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Direct-Indirect PWM vector controlled of the dual-star asynchronous motor based on a modified winding function approach using the current controller for a six-phase inverter

Abstract: *The study shown in this paper is concerned with the two-star asynchronous motor, and this motor is from the family of six-phase induction motors, which has many advantages in the industrial world. The featured in this article is the mathematical model of the double star motor by adopting the spatial harmonics of the inductance distribution on the squirrel-cage rotor bars and calculating the different inductances following the modified winding function approach (MWFA). Then we care about the control systems for this motor, especially the PWM command, by controlling a hexagonal inverter that feeds the DSAM. Finally, we make a preferential comparison between the two types of direct and indirect PWM control according to various operating circumstances, including load, torque, and speed fluctuations, considering the impact of spatial harmonics, to find out the best between them for this type of engine.*

Streszczenie. *Badanie przedstawione w tym artykule dotyczy dwugwiazdkowego silnika asynchronicznego, a ten silnik pochodzi z rodziny sześciofazowych silników indukcyjnych, która ma wiele zalet w świecie przemysłowym. W tym artykule omówiono model matematyczny silnika z podwójną gwiazdą, przyjmując harmoniczne przestrzenne rozkładu indukcyjności na prętach wirnika klatkowego i obliczając różne indukcyjności zgodnie z podejściem zmodyfikowanej funkcji uzwojenia (MWFA). Następnie dbamy o układy sterowania dla tego silnika, zwłaszcza polecenie PWM, sterując heksagonalnym falownikiem, który zasila DSAM. Na koniec dokonujemy preferencyjnego porównania między dwoma rodzajami bezpośredniego i pośredniego sterowania PWM w zależności od różnych okoliczności roboczych, w tym wahań obciążenia, momentu obrotowego i prędkości, biorąc pod uwagę wpływ harmonicznych przestrzennych, aby znaleźć najlepsze między nimi dla tego typu silnik.* (***Bezpośrednio-pośrednie sterowanie wektorowe PWM dwugwiazdowego silnika asynchronicznego w oparciu o podejście zmodyfikowanej funkcji uzwojenia z wykorzystaniem regulatora prądu dla falownika sześciofazowego***)

Keywords: Dual star asynchronous motor DSAM ; Modified winding function approach MWFA; Direct space vector PWM control;
Słowa kluczowe: silnik asynchroniczny, uzwojenia, sterowanie PWM

Introduction

Because the synchronous motor can be designed in various ways by varying the number of phases n, several forms exist from it. One of the best-known engines is DSAM because it is considered the most powerful, reliable, and very high efficiency, which gives us the work required of him, and unlike the single-star machine, the loss of one of his stars doesn't stop him from working [1].

This kind of machine distinguishes by its property of magnetic coupling between phases, it has the characteristic of interphase magnetic coupling, forming of n $n$spatial phase-shifting windings of $2\pi/n$ and driven by a temporal voltage [2].

For an analytical study of DSAM, we use a model of the machine that enters into his estimates structure of the flaw, we opt for this model with multiple winding, which depends on the modified winding function(MWF) approach, it provides a rational analysis of harmonic generation in the engine's healthy and out-of-order conditions [3].

Between the phases of the stator, the motor's non-generating electromagnetic torque and current produce improbable phenomena, this current can reach high amplitudes because of Low impedance, leakage inductance, and stator resistance, which take out joule losses, and this is the main drawback of the multi-phase winding machine. To bypass this obstacle, static converters made of power electronics elements (IGBT) use to supply DSAM, and communication with it realizes through a control strategy, and we resort to the help of the operative and famous one, which is the space vector PWM command [5] [6].

Later, the quality of the resulting parameters principles of the (DSAM) controlled by PWM direct and indirect is the focus of a comparative study that follows the discussion of the two distinct methods of PWM control (Direct, Indirect), which reveals in the simulation results section.

Calculations and applied theories

The entire power partitioning was the initial goal of increasing the number of phases over several arms in the multiphase machines, and the components of each theme are certified for reduced power allowing higher switching frequencies achieving, which results in lower ripples, current and lower torque.

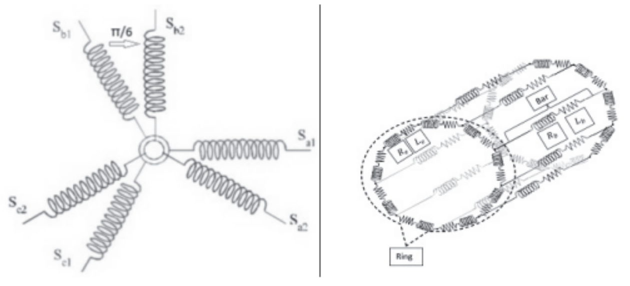


Fig. 1. DSAM: The dual stator (up) and the squirrel cage rotor(lowest)

There are two different kinds of multi-phase machines, depending on the number of stator phases [6][26], kinds one (1) and two (2) are those in which the amount of stator phases (q) is an odd number and a multiple of three, respectively, depending on the angular offset α between two neighbouring coils, there is the ability to have several machine configurations.

A (DSAM) whose number of stator phases $q = 6$ and the stars are shifted by α = pi/6 (Figure 1), has several advantages [30] [1] [4] [6]. Due to the fact that the stator of our machine consists of two three-phase windings with two separated neutrals, which are not coupled to the stator currents and hence are unable to contain homopolar components, we expressed the stator equations as compound voltage to eliminate the neutral voltage [9] (Figure 1).

The squirrel cage rotor as shown in (Figure 1) is formed by meshes from a polyphase winding whose number of phases is equal to the number of bars and each mesh consists of two adjacent bars and two short-circuit ring portions that connect, bars and ring portions represented by their corresponding resistances and leakage inductances.

0.1. A glimpse into the approach of modifying winding function (MWFA)

Relying on electromagnetic phenomena as a basis for studying machines leads to a better understanding of force distributions, flow, and current density [9][10][12].

The winding function is a successful method for analyzing electrical machines to focus their calculations on the actual and internal structure of the DSAM, we find the windings that form coils with one or more turns in a circular series placed in slots so that the modified winding function computes the inductance from the distribution of these windings. As in [9][10][12], the changed winding function's expression:

(1)

$$M = n(\theta_s{-}\theta) - \left(\frac{1}{2.\pi.g(\theta_s-\theta)}\right)\int_0^{2\pi} n(\theta_s{-}\theta).g(\theta_s-\theta)$$

Where: $n(\theta_s-\theta)$: is the turn-related function, often known as the distribution or turn-related function; $g(\theta_s-\theta)$: is the function of the air gap.

We learn the initial form of the expression for the winding function if the air gap is assumed to be uniform, in which case $g(\theta_s-\theta)^{-1}$ is constant [11] (Figure 2).

(2) $N(\theta_s-\theta) = n(\theta_s-\theta) - \big(n(\theta_s-\theta)\big) = n(\theta_s-\theta).\frac{1}{2.\pi}\int_0^{2\pi} n(\theta-\theta)d\theta_s$

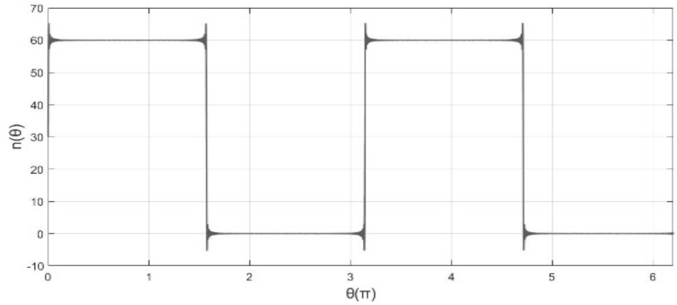


Fig. 2. The function of stator winding distribution

The current i_α is in motion through the windings of the machine "a" and "b" (or any other windings), causing the MMF through the air gap to take the following form (Figure 3):

(3) $F_a(\theta_s-\theta) = M_a(\theta_s-\theta)i_a$

The total flux of the winding "b" brought on by the current through it determines using the formula shown below:

(4) $\psi_{ba} = u_0 rl\int_0^{2\pi} N_b(\theta_s-\theta)F_a(\theta_s-\theta)g(\theta_s-\theta)^{-1}.d\theta_s$

By dividing the flux through winding "b" by the current through winding "a," the mutual inductance calculates as follows:

(5)

$$L_{ba} = \frac{\psi_b}{i_a} = u_0 rl\int_0^{2\pi} n_b(\theta_s{-}\theta)M_a(\theta_s{-}\theta)g(\theta_s{-}\theta)^{-1}d\theta_s$$

When windings "a" and "b" are similar, we observe:

(6)

$$L_{aa} = u_0 rl\int_0^{2\pi} N_a(\theta_s-\theta)M_a(\theta_s-\theta)g(\theta_s-\theta)^{-1}.d\theta_s$$

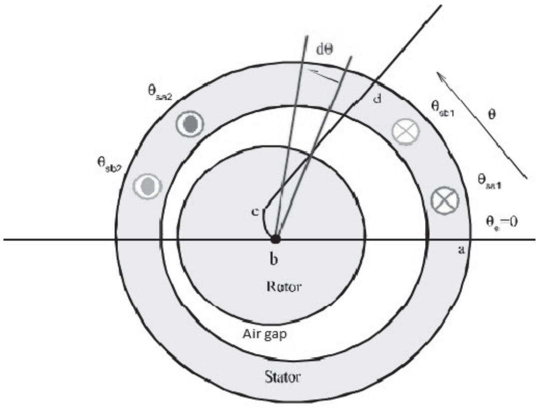


Fig. 3. The DSAM's multiple-winding design

As a result, we may determine whether windings are stationary, rotating, or rotating relative to one another by examining the expression that provides the mutual inductances and the magnetization inductances.

For a constant air gap, the magnetization inductance of the stator's phase q and star i is:

(7) $L_{sqi} = l_{sqi} + l_f$

Where l_f is the self-magnetizing inductor and:

(8) $L_{sqi} = \frac{u_0 rl}{g_0}.\frac{N_t^2 l}{p^2}\sum_{h=1}^{+\infty}\frac{k_{bh}^2}{h^2}$

- Mutual inductance between two stator windings:

(9) $M_{sqi} = \frac{4u_0 rl}{g_0}.\frac{N_t^2}{p^2}\sum_{h=1}^{+\infty}\frac{k_{bh}^2}{h^2}\cos(\emptyset^2)$

- Magnetizing inductor of the rotor:

(10) $L_{Mrk} = \frac{4}{\pi}\frac{u_0 rl}{g_0}\sum_{h=1}^{+\infty}\left(\frac{\sin\left(h\frac{\alpha_r}{2}\right)}{h^2}\right)^2$

where: $\alpha_r = \frac{2\pi}{n_b}$

- Mutual inductance between cell "j" and any disconnected cell "k"

$$M_{rjrk} = \frac{4}{\pi}\frac{u_0 rl}{g_0}\sum_{h=1}^{\infty}\left(\frac{sin(h\frac{\alpha_r}{2})}{h^2}\right)^2 cos(h_(j-k))\alpha_r$$

(11)

For two adjacent stitches:

$$Mrjrk = \frac{4}{\pi}.\frac{u_0 rl}{g_0}.\sum_{h=1}^{\infty}\left(\frac{sin(h\frac{\alpha_r}{2})}{h^2}\right)^2 cos(h\alpha_r)$$

(12)

- Mutual inductance between a rotor mesh and a stator phase (Figure 4):

(13)

$$M_{sqirk}(\theta) = \sum_{h=1}^{\infty} M_{sr}cos(hp(\theta{-}\theta_0)+(k{-}\frac{1}{2})\alpha_r{-}q\frac{2\pi}{3p}{-}i$$

where:

$$M_{sr}^{hp}=\frac{4}{\pi}\frac{u_0 rl}{g_0}\frac{N_t^2}{p^2}\frac{K_{ph}}{h^2}sin\frac{hp\alpha_r}{2} \quad (14)$$

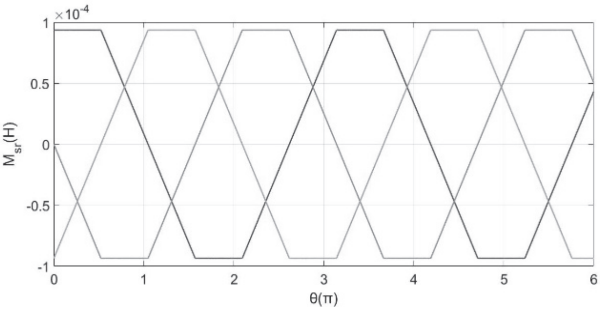


Fig. 4. Mutual inductance of rotor-stator

0.2. PWM control for space vector

PWM control builds on controlling the stator, rotor, or air gap elements by dropping them on the axis of the reference frame that rotates at speed w_s, which seeks to ensure the stability of the asynchronous motor for support the vast industrial performance of asynchronous drives with a high load (electric traction, paper mills, rolling mills, etc.) [17].

PWM control seeks to separate the electromagnetic torque-generating quantities and rotor flux, because of that, the law used must ensure the separation of the two [9][16][18][15].

First of all, we should mention that we have to reduce the number of equations regulating the motor as well as decouple the rotor and stator equations that exist at the matrix level of mutual inductances, using a model based on our calculation on generalized Concordia matrix for the quantity of stator in the double star motor of landmarks $(a_1a_2b_1b_2c_1c_2)$, are stated using three separate reference frames (αβ) (XY) and (o_1o_2) (Figure 5) (In the frames of because the two neutrals of two stars are separated), this prior model is often employed in calculations because it establishes the current flowing concerning the two three-phase stator windings, which streamlines the control procedure, the fictitious windings utilized in these references are similar to the actual windings.

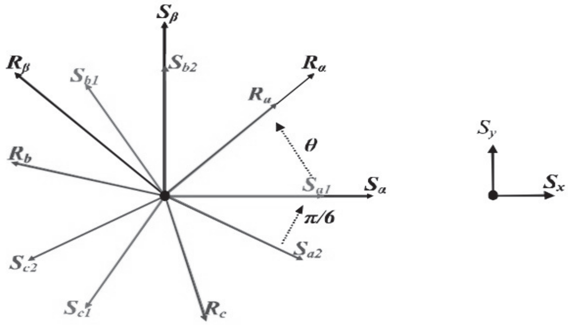


Fig. 5. Generalized Concordia model of the DSAM representation

Judging by the electrical and mechanical equations [9], we conclude that only static relations of the rotor and the (α, β) reference frame are magnetically correlated. Therefore, Just the elements of the stator and rotor's α and β currents are involved in the generation of torque.

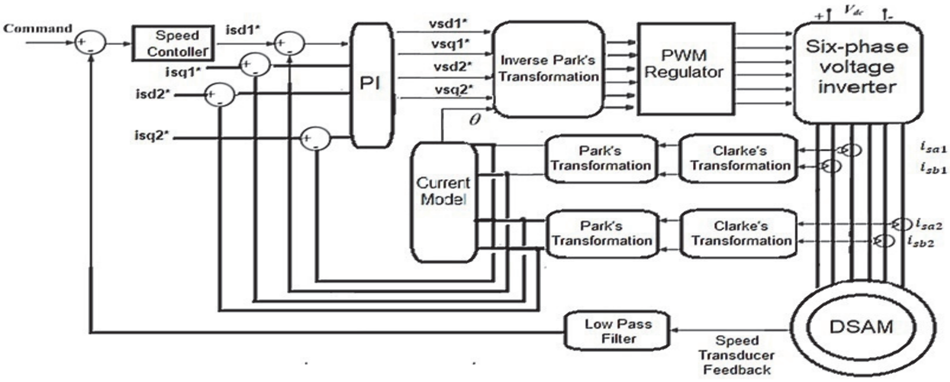


Fig. 6. Direct PWM control of DSAM in the overall diagram

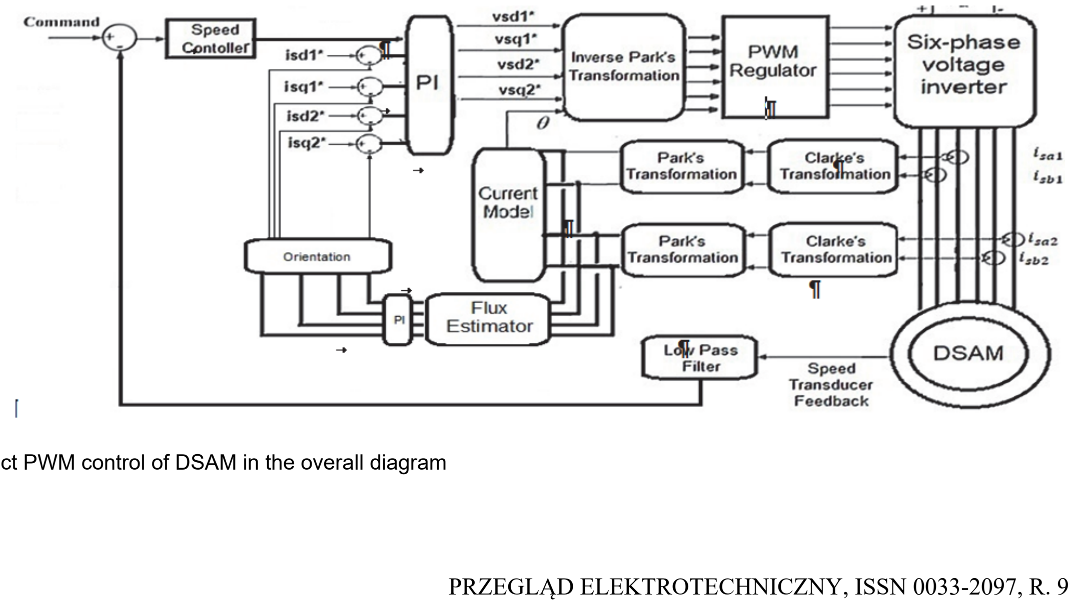


Fig. 7. Indirect PWM control of DSAM in the overall diagram

Controlling the DSAM supposed to be a floppy and complex process; however, it simplifies to a reasonable degree by using the (αβ) reference, which transforms into a three-phase machine control, with the inclusion number of PI controllers for the command's execution rationale [22], and There are two different types of directed flow vector control:

The first one uses the direct method, which calls for the actual rotor flow coefficient and the phase where they are controlled both by negative feedback [6][5], using measurements of the machine's ids and i_{qs}, and the pulsation of the rotor currents w_r, a rotor flux estimator ($\emptyset_r$) built for this purpose (Figure 6) The second way, known as the indirect method, controls the rotor flow in an open loop by relying simply on its location rather than its amplitude [19][15][20][16][21] (Figure 7).

Using pulse width modulation, an inverter with six stages is controlled to transform modulation into voltage in the form of continuous pulses produced at the output (Figure 8).

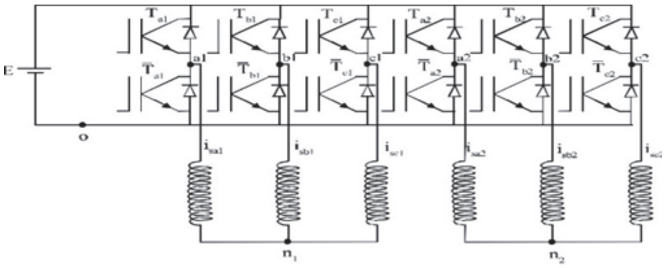
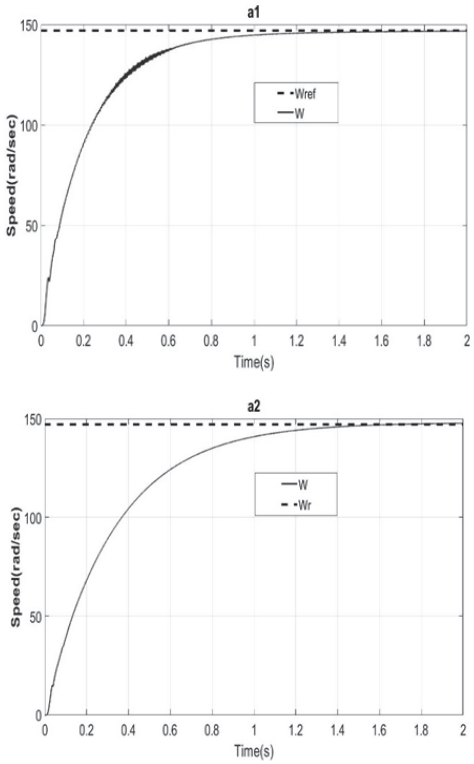


Fig. 8. Voltage inverter for six phases with two isolated neutrals

Simulation results

In our studies, we use an asynchronous double-star motor (1.1 kW), and the simulation doing with MATLAB / Simulink software.

In the first simulation, we aim to make the engine run at a normative speed of 147 rad/sec (see a_1, a_2) in (Fig. 9), but in (b_1,b_2) we are interested in changing the speed over time, so we start with a speed of 147 rad/sec, and then at the moment (T = 2s), we achieve a decrease in the speed value up to 100 rad /sec, and finally, at the time (T = 5 s) we return the speed to its original value. We can conclude that there is stability in the speed value and its good follow-up to its variable reference with time.



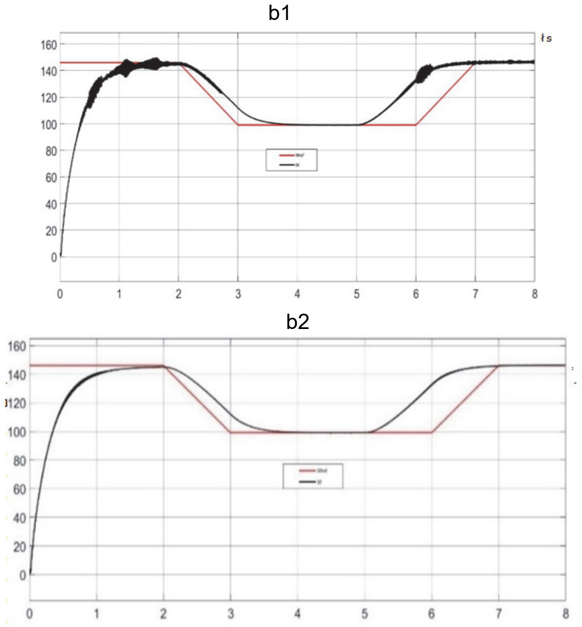
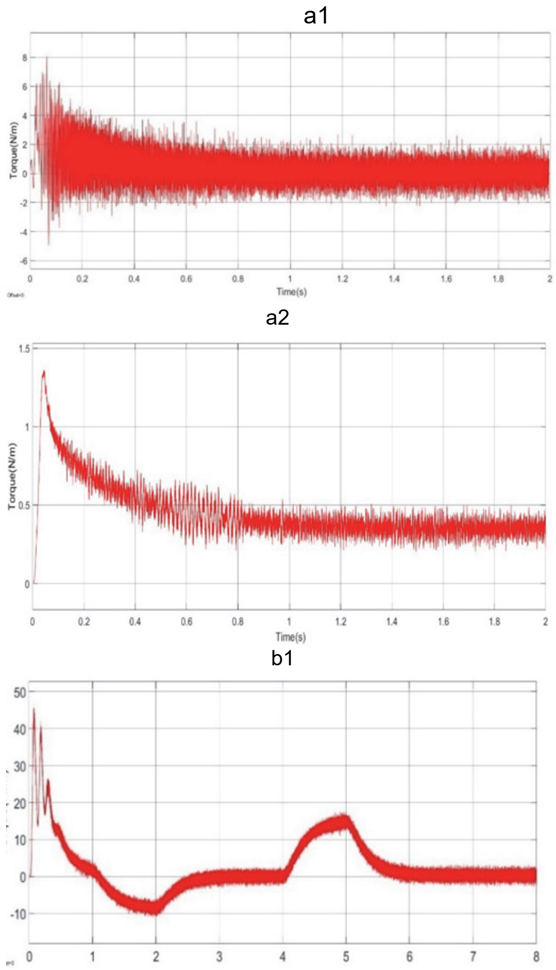


Fig. 9. Speed curves for the DSAM under direct PWM control (a1,b1) and indirect PWM control (a2,b2)



b2

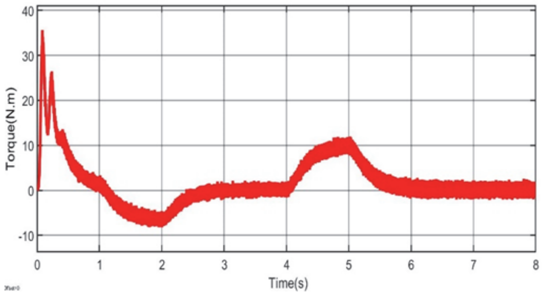
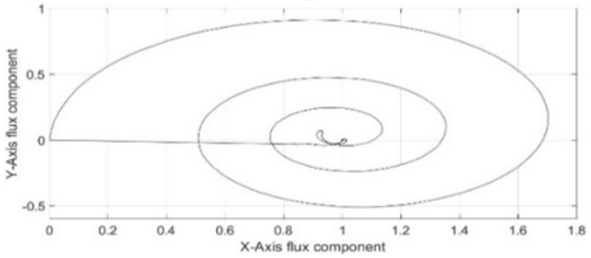


Fig. 10. Torque curves for the DSAM under direct PWM control (a1,b1) and indirect PWM control (a2,b2)

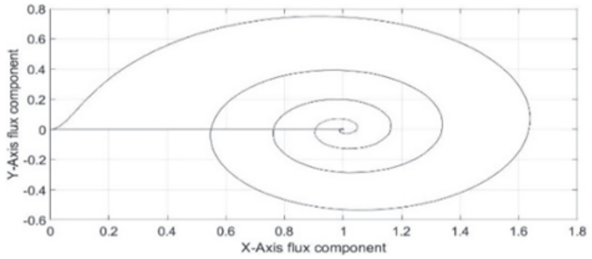
Noting that it forms an error with a peaking fault occurs when switching between two states, and this is in both types of PWM direct and indirect control.

The initial torque causes this oscillation which can see in (Figure 10) where the value of the load torque is 1.5 N/m at a time of 0.4 seconds.

a1

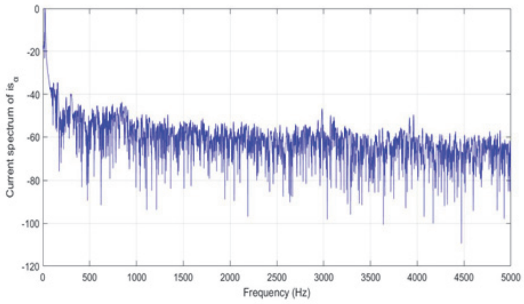


a2

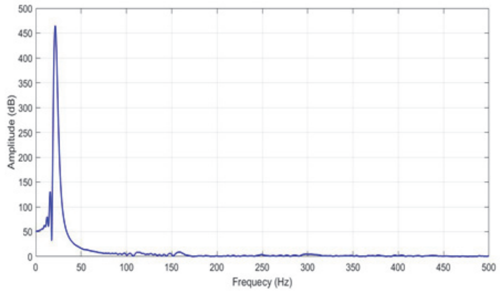


g. 11. Curves of stator flow: (a_1) direct PWM control and (a_2) indirect PWM control of DSAM

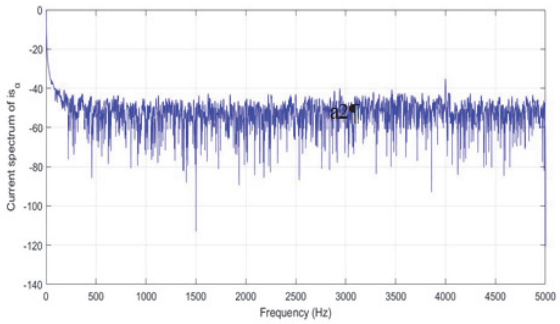
a1



a2



b1



b2

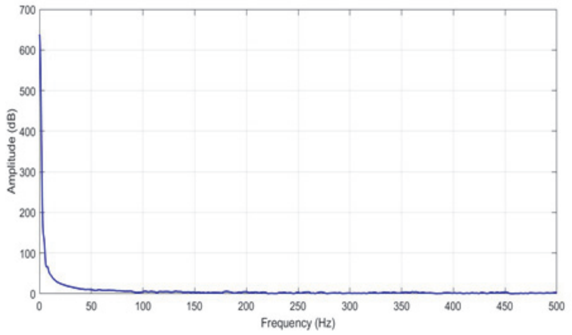
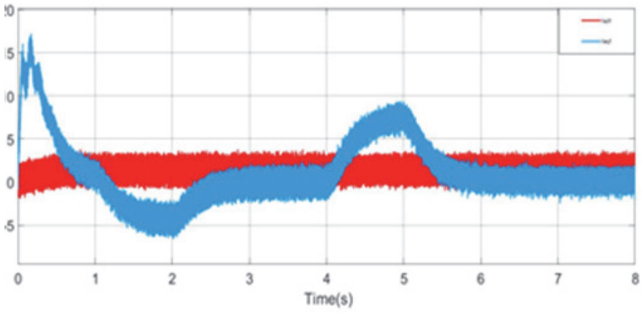
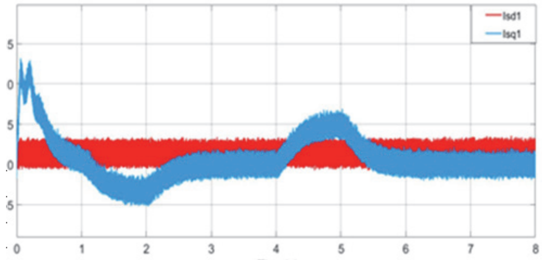


Fig. 12. Curves of FFT of $(is\alpha)$ and his amplitude: (a_1, a_2) direct PWM control and (b_1, b_2)indirect PWM control of DSAM

a1



a2



a2

Fig. 13. Curves of decoupling: (a_1) direct PWM control and (a_2) indirect PWM control of DSAM

We can conclude that there is stability in the speed value and its good follow-up to its variable reference with time, noting that it forms an error with a peaking fault occurs when switching between two states, and this is in both types of PWM direct and indirect control. The flow of the stator depicted in (Figure 11, a_2) has a polygon pattern that is more reminiscent of a circular pattern and exhibits a tenuous modulus fluctuation.

Although the decoupling maintains and grows with speed variation time, we find (a_1 higher than a_2) in (Figure 12). Lastly, (Figure 13) depicts the current $i_{s\alpha}$ and his amplitude for both commands as an FFT spectrum which we find the spectrum in (a_1) is more complicated than in (b_1).

Conclusion

Through this article, we have discussed two different methods of direct and indirect PWM control of DSAM by the utilization of the simulation's outcomes obtained when applying two previous commands to the system operating at different speeds and employing control signals of the inverter, which show the effectiveness of these two commands with this machine.

It should mention that the simulation outcomes of the use of indirect PWM command are superior and more effective than those achieved by using the direct PWM command. Moreover, it has many advantages, including its price cut (due to fewer PI regulators), and the indirect PWM control ensures good durability and excellent dependability reducing susceptibility to perturbations even with the existence of state harmonics.

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DSAM parameters

- Amount of bars in a rotor cage n_b: 22
- Axial length of the rotor L : 75 mm
- Diameter of the rotor r : 79 mm
- Harmonic range in space h
- Inductance of rotor l_r: 0.5534 H
- Inductance of magnetizing l_m: 0.4092 H
- Inductance of Stator Ls1 = Ls2 : 0.5595 H
- Normative current I : 2.7 A
- Normative voltage : 220 v
- Normative speed : 1400 rpm
- Normative frequency f : 50 Hz
- Number of pole pairs P : 2
- Number of series of turns in a phase N_t : 240
- Position of rotor θ
- Resistance of rotor R_r: 4.59 Ω
- Stator resistance R_{s1}= R_{s2}: 3.91 Ω
- Size of the gap g_0: 0.5 mm

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