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Speed Control of 3-phase Induction Motors under Fault Conditions Supplied by Wind Turbine Using Indirect Vector Control

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ABSTRACT

This article studies speed control of 3-phase Induction Motors (IMs) under fault conditions supplied by wind turbine using Indirect Vector Control (IVC). The wind turbine plays as a prime mover to a connected DC generator. Pulse Width Modulation (PWM) is used to obtain 3-phase AC voltage from the DC generator output. The proposed modified controller is able to control a star-connected 3-phase IM under normal, stator winding open-circuit fault and speed-sensor fault conditions. Simulation results are presented and shown the performance, validity and possibility of the proposed technique. The results demonstrate that, the proposed scheme provides good dynamic performance especially in reduction of IM speed and torque pulsations.

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1. INTRODUCTION

The AC drives, are used in a wide range of industrial applications as they are more reliable than the DC drives. Indirect Vector Control (IVC) method is one of the useful methods for implementing high performance vector control of Induction Motor (IM) drive systems [1]-[5]. IVC is widely used for electrical drives since it provides very accurate and quick responses. However, this technique does not have good dynamic performance under fault conditions such as open-phase/short-circuit fault in stator/rotor windings (for wound rotor type) and/or mechanical/electrical fault in sensors [6]-[17].

In the recent years, the reliability of the electric machine drives, particularly in some critical applications has become a very interesting research topic. In the literature, many researches have been presented on the fault-tolerant control strategies of electric machine drives [6]-[17]. In [6]-[9], some methods to control a 3-phase IM under speed-sensor fault, in [10]-[14], different methods to control a 3-phase motor under open-circuit fault and in [15]-[17], some techniques to control an IM under inverter faults have been proposed.

In this article, we propose speed control of a star-connected 3-phase IM under open-phase fault and speed sensor fault supplied by wind turbine using IVC method (It can be pointed out none of the presented methods in [6]-[17] proposes an analysis in the case of two types of faults for a 3-phase IM). The proposed method can be employed in applications where require fault-tolerant control. Simulation tests are presented to show the good performance of the proposed strategy. This paper is organized as follows: after introduction in section 1, in section 2, the system under study is presented. In section 3, the vector control of a 3-phase IM under normal and open-circuit fault conditions is presented. The proposed method to estimate motor speed is shown in section 4. To check the performance of the proposed methodology, simulation results are presented in section 5. Conclusions are listed in section 6.

2. SYSTEM UNDER STUDY

The system under study consists of wind turbine which plays as a prime mover to a connected DC generator. PWM is used to obtain 3-phase AC voltage from the DC generator output. The 3-phase AC voltage of PWM is supplied to the IM. The proposed controller based on IVC is used to speed control of IM. The block diagram of the system is shown in Figure 1.

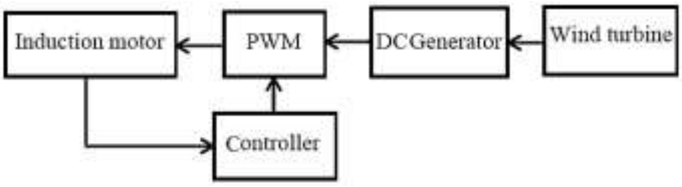


Figure 1. Block diagram of the system

2.1. Wind Turbine Model

The wind turbine is characterized by no dimensional curves of the power coefficient as a function of both the tip speed ratio and the blade pitch angle [19],[20].

$$C_p(\lambda,\beta)=C_1(C_2/\lambda_i-C_3.\beta-C_4)e(-C_5/\lambda_i)+C_6.\lambda \tag{1}$$

where [19],

$$\begin{aligned} &C_1=0.5176 \quad , \quad C_2=116 \quad , \quad C_3=0.4 \\ &C_4=5 \quad , \quad C_5=21 \quad , \quad C_6=0.0068 \end{aligned} \tag{2}$$

$$\lambda=\omega_t R/V_\omega \tag{3}$$

Moreover, β is the blade pitch angle, λ is the tip speed ratio, R is the wind turbine rotor radius, V_ω is the wind speed, C_P is the wind power coefficient and ω_t is the mechanical angular rotor speed of the wind turbine. The equation between λ and β can be expressed as [19],[20]:

$$\frac{1}{\lambda_i}=\frac{1}{\lambda+0.08\beta}-\frac{0.035}{\beta^3+1} \tag{4}$$

The maximum value of C_P characteristics is achieved for β=0 and λ=8.1. This particular value of λ is defined as the nominal value. The power output equation of wind turbine can be expressed as:

$$P_t=\frac{1}{2}\rho\Pi C_p V(\lambda,\beta)^3 R_A^2/735 \tag{5}$$

where, P_t is the wind power, ρ is the air density, V is the wind speed and R_A is the area of turbine blades.

2.2. DC Generator Model

The DC generator can be written in terms of following equations [19]:

$$V_f=R_f i_f+L_f\frac{di_f}{dt} \tag{6}$$

$$V_a = R_L i_a + L_L \frac{di_a}{dt} \tag{7}$$

$$i_f \omega M_{af} = R_t i_a + L_t \frac{di_a}{dt} \tag{8}$$

where, i_a, V_a are the armature generator current and terminal voltage. i_f, V_f are the field generator current and voltage. R_a, L_a are the armature resistance and inductance. R_f, L_f are the field resistance and inductance. M_{af} is the mutual inductance between stator and rotor. ω is speed. $R_t=R_a+R_L$. $L_t=L_a+L_L$. R_L, L_L are the load resistance and inductance.

2.3. 3-Phase IM Model

For the purposes of the present study, the 3-phase IM is described by the following equations (in these equations superscript "*s*" indicates the use of a stationary reference frame):

Stator voltage equations:

$$\begin{bmatrix} v_{ds}^s \\ v_{qs}^s \end{bmatrix} = \begin{bmatrix} r_s + L_{ds}\frac{d}{dt} & 0 \\ 0 & r_s + L_{qs}\frac{d}{dt} \end{bmatrix} \begin{bmatrix} i_{ds}^s \\ i_{qs}^s \end{bmatrix} + \begin{bmatrix} M_d \frac{d}{dt} & 0 \\ 0 & M_q \frac{d}{dt} \end{bmatrix} \begin{bmatrix} i_{dr}^s \\ i_{qr}^s \end{bmatrix} \tag{9}$$

Rotor voltage equations:

$$\begin{bmatrix} v_{dr}^s \\ v_{qr}^s \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix} = \begin{bmatrix} M_d \frac{d}{dt} & \omega_r M_q \\ -\omega_r M_d & M_q \frac{d}{dt} \end{bmatrix} \begin{bmatrix} i_{ds}^s \\ i_{qs}^s \end{bmatrix} + \begin{bmatrix} r_r + L_r \frac{d}{dt} & \omega_r L_r \\ -\omega_r L_r & r_r + L_r \frac{d}{dt} \end{bmatrix} \begin{bmatrix} i_{dr}^s \\ i_{qr}^s \end{bmatrix} \tag{10}$$

Torque equations:

$$T_e = \frac{pole}{2}\left(M_q i_{qs}^s i_{dr}^s - M_d i_{ds}^s i_{qr}^s\right) \tag{11}$$

$$T_e - T_l = \frac{2}{pole}\left(J \frac{d}{dt}\omega_r + B\omega_r\right) \tag{12}$$

where, v^s_{ds}, v^s_{qs}, v^s_{dr}, v^s_{qr}, i^s_{ds}, i^s_{qs}, i^s_{dr}, i^s_{qr} are the stator voltages, the rotor voltages, the stator currents and the rotor currents. r_s, r_r, L_{ds}, L_{qs}, L_r, M_d, M_q are the stator and rotor resistances, the stator and rotor self and mutual inductances. ω_r is the motor electrical speed. T_e, T_l, J and B are the electromagnetic torque, the load torque, the moment of inertia and the viscous friction coefficient respectively. Notice that (9)-(12) indicates normal 3-phase IM if [18],

$$M_d = \frac{3}{2}L_{ms}\ ,\ M_q = \frac{3}{2}L_{ms}\ ,\ L_{ds} = L_{ls} + \frac{3}{2}L_{ms}\ ,\ L_{qs} = L_{ls} + \frac{3}{2}L_{ms} \tag{13}$$

and faulty 3-phase IM (3-phase IM under stator winding open-circuit fault) if [13],

$$M_d = \frac{3}{2}L_{ms}\ ,\ M_q = \frac{\sqrt{3}}{2}L_{ms}\ ,\ L_{ds} = L_{ls} + \frac{3}{2}L_{ms}\ ,\ L_{qs} = L_{ls} + \frac{1}{2}L_{ms} \tag{14}$$

3. IVC OF A 3-PHASE IM

Among the various control techniques, IVC technique is more convenient. Due to the unsymmetrical structure of a 3-phase IM under open-circuit fault, the regular VC technique cannot be used for faulted IM. If regular VC technique is used to control faulted IM significant oscillations in the motor torque are produced [10]-[13]. It was recommended in [10], using suitable transformation matrices it is possible to remove the unsymmetrical structure of a 3-phase IM under open-circuit fault. These transformation matrices for the stator voltage and current variables are as (15) and (16):

$$\left[T_{si}^{e}\right]=\begin{bmatrix} \frac{M_d}{M_q}\cos\theta_e & \sin\theta_e \\ -\frac{M_d}{M_q}\sin\theta_e & \cos\theta_e \end{bmatrix} \tag{15}$$

$$\left[T_{sv}^{e}\right]=\begin{bmatrix} \frac{M_q}{M_d}\cos\theta_e & \sin\theta_e \\ -\frac{M_q}{M_d}\sin\theta_e & \cos\theta_e \end{bmatrix} \tag{16}$$

where, θ_e is the angle between the stationary reference frame and the rotating reference frame (in this paper, the superscript "e" indicates the variables are in a rotating reference frame). Using (15) and (16), the new mathematical model of the 3-phase IM can be written as [10]:

Stator voltage equations:

$$\begin{bmatrix} v_{ds}^{e} \\ v_{qs}^{e} \end{bmatrix}=\begin{bmatrix} r_s+L_{qs}\frac{d}{dt} & -\omega_e L_{qs} \\ \omega_e L_{qs} & r_s+L_{qs}\frac{d}{dt} \end{bmatrix}\begin{bmatrix} i_{ds}^{e} \\ i_{qs}^{e} \end{bmatrix}+\begin{bmatrix} M_q\frac{d}{dt} & -\omega_e M_q \\ \omega_e M_q & M_q\frac{d}{dt} \end{bmatrix}\begin{bmatrix} i_{dr}^{e} \\ i_{qr}^{e} \end{bmatrix}+\begin{bmatrix} \frac{M_q^2}{M_d^2}r_s-r_s & 0 \\ 0 & \frac{M_q^2}{M_d^2}r_s-r_s \end{bmatrix}\begin{bmatrix} i_{ds}^{-e} \\ i_{qs}^{-e} \end{bmatrix} \tag{17}$$

Rotor voltage equations:

$$\begin{bmatrix} 0 \\ 0 \end{bmatrix}=\begin{bmatrix} M_q\frac{d}{dt} & -(\omega_e-\omega_r)M_q \\ (\omega_e-\omega_r)M_q & M_q\frac{d}{dt} \end{bmatrix}\begin{bmatrix} i_{ds}^{e} \\ i_{qs}^{e} \end{bmatrix}+\begin{bmatrix} r_r+L_r\frac{d}{dt} & -(\omega_e-\omega_r)L_r \\ (\omega_e-\omega_r)L_r & r_r+L_r\frac{d}{dt} \end{bmatrix}\begin{bmatrix} i_{dr}^{e} \\ i_{qr}^{e} \end{bmatrix} \tag{18}$$

Torque equation:

$$T_e=\frac{pole}{2}\left(M_q i_{qs}^{s} i_{dr}^{s}-M_q i_{ds}^{s} i_{qr}^{s}\right) \tag{19}$$

where,

$$\begin{aligned} \begin{bmatrix} i_{ds}^{e} \\ i_{qs}^{e} \end{bmatrix}&=\begin{bmatrix} \cos\theta_e & \sin\theta_e \\ -\sin\theta_e & \cos\theta_e \end{bmatrix}\begin{bmatrix} i_{ds}^{s} \\ i_{qs}^{s} \end{bmatrix} \\ \begin{bmatrix} i_{ds}^{-e} \\ i_{qs}^{-e} \end{bmatrix}&=\begin{bmatrix} \cos^2\theta_e & -\sin\theta_e\cos\theta_e \\ -\sin\theta_e\cos\theta_e & \sin^2\theta_e \end{bmatrix}\begin{bmatrix} i_{ds}^{e} \\ i_{qs}^{e} \end{bmatrix} \end{aligned} \tag{20}$$

In (17), ω_e is the angular velocity of the rotor field-oriented reference frame. Since in the rotor field-oriented control method $\lambda_{dr}^{e}=|\lambda_r|$ and $\lambda_{qr}^{e}=0$, from (17)-(19) we can write:

$$|\lambda_r|=\frac{M_q i_{ds}^{e}}{1+\frac{L_r}{r_r}\frac{d}{dt}} \tag{21}$$

$$T_e = \frac{pole}{2}\frac{M_q}{L_r}|\lambda_r| i_{qs}^e \tag{22}$$

$$\omega_e = \omega_r + \frac{M_q i_{qs}^e}{\frac{L_r}{r_r}|\lambda_r|} \tag{23}$$

$$v_{ds}^e = v_{ds}^{ref} + v_{ds}^d + v_{ds}^{-e} \tag{24}$$

$$v_{qs}^e = v_{qs}^{ref} + v_{qs}^d + v_{qs}^{-e} \tag{25}$$

where,

$$\begin{aligned}
v_{ds}^d &= -\omega_e i_{qs}^e (L_{qs} - \frac{M_q^2}{L_r}) + (\frac{M_q}{L_r})(\frac{M_q i_{ds}^e - |\lambda_r|}{T_r}) \\
v_{ds}^{ref} &= (\frac{r_s M_q^2 + r_s M_d^2}{2M_d^2}) i_{ds}^e + (L_{qs} - \frac{M_q^2}{L_r})\frac{di_{ds}^e}{dt} \\
v_{qs}^d &= \omega_e i_{ds}^e (L_{qs} - \frac{M_q^2}{L_r}) + \omega_e M_q \frac{|\lambda_r|}{L_r} \\
v_{qs}^{ref} &= (\frac{r_s M_q^2 + r_s M_d^2}{2M_d^2}) i_{qs}^e + (L_{qs} - \frac{M_q^2}{L_r})\frac{di_{qs}^e}{dt} \\
\begin{bmatrix} v_{ds}^{-e} \\ v_{qs}^{-e} \end{bmatrix} &= (\frac{r_s M_q^2 - r_s M_d^2}{2M_d^2}) \begin{bmatrix} \cos 2\theta_e & -\sin 2\theta_e \\ -\sin 2\theta_e & -\cos 2\theta_e \end{bmatrix} \begin{bmatrix} i_{ds}^e \\ i_{qs}^e \end{bmatrix}
\end{aligned} \tag{26}$$

In (26), $T_r = L_r/r_r$. From the equations (21)-(26), it is possible to adopt the IVC scheme for a 3-phase IM under open-circuit fault condition. The block diagram of the IVC for a 3-phase IM under open-circuit fault condition is shown in Figure 2. In Figure 2 [10]:

$$[T_s] = \frac{\sqrt{2}}{2}\begin{bmatrix} 1 & -1 \\ 1 & 1 \end{bmatrix} \tag{27}$$

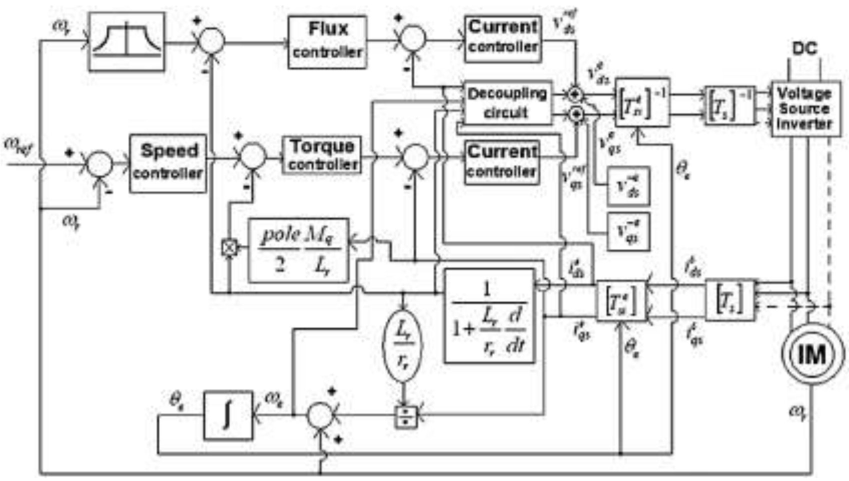


Figure 2. Block diagram of the IVC for a 3-phase IM under open-circuit fault condition

Notice that by only changing in motor parameter as given in (13) and changing in the transformation matrix as given in (28) the proposed scheme can be used for VC of the 3-phase IM under normal condition. In this condition, Figure 2 can be simplified as Figure 3 which is the same as regular controller.

$$[T_s]=\sqrt{\frac{2}{3}}\begin{bmatrix} +1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \tag{28}$$

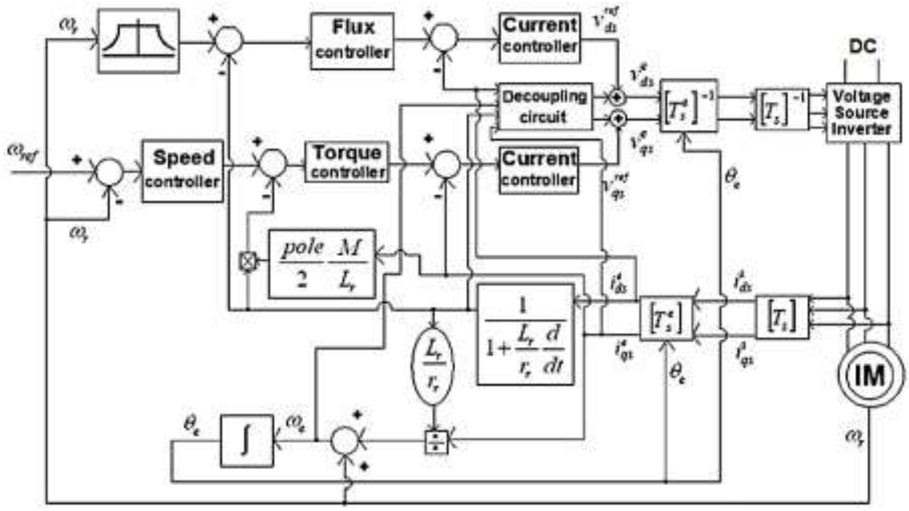


Figure 3. Block diagram of the regular IVC for a 3-phase IM

$$\begin{aligned} & M=\frac{3}{2}L_{ms} \\ & [T_s^e]=\begin{bmatrix} \cos\theta_e & \sin\theta_e \\ -\sin\theta_e & \cos\theta_e \end{bmatrix} \\ & [T_s]=\sqrt{\frac{2}{3}}\begin{bmatrix} +1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \end{aligned} \tag{29}$$

4. SPEED ESTIMATION OF A 3-PHASE IM

In order to compensate speed-sensor fault, this paper investigates a method that uses an estimator for estimation of the rotor speed. In this paper, a technique based on measurable stator variables (currents and voltages) is proposed to estimate the angular velocity of the rotor field-oriented reference frame (ω_e). Then, using (23), the motor speed is estimated.

The d-axis voltage is given by:

$$\begin{aligned} & v_{ds}^{e}=r_s i_{ds}^{e}-\hat{\omega}_e L_{qs} i_{qs}^{e}-\hat{\omega}_e M_q i_{qr}^{e}+\left(\frac{M_q^2}{M_d^2}r_s-r_s\right)i_{ds}^{-e} \\ & v_{ds}^{e}=r_s i_{ds}^{e}-\hat{\omega}_e i_{qs}^{e}\left(L_{qs}-\frac{M_q^2}{L_r}\right)+\left(\frac{M_q^2}{M_d^2}r_s-r_s\right)i_{ds}^{-e} \\ & \hat{\omega}_e=-\frac{1}{i_{qs}^{e}\left(L_{qs}-\frac{M_q^2}{L_r}\right)}\left(v_{ds}^{e}-r_s i_{ds}^{e}-\left(\frac{M_q^2}{M_d^2}r_s-r_s\right)i_{ds}^{-e}\right) \end{aligned} \tag{30}$$

From these equations, an estimate of the motor speed, can be calculated by:

$$\hat{\omega}_r = \hat{\omega}_e - \frac{M_q i_{qs}^e}{\frac{L_r}{r_r}|\lambda_r|} \tag{31}$$

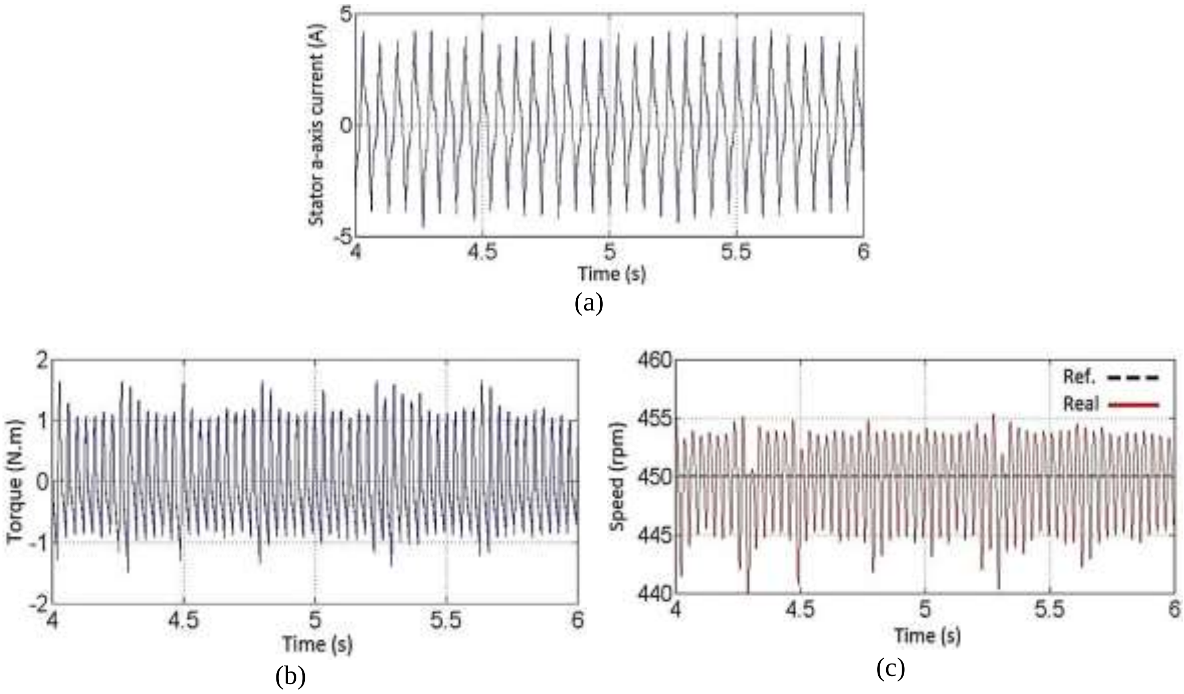
Notice that (31) can be used for estimation of motor speed in the normal and open-circuit fault conditions by only changing in motor parameter as given in (13) and (14).

5. SIMULATION RESULTS AND DISCUSSION

The regular (based on Figure 3) and proposed (based on Figure 2 and equations (30), (31)) controllers for a star-connected 3-phase IM is developed and simulated using Matlab software. The parameters of the simulated motor are as follows:

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

Simulation results of the conventional and proposed controllers such as stator a-axis current, torque and motor speed are shown in Figures 4-6. Figure 4 shows simulation results of the conventional technique (based on Figure 3) for VC of a 3-phase IM under open-circuit fault (Figure 4(a): stator a-axis current, Figure 4(b): torque and Figure 4(c): speed). Figure 5 shows simulation results of the proposed controller without speed estimator (based on Figure 2) for VC of a 3-phase IM under open-circuit fault (Figure 5(a): stator a-axis current, Figure 5(b): torque and Figure 5(c): speed). Figure 6 shows simulation results of the proposed controller with speed estimator (based on Figure 2 and equations (30), (31)) for VC of a 3-phase IM under open-circuit fault and speed sensor fault (Figure 6(a): stator a-axis current, Figure 6(b): torque and Figure 6(c): speed). To analyze dynamic and steady-state performance of all cases the motor is started on no-load with speed of 450rpm. At t=2s an open-phase fault is happened in phase "c". The simulation carried over a sampling time of 0.0001s.



(a)

(b)

(c)

Figure 4. Simulation results of the conventional technique for VC of a 3-phase IM under open-circuit fault; (a) Stator a-axis current, (b) Torque and (c) Speed

As can be seen both regular and proposed schemes are able to reach steady state 450rpm (see Figure 4 (c) and Figure 5 (c)). It can be observed from Figure 4 and Figure 5 that the dynamic performance of the proposed controller is better than regular controller. Using conventional controller, the pick to pick torque oscillation is ~ 2.4 N.m (see Figure 4 (b)) but using proposed controller, the pick to pick torque oscillation is ~ 0.2 N.m (see Figure 5 (b)). It is also evident from Figure 6 that using proposed IVC technique, the estimated speed of the 3-phase IM under open-circuit fault can follow the real speed without any steady-state error. In this case the pick to pick torque oscillation is ~ 0.3 N.m (see Figure 6 (b)). The presented results show a considerable reduction in speed and torque ripples and better steady-state behaviour when the proposed controller is used.

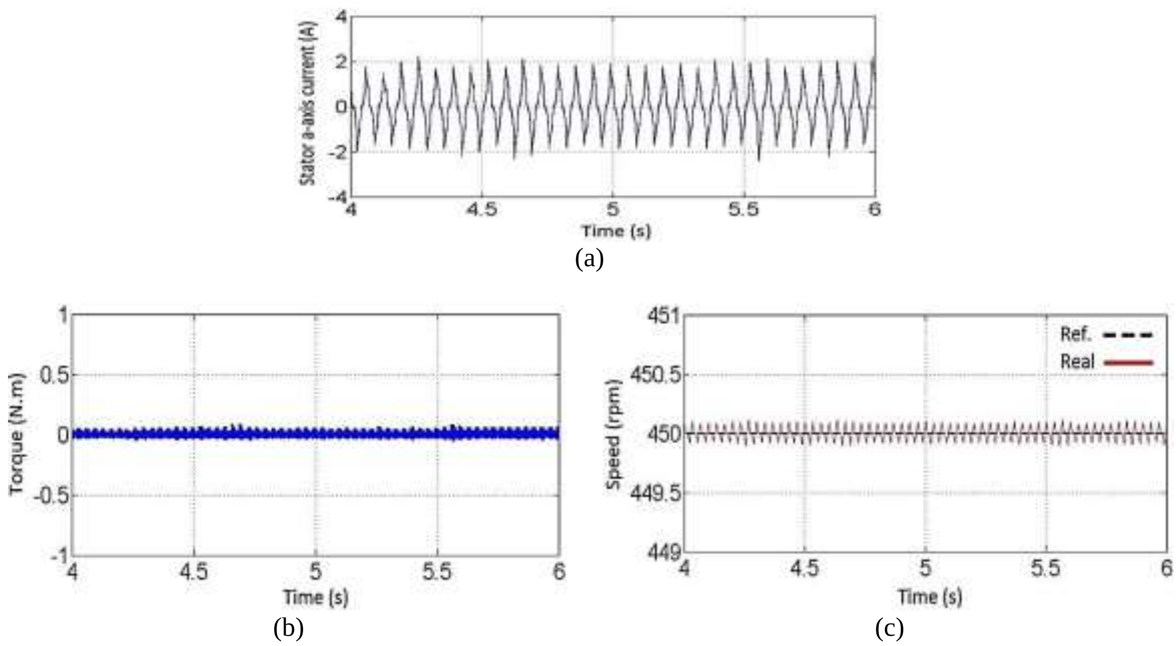


Figure 5. Simulation results of the proposed controller without speed estimator for VC of a 3-phase IM under open-circuit fault; (a) Stator a-axis current, (b) Torque and (c) Speed

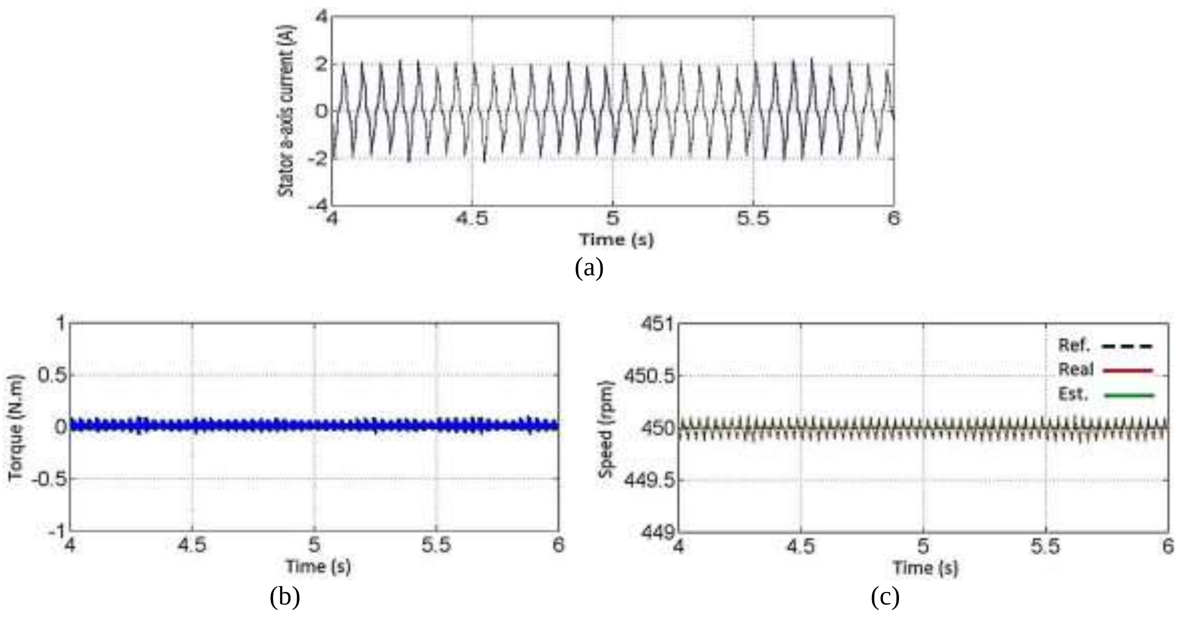


Figure 6. Simulation results of the proposed controller with speed estimator for VC of a 3-phase IM under open-circuit fault and speed sensor fault; (a) Stator a-axis current, (b) Torque and (c) Speed

6. CONCLUSION

This paper presented speed control of a 3-phase IM under fault conditions supplied by wind turbine using IVC strategy. This paper has shown that with some changes in the regular IVC strategy it is feasible to use same controller for VC of a star-connected 3-phase IM under open-circuit fault and speed-sensor fault. The simulation results have shown the correctness and possibility of the proposed methodology. The results demonstrate that in comparison with the regular IVC strategy, the performance of the proposed technique is satisfactory for VC of a 3-phase IM during fault conditions particularly in reduction of the motor speed and torque ripples.

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