Diagnostics of inter-turn short-circuit in the stator winding of the induction motor

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Abstract. A stator malfunction occurs due to insulation damage, which means that the stator is directly connected to the power supply, and a direct connection is the direct cause of a major accident. For this reason, a lot of research is being done to identify faults. In recent years, studies on Motor Electrical Signature Analysis are being performed, sensorless methods for fault diagnosis of the stator of an induction motor. However, it has problems with it, it has the difficulty in interpreting multi-faults and in detecting an inter-turn short circuit of a stator. This paper suggested a tool that can diagnose 2-turn short circuit, through the relationship between self-inductance and mutual inductance in the synchronous reference frame of a D-Q transformation.

1. Introduction

Three-phase asynchronous motors are important in the industrial world because of their reliability, low cost, low operating costs and high performance [1]. Driving asynchronous motor with frequency converters in combination with environmental conditions (high temperature, humidity and corrosive environments) and the internal state of the machine can lead to stator faults [2, 3]. These faults can turn into catastrophic failures if left unnoticed, and they can lead to financial losses due to costly repairs and downtime. Among the various types of faults in an asynchronous motor, the most frequent is an inter-turn short circuit between windings [4].

In fact, the occurrence of such a malfunction begins with the deterioration of the characteristics of insulating materials, which leads to the breakdown to the inter-turn insulation and thus to the incipient inter-turn short circuit faults. From this, it follows that a greater current will flow along the path with low impedance by increasing the temperature of the conductor [5], which can destroy the insulation of adjacent windings. Therefore, the initial detection of an inter-turn short circuit can prevent subsequent damage to the motor and significantly reduce economic losses [6, 7, 8].

Until recently, studies were carried out on the basis of the Park's vector approach to diagnose faults in the rotor and stator [9, 10]. However, this approach has problems in the definition of complex faults of various kinds and in the detection of the inter-turn short circuit of the stator. The solution of which is proposed in [10, 11, 12], but nevertheless, there is a difficulty in detecting a double-turn short circuit of the stator windings.

In this article, the characteristics of stator faults in the synchronous reference frame D-Q transformation were analyzed by observing changes in self-inductances and mutual inductances that are elements of the inductance and Park's vector approach, which can detect an inter-turn short circuit.

When an inter-turn short circuit occurs, circulating currents appear in the stator winding in the inductance loop, which appears in the winding (Figure. 1), which changes the total value of the
inductance and directly causes exposure to magnetic flux or electric current. Then the currents are fed to the counter EMF of phase A, which is different from the counter EMF of E1 generated in phase A.

Figure 1. Circulating current during inter-turn short circuit.

Flux linkage of a three-phase asynchronous motor is created both in the rotor and in the stator [14]. Thus, the formula for the flux linkage will be equal to the formula (1):

$$\begin{bmatrix}
\psi_a \\
\psi_b \\
\psi_c \\
\psi_s
\end{bmatrix} = 
\begin{bmatrix}
L_{aa} & L_{ab} & L_{ac} & L_{as} \\
L_{ba} & L_{bb} & L_{bc} & L_{bs} \\
L_{ca} & L_{cb} & L_{cc} & L_{cs} \\
L_{sa} & L_{sb} & L_{sc} & L_{ss}
\end{bmatrix}
\begin{bmatrix}
i_a \\
i_b \\
i_c \\
i_s
\end{bmatrix} +
\begin{bmatrix}
L_{ar} \\
L_{br} \\
L_{cr} \\
L_{sr}
\end{bmatrix}
\begin{bmatrix}I_r
\end{bmatrix}$$

(1)

However, for each phase of the stator self-inductance, mutual inductance of one phase and the mutual inductance between the phases must be taken into account in time. It is also necessary to take into account the change in mutual inductances in time under the action of voltage, which is induced by the rotor. Therefore, it is proposed to use the D-Q transformation method, which was originally used to implement vector motor control, because this method reduces from three-phase to two-phase.

2. Application of Park Vector Approach

Formula (2) shows in a vector way currents in the whole space of a three-phase asynchronous motor:

$$\vec{I}_s = \frac{2}{3} \left[ i_a(t) + a i_b(t) + a^2 i_c(t) \right],$$

(2)

where $a = e^{\frac{2\pi}{3}}$ and $a^2 = e^{\frac{4\pi}{3}}$, indicating an interval of 120 degrees between the current vectors in each phase.
\[
\begin{bmatrix}
i_α \\
i_β \\
\end{bmatrix} = \begin{bmatrix}
1 & \frac{1}{2} & \frac{1}{2} \\
\frac{1}{2} & \frac{\sqrt{3}}{2} & \frac{-\sqrt{3}}{2} \\
\frac{\sqrt{3}}{2} & \frac{-1}{2} & \frac{1}{2} \\
\end{bmatrix}
\begin{bmatrix}
i_a \\
i_b \\
i_c \\
\end{bmatrix}.
\] (3)

The conversion of a three-phase reference system into a two-phase one is called the Clarke transform, where the \(\beta\)-axis is perpendicular to the \(\alpha\)-axis, which is parallel to the magnetic flux (3):

\[
\begin{bmatrix}
i_d \\
i_q \\
\end{bmatrix} = \begin{bmatrix}
\cos \theta & \sin \theta \\
-\sin \theta & \cos \theta \\
\end{bmatrix}
\begin{bmatrix}
i_α \\
i_β \\
\end{bmatrix}.
\] (4)

Rotation of the vector at the zero point by changing \(\theta\) is called the Park vector approach or the synchronous reference system D-Q (4).

This article proposes a method for detecting an inter-turn short circuit. The method checks the frequency changes in accordance with the ratio of self-inductance to mutual inductance and collates the turn-to-turn short circuit time, which is aggravated in the synchronous frame of reference D-Q transformation.

3. The relation between the inter-turn short circuit and the inductance
If the inter-turn short circuit was divided exactly by one third of the original circuit, this value for \(L_0\) can be represented as \(L_1 + L_2 + L_3\):

\[L_0 = \frac{L_1 + L_2 + L_3}{3}\]

As you can see in Figure 2, short-circuit inductance has the value of the combined inductance (\(L_2\) and \(L_{\text{short}}\) parallel to each other), and the correlation between the two inductances is \(L_2 > L_{\text{short}}\), because \(L_{\text{short}}\) has a very small inductance value.

Previously, the simulation of self-inductance and mutual inductance is implemented through \(L_1 = L_2 = L_3\) (shorted inductance value: \(L_2 = L_{\text{short}}\)), but the actual inter-turn short circuit occurs in the inductance adjacent the common inductance, and it can be seen that the value of \(L_2\) will be significantly less \(L_0\). Impedance of the inter-turn short circuit in the stator winding decreases. In order to see the various changes appearing during a short circuit, the impedance values \(L_1\) and \(L_3\) were increased from 1 to 10 mH. \(L_0\) in steady state is 30 mH. Electric scheme was created to simulate the stator winding and monitor changes occurring in it, shown in Figure 3 with the following preliminary parameters:

- Pulse envelope: 5V;
- Pulse on time: 1ms;
- Full cycle: 2ms.

Figure 2. Separation inductance during inter-turn short circuit.
Figure 3. The circuit simulation of the impedance changes.

In Figure 4 (a) modeling was performed only taking into account self-inductances. With the occurrence of an inter-turn short circuit of 0.003% of the whole inductance, the result is similar to the result with steady-state inductance, and when an inter-turn short circuit occurs 0.05% of the total inductance, a serious frequency distortion occurs.

In Figure 4 (b) modeling was performed taking into account mutual inductances. With the occurrence of an inter-turn short circuit of 0.003% of the whole inductance, the level of the inductance frequency is higher than in the steady state. With an inter-turn short circuit of approximately 0.07% of the whole inductance, the range of results is similar, as with the steady-state inductance. A higher rate of short-circuit is more distorted, as if considering only self-inductances.

Figure 4. Variations in self-inductance values (a) and mutual inductance (b), and voltage regulation.

4. Monitoring inductance changes based on D-Q transformation

In Figure 5 shows the changes in the values of the vector approach of the Park with an inter-turn short circuit of 2, 4 and 6-turns short circuit. To calculate the values presented in table 1 were used formulas (3) and (4).
As seen in Figure 5, in the steady state, there is a noise effect caused by a power unbalance. A double-turn short circuit has a similar amplitude of the waveform, as in the absence of an inter-turn short circuit, but the total amplitude is narrower, and with a 6-turn short circuit, the amplitude is wider. Table 1 presents the results of changes occurring in the stator winding (without short circuit, 2, 4, ..., 12-turn short circuits). And in Figure 6 shows each value as a graph. The amplitude difference begins to occur with a 4-turn short circuit, and with a double-turn short circuit, it is not significant due to the imbalance of power. For this reason, when using a Park vector approach is difficult to detect double-turn short circuit.

![Figure 5. Changes in the synchronous reference frame during an inter-turn short circuit.](image)

| Table 1. Comparison of the maximum and minimum values of the number of closed turns of the winding. |
|---------------------------------------------------------------|
| Maximum value | Minimum value | Average value |
|----------------|----------------|----------------|
| Without short circuit | 1.9026 | 1.75862 | 1.83033 |
| 2 turn short | 1.83642 | 1.6717 | 1.7503 |
| 4 turn short | 1.89492 | 1.65308 | 1.77221 |
| 6 turn short | 2.03913 | 1.73635 | 1.8949 |
| 8 turn short | 2.24964 | 1.75646 | 2.0141 |
| 12 turn short | 2.36362 | 1.7514 | 2.07157 |

However, the average value in the case of a double-turn short circuit taking into account mutual inductances is lower compared to the absence of a short circuit, that is, according to the simulation result, in Figure 6, 4-turn short circuits occurred at approximately 0.07% inductance and 2-turn short circuits at less than 0.07% inductance.
Figure 6. Changes of the maximum and minimum values depending on the number of turn short circuit.

5. Conclusion
The article used the Park's vector approach to diagnose a 2-phase short circuit and proposed a method for detecting 2-turn short circuits by simulating the change in mutual inductances. In accordance with the result of the experiment with the use of D-Q transformation, there is a clear difference in amplitude with a short circuit of 4 or more turns compared with no short circuit, and for a 2 turn short circuit there is a slight change in the difference of amplitudes, while the total amplitude getting lower. The reason for this is the change in the proportion of common mutual inductances of the induction motor with inter-turn short circuit during operation at rated speed.

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