Application of Second Order Sliding Mode Control on the DOEWIM Powered by four Direct Matrix Converters Modulated by Space Vector Modulation

M. SELLAH[1], A. KOUZOU[1], A. L. DOURARI[2]

[1]LAADI Laboratory, University Ziane Achour of Djelfa, 17000, Algeria

[2]ICEPS Laboratory, University Djilali Liabes of Sidi Bel Abbes, Algeria

E-mail : mourad.sellah@yahoo.fr

Abstract - The work presented in this paper revealed the synthesis of constant switching frequency super twisting sliding mode control based on SVM technique, for the regulation of stator current, rotor flux and rotation speed of dual open-end winding induction motor (DOEWIM) powered by four three-phase direct matrix converters. The main objective of applying this nonlinear control technique with an open stator winding machine is to overcome the main disadvantages encountered in the application of conventional vector control to a classic motor, such as obtaining more robust performance towards external and internal disturbances, reduction of torque and flux ripples, minimization of stator current harmonics, and elimination of common mode voltage (CMV). The results obtained demonstrated the realization of the main advantages mentioned above, which confirms the validity of the proposed control on the topology of the induction motor studied.

Keywords - Super twisting sliding mode control, space vector modulation, dual open-end winding induction motor, direct matrix converter, common mode voltage.

I. INTRODUCTION

This Recently, the multi-phase machines have attracted the attention of many researchers, manufacturers and industrial due to their main features in overcoming many problems faced with the conventional three-phase machines. Indeed, the multi-phase machines offer an interesting alternative to reducing constraints on switches and windings where the multiplication of the number of phases allows splitting the power and currents among more number of phases. In addition, these machines can reduce the amplitude and the ripples of the developed torque, moreover, grants increased reliability by enabling operations in the event of one phase fault or two no-consecutive faulty phases [1, 2]. This feature allows them to have many properties such as low maintenance, robustness, scalability. Consequently, they gain more characteristics of flexibility and comfort, which pave the path for them to become widely used in high power applications, such as railway traction, naval propulsion, compressors and cement mills [2, 3]. One of the most common examples of multiphase machines is the DSIM, which is considered a six-phase machine. The use of this machine, which is practically only a three-phase machine. That comprises two three-phase stator winding with a certain offset between them at the level of the stator. This configuration will allow us to benefit from the advantages of the classic induction machine extensively used in most industrial applications [4]. At the same time, the DSIM offers, in addition to the advantages of induction machines, advantages of multiphase machines, which have been aforementioned. In order to improve the service quality of the DSIM and ensure its control in different industrial applications with higher reliability, the DSIM has been used with the new topology that requires the opening of both stator windings; thus, the machine is no longer a DSIM but it is a dual open-end winding induction machine (DOEWIM) [5]. Under this new configuration, it is necessary to control the machine with four three-phase voltage systems, with phase shifts well-calculated between them so that we can eliminate the common-mode voltage and rid of its several issues, such as the bearing currents and shaft voltages, which leads to rapid failures of machine bearings and shafts [6-7].

Thanks to the development and progress of semiconductor technology and micro computing, the accreditation of power electronics converters is increasingly important in various industrial applications, in particular, for variable speed drives using asynchronous machines, for which the choice of converters and their control offers an interesting alternative to the reduction of the constraints linked to the dimensioning and generation of current and torque harmonics. Indeed, for several years, these machines were supplied with power from a rectifier-filter-inverter chain, which increased the total weight and size of the converter and can be a disturbance source for the electrical network [8]. It is with the aim of alleviating these problems that the conventional converters can be replaced by other converter topologies, such as the matrix structure which offers many advantages including the direct alternative–alternative conversion without intermediate circuit, the elimination of the passive elements of the energy storage which form the intermediate circuit (generally capacitors), the possibility of considerably reducing the converter volume, the fast dynamics, the possibility of functional reversibility in the four quadrants, the input power factor can be adjusted independently of the load, high-quality input and output currents, and long-life duration [9].

The use of advanced modulation techniques makes it possible to synthesize the reference output voltages from the input voltages and the reference input currents from the output currents. Indeed, since the introduction of MC in electric motor driving, different modulation strategies have been proposed; initially, the scalar modulations were adopted but they demonstrated several defects, notably those associated with a lack of output voltage waveform quality and limited transformation ration. It was therefore necessary to use other advanced control techniques, such as the space vector modulation (SVM), in order to eliminate the aforementioned problems caused by the conventional scalar-based control technique [10-11].

Sliding mode control techniques have attracted the attention of different research groups, thanks to the attractive characteristics they possess, such as: finite-time convergence, robustness to modeling uncertainties and external disturbances. However, one of the disadvantages of these techniques is the undesirable phenomenon called chattering, which occurs due to the high switching frequency in the control, damaging the actuating devices subjected to intense operating stresses. For this, higher order sliding modes have been developed. These generalize the basic idea of the sliding mode, acting on the higher order time derivatives of the system deviation from the constraints imposed by the influence of the deviation of the first derivative as occurs in standard sliding modes. Preserving the main advantages of the original approach, while completely eliminating the chattering effect and also providing greater precision in performance. Some higher order controls have been described in the literature, such as the super-twisting algorithm, which is considered among the most important of these controls due to its many advantages [12].

Overall, this article is divided into seven sections, an introduction, five main sections, and a conclusion. The first main section presents the description of DOEWIM, which is characterized by the opening of the two ends of the two stator windings. The second section focuses on the presentation of the direct matrix converter MC, which is adapted to power the DOEWIM. In addition, the SVM strategy used to ensure the used MC is presented and discussed in the third section. the control technique based on the super twisting algorithm is presented and its main features are discussed in the fourth section. The fifth section includes an interpretation of the simulation results obtained. This paper is concluded by a conclusion presenting our perspectives and proposals, which can lead to a continuation of the present work.

II. DESCRIPTION AND MODELING OF DOEWIM

The DOEWIM is a DSIM with open stator windings and therefore consists of twelve stator terminals, six for each stator winding, forming the two identical stars which share the same stator and are shifted by an electric angle of (p/6). Hence, four groups of three terminals are obtained, which require four three-phase converters to ensure powering and controlling the studied machine.

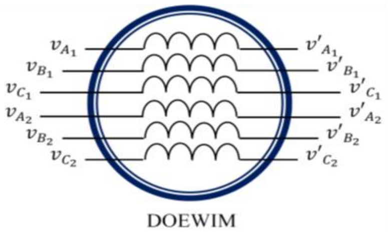

Fig. 1. Voltage supply dual open-end winding induction motor.

Consider v_{a1}, v_{b1}, v_{c1}, v'_{a1}, v'_{b1} and v'_{c1} are respectively the pole voltages at the six outputs of the first two converters that are feeding the first ends of the two-stator winding, and v_{a2}, v_{b2}, v_{c2}, v'_{a2}, v'_{b2} and v'_{c2} are respectively the pole voltages at the six outputs of the second two converters that are feeding the second ends of the two previous stator winding, as shown in the "Fig. 1".

The voltage across each phase winding among the six phases of the studied motor can be obtained based on the difference between the corresponding terminal voltages applied to its ends, as follows:

$$\text{First stator: } \begin{cases} V_{A_1} = v_{A_1} - v'_{A_1} \\ V_{B_1} = v_{B_1} - v'_{B_1} \\ V_{C_1} = v_{C_1} - v'_{C_1} \end{cases} \tag{1}$$

$$\text{Second stator: } \begin{cases} V_{A_2} = v_{A_2} - v'_{A_2} \\ V_{B_1} = v_{B_2} - v'_{B_2} \\ V_{C_1} = v_{C_2} - v'_{C_2} \end{cases} \tag{2}$$

Based on these assumptions, the DOEWIM model in the (d, q) frame can be presented as follows:

The stator and rotor voltages equations

$$\begin{cases} V_{ds_1} = R_{s_1} i_{ds_1} + \dot{\varphi}_{ds_1} - \omega_s \varphi_{qs_1} \\ V_{qs_1} = R_{s_1} i_{qs_1} + \dot{\varphi}_{qs_1} + \omega_s \varphi_{ds_1} \\ V_{ds_2} = R_{s_2} i_{ds_2} + \dot{\varphi}_{ds_2} - \omega_s \varphi_{qs_2} \\ V_{qs_2} = R_{s_2} i_{qs_2} + \dot{\varphi}_{qs_2} + \omega_s \varphi_{ds_2} \\ V_{dr} = R_r i_{dr} + \dot{\varphi}_{dr} - (\omega_s - \omega_r)\varphi_{qr} = 0 \\ V_{qr} = R_r i_{qr} + \dot{\varphi}_{qr} + (\omega_s - \omega_r)\varphi_{dr} = 0 \end{cases} \tag{3}$$

With:

$$\begin{cases} V_{ds_1} = v_{ds_1} - v'_{ds_1} \\ V_{qs_1} = v_{qs_1} - v'_{qs_1} \\ V_{ds_2} = v_{ds_2} - v'_{ds_2} \\ V_{qs_2} = v_{qs_2} - v'_{qs_2} \end{cases}$$

The stator and rotor flux equations

$$\begin{cases} \varphi_{ds_1} = L_{s_1} i_{ds_1} + L_m\left(i_{ds_1} + i_{ds_2} + i_{dr}\right) \\ \varphi_{qs_1} = L_{s_1} i_{qs_1} + L_m\left(i_{qs_1} + i_{qs_2} + i_{qr}\right) \\ \varphi_{ds_2} = L_{s_1} i_{ds_2} + L_m\left(i_{ds_1} + i_{ds_2} + i_{dr}\right) \\ \varphi_{qs_2} = L_{s_2} i_{qs_2} + L_m\left(i_{qs_1} + i_{qs_2} + i_{qr}\right) \\ \varphi_{dr} = L_r i_{dr} + L_m\left(i_{ds_1} + i_{ds_2} + i_{dr}\right) \\ \varphi_{qr} = L_r i_{qr} + L_m\left(i_{qs_1} + i_{qs_2} + i_{qr}\right) \end{cases} \tag{4}$$

The mechanical equation is :

$$\frac{J}{P}\frac{d\omega_r}{dt} = T_{em} - T_L - \frac{K_f}{P}\omega_r \tag{5}$$

III. DIRECT MATRIX CONVERTER

This device is designed to perform AC/AC conversion via a direct conversion matrix, and has an intermediate arrangement of nine four-segment switches with forced switching as shown in "Fig. 2", thus allowing the connection of each input phase to each output phase, the switching of the power poles is considered forced and takes place at high frequencies.

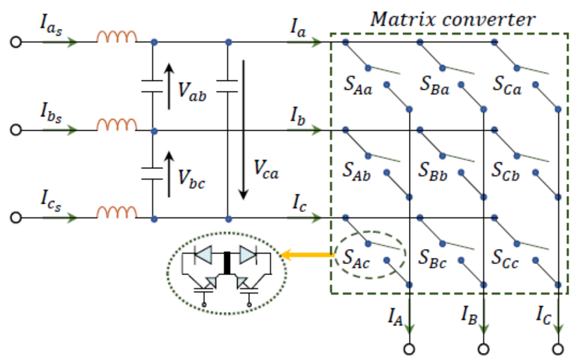

Fig. 2. Schematic diagram of 3-phase to 3-phase direct matrix converter.

The bidirectional switch's capabilities to conduct current in both directions and block voltage from both polarities allows a direct matrix converter to generate variable output voltages with unlimited frequency from AC supply voltages [13].

IV. SVM FOR DIRECT MATRIX CONVERTER

Direct vector modulation treats the MC for what it is: (a matrix converter). There are two relevant issues to address in direct SVM modulation. The first lies in determining the vector sequences to be applied during a modulator switching period. The second concerns the calculation of the times during which these vectors must be applied. The way to solve these problems is not as intuitive and requires a lot of mathematical complexity.

Although this technique is difficult to adopt as a modulator for the matrix converter, it offers many advantages, the most important of which is providing a waveform of the output voltage and input current of high quality.

The reference output voltage vector Vs and the reference input current vector Ie are the two vectors used for SVM, they are respectively defined as follows:

$$\overline{V}_s = \frac{2}{3}\left(V_{AB} + V_{BC}e^{\frac{2\pi}{3}j} + V_{CA}e^{-\frac{2\pi}{3}j}\right) \qquad (6)$$

$$\overline{I}_e = \frac{2}{3}\left(I_a + I_b e^{\frac{2\pi}{3}j} + I_c e^{-\frac{2\pi}{3}j}\right) \qquad (7)$$

Figure 3 shows in vector space a distribution of the vectors involved in the SVM strategy, in which the complex plane is divided into six sectors of output voltage and input current delimited by the active vectors and determined from the angle of the MC setpoints V_s and I_e.

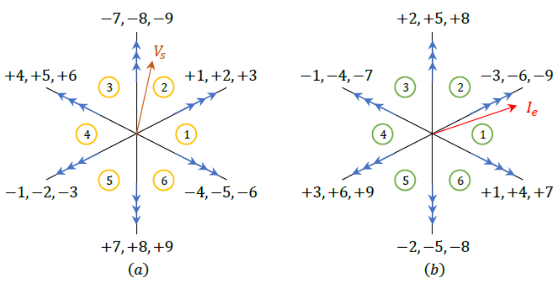

Fig. 3. SVM vectors, (a) output voltage vectors, (b) input current vectors.

V. SECOND ORDER SLIDING MODE CONTROL

The second-order sliding mode control technique generalized the basic idea of sliding mode by incorporating second-order derivatives of the sliding variable. The inclusion of second order derivatives, while maintaining the same robustness and performance as that of the conventional sliding mode, led to a reduction of the unwanted chattering effect inherent to the sliding mode technique [16].

To design the second-order sliding mode, a number of algorithms are available in the literature, the most common of which are: Twisting Algorithm (TA), Sub-Optimal Algorithm (SOA), Drift Algorithm (DA) and Super-Twisting Algorithm (STA), [MUH 12]. The STA algorithm is generally considered one of the best algorithms for achieving desired results.

The super-twisting algorithm had the advantage over other algorithms in that it did not require the time derivatives of the sliding variable. The control law used in this algorithm was composed of two terms. The first term ua was defined in terms of a discontinuous time derivative while the second term ub was a continuous function of a sliding variable [17].

$$u_{st} = u_a + u_b \qquad (8)$$

The first derivative of ua and the expression of ub are respectively as follows:

$$\begin{cases} \dot{u}_a = -\sigma_{st} sign(S) \\ u_b = -\beta_{st}|S|^{\alpha_{st}} sign(S) \end{cases} \qquad (9)$$

Where: $\sigma_{st}, \beta_{st}, \alpha_{st}$: positive constants, with $0 < \alpha_{st} < \frac{1}{2}$.

The model used to derive the system of state equations adopted in the synthesis of second-order control laws is the same as that applied in first-order sliding mode control which was obtained after decoupling by vector control, where all the electrical quantities are expressed in the frame of reference linked to the rotating field (d,q), and the state variables are the stator currents, the rotor flux and the mechanical speed.

The control law for a real second-order sliding mode is given by the following expression [18]:

$$u = u_{eq} + u_{st} \tag{10}$$

The STSMC is used to ensure the control of the rotor speed, the magnetic flux and the components of the stator currents. The application of the required order to the DOEWIM is based on the laws of sliding mode, with which the following formulas can be written.

$$\begin{cases} i_{qs} = i_{qs}^* = i_{qseq} + i_{qsst} \\ i_{ds} = i_{ds}^* = i_{dseq} + i_{dsst} \\ V_{ds_1} = V_{ds_1}^* = V_{ds_1eq} + V_{ds_1st} \\ V_{qs_1} = V_{qs_1}^* = V_{qs_1eq} + V_{qs_1st} \\ V_{ds_2} = V_{ds_2}^* = V_{ds_2eq} + V_{ds_2st} \\ V_{qs_2} = V_{qs_2}^* = V_{qs_2eq} + V_{qs_2st} \end{cases} \tag{11}$$

The equivalent commands for second-order sliding mode are the same as those defined in the case of the conventional sliding mode, and are given as follows:

$$\begin{cases} i_{qseq} = \frac{J}{P^2}\frac{L_m+L_r}{L_m\varphi_r^*}\left(\dot{\omega}_r^* + \frac{K_f}{J}\omega_r + \frac{P}{J}C_r\right) \\ i_{dseq} = \frac{L_m+L_r}{R_rL_m}\left(\dot{\varphi}_r^* + \frac{R_r}{L_m+L_r}\varphi_r\right) \\ V_{ds_1eq} = L_{s_1}i_{ds_1}^* + R_{s_1}i_{ds_1} - \omega_s^*\left(L_{s_1}i_{qs_1} + \tau_r\varphi_r^*\omega_{gl}^*\right) \\ V_{qs_1eq} = L_{s_1}i_{qs_1}^* + R_{s_1}i_{qs_1} + \omega_s^*\left(L_{s_1}i_{ds_1} + \varphi_r^*\right) \\ V_{ds_2eq} = L_{s_2}i_{ds_1}^* + R_{s_2}i_{ds_2} - \omega_s^*\left(L_{s_2}i_{qs_2} + \tau_r\varphi_r^*\omega_{gl}^*\right) \\ V_{qs_2eq} = L_{s_2}i_{qs_2}^* + R_{s_2}i_{qs_2} + \omega_s^*\left(L_{s_2}i_{ds_2} + \varphi_r^*\right) \end{cases}$$
(12)

Based on "(8)" and the system of "(9)", the discontinuous commands related to the control of speed, flux and current components can be written respectively according to the system below:

$$\begin{cases} i_{qsst} = -\beta_{\omega_r}|S(\omega_r)|^{\alpha_{st}}sign(S(\omega_r)) - \int\sigma_{\omega_r}sign(S(\omega_r)) \\ i_{dsst} = -\beta_{\varphi_r}|S(\varphi_r)|^{\alpha_{st}}sign(S(\varphi_r)) - \int\sigma_{\varphi_r}sign(S(\varphi_r)) \\ V_{ds_1st} = -\beta_{i_{ds_1}}|S(i_{ds_1})|^{\alpha_{st}}sign\left(S(i_{ds_1})\right) - \int\sigma_{i_{ds_1}}sign\left(S(i_{ds_1})\right) \\ V_{qs_1st} = -\beta_{i_{qs_1}}|S(i_{qs_1})|^{\alpha_{st}}sign\left(S(i_{qs_1})\right) - \int\sigma_{i_{qs_1}}sign\left(S(i_{qs_1})\right) \\ V_{ds_2st} = -\beta_{i_{ds_2}}|S(i_{ds_2})|^{\alpha_{st}}sign\left(S(i_{ds_2})\right) - \int\sigma_{i_{ds_2}}sign\left(S(i_{ds_2})\right) \\ V_{qs_2st} = -\beta_{i_{qs_2}}|S(i_{qs_2})|^{\alpha_{st}}sign\left(S(i_{qs_2})\right) - \int\sigma_{i_{qs_2}}sign\left(S(i_{qs_2})\right) \end{cases}$$
(13)

Figure 4 gives the general diagram of the control structure by super twisting sliding mode of a DOEWIM supplied by four three-phase direct matrix converters and controlled in speed, rotor flux and stator currents in a non-linear control plane.

This control technique is combined with the SVM for the purpose of achieving high performance.

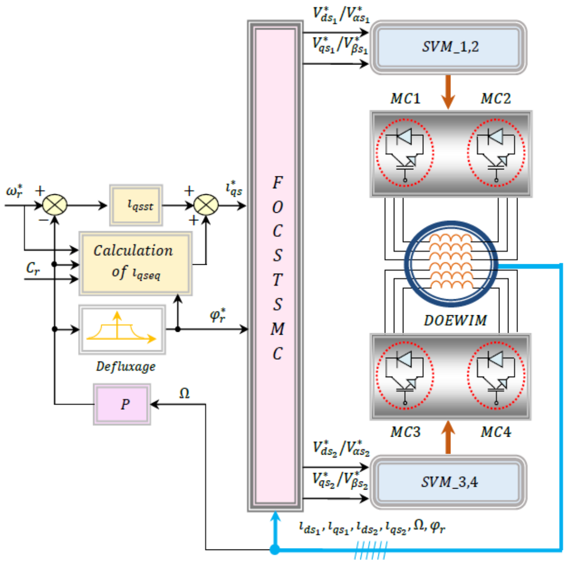

Fig. 4. Super twisting sliding mode control scheme applied on DOEWIM.

VI. Simulation Results and Discussions

In this section, the application of the super twisting sliding mode control for the command of the DOEWIM were carried out under simulation tests.

The main objective is to present a detailed the performances of this control technique based on the analysis of the dynamic behavior of the chosen electrical, electromagnetic, and mechanical control variables, such as the stator current, electromagnetic torque, stator flux, and rotor speed. In addition, the tests were carried out for a reference speed that is equal to 50% (157 rad/s) of the motor rated speed, taking into account the steps of starting-up under no load, load torque application, and speed reverse.

Indeed, these simulations include a sequence of steps that can imitate the practical cases in industrial applications. The machine starts up at t = 0 s with no load following an imposed reference speed profile, at t = 0.8 s a load torque of T_L= 7 N.m is applied which is considered as an external perturbation, at t = 1.2 s the applied load torque is increased to T_L = 14 N.m, then at t = 1.6 s the applied load torque is removed which means that T_L = 0 N.m. the second part of these simulations present the dynamic behavior of the proposed control technique against the speed revers, where at t = 2 s the reference speed is reverse without the application of any load torque.

The output voltage shape is shown in "Fig. 5 (a)", their levels are constructed according to the number of levels of the adopted matrix converter, which is two levels for each switching period. Considering the harmonic spectrum of the output voltage given according to "Fig. 5 (b)", which indicates a value of 86.52%, it is clear that the use of the direct matrix converter gave very satisfactory results in terms of harmonics rate in the output voltage.

Figure 6 shows the rotor speed and its reference for the second order sliding mode control applied to the DOEWIM. Note that the two passages from 0 rad/s to 157 rad/s then from 157 rad/s to -157 rad/s are carried out by the rotor speed in a linear manner without any overshoot, completely identical to the practical case. In the steady state, the rotor speed perfectly follows the reference speed without showing a real influence for different load applications, moreover the error representing the difference between the two speeds is very low. Overall, the rotor speed response is very satisfactory at all stages of operation, indicating the robustness and accuracy of the proposed control approach.

Figre 7 gives the electromagnetic torque developed by the machine studied. The electromagnetic torque exhibits high dynamics characterized by minimal fluctuations, as confirmed by the zoom windows listed in Fig. 7. The width of the torque fluctuation band appears very small, which confirms the existence of the SVM technique on the one hand and highlights the precision of the proposed control by eliminating chattering on the other hand. The torque response to the application of loads and to the reversal of direction of rotation is carried out with great precision and without any overshoot thanks to the great robustness of the super twisting sliding mode control.

The stator phase currents of the first DOEWIM star are shown in "Fig. 8 (a)". At start-up, the currents are unequal due to the induction of the circuit, then in the equilibrium state the amplitude of these currents is constant, then, when the load is introduced or the direction of rotation is reversed, the amplitudes currents increase, which suggests a strong performance of the second order sliding mode control. A balanced sinusoidal waveform is obtained with reduced harmonic content due to the application of the SVM technique, as can be clearly seen from the zoom areas shown in "Fig. 9". "Fig. 8 (b)" gives the THD value of the stator currents according to the super twisting command. We can say that this value is excellent, which reflects positively on the overall performance of the machine.

The components of the direct and quadratic rotor flux for the DOEWIM powered by direct matrix converters are represented by "Fig. 10 (a)". We note that the two components φ_{dr} and φ_{qr} pass a very short-term transient regime then reach perfect stability successively at the values 1 Wb and 0 Wb in steady state, which proves that the complete decoupling between the torque and the flux is maintained by the super twisting command. Through "Fig. 10 (b)", which gives the response of the rotor flux, it is clear that the flux very quickly reaches its reference value of 1 Wb without any overshoot and without any influence by the introduction of load torque or l reversal of direction of rotation. This response confirms the great robustness of the proposed control approach. The zooms listed in "Fig. 10 (b)" show that the harmonic content is considerably small.

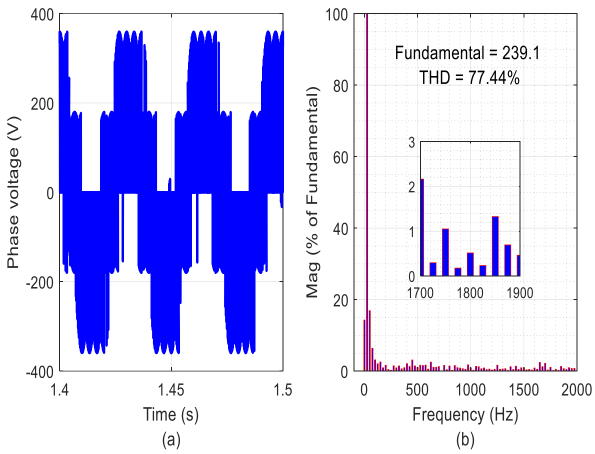

Fig. 5. Voltage, (a) phase voltage,
(b) harmonics spectrum of the voltage.

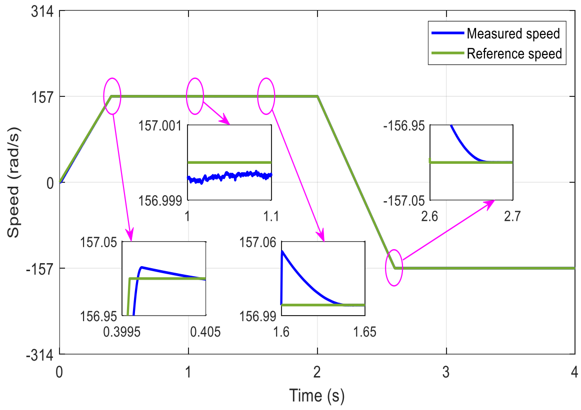

Fig. 6. Rotor speed of the DOEWIM.

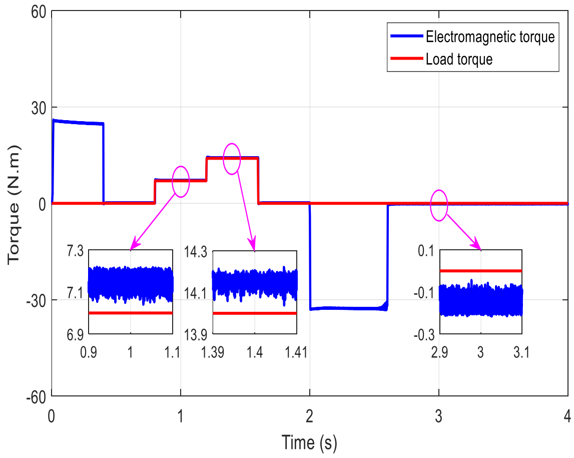

Fig. 7. Electromagnetic torque developed by the DOEWIM.

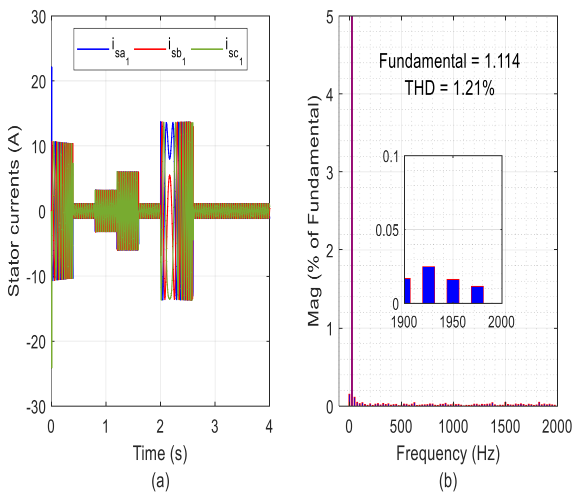

Fig. 8. Current, (a) phase current, (b) harmonics spectrum of the current.

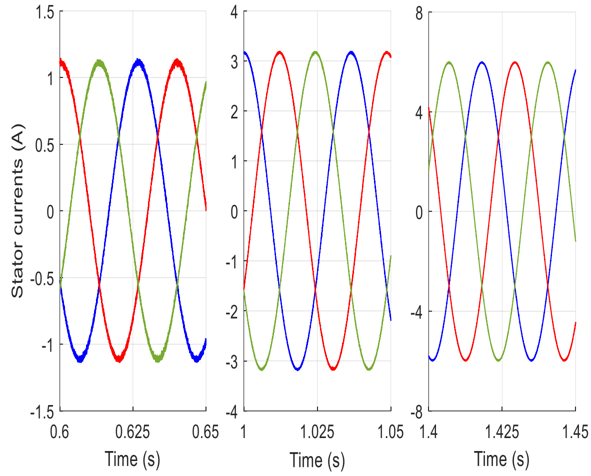

Fig. 9. Current, (a) phase current, (b) harmonics spectrum of the current.

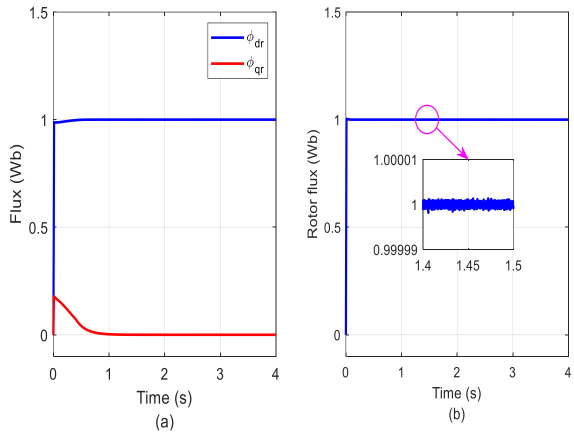

Fig. 10. Flux, (a) components of the rotor flux, (b) rotor flux.

VII. Conclusion

At the end of this work, we can affirm that the proposed control technique presented a very competitive and promising solution for the control of multiphase machines, particularly with open stator winding topologies. In fact, the application of the control technique studied in this paper to DOEWIM can be considered an original work that has not been addressed before. The results obtained with this nonlinear control technique developed in this work demonstrated the improvement in control performance and the exceptional efficiency of the proposed control system following different severe operating scenarios. Thus, this control technique can be used effectively to overcome the main problems encountered in the control of multi-phase machines, especially in high-power industrial applications, where maintenance is difficult and fault tolerance is necessary to avoid interruption. the operating mode of the machine.

VIII. REFERENCES

[1] Kali, Y.; Saad, M.; Doval-Gandoy, J.; Rodas, J. Discrete Terminal Super-Twisting Current Control of a Six-Phase Induction Motor. Energies 2021, 14, 1339.

[2] Kali, Y.; Ayala, M.; Rodas, J.; Saad, M.; Doval-Gandoy, J.; Gregor, R.; Benjelloun, K. Current Control of a Six-Phase Induction Machine Drive Based on Discrete-Time Sliding Mode with Time Delay Estimation. Energies 2019, 12, 170.

[3] Marouani, K.; Baghli, L.; Hadiouche, D.; Kheloui, A.; Rezzoug, A. A New PWM Strategy Based on a 24-Sector Vector Space Decomposition for a Six-Phase VSI-Fed Dual Stator Induction Motor. IEEE Trans. Ind. Electron. 2008, 55, 1910–1920.

[4] Rahali, H.; Zeghlache, S.; Benyettou, L.; Benalia, L. Backstepping Sliding Mode Controller Improved with Interval Type-2 Fuzzy Logic Applied to the Dual Star Induction Motor. Int. J. Comput. Intell. Appl. 2019, 18, 1950012.

[5] Nirsha, K.I.; Rajeevan, P.P. A direct torque control scheme for dual inverter fed induction motor drive with a common DC voltage source. In Proceedings of the IECON 2017—43rd Annual Conference of the IEEE Industrial Electronics Society, Beijing, China, 29 October–1 November 2017.

[6] Ranjit, M.; Gowtami, S.; Babu, B.G. Reduction of zero sequence voltage using multilevel inverter fed open-end winding induction motor drive. Acta Electrotech. Inform. 2016, 16, 52–60.

[7] Foti, S.; Testa, A.; De Caro, S.; Scimone, T.; Scelba, G.; Scarcella, G. Multi-level open end windings multi-motor drives. Energies 2019, 12, 861.

[8] Ansari, S.; Chandel, A. Simulation based comprehensive analysis of direct and indirect matrix converter fed asynchronous motor drive. In Proceedings of the 2017 4th IEEE Uttar Pradesh Section International Conference on Electrical, Computer and Electronics (UPCON), Mathura, India, 26–28 October 2017.

[9] Benachour, A.; Berkouk, E.M.; Mahmoudi, M.O. Study and comparison between two DTC strategies of induction machine fed by direct matrix converter. J. Renew. Sustain. Energy 2017, 9, 55501.

[10] Van Huynh, V.; Nguyen, T.D.; Dao, V.-T.; Tran, Q.-H. An Efficient Carrier-Based Modulation Strategy for Five-Leg Indirect Matrix Converters to Drive Open-End Loads with Zero Common-Mode Voltage. Electr. Power Compon. Syst. 2019, 47, 1303–1315.

[11] Lavanya, N.; Rao, M.V.G. Control of indirect matrix converter by using improved SVM method. Int. J. Power Electron. Drive Syst. 2015, 6, 370–375.

[12] A. Levant, "Higher-order sliding modes, differentiation and output-feedback control", International Journal of Control, vol. 76, no. 09-10, pp. 924-941, 2003.

[13] Laszlo Gyugyi, ''Static Power Frequency Changers: Theory, Performance and Applications'', Book, New York: Wiley, c76, 1976.

[14] Marco Matteini, "Control Techniques for Matrix Converter Adjustable Speed Drives", PhD thesis, Department of Electrical Engineering, University of Bologna, 2001.

[15] François Gruson, "Modulation Naturelle Généralisée des Convertisseurs Matriciels pour la Variation de Vitesse", Thèse de doctorat, Ecole centrale de Lille, 2010.

[16] [Arie Levant, "Higher Order Sliding Modes and Their Application for Controlling Uncertain Processes", PhD theses, Institute for System Studies of the USSR Academy of Science, Moscow, 1987.

[17] Mohammad Khalid-Khan, "Design and Application of Second Order Sliding Mode Control Algorithms", PhD thesis, Department of Engineering, University of Leicester, 2003.

[18] Chaabane Hadji, "Contribution à la Commande Robuste de la Machine Asynchrone à Double Etoile", Thèse de Doctorat en sciences, Département de Génie Electrique, Faculté de Technologie, Université de M'sila, Algérie, 2020.