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Calculation of derating factors based on steady-state unbalanced multiphase induction machine model under open phase(s) and optimal winding currents

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ABSTRACT

Multiphase machines have become a promising candidate in high-power applications as they offer many advantages over their three-phase counterparts. The main salient feature is the high fault tolerance capability. During faults, two alternatives for machine operation are possible, namely; open loop control and optimal current control. While the former corresponds to higher torque ripple and unbalanced winding currents, the latter option necessitates unbalanced phase voltages and typically an increased DC-link voltage to source the required optimal currents. Consequently, an increase in the employed semiconductor device rating is required, which is a critical design factor especially in medium voltage applications. This paper investigates an eleven-phase induction machine with concentric windings under fault conditions. An unbalanced steady-state machine model based on symmetrical components theory is developed as a mathematical tool to estimate different machine currents and total developed torque under open circuit phase(s). The effect of different sequence planes is also included in the derived model. This model is then experimentally verified. It is shown that the application of optimal current control in multiphase induction machines with open circuited phase(s) optimizes torque production while maintaining minimum stator copper loss and torque ripples. This optimization problem usually incorporates solving complicated nonlinear equations that increase in complexity with higher numbers of phases. Alternatively, a genetic algorithm is used in this paper to provide a simple method to obtain the optimum currents in the remaining healthy phases. Based on the derived optimal currents, the steady-state model is used to estimate the required DC-link voltage reserve that ensures no machine de-rating. Finally, the required derating factors to avoid machine overheating are calculated for different numbers of disconnected phases when DC-link voltage limitation is introduced.

1. Introduction

Multiphase machines have become serious contenders for safety-critical application and high power applications [1–6]. The additional degrees of freedom provided by multiphase machines [1,7,8] enable meeting the stringent requirements typical of high power and/or wide fault tolerance applications in electric ships, hybrid vehicles, pumps, compressors, and electric aircraft. The advantages of multiphase machine drives over conventional three-phase machines include [1,7,9–14]:

- They can be designed with a reduced per-phase voltage, correspondingly, reduced semiconductor device voltage rating; which is highly desirable in medium voltage applications;
- Enable independent control of the fundamental and spatial harmonics leading to higher torque density [15];
- Can operate as a multi-motor drive system [1];
- Possess additional degrees of freedom that can be exploited to improve fault tolerant capability where the machine can continue running with $(n-3)$ disconnected phases [1,6].

The most salient feature of multiphase machines is their ability to operate under open-phase conditions. This can occur due to one of the phase terminals being disconnected, internal winding rupture, or one or more of the inverter phase legs failing open (disconnecting). Multiphase machine performance with open circuit faults has been studied in literature [11–14,16–18] and a

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number of control strategies to ensure fault tolerant operation with the same pre-fault magneto-motive force have been proposed. During faults, two alternatives for machine operation are possible, namely, open loop control and optimal current control. Despite being a simple option, open-loop control results in higher torque ripples and unbalanced winding currents, which limits its application especially for machines with a low number of phases. Therefore, optimal current control is commonly employed with an objective function such as minimizing torque ripples, optimizing flux distribution, and minimizing copper loss [15].

Obtaining optimum phase currents for multiphase machines during fault conditions implies solving complicated nonlinear equations [11–14,16–18]. The solution will mainly depend on the applied constraints that need to be imposed in order to obtain a number of equations that equals the number of variables in the problem. Yet, the optimization problem may result in multiple suboptimal solutions as the number of phases increases. Although these solutions will satisfy the control objectives, the resulting harmonic sequence currents may yield non-optimal flux distribution [15]. In earlier work [15], genetic algorithms (GA) were used to simplify the optimization problem and avoid solving such nonlinear equations for an eleven phase induction machine. It has also been shown that the solution obtained from GA method produces more symmetrical flux distribution.

Unfortunately, optimal current control results in higher current in the healthy phases compared to machine's rated value (higher copper loss), unbalanced phase voltages, and typically an increased DC-link voltage is needed to source the required optimal currents. Consequently, an increase in the employed semiconductor device rating is required, which is a critical design factor especially in medium voltage applications. Practically, machine derating is suggested to avoid the excessive copper loss and need for increased dc link voltage. Most of the published work assumes that the DC-link voltage is capable of producing the required phase voltage to achieve certain control objectives [11–14,16–19]. In drive systems, especially in medium voltage applications, DC-link voltage is determined based on the machine phase voltages [20]. Retaining a DC-link reserve for driving the rated machine load during fault conditions increases the inverter rating and cost. While imposing voltage constraints on the DC-link voltage requires a corresponding machine derating to avoid undesirable machine overloading and to maintain other optimal control objectives like minimized torque ripples, optimized flux distribution, and minimum copper loss. In Ref. [14], machine de-rating due to voltage unbalance is studied using symmetric component transformation to calculate the currents and determines the required machine derating to avoid uneven distribution of stator losses. In inverter-fed motors, machine unbalance mostly occurs due to failure in inverter leg(s) rather than inverter voltage unbalance. Hence, it is important to find the required derating factors by which the machine should be derated under open phase(s) operation. A comprehensive evaluation of this challenge has not been addressed in literature.

Obtaining such derating factors requires a powerful mathematical model to represent the machine under fault conditions. Modeling of multiphase induction machines under normal as well as fault conditions has been a topic of significant research interest [1,3,4,7,9,21–26]. The conventional three-phase model has been extended to a general n-phase machine with appropriate transformations. Additional space planes were added to account for the additional degrees of freedom. Nevertheless, the effect of other sequence planes on the machine performance is mainly dependent on the winding arrangement. In a double layer distributed winding arrangement with near-sinusoidal MMF, the effect of sequence planes other than the fundamental on the machine flux distribution and torque production can be neglected. Hence, its performance is similar to conventional three-phase machines [20,27]. On the other hand, the effect of spatial harmonics in single layer distributed winding or fully pitched concentrated windings cannot be neglected [4]. Most of the published mathematical models consider multiphase machines with triplen numbers of phases where the effect of other sequence planes is similar to the zero sequence. For machines with odd numbers of phases [27], similar assumptions are typically employed. This may be acceptable for winding arrangements with near-sinusoidal MMF. However, multiphase machines with an odd number of phases are usually designed with a relatively low number of slots per phase per pole, yielding an approximate quasi-square MMF to benefit from the increased power density using harmonic injection [1]. Hence, the generic assumption of sinusoidal MMF yields considerable error as the flux distribution becomes distorted [15].

This paper investigates an induction machine with a high odd number of phases, eleven phases, under open-phase(s) conditions. The study aims to assess machine performance under open-loop and optimal current control cases while considering copper losses and DC-link voltage limitations. Hence, the required derating factor under optimal current control is calculated. The paper flow can be summarized as follows:

- First, an unbalanced steady-state model for multiphase machines with concentric windings is developed in order to consider the effect of non-fundamental sequences. The main difference between this model and those in the literature is also highlighted. Then, this model is verified using experimental results obtained from a prototype eleven-phase IM under open-loop control for different numbers of open phases.
- Next, based on the work in [15], the required optimum currents for the eleven-phase machine are found using a Genetic Algorithm.
- The calculated optimum currents along with the presented mathematical model are used to estimate the machine performance and characteristic curves for the cases of one and two adjacent open phases.
- Based on the calculated characteristic curves, the required derating factors to avoid excessive copper loss are presented. The effect of DC-link voltage limitation is also introduced.

2. Unbalanced steady state model of a concentric winding multiphase machine

As aforementioned, multiphase machine modeling has been thoroughly addressed in the literature. Nevertheless, multiphase machine modeling and parameter identification are still challenging research areas [27]. Under healthy operation, the machine model and performance are much similar to the three-phase case. However, under fault conditions, the effect of non-fundamental sequence planes is detrimental and depends mainly on the winding arrangement [27]. Due to physical constraints in machines with a high number of phases, a concentric winding is normally employed resulting in an approximate quasi-square MMF that also benefits machine power density when harmonic injection is employed [4]. The first attempt to account for this effect in five-phase machine model is given in [27], where machine physical dimensions are used to find the equivalent parameters in each sequence plane. In earlier work by the authors [4], the model is extended to the eleven-phase case with concentric winding.

In this section, the steady state model of an unbalanced n-phase multiphase machine with concentric windings is presented. The main difference between this model and those available in the literature [20–25] is that it accounts for the effect of induced sequence currents in the rotor circuit by including the equivalent impedance of the rotor circuit corresponding to other sequence planes. This