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ADVANTAGES OF OPEN-END STATOR WINDING COMPARED WITH STAR WINDING FOR WOUND ROTOR SYNCHRONOUS MACHINE WITH DAMPERS

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Key words: Dual open-end stator windings synchronous machine, Double star synchronous machine, Open-end winding synchronous machine (OEWSM), Power segmentation.

In this work, a comparative analysis between the different performances of stator windings structures for salient-pole synchronous machine with dampers where each structure is supplied by voltage source inverters is presented. In this comparison, the proposed structures which are the open-end stator windings synchronous machines improve the total harmonic distortion (THD) of the voltage, THD stator current and offer best quality of the torque for the high-power applications. Furthermore, the dual open-end winding synchronous machine ensures the power segmentation to increase the freedom degrees of drive system in degraded mode. Indeed, this machine is fed by four voltage source inverters where the dimensioning of inverters is reduced to a quarter power of the machine.

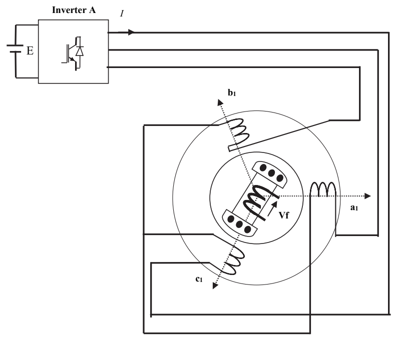
1. INTRODUCTION

The synchronous machines are used in the field of electrical energy production [1–4]. They are used at low and high speeds. They have a wide range of operations in terms of power (from few watts to several MW) with a better torque density compared with asynchronous machines. The ac machines are widely used in industrial applications with variable speed such as railways applications, electrical propulsion of ships, aeronautics and electrical vehicles system [5–7]. To improve the reliability of drive systems and ensure better service continuity, several researches have been developed in the ac machine structures including the multi-star machines [8–11]; the multi-phase machine [12,13]; the three-phase open-end winding [14–19]; the multi-phase open-end winding machine [20, 21] and the two three-phase open-end stator windings machine that has recently been proposed and studied. Currently, the proposed studies focus on the dual open-end stator windings ac machines [22–24]. These machines offer multiple redundancy degrees, since the loss of one star does not stop the machine. Furthermore, the mathematical model of the novel dual three-phase open-end wound rotor synchronous machine with dampers is presented in the [25].

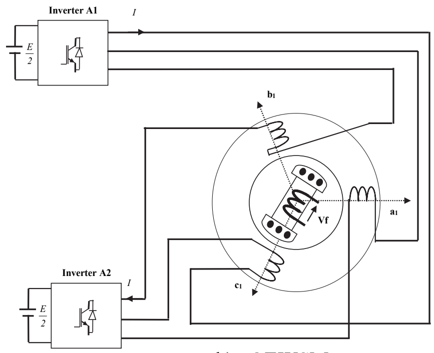
In this paper, the authors have presented a comparison between four salient-pole wound rotor synchronous machine with windings dampers namely classical synchronous machine « SM », double star synchronous machine « DSSM », open-end winding synchronous machine « OEWSM » and the dual three-phase open-end stator windings synchronous machine « DOEWSM ». The different machine structures are supplied by voltage source inverters, as shown by Fig. 1.

In the first part, the different synchronous machine structures are simulated in Matlab Simulink environment.

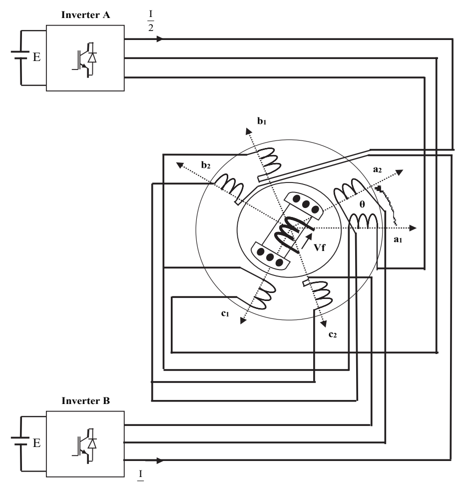
In the second part, a comparative analysis of the four machine structures is carried out using THD voltage, THD stator current and torque undulation. The importance advantage of the open-end stator windings structures is shown. In addition, a comparison was made between the different structures based on the power segmentation.



a) «SM»



b) «OEWSM»



c) «DSSM»

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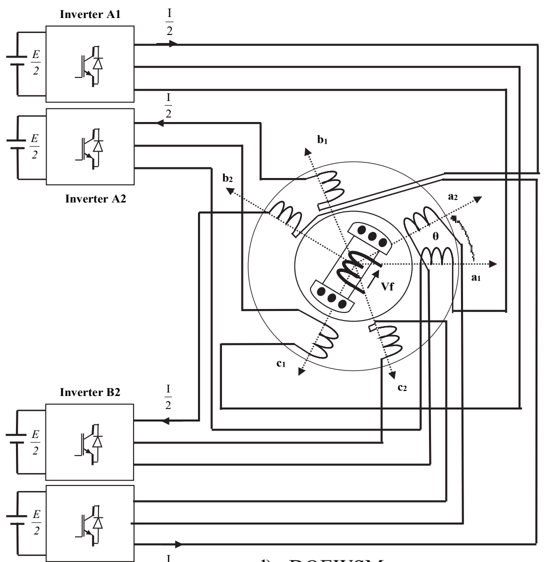


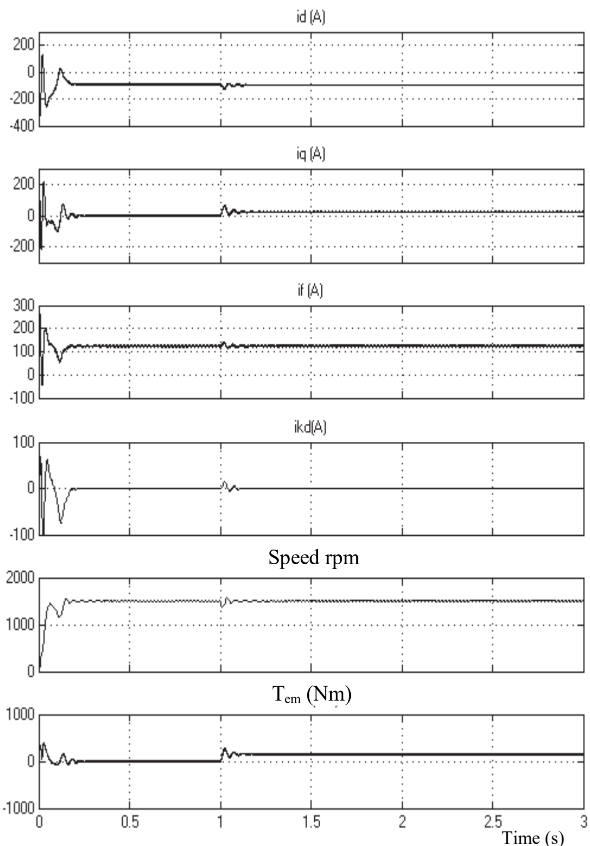
d) «DOEWSM»

Fig. 1 – Different salient-poles synchronous machine structures with dampers.

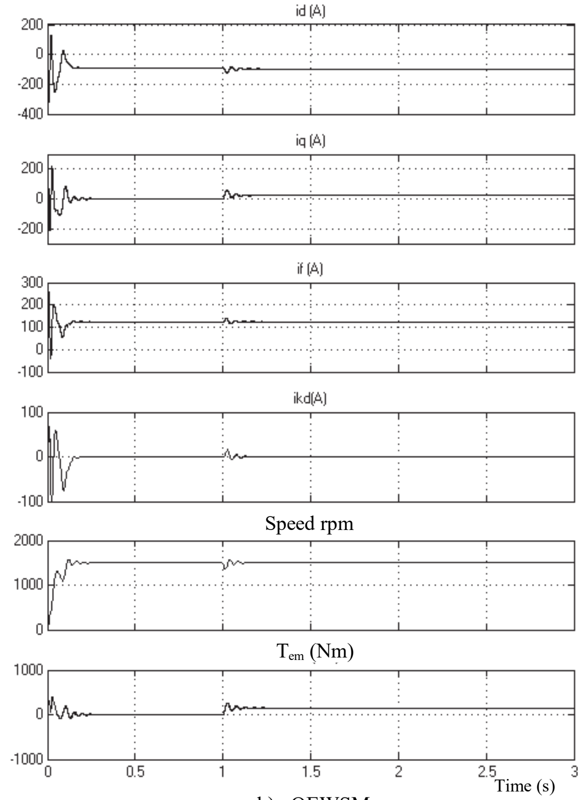
It has shown the benefits of the two three-phase open-end stator windings « DOEWSM».

2. SUPPLY BY VOLTAGE SOURCE INVERTERS

The different machine structures are supplied by voltage source inverters based on PWM technique. Figure 2 shows the simulation results of the stator currents, speed and the torque for the machines with one three-phase stator winding (« SM » and «OEWSM»). In this simulation, the impact of torque $T_r = 150$ Nm is applied at time $t = 1$ s.



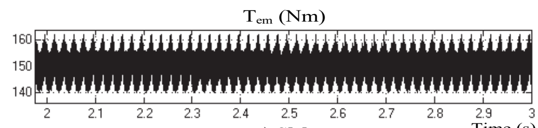
a) SM



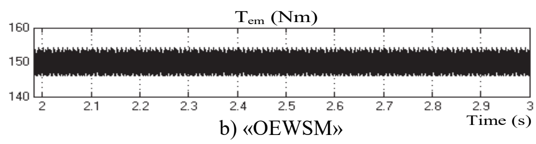
b) «OEWSM»

Fig. 2 – Evolution of the stator currents, speed and torque for one stator winding machines.

Figure 3 shows the enlarging effect of the torque of the two machines for one three-phase winding stator during the permanent mode for a load torque $T_r = 150$ Nm.



a) SM



b) «OEWSM»

Fig. 3 – Enlarging effect of the waveform torque.

In order to analyze the torque undulations, the definition of ΔT_{em} is presented by the following expression:

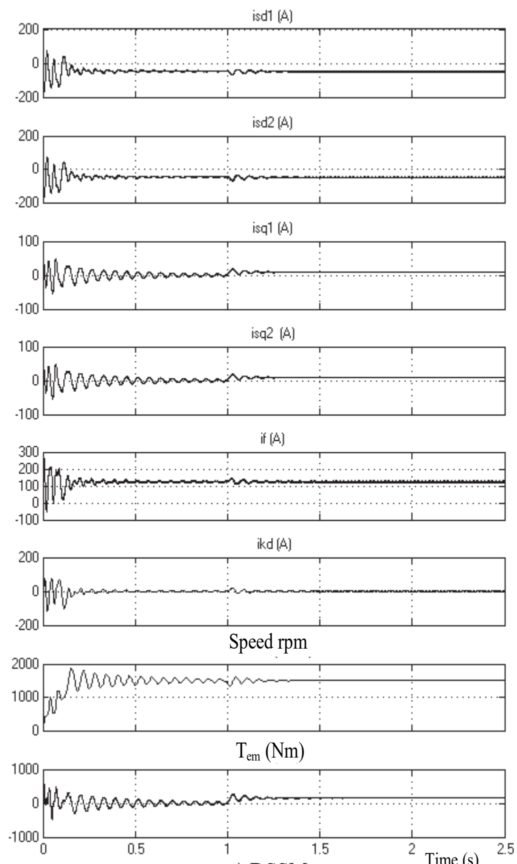
$$\Delta T_{\text{em}} = \frac{T_{\text{Max}} - T_{\text{Moy}}}{T_{\text{moy}}} 100 \,. \tag{1}$$

Then, the calculate of the torque undulation is shown for this operation mode for:

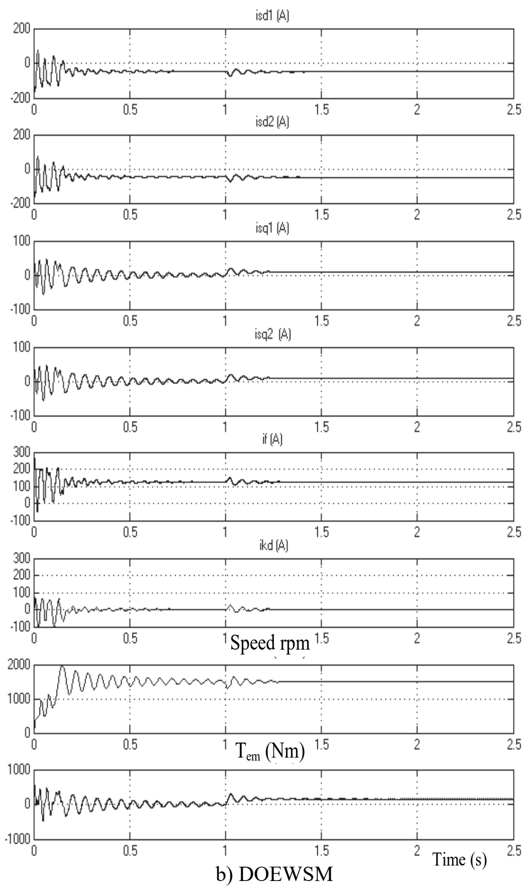
– « SM »: $\Delta T_{\text{em}} = \dfrac{162-150}{150}100 = 8\%$

– « OEWSM »: $\Delta T_{\text{em}} = \dfrac{154.1-150}{150}100 = 2.73\%$.

Figures 4 shows the simulation results of the currents of the stator, speed and the torque for the two machines with two three-phase stator windings (« DSSM » and «DOEWSM»).

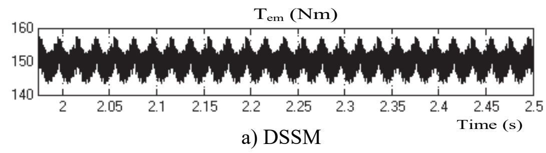


a) DSSM

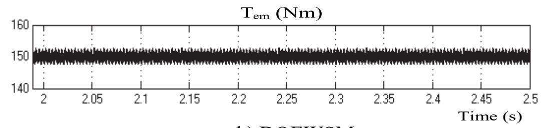


b) DOEWSM

Fig. 4 – Evolution of the stator currents, speed and torque for two three-phase stator winding machines.



a) DSSM



b) DOEWSM

Fig. 5 – Enlarging effect of the waveform torque.

In the permanent mode for a load torque T_r = 150 Nm, the enlarging effect of the torque for the two machines (« DSSM » and «DOEWSM») is shown in Fig. 5.

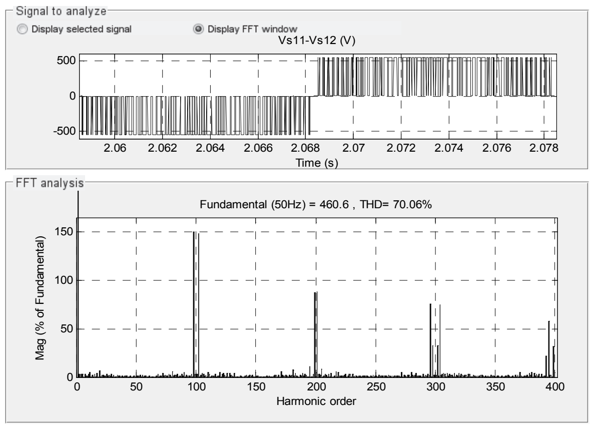
Then:

– « DSSM »: $\Delta T_{em} = \frac{157.2 - 150}{150} 100 = 4.8\%$

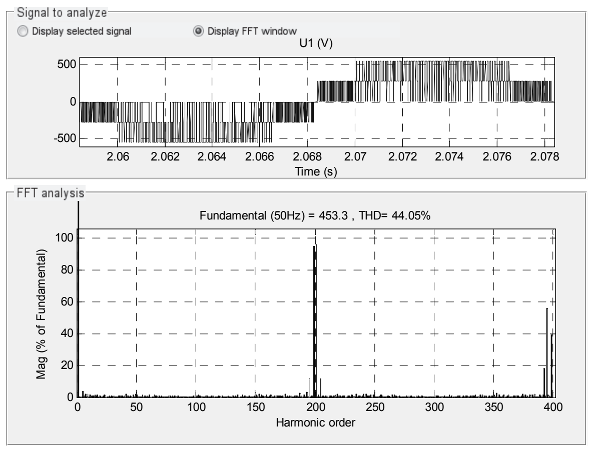
– « DOEWSM »: $\Delta T_{em} = \frac{152.7 - 150}{150} 100 = 1.8\%$

The results of the torque undulation show that the synchronous machines with open-end stator windings structures clearly improve the torque undulation when compared with star stator windings structures.

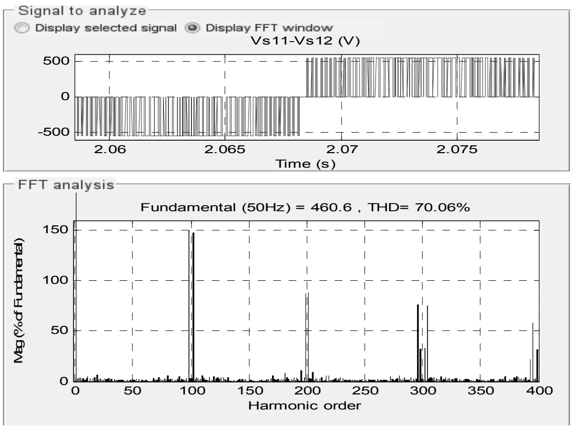
The simulation results of the waveform and the harmonic content of the voltage between two phases for the four machines are shown by Fig. 6.



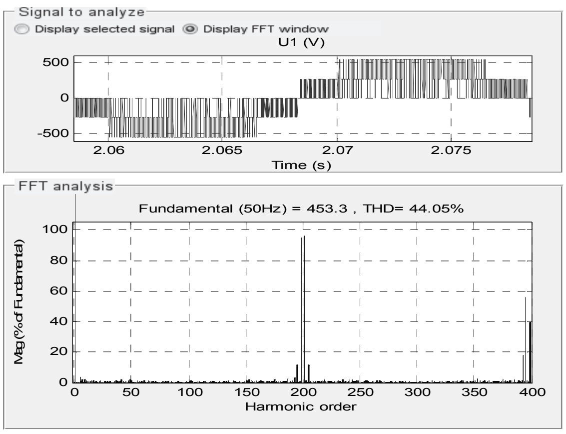
a) SM



b) OEWSM



c) DSSM

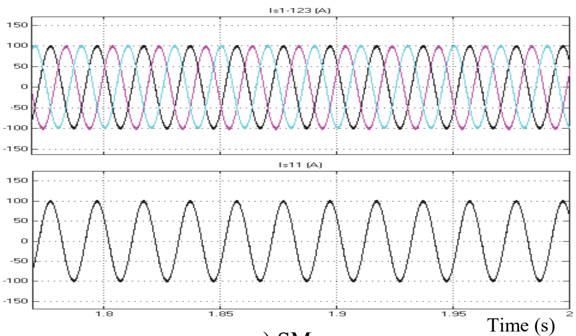


d) DOEWSM

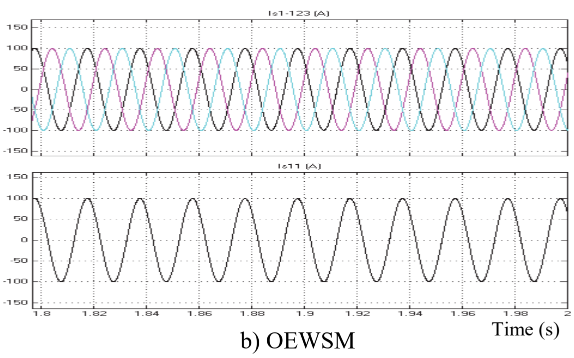
Fig. 6 – Waveform and harmonic ration of machine voltage.

The open-end stator winding SM structures increase the level of the voltage between phases, improve the total harmonic distortion of voltage and extend the band-width.

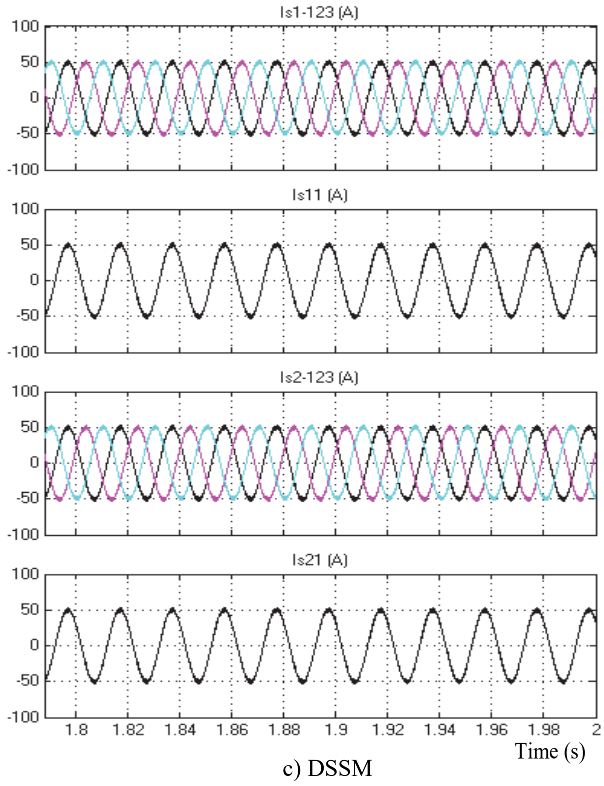
In the permanent mode, the evolution of the currents of the stator for four machines is shown by the Fig. 7.



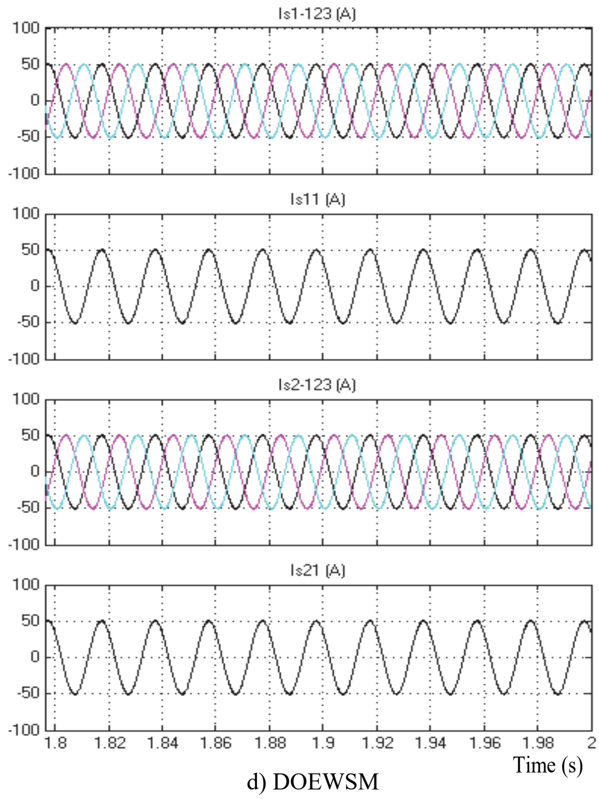
a) SM



b) OEWSM



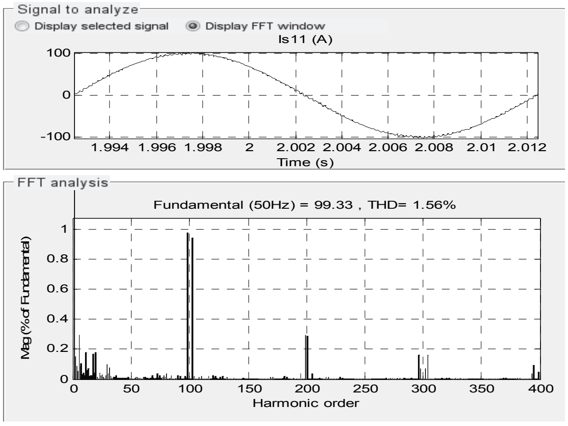
c) DSSM



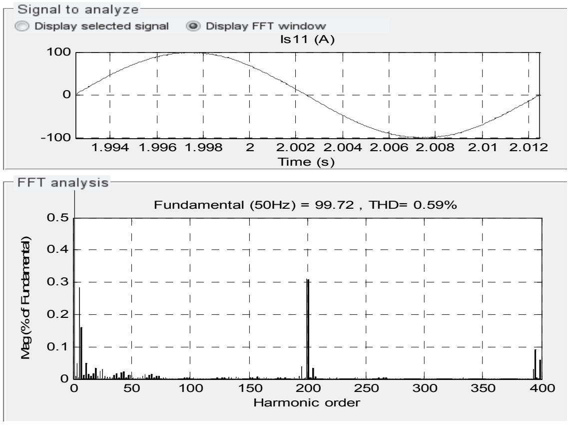
d) DOEWSM

Fig. 7 – Evolution of stator currents.

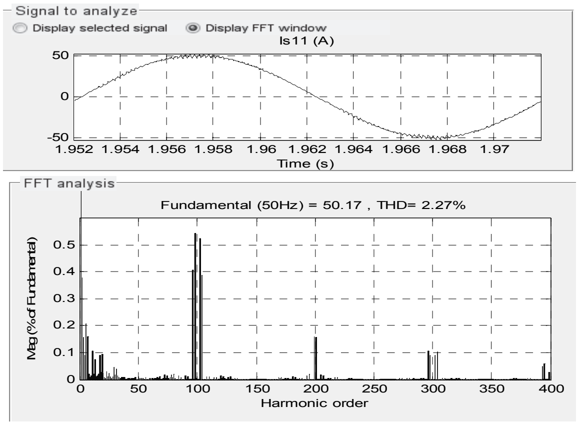
Figure 8 shows the simulation results of the waveform of the stator current and the harmonic content for one and two three-phase stator windings machines.



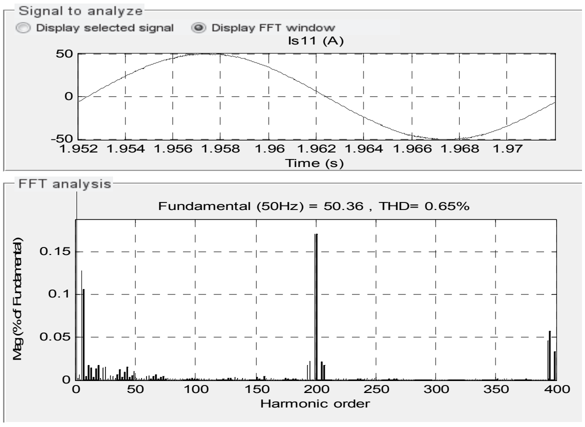
a) SM



b) OEWSM



c) DSSM



d) DOEWSM

Fig. 8 – Waveform and harmonic ration of stator current.

The simulation results of the THD stator current present the important advantage of the open-end stator winding than the stator windings machines in star.

The different simulations of THD voltages, THD current of stator and undulations of torque for the different machine structures are summarized in Table 1.

Table 1

THD voltages, THD stator current and torque undulations

	SM	OEWSM	DSSM	DOEWSM
ΔTem (%)	8	2.73	4.8	1.8
THD voltage (%)	70.05	44.05	70.05	44.05
THD current (%)	1.56	0.59	2.27	0.65

The open-end stator windings structures offer the best quality of torque and the better THD of voltage and stator current of the machine.

3. POWER SEGMENTATION

Considering a synchronous machine of *P* power, we have dimensioned the different inverters feeding the four machines previously studied. Then, Table 2 gives the different values of voltages and stator currents necessary to supply each machine.

Table 2

Different values of voltages and stator currents for each machine

	SM	OEWSM	DSSM	DOEWSM
Voltage	*E*	*E*/2	*E*	*E* /2
Current	*I*	*I*	*I*/2	*I*/2
Power of inverter	*P*	*P*/2	*P*/2	*P*/4

Table 2 shows the significant advantage of the dimension of the inverters to a quarter power for the feeding the machine « DOEWSM » when compared with the structures « SM », « DSSM » and « OEWSM ». Consequently, it is a good solution for power segmentation. In addition, it is also a good solution for high-power machines that need inverters out of catalogs.

Table 3 shows the degrees of freedom of the drive system of each machine structure in degraded mode.

Table 3

Degrees of freedom of the system in degraded mode

	SM	OEWSM	DSSM	DOEWSM
Degrees of freedom	0	1	1	3

The OEWIM and DSIM offer one degrees of freedom in degraded mode when the type of this structure can tolerate the failure of the inverter and ensure the continuity of service of the drive system. The « DOEWSM» have the advantage of two machine structures OEWIM and DSIM which gives 3 degrees of freedom. Indeed, it can continue the operation of the drive system with three successive failures of the inverters appears.

4. CONCLUSIONS

The simulations of the different synchronous machine structures which are supplied by voltage source inverters are implemented in the « Matlab Simulink » environment.

It is clear the double star synchronous machine improved the quality of the torque but affects the quality of the stator current.

The open-end stator windings synchronous machine structures present a important advantage compared with the synchronous machines in star. Indeed, these structures offer a best torque quality, increase the level of the machine voltage, improve the total harmonic distortion (THD) of the voltage, the THD ratio of the stator current and extend the band-width. Moreover, the use of the « DOEWSM » reduces the dimensioning of the inverters to a quarter power (P/4) of the machine. This supply structure offers the power segmentation and the reducing of the space requirement. Then, it increases the freedom degrees in degraded mode which improved the reliability and availability of drive system. In addition, this structure can continue to operate the service of drive system when a default appears in three successive inverters of the four supply inverters. Finally, this study shows the significant advantages that present the "DOEWSM" compared with other synchronous machines including "SM", "DSSM" and "OEWSM".

APPENDIX

The characteristics of the machine used:

Rated power $P = 40$ kW, Speed $n = 1500$ rpm, resistance of stator $R_s = 0.5\ \Omega$, resistance of wound rotor $R_f = 0.643\ \Omega$, resistance of damper $R_{kd} = 0.45747\ \Omega$, $R_{kq} = 0.41637\ \Omega$, inductance of stator $L_d = 29.85$ mH, $L_q = 14.87$ mH, inductance of rotor $L_f = 30.89$ mH, inductance of damper $L_{kd} = 30.981$ mH, $L_{kq} = 15.882$ mH, mutual inductance of stator 1 and 2 $M_d = 28.89$ mH, mutual inductance of stator 1 and 2 $M_q = 28.89$ mH, mutual inductance between stator 1, 2 and rotor $M_{fd} = 28.89$ mH, mutual inductance between damper axis d and rotor $M_{fkd} = 28.89$ mH, mutual inductance between stator 1, 2 and dampers axis d $M_{kd} = 28.89$ mH, mutual inductance between stator 1, 2 and dampers axis q $M_{kq} = 13.8$ mH, inertia moment $J = 0.1$ kg · m², viscous force $f = 0.001$ N · m · s/rad.

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