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On the Behavior of Five-Phase Induction Motor Drive Under Normal and Faulty Conditions

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ABSTRACT

This paper describes the importance and applications of multi-phase electrical machines. The components of the five-phase electrical drive were analyzed. Due to the MATLAB/Simulink model, the simulation of the electrical drive under normal mode and faulty conditions was carried out to analyze the performance of the five-phase induction motor. Several cases of faulty conditions caused by unbalanced voltage system were considered and the simulation results of stator phase's currents, rotor speed and electromagnetic torque were analyzed in more detail. The importance of this study is related to the various applications of multi-phase machines in different fields of industry and a lot of scientific researches based on this topic. Simulation results have shown that the five-phase machine is very reliable and it has better fault tolerance due to its slightly affected by the unbalanced voltage system.

Keywords: Multi-phase electrical machines, five-phase induction motor, field-oriented control method, MATLAB/Simulink

1. INTRODUCTION

The first proposal type of multi-phase motor drive dates to 1969, when it was proposed a five-phase voltage source inverter feeding to induction motor [1]. Since the beginning of the last century, multi-phase electrical machines have been recognized as a really interesting alternative comparing to conventional three-phase machines. The attention to multi-phase electrical drives was increased by the development of power switching devices and electronic converters [2]. The higher number of inverter's legs has made possible to increase the number of output phases. This great opportunity has positively affected the development of electrical machines with more than three phases.

The importance of multi-phase machines is due to many advantages such as better fault tolerance operation [3], reduction of the required power rating per inverter leg (enabling use of semiconductor switches of lower power range) [4], higher efficiency compared to three-phase electrical machines (lower space-harmonic content of the magnetic flux) [5], higher torque density [5], reduced torque ripple [6], improvement in noise characteristics.

The multi-phase electrical machines are used in different critical applications such as hybrid and electric vehicles, ship propulsion [4, 7], electric aircraft [8], general aerospace applications, railway traction [5] and wind power generation systems. The five-phase machine is frequently considered in many research works, but other multi-phase machines have been used during the last few years due to the development of power electronic microprocessors [9-11].

2. THE FIVE-PHASE INDUCTION MOTOR DRIVE

The five-phase electrical drive consists of an electrical machine, electronic converters, a control block and a power supply, as shown in figure 1. First of all, the three-phase symmetrical power supply voltage is converted to DC voltage by using a rectifier and it is filtered to remove the output ripple. In order to provide five-phase controllable voltage and controllable frequency supply to feed the induction motor, it is necessary an important component of the electrical drive, which is a five-phase inverter [12].

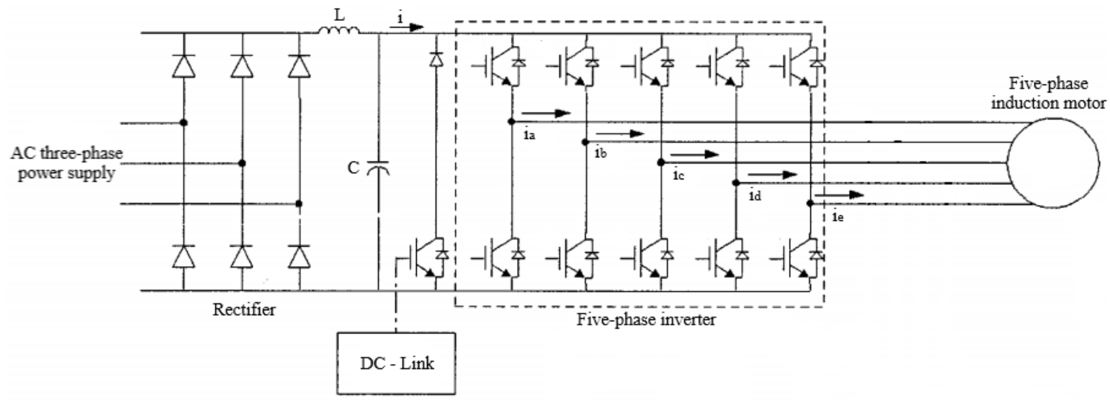

Figure 1. Five-phase induction motor drive system.

The structure of the five-phase inverter is similar to that of the three-phase inverter, but has two additional legs, as shown in Figure 2 [12]. The electronic switches of an inverter consist of two power semiconductors, which are connected in anti-parallel [13]. The first element is a controllable semiconductor, such as an IGBT or MOSFET transistor and the second element is a non-controllable semiconductor, such as a diode. The voltage between the output terminal of the inverter and the neutral point of the load is determined as the phase voltage. The voltage between the two output terminals of the inverter is called the line voltage.

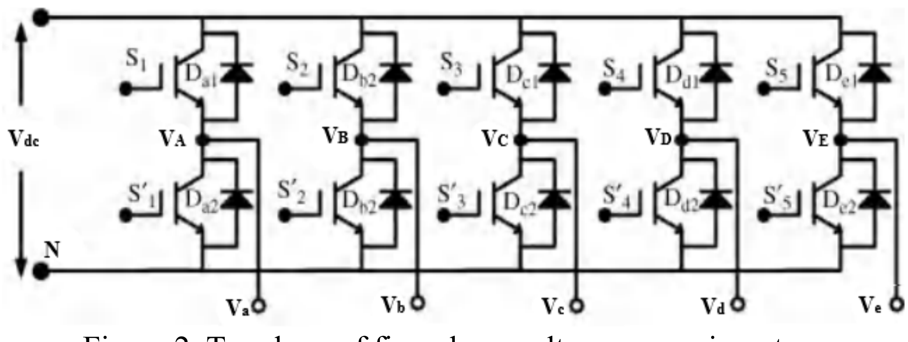

Figure 2. Topology of five-phase voltage source inverter.

The same structure as other electrical machines, the five-phase machine has also two main parts, which are stator and rotor. There are five-phase windings in each of these structural parts and the spatial displacement between phases is exactly 72° or 2π/5 radians. The model of five-phase electrical machine has been analyzed in terms of phase variables form [14]. The voltage equilibrium equation of each phase of the stator or the rotor has the same form. The Clark's and Park's transformations were applied to simplify the mathematical model by removing the time-varying inductance terms and considering the d-q-x-y-0 model of the induction machine [14].

3. THE FIELD ORIENTED CONTROL MODEL OF FIVE-PHASE INDUCTION MOTOR DRIVE IN SIMULINK

The field-oriented control model of the five-phase motor is very important for analysis and simulation of the electrical drive in the MATLAB/Simulink environment. This Simulink model is shown in more detail in Figure 3 [15]. The main blocks of this model are vector controller block, comparator block, hysteresis current controller block, five-phase inverter model, transformation block and electrical machine model. The model of the vector controller block is shown in Figure 4 [15].

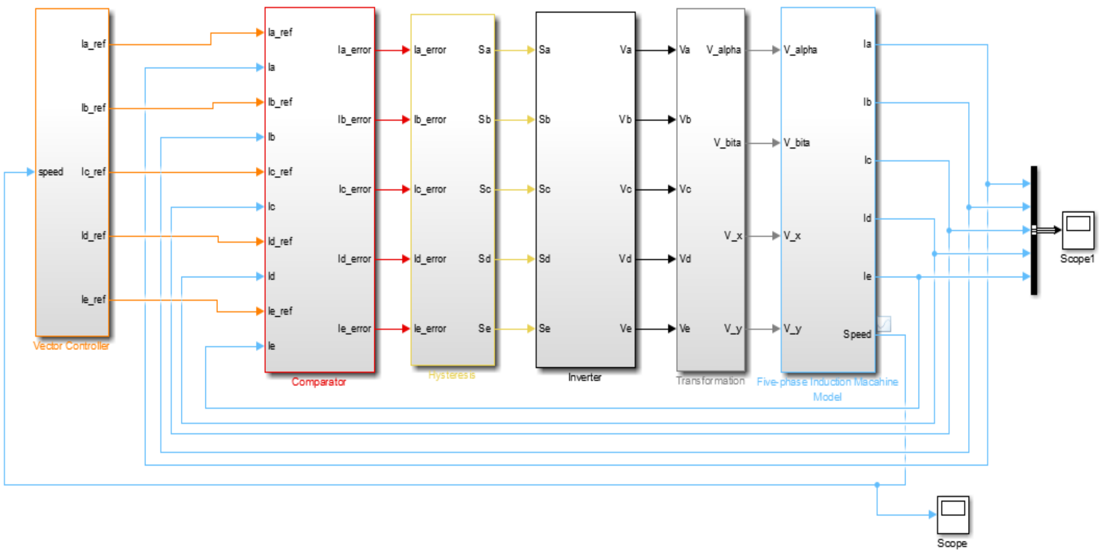

Figure 3. The Simulink model of field-oriented control of five-phase induction motor drive.

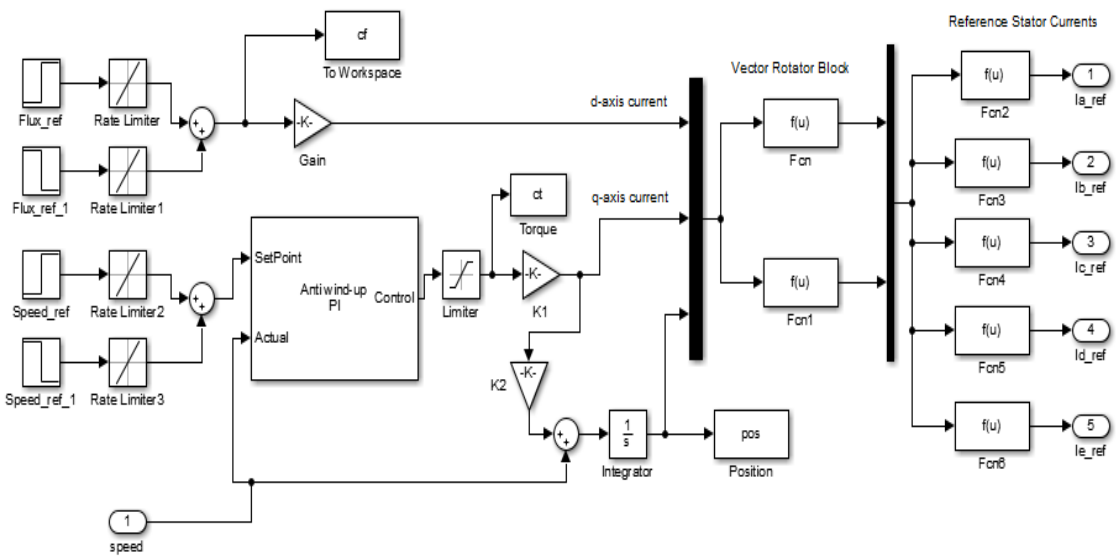

Figure 4. The Simulink model of vector controller block.

The model of the electrical machine was designed in the Simulink environment based on equivalent circuit parameters per phase. The frequency is $50Hz$ and the electrical machine number of pole pairs is 2. Furthermore, rated phase current and phase voltages are $2{,}1A$ and $220V$, respectively [15]. The electric parameters of the machine are listed in table 1.

Table 1. The electric parameters of five-phase motor.

Electric parameters of the machine	Parameters value
f	50 Hz
p	2 pole pairs
J	0,03 kg.m^2
R_s	10 Ω
R_r	6,3 Ω
L_{ls}	0,04 H
L_{lr}	0,04 H
L_m	0,42 H

4. NORMAL MODE OPERATION OF FIVE-PHASE INDUCTION MOTOR

The simulation of the electrical drive under normal mode was carried out to analyze the performance of the five-phase motor. Firstly, the operation of the machine takes place under a no-load operation, followed by loading at a specific time and finally reversing. The reference speed command of 1200 *rpm* is given at time $t = 0{,}2s$ and it is kept constant during the operation. The load torque is applied at time $t = 1s$ and it causes a small dip in the rotor speed. The motor torque immediately follows the reference torque by compensating the small speed dip after about $t = 100 – 150ms$. The reference speed command of reversing is applied at time $t = 1{,}5s$ and the actual electromagnetic torque nearly follows the reference torque.

The stator phase's currents, rotor speed and electromagnetic torque are the parameters that are selected to assess the performance of the electric machine, as shown in figures 5, 6, 7 and 8.

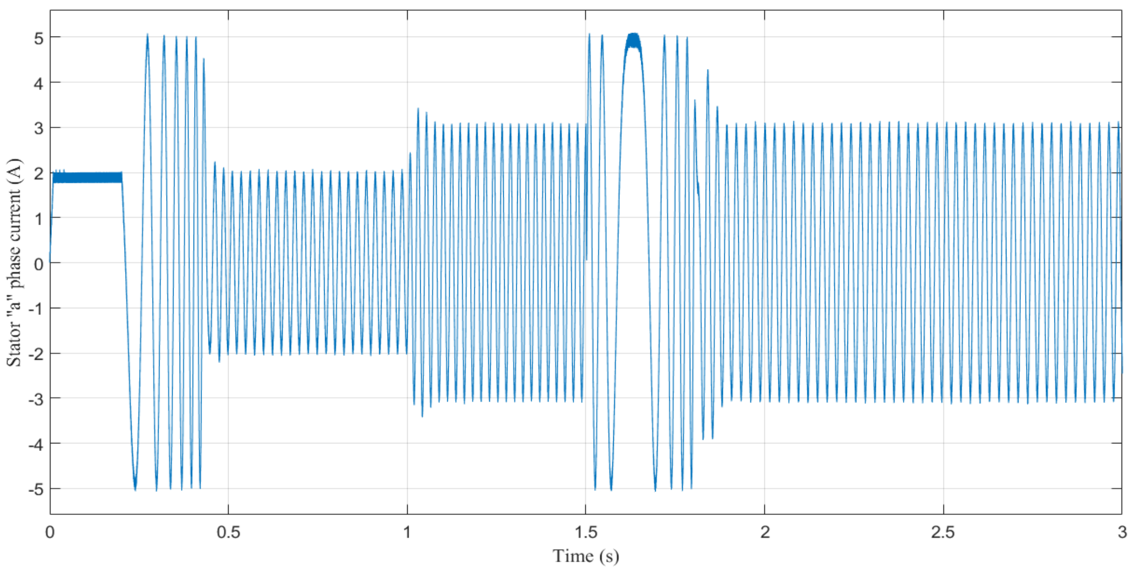

Figure 5. Stator "*a*" phase current.

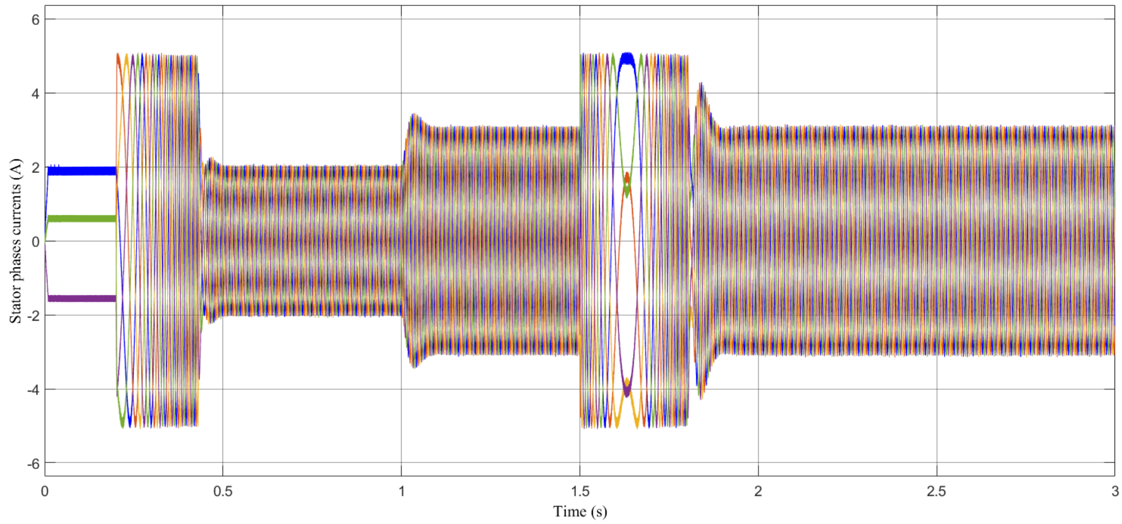

Figure 6. Stator phases currents.

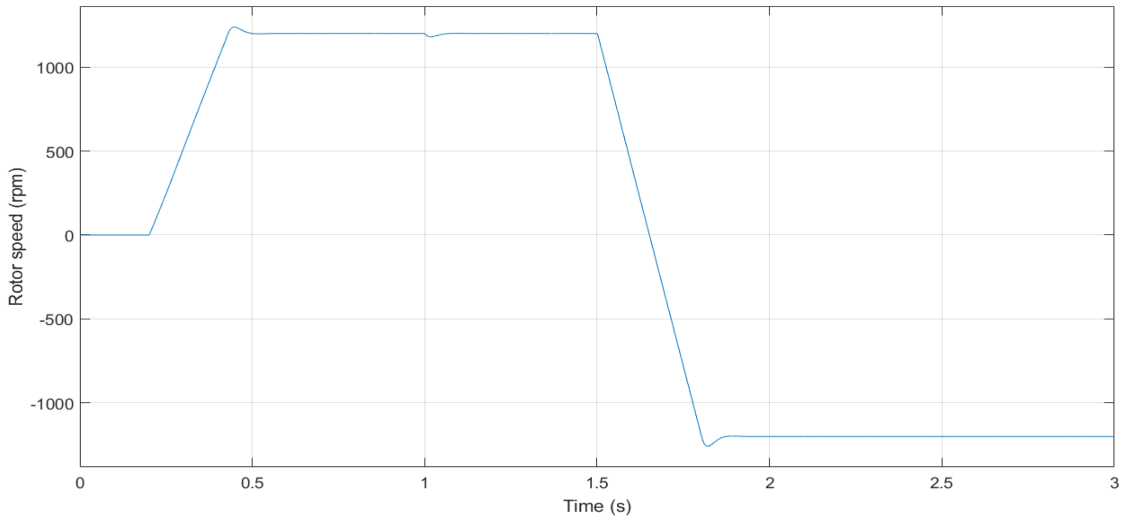

Figure 7. Rotor speed.

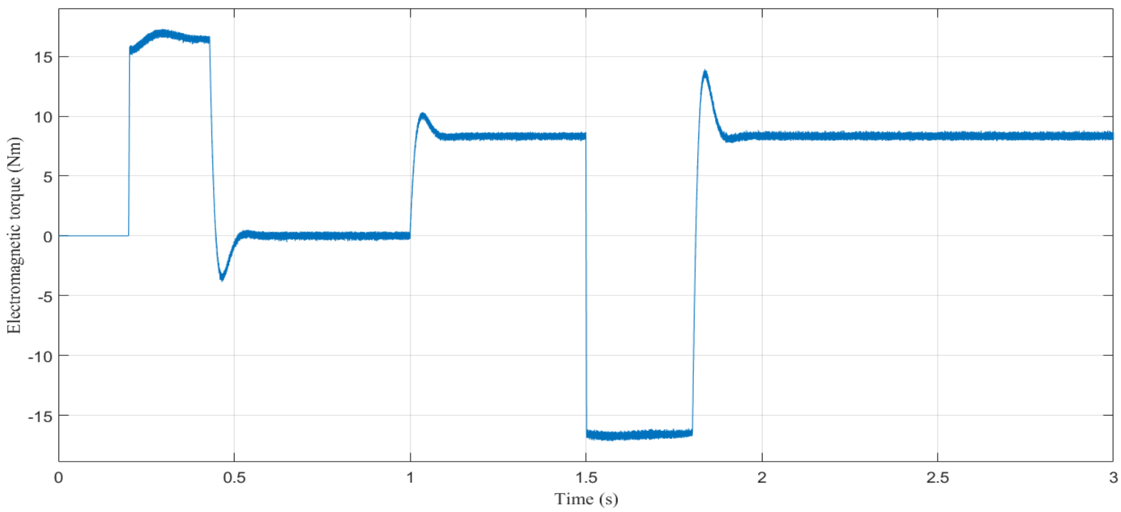

Figure 8. Electromagnetic torque.

5. FAULTY CONDITIONS OPERATION OF FIVE-PHASE INDUCTION MOTOR

Different types of faults may appear in an electrical drive and this is the reason that fault tolerance is an important advantage of multi-phase electrical machines [5]. The faults can be classified into several groups depending on the location of the overall system and depending on their nature that can be an electrical or mechanical problem. Three main groups of fault types on a multi-phase electrical drive are: power converter faults, electronic sensor faults and electrical machine faults [9]. These faults lead to an unbalanced system of voltages and stator currents, the reduction of electromagnetic torque, the appearance of high-order harmonics in the phase currents, increased level of noise and vibrations [9]. All types of faults have a negative impact on the multi-phase electrical machine performance, but at the same time, it is taken the advantage of continuing the operation in faulty conditions. Multi-phase drives do not need extra electrical equipment to manage the post-fault operation, but requiring only proper post-fault control techniques to continue operating [16].

Moreover, the simulation of the electrical machine under faulty conditions operation was also realized in Simulink. In our case study, it was analyzed the faulty condition affected by an unbalanced voltage system, which was created in the "*a*" phase of the inverter. Different cases of unbalanced voltage system have been considered including 20%, 40%, 60%, 80% and 100% under-voltage of just one phase. The rotor speed and electromagnetic torque are the parameters that are selected to assess the performance of the electric machine.

The rotor speed results during normal mode operation (orange) and faulty conditions, including 60% (blue), 80% (green) and 100% (purple) under-voltage of the stator "*a*" phase are shown in figure 9.

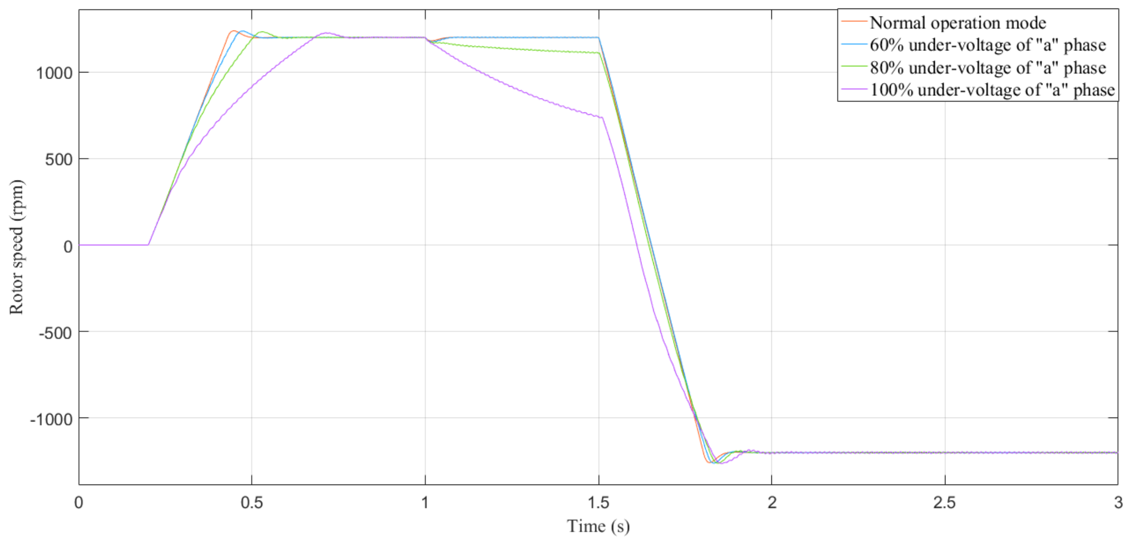

Figure 9. Rotor speed during normal mode and 60%, 80%, 100% under-voltage of "*a*" phase.

Furthermore, it was analyzed the torque of the machine for each of the above-mentioned faulty conditions. The electromagnetic torque results during normal mode operation and 40% (green), 60% (blue) under-voltage of the stator "*a*" phase are shown separately in figure 10 and figure 11, respectively.

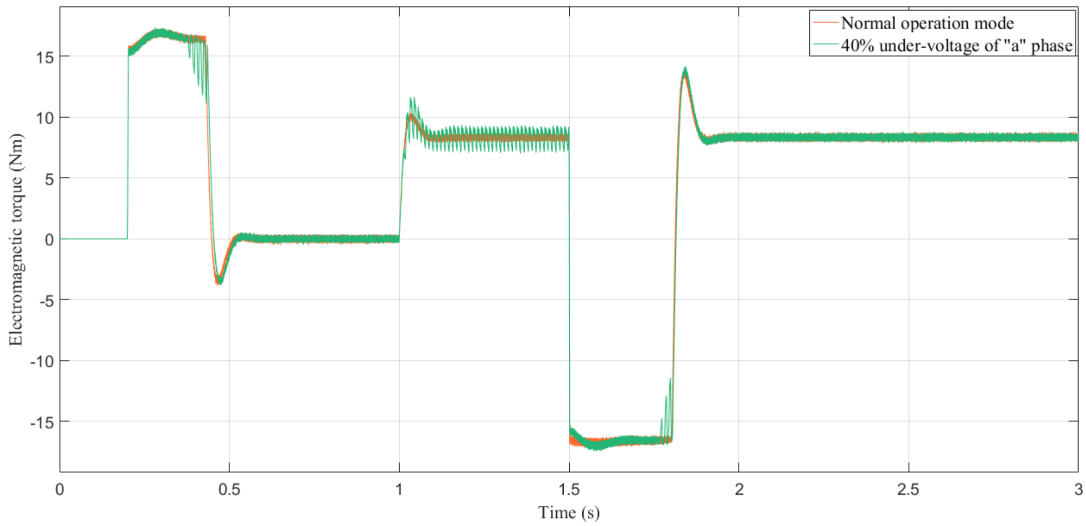

Figure 10. Electromagnetic torque during normal mode and 40% under-voltage of "*a*" phase.

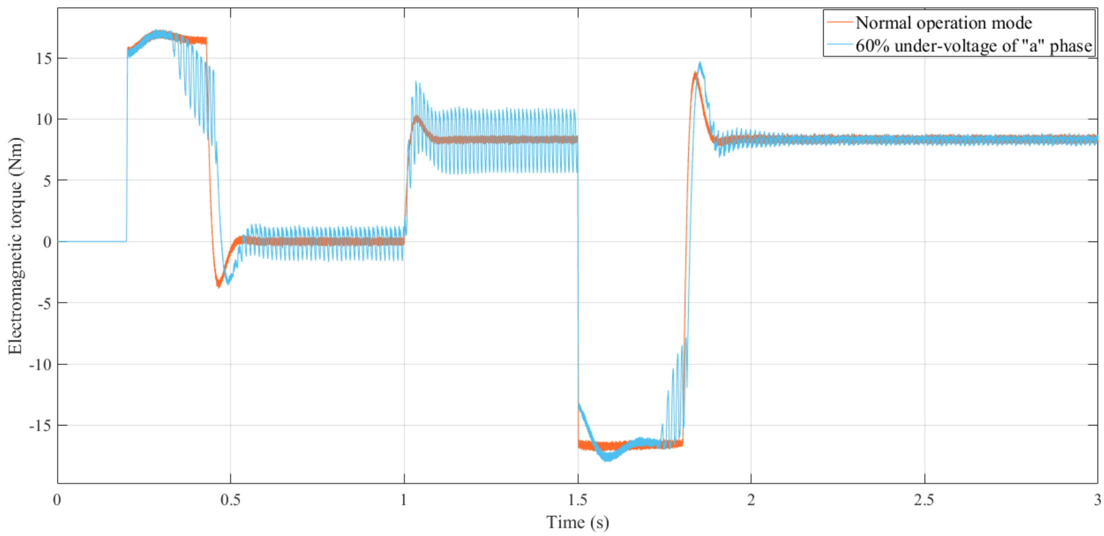

Figure 11. Electromagnetic torque during normal mode and 60% under-voltage of "*a*" phase.

In order to see clearly the changes in the simulation results, the electromagnetic torque during normal mode operation (orange) and 60% (blue), 80% (green) and 100% (purple) under-voltage conditions of the stator "*a*" phase is shown in Figure 12. The obtained simulation results are very important to understand that the selected parameters are getting slightly affected by an unbalanced voltage system. During the faulty condition operation for 20% and 40% under-voltage of the stator "*a*" phase, the rotor speed, electromagnetic torque and stator's current are similar to the results during the normal mode of operation. By increasing the unbalanced level until 100% under-voltage of the "*a*" phase, the mentioned parameters have changed more than previous cases by providing a negative effect on the electrical machine's performance. However, the five-phase motor can continue the operation in faulty conditions, which is an important advantage of the multi-phase electrical machines. Furthermore, the values of electromagnetic torque ripples for every case of under-voltage of the stator phase are listed in Table 2.

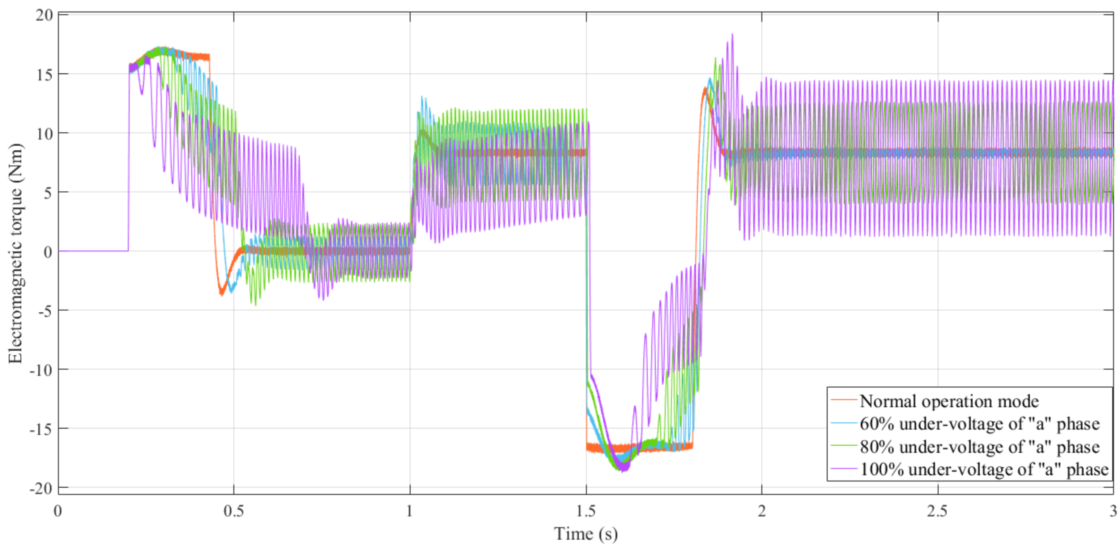

Figure 12. Electromagnetic torque during normal mode and 60%, 80%, 100% under-voltage of "*a*" phase.

Table 2. The values of electromagnetic torque ripples during faulty conditions operation of five-phase machine.

Under-voltage level of stator "*a*" phase	**The values of electromagnetic torque ripples of the machine**
0 %	±3,60 %
20 %	±4,22 %
40 %	±12,65 %
60 %	±31,33 %
80 %	±45,78 %
100 %	±74,70 %

6. CONCLUSION

The main conclusions of this research study are listed as follows:

- The multi-phase electrical machines are recognized as a very interesting alternative comparing to conventional three-phase machines due to their various advantages, such as the ability to use these machines in faulty conditions, high overall system reliability, the reduction in the total power per phase, higher torque density, reduced torque ripples and improvement in noise characteristics. The multi-phase machines are used in different critical applications such as electric vehicles, general aerospace applications, wind power generation systems and railway traction.
- Based on the Simulink model, the simulation of the five-phase electrical drive under normal mode and faulty conditions was carried out to analyze the machine's performance. During the faulty conditions operation for 20% and 40% under-voltage of the "*a*" phase, the simulation's results of stator phase currents, rotor speed and electromagnetic torque are similar to the results of normal mode operation.

- During the operation by increasing the unbalanced level from 60% until 100% under-voltage of the "*a*" phase, the simulation's results of the electrical machine have changed more than in previous cases by providing a negative effect on the machine's performance, but it can still continue the operation.
- Based on the theoretical and simulation results, the five-phase machine is very reliable and it has better fault tolerance because it is slightly affected by the unbalanced voltage system.

CONFLICT OF INTEREST

The authors confirm that there is no conflict of interests associated with this publication and there is no financial fund for this work that can affect the research outcomes.

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