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Introducing the Filtered Park's and Filtered Extended Park's Vector Approach to detect broken rotor bars in induction motors independently from the rotor slots number

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ABSTRACT

The Park's Vector Approach (PVA), together with its variations, has been one of the most widespread diagnostic methods for electrical machines and drives. Regarding the broken rotor bars fault diagnosis in induction motors, the common practice is to rely on the width increase of the Park's Vector (PV) ring and then apply some more sophisticated signal processing methods. It is shown in this paper that this method can be unreliable and is strongly dependent on the magnetic poles and rotor slot numbers. To overcome this constraint, the novel Filtered Park's/Extended Park's Vector Approach (FPVA/FEPVA) is introduced. The investigation is carried out with FEM simulations and experimental testing. The results prove to satisfyingly coincide, whereas the proposed advanced FPVA method is desirably reliable.

1. Introduction

The broken rotor bar fault constitutes about the 10% of total induction motor (IM) faults, as reported in several surveys [1,2]. This occurrence rate has proven to be even much larger for large motors that often are the most expensive, critical and difficult to repair [3]. Past works have shown that the breakage of a rotor bar leads to over-currents in the adjacent bars which are more prone to break next [4,5]. However, cases where the broken bars were located in non-adjacent positions have also been reported in the field [6]. Prompt and reliable diagnosis of the broken rotor bars fault is required to avoid forced outages lead to heavy financial costs [7–9].

Different diagnostic variables have been studied and used and different methods have been applied over the years, providing a strong insight in this specific fault and its characteristics. The electric power [10,11], torque [12], speed [13], magnetic flux [14,15] and other quantities, have been successfully used in the past. However, the most popular technique for diagnosing rotor cage damages is the Motor Current Signature Analysis MCSA [16] that relies on the Fast Fourier Transform (FFT) of the steady-state stator current [17]. This technique is widely used due to its non-intrusiveness, low cost, simplicity and the ability to be applied on-line. Despite its indubitable advantages, the MCSA can have certain drawbacks. Some of these drawbacks are related to the lack of discrimination between the broken rotor bars fault and other conditions which

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produce the same harmonic signatures [18,19]. Moreover, the iron core saturation can affect the diagnosis [20]. Finally, traditional MCSA is incapable to detect the fault at no-load or low-load operation although some recent works have addressed this need [21,22]. The above issues have led researchers to the development of other techniques that analyze the stator current with alternative tools such as Wavelets [23], Hilbert transform [24], MUSIC [25] etc. Latest review papers in the field can be much informative and provide more details [14–27].

Regardless of the analysis method applied, maintenance operators are not usually familiar with the output provided by most of these methods, so that a certain user expertise becomes a major requirement. This may be a serious constraint for their industrial applicability. To avoid this constraint, diagnosis methods that provide more user friendly representations (and, at the same time, maintain a high diagnosis reliability) need to be invented and applied. A possible answer to this need may be the symbolic representation [28,29].

The Park's Vector Approach (PVA) is considered a traditional method for condition monitoring, as it was introduced more than three decades ago [30]. Since then, it has been extensively used to diagnose electrical machines faults, as well as power electronics failures. Later, more sophisticated methods based on the PVA are the Extended Park's Vector Approach (EPVA) [31], the On-Load Exciting Current Extended Park's Vector Approach [32], the Errors of Normalized Currents Average Absolute Values (ENCAAV) [33], the Current Park's Vector Phase and Currents Polarity (CPVPCP) [34], the Normalized Currents Average Values (NCAV) [35] and the Normalized Reference Current Errors (NRCEs) [36].

Regarding the application of the PVA methods' family on the broken rotor bars fault diagnosis, many interesting contributions can be found in the literature and are historically presented here.

Originally, the PVA was used in [37] to detect the broken rotor bars fault. Also, in the same paper, the authors observed and related the thickness of the Park's Vector ring pattern to the number of the broken bars. Some years afterwards, the EPVA was used to solve rotor faults in induction motors [38]. This method relies on the study of the PV modulus frequency spectrum. Note that, in the important comparative work by Eltabach et al. [10], the EPVA proved to be the second best (among thirteen studied methods) to diagnose broken rotor bars in induction motors (average of full, medium and low load operation) and the best option for low load operation.

It was shown later that the active and reactive current Park vectors are capable of discriminating the broken bar fault from load oscillations [39]. In the same work, the authors observed that the conventional PVA was incapable of discriminating the two above conditions. Furthermore, in [40,41], the authors proposed the use of the Hilbert transform before calculating the PV. Their method proved to be reliable for diagnosing a variety of IM faults, including the broken rotor bars fault. Moreover, the PVA could not provide satisfyingly reliable results for the case of frequency converter fed IM suffering from a broken rotor bar fault [42]. The combination of PVA and robust linear discrimination has also been applied to detect broken rotor bars in IM [43]. Additionally, the Adaptive Neuro Fuzzy Inference System (ANFIS) was applied after the application of PVA with satisfying results [44]. Furthermore, the combination of Negative Selection Algorithm and the PVA proved to be reliable for broken bar fault diagnosis even at an early stage [45]. Finally, the Multilayer Park's Vector Approach (MPVA) was recently introduced to detect broken rotor bars in IM adding an important new characteristic which is the fault diagnosis at transient operation [46].

In this paper, the authors present the novel Filtered Park's and Filtered Extended Park's Vector Approach (FPVA and FEPVA, respectively) to reliably diagnose the broken rotor bars fault in IM. The method relies on the monitoring of higher harmonic index of the Park's vector. The work is carried out with FEM simulations and experimental testing and the results prove the method's effectiveness and reliability. Moreover, it is especially remarkable that, unlike other techniques, this method provides a completely user friendly output that enables to clearly identify the fault condition, even by non-expert users. This may be especially useful to implement the method in real industrial systems as well as to facilitate the automation of the diagnosis process, which is a crucial aspect for implementation in portable condition monitoring devices.

2. Theoretical investigation

The traditional PVA, as well as later methods derived on it, rely on the monitoring of the three-phase or line currents of the IM namely: i_a, i_b, i_c.

The Park's Vector components, I_d and I_q, are then calculated by:

$$I_d = \left(\sqrt{2}\Big/\sqrt{3}\right)i_a - \left(1\Big/\sqrt{6}\right)i_b - \left(1\Big/\sqrt{6}\right)i_c \tag{1}$$

$$I_q = \left(1\Big/\sqrt{2}\right)i_b - \left(1\Big/\sqrt{2}\right)i_c \tag{2}$$

Under ideal conditions, i. e. for a healthy three-phase IM, fed by a direct three-phase sinusoidal voltage supply system, the three phase currents lead to a Park's vector with the following components:

$$I_d = \left(\sqrt{6}\Big/\sqrt{2}\right)I_M \sin(\omega t) \tag{3}$$

$$I_q = \left(\sqrt{6}\Big/\sqrt{2}\right)I_M \sin(\omega t - \pi/2) \tag{4}$$