Electrical Power and Energy Systems 88 (2017) 75–86

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

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

On-line switched control of a six-phase induction generator in faulted mode

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ARTICLE INFO

Article history:
Received 10 May 2016
Received in revised form 5 November 2016
Accepted 9 December 2016

Keywords:
Six-phase induction generator
Open-phase fault
Online controller modification
Power ripples reduction
Controller switching
Online initial condition setting

ABSTRACT

The operation of multiphase machines in open-phase fault conditions is always associated with undesirable ripples in torque and power, even in steady state conditions. In the literature, several methods have been proposed to reduce these oscillations considering a fixed-fault situation without taking into account the transient behavior during the modification. In this way, this paper deals with the design and implementation of a multi-control system for all possible open-phase situations of a symmetrical squirrel cage six-phase induction generator (SC6PIG) up to three opened phases in such a way to extract a qualified electrical power. For this, a general model of the SC6PIG in healthy and open-phase fault situations is employed to design the multi-control system. The control systems are re-arranged regarding the situation of the generator in different open-phase fault conditions to provide the output power as close as in healthy mode. A simple detection system is associated to define the state of the generator (number and type of opened phases in faulty operation) and to switch to the appropriate control system. Furthermore, in order to minimize the transient problems during the switching process between the different control systems, an on-line initial condition setting is imposed to the control systems during the motion. An experimental set up including a SC6PIG driven by a permanent magnet dc motor has been built to prove the capacities of the proposed on-line switched control system in different cases such as healthy, one opened phase and two opened phases situations with smooth switching.

1. Introduction

Since many years, induction motors have found a wide popularity in industry by substituting dc machine since they are more rugged and reliable. Nowadays, with the emergence of renewable energy sources, a new special field of the induction machine is the power generation [1–6] especially in wind turbine systems due to the simplicity, the low maintenance and the robustness of the brushless structure of its rotor [7]. Nevertheless, with a classical 3-phase induction machine (3PIM), when one or more phases fail, the generator cannot deliver any significant power and therefore one straightforward solution is to increase the number of phases of the machine and to associate a suitable control technique. Indeed, the multiphase machine presents many advantages over conventional 3PIM one such as reducing the rotor harmonic currents, reducing the current per phase without increasing the voltage per phase, decreasing the dc-link current harmonics, reducing the magnitude and increasing the frequency of the torque pulsation [8–10] but the main one for embedded systems such as wind turbine is its improved reliability and its continuous system operation even in faulted mode following the loss of excitation of one or more stator phases [11,12]. Undeniably, nonstop operation is required for generators used in wind energy systems, in particular offshore ones for which the maintenance of the generator is always associated with some difficulties. In this way, reliable operations even in generator windings failures can be achieved by using a multiphase generator such as a six-phase induction generator proposed in this paper. Indeed, contrary to three-phase machine configurations which require an extra wire (connection between neutral point and mid-point) for implementing a fault-tolerant control strategy [13], it is not necessary for multiphase ones since at least three healthy phases are remaining.

In the literature, one can find different multiphase structures but one of the most popular is the symmetrical squirrel cage six-phase induction machine (SC6PIM) both in motor [14–17] and in generator modes [18]. Of course, in faulted mode (loss of one or more phases), the aim is to produce in motor and generator operating modes suitable electromagnetic torque and output power,

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http://dx.doi.org/10.1016/j.ijepes.2016.12.004
0142-0615/

respectively, with minimum ripples [15,19–26]. Many studies [19–26] in the six-phase machines area have analysed machine performance and have introduced novel fault-tolerant control techniques to eliminate the torque ripples in open-phase fault conditions. In this way, offline fault-tolerant open-loop and closed-loop control of a SC6PIM has been reported in [15,17,18], respectively, for all possible open-phase fault conditions by tuning appropriate reference current values of remaining healthy phases. Nevertheless, they focus on the steady state condition when open-phase faults occur and the transient behavior from pre- to post-fault control system has not been attended.

Furthermore, the main analyses in open-phase condition of multiphase machines have been performed in motor operating mode while they have been analysed only in healthy condition for generation systems [27–29]. However, in both modes, a robust control strategy has to be associated to the indirect rotor field oriented control (IRFOC) in such a way to cope with the plant parameters variations due to the faulted mode. For this, one solution may consist in using only one robust controller for each loop such as fuzzy logic or sliding mode controls [30,31] and the other one consists in using different control systems (one for each faulted mode) and corresponding transformation matrices and to switch between them as a function of a fault detection system decision.

This paper focuses on the second solution to control the output power of a SC6PIG by switching between ten different couples of proportional-integral (PI) controllers (corresponding to the 42 faulted cases) associated to IRFOC when faulted mode occurs (one to three phases missing). The ten different control systems are designed regarding the faulted model of the SC6PIG for all possible open-phase conditions. The detection of the faulted mode and the smooth switching by initial condition imposition between control systems is made on-line using an appropriate decision system. An experimental set up including a SC6PIG driven by a permanent magnet dc motor has been developed in our laboratory to validate experimentally the capacities of the proposed strategy. Section 2 is devoted to the modeling in healthy and faulted modes of the SCP6PIG and the control scheme while Section 3 is dedicated to the fault detection system and the on-line smooth switching process. Then, experimental results assessing the feasibility and the capacities of the proposed control strategy are presented in Section 4 while Section 5 is devoted to conclusions and perspectives.

2. Modeling and control of the SC6PIG in healthy and faulty conditions

2.1. Model of the SC6PIG in unbalanced operating conditions

Fig. 1 depicts the stator and rotor windings arrangement of a symmetrical SC6PIG with an isolated neutral point. It is assumed that the windings of each six phases are uniformly distributed and that the produced electromagnetic field is significantly sinusoidal.

Let us define faulty operations of the SC6PIG where one or more phases of the stator are opened. In this situation, the dimension of the stator variables (6 in healthy operation) decreases to N – which is defined as the number of active phases – while the rotor variables dimension is still equal to 6 since it can be considered as in healthy mode. By applying corresponding Clark transformation matrices for each fault case as T_N [15,19] and T_6 for the healthy condition, respectively to the stator and rotor variables, gives a general model for both healthy and faulty conditions as written in (1) and (2). In this model, the electromagnetic conversion takes place in the $\alpha\beta$ subspace (1) while z subspace is related to losses (2).

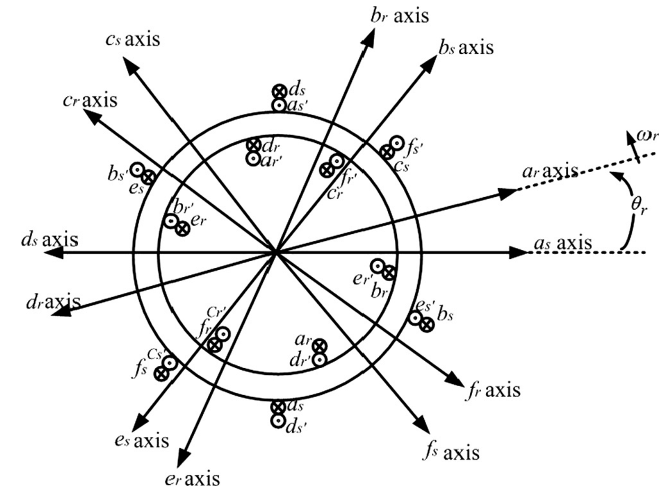

Fig. 1. Stator and rotor winding axes of SC6PIG.

$$\begin{cases} [V_s^{\alpha\beta}] = [R_s]\cdot[I_s^{\alpha\beta}] + \frac{d[\psi_s^{\alpha\beta}]}{dt} \\ 0 = [R_r]\cdot[I_r^{\alpha\beta}] + \frac{d[\psi_r^{\alpha\beta}]}{dt} + \begin{bmatrix} 0 & \omega_r \\ -\omega_r & 0 \end{bmatrix}[\psi_r^{\alpha\beta}] \\ [\psi_s^{\alpha\beta}] = \begin{bmatrix} l_{s\alpha} & 0 \\ 0 & l_{s\beta} \end{bmatrix}\cdot\left[I_s^{\alpha\beta}\right] + \begin{bmatrix} M_\alpha & 0 \\ 0 & M_\beta \end{bmatrix}\cdot\left[I_r^{\alpha\beta}\right] \\ [\psi_r^{\alpha\beta}] = \begin{bmatrix} M_\alpha & 0 \\ 0 & M_\beta \end{bmatrix}\cdot[I_s^{\alpha\beta}] + \begin{bmatrix} l_r & 0 \\ 0 & l_r \end{bmatrix}\cdot[I_r^{\alpha\beta}] \end{cases} \quad (1)$$

$$\begin{cases} v_s^{z_i} = r_s i_s^{z_i} + l_{ls}\frac{d}{dt}i_s^{z_i} \\ 0 = r_r i_r^{z_i} + l_{lr}\frac{d}{dt}i_r^{z_i} \end{cases} \quad for \quad i = 1,\ldots,(N-2) \quad (2)$$

The parameters of this model such as $l_{s\alpha}$, $l_{s\beta}$, M_α and M_β depend on the state of the generator (healthy or different faulty conditions). The parameter computation for each open-phase fault case can be found in [15].

Let us define a Boolean variable k for each phase representing the state of the phase (0 for healthy and 1 for opened situation). Then, the 64 possible situations of the SC6PIG in healthy and faulty operations can be listed as in Table 1. It is clear that the power generation will be no more possible when more than 3 phases are lost [11]. Therefore, from Table 1, 22 states will not be considered. For the 42 remaining ones, only 10 are physically different. These 10 configurations with associated parameters are listed in Table 2 and therefore 10 parametrically different control systems can be considered for all open-phase conditions up to three opened phases.

2.2. Field oriented control of a SC6PIG in unbalanced operating conditions

2.2.1. Healthy control system of a SC6PIG in unbalanced operation

Let us divide our system into two general parts: the real test bed including all the devices (see Fig. 3) and the control system including the feedback signals, the transformation matrices, the PI controllers, the added decoupling voltages, the flux estimation, the FOC computations and the reference signals required for the multiphase converter. In this analysis, we call "healthy machine" when all of the six phases are properly connected to the machine windings and "faulty machine" when one or more stator phases are missing. Similarly, the control systems designed for healthy or faulty machine are named as healthy or faulty control systems, respectively. It has also to be mentioned that, when one phase is lost, the voltage reference of this one is set to zero.