Simplified Fourier Series Based Transistor Open-Circuit Fault Location Method in Voltage-Source Inverter Fed Induction Motor

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\textbf{ABSTRACT} Transistors in three-phase voltage-source inverter often suffer from open-circuit failures due to the lifting of bonding wires caused by thermic cycling, resulting in performance degradation with ripple torque and current harmonics. Current-spectral-analysis based methods are widely applied to failure diagnosis; however, high calculation consumption and complex implementation limit their application in some real-time occasion. In this paper, a simplified Fourier series method is proposed by the product between reconstructed phase currents and reference signals. Meanwhile, a novel normalized method for DC and fundamental components of simplified Fourier series are proposed to locate twenty-one transistor open-circuit faults. Numerical results show that the proposed Fourier series method coincides with that of Fast Fourier Transform. Experimental results and the comparison with previous methods show high efficiency and merits of its application to transistor open-circuit fault location in the voltage-source inverter.

\textbf{INDEX TERMS} Voltage-source inverter, real-time, current spectral, open-circuit, fault location.

\textbf{NOMENCLATURE}

VSI Voltage-Source Inverter
IM Induction Motor
FOC Field Oriented Control
RLT Rated Load Torque
CDR Current Data Reconstruction
FFT Fast Fourier Transformation
ZCS Zero-Crossing Sample
CL Current Linklist
ω\textsuperscript{*} rad/s, Reference Angle Speed
m Representative of a, b, c
i\textsubscript{m} Three-Phase Currents
I\textsubscript{m} Current Linklists
\hat{I}\textsubscript{m} Reconstructed Current Linklists
D\textsubscript{m} DC Component of I\textsubscript{m}
\hat{D}\textsubscript{m} Normalized DC Component of I\textsubscript{m}
D\textsuperscript{*}\textsubscript{m} Filtered Normalized DC Component of I\textsubscript{m}
\hat{A}\textsubscript{m,h} \textsuperscript{1h} Fourier Series of I\textsubscript{m}
\hat{A}\textsubscript{m,h} \textsuperscript{1h} Normalized Fourier Series of I\textsubscript{m}
A\textsuperscript{*}\textsubscript{m,h} \textsuperscript{1h} Filtered Normalized Fourier Series of I\textsubscript{m}
ψ\textsubscript{m} Phase angle of Fourier Series
T\textsuperscript{*} Current Period
T\textsubscript{sp} Current Sampling Period
L Current Samples in a Period
k Sampling Instant
H\textsubscript{m} Position of Down-to-Up Zero-Crossing Sample
N\textsubscript{1}, N\textsubscript{2} Filters constant
ξ\textsubscript{1}, ξ\textsubscript{0} Boundaries of Equality to 1 and 0

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I. INTRODUCTION

Three-phase VSIs are widely used in industrial applications due to their superior performance. Their health condition makes a vital contribution to the reliability of motor drives. It is reported that the failure rate of power semiconductor takes up a large scale of the failure in motor drives, followed by capacitor and gate drives [1]. Consequently, lots of researches had been done on the fault diagnosis in three-phase VSIs to reach convenient maintenance and fault-tolerant in recent decades [2]–[6].

Generally, failures in three-phase VSIs can be divided into two categories: short-circuit and open-circuit. Short-circuit will cause overcurrent and has great damage to VSIs immediately [7]. Some positive protection is often taken, such as fault isolation by hardware design, as well as shut down the drive system immediately. The open-circuit fault is less destructive and causes system performance degraded by generating torque ripple and harmonics. The healthy components continue suffering overcurrent and overvoltage, which is extremely easy to cause secondary failure or even destroy the system if no positive actions are taken.

It should be noticed that the fault diagnosis consists of fault detection and fault location. Fault detection is applied to monitor system healthy conditions and provide safety strategies, such as shutting down the system. Fault location focuses on the position of fault after detection, which makes much sense to maintenance or switch to tolerant strategies.

The reported fault diagnosis methods in three-phase VSIs include two kinds: signal of component-based and signal of system-based. The former one uses the internal signal as diagnostic features by failure mechanism in the physical and electrical model of power component, such as collector-to-emitter voltage, the drain-to-source voltage, and gate-to-source voltage during the IGBT turn-on transient are used for healthy condition [8], [9]. Fast-detection, fair robustness to system disturbance and portability can be achieved by these methods. However, extra electrical circuit equipped with every power components will increase the cost and system volume, which limit their applications. System signal-based fault diagnosis methods are the most widely researched, normalized DC current and its vector, such as collector- 

between the reference currents and the measured currents, compared with real-time methods, however, they have fair portability.

Lots of spectral analysis are used to locate the faulty transistor by analyzing the spectral distribution of phase currents [27], [28]. It should be noticed that these methods need extra signal processing hardware due to the complex calculation, which limits their application. In [19], the Fourier Series of currents are estimated by the motor rotating angle [19]; however, the estimation will be biased after fault occurrence, what is more, these methods are only available to single open-circuit fault.

To overcome the complex calculation of traditional current spectral analysis methods. A simplified Fourier Series method is proposed, novel normalized DC and fundamental components are proposed for fault location for both single and multiple open-circuit faults. Two contributions are made in this paper, listed as follows.

1) A simplified Fourier series method is proposed by the product between reconstructed CLs and reference signals, and the computational complexity is \( O(\log_2 L) \).

2) Novel normalized method for DC and fundamental components by simplified Fourier series are proposed to locate twenty-one transistor open-circuit, experimental results show high efficiency and merits.

The structure of this paper is as follows: Section II elaborates the proposed simplified Fourier series theory, including continuous and discrete systems, the concept of CDR. Section III concentrates the novel normalized method for DC and fundamental components and transistor open-circuit location. Section IV gives out experimental results, including
the comparison of proposed simplified Fourier series method with FFT, fault location results and the comparison with previous spectral-analysis based methods. A conclusion is made in Section V.

II. SIMPLIFIED FOURIER SERIES IN VSI FED IM

The structure of three-phase VSI fed IM is showed in Fig. 1, $U_d$ is the input voltage of the drive system, $C_1$, $C_2$ are two symmetrical capacitors to eliminate high frequently harmonics of the supply voltage. T1, T2, T3, T4, T5, T6 are six power transistors, they are the core components of the drive system. D1, D2, D3, D4, D5, D6 are six stream diodes to avoid the impact caused by inductive rotating load. Three-phase currents ($i_d$, $i_b$, $i_c$), measured speed ($\omega$), reference current in $d$-axis ($i_{d*}$) and reference speed are the inputs of control systems, pulse-width modulation signals are generated to switch their operation states between ‘on’ and ‘off’, alternately. As a result, DC to AC energy conversion is achieved.

![Structure of three-phase VSI fed IM.](image)

In healthy conditions, three-phase currents are sinusoidal time series; their frequencies and amplitudes are the same, only with $2/3\pi$ phase difference between every two among them. In faulty conditions with open-loop control strategy, the phase currents of undamaged legs still keep the same as healthy condition, while the phase current of the damaged leg is distorted. However, in faulty condition with closed-loop control strategy, phase currents of undamaged legs will be spread by the phase current of the damaged leg for the feedback strategy. This paper focuses on transistor open-circuit fault location in VSI fed IM with FOC.

A. FOURIER SERIES IN CONTINUOUS SYSTEM

Three-phase output currents are periodic time series with period $T$. $T$ is given as following Equation (1), Considering measurement error and system noise, reference speed is used in Equation (1).

$$ T = \frac{30\omega^s}{9.55\pi p} $$ (1)

Three-phase currents can be represented by Fourier Series corresponding to a sum of harmonically related time series. The frequencies of these Fourier Series are integer multiples of the fundamental frequency ($\omega_0 = 2\pi/T$). These periodic Fourier Series are of the form,

$$ I_m(t) = D_m + \sum_{h=1}^{+\infty} A_{m,h} \sin(h\omega_0 t + \varphi_m) $$ (2)

$A_{m,h}$ are the amplitude of related exponential time series with frequency of $h\omega_0$. The integration of Equation (2) in a period is given,

$$ \int_0^T I_m(t)dt = \int_0^T D_mdt + A_{m,h} \sum_{h=1}^{+\infty} \int_0^T \sin(h\omega_0 t + \varphi_m)dt $$ (3)

$$ \forall h \in Z^+, \int_0^T \sin(h\omega_0 t + \varphi_m)dt = 0, D_m can be given as follows,

$$ D_m = \frac{1}{T} \int_0^T I_m(t)dt $$ (4)

Equation (2) is multiplied by a reference signal, whose frequency is $z\omega_0$. phase angle is the same as original signal, there is,

$$ I_m(t) = D_m \sin(z\omega_0 t + \varphi_m) $$

$$ + \sum_{h=1}^{+\infty} A_{m,h} \sin(h\omega_0 t + \varphi_m) \sin(z\omega_0 t + \varphi_m) $$ (5)

The integration of Equation (5) in a period is given,

$$ \int_0^T I_m(t) \sin(z\omega_0 t + \varphi_m) dt = D_m \int_0^T \sin(z\omega_0 t + \varphi_m)dt $$

$$ + A_{m,h} \int_0^T \sum_{h=1}^{+\infty} \sin(h\omega_0 t + \varphi_m) \sin(z\omega_0 t + \varphi_m)dt $$ (6)

The orthogonality of trigonometric functions has a characteristic showed as Equation (7),

$$ \int_0^T \sin(h\omega_0 t) \sin(z\omega_0 t) dt = 0 $$ (7)

$$ h \neq z $$

Substituting Equation (7) in (6) and simplifying yields,

$$ \int_0^T I_m(t) \sin(z\omega_0 t + \varphi_m) dt $$

$$ = A_{m,z} \int_0^T \sin(z\omega_0 t + \varphi_m) \sin(z\omega_0 t + \varphi_m) dt $$ (8)

$A_{m,z}$ can be calculated as Equation (8),

$$ A_{m,z} = \frac{\int_0^T I_m(t) \sin(z\omega_0 t + \varphi_m) dt}{\int_0^T \sin^2(z\omega_0 t + \varphi_m) dt} $$ (9)
B. FOURIER SERIES IN DISCRETE SYSTEM

In discrete system, three-phase currents in a period are composed of \( L \) samples, named CLs, their length is given as following.

\[
L = \frac{T}{T_{sp}} \tag{10}
\]

In \( k \) instant, \( t \) is defined as the ending position of CL,

\[
t = k - L + 1 \tag{11}
\]

Three phase CLs are given,

\[
I_m = [i_m(t), i_m(t + 1), \cdots, i_m(k)] \tag{12}
\]

1) DC COMPONENT

\[
D_m(k) = \frac{1}{L} \sum_{j=t}^{j=k} I_m(j) \tag{13}
\]

2) AC COMPONENT

\[
A_{m, z}(k) = \frac{\sum_{j=t}^{j=k} I_m(j) \sin(\frac{1}{L}T_{z\omega_0} + \varphi_m(k))}{\sum_{j=t}^{j=k} \sin^2(\frac{1}{L}T_{z\omega_0} + \varphi_m(k))} \tag{14}
\]

DC component can be easily calculated. However, the real-time calculation of AC component is challenging because \( \varphi_a, \varphi_b, \varphi_c \) are uncertain variables. In every sampling instant, \( \varphi_a \neq \varphi_b \neq \varphi_c \), what’s more, in any two sampling instants during a period, there is \( \varphi_m(p) \neq \varphi_m(g) \), where \( p, g \in \{t, t + 1, \cdots, k\} \).

In order to eliminate the difference between \( \varphi_a, \varphi_b, \varphi_c \) and the difference in any two sampling instants during a period \( \varphi_m(p), \varphi_m(g) \), a CDR algorithm is proposed.

C. CDR AND SIMPLIFIED FOURIER SERIES

There are two ZCSs in every CL, one is up-to-down ZCS, the other one is down-to-up ZCS. The positions of down-to-up ZCS in CLs \( I_m \) are marked as \( H_m \). In, all samples before \( H_m \) are removed back to the last sample \( i_m(k) \) to form \( \hat{I}_m \).

The CDR process of phase-\( a \) when \( T4 \) fails is showed as subplot (a) in Fig. 2, and the reconstructed result is showed in subplot (b) in Fig. 2. Compared with the original CLs, in the reconstructed CLs, only the order of the samples changes.

Here, assuming that the phase angle of ZCS in every instant is approximated to \( \varphi_m \), then \( \varphi_a \) is showed in Fig. 2, the reconstructed CLs are nearly the same with \( \varphi_m \approx 0 \), shown in Fig. 3.

In order to eliminate the difference between \( \varphi_a, \varphi_b, \varphi_c \) and the difference in any two sampling instants during a period \( \varphi_m(p), \varphi_m(g) \), a CDR algorithm is proposed.

![Figure 2](image-url)

**FIGURE 2.** Illustration of CDR in phase-\( a \) when \( T1 \) open-circuit fault occurs. (a) original phase current. (b) reconstructed phase current.

![Figure 3](image-url)

**FIGURE 3.** Simulation results of reconstructed CL in phase-\( a \) when \( T1 \) open-circuit fault occurs within 0.01s.

![Figure 4](image-url)

**FIGURE 4.** Algorithm flowchart of down-to-up ZCS position calculation in \( k \) instant.
Three-phase currents are firstly filtered, as following,

\[ I_m(k) = \frac{\sum_{j=k-N_1+1}^{k} I_m(j)}{N_1} \]  

(15)

where \( N_1 \) is a constant. Secondly, \( \forall j = k - N_2, \forall \in \{k - N_2 + 1, k - N_2 + 2, \ldots, k\} \), if

\[
\begin{cases}
I_m(j) < 0 \\
I_m(v) \geq 0
\end{cases}
\]  

(16)

Then, \( H_m = k - N_2 \). The proposed ZCS calculation algorithm has a short delay-time with \( N_2 T_s \) because \( I_m(k - N_2) \) is checked in \( k \) instant. If Equation (16) is established, \( H_m \) is replaced by the position of the new down-to-up ZCS \( k - N_2 \), if Equation (65) is not established, \( H_m \) shifts left because \( I_m \) updates. As a result, in every instant, the original CLs \( I_m \) are replaced by reconstructed CLs \( \hat{I}_m \), \( \varphi_j(k) = \varphi_b(k) = \varphi_c(k) \). The proposed simplified Fourier series can be presented as following.

\[ A_{m,v}(k) = \frac{\sum_{j=1}^{L} \hat{I}_m(j) \sin(\frac{j}{L} T z_0 \omega_0)}{\sum_{j=1}^{L} \sin^2(\frac{j}{L} T z_0 \omega_0)} \]  

(17)

### III. PROPOSED FAULT LOCATION METHOD

The accuracy of harmonics amplitude and phase errors in three-phase currents can all be controlled within 5% in healthy condition. When the transistor open-circuit fault occurs, Fourier series of three-phase currents change with high DC component and harmonics. A different open-circuit fault will lead to different harmonics distributions in three-phase currents. Compared with FFT or other improved methods, the proposed simplified Fourier series can be easily implemented with low calculation consumption. VSI transistor open-circuit fault location method is proposed by analyzing the Fourier series.

#### A. THREE PHASE CURRENT SPECTRAL ANALYSIS

In healthy conditions, the fundamental series accounts for the vast majority in three-phase currents. In faulty condition, the Fourier Series associated with a frequency of \( z_0 \omega_0 \) increase. Here, twenty-one single and multiple open-circuit faults are divided into four categories: single open circuit fault, multiple open-circuit fault in the same leg, and multiple open-circuit fault both on the upper or on the lower of different legs, multiple open-circuit fault that one is on the upper and the other one is on the lower of different legs, respectively. Fourier series distributions of three-phase currents are different among four categories, and they are the same within categories.

In FFT, the amplitudes \( D_m, A_{m,z} \) or percentages \( \bar{D}_m, \bar{A}_{m,z} \) of DC and AC components are used for fault diagnosis. Where \( \bar{D}_m, \bar{A}_{m,z} \) are defined as following.

\[
\begin{align*}
\bar{D}_m & = |D_m| \bigg/ |D_m| + \frac{|\sum_{z=1}^{L/2} A_{m,z}|}{\sum_{z=1}^{L/2} |A_{m,z}|} \bigg/ \sum_{z=1}^{L/2} |A_{m,z}| \\
\bar{A}_{m,z} & = |A_{m,z}| \bigg/ |D_m| + \frac{|\sum_{z=1}^{L/2} A_{m,z}|}{\sum_{z=1}^{L/2} |A_{m,z}|}
\end{align*}
\]  

(18)

These features focus on the characteristics without considering the interaction. However, in the closed-loop system, transistor open-circuit fault on the faulty leg will propagate to healthy legs. Hence, a novel normalized method for DC and AC components is proposed by taken into the interaction. AC components are divided by the maximum amplitude of fundamental components; DC components are divided by the maximum absolute value of the sum of CLs, shown as follows.

\[
A_{max,1} = \max(|A_{a,1}|, |A_{b,1}|, |A_{c,1}|) \\
D_{max} = \max(\sum_{j=1}^{k} |D_a(j)|, \sum_{j=1}^{k} |D_b(j)|, \sum_{j=1}^{k} |D_c(j)|) \\
A_{m,z} = \frac{\bar{D}_m \cdot D_{max}}{\bar{A}_{max,1} \cdot A_{m,z}}
\]  

(19)

Substituting Equation (17) in (19) and simplifying yields, normalized AC components can be online calculated by (20), where \( \hat{I}_v(\nu = a, b, c) \) is the CL of \( A_{max,1} \).

\[
\hat{A}_{m,z} = \frac{\sum_{j=1}^{L} \hat{I}_m(j) \sin(\frac{2\pi j}{L})}{\sum_{j=1}^{L} \hat{I}_m(j) \sin(\frac{2\pi j}{L})}
\]  

(20)

Table 1 gives the FFT and proposed normalized Fourier Series of currents under 30% IM RLT at 1000r/min, these data are from experimental board and off-line calculated by Matlab. The motor parameters are listed in Table 2. The first part in Table 1 gives \( \bar{D}_m, \bar{A}_{m,z}(z = 1, 2, 3, 4, 5) \) calculated by Equation (18). The second part in Table 1 are normalized Fourier series \( |\bar{D}_m|, |\bar{A}_{m,z}|(z = 1, 2, 3, 4, 5) \) calculated by Equation (19). Compared with the FFT, features are much more recognizable in the proposed normalized Fourier Series.

1) The normalized fundamental components of healthy legs are larger than that of faulty legs.

2) The normalized DC components are not equal to zero in faulty legs.

The operation principle of VSI is applied to explain the mentioned features. Fig. 5 shows the negative and positive current flows in a faulty leg with lower transistor \( T_{k+1} \) open-circuit, \( T_k \) is turned on and off alternatively. When \( i_m > 0 \), the current flows from DC-link to IM in two cases, one case is through \( T_k \) directly if it is turned on, another case is through \( V_{k+1} \) during the dead-time interval that is applied to
TABLE 1. Traditional and proposed normalized fourier series of three phase currents calculated by FFT.

| Fourier series | T4 open failure | T3T4 open failure | T4T5 open failure | T4T6 open failure |
|----------------|-----------------|------------------|------------------|------------------|
| Dm(%)          | 2.65            | 1.59             | 0.90             | 28.73            |
| Am,1(%)        | 38.96           | 51.42            | 40.18            | 25.89            |
| Am,2(%)        | 18.22           | 3.07             | 21.07            | 16.49            |
| Am,3(%)        | 11.13           | 19.38            | 4.85             | 7.55             |
| Am,c(%)        | 7.22            | 1.80             | 2.72             | 3.87             |
| Am,l(%)        | 5.54            | 7.44             | 0.77             | 2.38             |

| Dm | 0.0384 | 0.0991 | 0.5407 | 0.1192 | 0.0108 | 0.1084 | 0.0224 | 1.0656 | 1.0432 | 1.1353 | 0.6553 | 0.4800 |
| Am,1 | 0.8934 | 0.4460 | 1      | 0.9994 | 0.0016 | 1      | 0.7672 | 0.7897 | 1      | 0.7010 | 0.4080 |
| Am,2 | 0.4019 | 0.1510 | 0.3109 | 0.0660 | 0.0046 | 0.0657 | 0.5244 | 0.2153 | 0.3425 | 0.6024 | 0.5990 | 0.2726 |
| Am,3 | 0.2456 | 0.0640 | 0.2176 | 0.3568 | 0.0041 | 0.3547 | 0.1207 | 0.1049 | 0.0381 | 0.2390 | 0.3671 | 0.1857 |
| Am,4 | 0.1593 | 0.0609 | 0.1085 | 0.0445 | 0.0013 | 0.0459 | 0.0677 | 0.0273 | 0.0383 | 0.1158 | 0.2089 | 0.1550 |
| Am,5 | 0.1223 | 0.0356 | 0.0880 | 0.1166 | 0.0028 | 0.1139 | 0.0192 | 0.0231 | 0.0254 | 0.0679 | 0.1623 | 0.0944 |

TABLE 2. Motor parameters.

| Parameters                        | Values | Parameters                        | Values |
|----------------------------------|--------|----------------------------------|--------|
| Rotor resistance                 | 2.71811| Rated Power                      | 2.2kW  |
| Rotor leakage inductance         | 10.33mH| Frequency                        | 50Hz   |
| Magnetizing inductance           | 319.7mH| Poles                            | 4      |
| Stator leakage inductance        | 10.33mH| RLT                              | 14N-m  |
| Stator leakage resistance        | 2.804Ω | flux-leakage                      | 0.6Wb  |

B. PROPOSED FAULT LOCATION METHOD

Fundamental components of three phase currents are used to distinguish faulty leg from healthy legs, DC components are used to locate the faulty transistor. Assuming that three legs are leg-m, leg-n, leg-l, m, n, l = a, b, c, m ≠ n ≠ l.

For one faulty leg, such as leg -m: absolute values of normalized fundamental components in phase currents will be: \(|\hat{A}_m,1| < 1\), |\(\hat{A}_n,1\)|, |\(\hat{A}_l,1\)| are closed to 1. Specially, if the faulty transistor is on the upper, \(D_m < 0\); if the faulty transistor is on the lower, \(D_m > 0\); if both the lower and the upper transistors are faulty, \(D_m = 0\).

For two faulty legs, such as leg -m and leg -n, absolute values of normalized fundamental components in phase current will be: |\(\hat{A}_m,1\)| < 1, |\(\hat{A}_n,1\)| < 1, |\(\hat{A}_l,1\)| = 1. Specially, \(D_m > 0\), \(D_n > 0\) indicates both two faulty transistors are on the upper of the legs, \(D_m < 0\), \(D_n < 0\) indicates both two faulty transistors are on the upper of the legs, \(D_m > 0\), \(D_n < 0\) indicates the upper transistor of leg -m and the lower transistor of leg -n are faulty, \(D_m < 0\), \(D_n > 0\) indicates the upper transistor of leg -m and the lower transistor of leg -n are faulty.

Considering system noise and measurement errors, two symmetrical boundaries near predefined constant are set as Fig. 6, where the predefined constant is \(v\), the distance between boundaries is 2ξ. If a variable is inside two boundaries, shown as the light green zone, it is considered equal to \(v\). Otherwise, if a variable is larger than the upper boundary,
it is considered larger than the \( v \), if a variable is smaller than the lower boundary, it is considered smaller than the \( v \), the criterion is given as,

\[
F = \hat{D}_m, \hat{A}_m, 1 \\
\begin{cases} 
F = v, & |F - v| \leq \xi \\
F > v, & F - v > \xi \\
F < v, & v - F < \xi 
\end{cases}
\]

(21)

Based on the analysis above, a fault location table to locate twenty-one single and multiple open-circuit faults are proposed as Table 3. Where \( \times \) means a does not care condition, \( D^*_m, A^*_m \) are filtered values of \( \hat{D}_m, \hat{A}_m \), given as,

\[
\begin{align*}
D^*_m(k) &= \frac{1}{L} \sum_{j=1}^{k} \hat{D}_m(j) \\
A^*_m(k) &= \frac{1}{L} \sum_{j=1}^{k} \hat{A}_m(j)
\end{align*}
\]

(22)

Absolute values of \( A^*_m, 1 \) are applied to locate faulty legs, sign, and values of \( D^*_m \) are applied to locate the position of the faulty transistor. The flowchart of the proposed fault location algorithm is given as Fig. 7, which includes three steps:

1) CDR to eliminate \( \varphi_m(k) \)
2) Normalized DC and fundamental components calculation, equation (17)-(22)
3) Look up Table 3

C. TUNING EFFORT

An important property of diagnosis algorithm is low tuning effort. The proposed fault location method needs four parameters, \( N_1, N_2, \xi_0 \text{and } \xi_1 \). \( N_1, N_2 \) are two constants applied to ZCS calculation, \( N_1 \) is a filter constant, it makes sense when the currents contain high harmonics. \( N_2 \) is applied to search for the position of ZCS. It plays an important role in the proposed algorithm. In fact, the number of positive samples on the right of ZCS is smaller than \( L/2 \). Hence, the upper limit of \( N_2 \) is \( L/2 \), and \( N_2 \) is suggested to set as large enough to improve the accuracy of CDR. \( \xi_0, \xi_1 \) are applied to measure the equivalent relationship with 0, 1, respectively. The value ranges of these four parameters are shown in Table 4, where large efficient value ranges show low tuning effort.

\[
\begin{array}{cccc}
\text{Parameters} & N_1 & N_2 & \xi_0, \xi_1 \\
\text{value ranges} & 4-10 & L/20 - L/3 & 0.1-0.3, 0.1-0.3
\end{array}
\]

(23)

IV. EXPERIMENTAL RESULTS

The following analyses are based entirely on the experimental results since they give an understandable presentation of the
algorithm performance in the presence of nonideal properties, such as model uncertainty, measurement noise, dead-time effects, etc. FOC with SVPWM was the control algorithm in the experiment. Some indices were presented to evaluate the performance of the proposed fault location method, such as location time, effectiveness, etc. Four typical faulty operating conditions were investigated. All kinds of transistor open-circuit faults were performed by inhibiting their respective gate signals while keeping the bypass diode still connected. The experimental results are presented by signal FaultType.

The experimental validation of the proposed fault diagnosis method was implemented in a TMS320F2806 board. The experimental setup was shown in Fig. 8, consisting of a 2.2kW squirrel-cage IM with 380V rated voltage, 4.9A rated current, a power converter with a switching frequency of 20kHz and the dead time of 3.2μs, a control board, a magnetic power brake, and a constant current source. The parameters of IM were listed in Table 2. The thresholds $N_1, N_2$ for CDR were set as 4, 50, respectively. The thresholds $\xi_0$ was set 0.2, $\xi_1$ was set 0.25.

![FIGURE 8. Experimental setup.](image)

**A. COMPARISON OF PROPOSED FOURIER SERIES APPROXIMATED ALGORITHM WITH FFT**

The comparison of proposed online simplified Fourier series approximated algorithm with offline FFT algorithm for normalized DC and AC components were made when T1 and T1T4 fault occur at a reference speed of 1000rpm with 30% IM RLT, showed as subfigure (a) and (b) of Fig. 9, respectively. The absolute values of normalized $D_m$, $A_{m,h}$ ($h = 1, 2, \ldots, 9$) coincide with that of FFT besides parts of $3^{rd}$ harmonics, the efficiency of the assumption to eliminate $\nu_{m}(k)$ by CDR is proved.

**B. RESULTS OF PROPOSED FAULT LOCATION ALGORITHM**

Fig. 10 (a),(b),(c) present three-phase reconstructed CLs in every sampling instant for single open-circuit fault in T4 at 1000rpm with 30% RLT, the left subfigures are the 3-D view of the reconstructed CLs during 0.4s, the color of bar represents the amplitude, the right subfigures are the side view of reconstructed CLs during 0.4s. The number of current samples during a period is 300, calculated by Equation (10), representing the length of CLs, the fault occurs at 0.28s. All phase differences are eliminated in three-phase currents in every instant. For $p, g(p \neq g)$, there is $\nu_{m}(p) = \nu_{m}(g)$, showed in three subfigures respectively. There is $\nu_{a}(k) = \nu_{b}(k) = \nu_{c}(k)$, showed among three subfigures, the phase angles of three-phase CLs nearly coincide. In every phase, reconstructed CL has two states, healthy states, and faulty states, shown as the side view subfigures.

![FIGURE 9. Comparison of proposed real-time Fourier series approximated algorithm with FFT. (a) T1 fails, (b) T3 and T4 fail.](image)

Fig. 11 presents the experimental results for a single fault in T6, under 30% IM RLT and 500r/min reference speed. Torque ripples and distorted currents occur after fault, showed as subfigure 1, 2. The normalized DC and fundamental components of the simplified Fourier series by the proposed method are presented in subfigure 3, 4, respectively. Subfigure 5 gives out the fault location result.

In healthy conditions, three-phase currents are sinusoidal, $|\hat{A}_{m,1}| = 1$, normalized DC components, and harmonics are nearly equal to zero. After T6 fails, DC component of leg-c, $\hat{D}_c$ raises. Due to $\hat{D}_a + \hat{D}_b + \hat{D}_c = 0$, DC components will also exist in healthy legs. Meanwhile, the fundamental component is nearly equal to 1 in the healthy leg, while it is smaller than 1 in the faulty leg. In subfigure 4, $\hat{A}_{a,1}, \hat{A}_{b,1}$ are inside the boundaries made up by $\xi_1$, while $\hat{A}_{c,1}$ are outside $\xi_1$, which indicates leg-c is faulty. In subfigure 3, $\hat{D}_c$ is larger than $\xi_0$, the DC component in phase current of leg-c is positive, which indicates the lower transistor is faulty. Combining the results of subfigure 3 and 4, the fault can be located to T6 by looking up Table 3, the location flag FaultType raises to 8, showed in subfigure 5.

Fig. 12 presents the experimental results for multiple open-circuit faults, under 30% IM RLT and assuming a reference
Fig. 13 presents the experimental results for multiple open-circuit fault at 0.28s, under 30% IM RLT and assuming a reference speed of 1000r/min. Motor measured speed and three-phase currents are showed in subfigure 1, 2, respectively. Normalized DC, fundamental and $2^{nd} - 8^{th}$ components are given in subfigure 3-4. In subfigure 4, $|A^*_{a,l}| = |A^*_{c,l}| = 1$, $A^*_{b,l}$ are smaller than $\xi_1$, which indicates leg-$b$ is faulty. In subfigure 3, $D^*_b$ is inside the boundaries made up by $\xi_0$ before and after fault occurrence, which indicates both the upper and lower transistors are faulty. As a result, the open-circuit fault can be located in T3 and T4. The location flag is showed in subfigure 5.
FIGURE 11. Experimental results concerning the time-domain waveforms of motor speed, three phase currents, real-time Normalized DC, AC components and fault location flag for a single open-circuit fault in T6.

FIGURE 12. Experimental results concerning the time-domain waveform of motor speed, three phase currents, real-time Normalized DC, fundamental components, and fault location flag for multiple open-circuit fault in T4 and T5.

FIGURE 13. Experimental results concerning the time-domain waveforms of motor speed, three phase currents, real-time Normalized DC, AC components and fault location flag for multiple open-circuit fault in T3 and T4.

FIGURE 14. Experimental results concerning the time-domain waveform of motor speed, three phase currents, real-time Normalized DC, fundamental components, and fault location flag for multiple open-circuit fault in T4 and T6.

Real-time calculated normalized DC, fundamental components are showed in subfigure 3, 4, respectively. In subfigure 4, only $A_{a,1}^*$ is inside $\xi_1$, $A_{b,1}^*$, $A_{c,1}^*$ are outside the boundaries made up by $\xi_1$, $|A_{a,1}^*| = 1$, $|A_{b,1}^*|$, $|A_{c,1}^*| < 1$, which indicates phase-a is healthy. In subfigure 3, $D_{b}^a > 0$, $D_{c}^a < 0$ and $|D_{a}^*| = ||D_{b}^a| - |D_{c}^a||$, which indicates the lower transistor of leg-b and the upper transistor of leg-c are broken. As a result, fault is located to T4 and T5, showed in subfigure 5.

Fig. 14 presents the experimental results for multiple open-circuit fault at 0.27s, under 30% IM RLT and assuming
a reference speed of 1000r/min. Motor measured speed and three phase currents are showed in subfigure 1, 2, respectively. Real-time calculated DC, fundamental components are showed in subfigure 3, 4, respectively. In subfigure 4, only $A_{b1}^c$ is inside $\xi_1$, $A_{a1}^b$, $A_{a1}^c$ are outside the boundaries made up by $\xi_1$, $|A_{b1}^a| = 1$, $|A_{b1}^b|$, $|A_{b1}^c| < 1$, which indicates phase-$a$ is healthy. In subfigure 3, $D_0^a > 0$, $D_1^a = |D_0^a| + |D_1^a|$, which indicates the lower transistors of leg-$b$ and leg-$c$ are broken. As a result, fault is located to T4 and T6, showed in subfigure 5.

C. COMPARISON WITH PREVIOUS SPECTRAL ANALYSIS BASED VSI FAULT LOCATION METHODS

The performance of the proposed transistor open-circuit fault location method is compared with previous methods in calculation consume, efficiency, cost, implementation, and tuning effort. Reference [27] and the proposed method can locate both single and multiple open-circuit faults. References [19], [20] and the proposed method are both low-implemented. In [19], [20], fundamental components are calculated in $a\beta$-axis by calculating the rotating angle, the Fourier series are calculated by FFT in [27], [28], the calculation consume is $O(L \log L)$. In the proposed method, the fundamental components are approximated by CDR. The calculation complex is $O(\log_2 L)$. The tuning effort is relatively lower because of the large efficient value ranges of thresholds. Consequently, the proposed method shows advantages in efficiency, calculation consumption, and low implementation.

V. CONCLUSION

Signal spectral analysis based methods are widely used in fault diagnosis. However, the calculation consumes limits the application in the real-time system, such as transistor open-circuit fault diagnosis in VSIs fed IM. In this paper, a real-time, easy-implemented simplified Fourier series algorithm for low-frequency periodic signals by data reconstruction with the position of ZSC is proposed, the Fourier series can be calculated in every sampling instant by product between reconstructed signals and reference signals. Especially, a novel normalized method of DC and fundamental components of simplified Fourier series is proposed to VSIs transistor open-circuit fault location. Comparison results show that the proposed simplified Fourier series algorithm nearly coincides with FFT. Experimental results show the high efficiency of proposed methods, both single and multiple of transistor open-circuit fault can be located in VSIs fed IM.

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