Effect of the angular offset of the stator windings on DSIM performance

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ABSTRACT

The study outlined in this paper aims to analyze the effect of the different displacement angles between the two stator windings on the performance of a dual stator induction motor, which is a squirrel cage induction motor with two identical windings in its stator. The rated power of each winding is 1.1 kW and fed by an inverter operating with the pulse width modulation technique. The analytical model of the machine is used to analyze its characteristics to investigate the impact of the displacement angles between the two stator windings**.** A simulation program for the system has been developed using MATLAB/Simulink. Simulation results characterizing the comportment of this machine for different displacement angles of the stator windings show that the torque pulsations are noticeably lower at 30° shift than in the other two scenarios of 0° and 60°, the model exhibits noteworthy performances at this shift. The torque pulsations are noticeably lower at 30° shift than in the other two scenarios of 0° and 60°, and the model exhibits noteworthy performance at this shift. In this case, there are also reduced rotor current ripples, which decrease rotor heating. Despite this, the harmonics increased the peak stator phase currents for a 30° electrical offset.

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NOMENCLATURE

R_{s1}	:	Resistance of stator 1 winding	L_m	:	Magnetization inductance
R_{s2}	:	Resistance of stator 2 winding	p	:	Pole pairs number
R_r	:	Rotor resistance	ω_s	:	Angular rotation speed
L_{s1}	:	Stator 1 inductance	(i_{ds1}, i_{qs1})	:	Stator 1 current (d, q) components
L_{s2}	:	Stator 2 inductance	(i_{ds2}, i_{qs2})	:	Stator 2 current (d, q) components
L_r	:	Rotor inductance	(i_{dr}, i_{qr})	:	Rotor current (d, q) components

1. INTRODUCTION

Compared to traditional three-phase machines for industrial drives applications, multiphase induction machines offer several benefits, for example, minimized torque fluctuations, reduced per-phase stator current without a corresponding increase in phase voltage, decreased harmonic components of the rotor current, and increased fault tolerance [1]-[3]. It is particularly possible to continue operating a multi-phase induction machine characterized by an asymmetric winding configuration with unbalanced phase excitation, in this case, one or more stator winding excitation sets are lost [4]. Multiphase drives offer improved power distribution, more freedom to integrate new operating modes, and more post-fault tolerance without the need for additional hardware [5], [6]. Dual stator machines first appeared in the early 1900s [7]. Due to its benefits over traditional machines, this type of machine is becoming more and more popular for applications based on generators and motors [8]. In generator mode, the use of the dual stator induction machine, which is also called brushless doubly fed machine (BDFM), in a wind turbine was an attempt to acquire the benefits of a doubly fed induction generator (DFIG) in a more robust structure, which remains the primary motivation for the most recent push in BDFM research [9]. Modeling of a wind turbine based on dual DFIG generators is given by [10]. Preview study [11], the feasibility of BDFM used in a variable speed wind turbine was tested. Induction machines with two stator windings in the motor mode are the subject of multiple research studies. The analysis of multiphase induction machines in terms of winding faults was analyzed in [12]. Dual stator induction machine has been the focus of numerous studies. The concept of a dual stator winding induction motor (DSWIM) with two isolated three-phase windings having unequal numbers of poles was introduced in [13], where the authors examined the effects of the number of stator dissimilar numbers of poles. The effect of winding configuration on the parameters and performance of a six-phase induction machine is presented in [14]. Modelling and analysis of dual stator winding induction machine using complex vector approach is given in [15]. Modeling and simulation of dual three-phase induction machine using MATLAB/Simulink in [16].

In the literature, many works have been carried out on the dual-stator induction machine, taking into account the angular offset between the two stator windings. Preview study [17], a general review of polyphase machines for integrated motor drives is presented. An induction machine with six-phase supply by a multi-level inverter with consideration of 0°, 30°, and 60° displacements between two stator winding sets, as well as a comparison of three distinct cases, is studied in [18]. Performance enhancement and assessment of the dual stator induction motor are given in [19]. The behavior study of the dual-star induction motor under stator and rotor faults is investigated in [20]. In permanent magnet synchronous machines, the angular displacement between dual stator windings plays a crucial role in influencing fault currents and overall machine performance, with phase shifts of 30° and 60° shown to provide optimal results [21]. Qiu and He [22] show that a 30° phase shift between the stator windings in bearing-less motors significantly reduces total harmonic distortion, thus improving overall performance and reliability. The impact of electrical phase displacement in dual three-phase PMSMs was studied in detail in [23], demonstrating how unconventional angles can improve torque ripples and reduce losses. Khlifi [24] presents the modeling and simulation of a double stator winding induction machine fed by a multilevel inverter with neutral point, assessing the influence of angular displacements of 0°, 30°, and 60° between the two windings on torque ripple and harmonic distortion.

Based on the above-mentioned studies of the effect of the angular offset between the two stator windings on the performance of each type of machine with two stator windings. As a follow-up to these studies, our work will examine how this angular offset affects the same performance in the case of a double-stator induction motor powered by pulse width modulation (PWM) inverters. Our work also aims to confirm that the 30° electrical offset between the stator windings offers the best performance, as suggested by some previous work.

In this work, we present the development of a mathematical model for a dual stator induction motor (DSIM), expressed using a generalized reference frame with taking into account the effect of mutual leakage inductance. The dual stator induction motor is powered by two identical voltage source inverters, considering the phase shift between the two sets of three-phase stator windings (0°, 30°, 60°). A comparative analysis of these three configurations will be analyzed. The structure of the paper is as follows: Section 2 is a description and modelling of the DSIM; Simulation results are shown to demonstrate the validity of the suggested model of the dual stator induction motor will be discussed in section 3; and the conclusion of this work is thoroughly presented in section 4.

2. DESCRIPTION AND MODELLING OF THE DSIM

Before developing the DSIM model, it is important to provide a brief description of this machine. This includes an overview of its construction. Next, the spatial arrangement of the stator and rotor windings will be described. Finally, the structure of the different angular offsets between the two stator windings will be presented.

2.1. Description of the DSIM

The name dual stator induction motor is due to the fact that the stator contains two windings. It's also called a dual-star induction motor when the windings or the two stators are both star-connected. The rotor is a squirrel cage one, identical to that of a conventional induction motor. The two windings housed in the same stator have the same number of pole pairs. The dual stator induction motor (DSIM) consists of two stationary three-phase stator windings, referred to as stator 1 and stator 2, which are spatially displaced by an electrical angle α (see Figure 1), with a rotor in squirrel-cage form that is common to both stators [25]. Figure 2 shows the configuration of different angular offset angles between the two stator windings.

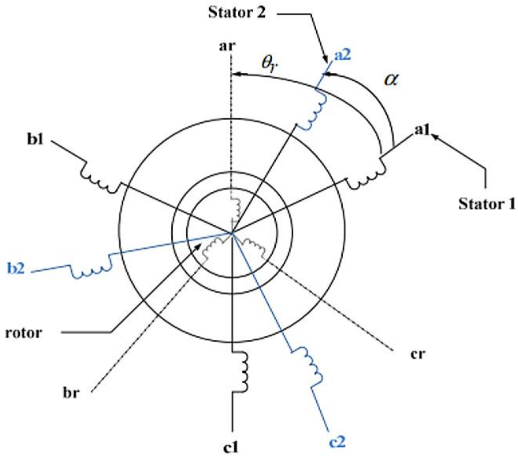

Figure 1. Diagram of the stator and rotor windings of a DSIM

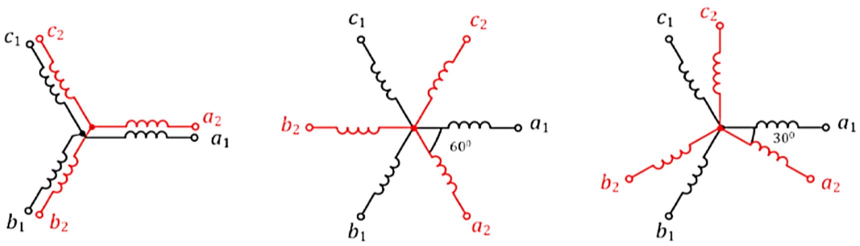

Figure 2. Configuration of different angular offset angles between the two stator windings

2.2. Mathematical modelling of the DSIM

The mathematical model of the dual stator induction machine is based on Park's transformation to simplify the system of differential equations [26]. It is characterized by the voltage and flux equations as (1)-(6) represent the stator 1, stator 2, and rotor voltages, respectively, expressed in the (d, q) reference frame.

$$v_{ds1}=R_{s1}.i_{ds1}+\frac{d\varphi_{ds1}}{dt}-\frac{d\theta_{s1}}{dt}.\varphi_{qs1} \tag{1}$$

$$v_{qs1}=R_{s1}.i_{qs1}+\frac{d\varphi_{qs1}}{dt}+\frac{d\theta_{s1}}{dt}.\varphi_{ds1} \tag{2}$$

$$v_{ds2}=R_{s2}.i_{ds2}+\frac{d\varphi_{ds2}}{dt}-\frac{d\theta_{s2}}{dt}.\varphi_{qs2} \tag{3}$$

$$v_{qs2}=R_{s2}.i_{qs2}+\frac{d\varphi_{qs2}}{dt}+\frac{d\theta_{s2}}{dt}.\varphi_{ds2} \tag{4}$$

$$v_{dr}=R_r.i_{dr}+\frac{d\varphi_{dr}}{dt}-\frac{d\theta_r}{dt}\varphi_{qr}=0 \tag{5}$$

$$v_{qr}=R_r.i_{qr}+\frac{d\varphi_{qr}}{dt}+\frac{d\theta_r}{dt}.\varphi_{dr}=0 \tag{6}$$

The (7) and (8) represent the stator 1, (9)-(10) the stator 2, (11) and (12) the rotor flux, respectively, expressed in the (d,q) reference frame.

$$\varphi_{ds1} = (L_{s1}+L_m)i_{ds1}+L_m(i_{ds2}+i_{dr}) \quad (7)$$

$$\varphi_{qs1} = (L_{s1}+L_m)i_{qs1}+L_m(i_{qs2}+i_{qr}) \quad (8)$$

$$\varphi_{ds2} = (L_{s2}+L_m)i_{ds2}+L_m(i_{ds1}+i_{dr}) \quad (9)$$

$$\varphi_{qs2} = (L_{s2}+L_m)i_{qs2}+L_m(i_{qs1}+i_{qr}) \quad (10)$$

$$\varphi_{dr} = (L_m+L_r)i_{dr} + (i_{ds1}+i_{ds2})L_m \quad (11)$$

$$\varphi_{qr} = (L_m+L_r)i_{qr} + (i_{qs1}+i_{qs2})L_m \quad (12)$$

The equation for electromagnetic torque is provided by (13).

$$C_{em} = p\frac{L_m}{L_r+L_m}\left[(i_{qs1}+i_{qs2})\, j_{dr} - (i_{ds1}+i_{ds2})\, j_{qr}\right] \quad (13)$$

2.3. Development of a simulation model in MATLAB/Simulink environment

Based on the various equations characterizing the model of the double stator induction motor with each stator winding supplied by a PWM inverter, a simulation program was developed using MATLAB/Simulink environment. This model is shown in Figure 3, and allows us to examine the behavior of the motor in question for three cases of offset between the two stator windings (0°, 30°, 60°).

The simulation program developed using MATLAB/Simulink is composed by the following five blocks. Block 1 represents the two PWM inverters supplying the double stator induction motor, the voltages at the output of this block are in the (a, b, c) reference frame. Their transformation in Park's reference frame is performed in block 2. The different angles involved in the equations describing the model of the motor in question are presented in block 3. Block 4 represents the model of the motor. To enable visualization of the stator and rotor currents in (a, b, c) reference frame, Park's inverse transformation is required, which is included in block 5.

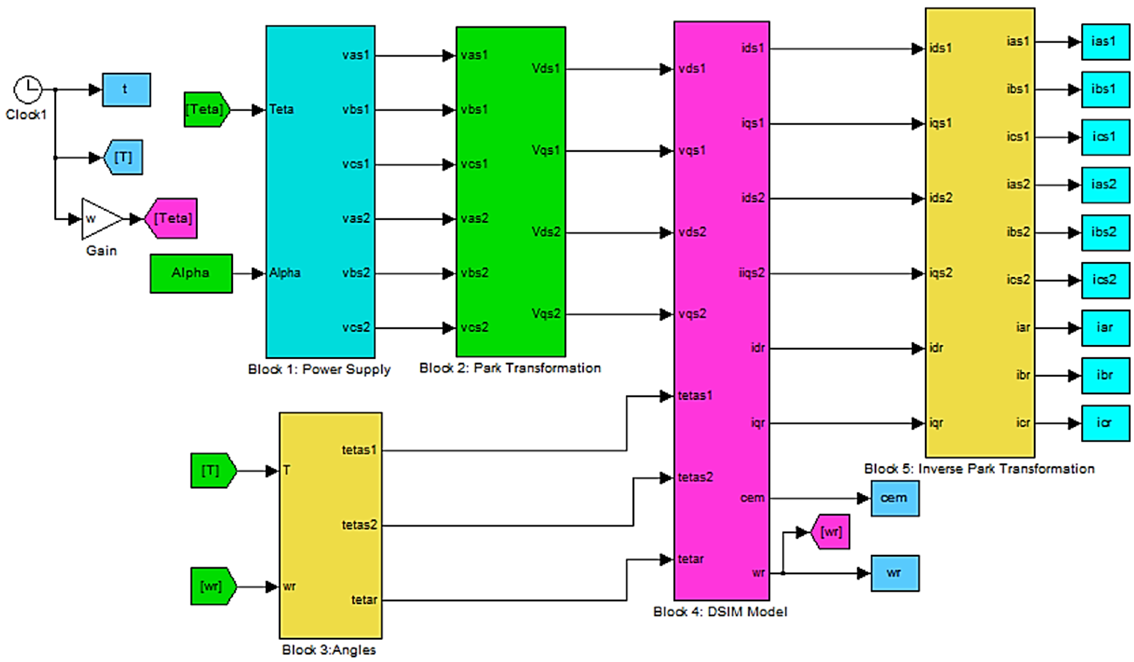

Figure 3. MATLAB/Simulink-based dual stator induction motor model

3. RESULTS AND DISCUSSION

Table 1 lists the parameters of the dual stator induction machine used in this study. Using the model of this machine with different displacements between the two stator windings, a series of tests was performed by modifying the load in three stages at various time intervals (Cr1 = 0 Nm at t_1 = 0 s; Cr2 = 1 Nm at t_2 = 0.8 s, and Cr3 = 1.4 Nm at t_3 = 1.8 s). The behavior study and the performance of this machine under these steps load change with different displacements between the two stator windings, which are supplied by two identical inverters.

The supply voltage of the two stators is represented by the output voltage waveform inverter (vas1) supplying the first phase of stator 1, and its zoom is given respectively by Figures 4 and 5. Different load conditions distinguishing operating modes of the machine are characterized in Figure 6. The electromagnetic torque is given by Figure 7, it is approximately equal to zero at no-load condition and is almost equal to the load torque when the motor is operating at load.

Using the zoom of the electromagnetic torque curve (see Figure 8), we can observe the pics of the torque ripples, which are very significant for 0° and 60° compared to the 30° shift. This is confirmed by the characteristic torque-speed of the DSIM, which is represented by Figure 9. The relative torque ripple rates for the three cases of the two stator windings displacement are given in Table 2.

Figure 10 illustrates that the rotor speed remains nearly free from pulsations; it is not affected by the displacement between the stator windings. At no load, the speed is equal to 156.2 rad/s and varies with load, taking values of 138.2 rad/s and 126.4 respectively, in [0.8-1.8 s] and [1.8-2.5 s]. Figure 11 represents the stator current of the phase "a" of the first stator. The zooms of the stator current waveform during the no-load and the load conditions are respectively given by Figures 12 and 13. The amplitude of pulsations in the stator current is very considerable when the displacement between the two stators is equal to 30° compared to the other displacements, which are 0° and 60°.

Table 1. DSIM parameters

Parameter	Value
Nominal rated power of the DSIM	Pn = 1.1 kW
Frequency	f = 50 Hz
Number of pairs of poles	$p_1 = p_2 = 2$
Stator 1 resistance	Rs1 = 7.73 Ω
Stator 2 resistance	Rs2 = 7.73 Ω
Stator 1 inductance	Ls1 = 0.0150 H
Stator 2 inductance	Ls2 = 0.0150 H
Magnetization inductance	Lm = 0.44 H
Resistance of the rotor	Rr = 4.01 Ω
Inductance of the rotor	Lr = 0.0150 H
Moment of inertia	J = 0.00075 kg.m^2

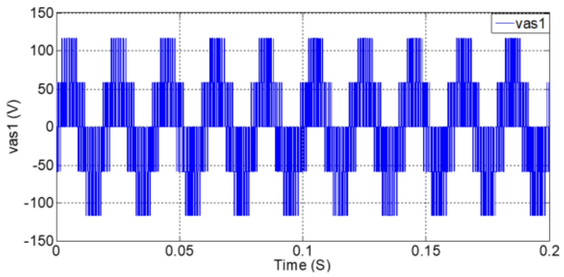

Figure 4. Output voltage waveform inverter (vas1)

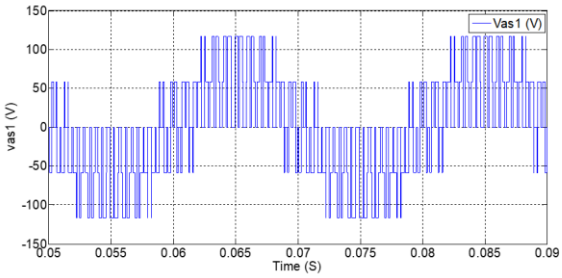

Figure 5. Zoom of the output voltage waveform

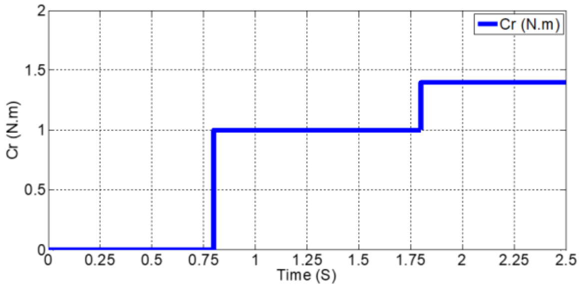

Figure 6. Step load torque waveform

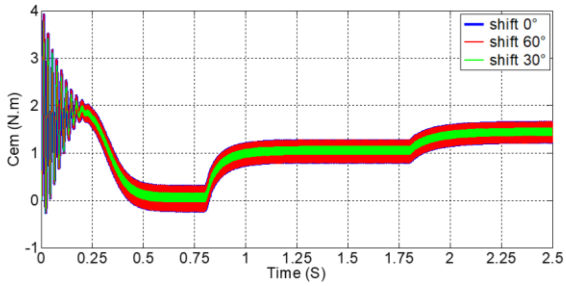

Figure 7. Electromagnetic torque

Table 2. Variation in torque ripple ratio as a function of offset angle

Shift angle (°)	Δ cem (%)
0°	06,60 %
30°	20,76 %
60°	20,76 %

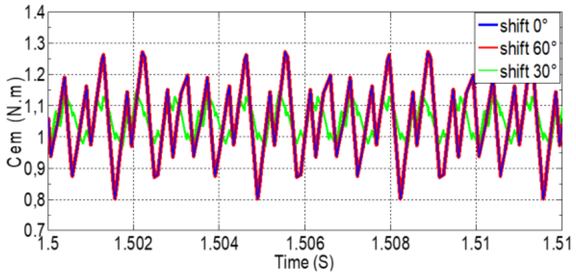

Figure 8. Zoom of the electromagnetic torque

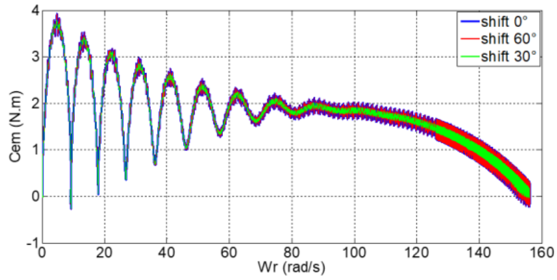

Figure 9. Characteristic torque-speed of the dual stator induction motor

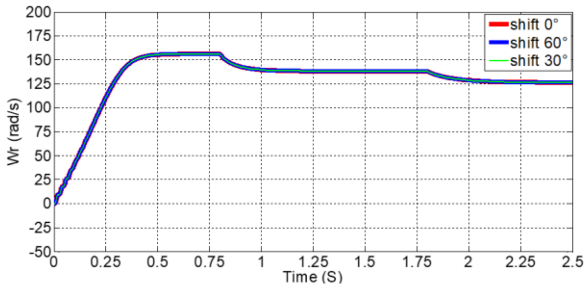

Figure 10. Rotor speed waveform

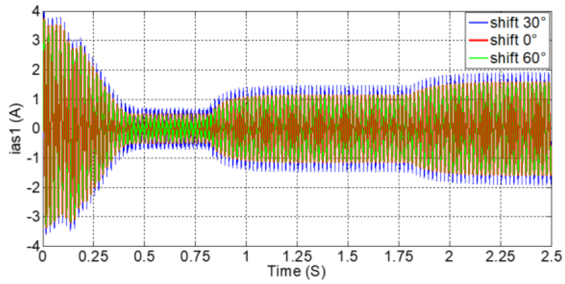

Figure 11. Phase "a" stator 1 current waveform (ias1)

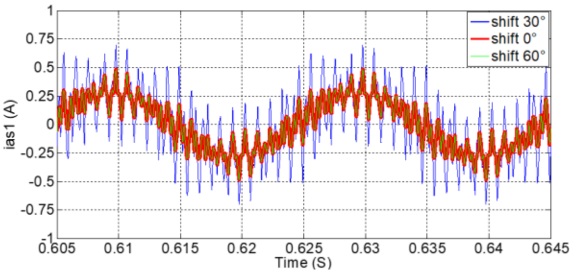

Figure 12. Zoom of the phase "a" stator 1 current at no-load condition

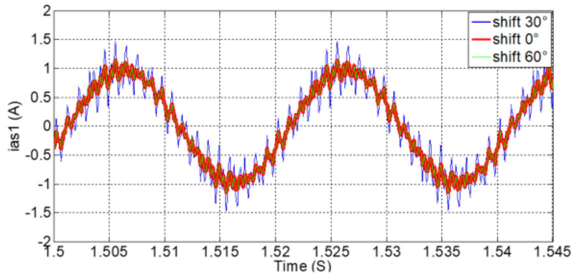

Figure 13. Zoom of the phase "a" stator 1 current at load condition

Figure 14 shows the rotor current, where its value fluctuates around zero during the no-load condition. The rotor current frequency is determined by the following relationship: $\omega_r = \omega_s - p * \Omega_r = g * \omega_s$, where g denotes the slip. Furthermore, the amplitude of the rotor current increases as the slip rises. Concerning the rotor current pulsations, the zooms of the rotor current curve (Figures 15 and 16) indicate that in the case of a 30° shift between the two stators, the rotor current ripples are smaller than those noted when the shift is equal to 0° or 60°.

The results above illustrate the electrical and mechanical behavior of the dual stator induction motor fed by two PWM inverters, during two operating modes: no load and in load conditions. Three situations of displacement between the stator windings are studied (0°, 30°, and 60°).

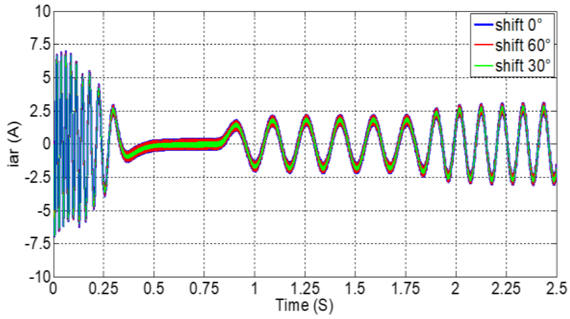

Figure 14. Rotor current waveform

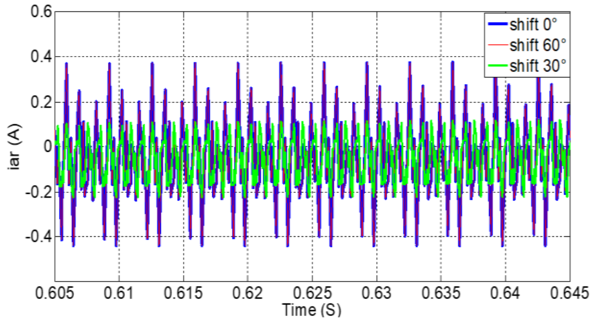

Figure 15. Zoom of the rotor current at no-load condition

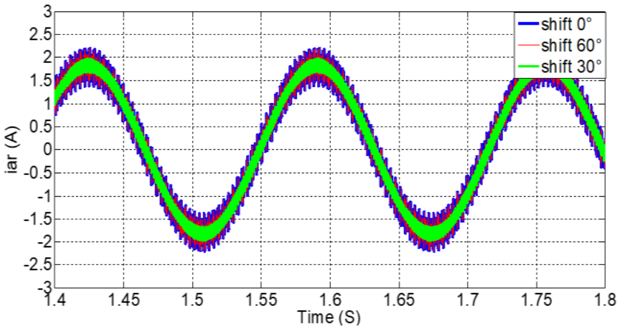

Figure 16. Zoom of the rotor current at the load condition

4. CONCLUSION

This paper investigates the performance analysis of a DSIM supplied by two voltage source inverters using the PWM technique for three cases of the shift angles between the two stator windings. After the modeling of this machine, a simulation program is established using MATLAB/Simulink environment. The developed model is valid for any angle shift between the two three-phase stator windings and in all reference frames. The simulation results obtained have enabled us to analyze the behavior of the machine in two operating modes, at no load and under load conditions. Considering the different displacements between the two stator windings, which are 0°, 30°, and 60°. The model presents significant performances at 30° shift, because the torque pulsations are clearly reduced compared to the two other cases, 0° and 60°. The ripples of the rotor current are also smaller in this case, as a result, the reduction of the rotor heating. Nevertheless, the peak of the stator currents per phase was increased for a 30° electrical degrees shift, which is a consequence of the presence of additional harmonics in the stator current.

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Salah Haddad		✓	✓	✓	✓		✓		✓	✓	✓	✓		

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

No conflicts of interest have been identified by the authors regarding this work.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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