Fault feature extraction of rotor broken bar and stator winding inter-turn short circuit of asynchronous motors

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Abstract: In order to accurately identify the stator and rotor faults of three-phase squirrel cage induction motor, it is necessary to extract the fault characteristics of the motor accurately and quickly. A normal induction motor, the stator phase current only have the fundamental component in theory, but it will produce harmonic components of different frequencies or change the energy of the original harmonic components when a fault occurs. Convert the fault current to frequency domain and get its spectrum, will be found that the amplitude of fundamental current is very large and the amplitude of harmonic current is very small, and their frequency is very close when the rotor bar is broken. Because of the influence of fundamental current, it is difficult to identify the fault feature components in the spectrum. In this paper use a hybrid genetic algorithm based on Nelder-Mead simplex method to estimate the fundamental current, obtain the expression of fundamental wave current and remove it from the fault current. In this way, the fault characteristics of motor stator or rotor can be obtained.

1. Introduction

With the development of industry and the improvement of productivity, induction motors is widely used in life. Therefore, the fault diagnosis of motor is becoming more and more important. The research results show that the rotor bar breakage accounts for about 10% of the motor faults, and the inter-turn short circuit of the stator winding accounts for about 30%~40% of the motor faults[1-3]. The problem of the fault diagnosis of stator and rotor is essentially a state recognition problem, and the premise of state recognition is to accurately and quickly extract the fault characteristics of the motor.
2. Principle Analysis of motor fault feature extraction

A normal induction motor, only the fundamental current signal is present in the stator phase current in theory. Although there are some harmonic components due to inherent asymmetry in the motor structure, but their amplitudes are very small and can be ignored \[^2\]. At this time, phase current expression can be written as

\[ i_a(t) = I_1 \cos(w_1 t + \phi_1) \]  

In this expression: the parameter \( I_1 \) is the fundamental wave amplitude; \( w_1 \) is the angular frequency; \( \phi_1 \) is the initial phase.

A fault characteristic component with frequency \( f_{brk} \) will be generated in the stator current when the rotor is broken or end-ring cracking. The general current signal expression of the induction motor with rotor broken bar fault\[^6\] is as follows

\[ i_a(t) = I_1 \cos(w_1 t + \phi_1) + \sum_{k=1}^{N} I_{bpk} \cos((1 - 2ks)w_1 t + \phi_{bpk}) + \sum_{k=1}^{N} I_{bnk} \cos((1 + 2ks)w_1 t + \phi_{bnk}) + n(t) \]  

In this expression: the parameter \( I_1 \), \( w_1 \), \( \phi_1 \) is the amplitude, angular frequency and initial phase of the fundamental current, \( I_{bpk} \), \( I_{bnk} \) is the amplitudes of the harmonic current, \( k=1,2,3,\ldots,N \), \( \phi_{bpk} \), \( \phi_{bnk} \) is the initial phase of the harmonic current, \( n(t) \) is white noise with a mean value of 0, respectively.

Meanwhile, the stator current will generate more harmonic components or enhance some original harmonic components when the stator winding of the motor suffers from inter-turn short circuit fault\[^8\]. the expression of the phase current can be written as follows

\[ i_a(t) = I_1 \cos(w_1 t + \phi_1) + \sum_{k=2}^{N} I_k \cos(\omega_k t + \phi_k) + n(t) \]  

In this expression: the parameter \( I_1 \), \( \omega_1 \), \( \phi_1 \) are the amplitude, angular frequency and initial phase of the fundamental current, \( I_k, \omega_k, \phi_k \) are the amplitude, angular frequency and initial phase of each harmonic current, \( k=2,3,\ldots,N \), \( n(t) \) is white noise with a mean value of 0, respectively.

Therefore, in order to obtain the motor fault characteristics, this paper chooses to remove the fundamental current. According to document \[^2\], this paper set a set of base function of unit orthogonal cosine function \( \{ \psi_n(t) \} \) at first. Because the fundamental wave and harmonic frequencies of the fault current are different, and the energy of the fundamental wave is the largest, have the largest amplitude in the spectrum. Therefore, calculate the absolute value of the inner product of the fundamental wave and the unit cosine basis function, the absolute value of their inner product has a maximum only when the unit cosine basis function has the same frequency and phase as fundamental wave. Similarly, the unit cosine basis function frequency and phase are the frequency and phase of current fundamental wave when the absolute value of their inner product is the maximum. Moreover, because the cosine basis function is unit orthogonal, so the absolute value of its inner product is the amplitude of fundamental wave signal. Fundamental wave expression can be constructed from this relationship and its expression is as follows. In the expression: \( \psi_n \) is the cosine basis function, \( C_n \) is the normalization coefficient, \( a_1 \) is the amplitude of the fundamental current, \( I_1 \) is the fundamental current, and \( I_{11} \) is the harmonic signal of the current fault.
\[ \psi_n = C_n \cos(\omega_n t + \varphi_n) \]  
(4)

\[ a_1 = (i_a(t), \psi(t)) = \max\{|i_a(t), \psi_n(t)|\} \]  
(5)

\[ I_1 = a_1 \cos(\omega_n t + \varphi_n) \]  
(6)

\[ I_{11} = i_a(t) - I_1 \]  
(7)

3. Hybrid genetic algorithm based on Nelder-Mead simplex method

Genetic algorithm is a parallel, efficient and global search method which simulates the process of inheritance and evolution of organisms in natural environment. It codes optimized variables to simulate biological chromosomes, and then iterates through the operations of selection, crossover and mutation. Each iteration retains the best individuals of the previous generation, and completes the iteration after a specified genetic algebra. Finally, the best individual is selected from the group.

Nelder-Mead algorithm is an improved simplex method proposed by J.A. Nelder and R. Mead in 1965. It is a direct method for solving function optimization problems and does not need to find the first or second derivatives of the objective function, but only uses the information of the objective function value. The optimal solution can be found directly through four simple heuristic operations: reflection, expansion, contraction and compression of the edge length[9].

Genetic algorithm has strong global search ability, but its local search ability is not strong and its convergence is slow. Simplex method has the advantages of direct efficiency and fast search speed, but because the algorithm only uses local information of search space, so it is difficult to find global minimum when it converges to a local stagnation point[5].

This paper introduces the simplex method into the genetic algorithm, and the simplex search is performed on the optimal value of each generation in the genetic algorithm. It can improve the local search ability of the genetic algorithm and improve the quality of the global extreme points quickly. The algorithm flow chart is shown in figure 1.

![Figure1. Flowchart of hybrid genetic algorithm](image-url)

This paper use the hybrid genetic algorithm to estimate the parameters of the fundamental current, the formula (5) is used as the fitness function of the algorithm to find its maximum value. The frequency and phase of the unit cosine basis function are the two variable factors of the algorithm. The
population size is set at 30, the maximum genetic algebra is set at 30, the crossover probability is set at 0.7, and the mutation probability is set at 0.1, the number of iterations per simplex search is 50, the location threshold between particles is 1e-4, and the fitness threshold is 1e-9. The frequency, phase and amplitude are the parameters corresponding to the fundamental current wave when the fitness function is convergent. Then based on these parameters, the expression of the current fundamental wave is obtained.

4. Validation with simulation data

This paper selects the rotor broken bar fault signal to verify the adopted method. The amplitude of the $f_{br1} = (1 \pm 2s)f_1$ is the largest in all rotor fault bars harmonic component, therefore, this paper choose the expression (8) as the analog signal of rotor broken bar

$$i_a(t) = I_1\cos(\omega_1t + \phi_1) + I_{bp1}\cos[(1 - 2s)\omega_1t + \phi_{bp1}] + I_{bn1}\cos[(1 + 2s)\omega_1t + \phi_{bn1}] + n(t)$$  \hspace{1cm} (8)

In this expression: $I_1$, $\omega_1$, $\phi_1$ are the amplitudes, angular frequencies and initial phases of the fundamental current, which are $10A$, $2\pi\times50\text{rad/s}$ and $\pi/4\text{rad}$, respectively. The amplitude of the $(1 \pm 2s)f_1$ is very small relative to the $f_1$ (The ratio is about 0.02~0.05) when the rotor is slightly broken. At the same time, due the slip ratio ‘s’ is very small, so the frequency interval between $(1 \pm 2s)f_1$ and $f_1$ is very close (The difference is about 0.5~5Hz)\cite{4}. This paper set $I_{bp1} = I_{bn1} = 0.2$, $(1 - 2s)f_1=2\pi\times49.5$, $(1 + 2s)f_1=2\pi\times50.5$, $\phi_{bp1}=\pi/2$, $\phi_{bn1}=\pi$. n(t) is a random interference signal evenly distributed within [-0.2,0.2]. The sampling frequency of analog current signal is 250 Hz and the sampling length is 1000\cite{2}.

As shown in Fig.2, it is the current signal diagram of the Broken rotor of motor. Fig. 3 is its spectrum diagram. It can be seen that the amplitude of the fundamental component is too large, which basically conceals the fault characteristic component. Therefore, to find out the fundamental components by the hybrid genetic algorithm and remove it. Fig.4 is the fitness evolutionary curve of genetic algorithm without introduce simplex method. Fig.5 is the fitness evolution curve of hybrid genetic algorithm. After obtaining the parameters of the fundamental component, the fault characteristic component is calculated according to Eq. (7). Fig. 6 is the spectrum of the fault characteristic component.

![Fig. 2 Analog fault current signal](image1)

![Fig. 3 Spectrum of analog current](image2)
As can be seen from the above figure, the hybrid genetic algorithm can extract the fault characteristics of the motor well. In order to further observe the error of the algorithm, this paper compare the estimated value of the algorithm with the actual value of the parameters. As shown in table 1, the estimated value of the algorithm is almost the same as the actual value of the parameter.

Table 1 Actual value and estimated value of current component

|                | Frequency/Hz | Phase/rad | Amplitude/A |
|----------------|--------------|-----------|-------------|
| Actual value   | 50.00        | π/4       | 10.00       |
| Estimated value| 50.00        | 0.78      | 10.00       |

5. conclusion
In this study, aiming at the influence of current fundamental wave on motor fault feature extraction, this paper adopt a hybrid genetic algorithm based on Nelder-Mead simplex method to estimate the fundamental wave current and remove it. In this way, clear fault harmonics can be obtained. Finally, this paper use simulation data to validate the method. The results show that the method is fast and accurate, and has good effects in fault feature extraction.

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