TELKOMNIKA Indonesian Journal of Electrical Engineering
Vol. 13, No. 2, February 2015, pp. 264 ~ 270
DOI: 10.11591/telkomnika.v13i2.6910

DTC Method for Vector Control of 3-Phase Induction Motor under Open-Phase Fault

M. Jannati*, N. R. N. Idris, M. J. A. Aziz
Universiti Teknologi Malaysia, UTM-PROTON Future Drive Laboratory, Faculty of Electrical Engineering,
Universiti Teknologi Malaysia, 81310 Skudai, Johor Bahru, MALAYSIA
*Corresponding author, e-mail: jannatim94@yahoo.com

Abstract

Three-phase Induction Motor (IM) drives are widely used in industrial equipments. One of the essential problems of 3-phase IM drives is their high speed and torque pulsation in the fault conditions. This paper shows Direct Torque Control (DTC) strategy for vector control of a 3-phase IM under open-circuit fault. The objective is to implement a solution for vector control of 3-phase IM drives which can be also used under open-phase fault. MATLAB simulations were carried out and performance analysis is presented.

Keywords*: 3-phase IM, DTC, open-phase fault, simulation results*

1. Introduction

3-phase Inductiom Motor (IM), because of its simplicity of construction, low cost, and robustness, is a good candidate for industrial applications [1]. The IM can be affected by many different types of faults. These faults include the following: 1) stator faults (open or short circuit faults); 2) rotor electrical faults (open or short circuit faults for wound rotor IM and broken bar(s) or cracked end-ring for squirrel-cage IM); 3) rotor mechanical faults (bearing damage, eccentricity, bent shaft, and misalignment) [2-7]. In some critical applications, a backup approach must be implemented to guarantee that the fault is handled in such a way that there will be no damage. Fault-tolerant control is part of this backup approach. It aims at insuring a degraded operation mode in the presence of faults.

The basic vector control schems such as Field-Oriented Control (FOC) or Direct Torque Control (DTC) which are employed to control 3-phase IM under balanced condition cannot be used directly for vector control of 3-phase IM under unbalanced condition (fault condition). If a basic vector control method is used to control unbalanced IM, high oscillations in the machine torque and speed can be observed. In these conditions, it is necessary a new control algorithm is applied [8-23].

The main contribution of this research is to introduce a novel and simple vector control technique based on DTC for 3-phase IM which can be also used for 3-phase IM under fault condition (open-phase fault). Differently from the previous techniques to control IM under open-phase fault (e.g., [8-23]), the rotational transformation matrices are not need to control faulty machine. (the previous methods to control IM in [8-24] are based on FOC). This research is organized as follows: In section 2, d-q model of faulty 3-phase IM is presented. After that, vector control equations for faulty 3-phase IM based on DTC are presented in section 3. The MATLAB simulation results and copmarisions are shown in section 4 and section 5 concludes the paper.

2. Faulty Machine Model

The d-q model of 3-phase IM under open-circuit fault can be shown as following equations [9]:

Received October 26, 2014; Revised December 8, 2014; Accepted December 22, 2014

$$\begin{bmatrix} v_{ds}^{s} \\ v_{qs}^{s} \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} r_s + \left(L_{ls} + \frac{3}{2}L_{ms}\right)\frac{d}{dt} & 0 & \left(\frac{3}{2}L_{ms}\right)\frac{d}{dt} & 0 \\ 0 & r_s + \left(L_{ls} + \frac{1}{2}L_{ms}\right)\frac{d}{dt} & 0 & \left(\frac{\sqrt{3}}{2}L_{ms}\right)\frac{d}{dt} \\ \left(\frac{3}{2}L_{ms}\right)\frac{d}{dt} & \omega_r\left(\frac{\sqrt{3}}{2}L_{ms}\right) & r_r + L_r\frac{d}{dt} & \omega_r L_r \\ -\omega_r\left(\frac{3}{2}L_{ms}\right) & \left(\frac{\sqrt{3}}{2}L_{ms}\right)\frac{d}{dt} & -\omega_r L_r & r_r + L_r\frac{d}{dt} \end{bmatrix} \begin{bmatrix} i_{ds}^{s} \\ i_{qs}^{s} \\ i_{dr}^{s} \\ i_{qr}^{s} \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} \lambda_{ds}^{s} \\ \lambda_{qs}^{s} \\ \lambda_{dr}^{s} \\ \lambda_{qr}^{s} \end{bmatrix} = \begin{bmatrix} \left(L_{ls} + \frac{3}{2}L_{ms}\right) & 0 & \frac{3}{2}L_{ms} & 0 \\ 0 & \left(L_{ls} + \frac{1}{2}L_{ms}\right) & 0 & \frac{\sqrt{3}}{2}L_{ms} \\ \frac{3}{2}L_{ms} & 0 & L_r & 0 \\ 0 & \frac{\sqrt{3}}{2}L_{ms} & 0 & L_r \end{bmatrix} \begin{bmatrix} i_{ds}^{s} \\ i_{qs}^{s} \\ i_{dr}^{s} \\ i_{qr}^{s} \end{bmatrix} \quad (2)$$

$$\tau_e = \frac{Pole}{2}\left(\left(\frac{\sqrt{3}}{2}L_{ms}\right)i_{qs}^{s}i_{dr}^{s} - \left(\frac{3}{2}L_{ms}\right)i_{ds}^{s}i_{qr}^{s}\right) \quad (3)$$

$$\frac{Pole}{2}\left(\tau_e - \tau_l\right) = J\frac{d\omega_r}{dt} + F\omega_r \quad (4)$$

Where, v^s_{ds}, v^s_{qs}, i^s_{ds}, i^s_{qs}, i^s_{dr}, i^s_{qr}, λ^s_{ds}, λ^s_{qs}, λ^s_{dr} and λ^s_{qr} are the d-q axes voltages, currents, and fluxes of the stator and rotor in the stator reference frame (superscript "*s*"). r_s and r_r denote the stator and rotor resistances. L_{ls}, L_{ms} and L_r denote the stator and rotor leakage and mutual inductances. ω_r is the machine speed. τ_e, τ_l, J and F are electromagnetic torque, load torque, inertia and viscous friction coefficient. The d-q model of 3-phase IM under open-circuit fault was obtained using an approach like that used to obtain the model for a healthy 3-phase IM [9].

3. DTC of faulty 3-phase IM

In this section, DTC strategy is adapted to a faulty 3-phase IM (in this paper SVPWM DTC is used). Due to the fact that the unequal parameters in the model of faulty 3-phase IM there is an oscillating term in the electromagnetic torque of machine. It is possible to remove the oscillating term of electromagnetic torque by using The transformation element. This transformation element is:

$$k = \sqrt{3} \Rightarrow \begin{cases} i_{ds}^{s} = i_{ds1}^{s}, i_{qs}^{s} = \sqrt{3}i_{qs1}^{s} \\ v_{ds}^{s} = v_{ds1}^{s}, v_{qs}^{s} = \frac{1}{\sqrt{3}}v_{qs1}^{s} \end{cases} \quad (5)$$

Using (5), the faulty machine model (equations (1)-(4)) can be obtained as following equations:

$$v_{ds1}^{s} = r_s i_{ds1}^{s} + \frac{d\lambda_{ds1}^{s}}{dt} \quad (6)$$

$$\frac{\sqrt{3}}{3}v_{qs1}^{s} = \sqrt{3}r_s i_{qs1}^{s} + \frac{\sqrt{3}}{3}\frac{d\lambda_{qs1}^{s}}{dt} \quad (7)$$

Equations (6) and (7) can be written as:

$$v_{ds1}^{s} = \frac{\lambda_{ds1}^{s}}{T_r\sigma_s} - \frac{M\lambda_{dr1}^{s}}{T_r\sigma_s L_r} + \frac{d\lambda_{ds1}^{s}}{dt} \tag{8}$$

$$v_{qs1}^{s} = 3r_s i_{qs1}^{s} + L_s\sigma_s\frac{di_{qs1}^{s}}{dt} + \frac{M}{L_r}\frac{d\lambda_{qr1}^{s}}{dt} \tag{9}$$

Moreover, the electromagnetic torque of faulty machine is given by:

$$\tau_e = \frac{Pole}{2}\left(i_{qs1}^{s}\lambda_{ds1}^{s} - i_{ds1}^{s}\lambda_{qs1}^{s}\right) \tag{10}$$

Where:

$$\sigma_s = 1 - \frac{M^2}{L_s L_r} \tag{11}$$

Since, the stator flux vector is aligned with d-axis then Equation (8)-(10) can be re-written as (in these equations superscript "*sf*" indicate that the variables are in the stator reference frame:

$$v_{ds1}^{sf} = \frac{|\lambda_s|}{T_r\sigma_s} + \frac{d|\lambda_s|}{dt} \underbrace{- \frac{M}{T_r\sigma_s L_r}\left(\frac{L_r|\lambda_s|}{M} - \frac{L_r L_s}{M}di_{ds1}^{sf} + Mi_{ds1}^{sf}\right)}_{e_{ds1}^{sf}} \tag{12}$$

$$v_{qs1}^{sf} = r_s i_{qs1}^{sf} + L_s\sigma_s\frac{di_{qs1}^{sf}}{dt} + \underbrace{\frac{r_r L_s}{L_r} i_{qs1}^{sf}}_{e_{qs1}^{sf}} \tag{13}$$

$$\tau_e = \frac{Pole}{2}\left(i_{qs1}^{s}|\lambda_s|\right) \tag{14}$$

Based on (12) and (13), the necessary voltages for faulty machine (v_{ds1}^{sf} and v_{qs1}^{sf}) can be produced by 2 PI controllers and e_{ds1}^{sf} and e_{qs1}^{sf}. Therefore, Figure 1 can be presented for vector control based DTC of 3-phase IM under open-phase fault.

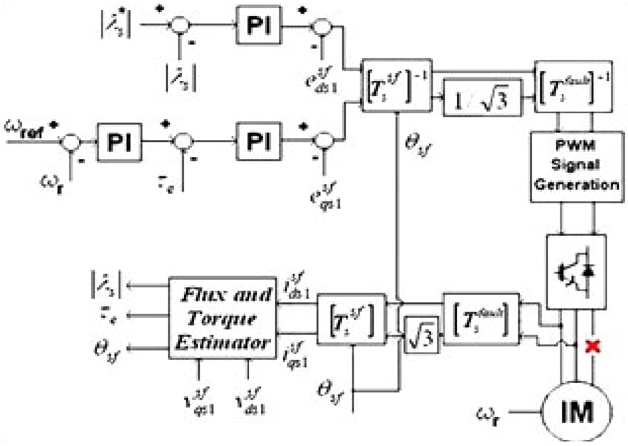


Figure 1. DTC block diagram of faulty 3-phase IM

In this Figure, [T_s^{sf}] performs signal transformation from stator reference frame to stationary reference frame. Moreover, the block [T_s^{fault}] is 2 to 2 transformation for the stator current variables and difined as follows [9]:

$$\left[T_s^{fault}\right] = \frac{\sqrt{2}}{2}\begin{bmatrix} 1 & -1 \\ 1 & 1 \end{bmatrix} \tag{15}$$

In addition:

$$\begin{aligned} |\lambda_s| &= \sqrt{\left(\lambda_{ds1}^s\right)^2 + \left(\lambda_{qs1}^s\right)^2} \\ \theta_{sf} &= \tan^{-1}\left(\frac{\lambda_{qs1}^s}{\lambda_{ds1}^s}\right) \end{aligned} \tag{16}$$

Based on Figure 1, Figure 2 can be proposed for vector control of both healthy and faulty 3-phase IM. To switch between the two conditions (balanced and unbalanced conditions), four switches are used whereby the switches will change positions from balanced condition to unbalanced condition after fault detection. The parameters in the proposed scheme that require to be changed from balanced condition to unbalanced condition are given in Table 1.

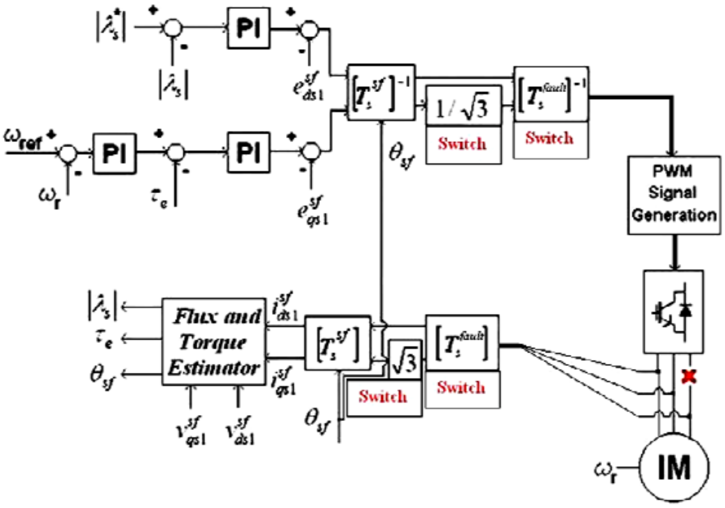


Figure 2. DTC block diagram of healthy and faulty 3-phase IM

Table 1. Comparison between Two Vector Control Techniques

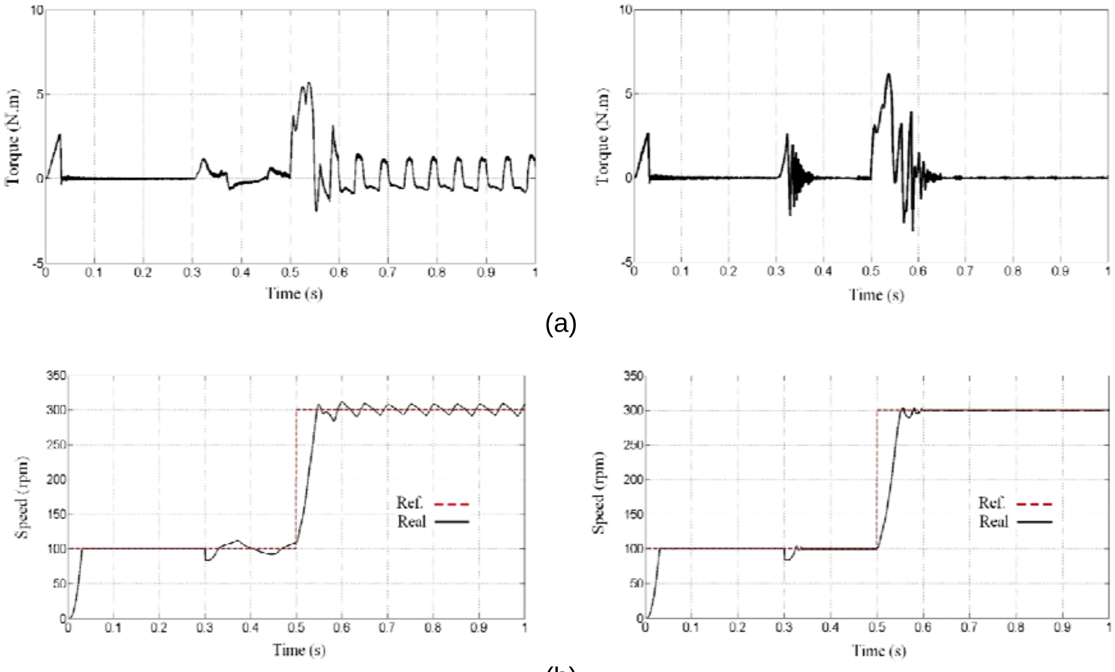
	3 to 2 (2 to 2) transformation matrix for the stator variables:	Transformation matrix for stator q-axis variables:
Healthy 3-phase IM	$\begin{bmatrix} i_{ds}^s \\ i_{qs}^s \end{bmatrix} = \sqrt{\frac{2}{3}}\begin{bmatrix} +1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}\begin{bmatrix} i_{as} \\ i_{bs} \\ i_{cs} \end{bmatrix}$	$k = 1$
Faulty 3-phase IM	$\begin{bmatrix} i_{ds}^s \\ i_{qs}^s \end{bmatrix} = \frac{\sqrt{2}}{2}\begin{bmatrix} 1 & -1 \\ 1 & 1 \end{bmatrix}\begin{bmatrix} i_{as} \\ i_{bs} \end{bmatrix}$	$k = \sqrt{3}$

4. Simulation Results and Comparisions

Some MATLAB simulations were done to evaluate the propsed vector control strategy performance. The 3-phase IM is fed by an ideal 3-leg voltage source inverter. The reference speed is given by: (100, 100, 300, 300)rpm at (0, 0.5, 0.5, 1)s, respectively. The simulated 3-phase machine parameters are given as follows:\

$$v = 125V \ , \ f = 50HZ \ , \ Pole = 4 \ , \ r_s = 20.6\Omega \ , \ r_r = 19.15\Omega$$
$$L_{ls} = 0.0814 \ , \ L_{lr} = 0.0814H \ , \ L_{ms} = 0.851H \ , \ power = 475W$$

The simulation results for the first test, which consists in using the basic DTC approach is shown in Figure 3 (left). In the second test, the proposed DTC approach based on Figure 2 is used for healthy and faulty 3-phase IM. In both tests, the 3-phase machine started in the healthy condition and then at t=0.3s a phase cut-off fault is occured. In Figure 3(a), the torque waveform is presented. Moreover, Figure 3(b) shows the reference and actual value of the motor speed. As can be seen from Figure 3, in the healthy condition, both conventional and proposed vector control scheme show good performance and fast response without any transient and steady-state error. Compared to the basic DTC algorithm, the IM speed and torque of the proposed scheme contains very low speed osillations. Based on Figure 3(a), using proposed DTC scheme, the electromagnetic torque waveforms contain low osillations even after fault condition. It is shown that the proposed DTC scheme for healthy and faulty 3-phase IM vector control has adequate vector control characteristics.



(a)

(b)

Figure 3. Simulation results of the comparison between conventional DTC (left) and proposed DTC (right) for vector control of healthy and faulty 3-phase IM; (a) Torque, (b) Speed

5. Conclusion

In this paper, two control strategies for vectrol control of healthy and faulty 3-phase IM drive based on DTC has been discussed and simulated (the fault condition in this paper is limited to open-circuit fault). In the first scheme, basic DTC algorithem is used for both healthy and faulty 3-phase IM. The simulation results of the basic DTC shown that, the conventional DTC algorithem is unable to control the faulty 3-phase IM properly.

The second vector control scheme (proposed method) is derived from the conventional DTC scheme by some modifications on it. The proposed method partially compensated the ripples that occur on the speed and torque responces of conventional DTC algorithem. Analyzing the simulation results, it is possible to implement high performance vactor control of AC 3-phase IM drives with a faulty 3-phase IM.

Although this method has a simple implementation but it has some drawbacks such as torque distortions, low-speed operation problems.

References

[1] AB Jidin, NRN Idris, AHM Yatim, ME Elbuluk, T Sutikno. A wide-speed high torque capability utilizing overmodulation strategy in DTC of induction machines with constant switching frequency controller. *IEEE Transactions on Power Electronics*, 2012; 27(5), 2566-2575.

[2] M Arkan, DK Perovic, P Unsworth. *Online stator fault diagnosis in induction motors*. In IEE Proceedings Electric Power Applications. 2001; 406-418.

[3] AM Da Silva, RJ Povinelli, NA Demerdash. Induction machine broken bar and stator short-circuit fault diagnostics based on three-phase stator current envelopes. *IEEE Transactions on Industrial Electronics*, 2008; 55(3), 1310-1318.

[4] A Siddique, GS Yadava, B Singh. A review of stator fault monitoring techniques of induction motors. *IEEE Transactions on Energy Conversion*, 2005; 20(1), 106-114.

[5] Y Lei, Z He, Y Zi. Application of the EEMD method to rotor fault diagnosis of rotating machinery. *Mechanical Systems and Signal Processing*, 2009; 23(4), 1327-1338.

[6] A Bellini, A Yazidi, F Filippetti, C Rossi, GA Capolino. High frequency resolution techniques for rotor fault detection of induction machines. *IEEE Transactions on Industrial Electronics*, 2008; 55(12), 4200-4209.

[7] M Haji, HA Toliyat. *Pattern recognition-a technique for induction machines rotor fault detection" eccentricity and broken bar fault*. In Industry Applications Conference. 2001; 1572-1578.

[8] M Jannati, E Fallah. *Modeling and Vector Control of Unbalanced induction motors (faulty three phase or single phase induction motors)*. 1st. Conference on Power Electronic & Drive Systems & Technologies (PEDSTC). 2010; 208-211.

[9] M Jannati, NRN Idris, MJA Aziz. Speed Sensorless Fault Tolerant Drive System of 3-Phase Induction Motor Using Switching Extended Kalman Filter. *TELKOMNIKA Indonesian Journal of Electrical Engineering*. 2014; 12(11).

[10] M Jannati, NRN Idris, MJA Aziz. *A new method for RFOC of Induction Motor under open-phase fault*. In Industrial Electronics Society, IECON. 2013; 2530-2535.

[11] M Jannati, NRN Idris, Z Salam. *A New Method for Modeling and Vector Control of Unbalanced Induction Motors*. IEEE Energy Conversion Congress and Exposition. 2012; 3625-3632.

[12] M Jannati, A Monadi, NRN Idris, MJA Aziz, AAM Faudzi. Vector Control of Faulty Three-Phase Induction Motor with an Adaptive Sliding Mode Control. *Prz Elektrotech*. 2013; 89(12): 116-120.

[13] M Jannati, SA Anbaran, MI Alsofyani, NRN Idris, MJA Aziz. *Modeling and RFOC of faulty three-phase IM using Extended Kalman Filter for rotor speed estimation.* In 8th International Power Engineering and Optimization Conference (PEOCO). 2014; 270-275.

[14] M Jannati, A Monadi, NRN Idris, MJA Aziz. Speed Sensorless Vector Control of Unbalanced Three-Phase Induction Motor with Adaptive Sliding Mode Control. *International Journal of Power Electronics and Drive Systems (IJPEDS)*. 2014; 4(3): 406-418.

[15] M Jannati, NRN Idris, MJA Aziz. Indirect Rotor Field-Oriented Control of Fault-Tolerant Drive System for Three-Phase Induction Motor with Rotor Resistance Estimation Using EKF. *TELKOMNIKA Indonesian Journal of Electrical Engineering*. 2014; 12(9).

[16] M Jannati, NRN Idris, MJA Aziz. Indirect Flux-Oriented Control of Faulty Single-Phase Induction Motors. *TELKOMNIKA Indonesian Journal of Electrical Engineering*. 2014; 12(10): 7167-7175.

[17] M Jannati, SA Anbaran, NRN Idris, MJA Aziz. A Novel Technique for Vector Control of Single-Phase Induction Motors Based on Rotor Field-Oriented Control. *TELKOMNIKA Indonesian Journal of Electrical Engineering*. 2014; 12(12).

[18] M Jannati, NRN Idris, MJA Aziz. A Simple Vector Control Method Based on Field-Oriented Control for Faulty 3-Phase Induction Motor under Open-Circuit Fault. *TELKOMNIKA Indonesian Journal of Electrical Engineering*. 2014; 12(12).

[19] M Jannati, NRN Idris, MJA Aziz. Speed Sensorless Fault-Tolerant Drive System of 3-Phase Induction Motor Using Switching Extended Kalman Filter. *TELKOMNIKA Indonesian Journal of Electrical Engineering*. 2014; 12(11).

[20] M Jannati, A Monadi, SA Anbaran, NRN Idris, MJA Aziz. An Exact Model for Rotor Field-Oriented Control of Single-Phase Induction Motors. *TELKOMNIKA Indonesian Journal of Electrical Engineering*. 2014; 12(7): 5110-5120.

[21] M Jannati, NRN Idris, MJA Aziz, A Monadi, AAM Faudzi. A Novel Scheme for Reduction of Torque and Speed Ripple in Rotor Field Oriented Control of Single Phase Induction Motor Based on Rotational Transformations. *Research Journal of Applied Sciences, Engineering and Technology*. 2014; 7(16): 3405-3409.

[22] M Jannati, E Fallah. *A New Method for Speed Sensorless Vector Control of Single-Phase Induction Motor Using Extended Kalman Filter*. Conf. Proc. Of ICEE. 2011; 1-5.

[23] M Jannati, SH Asgari, NRN Idris, MJA Aziz. Speed Sensorless Direct Rotor Field-Oriented Control of Single-Phase Induction Motor Using Extended Kalman Filter. *International Journal of Power Electronics and Drive Systems (IJPEDS)*. 2014; 4(4).

[24] M Jannati, NRN Idris, MJA Aziz. *A simple vector control technique for 3-phase induction motor under open-phase fault based on GA for tuning of speed PI controller*. In 2014 IEEE Conference on Energy Conversion (CENCON). 2014; 213-218.