C are given as:

$$A_c = \frac{1}{D}\begin{bmatrix} -L_{rr}R_s & L_{sr}R_r & \frac{2}{3}r_s L_r f_x \\ L_{sr}R_r & -L_{ss}R_r & -\frac{2}{3}r_s L_m f_x \\ 0_{1\times2} & 0_{1\times2} & 0 \end{bmatrix} + \frac{1}{L_{fs}}\begin{bmatrix} 0_{2\times2} & 0_{2\times2} & -\frac{2}{3}r_s f_x \\ 0_{2\times2} & 0_{2\times2} & 0_{2\times1} \\ 0_{1\times2} & 0_{1\times2} & -r_s \end{bmatrix} \quad (14)$$

$$A_\omega = \frac{1}{D}\begin{bmatrix} L_m^2 J & L_r L_m J & -\frac{2}{3}L_m^2 J f_x \\ -L_s L_m J & -L_s L_r J & -\frac{2}{3}r_s L_m f_x \\ 0_{1\times2} & 0_{1\times2} & 0 \end{bmatrix} \quad (15a)$$

$$D = L_s L_r - L_m^2 \quad (15b)$$

$$B_c = \frac{1}{D}\begin{bmatrix} L_{rr} & -L_{sr} \\ -L_{sr} & L_{ss} \\ 0_{1\times2} & 0_{1\times2} \end{bmatrix} \quad (16a)$$

$$B_\theta = \frac{1}{L_{fs}}\begin{bmatrix} -2f_x f_x^T & 0_{2\times2} \\ 0_{2\times2} & 0_{2\times2} \\ -3f_x^T & 0_{1\times2} \end{bmatrix} \quad (16b)$$

$$C = \begin{bmatrix} I_{4\times4} & 0_{4\times1} \\ 0_{1\times4} & 0 \end{bmatrix} \quad (16c)$$

II. TS FUZZY PROPORTIONAL INTEGRAL OBSERVER DESIGN

A. *Indirect Field-Oriented Control Strategy*

The vector control scheme for the wind turbine DFIG, as portrayed in Figure 2, aims to emulate the behavior of a DC machine with separate excitation by achieving decoupling between the flux and the electromagnetic couple. The decision to implement vector control in the DFIG is based on orienting the stator flux along the direct axis d, which results in:

$$\begin{cases} \phi_{ds} = \phi_s \\ \phi_{qs} = 0 \end{cases} \quad (17)$$

By adjusting the d-q voltage control signals through the generator-side AC-DC converter and the grid-side DC-AC inverter, the active power and reactive power supplied by the DFIG to the grid can be controlled separately. In order to extract the maximum power and force the generator to operate in the optimum zone, the aerodynamic power input to the rotor can be adjusted with the optimum rotor speed, Ω_{mopt}.

B. *Uncertain Takagi-Sugeno Fuzzy Model of the Double-Fed Induction Generator with Inter-Turn Short-Circuit Fault*

The state space model (11), which is used to design the TS fuzzy PIO, can be re-written as [9, 10]:

$$\dot{x}(t) = A(\Omega_m)x(t) + B_c u(t) + R\left(u_{sd}, u_{sq}\right)\theta(t) \quad (18)$$

where:

$$R\left(u_{sd}, u_{sq}\right) = \frac{1}{L_{ls}}\begin{bmatrix} -2.f_x.f_x{}^T \\ 0_{2\times2} \\ -3f_x^T \end{bmatrix}\begin{bmatrix} u_{sd} \\ u_{sq} \end{bmatrix}.$$

For all ITSC stator fault position that occurs in phase a, b and c, $f_x\ f_x^T$ are given as [9, 10]:

$$f_a f_a^T = \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix} \quad (19a)$$

$$f_b f_b^T = \begin{bmatrix} \frac{1}{4} & -\frac{\sqrt{3}}{4} \\ \frac{\sqrt{3}}{4} & \frac{3}{4} \end{bmatrix} \quad (19b)$$

$$f_c f_c^T = \begin{bmatrix} \frac{1}{4} & \frac{\sqrt{3}}{4} \\ \frac{\sqrt{3}}{4} & \frac{3}{4} \end{bmatrix} \quad (19c)$$

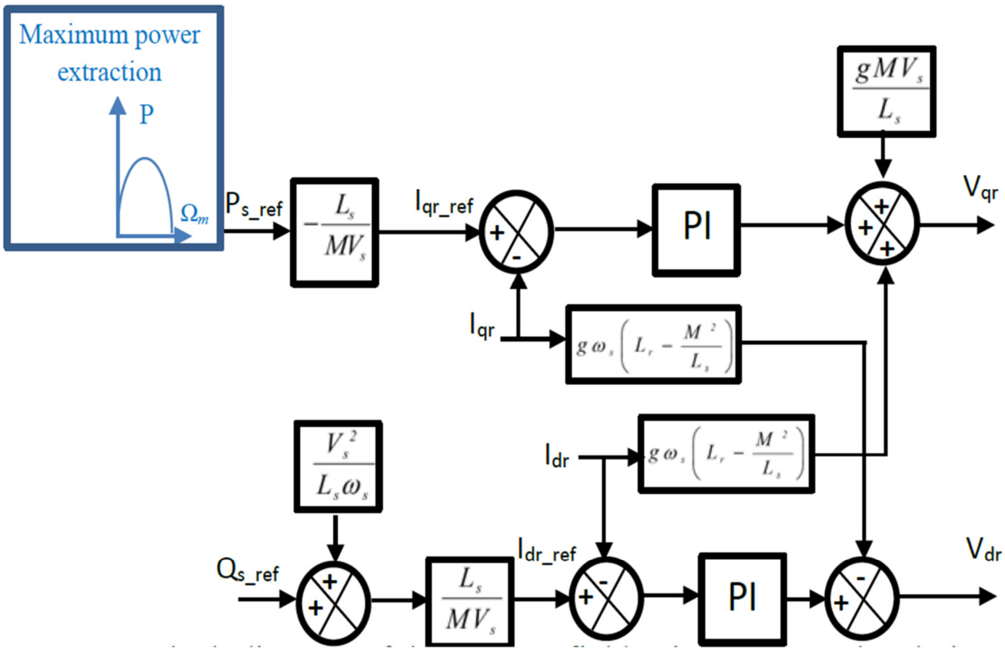

Fig. 2. Block diagram of the indirect field-oriented control technique.

Therefore, depending on the position of the ITSC fault, the matrix R is calculated as [9, 10]:

$$R_a = \frac{1}{L_{ls}}\begin{bmatrix} -2u_{sd} \\ 0_{3\times 1} \\ -3u_{sd} \end{bmatrix} \quad (20a)$$

$$R_b = \frac{1}{L_{ls}}\begin{bmatrix} -\frac{1}{2}u_{sd} + \frac{\sqrt{3}}{2}u_{sq} \\ \frac{\sqrt{3}}{2}u_{sd} - \frac{3}{2}u_{sq} \\ 0_{2\times 1} \\ \frac{3}{2}u_{sd} - \frac{3\sqrt{3}}{2}u_{sq} \end{bmatrix} \quad (20b)$$

$$R_c = \frac{1}{L_{ls}}\begin{bmatrix} -\frac{1}{2}u_{sd} - \frac{\sqrt{3}}{2}u_{sq} \\ -\frac{\sqrt{3}}{2}u_{sd} + \frac{3}{2}u_{sq} \\ 0_{2\times 1} \\ \frac{3}{2}u_{sd} + \frac{3\sqrt{3}}{2}u_{sq} \end{bmatrix} \quad (20c)$$

In (9), the generator speed Ω_m is contingent on the wind speed V_w, thus classifying it as a Linear Parameter-Varying (LPV) system. Therefore, using the sectoral nonlinearity approach, a fuzzy TS model is created, where the nonlinear terms of model (9) are:

$$\begin{cases} z_1(t) = \Omega_m(t) \\ z_2(t) = u_{sd}(t) \\ z_3(t) = u_{sq}(t) \end{cases} \quad (21)$$

In order to further analyze the functions $F_{ij}(z(t))$, it is necessary to consider the premise variable $z_k(t)$, as well as the fuzzy subsets F_{ij}:

$$\begin{cases} F\,\frac{z_k(t) - min(z_k(t))}{max(z_k(t)) - min(z_k(t))}_{k,min} \\ F\,\frac{max(z_k(t)) - z_k(t)}{max(z_k(t)) - min(z_k(t))}_{k,max} \end{cases}, k = \{1,2,3\} \quad (22)$$

The DFIG with ITSC fault by a TS fuzzy model as rule is written:

If $z_1(t)$ is F_{1i} and $z_2(t)$ is F_{2i} and $z_3(t)$ is F_{3i}, $then\ \dot{x}(t) = (A_i + \Delta A_i)x(t) + (B_c + \Delta B_c)u(t) + R_i\theta(t), i = \{1,2,..,8\}$ (23)

The aggregation of eight local models by means of THE weighting functions $h_i(z(t))$, leads to the TS multi-model by the nonlinear state:

$$\begin{cases} \dot{x}(t) = \sum_{i=1}^{8} h_i(z(t)) \begin{pmatrix} (A_i + \Delta A_i)x(t) + \\ (B_c + \Delta B_c)u(t) + R_i\theta \end{pmatrix} \\ y(t) = Cx(t) + D\theta(t) \end{cases} \quad (24)$$

where ΔA_i and ΔB_c are the parametric uncertainties, such as $\Delta A_i = M_{ai}\, F_{ai}(t) N_{ai}$ and $\Delta B_i = M_{bi} F_{bi}(t) N_{bi,}$ and $F_i(t)$ is an unknown function satisfying $F_i(t)F_i^T(t) < I$.

C. *Proportional Integral Takagi-Sugeno Observer Δesign*

This paper examines the design of a robust PIO for a multi-model wind turbine system. The system is affected by a short circuit fault in the stator winding, calculated by the value of the parameter μ, and estimating the unknown inputs $\theta(t)$ that affect the system are estimated. In order to estimate the state of the TS fuzzy model with unknown inputs (23), the structure of the TS observer considered with unknown inputs has the following form:

$$\begin{cases}\dot{\hat{x}}(t)=\sum_{i=1}^{8}h_i(z(t).\begin{pmatrix}A_i\hat{x}(t)+Bu(t)+\ R_i.\hat{\theta}(t)+\\ L_{1i}(y(t)-\hat{y}(t))\end{pmatrix}\\ \dot{\hat{\theta}}(t)=\sum_{i=1}^{8}h_i(z(t).\left(L_{2i}(y(t)-\hat{y}(t))\right)\\ \hat{y}(t)=C\hat{x}(t)+D\hat{\theta}(t)\end{cases} \quad (25)$$

where L_{1i} and L_{2i} are the observer's gain matrices to be determined in order to simultaneously estimate θ(t) and *x(t)*. The observer design depends on finding the gains L_{1i} and L_{2i} so that the estimation error of the state and the unknown input are generated by a stable system.

1) Theorem 1

The TS fuzzy observer (25) that estimates the state $x(t)$ and the unknown input $\theta(t)$ of the system (23) while minimizing the L_2 gain of the transfer from the unknown input to the estimation error is obtained when there are positive definite symmetric matrices P_1, P_2, matrices Z_i, and scalars ε_{ai}, ε_{bi} that satisfy the following optimization problem:

$$\begin{bmatrix}\Pi_{11} & 0 & 0 & 0 & P_1\bar{M}_{ai} & P_1\bar{M}_{bi} & P_1\\ * & \Pi_{22} & P_2B_c & P_2E_i & P_2M_{ai} & P_2M_{bi} & 0\\ * & * & \varepsilon_{bi}N_{bi}^TN_{bi} & 0 & 0 & 0 & 0\\ * & * & * & -\rho.I & 0 & 0 & 0\\ * & * & * & * & -\varepsilon_{ai} & 0 & 0\\ * & * & * & * & * & -\varepsilon_{bi} & 0\\ * & * & * & * & * & * & -Q^{-1}\end{bmatrix}<0 \quad (26)$$

where:

$$\Pi_{11}=\bar{A}_i^TP_1+P_1\bar{A}_i-Z_i\bar{C}-C^T\bar{Z}_i^T$$

$$\Pi_{22}=A_i^TP_2+P_2A_i^T+\varepsilon_{ai}N_{ai}^TN_{ai}$$

$$\bar{A}_i=\begin{bmatrix}A_i & R_i\\ 0 & 0\end{bmatrix}$$

$$\bar{B}_c=\begin{bmatrix}B_c\\ 0\end{bmatrix}$$

$$\bar{L}_i=\begin{bmatrix}L_{1i}\\ L_{2i}\end{bmatrix}$$

$$\bar{C}=[C \quad D]$$

$$\bar{M}_{ai}=\begin{bmatrix}M_{ai}\\ 0\end{bmatrix}$$

$$\bar{N}_{ai}=\begin{bmatrix}N_{ai}\\ 0\end{bmatrix}$$

$$\Delta\bar{A}_i=\begin{bmatrix}\Delta A_i & 0\\ 0 & 0\end{bmatrix}$$

$$\Delta\bar{B}_c=\begin{bmatrix}\Delta B_c\\ 0\end{bmatrix}$$

The observer gains are:

$$\bar{L}_i=P_1^{-1}\bar{Z}_i$$

In order to prove the above theorem, the augmented state vector is defined as:

$$x_a(t)=\begin{bmatrix}x(t)\\ \theta(t)\end{bmatrix} \quad (27a)$$

$$\hat{x}_a(t)=\begin{bmatrix}\hat{x}(t)\\ \hat{\theta}(t)\end{bmatrix} \quad (27b)$$

The estimation error of the augmented state is defined as:

$$e_a(t)=x_a(t)-\hat{x}_a(t) \quad (28)$$

The TS model (16) and PIO (17) can then be written as:

$$\begin{cases}\dot{x}_a(t)=\sum_{i=1}^{8}h_i(z(t))\begin{pmatrix}(\bar{A}_i+\Delta\bar{A}_i)x_a(t)+\\ (\bar{B}_c+\Delta\bar{B}_c)u(t)\end{pmatrix}\\ y(t)=\bar{C}x_a(t)\end{cases} \quad (29)$$

$$\begin{cases}\dot{\hat{x}}(t)=\sum_{i=1}^{8}h_i(z(t).\begin{pmatrix}\bar{A}_i\hat{x}(t)\\ +\bar{B}_cu(t)+\ \bar{L}_i\bar{C}e_a(t)\end{pmatrix}\\ \hat{y}(t)=\bar{C}\hat{x}_a(t)\end{cases} \quad (30)$$

The estimation error of the augmented state is:

$$\dot{\bar{x}}(t)=\sum_{i=1}^{8}h_i\,(z(t))(\bar{G}_i\bar{x}(t)+\bar{E}_i\,u(t)) \quad (31)$$

where:

$$\bar{x}=\begin{bmatrix}e_a(t)\\ x_a(t)\end{bmatrix}$$

$$\bar{G}_i=\begin{bmatrix}\bar{A}_i-\bar{L}_i\bar{C} & 0\\ 0 & \bar{A}_i\end{bmatrix}$$

$$\bar{E}_i=\begin{bmatrix}\Delta\bar{B}_c\\ \bar{B}_c+\Delta\bar{B}_c\end{bmatrix}$$

The Lyapunov candidate function, $V(e_a(t), x(t))$ is:

$$V(e_a,x_a)=\begin{bmatrix}e_a(t)\\ x_a(t)\end{bmatrix}^T\begin{bmatrix}P_1 & 0\\ 0 & P_2\end{bmatrix}\begin{bmatrix}e_a(t)\\ x_a(t)\end{bmatrix}=\bar{x}^T(t)\bar{P}\bar{x}(t) \quad (32)$$

The objective is to find the observer gains that minimize the L_2-gain of the transfer from the input $u(t)$ to the estimation error, and is bounded by the scalar ρ if:

$$\dot{V}(\bar{x}(t))+\bar{x}(t)^T\bar{Q}\bar{x}(t)-\rho^2u(t)^Tu(t)<0 \quad (33)$$

Taking into account the time-derivative of the function (33) and the augmented state (31):

$$\sum_{i=1}^{8}h_i(z(t))h_j(z(t))\begin{bmatrix}e_a(t)\\ x_a(t)\end{bmatrix}^T\begin{bmatrix}\bar{G}_i^T\bar{P}+\bar{P}\bar{G}_i+\bar{Q} & \bar{P}\bar{E}_i\\ \bar{E}_i^T\bar{P} & -\rho^2.I\end{bmatrix}\begin{bmatrix}e_a(t)\\ x_a(t)\end{bmatrix}<0 \quad (34)$$

By using the property of the congruent transformation and by separating the definite and the indefinite terms, (34) is:

$$\Upsilon_i+\Delta\Upsilon_i<0 \quad (35)$$

where:

$$\Upsilon_i=\begin{bmatrix}\Pi_{11} & 0 & 0 & 0 & P_1\\ * & \Pi_{22} & P_2B_c & P_2E_i & 0\\ * & * & -\rho.I & 0 & 0\\ * & * & * & -\rho.I & 0\\ * & * & * & * & -Q^{-1}\end{bmatrix}$$

$$\Delta\Upsilon_i = \begin{bmatrix} P_1\bar{M}_{ai} \\ P_2 M_{ai} \\ 0 \\ 0 \\ 0 \end{bmatrix} F_a(t) \begin{bmatrix} 0 \\ N_{ai}^T \\ 0 \\ 0 \\ 0 \end{bmatrix}^T + \begin{bmatrix} P_1\bar{M}_{bi} \\ P_2 M_{bi} \\ 0 \\ 0 \\ 0 \end{bmatrix} F_b(t) \begin{bmatrix} 0 \\ 0 \\ 0 \\ N_{bi}^T \\ 0 \end{bmatrix}^T$$

All matrices X, Y and $F(t)$ of appropriate dimensions satisfying $F(t)^T F(t) \leq I$ and for any positive scalar ε:

$$XF(t)Y^T + YF(t)^T X^T < \varepsilon XX^T + \varepsilon^{-1} YY^T \qquad (36)$$

Finally, using condition (36) and applying the Schur addition, (35) is transformed into LMI (26).

III. SIMULATION RESULTS

In order to describe the effectiveness of the proposed fuzzy PIO in diagnosing the different levels of ITSC faults in the stator winding, two levels of faults in phase b are examined, as depicted in Figure 3.

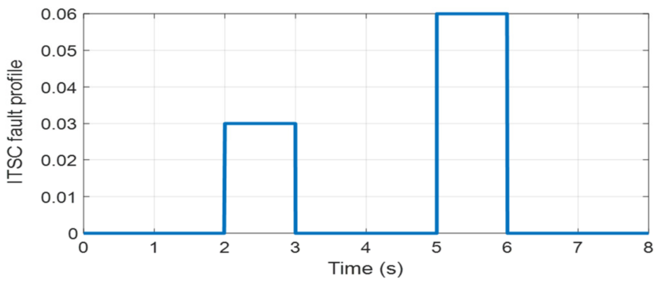

Fig. 3. ITSC fault profile.

The DFIG parameters are R_s=1.94 Ω, R_r=0.3 Ω, L_s=201 mH, L_r=19 mH, L_m=59 mH, and P_n=3 kW. The proposed PIO is tested for a step range of wind speed from 8 m/s to 10 m/s at 4 s. It is assumed that the uncertain fuzzy model (16) has a 5% parametric variation from the nominal model. The TS fuzzy model (24) of the DFIG shows the dynamic behavior of the disturbed system (12) under the bounded interval of the premise variables: Ω_{min}=-200 rd/s, Ω_{max}=200 rd/s, u_{sdmin} =-100 V, u_{sdmax} =100 V, u_{sqmin} =-380 V, and u_{sqmax} =380 V. Figure 4 exhibits that the direct stator current *isd* is maintained at zero, despite the changes in wind speed and model parameters, demonstrating that the indirect field-oriented control technique ensures decoupling between the torque and stator flux. In addition, the estimated quadratic stator currents *isq* follow the actual currents. This confirms that the fuzzy PIO is not affected by the parameter variations.

Figure 5 demonstrates that the estimated generator speed Ω_m follows the actual speed, forcing the turbine to operate in the maximum power range and transfer the maximum power to the load.

Figures 6 and 7 display the unknown input $\theta(t)$, the shorted winding fraction $\mu(t)$, and their estimated curves. It can be observed that the PIO (25) supplied with the unknown input $\theta(t)$ provides a good estimate of μ.

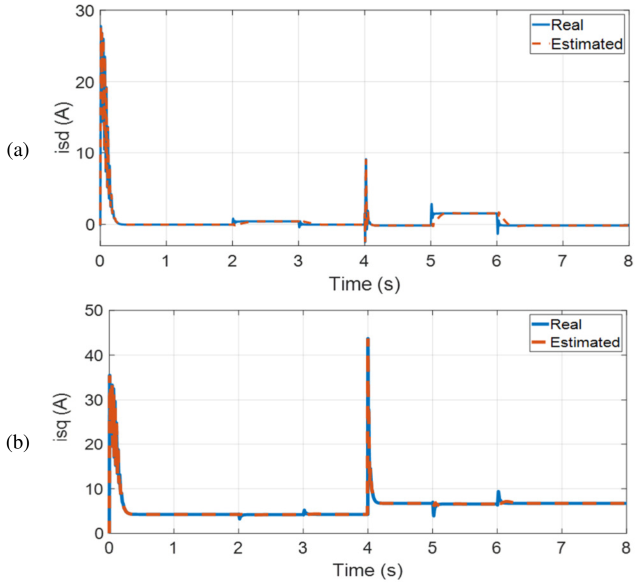

Fig. 4. D-q axis stator current: (a) *isd*, (b) *isq*.

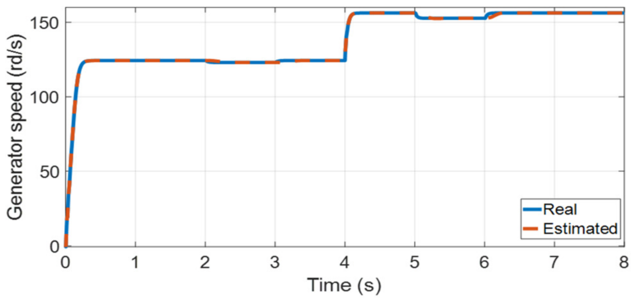

Fig. 5. Variation of generator speed.

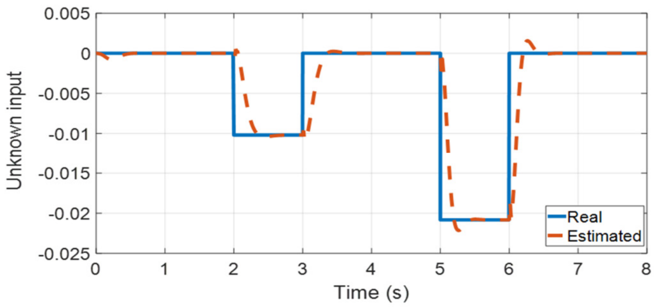

Fig. 6. Variation of the unknown input $\theta(t)$.

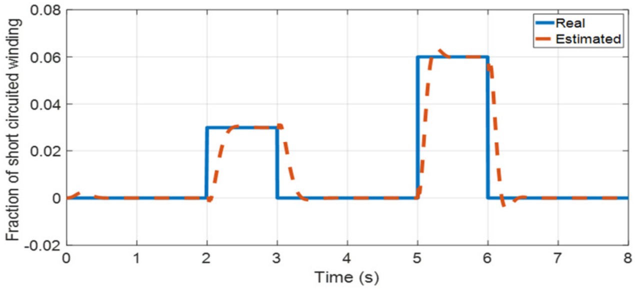

Fig. 7. Variation of the fraction of short-circuited winding $\mu(t)$.

IV. CONCLUSIONS

This paper addresses the problem of Inter-Turn Short Circuit (ITSC) fault detection and isolation in a stator winding for a Double-Fed Induction Generator (DFIG) driven by a wind turbine. Using Takagi-Sugeno (TS) fuzzy models for state estimation $x(t)$ and ITSC fault detection $\mu(t)$, a robust Proportional-Integral observer (PIO) with unknown input $\theta(t)$ is proposed. The developed PIO provides an unbiased estimation of the state and ITSC level error. In order to determine the gains of the PIO while minimizing the effect of the ITSC error on the observer estimation performance, sufficient LMI conditions are developed. The simulation results show that the proposed PIO can simultaneously estimate the system state and the ITSC fault level in a wide range of generator speed variations and despite DFIG parameter variations. This allows the system to operate in the optimum zone and maximize the extraction of wind turbine energy to the electrical grid.

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