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Association smooth-pole dual open-end windings permanent magnet synchronous machine with cascaded 2-level inverters for improved performances

Introduction. *Power segmentation is an increasingly important priority in high-power industrial drive applications that utilize AC machines.* ***Problem****. To improve the dynamic performance, reliability and power segmentation of drive systems in high-power applications (above the megawatt range), it's advantageous to replace a single high-power converter with several low-power converters. This principle is applied to the combination of AC machines and inverter structures.* ***Goal.*** *The authors propose a novel dual open-end windings permanent magnet synchronous machine. This machine reduces the required size of the power supply inverters while also improving dynamic performances and lifespan. Its power supply using 2-levels cascading inverters, further enhances these performances.* ***Methodology.*** *For this study, the mathematical model of the system in the Park reference frame is introduced and validated using the MATLAB/Simulink environment. First, simulation results are presented for the proposed machine supplied by four conventional two-level inverters based on the pulse width modulation technique. Next, the new machine is fed by four multilevel converters, with each converter consisting of two two-level inverters. To further demonstrate the benefits of this converter structure, the authors then use a configuration with three cascaded two-level inverters. The* ***results*** *demonstrate that the use of the new machine with conventional two-level inverters ensures power segmentation and improves the quality of the voltage, stator current, and torque. Furthermore, associating this same machine with cascaded multilevel inverter structures significantly enhances dynamic performance and reliability. The* ***scientific novelty*** *lies in the synergy achieved by integrating the novel synchronous machine with the cascaded two-level inverters, enabling the system to simultaneously surpass conventional limitations in both performance and reliability.* ***Practical value.*** *A simulation model of the novel dual open-end winding permanent magnet synchronous machine was implemented to validate the superior performance achieved with cascaded multilevel inverter structures for voltage supply compared to conventional two-level inverters.* References 19, table 2, figures 17.

Key words: **smooth-pole dual open end permanent magnet synchronous machine, cascaded 2-levels inverters, power segmentation, reliability.**

Вступ*. Сегментація потужності стає все більш важливим завданням у потужних промислових приводних системах, що використовують машини змінного струму.* ***Проблема****. Для покращення динамічних характеристик, надійності та сегментації потужності приводних систем у потужних установках (вище мегаватного діапазону) доцільно замінити один потужний перетворювач кількома малопотужними перетворювачами. Цей принцип застосовується для комбінації машин змінного струму та інверторних структур.* ***Мета****. Автори пропонують нову синхронну машину з двома відкритими обмотками та постійними магнітами. Ця машина зменшує необхідні розміри інверторів живлення, одночасно покращуючи динамічні характеристики та термін служби. Її живлення із використанням дворівневих каскадних інверторів додатково підвищує ці характеристики.* ***Методика****. Для цього дослідження розроблена математична модель системи у системі координат Парка, яка перевірена у MATLAB/Simulink. Спочатку представлені результати моделювання для пропонованої машини, що живиться чотирма звичайними дворівневими інверторами на основі методу широтно-імпульсної модуляції. Потім нова машина заживлювалась від чотирьох багаторівневих перетворювачів, кожен із яких складається з двох дворівневих інверторів. Для подальшої демонстрації переваг даної структури перетворювача автори використовують конфігурацію з трьома каскадно з'єднаними дворівневими інверторами.* ***Результати*** *показують, що використання нової машини із звичайними дворівневими інверторами забезпечує сегментацію потужності та покращує якість напруги, струму статора та крутного моменту. Крім того, поєднання цієї машини з каскадно з'єднаними багаторівневими інверторними структурами значно підвищує динамічні характеристики і надійність.* ***Наукова новизна*** *полягає в синергії, яка досягається за рахунок інтеграції нової синхронної машини з каскадно з'єднаними дворівневими інверторами, що дозволяє системі одночасно долати традиційні обмеження як за продуктивністю, так і за надійністю.* ***Практична значимість****. Реалізована імітаційна модель нової синхронної машини з двома відкритими обмотками та постійними магнітами для підтвердження високих характеристик, що досягаються за допомогою каскадно з'єднаних багаторівневих інверторних структур для живлення напруги порівняно із звичайними дворівневими інверторами.* Бібл. 19, табл. 2, рис. 17.

Ключові слова: **гладкополюсна синхронна машина з постійними магнітами та двостороннім відкритим виводом, каскадні дворівневі інвертори, сегментація потужності, надійність.**

Introduction. The machine-converter associations are widely used in application industrial drives [1–3]. But this association machine with conventional converter is not without disadvantage especially in high power. To ensure the power segmentation, the improvement the reliability and consequently the availability of this association inverter-machine, several researches have also been developed. The research at the level of inverter structures includes cascaded H-bridge multilevel inverters, diode clamped multilevel inverters, flying-capacitor multilevel inverters, cascaded two-level inverters and other structures [4–8] and in synchronous or asynchronous machines structures, in particular the permanent magnet synchronous machine (PMSM) includes multiphase machines [9, 10], the multi-star machines [11, 12], the open-end stator winding machine [13, 14] and the multiphase open-end stator windings machine [15]. Recently, some researchers have developed the new machine structure; it is the dual three-phase open-end stator windings AC machines supplied by four voltage source inverters [16–18]. Furthermore, this machine offers good solution for the power segmentation and best dynamic performance compared with classic machine, double star machine and open-end stator winding machine. Also, this machine increases the liberty degrees of system drive in degraded mode.

The **goal** of this work is to present a novel dual open-end windings permanent magnet synchronous machine (DOEWPMSM). This machine is designed to improve dynamic performance and lifetime, while reducing the size of the required power inverters. The use of cascaded two-level inverters improves these performances. In the first part, the mathematical modeling of novel machine is presented in the Park reference frame and implemented in MATLAB/Simulink environment. In the second part, the proposed machine is fed by four voltage source inverters using a pulse width modulation (PWM) technique. The results obtained for the total harmonic distortion (THD) of the phase-to-phase voltage, the THD of the stator current, and the torque ripple are shown. To improve the performance of the new machine, a combination of cascaded inverter structures is used. In the first configuration, two cascaded 2-level inverters are used, while the second configuration consists of three cascaded 2-level inverters [19]. The simulation results obtained from the cascaded configurations show significant advantages in terms of voltage, current and torque quality.

Modeling of the smooth-pole DOEWPMSM. The windings of this machine shifted by 0° in the (*d*, *q*) Park reference ($\omega_{(d,\,q)} = \omega_r$) are represented in Fig. 1.

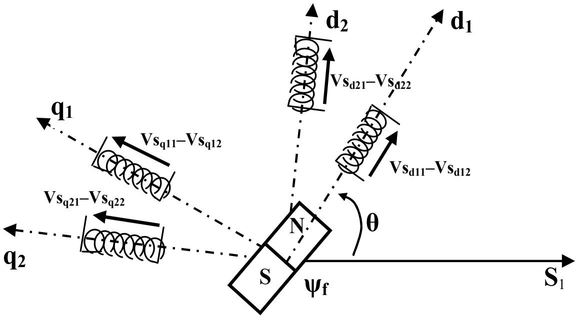

Fig. 1. Windings representation in the (*d*, *q*) reference frame

The relation that links the flux and the currents is:

$$\begin{bmatrix}\psi_{\mathrm{sd1}}\\ \psi_{\mathrm{sd2}}\\ \psi_{\mathrm{sq1}}\\ \psi_{\mathrm{sq2}}\end{bmatrix}=\begin{bmatrix}L_{\mathrm{d}} & M_{\mathrm{d}} & 0 & 0\\ M_{\mathrm{d}} & L_{\mathrm{d}} & 0 & 0\\ 0 & 0 & L_{\mathrm{q}} & M_{\mathrm{q}}\\ 0 & 0 & M_{\mathrm{q}} & L_{\mathrm{q}}\end{bmatrix}\begin{bmatrix}i_{\mathrm{sd1}}\\ i_{\mathrm{sd2}}\\ i_{\mathrm{sq1}}\\ i_{\mathrm{sq2}}\end{bmatrix}+\begin{bmatrix}\psi_{\mathrm{f}}\\ \psi_{\mathrm{f}}\\ 0\\ 0\end{bmatrix}. \quad (1)$$

The voltage is related by the following matrix:

$$\begin{bmatrix}V_{\mathrm{sd11}}-V_{\mathrm{sd12}}\\ V_{\mathrm{sd21}}-V_{\mathrm{sd22}}\\ V_{\mathrm{sq11}}-V_{\mathrm{sq12}}\\ V_{\mathrm{sq21}}-V_{\mathrm{sq22}}\end{bmatrix}=\begin{bmatrix}R_{\mathrm{s}} & 0 & 0 & 0\\ 0 & R_{\mathrm{s}} & 0 & 0\\ 0 & 0 & R_{\mathrm{s}} & 0\\ 0 & 0 & 0 & R_{\mathrm{s}}\end{bmatrix}\begin{bmatrix}i_{\mathrm{sd1}}\\ i_{\mathrm{sd2}}\\ i_{\mathrm{sq1}}\\ i_{\mathrm{sq2}}\end{bmatrix}+\frac{\mathrm{d}}{\mathrm{d}t}\begin{bmatrix}\psi_{\mathrm{sd1}}\\ \psi_{\mathrm{sd2}}\\ \psi_{\mathrm{sq1}}\\ \psi_{\mathrm{sq2}}\end{bmatrix}+ \quad (2)$$

$$+\begin{bmatrix}0 & 0 & -\omega_{\mathrm{dq}} & 0\\ 0 & 0 & 0 & -\omega_{\mathrm{dq}}\\ \omega_{\mathrm{dq}} & 0 & 0 & 0\\ 0 & \omega_{\mathrm{dq}} & 0 & 0\end{bmatrix}\begin{bmatrix}\psi_{\mathrm{sd1}}\\ \psi_{\mathrm{sd2}}\\ \psi_{\mathrm{sq1}}\\ \psi_{\mathrm{sq2}}\end{bmatrix},$$

where R_{s} is the stator resistance; $L_{\mathrm{d}} = L_{\mathrm{q}} = L$ is the stator inductance in *d*, *q* axis for the smooth-pole synchronous machine; M_{d} is the mutual inductance of the stator in d_1, d_2 axis; M_{q} is the mutual inductance of stator in q_1, q_2 axis; ψ_{f} is the flux of the permanent magnet by pole.

If the smooth-pole DOEWPMSM is supplied by voltage sources, the mathematical current model is written in (*d*, *q*) reference frame, and described as:

$$\frac{\mathrm{d}}{\mathrm{d}t}[I]=[A]\cdot[I]+[B]\cdot[V], \quad (3)$$

where: $[\boldsymbol{I}]=\begin{bmatrix}i_{\mathrm{sd1}} & i_{\mathrm{sd2}} & i_{\mathrm{sq1}} & i_{\mathrm{sq2}}\end{bmatrix}^T$ is the state vector;

$$[\boldsymbol{V}]=\begin{bmatrix}V_{\mathrm{sd11}}-V_{\mathrm{sd12}}\\ V_{\mathrm{sd21}}-V_{\mathrm{sd22}}\\ V_{\mathrm{sq11}}-V_{\mathrm{sq12}}\\ V_{\mathrm{sq21}}-V_{\mathrm{sq22}}\\ \psi_{\mathrm{f}}\end{bmatrix}^T$$ is the control vector.

The state matrix [***A***] is:

$$[\boldsymbol{A}]=-\begin{bmatrix}\dfrac{R_{\mathrm{s}}L}{L^2-M_{\mathrm{d}}^2} & \dfrac{-R_{\mathrm{s}}L}{L^2-M_{\mathrm{d}}^2} & -\omega_{\mathrm{dq}} & 0\\ \dfrac{-R_{\mathrm{s}}L}{L^2-M_{\mathrm{d}}^2} & \dfrac{R_{\mathrm{s}}L}{L^2-M_{\mathrm{d}}^2} & 0 & -\omega_{\mathrm{dq}}\\ \omega_{\mathrm{dq}} & 0 & \dfrac{R_{\mathrm{s}}L}{L^2-M_{\mathrm{q}}^2} & \dfrac{-R_{\mathrm{s}}M_{\mathrm{q}}}{L^2-M_{\mathrm{q}}^2}\\ 0 & \omega_{\mathrm{dq}} & \dfrac{-R_{\mathrm{s}}M_{\mathrm{q}}}{L^2-M_{\mathrm{q}}^2} & \dfrac{R_{\mathrm{s}}L}{L^2-M_{\mathrm{q}}^2}\end{bmatrix}. \quad (4)$$

The matrix [***B***] is:

$$[\boldsymbol{B}]=\begin{bmatrix}\dfrac{L}{L^2-M_{\mathrm{d}}^2} & \dfrac{-M_{\mathrm{d}}}{L^2-M_{\mathrm{q}}^2} & 0 & 0 & 0\\ \dfrac{-M_{\mathrm{d}}}{L^2-M_{\mathrm{q}}^2} & \dfrac{L}{L^2-M_{\mathrm{d}}^2} & 0 & 0 & 0\\ 0 & 0 & \dfrac{L}{L^2-M_{\mathrm{d}}^2} & \dfrac{-M_{\mathrm{q}}}{L^2-M_{\mathrm{q}}^2} & \dfrac{-\omega_{\mathrm{dq}}}{L-M_{\mathrm{q}}}\\ 0 & 0 & \dfrac{-M_{\mathrm{q}}}{L^2-M_{\mathrm{q}}^2} & \dfrac{L}{L^2-M_{\mathrm{d}}^2} & \dfrac{-\omega_{\mathrm{dq}}}{L-M_{\mathrm{q}}}\end{bmatrix}. \quad (5)$$

The electromagnetic torque of the DOEWPMSM is:

$$T_{\mathrm{em}}=\frac{3}{2}p((M_{\mathrm{d}}-M_{\mathrm{q}})(i_{\mathrm{sd2}}i_{\mathrm{sq1}}+i_{\mathrm{sd1}}i_{\mathrm{sq2}})+\psi_{\mathrm{f}}(i_{\mathrm{sq1}}+i_{\mathrm{sq2}})). \quad (6)$$

The drive mechanical equation is:

$$T_{\mathrm{em}}-T_{\mathrm{r}}=J\frac{\mathrm{d}\omega}{\mathrm{d}t}+f\cdot\omega. \quad (7)$$

Case 1. Supply of the DOEWPMSM by 2-levels inverters. The DOEWPMSM is fed by four three-phase 2-level inverters based on PWM technique (Fig. 2) with:

Vs_{A11}, Vs_{A12}, Vs_{A13} are the simple voltage of inverter A_1;

Vs_{A21}, Vs_{A22}, Vs_{A23} are the simple voltage of inverter A_2;

Vs_{B11}, Vs_{B12}, Vs_{B13} are the simple voltage of inverter B_1;

Vs_{B21}, Vs_{B22}, Vs_{B23} are the simple voltage of inverter B_2;

$(Vs_{\mathrm{A11}}–Vs_{\mathrm{A12}})$ is the pole voltage of inverter A_1;

$(Vs_{\mathrm{A21}}–Vs_{\mathrm{A22}})$ is the pole voltage of inverter A_2;

$(Vs_{\mathrm{B11}}–Vs_{\mathrm{B12}})$ is the pole voltage of inverter B_1;

$(Vs_{\mathrm{B21}}–Vs_{\mathrm{B22}})$ is the pole voltage of inverter B_2;

$U_{\mathrm{A}} = (Vs_{\mathrm{A11}}–Vs_{\mathrm{A12}})–(Vs_{\mathrm{A21}}–Vs_{\mathrm{A22}})$ is the phase-to-phase voltage of machine stator winding A;

$U_{\mathrm{B}} = (Vs_{\mathrm{B11}}–Vs_{\mathrm{B12}})–(Vs_{\mathrm{B21}}–Vs_{\mathrm{B22}})$ is the phase-to-phase voltage of machine stator winding B.

The voltages $(Vs_{\mathrm{A11}}–Vs_{\mathrm{A12}})$, $(Vs_{\mathrm{A21}}–Vs_{\mathrm{A22}})$, U_{A} (winding A) and same simulation results for winding B are shown in Fig. 3.

Figure 4 shows the harmonic content of the phase-to-phase machine voltage.

Figure 5 shows the simulation results of the speed and the torque. At time $t = 1$ s the impact of torque $T_{\mathrm{r}} = 180$ N·m is applied.

In order to analyse the torque quality, the definition of the torque undulations ΔT_{em} by the expression is:

$$\Delta T_{\mathrm{em}}=\frac{T_{\max}-T_{\mathrm{em}}}{T_{\mathrm{em}}}\cdot 100\%. \quad (8)$$

The enlarging effect of the torque for a load torque $T_{\mathrm{r}} = T_{\mathrm{n}}$ is indicated in Fig. 6.

Then, the torque undulation is:

$$\Delta T_{\mathrm{em}}=\frac{211.5-180}{180}\cdot 100\%=17.5\%.$$

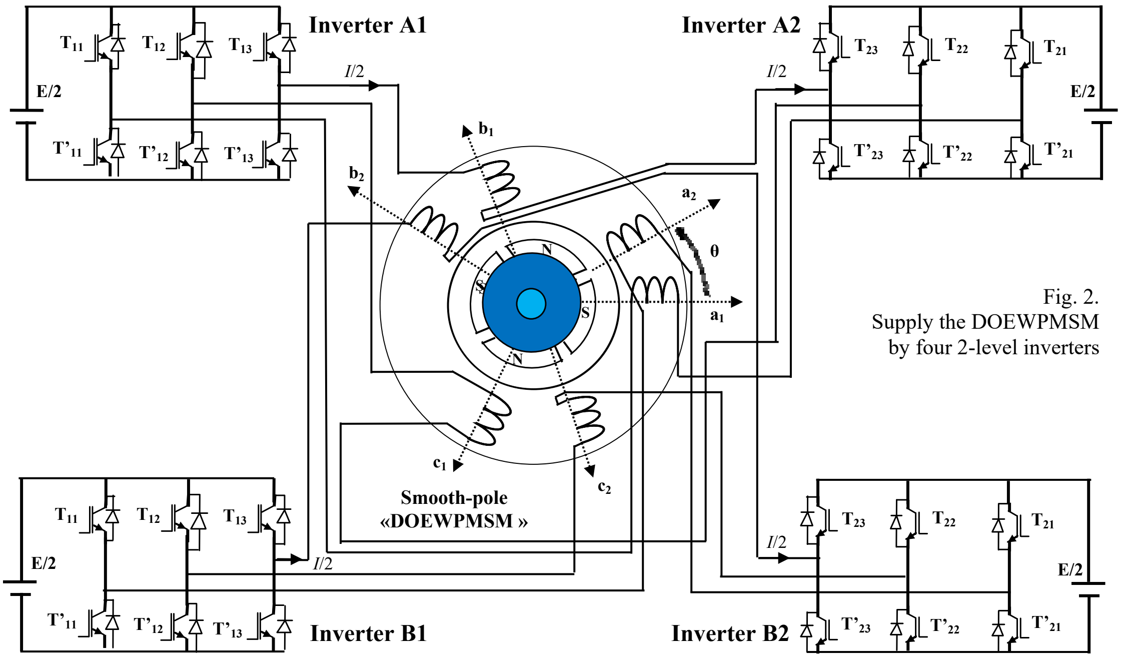

Fig. 2.
Supply the DOEWPMSM
by four 2-level inverters

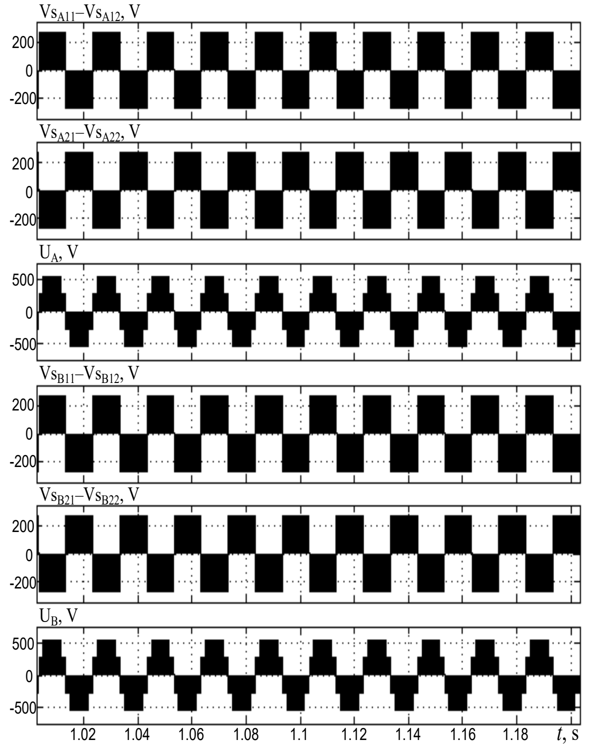

Fig. 3. Pole voltages of inverters and phase-to-phase voltages of machine stator windings A and B

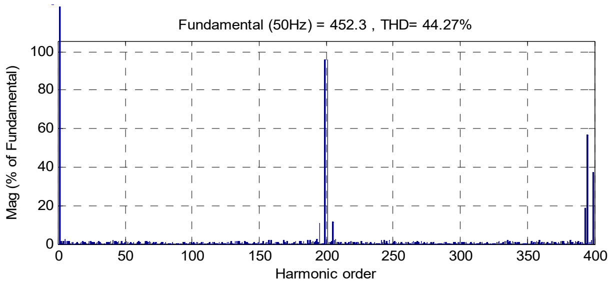

Fig. 4. Harmonic content of machine voltage

The simulation results of the stator currents I_{s11} of the winding A and I_{s21} of the winding B are shown in Fig. 7.

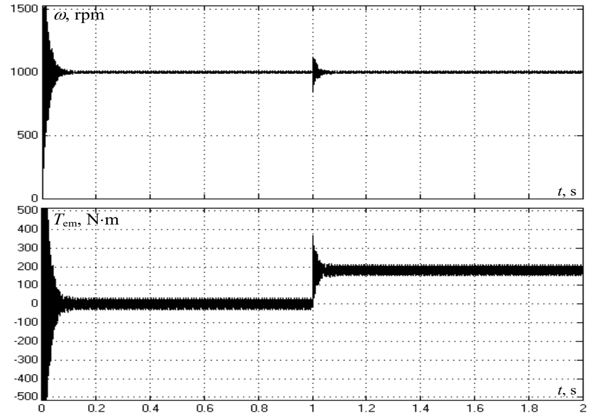

Fig. 5. The simulation results of the speed and the torque

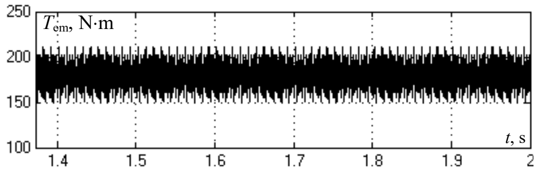

Fig. 6. Enlarging effect of the waveform torque

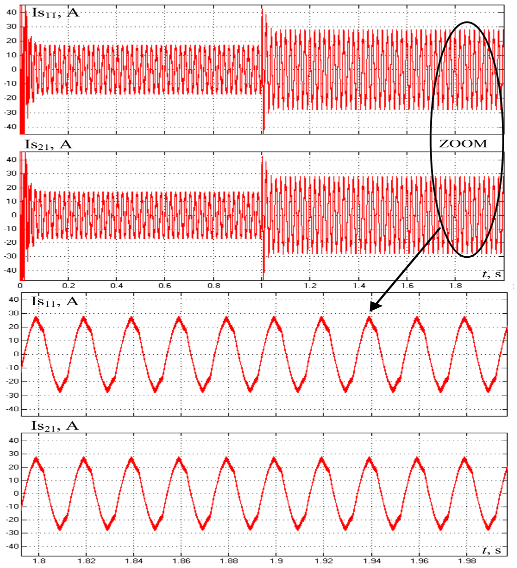

Fig. 7. The simulation results of the stator currents

The harmonic content of the stator current Is_{11} of the winding A is shown in Fig. 8.

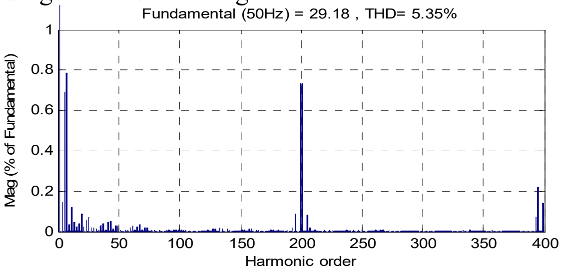

Fig. 8. The harmonic content of the stator current

Case 2. Supply of the DOEWPMSM by two 2-levels inverters in cascading. To enhance the performance of the DOEWPMSM in terms of voltage, current and torque quality, it's essential to supply it with a multi-level inverter. As shown in Fig. 9, this inverter is a cascaded configuration of two 2-level inverters [19].

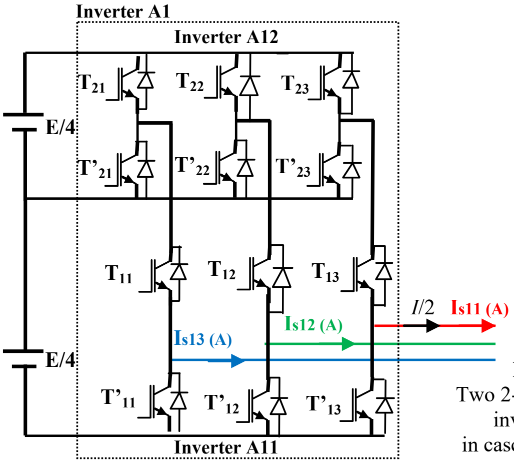

Fig. 9. Two 2-levels inverters in cascading

In order to control the two cascaded 2-level inverters, the phase disposition PWM technique was used, as shown in Fig. 10.

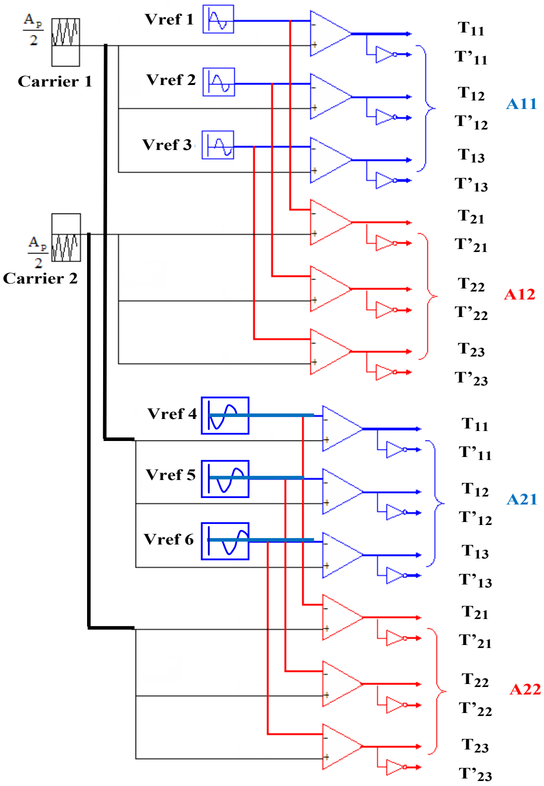

Fig. 10. Principle of the phase disposition PWM technique

Three reference voltages with a frequency of f_s and a 120° phase shift between them are compared with two amplitude carriers. This method controls the two cascaded inverters at input A1 of stator winding A. Similarly, three other reference voltages, shifted by 180° relative to the first three, are compared with the same carriers to control the two cascaded inverters at input A2 of stator winding A. This same control principle is applied to the two cascaded inverters located at inputs B1 and B2 of stator winding B.

Figure 11 shows the pole voltages (Vs_{A11}–Vs_{A12}), (Vs_{A21}–Vs_{A22}) and the phase-to-phase voltage U_A of the stator winding A, which have five voltage levels between phases of the machine. The same applies to the stator winding B.

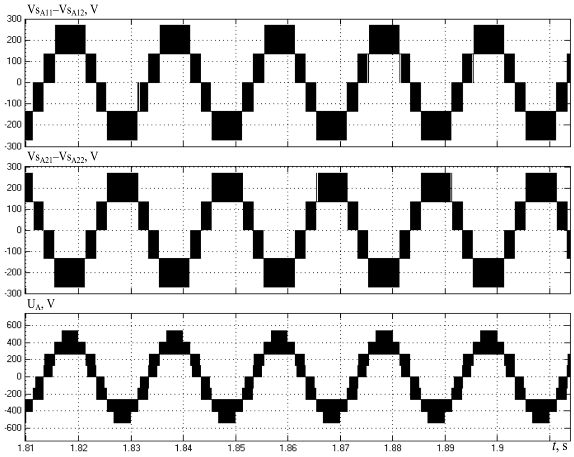

Fig. 11. The pole voltages and the phase-to-phase voltage of the stator winding A (case 2)

The harmonic content of the phase-to-phase machine voltage for the DOEWPMSM is shown in Fig. 12.

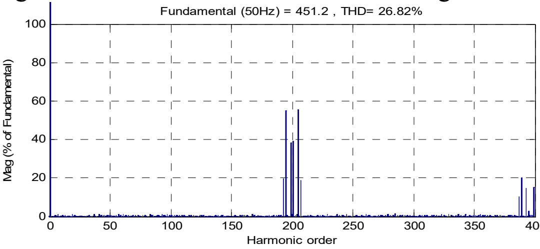

Fig. 12. The harmonic content of the machine voltage

Using multi-level voltage converters to feed the DOEWPMSM significantly improves the voltage level and reduces its THD from 44.27 % with a conventional inverter to 26.82 % with cascaded 2-level inverters. The enlarging effect of the torque is indicated in Fig. 13. Then, the torque undulation is:

$$\Delta T_{em} = \frac{193-180}{180}\cdot 100\% = 7.22\% .$$

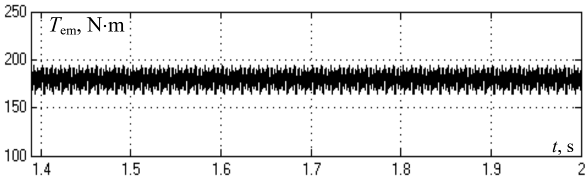

Fig. 13. Enlarging effect of the waveform torque

The harmonic content of stator current is shown in Fig. 14. Connecting the machine to two cascaded 2-level inverters, instead of a conventional inverter, improved the stator current's THD from 5.35 % to 3.86 %. It also reduced torque ripple from 17.5 % to 7.22 %.

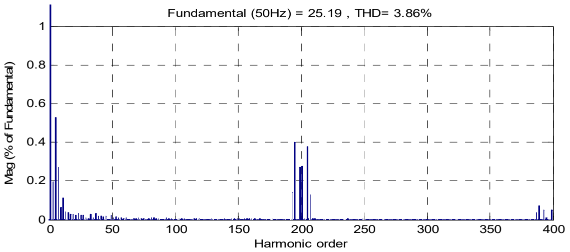

Fig. 14. The harmonic content of the stator current

Case 3. Supply of the DOEWPMSM by three 2-levels inverters in cascading. To demonstrate the performance improvement gained by using cascaded 2-level inverters, the proposed machine is also supplied by a second cascaded multi-level inverter structure at each input (A1, A2, B1 and B2). This structure is formed by three 2-level inverters connected in a cascade (Fig. 15).

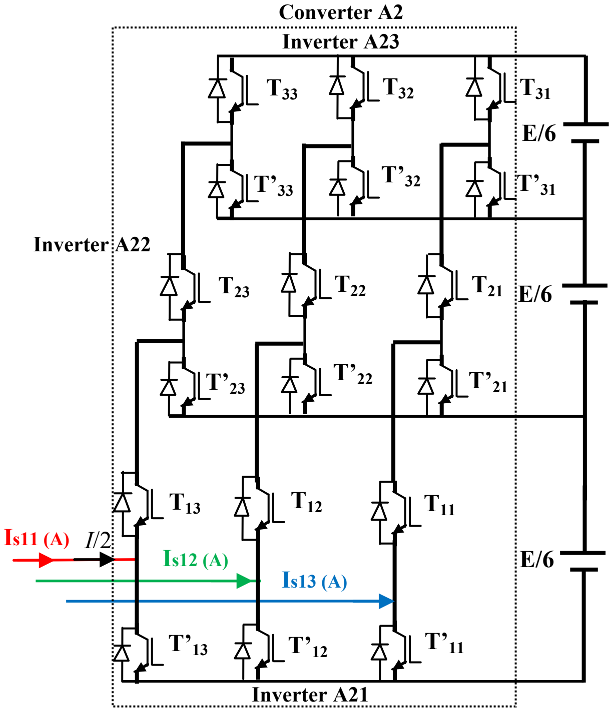

Fig. 15. Three 2-levels inverters in cascading

Figure 16 shows the pole voltages ($Vs_{A11}–Vs_{A12}$), ($Vs_{A21}–Vs_{A22}$) and phase-to-phase voltage U_A of the stator winding A. The results indicate that an increase in the voltage level enhances the lifespan of this machine.

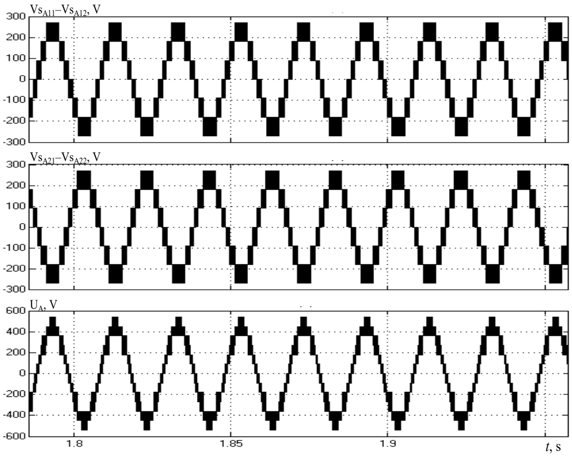

Fig. 16. The pole voltages and the phase-to-phase voltage of the stator winding A (case 3)

The enlarging effect of the waveform torque is shown in Fig. 17.

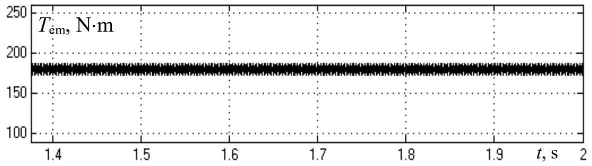

Fig. 17. Enlarging effect of the waveform torque

Then, the torque undulation is:

$$\Delta T_{\mathrm{em}} = \frac{187.4-180}{180}\cdot 100\% = 4.11\% .$$

Table 1 presents the results obtained with three cascaded inverters, along with those from the two other types of power supply structures. This table clearly illustrates the advantages of the DOEWPMSM when combined with cascaded 2-level inverters. Indeed, the use of these cascaded structures improves stator current quality, voltage THD and reduces torque ripple.

Table 1

Different results for three structures

Inverter A1	1 inverter	2 cascaded inverters	3 cascaded inverters
THD voltage, %	44.27	26.82	16.42
THD current, %	5.35	3.86	1.63
ΔT_{em}, %	17.5	7.22	4.11

Assuming the machine has a total power *P*. Table 2 summarizes the specifications for its power supply system. The table details the power ratings for the two cascaded inverters, as well as the required stator current and the voltage of the switches needed to supply the machine. This same process is applied to all inverter modules at each of the machine's inputs, ensuring consistent sizing across the entire system [19].

Table 2

Sizing of the two cascaded inverters

Inverter A1	Power inverter	Stator current, A	Switches voltage, V
Inverter A11	$P/4$	I/2	$V_{T11} = E/2$
Inverter A12	$P/8$	I/2	$V_{T21} = E/4$

Table 2 demonstrates that using two cascaded inverters to supply the DOEWPMSM is not a constraint but rather a key component of power segmentation. The table shows that the cascaded inverter A12 has a significantly lower power rating *P*/8 than the principal inverter A11. This finding is crucial because it indicates that the system can be built with a smaller and more cost-effective secondary inverter while still achieving the benefits of a multilevel configuration.

The combination of a DOEWPMSM with cascaded inverters provides a reliable solution for degraded-mode operation. However, to ensure the drive system's continued performance, specific operational conditions must be met in the event of an inverter failure. This involves a precise reduction of the machine's speed to prevent a rise in current draw, which in turn avoids the overheating of both the motor windings and, most importantly, the semiconductor devices.

The characteristics of the machine are: nominal power $P = 40$ kW, speed 1000 rpm, stator resistance $R_s = 65$ mΩ, stator inductance $L_d = L_q = 0.655$ mH, mutual inductance of stator $d_{1,2}$ axis $M_d = 0.545$ mH, mutual inductance of stator $q_{1,2}$ axis $M_q = 0.545$ mH, magnet flux $\psi_f = 0.8$ Wb, inertia moment $J = 0.02$ kg·m^2, viscous force $F = 2\ 10^{-3}$ N·m·s/rad.

Conclusions. The novel smooth-pole dual open-end windings permanent magnet synchronous machine (DOEWPMSM) when associated with cascaded inverters structures offers a significant advantage over the conventional 2-levels inverters. The mathematical model of the DOEWPMSM is presented and simulated in MATLAB/Simulink. The machine is first fed by conventional 2-level inverter and then by cascaded 2-level inverter structures. The new machine offers such benefits:

- a good solution for power segmentation, reducing clutter, improving the availability of the drive system, and increasing redundancy in degraded mode compared to a classic synchronous machine.
- When the new machine is powered by cascaded 2-level inverter structures, it provides a better voltage level between the machine phases. With a conventional 2-level inverter, three levels are obtained. With two 2-level inverters in cascading, five levels are obtained, and with three 2-level inverters in cascading, seven levels are obtained.
- A better voltage THD. If the THD is 44.27 % with a conventional inverter, it drops to 16.42 % when powered by three 2-level inverters in cascading.
- A better quality of stator current. With a conventional inverter, the THD is 5.35 %. Using three cascaded 2-level inverters, the THD becomes 1.63 %.
- A better torque quality. The value decreases from 17.5 % to 4.11 % with three cascaded 2-level inverters.
- A reduced the DC bus voltage value of E going from $E/2$ to $E/6$ with three cascaded 2-level inverters.
- An extended bandwidth.

In future work it is planned to experimentally confirm the advantages of the proposed new DOEWPMSM and powered using cascaded 2-level inverters.

Conflict of interest. The authors declare that they have no conflicts of interest.

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