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EPSR-4707; No. of Pages 10

ARTICLE IN PRESS

Electric Power Systems Research xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Electric Power Systems Research

journal homepage: www.elsevier.com/locate/epsr

Review

Variable speed control of a 5-phase permanent magnet synchronous generator including voltage and current limits in healthy and open-circuited modes

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ARTICLE INFO

Article history:
Received 8 September 2015
Received in revised form 21 March 2016
Accepted 20 May 2016
Available online xxx

Keywords:
Synchronous multiphase generator
Fault mode
Healthy mode
Flux weakening
Maximum current
Maximum voltage

ABSTRACT

This paper proposes a novel variable speed control strategy of a particular 5-phase Permanent Magnet Synchronous Generator (PMSG) in healthy and faulty modes by taking into account the constraints on voltages and currents. These constraints are related to the converter and machine design. The considered faults are open-circuited phases (one phase, two adjacent phases and two non-adjacent phases). A variable speed control strategy is presented, including flux weakening operations. Based on analytical formulations, a numerical computation is proposed to bring out the torque–speed characteristics. This method allows the determination of the current references which ensure the functioning of a 5-phase PMSG at variable speed while keeping phase voltages and currents below their limits. Theoretical, numerical and experimental results are presented. These results are compared in order to validate the proposed approach.

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http://dx.doi.org/10.1016/j.epsr.2016.05.024
0378-7796/

Please cite this article in press as: O. Fall, et al., Variable speed control of a 5-phase permanent magnet synchronous generator including voltage and current limits in healthy and open-circuited modes, Electr. Power Syst. Res. (2016), http://dx.doi.org/10.1016/j.epsr.2016.05.024

1. Introduction

Higher reliability of classical 3-phase drives can be achieved by oversizing the converter-machine set but this solution increases the cost of the whole system. Even if this oversizing is chosen, in case an open-circuit fault appears in one or two phases of the drive, the system cannot ensure a functioning even at reduced power.

Using multiphase drives instead of three-phase ones makes it possible to increase the power density, fault-tolerance capability and to reduce torque pulsations at low frequencies [1–3]. In fault mode, this kind of drives is able to work at a reduced power with satisfactory performances. This aspect is very important in systems which are designed for specific applications, such as offshore energy harvesting or electrical vehicles. As an example, in offshore renewable energy context, fault-tolerant systems allow continuing to extract energy even if a fault occurs inside the generator drive. Some research works propose to use multiphase machines to obtain a higher functioning reliability [4–6]. Multiphase PMSM, especially 5-phase and 7-phase ones, have been studied recently under open-circuit faults. The authors have demonstrated that it is possible to obtain a constant required torque if the fault is detected and identified. Several fault-tolerant control strategies have been proposed to calculate optimal current references in order to maximize the torque to copper losses ratio. One of them is based on the Lagrange multiplier [7,8]. A vector approach is proposed in [9,10]. In [11,12], a method based on a geometrical representation makes it possible to obtain optimal currents in both healthy and faulty modes. A numerical approach is reported in [13] where fault tolerant controls of a 5-phase PMSM for different stator winding connections are proposed. They aim to calculate optimal currents in order to minimize copper losses and torque pulsations. In [14], an optimal current waveform which aims to cancel torque ripples and to minimize copper losses in fault mode, for non-salient multiphase permanent magnet synchronous machine where each phase is supplied by its own H-bridge Voltage Source Inverter (VSI), has been presented. A control strategy whose objective is to keep the electromagnetic torque constant under asymmetric fault condition, by using through a specific transformation harmonics of current and back electro-motive forces (back-EMF) as DC component, which contribute to the torque, is presented in [15].

In the previous cited approaches the peak current, whose value can be quite dependent on the parameters of the machine (cogging torque, harmonics of the back-EMF, etc.), is not considered. However, this peak current value is a key parameter for the sizing and the cost of the VSI. As a consequence, the proposed optimizations without taking into account this constraint can induce an important over-cost.

The proposed paper will consider this constraint for the design of the control laws which are based mainly on methodologies described in [16–18] but adapted to a particular family of PMSG.Jen-Ren and Lipo [16] and Toliyat [17] aim to identify current expression for a 5-phase induction machine in order to have a constant torque under assumption of perfect sinusoidal winding functions. By keeping the same rotating field, the drive can be operated in fault mode (one or two phases opened). In this case, only the rotating field corresponding to the first harmonic of magneto motive force (MMF) generates the torque. The approach developed in [16,17] has been adapted in [18] for trapezoidal back-EMF PMSG by considering first and third harmonics in the winding functions. The main difference between Jen-Ren and Lipo and Toliyat [16,17] and Parsa and Toliyat [18] is that a third harmonic of the back-EMF is taken into account in [18]. As a consequence, this 3rd harmonic of EMF is associated with a torque leading to ripples in fault mode even if the first harmonic of the rotating MMF is controlled.

Moreover, the main limit of the proposed methods in [16–18] is that the limitations related to the converter voltage saturation and rated current at high-speed operations (over the base speed) are not taken into account. In some existing situations, it is necessary to apply a flux weakening strategy for satisfying converter-machine voltage limit. This is particularly the case of electrical cars and renewable energy applications which are characterized by a large range of operating speeds. It can be noticed that, for these kinds of application, a new generation of machines with fractional slot tooth concentrated winding and obviously non sinusoidal winding functions [19] has been developed.

Until now, flux weakening strategies have been studied in healthy operations [20–24]. In [25], an enhanced optimal torque control strategy in fault mode of a 5-phase permanent-magnet machine under flux weakening operation is studied but the voltage limits are not strictly respected. This work deals with flux weakening strategy even if the system is working in fault mode, but systems still exhibit torque ripples because of the non-sinusoidal back-EMF. The fault modes that are considered are only one phase opened or short-circuited so the cases where more phases are in fault are not taken into account.

In the proposed paper, a 5-phase PMSG with sinusoidal back-EMF will be considered, leading to fewer constraints for the control than in [18,19]. In this case, controlling only the first harmonic of rotating MMF allows the machine to obtain a constant torque. As a consequence, only two degrees of freedom (DOF) are required to maintain a constant torque and the other DOF could be used for other criteria of optimization. It is thus possible to manage voltage limitation related to flux weakening strategy. This voltage limitation is useful for systems as off-shore renewable energy application where high speed (higher than the base speed) has to be reached to harness efficiently the energy.

The present paper studies fault-tolerant capabilities of such PMSG with sinusoidal back-EMF in case of one or multiple open-phase faults. A control strategy which is able to keep a constant torque is proposed. For this purpose, an analytical formulation of the corresponding current references is presented. In a second step, numerical optimization (based on Fmincon function of MATLAB) is used in order to calculate the maximum torque and the corresponding current references under current and voltage limits. This approach allows flux weakening operations at high speed, taking into account these limitations coming from the drive (converter/machine) both in healthy and faulty mode.

The paper is organized as follows. Section II is dedicated to the modelling of the multiphase drive. The control strategy of the system under healthy and faulty modes with voltage and current limits is presented in section III. Section IV gives some simulation results. In Section V, experimental results are reported. A conclusion is given in Section VI.

2. Multiphase machine modelling

The drive considered in this work is shown in Fig. 1.

To model the 5-phases PMSM, the following assumptions are considered:

- The 5 phases of the machine are regularly shifted;
- The saturation of the magnet circuits is not taken into account in the calculation of the back-EMF and the fluxes;
- Windings are wye connected;
- Armature reaction is not taken into account in the back-EMF waveforms;

The voltage vector can then be written as:

$$[v] = R_s\,[i] + \frac{\mathrm{d}\,[\phi]}{\mathrm{d}t} + [e] \tag{1}$$

where: