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# Artificial Intelligence-Based Fault Tolerant Control Strategy in Wind Turbine Systems

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**Abstract-** Power converters play an important role as an enabling technology in the electric power industry, especially in Wind Energy Systems (WESs). Where they ensure to regulate the exchanging powers between the system and the grid. Therefore; any fault occurs in any parts of these converters for a limited time without eliminating, it may degrade the system stability and performance.

This paper presents a new artificial intelligence-based detection method of open switch faults in power converters connecting doubly-fed induction (DFIG) generator wind turbine systems to the grid. The detection method combines a simple Fault Tolerant Control (FTC) strategy with fuzzy logic and uses rotor current average values to detect the faulty switch in a very short period of time. In addition, following a power switch failure, the FTC strategy activates the redundant leg and restores the operation of the converter. In order to improve the performance of the closed-loop system during transients and faulty conditions, current control is based on a PI (proportional-integral) controller optimized using genetic algorithms. The simulation model was developed in Matlab/Simulink environment and the simulation results demonstrate the effectiveness of the proposed FTC method and closed-loop current control scheme.

**Keywords** Doubly Fed Induction Generator (DFIG); Wind Turbine; Open Switch Fault; Fuzzy Logic; Maximum Power Point Tacking (MPPT); Grid Side Converter; Genetic Algorithm; Fault Tolerant Control (FTC).

## 1. Introduction

The increased penetration of Renewable Energy Sources (RESs) into the power grids will ultimately result in a reduced dependency on fossil fuels and their impacts on the environment. In 2013, 22% of the global electricity generation is accounted from RESs and this is expected to increase to 26% in 2020. Solar and wind energies are currently the most widely used RESs in the world and their penetration rates were estimated at 50.6% and 26.1% from 2002 to 2012 respectively [1].

Wind power technology can be considered as the most cost competitive renewable energy technology today. Different types of Wind Turbine systems (WTs) configurations have been extensively developed, studied and built. These have been broadly classified as fixed speed wind turbine (FSWT) and variable speed wind turbine (VSWT). VSWTs use a power converter which offers better control of the wind energy and are currently the most popular type of WT configurations [2]. In this work, a VSWT based on DFIG has been used. The wind energy conversion system is

connected directly to the grid via stator and via back-to-back indirect PWM converter (AC/DC/AC) commonly known as grid-side converter (GSC) and rotor side converter (RSC). The RSC has been controlled in order to ensure the decoupled between the two stator powers (reactive and active powers) using the electromagnetic torque delivered by the maximum power point tacking control (MPPT). The GSC controls the power flow exchange with the grid via the rotor, by maintaining the DC bus at the constant voltage level [3,4].

The increased grid-integration of renewable energy electricity brings new technical challenges associated with quality and reliability of supply, distribution system stability and complexity of control. The most popular faults accounted in the industrial variable speed systems types are the result of the power's converters devices failures, which estimated that about 38% of the global industrial system faults have been created by the power converters [5]. If not detected quickly; these faults may affect the performance and the stability of the system.

Switch faults are among the most popular faults in power converters. They can be classified as either open-circuit or

short-circuit faults. The first one (open-circuit fault), may occur for some reasons which are: a disconnected or damaged in the semiconductor device or a malfunction control signal gate. However, the second one (short-circuit faults) represents the most serious class of faults which, very often, causes an over current that can be dealt with by standard protection devices [6].

There has been an extensive research in the area of fault diagnosis and detection in converter power switches. The authors in [5] presented the existing methods fault switch detection studying (IGBT's faults) with their comparative literature review, including open-circuit and short-circuit faults. More than thirty methods fault diagnosis for short and open-circuit fault have been evaluated and compared in term of detection time, effectiveness, implementation, tuning complexity and resistivity. Open-circuit fault methods based on wavelets, fuzzy logic and neural network have been found to offer superior performance as compared to other methods. In [6], a grid-side converter (GSC) fault tolerant compensation approach is proposed for WES. The GSC has three redundant legs to be used under faulty conditions. In [7], the authors proposed a fault diagnostic system using neural networks to identify the faulty location in a multilevel inverter. However, this technique was found too slow due to the computational effort involved.

In this paper, a fuzzy logic-based detection method of open circuit faults with a FTC strategy for the RSC of a DFIG wind energy system has been proposed. The RSC has a redundant topology which consists of an extra leg connected via three Triacs. Furthermore, the control of the powers delivered to the grid via the rotor currents is based on two conventional PI controllers tuned by a genetic algorithm-based optimization technique.

## 2. Wind Energy System Configuration and Control Scheme

The DFIG is one of the most popular machines used in VSWT energy conversion systems. The DFIG is connected to the electrical grid via the stator and rotor sides. This configuration reduces wear and damage of the overall system especially in the AC/DC/AC power converter. Figure 1 presents the overall structure of the DFIG-based WES with its control strategy. The proposed switch fault detection method FDM is applied only to the RSC. The main components are: (i) the maximum power point tracking (MPPT) strategy, (ii) the RSC which controls the rotor currents and the stator powers, (iii) the fuzzy logic fault detection algorithm and (iv) the fault tolerant control block.

### 2.1 Maximum power point tracking (MPPT) strategy

VSWTs are preferred due to their ability to achieve maximum power at any wind speed condition. The WT generates power which is proportional to some parameters which are: the swept area, power coefficient and wind speed [8].

$$P = \frac{1}{2} \rho A C_p(\lambda) V_{\text{wind}}^3 \quad (1)$$

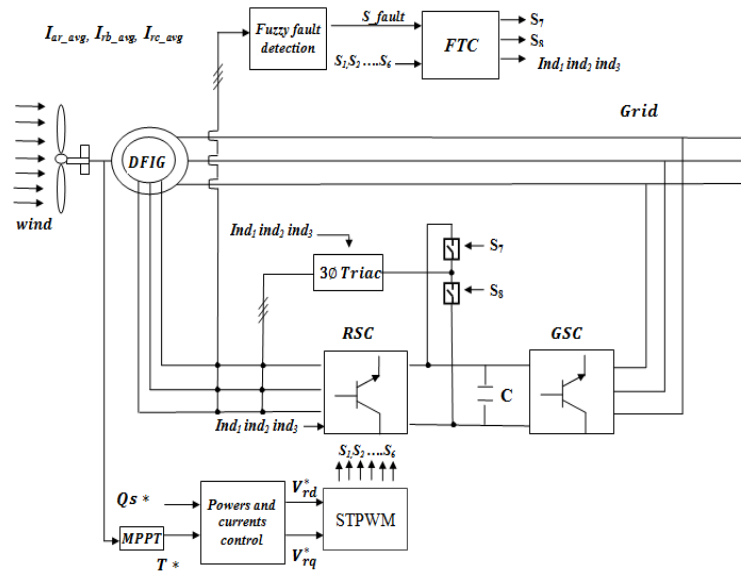


Fig. 1. Wind energy conversion system Structure and its control scheme.

Where  $\rho$  is the density of the wind,  $A$  is the area swept by the blades,  $V_{\text{wind}}$  is the wind speed and  $C_p(\lambda)$  is the power coefficient which is a nonlinear function of the tip speed ratio (TSR)  $\lambda$  defined by:

$$\lambda = \frac{\omega_r R}{V_{\text{wind}}} \quad (2)$$

Where  $\omega_r$  is the wind turbine speed and  $R$  is the radius of the turbine blades.

From equations (1) and (2), it can be noticed that maximum power can be extracted when the TSR is kept at its optimal value  $\lambda_{\text{opt}}$  for any value of the wind speed. The MPPT algorithm requires measurement of the wind speed and turbine speed in addition to the knowledge of the optimal TSR value as shown Figure 2 [9].

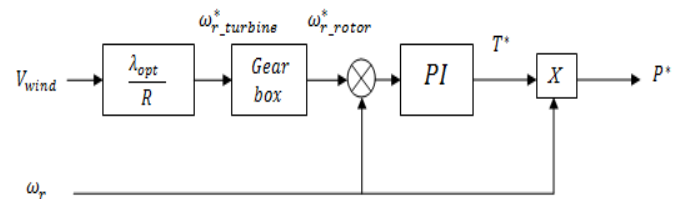


Fig. 2. MPPT control block diagram.

The open loop rotor speed control transfer function is presented as follow:

$$G_{\text{MPPT}}(s) = \frac{1}{Js + F} \quad (3)$$

### 2.2 Rotor side converter control

The DFIG is connected to the grid through two sides, directly from the stator to generate the demanded reactive and active powers and controlled from its rotor through an AC/DC/AC power converter. The powers controlled between the grid and the machine are based on vector control with direct stator flux orientation. The important grandeurs of this

system like: the electromagnetic torque and the reactive and active stator powers are expressed in the Park frame as follows [4,10]:

$$P_s = -V_{sq} \frac{M_{sr}}{L_s} I_{rq} \quad (4)$$

$$Q_s = V_{sq} \frac{\varphi_{sd}}{L_s} - V_{sq} \frac{M_{sr}}{L_s} I_{rd} \quad (5)$$

$$T = -p \frac{M_{sr}}{L_s} \varphi_{sd} I_{rq} \quad (6)$$

Figure 3 shows the schematic bloc diagram of the RSC control.

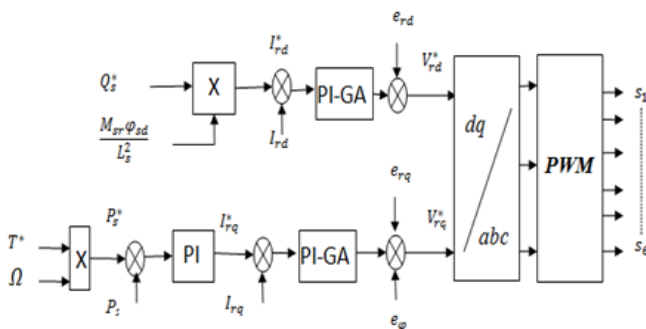


Fig. 3. Rotor side converter control system.

A Proportional-Integrator regulator is used to control the stator active power in order to obtain the maximum power as delivered by the MPPT control strategy. The two others regulators (PI-GA) are used to control the direct and quadrature rotor currents and they are tuned using a GA-optimization technique [11,12]. The GA operations of selection, crossover and mutation are described by the flowchart of Figure 4.

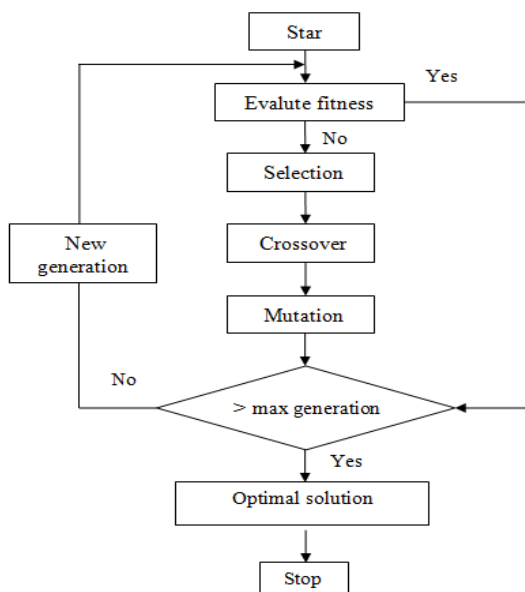


Fig. 4. Flowchart of the GA optimization technique.

The GA parameters used in this work are listed in Table 1.

Table 1. GA parameters used in the model.

Population size	80
Variable bounds	[0 40 ; 0 40]
Max N° of generation	100
Tolerance	1e-6
Performance index/ fitness function	Mean square error
Probability selection	0.08
Crossover method	Arithmetic crossover
Mutation operator	Multi Non uniformly distributed
Probability of mutation	0.1%

### 2.3 Power converter topology and PWM control strategy

The RSC used in this system consists of three legs each one has two bidirectional IGBT switches with free-wheeling diode as shown Figure 5. The inverter is fed from a DC voltage source which is generated and controlled by the GSC control (not studied in this paper).

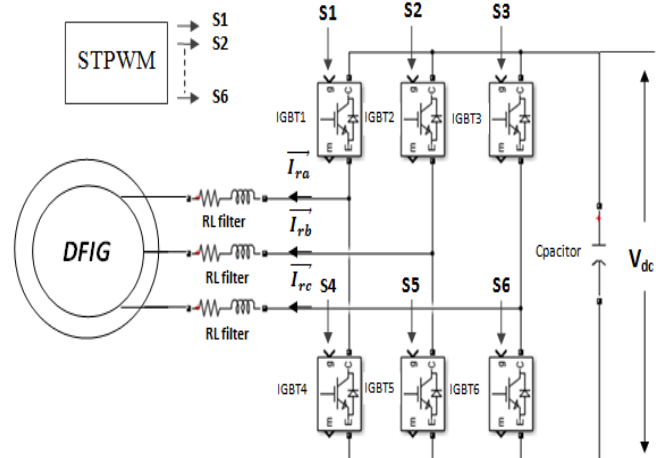


Fig. 5. RSC topology.

The sine-triangle PWM (STPWM) control [13] is based on the comparison of a high frequency triangular carrier voltages with a sinusoidal modulating waves that represent the desired fundamental components of the voltages waveform as shown in Figure 6 (in our system the desired fundamental components are the voltages delivered by the PI-GA regulators in the RSC control block of Figure 3). An RL (resistance-inductance) filter is used in series with the DFIG rotor for each phase in order to reduce the harmonics contents in the three-phase AC voltage output.

The amplitude modulation and carrier modulation are respectively equal:

$$m_t = \frac{V_s}{V_t} = 0.8 \text{ and } m_c = \frac{f_t}{f_s} = 200.$$

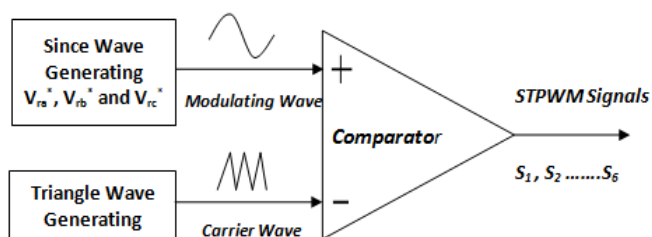


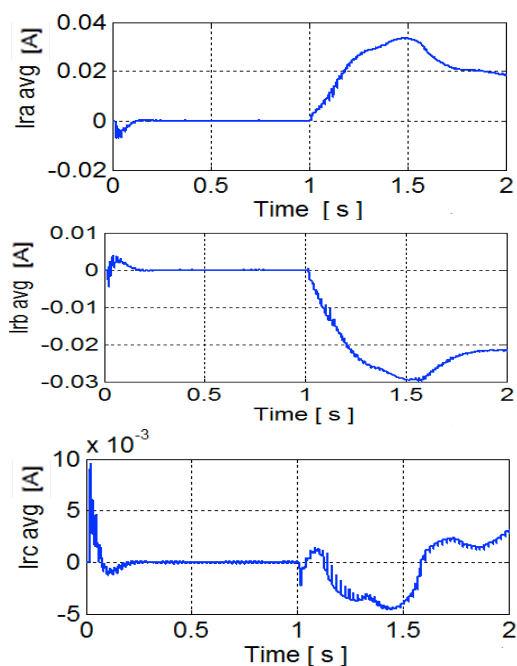
Fig. 6. Analog scheme for STPWM implementation.

### 3. Fault Tolerant Control Strategy

#### 3.1 Fuzzy logic open switch FDM

Faulty switches produce unbalanced AC input currents including harmonics and distortions, which may result in severe secondary faults in the other devices [14,15]. In this work, a fault detection and isolation method of inverter open switch faults is proposed which can be equally applied to the rectifier circuit.

The first step is the calculation of the three-phase currents average values of the RSC which provide an indication on the status of the system. Under healthy conditions, these values are ideally equal to zero. However, when a fault occurs in the inverter switch, these values are no longer equal to zero as shown in Figure7 (in this figure, the fault is in the first switch).



The waveforms of the 3-phase current average values for all switch faults are studied and represented in Table2.

Fig. 7. Three-phase RSC currents mean values

Table 2. Average values of three-phase currents under different open switch fault.

$I_{ra\_avg}$	$I_{rb\_avg}$	$I_{rc\_avg}$	Combination	Switch fault
1	-1	-1	1	S1 fault
-1	-1	1	2	S2 fault
-1	1	-1	3	S3 fault
-1	1	1	4	S4 fault
1	1	-1	5	S5 fault
1	-1	1	6	S6 fault
0	0	0	0	No fault

Based on Table1, the flowchart of Figure 8 is derived which will simplify the synthesis of the fuzzy logic-FDM.

When the average value of the current of each phase increases above the threshold value of  $6 \times 10^{-4}$  the output of the detector is 1, when it decreases above the threshold value of  $-2 \times 10^{-4}$  the output of the detector is -1 and when it assumes between an interval equal to  $[-2 \times 10^{-4}; 6 \times 10^{-4}]$  (healthy condition) the output of the detector is 0.

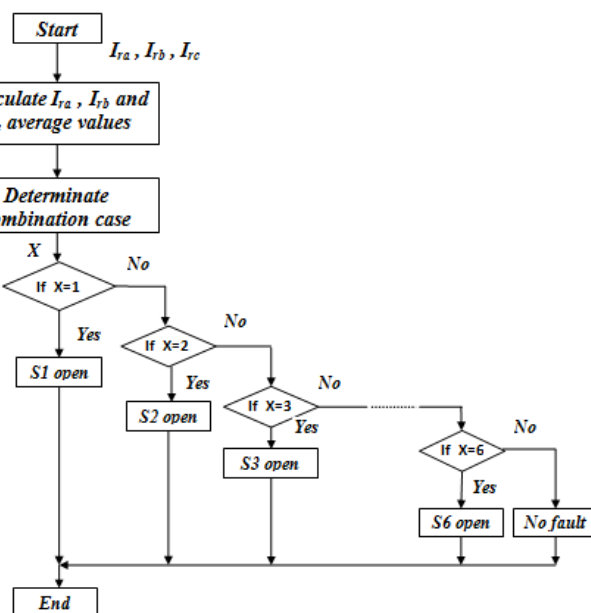


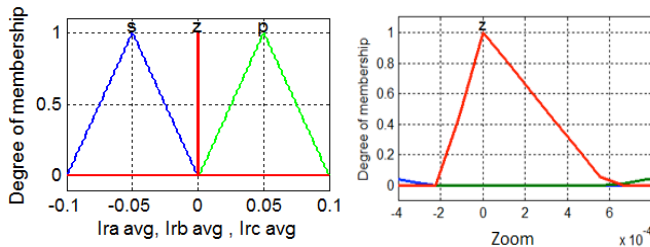
Fig. 8. Flowchart of the fuzzy logic-based open switch FDM

The fuzzy sets are designated by the labels: S (negative), Z (zero) and P (positive). Table3 shows the rules of fault detection. The membership functions for the input variables which present the average values of  $I_{ra}$ ,  $I_{rb}$ ,  $I_{rc}$  and the output variable switch fault surface is shown in Figure 9. Sugeno-type fuzzy inference system was used and defuzzification was based on the centre of gravity method.



**Table 3.** Rules of the fuzzy logic-based open switch FDM

$I_{ra\_avg}$	$I_{rb\_avg}$	$I_{rc\_avg}$	Number switch fault	Switch fault
P	S	S	1	S1 fault
S	S	P	2	S2 fault
S	P	S	3	S3 fault
S	P	P	4	S4 fault
P	P	S	5	S5 fault
P	S	P	6	S6 fault
Z	Z	Z	0	No fault

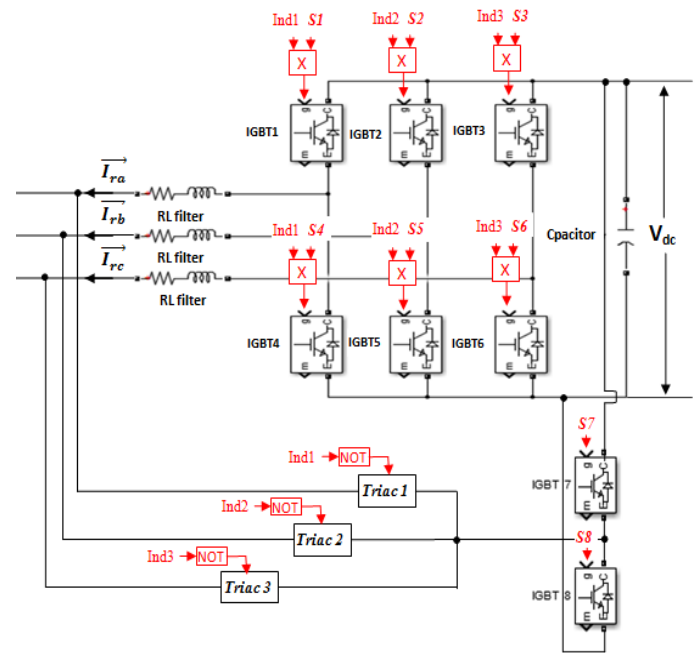


### 3.2 Fault tolerant control strategy

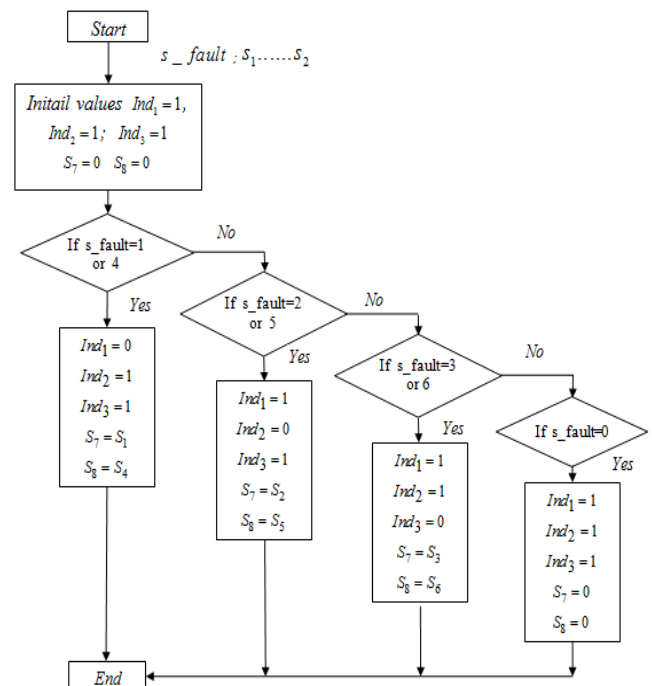
After the fault is detected and in order to avoid any subsequent failure in the other devices, the faulty switch must be isolated and replaced with a healthy one. As shown in Figure 1, the inverter circuit has an additional leg which contains two switches numbered  $s_7$  and  $s_8$ . The redundant leg is connected to both the DC side and to the rotor side phases via a three-phase Triacs circuit (TRIAC1, TRIAC2 and TRIAC3).

This proposed FTC strategy is simple and allows the system to operate without interruption after the occurrence of

a switch fault. Figures 10 and 11 describe the implementation of the circuit. The faulty leg is replaced by the healthy leg by changing the three indices ( $Ind_1$ ,  $Ind_2$  and  $Ind_3$ ) and the status of switches  $S_7$  and  $S_8$  based on the detected faulty switch and the status of the six switches ( $S_1$ ,  $S_2$ , ...,  $S_6$ ). The three indices take value equals to 1 when there is no switch fault.  $Ind_1 = 0$ , if the faulty switch is either the 1<sup>st</sup> or the 4<sup>th</sup> switch,  $Ind_2 = 0$  if the faulty switch is either the 2<sup>nd</sup> or 5<sup>th</sup> switch, and finally,  $Ind_3 = 0$ , when the faulty switch is either the 3<sup>rd</sup> or the 6<sup>th</sup> switch.



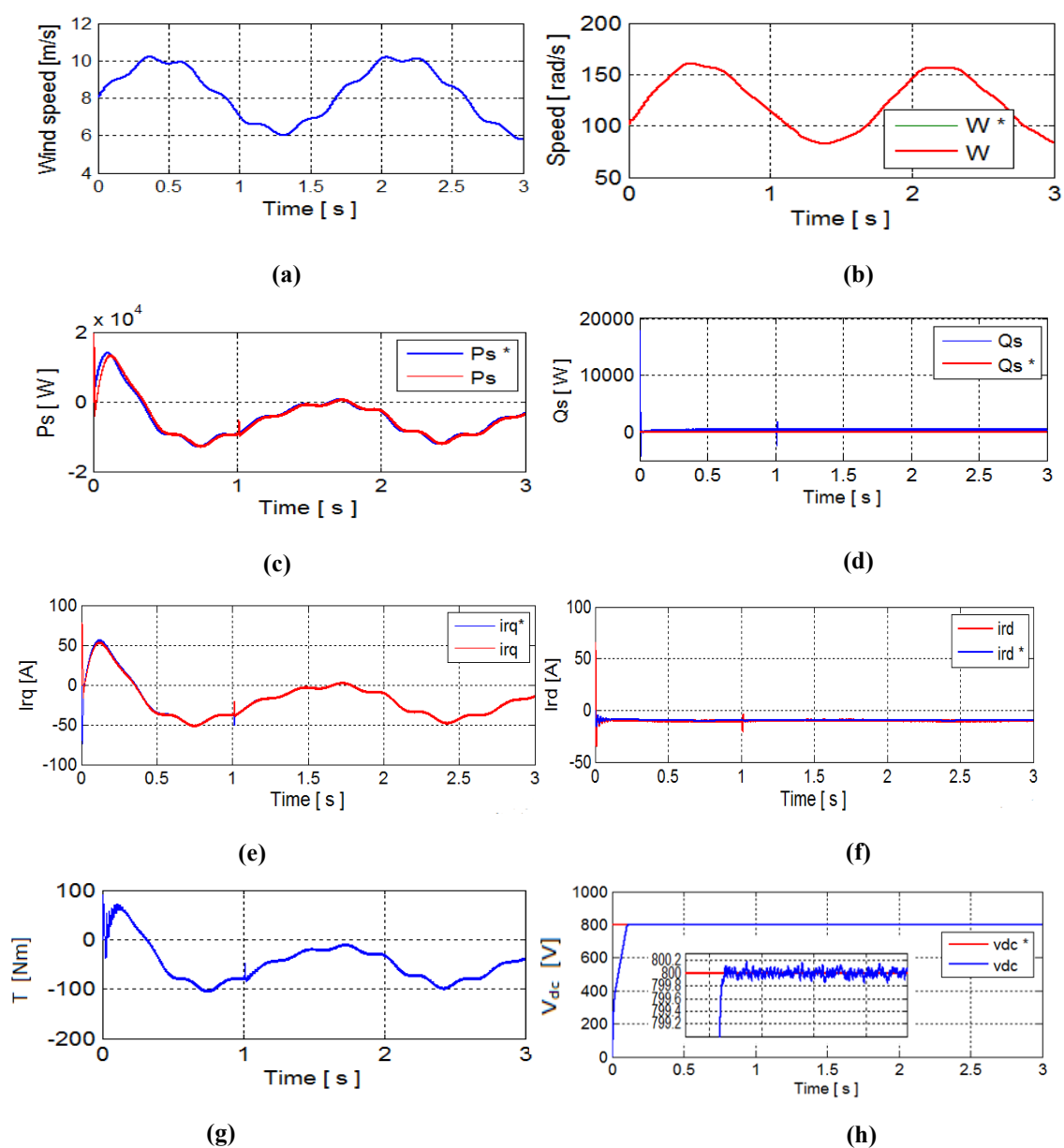
**Fig. 10.** Circuit configuration of the FTC strategy.



**Fig. 11.** Flowchart of the FTC strategy.

**Table 4.** Parameters of the DFIG model.

Rated power	7.5Kw	$R_s$	0.455 $\Omega$
Stator voltage	220 V	$R_r$	0.62 $\Omega$
Stator/rotor turns ratio	1	$L_s$	0.084 H
Turbine power	10 Kw	$L_r$	0.081 H
Radius pale	3 m	$M_{sr}$	0.078 H
Reducer gain $G$	5.4	C filter	2 mF
Lumped inertia constant	0.3125	$L_f$ filter	0.014 H
Number of pole pairs	2	$R_f$ filter	0.3 $\Omega$
Switching frequency $F_s$	10 kHz	DC Link voltage	800 V



**Fig. 12.** (a) Wind speed (b) Speed of DFIG with MPPT, (c)  $P_s$  (d)  $Q_s$ , (e)  $I_{rd}$  current (f)  $I_{rq}$  current, (g) Torque, (h)  $V_{dc}$  voltage

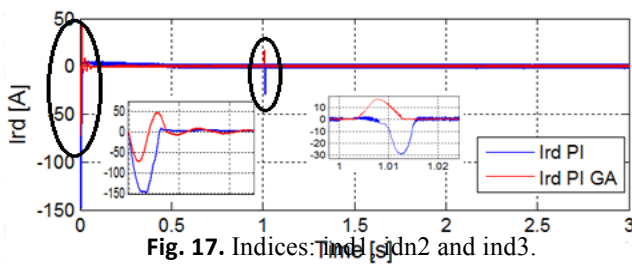
#### 4. Simulation Results

The overall system model is developed using MATLAB/Simulink. In the following simulations, the WES is assumed to operate in the region of optimal operation. The DFIG is rated at 7.5 kW and its parameters are listed in Table 4.

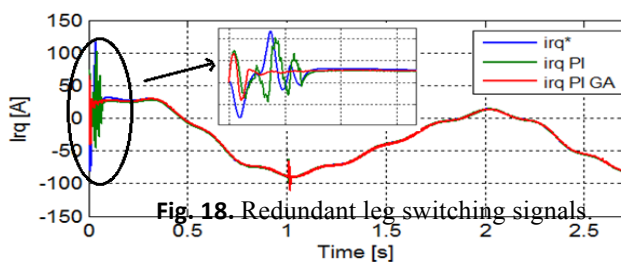
The wind speed takes an average value equal to 8m/s as shown Figure 12-a. The wind energy must be maximum absorbed by the system to achieve a maximum power using MPPT control which delivered the reference torque from the rotor speed controller as shown Figures 12-b and 12-g.

Figures 12-c and 12-d show the active and reactive stator powers with their reference values. Figure 12-h shows the DC link voltage regulation at 800 V for grid side converter.

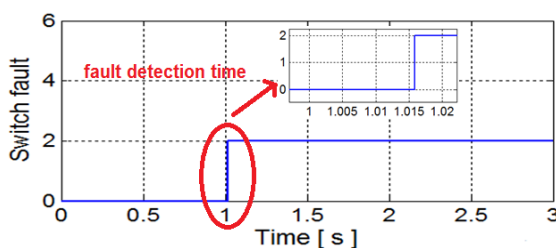
Figures 12-f and 12-e show the direct and quadrature rotor currents controlled by the PI-GA-optimised controllers respectively. Figure 13 and 14 show the comparison responses of the direct and quadrature rotor currents with PI-GA-optimised and conventional PI controllers respectively. PI-GA controllers give a better transient responses than the conventional counterpart. Figure 16 presents' PI-GA controllers gains  $K_p$  and  $K_i$ .



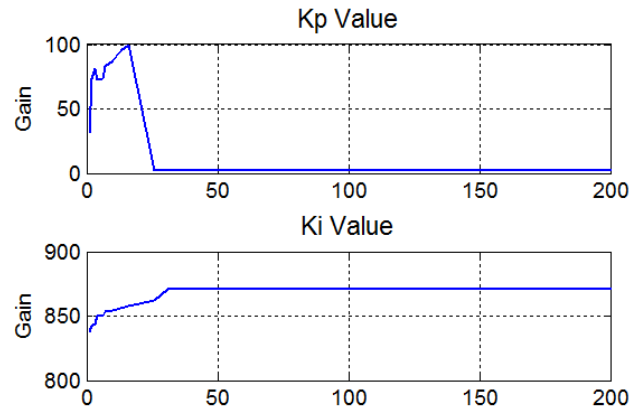
**Fig. 13.** Direct rotor current: Comparison of GA-tuned PI controller and conventional PI controller



**Fig. 14.** Quadrature rotor current: Comparison of GA-tuned PI controller and conventional PI controller



**Fig. 15.** Fuzzy logic open switch fault detection.



**Fig. 16.** GA-based PI controllers gains  $K_p$  and  $K_i$ .

Figure 15 shows the fuzzy logic open switch fault detection for the rotor side power converter, where the fault has been detected on the second switch for detection time equal to 0.015 s.

Figure 17 and 18 show respectively the three indices (ind1, ind2, ind3) and succours leg switches signal (s7, s8). These indices and switching signals change according to the faulty switch detection via a FTC algorithm strategy to ensure the service continuity.

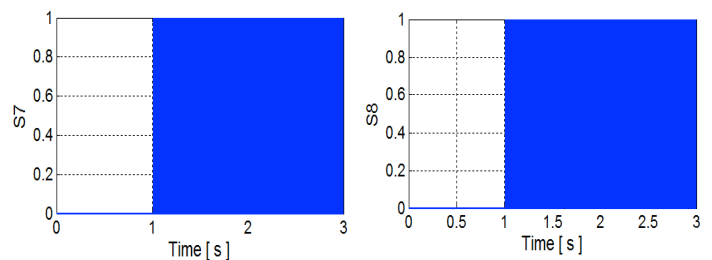
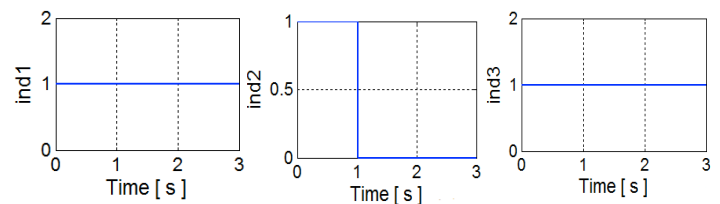


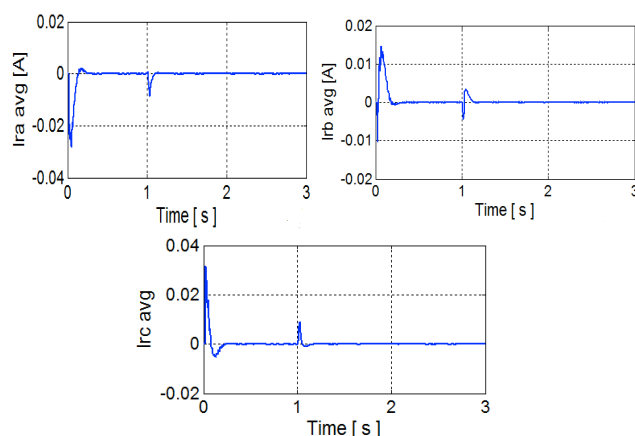
Figure 19 shows the average rotor current values before the open switch fault and after the replacement of the faulty leg via the triacs circuit.

#### 5. Conclusion

This paper presented an artificial intelligence-based open switch FDM of power converter in VSMT systems. The WES developed in this study consists of three parts; the first part includes the MPPT and the rotor side converter control, where the stator powers and rotor currents must be regulated to control the energy exchange between the grid and the system compasaison with the propertional one. GA optimization technique was used to tune the direct and



quadrature rotor currents PI controllers which improved the transient performance of the system comparison with conventional one.



The second and the third parts presented a new open switch fault detection method for the AC/DC PWM power converter and its FTC strategy. The detection method was based in fuzzy logic and used the average values of three-phase currents to detect the open switch during time less than one period compared by the conventional method cited in the reference [5]. The FTC strategy successfully isolated and replaced the faulty switch immediately after a fault has been detected. As shown in the simulation results

The artificial intelligence using in this system improved the reliability and the performance of the global system and enhanced its robustness with respect to converter faults. The method could be readily applied to the second converter.

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