

Modelling a multi-phase short circuit in the stator winding of an induction motor

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Inter-turn short circuits in the stator winding constitutes a critical fault in induction motors, significantly impacting their operational reliability and efficiency. Although in the literature inter-turn short circuits are commonly considered as single phase faults, in this article, short circuits in all three phases of the machine are analysed. The proposed approach accounts for detailed electromagnetic modelling and the asymmetry caused by multi-phase faults. The presented results can be used for advanced diagnostic techniques for multi-phase inter-turn short circuits.

Index Terms—Electrical machines, Fault modelling, Multi-phase short circuit, Stator winding

I. INTRODUCTION

Inter-turn short-circuits in the winding of induction motors are among the most prevalent failures, typically attributable to degradation of the winding insulation, and result in a reduction in machine operating time. Existing models predominantly focus on analysing faults confined to a single phase, which limits the ability to fully reflect the impact of these phenomena on machine operation. An analysis of inter-turn short circuits in one phase is presented in [1]. The presented paper proposes an extended approach to modeling inter-turn faults, considering their simultaneous occurrence in all three phases. The presented methodology enables a more accurate analysis of electromagnetic asymmetries and their effect on motor performance parameters, providing critical data for the development of diagnostic algorithms.

II. MODELLING OF SHORT-CIRCUITS IN THE STATOR WINDINGS OF INDUCTION MOTORS

A. Equivalent diagram of the stator winding

The present article focuses on the presentation of the alterations in the equivalent diagram of the stator winding of an induction motor in the event of a short circuit of the winding appearing in all phases of the stator winding. One of the consequences of a short circuit of the winding appearing in the stator winding is its division into two parts: the faulty part (parameters marked with superscript F) and the shorted part (parameters marked with superscript S). As illustrated in Figure 1, an equivalent diagram is presented for the i -th phase of the winding, with the resistance R_i^{SC} of the shorted circuit included for additional clarity. In the majority of studies, the assumption is made that the short circuit is galvanic, leading to the simplification of $R_i^{SC} = 0$. For the purpose of further analysis, the number of turns in the faulty part

of the i -th phase winding is designated as N_i^F , and the number of shorted turns in the same phase is denoted as N_i^S .

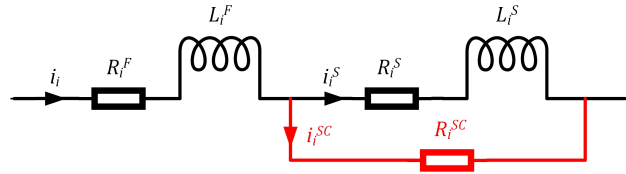


Fig. 1. Inter-turn short-circuit in i -th phase of stator winding

B. Stator winding fault factors

The utilisation of the equivalent circuit diagram of the stator winding of an induction machine that has been presented enables the formulation of a system of voltage equations in concise matrix form:

$$\mathbf{U}_S = \mathbf{R}_S \mathbf{i}_S + d/dt(\Psi_S) \quad (1)$$

where: $\mathbf{U}_S$ is the voltage vector, $\mathbf{R}_S$ is the resistance matrix, $\mathbf{i}_S$ is the current vector, Ψ_S is the stator winding associated flux matrix.

The vector of fluxes associated with the winding can be expressed in terms of the lumped parameters of the equivalent scheme as follows:

$$\Psi_S = \mathbf{L}_{SS} \mathbf{i}_S + \mathbf{L}_{SR} \mathbf{i}_R \quad (2)$$

where: $\mathbf{L}_{SS}$ is the stator winding self-inductance matrix, and $\mathbf{L}_{SR}$ is the mutual inductance matrix between the stator and the rotor.

Two equivalent approaches can be used to calculate the individual values in the resistance and inductance matrices of the stator winding, taking into account winding shorts. The difference between them lies in the reference point used. In the first approach, the values of resistance

and inductance are determined based on the number of turns of the faulty part referenced (N_i^F) relative to the phase number of turns of the winding (N_i). In this case, the following factor can be introduced:

$$k_i^F = N_i^F / N_i \quad (3)$$

In (3) the symbol i is used to denote the phase of the stator winding, i.e. phase A, phase B or phase C.

The second approach involves the reference to the number of shorted turns (N_i^S) in relation to the phase number of turns (N_i):

$$k_i^S = N_i^S / N_i \quad (4)$$

The relationship between the coefficients of k_i^F and k_i^S can be expressed as follows:

$$\begin{aligned} k_i^S &= N_i^S / N_i \\ &= (N_i - N_i^F) / N_i \\ &= 1 - k_i^F \end{aligned} \quad (5)$$

The coefficients, thus defined as k_i^F and k_i^S , can be used to calculate the resistance values of the faulty part of the winding and the shorted part as follows:

$$\begin{aligned} R_i^F &= R_i \cdot k_i^F \\ &= R_i \cdot (1 - k_i^S) \end{aligned} \quad (6)$$

$$\begin{aligned} R_i^S &= R_i \cdot k_i^S \\ &= R_i \cdot (1 - k_i^F) \end{aligned} \quad (7)$$

In a manner analogous to the calculation of resistance values, the inductance values of the faulty part of the winding and the shorted part can be determined as follows:

$$\begin{aligned} L_i^F &= L_i \cdot (k_i^F)^2 \\ &= L_i \cdot (1 - k_i^S)^2 \end{aligned} \quad (8)$$

$$\begin{aligned} L_i^S &= L_i \cdot (k_i^S)^2 \\ &= L_i \cdot (1 - k_i^F)^2 \end{aligned} \quad (9)$$

The following interpretation can be proposed for the individual coefficients. Firstly, the coefficient k_i^F is capable of determining which part of the winding is undamaged. Secondly, the coefficient k_i^S is able to determine how much of the winding is shorted, i.e. damaged.

The presented approach was utilised to calculate the individual resistance and inductance values of the equivalent stator winding circuit. This approach resulted in the development of a numerical model of a squirrel-cage induction motor, which was found to have the following ratings: power 3 kW, speed 1415 rpm.

III. SELECTED RESULTS OF SIMULATION CALCULATIONS

The developed model of a squirrel-cage induction machine was employed to facilitate simulation calculations in ANSYS/Maxwell. Figure 2 shows the calculation results for the fault configuration: 4 shorted turns in phase A ($N_A^S = 4$), 1 shorted turn in phase B ($N_B^S = 1$) and 3 shorted turns in phase C ($N_C^S = 3$). This figure shows the calculated phase current waveforms in phase A, phase B and in phase C denoted VIA, VIB and VIC respectively.

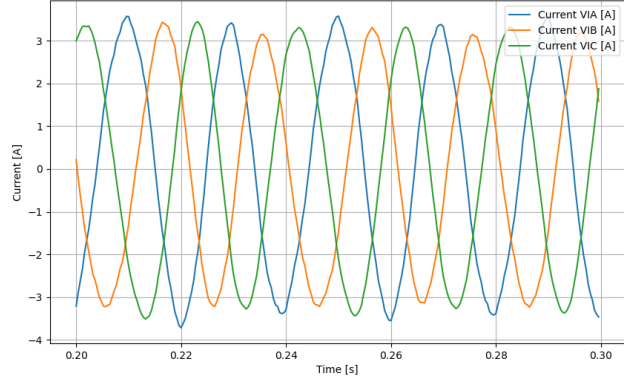


Fig. 2. Phase current waveforms for the faulty motor at no load test ($T_L = 0$)

From the waveforms obtained (see Figure 2), it is challenging to determine the cause of the observed asymmetry. Consequently, the utilization of machine learning methodologies for the interpretation of results is advantageous, as these methods can effectively assess the technical condition of the machine.

IV. SUMMARY AND CONCLUSIONS

This paper proposes two methodologies for calculating the resistance and inductance values of the equivalent stator winding diagram of a squirrel-cage induction machine. The first approach is based on the number of unshorted turns of a stator winding, while the second is based on the number of shorted turns of a stator winding in the induction machine. The validity of both approaches is demonstrated through a comparative analysis, which confirms their equivalence. The paper further presents a calculation example of current waveforms in a faulty stator winding and concludes with the assertion that the presented approaches can be effectively applied to the analysis of failures in squirrel-cage induction machines.

REFERENCES

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