Simulation Analysis for Induction Motor Drive Fault Detection and Localization Under Variable Load and Speed Operation

Sazali Yaacob*, Amir Rasyadan †, Pranesh Krishnan†

* UniKL Malaysian Spanish Institute, Malaysia
† UniKL Malaysian Spanish Institute, Malaysia

E-mail: sazali.yaacob@unikl.edu.my

Abstract. The induction motors are widely used in the industry for their advantage of being reliable, rugged, and simple in construction. Nonetheless, the use of inverter-based drives has increased the overall system failure possibility mainly because of the power electronics switches used in the inverter itself. For that reason, it is crucial to monitor the inverter switches health during operation to avoid total system breakdown. A method to do so is by using the current vector trajectory analysis on the induction motor stator current signal. However, one disadvantage of using this method is that it is negatively affected by the load and speed variations. This paper is intended to discuss further on the matter and look into the methods that can be used to minimize the effects associated with the load and speed variations using computer simulation analysis.

1. Introduction
Traditionally, the induction motors were driven by fixed speed drives limited for use in applications that only requires simple electrical to mechanical power conversions system. However, this limitation has been lifted off with the introduction of inverter-based drives, the use of inductions motors has now been extended to myriad of new applications that may also involve complex and precise speed control. Nonetheless, the use of the power electronic switches in the inverter have also introduce new failure possibilities. The power inverter is known to be the weakest component in the drive system with around 38% of the drive faults are due to their power switch devices [1-3].

Generally, the faults can be classified into open-circuit and short-circuit fault. A short-circuit switch can generate abnormal overcurrent that could quickly destroy the motor whereas an open-circuit switch fault does not completely halt motor operation, but it stresses the system, noise can be induced causing performance degradation and by time will also lead to total system failure [4-6]. This paper only focuses on the open-circuit fault analysis since the short-circuit faults are mostly detected by means of hardware circuit [7-9].

Based on previous literatures, there are a number of works that focuses on the inverter open-circuit Fault Detection and Localization (FDL). One of the most popular FDL method is the current vector trajectory analysis which uses the Lissajous Curve of the phase current signals to detect the faulty inverter leg and then calculating the average value within one current period to localize the faulty...
switch. It is simple, does not require extra sensors, and produces considerably fast detection time [8, 10].

The downside of this method is that it is dependent on the load and the supply frequency variations applied to control the speed of the motor [7, 11]. In separate works, different current signal normalization techniques were discussed, namely; Maximum Current normalization [7], Schmitt Trigger model [11, 12], and Park’s Vector Modulus (PVM) Normalization [8, 13]. However, their works are short in terms of comparison between the three methods. Further studies are required to understand why the current normalization is needed and the difference on how the three methods work.

This paper is intended to present an analysis on the induction motor operation under variable load and speed especially on the stator current signal which is the one being monitored for fault detection and localization. The use of the three current normalization methods are then discussed and being compared to see which performs the best.

2. Induction Motor Drive with Fault Detection and Localization Model

To further look into the details of the current vector trajectory based FDL under variable load and speed operation, it is convenient to analyze the system in a computer simulation software.

2.1. Induction motor drive model

The induction motor drive model is built in MATLAB Simulink. The model consists of three main parts; a Sinusoidal Pulse Width Modulation (SPWM) signal generator, a three-phase voltage source inverter, and a three-phase induction motor model. The SPWM generator is built customly by using three sinusoidal reference signals that each set 120-degree phase apart from other; \(V_a\), \(V_b\), \(V_c\) are compared with a high frequency triangular signal \(V_T\). \(V_a\), \(V_b\), \(V_c\) are generated using a phase accumulator. The reference signals modulate the three-phase PWM duty ratio, hence, their frequency is the desired fundamental frequency \(f_o\) of the inverter. This way, the frequency of the SPWM signal can be varied as intended to provide control over the speed of the motor. The fault control block is then used to simulate the open-circuit conditions by overriding any of the six switches PWM. Figure 1 (a) shows the SPWM signal generator with the fault control block and Figure 1 (b) shows the three-phase inverter connected to the induction motor model.

![Figure 1](image)

**Figure 1.** (a) SPWM generator and fault control. (b) Three-phase inverter connected to Induction motor model.

To simulate the variable load and speed operation, the induction motor DQ-model is supplied with a load torque profile and SPWM reference frequency profile that consists of ramp, step, and sinusoidal inputs built using piecewise function shown in equation (1), (3), and (4) respectively.
Ramp: \[ Y(t) = m \times Y(t - \tau) + A \] (1)

\[ m = \frac{Y_2 - Y_1}{t_2 - t_1} \] (2)

Step: \[ Y(t) = C \] (3)

Sinusoidal: \[ Y(t) = A \sin(2\pi f(t - \tau)) + B \] (4)

Where:
- \( A \) = Amplitude Scale
- \( B \) = Amplitude Shift
- \( C \) = Constant
- \( \tau \) = Time shift
- \( m \) = Gradient

Based on these equations, the load and SPWM reference frequency profile can be built as intended.

2.2. Fault Detection and Localization algorithm

The Fault Detection algorithm requires the monitored three-phase current to be transformed into an equivalent two-phase component by using Park’s transformation. The relations are given in (5) and (6):

\[ i_d = \frac{2}{\sqrt{3}} i_a - \frac{1}{\sqrt{6}} i_b - \frac{1}{\sqrt{6}} i_c \] (5)

\[ i_q = \frac{1}{\sqrt{2}} i_b - \frac{1}{\sqrt{2}} i_c \] (6)

From the two-phase current components \( i_d \) and \( i_q \), the Lissajous figure can be plotted to get a good view of the phase current trajectory. Under healthy inverter operation, a circular figure is formed within one fundamental current period, and if faults occur the figure should deform accordingly.

To extract valuable information from the Lissajous figure, the slope \( P \) between two points of the Lissajous figure is calculated, this value reveals the condition of the inverter. The use of the slope calculation method for inverter fault detection was discussed in [8, 12] with the equation as follows.

\[ P = \frac{\Delta i_d}{\Delta i_q} = \frac{i_d(k-h)-i_d(k)}{i_q(k-h)-i_q(k)} \] (7)

Where \( k \) is the present sample and \( h \) is the previous number of sample.

During healthy inverter operation, the Lissajous figure is circular in shape, hence the slope \( P \) values are always varying throughout one current period, but during open switch faults, \( P \) can take only one constant value (zero when leg 2 faulty, \( \sqrt{3} \) when leg 1 faulty, or \( -\sqrt{3} \) when leg 3 is faulty) during half a current period depending on which leg is faulty.

The Fault Localization algorithm is then used to localize the faulty switch within the faulty leg. The strategy is based on monitoring of the phase current polarity within one current period as an indicator of either the upper, lower or both the switches is in faulty condition. This can be done by calculating the average values within one current period as shown in the following equation.

\[ \langle Mu_n(k) \rangle = \frac{1}{M} \sum_{j=0}^{M-1} i_n(k - j) \] (8)

Where:
- \( Mu_n \) = Phase a, b, c average current variables.
- \( M \) = Number of samples per current period

The average values are calculated using a sliding window so that the mean value is updated at every \( k^{th} \) sample for faster fault localization.
However, under variable load and speed condition, transient current condition will occur before the motor gets into steady state. Taking these into consideration, some methods are required to handle such variations without causing false alarms.

3. FDL Under Variable Load and Speed Operation

The variable load condition is simulated by using a load profile. In the time span of ten second, a few load variation types are introduced, the inverter is working in healthy condition with the SPWM reference signals frequency $f_{ref}$ being fixed at 60Hz. Fig. 2 shows the load torque profile applied, the phase currents, and the rotor speed.

![Load Profile](image)

**Figure 2.** Load torque profile applied, phase currents, and rotor speed.

As observed, load variation directly affects the phase current amplitude, transient region can also be seen when load change occurred before the motor gets into a steady state condition. Yet, the phase currents change smoothly even under a step load increase from 0% to 100% at time 4.5s. It should be noted that under load variation, only the current amplitude changes while the frequency remains constant.

In the case of variable speed operation, the condition is simulated by supplying the SPWM generator model with a custom frequency profile as the SPWM reference signals frequency $f_{ref}$. In the time span of ten second, a few frequency variations are introduced, the inverter is working in healthy condition with the load being constant at 25%. Figure 3 shows the frequency profile and the effects of the frequency variations to the phase currents and the rotor speed.

![Frequency Profile](image)

**Figure 3.** $f_{ref}$ frequency profile applied, phase currents, and rotor speed.

As expected, changing the $f_{ref}$ do provide control over rotor speed. However, it is also observed that when $f_{ref}$ changes, transient current surge is induced especially during steep frequency change.
These transient current condition during load change and frequency change does not affecting the fault detection algorithm that is based on the Lissajous figure slope calculation. As an example, Figure 4 shows the Lissajous figure of the DQ current components at time between time 4.4s to 4.6s where at time 4.5s, a step load increase from 0% load to 100% load is introduced.

**Figure 4.** Lissajous figure of DQ current components between $t=4.4s$ to $t=4.6s$.

The Lissajous figure shows a smooth transition from zero load to max load operation. Fig. 5 shows the zoomed in plot of the phase currents $i_{abc}$ and the slope variable $P$ between time $t=4.4s$ to $t=4.6s$.

**Figure 5.** Phase currents and the slope variable.

This shows that even under a step load transition from 0% load to 100%, the current still changes smoothly, hence the slope variable is not affected of this condition and no sign of false alarm occurred.

However, the transient current condition does affect the fault localization variable. Fig. 6 shows the phase-a average current variable $M_{ua}$ in the time span of 10 seconds, high spikes are observed especially at fast transient regions which occurs during motor starting, and the regions where step load changes are introduced.

**Figure 6.** Phase-a average current variable.
This is due to the unbalance of the current flow in negative and positive direction within one current period. For this reason, current signal normalization methods are required to first normalize the current signals before the Fault Localization algorithm is applied.

4. Current Signal Normalization and Phase Current Averaging Compensation

There are three methods being discussed in this work as follows.

4.1. Maximum Current Normalization

One way to normalize the phase current signal is by using the max current value within the sliding window of one current period $I_{\text{max}}$. Dividing each of the instantaneous sample with the obtained $I_{\text{max}}$ gives a normalized current signal with the equation as follows.

$$i_{nN} = \frac{i_n}{i_{n,\text{max}}} = \begin{cases} i_{aN} = \frac{i_a}{i_{a,\text{max}}} \\ i_{bN} = \frac{i_b}{i_{b,\text{max}}} \\ i_{cN} = \frac{i_c}{i_{c,\text{max}}} \end{cases}$$

(9)

![Figure 7. Unnormalized phase current, Maximum current ($I_{\text{max}}$) normalized phase currents, and comparison of phase-a average current variable $Mu_a$.](image)

Based on the simulation results, the $I_{\text{max}}$ normalization method seems to be capable of suppressing the high average current deviation.

4.2. Schmitt Trigger Model

This second method mimics the behavioral model of a Schmitt trigger. Rather than using the maximum current value to normalize the instantaneous phase current amplitude, this method uses two defined
threshold values to determine whether the current is in positive or in negative direction as shown in equation (10).

\[
i_{nN}(k) = \begin{cases} 
+1, & i_n > +i_{th} \\
-1, & i_n < -i_{th} \\
i_{nN}(k-1), & \text{otherwise}
\end{cases}
\]  

(10)

The normalization output is set as high (+1) when the input signal rises above the high-level threshold value (+i₀) and does not go low (-1) until the input falls below the lower threshold (-i₀) value. The value of i₀ used in this simulation is 0.3.

Fig. 8 shows the unnormalized phase current, the Schmitt trigger model outputs, and the comparison of phase-a average current variable Muₐ during the fast transient region between time 4.4s to 4.6s.

![Unnormalized phase current, the Schmitt trigger model outputs, and the comparison of phase-a average current variable Muₐ.](image)

**Figure 8.** Unnormalized phase current, the Schmitt trigger model outputs, and the comparison of phase-a average current variable Muₐ.

The result shows that this method is also able to suppress the current average value deviations during transient condition.

4.3. Park’s Vector Modulus

The other method is known as Park’s Vector modulus (PVM) normalization, it is done by using the following equation.

\[
|i_{PVM}| = \sqrt{i_d^2 + i_q^2}
\]

(11)

\[
i_{nN} = \frac{i_n}{|i_{PVM}|} = \begin{cases} 
i_{aN} = \frac{i_a}{|i_{PVM}|}, & \text{for } a \in \{a, b, c\} \\
i_{bN} = \frac{i_b}{|i_{PVM}|}, & \text{for } a \in \{a, b, c\} \\
i_{cN} = \frac{i_c}{|i_{PVM}|}, & \text{for } a \in \{a, b, c\}
\end{cases}
\]

(12)

Where \(i_d\) and \(i_q\) is obtain from the transformation of the three-phase to two-phase current as describe in equation (11) and (12). Fig. 9 shows the unnormalized phase current, the PVM normalized currents, and the comparison of their average values during the fast-transient region (t=4.4s to 4.6s).
As observed from the results, the PVM normalization method have also shown the capability to suppress the average current value deviations during transient conditions.

4.4. Comparison of Current Signal Normalization Methods

Based on the results, all the three normalization methods presented have shown their ability to suppress the transient current effects on the average current variable ($M_{u_a}$). However, in comparison of the three normalization methods, there are some difference between the three. Fig. 10 shows the zoomed in look of the $M_{u_a}$ variable at the fast-transient region ($t=4.4s$ to $4.6s$).

Figure 9. Unnormalized phase current, the PVM normalized currents, and phase-a average current variable $M_{u_a}$.

Figure 10. Comparison of the three current normalization methods.
Overall, it is observed that $i_{\text{max}}$ normalization gives the poorest results while PVM normalization shows the least deviations during transient condition.

5. Conclusions

This paper presents a simulation analysis on the current vector trajectory fault detection and localization method for inverter open-circuit faults under variable load and speed condition. The simulation shows that during variable load and speed, transient current conditions are induced thus affecting the fault localization process. Three current signal normalization methods that include Maximum Current normalization, Schmitt Trigger model, and the Park’s Vector Modulus Normalization (PVM) are discussed to compensate this issue. All the three methods have shown their capability to reduce the effects of transient current condition on the fault localization process, but in comparison of the three, the PVM normalization gives the lowest deviations thus are the most favorable method to be used.

References

[1] Cherif BDE, Bendjebbar M, Benouzza N, Boudinar H, Bendiabdellah A, editors. A comparative study between two open-circuit fault detection and localization techniques in a three-phase inverter fed induction motor. 2016 8th International Conference on Modelling, Identification and Control (ICMIC); 2016 15-17 Nov. 2016.

[2] Errabelli RR, Mutschler P. Fault-Tolerant Voltage Source Inverter for Permanent Magnet Drives. IEEE Trans Pow Electr. 2012;27(2):500-8.

[3] Tabbache B, Benbouzid M, Kheloui A, Bourgeot J, Mamoune A, editors. PWM inverter-fed induction motor-based electrical vehicles fault-tolerant control. IECN 2013 - 39th Annual Conference of the IEEE Industrial Electronics Society; 2013 10-13 Nov. 2013.

[4] Asghar F, Talha M, Kim SH. Neural Network Based Fault Detection and Diagnosis System for Three-Phase Inverter in Variable Speed Drive with Induction Motor. Journal of Control Science and Engineering. 2016;2016:1286318.

[5] Hang C, Ying L, Shu N. Transistor open-circuit fault diagnosis in two-level three-phase inverter based on similarity measurement. Microelectronics Reliability. 2018;91:291-7.

[6] Shu C, Ya-Ting C, Tian-Jian Y, Xun W. A Novel Diagnostic Technique for Open-Circuited Faults of Inverters Based on Output Line-to-Line Voltage Model. IEEE Trans Indust Electr. 2016;63(7):4412-21.

[7] Dhumble RB, Lokhande SD. Neural Network Fault Diagnosis of Voltage Source Inverter under variable load conditions at different frequencies. Measurement. 2016;91:565-75.

[8] Trabelsi M, Boussak M, Benbouzid M. Multiple criteria for high performance real-time diagnostic of single and multiple open-switch faults in ac-motor drives: Application to IGBT-based voltage source inverter. Electric Power Systems Research. 2017;144:136-49.

[9] Zhang W, Xu D, Enjeti PN, Li H, Hawke JT, Krishnamoorthy HS. Survey on Fault-Tolerant Techniques for Power Electronic Converters. IEEE Trans Pow Electr. 2014;29(12):6319-31.

[10] Rasyadan A, Ibrahim Z, Dir TMABT, Yaacob S, editors. Modeling of Time Domain Analysis for Single and Double Open-Circuit Inverter Switch Faults in Three-Phase Induction Motor Drives. 2018 International Conference on Computational Approach in Smart Systems Design and Applications (ICASSDA); 2018 15-17 Aug. 2018.

[11] Yu Y, Hu J, Wang Z, Xu D, editors. IGBT open circuit fault diagnosis in VSI fed induction motor drives based on modified average current method. 2014 9th IEEE Conference on Industrial Electronics and Applications; 2014 9-11 June 2014.

[12] Trabelsi M, Boussak M, Gossa M, editors. Multiple IGBTs open circuit faults diagnosis in voltage source inverter fed induction motor using modified slope method. The XIX International Conference on Electrical Machines - ICEM 2010; 2010 6-8 Sept. 2010.

[13] Estima JO, Freire NMA, Cardoso AJM, editors. Recent advances in fault diagnosis by Park's vector approach. 2013 IEEE Workshop on Electrical Machines Design, Control and Diagnosis (WEMDCD); 2013 11-12 March 2013.