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Diagnosis of stator faults in induction motor based on zero sequence voltage after switch-off*

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Abstract: To improve the accuracy of the stator winding fault diagnosis in induction motor, a new diagnostic method based on the Hilbert-Huang transform (HHT) was proposed. The ratio of fundamental zero sequence voltage to positive sequence voltage after switch-off was selected as the stator fault characteristic, which could effectively avoid the influence of the supply unbalance and the load fluctuation, and directly represent the asymmetry in the stator. Using the empirical mode decomposition (EMD) based on HHT, the zero sequence voltage after switch-off was decomposed and the fundamental component was extracted. Then, the fault characteristic can be acquired. Experimental results on a 4-kW induction motor demonstrate the feasibility and effectiveness of this method.

Key words: Induction motor, Stator fault diagnosis, Hilbert-Huang transform (HHT), Zero sequence voltage, Empirical mode decomposition (EMD)
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INTRODUCTION

Induction motors are widely used and play a crucial role in modern industry systems. The stator winding inter turn short circuit fault is one of the major causes of motor failures. The thermal, electrical, mechanical and environmental forces cause the stator windings insulation aging and degradation, and further easily cause the inter turn short circuit fault. A slight inter turn short circuit fault may eventually cause turn to turn and turn to ground faults, and finally leads to a catastrophic failure (Nandi *et al.*, 2005). Therefore, in order to cut down the expensive maintenance cost and avoid big financial loss due to the key motors' failures in the systems, it is necessary to detect and diagnose the incipient fault of the motor stator windings inter turn short circuit.

In recent decades, lots of domestic and foreign experts have done much research in the field of condition monitoring and stator winding fault diagnosis of induction motors, and proposed many kinds of approaches. A number of diagnostic techniques were developed (Albizu *et al.*, 2006), for example, the negative sequence impedance (Sottile and Kohler, 1993), the negative sequence current (Kliman *et al.*, 1996), the voltage mismatch (Trutt *et al.*, 2002), the power decomposition (Arkan *et al.*, 2001), the zero sequence voltage (Cash *et al.*, 1998; Garcia *et al.*, 2004), the multiple reference frames theory (Cruz and Cardoso, 2005), the parameter estimation (Bachir *et al.*, 2006), and the swing angle (Mirafzal and Demerdash, 2006), etc. However, the unideal working circumstances such as the asymmetry of supply and the fluctuation of load affect the accuracy of fault diagnosis. Therefore, Nandi *et al.* proposed the frequency analysis on the inductive stator voltage after switch-off to the fault diagnosis (Nandi and Toliyat, 2002; Nandi, 2005). The advantage of this method is to avoid the influence of supply and load, and is able to acquire the reliable information directly concerned to the motor itself. Nevertheless, the voltage after

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switch-off is a time-variant signal, whose frequency and amplitude decrease continuously. Thus, the analysis of spectrum is difficult comparatively and the component according to the fault characteristic frequency is not very evident.

In order to resolve the above problems, this paper presents a new fault diagnosis method by taking advantage of Hilbert-Huang transform (HHT) non-stationary signal analyzing. Experimental results demonstrate that the method can not only detect the stator winding inter turn short circuit fault exactly but also estimate the fault severity.

RESIDUAL VOLTAGE ANALYSIS

As a running motor is switched off, the stator current and flux drop down to zero suddenly. Since the flux which circles along the stator winding and rotor winding would not change suddenly, an induction current occurs in the rotor winding. The induction current, a slowly varying DC, attenuates according to the rotor time constant. And it produces a rotor magnetic motive force which will induce a residual voltage in the stator winding. Before switch-off, the stator voltage's fundamental frequency is $f_s=\omega_s/(2\pi)$, the same as the supply frequency, and the rotor electrical angular velocity is $\omega_r=(1-s)\omega_s$, where s is the slip of the motor. The residual voltage in the stator winding is induced by the DC in the rotor winding, so its frequency will abruptly decrease from f_s to $(1-s)\omega_s/(2\pi)$, then descend gradually.

In the ideal condition, the motor's three windings are symmetrical and the residual voltage after switch-off is also symmetrical. The zero sequence voltage should be zero, i.e.,

$$(v_a+v_b+v_c)/3=0. \tag{1}$$

Actually, due to the discrepancies occurred during the process of manufacturing, installing, and repairing, etc., the motor is not always symmetrical. And any tiny difference among the three stator windings may result in a non-zero of the zero sequence voltage:

$$(v_a+v_b+v_c)/3=v_0\neq 0. \tag{2}$$

When the inter turn short circuit fault occurs, the asymmetry of the three impedance expands remarkably. The asymmetry makes the zero sequence voltage after switch-off increase greatly. The root means square of the fundamental component can index the stator fault (Garcia *et al*., 2004):

$$V_0=\sqrt{\frac{1}{N}\sum_{n=1}^{N}(v_{01})_n^2}, \tag{3}$$

in which v_{01} is the fundamental zero sequence voltage after switch-off.

Both amplitude and frequency of the zero sequence voltage, which are time-variant signals, decline continuously after switch-off. The fundamental component is extracted by the HHT, which is suitable to process the non-stationary signal.

HILBERT-HUANG TRANSFORM

Definition of instantaneous frequency

For an arbitrary time data $X(t)$, its Hilbert transform (HT) is

$$Y(t)=\frac{1}{\pi}\int_{-\infty}^{+\infty}\frac{X(\tau)}{t-\tau}\mathrm{d}\tau . \tag{4}$$

Its reverse transform is

$$X(t)=\frac{1}{\pi}\int_{-\infty}^{+\infty}\frac{Y(\tau)}{\tau-t}\mathrm{d}\tau . \tag{5}$$

With this definition, $X(t)$ and $Y(t)$ form the complex conjugate pair, so an analytic signal $Z(t)$ can be obtained:

$$Z(t)=X(t)+\mathrm{j}Y(t)=a(t)\mathrm{e}^{\mathrm{j}\theta(t)}, \tag{6}$$

where $a(t)=\sqrt{X^2(t)+Y^2(t)}$, $\theta(t)=\arctan[Y(t)/X(t)]$.

Thus, the HT provides a unique way of defining magnitude and phase of a signal. Essentially, Eq.(4) defines the HT as a convolution of $X(t)$ with $1/t$. It emphasizes the local properties of $X(t)$ and is the best local fit of an amplitude and phase varying trigonometric function to $X(t)$. Based on this, the instantaneous frequency can be defined as

$$\omega=\frac{\mathrm{d}\theta(t)}{\mathrm{d}t}. \tag{7}$$

Intrinsic mode function components

Using the local constraining conditions (i.e., the local mean of the data being zero, and the number of extrema and the number of zero crossings must be equal) to take the place of the global constraining conditions, a meaningful instantaneous frequency can be defined by the HT.

An intrinsic mode function (IMF) that satisfies the following two conditions can thus be defined:

(1) In the whole data, the number of extrema and the number of zero crossings must be either equal or different at most by one;

(2) At any point, the mean value of the envelope defined by the local maxima and the mean value of the envelope defined by the local minima are both zero.

Having defined IMF, the definition given in Eq.(7) gives the best instantaneous frequency. An IMF after the HT can be expressed as what in Eq.(5). If a Fourier transform on $Z(t)$ is performed, then

$$W(\omega)=\int_{-\infty}^{+\infty}a(t)\mathrm{e}^{\mathrm{j}\theta(t)}\mathrm{e}^{-\mathrm{j}\omega t}\mathrm{d}t=\int_{-\infty}^{+\infty}a(t)\mathrm{e}^{\mathrm{j}(\theta(t)-\omega t)}\mathrm{d}t. \quad (8)$$

By the stationary phase method, the maximum contribution to $W(\omega)$ is given by the frequency satisfying the condition

$$\frac{\mathrm{d}(\theta(t)-\omega t)}{\mathrm{d}t}=0. \quad (9)$$

Therefore, Eq.(7) follows. This is a much better definition for instantaneous frequency than the zero-crossing frequency. Furthermore, it agrees with the definition of frequency for the classic wave theory.

As given in Eq.(9), the frequency defined through the stationary phase condition agrees also with the best fit sinusoidal function locally. Therefore, a whole oscillatory period to define a frequency value is not needed. It can be defined for every point with the value changing from point to point. In this sense, even a monotonic function can be treated as part of an oscillatory function and has an instantaneous frequency assigned according to Eq.(7).

But for a complicated signal, it is more than one instantaneous frequency at a time locally. In order to use this definition of instantaneous frequency, an arbitrary data has to be decomposed into IMF components from which an instantaneous frequency value can be assigned to each IMF component.

Empirical mode decomposition

In order to decompose a complicated non-stationary signal into IMF components, Huang *et al*. (1998) proposed the empirical mode decomposition method. It is also called local wave decomposition because the method is based on the local characteristic of the signal.

For an arbitrary time data $X(t)$, m_1 is defined as the mean of two envelopes defined by its local maxima and minima, respectively, and the difference between the data and m_1 is the first component h_1, i.e.,

$$X(t)-m_1=h_1. \quad (10)$$

Ideally, h_1 should be an IMF. In reality, however, the envelope mean may be different from the true local mean for complicated non-stationary data, some asymmetric wave forms can still exist. In order to eliminate riding waves and let the wave be more symmetrical, the above process should repeat k times till h_k satisfies the requirements. Then the first IMF component c_1 can be obtained (h_k is treated as the original data in the following process).

c_1 can be separated from the rest of the data by

$$X(t)-c_1=r_1. \quad (11)$$

The residue, r_1, can be treated as a new data and the following result will be achieved when the same process is performed for n times:

$$\begin{cases} r_1-c_2=r_2, \\ r_2-c_3=r_3, \\ \quad\vdots \\ r_{n-1}-c_n=r_n. \end{cases} \quad (12)$$

By summing up Eqs.(11) and (12), $X(t)$ can be finally obtained:

$$X(t)=r_n+\sum_{i=1}^{n}c_i. \quad (13)$$

Thus, the original data is decomposed into n IMF components c_1, c_2, …, c_n and a residue r_n, which can be either the mean trend or a constant. The decomposition is completed when the number of local extrema of the final residue r_n is less than two.

The Hilbert spectrum

After performing HT on each component as described in Eq.(10), the data can be expressed in the following form:

$$X(t)=\mathrm{Re}\left(\sum_{i=1}^{n}a_i(t)\mathrm{e}^{\mathrm{j}\phi_i(t)}\right)=\mathrm{Re}\left(\sum_{i=1}^{n}a_i(t)\mathrm{e}^{\mathrm{j}\int\omega_i(t)\mathrm{d}t}\right). \tag{14}$$

Here the residue r_n is left out and Re denotes the real part of a complex number. Eq.(11) is defined as the Hilbert magnitude spectrum, or Hilbert spectrum for short,

$$H(\omega,\ t)=\mathrm{Re}\left(\sum_{i=1}^{n}a_i(t)\mathrm{e}^{\mathrm{j}\int\omega_i(t)\mathrm{d}t}\right). \tag{15}$$

The marginal spectrum can also be defined as

$$h(\omega)=\int_{-\infty}^{+\infty}H(\omega,\ t)\mathrm{d}t. \tag{16}$$

The above EMD together with the corresponding Hilbert spectrum analysis method is called as HHT.

DEFINITION OF FAULT CHARACTERISTIC

The fundamental zero sequence voltage can be extracted by HHT. As the load before switch-off is different, the RMS of fundamental zero sequence voltage after switch-off are not equal. Fig.1 shows the residual voltage at different load levels, as a DC generator being the load. The descend speed of residual voltage are different. This makes the RMS of zero sequence voltage under the two conditions be also unequal.

Consider that the zero sequence voltage declines with the positive sequence voltage synchronously, the ratio of them is defined as the stator fault characteristic:

$$V_{0\_\mathrm{Index}}=V^0/V^+, \tag{17}$$

in which V^+ denotes the positive sequence voltage after switch-off.

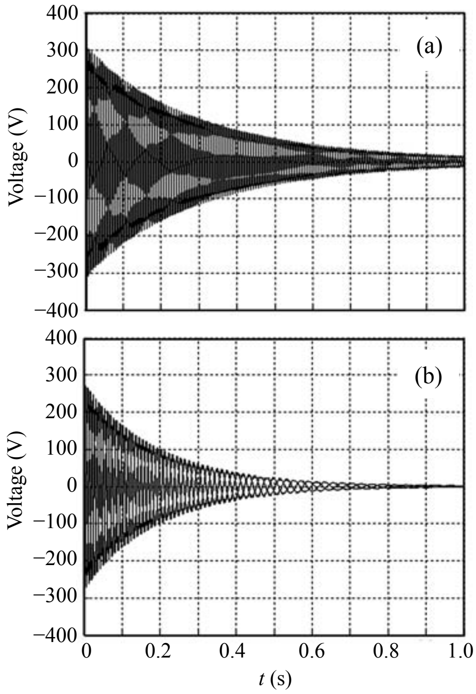

Fig.1 Residual voltage after switch-off at different load levels. (a) No-load; (b) Rated load

EXPERIMENTAL RESULTS

The proposed method is tested on a 4 kW, 380 V, 50 Hz, wye-connected, 4-pole induction motor coupled to a DC generator as the load. The stator windings are modified to form several accessible taps that are used to imitate the inter turn short circuits. Tests are achieved by connecting an external shorting variable resistor between terminal pairs to introduce the short circuit fault. The resistor allows the fault current to be controlled so as to avoid damaging the stator windings when the inter turn short circuit appears, as shown in Fig.2. Adjusting the resistor can change the severity of the inter turn short circuit fault. The voltage signal can be obtained through three voltage sensors, and a low pass filter is used to eliminate the high frequency interferences derived from experimental error.

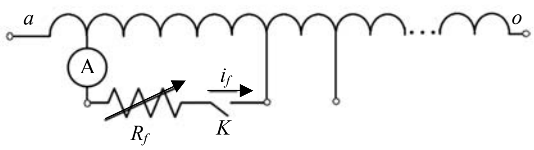

Fig.2 Schematic diagram of the stator winding inter turn short circuit experiment

Fig.3 shows the zero sequence voltage waveform of a normal motor and a faulty motor after switch-off. The motor was running under no-load condition before switch-off, the short circuit turns are almost 5% of the total turns in the a-phase, and the short circuit current is 4 A. From the figure, it is obvious that the amplitude of the fundamental component of a faulty motor is much bigger than that of the healthy one.

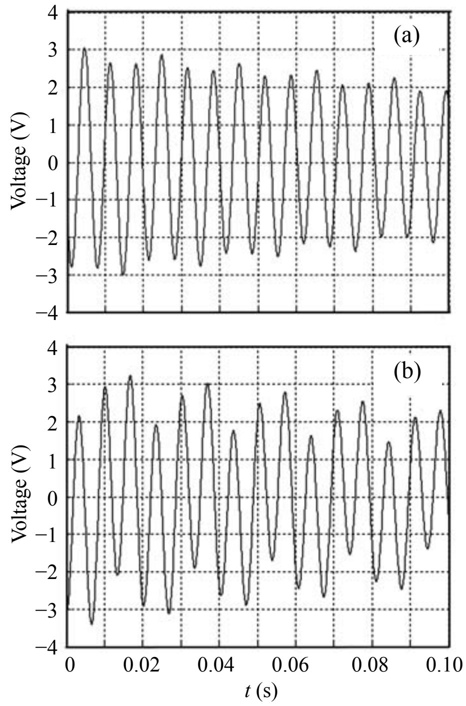

Fig.3 Zero sequence voltage after switch-off. (a) Healthy motor; (b) Faulty motor

According to the principles of EMD, it is known that construction of the envelope line, which influences the whole decomposition process and results, is the key to HHT. The upper and lower envelopes determined by local maxima and minima are used to achieve the local mean. Once the extrema are identified, all the local maxima are connected by a cubic spline line as the upper envelope. Repeat the procedure for the local minima to produce the lower envelope. The upper and lower envelopes should cover all the data between them. Their mean is defined as the mean of the whole data.

During the decomposition, the ending effect will distort the signal. For solving this problem, the signal is extended at the two ends and intercepted after EMD. Through this process, the authenticity of the signal can be kept.

In Fig.4, the two zero sequence voltages are decomposed by the EMD and IMF. c_1 and c_2 are acquired. c_1 is three times harmonics and c_2 is the fundamental component.

The three times harmonics are almost changeless, but the fundamental component increases remarkably due to the asymmetry caused by inter turn short circuit fault.

Because of the intrinsic asymmetry of the motor and the different gains of three voltage sensors, the fundamental zero sequence voltage of healthy motor is not exactly zero, as shown by Fig.4a. This brings inconvenience to the diagnosis, so a calibration should be performed. The coefficient k_{ua}, k_{ub} and k_{uc} can be adjusted to make the fundamental zero sequence voltage of healthy motor tending to zero:

$$v_0=(k_{ua}v_a+k_{ub}v_b+k_{uc}v_c)/3\approx 0. \quad (18)$$

These coefficients will be saved and used for the process of diagnosis. Through calibration, the two fundamental zero sequence voltages are displayed in Fig.5. Now, the fundamental zero sequence voltage of healthy motor is nearly zero.

All the short circuit fault experiments above were done under the no-load condition. In order to compare the fault characteristics at different load levels, Fig.6 shows the experimental results under the rated load, where the fault conditions are the same as above.

Through the comparison and calculation, the fault characteristics of a healthy motor are 0.0191% and 0.0186%, respectively, while the fault characteristics of a faulty motor are 0.2654% and 0.2489%, respectively. Thus, the fault characteristic is immune to the load level and reflects the fault directly.

According to the scheme of Hilbert transform to seek the signal's instantaneous frequency, the instantaneous frequencies of fundamental zero sequence voltage after switch-off are displayed in Fig.7. They are faulty motors and had the same short circuit fault.

Although the instantaneous frequency indicates that the descend speeds of the zero sequence voltage are unequal, their fault characteristics are almost equal. It illustrates again that the fault characteristic is not affected by load.

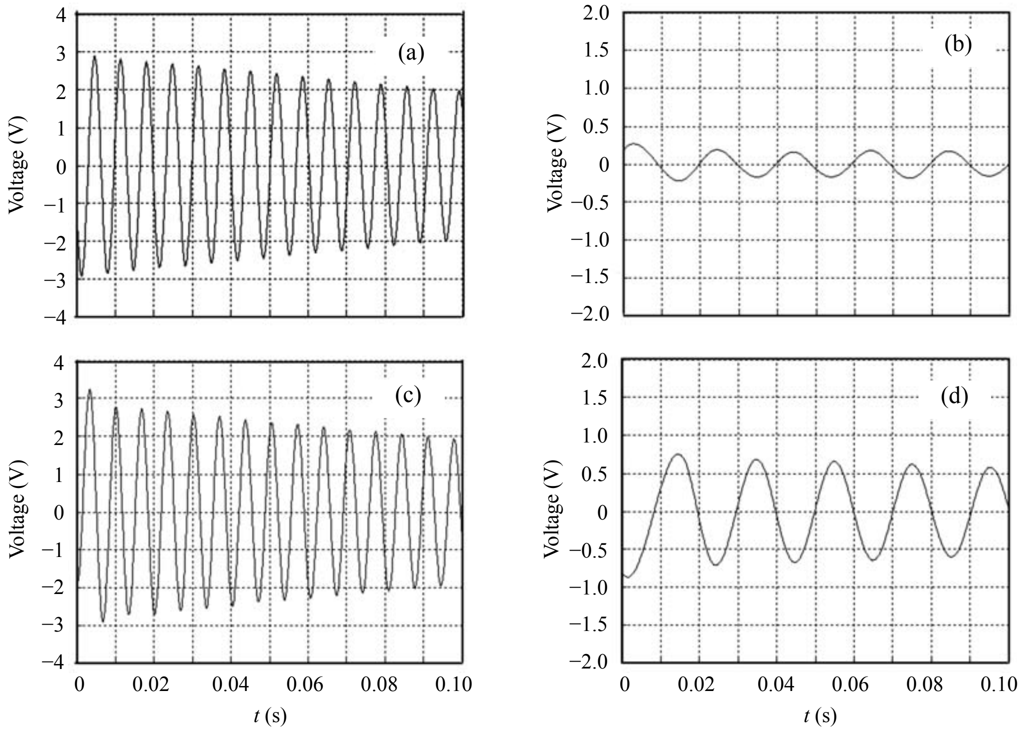

Fig.4 IMF of zero sequence voltage after switch-off, decomposed by means of EMD
(a) Healthy motor, three times harmonics; (b) Healthy motor, fundamental component;
(c) Faulty motor, three times harmonics; (d) Faulty motor, fundamental component

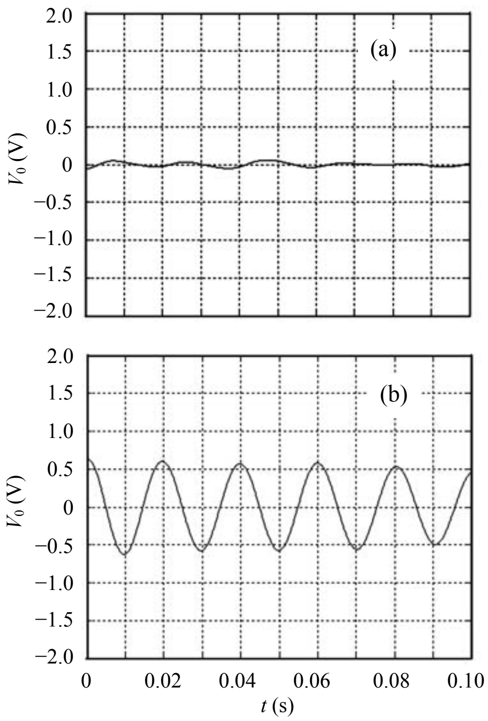

Fig.5 The fundamental zero sequence voltage after calibration with no-load through the factor verification. (a) Healthy motor; (b) Faulty motor

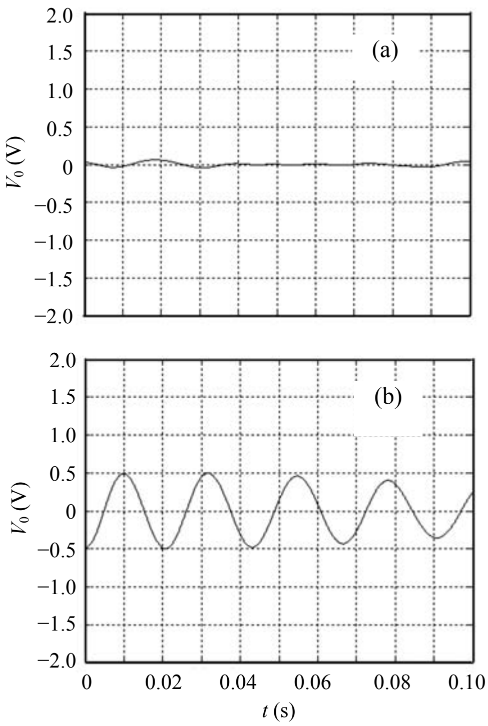

Fig.6 The fundamental zero sequence voltage after calibration with rated load through the factor verification. (a) Healthy motor; (b) Faulty motor

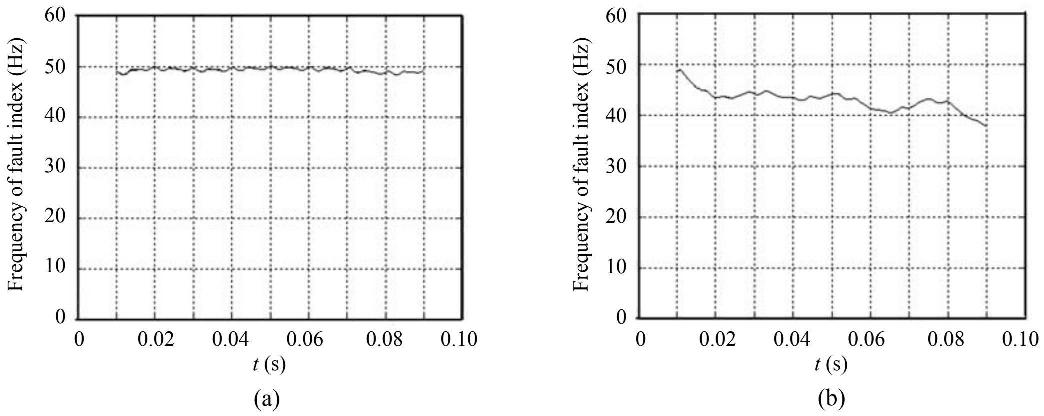

Fig.7 Instantaneous frequency of fundamental zero sequence voltage after switch-off, faulty motor under the same fault condition. (a) No-load; (b) Rated load

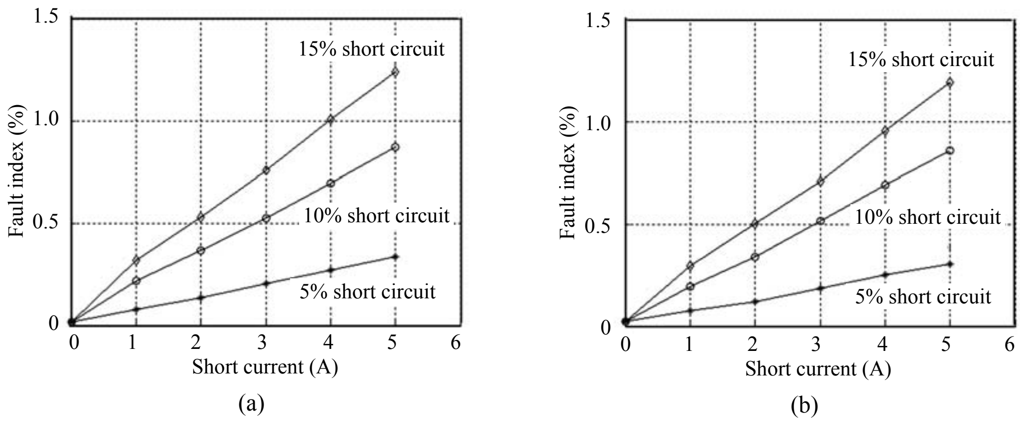

Fig.8 Evolution of fault characteristic with short circuit fault severity. (a) No-load; (b) Rated load

A series of experiments were performed through changing the stator winding taps which connect to the resistor to make the short circuit turns be 5%, 10% and 15%, respectively. The fault severity can be acquired by adjusting the short circuit current. Fig.8 displays the experimental results under the conditions of no-load and rated load.

The inter turn short circuit faults are set in the same phase and the same pole. Therefore, the stator fault characteristics should increase monotonically with the number of short circuit turns and the value of short circuit current. The experimental results demonstrated the rule excellently. Furthermore, the fault characteristic is related to the fault severity only and immune to the load level, which is well coincident.

CONCLUSION

A new method for diagnosing stator winding inter turn short circuit fault is proposed in this paper. The ratio of fundamental zero sequence voltage to positive sequence voltage after switch-off is defined as the fault characteristic, which is immune to the influence of supply and load, and reflects the stator fault directly. Based on the HHT, the fundamental zero sequence voltage is extracted by means of EMD, and the fault characteristic can be calculated. Experimental results verified the feasibility and reliability of this stator fault diagnosis method. Nevertheless, there is a limitation to this method, namely the fault cannot be diagnosed on-line.

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