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Experimental Prototype of Open-End Stator Winding Induction Machine Fed by Three Phase Inverters

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***Abstract*—In this paper, the experimental prototype of three-phase open-end stator winding induction machine is presented. Firstly, the proposed machine is supplied by sinusoidal voltage using a three-phase transformer with two secondary voltages in phase opposition. Secondly, this prototype is fed by two 2-levels three-phase inverters with half DC-link (E/2) of each inverter based on law V/f, when the scalar control is implemented on FPGA Spartan 3E Board. The obtained experimental results of voltages of each inverter for feeding the scheme machine for the power 1.5 kW and stator current are presented.**

***Keywords*—open-end winding induction machine; two levels inverter; scalar control; FPGA; power segmentation.**

I. INTRODUCTION

The power segmentation of the association induction machine with conventional inverter is attractive for high power application such as railways applications, aeronautics, electrical propulsion of ships and electrical vehicles system [1-2]. In order to achieve this objective, the feeding of the induction machine is based on the replacement of large converter of high power by the association of several converters of lower powers. The power segmentation of the electric machines and inverters is now a major interest in electrical engineering researches for the improvement the reliability, modularity, standardization, scalability, reconfigurability and reduced cost of electrical systems. Several researches have also been developed in machine structures including multiphase machines, where each phase is supplied by its own voltage inverter [3-5], multi star machines, where each star is supplied by its own three phase voltage inverter [6-9] and open-end stator windings machines where it is fed by two voltage source inverters [10-16].

In the first part, the mathematical modelling of the open-end winding induction machine for supply voltage is implemented in the « Matlab Simulink » environment. Then, simulation results of the feeding scheme machine by two voltage source inverter based on V/f law are presented.

The second part is presented the experimental platform of prototype of proposed machine for a 1.5 kW power supplied by sinusoidal voltage and secondly by two 2-level inverters of type Semikron using scalar control implemented on FPGA Spartan 3E for control. The experimental results of voltages and stator current are shown.

II. MODEL OF SIMULATION FOR VOLTAGE SUPPLY

If the open-end stator winding asynchronous machine is supplied by two voltage sources. The mathematical flux model is written in (d,q) reference frame, and described by the following state equation representation:

$$\frac{dX(t)}{dt} = \left[A(\omega,\omega_{dq})\right]\left[X(t)\right] + \left[B\right] U(t) \qquad (1)$$

$$Y(t)=\left[C\right].X(t)$$

$X(t)=\begin{bmatrix}\Phi_{sd} & \Phi_{sq} & \Phi_{rd} & \Phi_{rq}\end{bmatrix}^T$: State vector

$U(t) = U_1(t) - U_2(t) = \begin{bmatrix}V_{sd1}-V_{sd2} & V_{sq1}-V_{sq2}\end{bmatrix}^T$: Control vector

$Y(t)=\begin{bmatrix}I_{sd} & I_{sq} & I_{rd} & I_{rq}\end{bmatrix}^T$: The output vector

The functional diagram is given by figure 1:

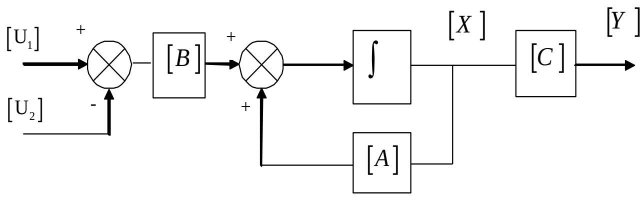

Fig.1. Functional diagram of the open-end winding machine.

The matrix $\left[A\right]$

$$[A]=\begin{bmatrix} -\frac{1}{\sigma T_s} & \omega_{dq} & \frac{M_{sr}}{\sigma T_s L_r} & 0 \\ -\omega_{dq} & -\frac{1}{\sigma T_s} & 0 & \frac{M_{sr}}{\sigma T_s L_r} \\ \frac{M_{sr}}{\sigma T_r L_s} & 0 & -\frac{1}{\sigma T_r} & \omega_{dq}-\omega \\ 0 & \frac{M_{sr}}{\sigma T_r L_s} & -(\omega_{dq}-\omega) & -\frac{1}{\sigma T_r} \end{bmatrix} \qquad (2)$$

With:

$T_s = \frac{L_S}{R_s}$ Constant of time for the stator

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$T_r = \dfrac{L_r}{R_r}$ Constant of time for the rotor

$\sigma = 1 - \dfrac{M_{sr}^{\ 2}}{L_s L_r}$: Coefficient of dispersion of Blondel.

$Msr = \dfrac{3}{2} m_{sr}$

$Ls = L_{sa} - m_{ss}$

$Lr = L_{ra} - m_{rr}$

$\mathbf{m_{ss}}$:Mutual Inductance between two stator phases of same star shifted of 120°

$\mathbf{m_{sr}}$: Mutual Inductance between stator and rotor

$\mathbf{m_{rr}}$: Mutual Inductance between two rotor phases of same star shifted of 120°

$\mathbf{L_{sa}}$:Self inductance of stator winding

$\mathbf{L_{ra}}$:Self inductance of rotor winding

The matrix $[B]$

$$[B] = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \qquad (3)$$

The matrix [C]

$$[C] = \begin{bmatrix} \dfrac{1}{\sigma L_s} & 0 & \dfrac{-M_{sr}}{\sigma L_s L_r} & 0 \\ 0 & \dfrac{1}{\sigma L_s} & 0 & \dfrac{-M_{sr}}{\sigma L_s L_r} \\ \dfrac{-M_{sr}}{\sigma L_s L_r} & 0 & \dfrac{1}{\sigma L_r} & 0 \\ 0 & \dfrac{-M_{sr}}{\sigma L_s L_r} & 0 & \dfrac{1}{\sigma L_r} \end{bmatrix} \qquad (4)$$

The drive mechanical equation is given as follows:

$$Tem - Tr = j\frac{d\omega}{dt} + f\ \omega \qquad (5)$$

$$Tem = \frac{3}{2} p(\Phi_{s\alpha} I_{s\beta} - \Phi_{s\beta} I_{s\alpha}) \quad (6)$$

Tem: Electromagnetic torque

Tr: Load torque

III. VALIDATION OF THE MODEL OF THE OPEN–END WINDING INDUCTION ASYNCHRONOUS MACHINE

The simulation model is validated in the environment of « Matlab simulink ». In figure 2, the open-end winding induction machine is fed by two PWM voltage source inverters based on V/f law with half Dc-link (E/2) of each inverter using a Three phase transformer with two secondary in phase opposition (m = 1/2) for isolated the two voltage source inverters.

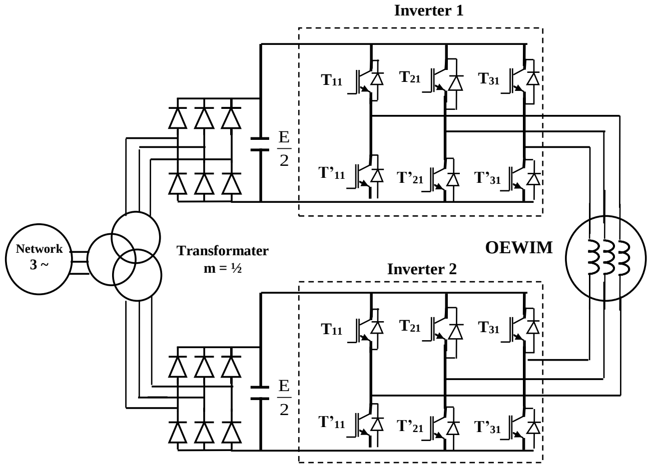

Fig.2. Open-end winding induction machine supplied by two PWM voltage source inverters.

Figure 3 shows the voltage (Vs_{11}-Vs_{12}), (Vs_{21}-Vs_{22}) and phase-to-phase machine voltage U_1 which is 3 levels to supply with two three-level inverters.

With:

Vs_{11}, Vs_{12} simple voltage of inverter 1

Vs_{11} -Vs_{12} pole voltage of inverter 1

Vs_{21}, Vs_{22} simple voltage of inverter 2

Vs_{21} -Vs_{22}pole voltage of inverter 2.

$U_1 = (Vs_{11}\text{-}Vs_{12}) - (Vs_{21}\text{-}Vs_{22})$ pole voltage of the machine.

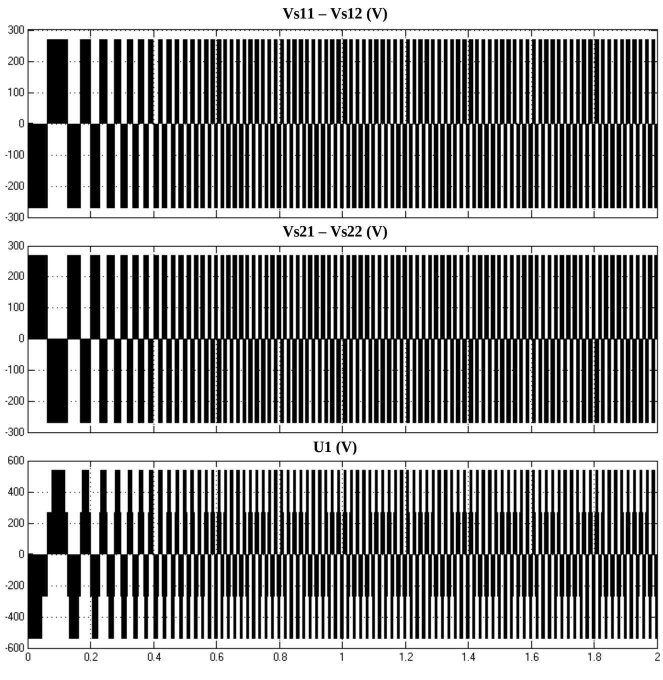

Fig. 3. Evolution of the voltages for inveter and machine.

Figure 4 shows the zoom of the simulation results of the voltages for feeding the proposed machine. This machine increases the level of waveform voltages.

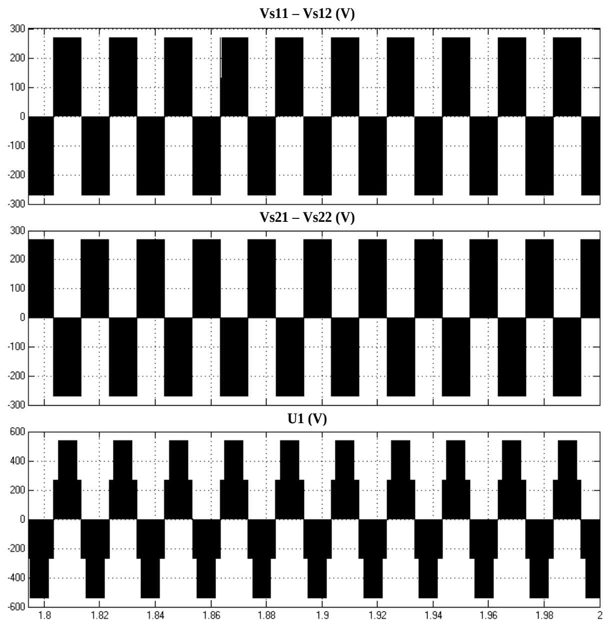

Fig. 4. Enlarging effect of the waveformvoltages

The following cycle of operation, at t = 0 s to t = 0.6 s, the system has a starting cycle, from t = 0.6 s to t = 1 s, the machine is working in no-load conditions. At time t = 1 s, a load torque Tr = 10 mN is applied. Figure 5 shows the simulation results of the stator currents, speed and electromagnetic torque.

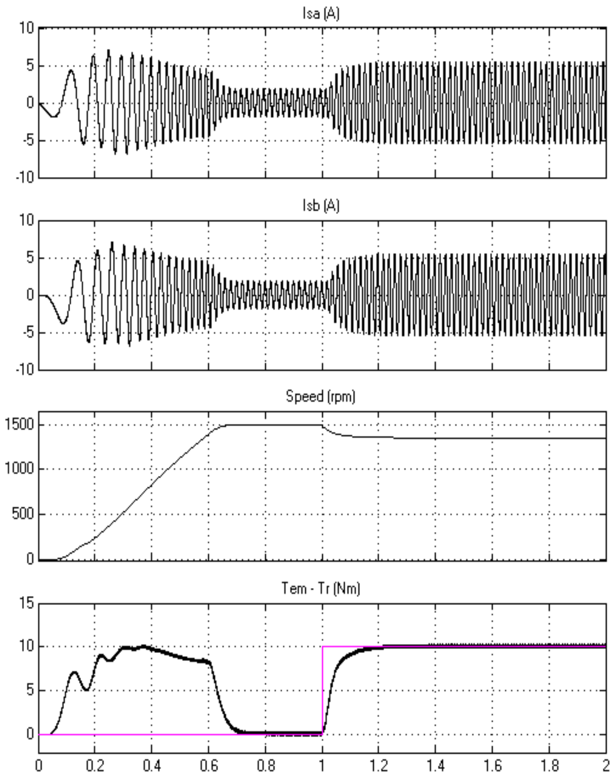

Fig. 5. Evolution of the speed, stator current and torque.

The characteristics of the machine used:

- Nominal power P = 1.5 KW.
- Speed n = 1410 rpm.
- Resistance of stator Rs = 7.5 Ω.
- Resistance of rotor Rr = 4.2 Ω.
- Inductance of stator Ls = 462.9 mH.
- Inductance of rotor Lr = 462.6 mH.
- Mutual inductance Msr = 440.0 mH.

IV. Realization of Open-End Winding Induction Machine Prototype

To show the prototype of the open-end winding induction machine, we are carried out this prototype from a conventional induction motor. The realization of an experimental prototype of proposed machine of power P = 1.5kW, 24 slots induction machine is represented by the figure 6. This motor has asignage plate that presents the following information:

Type: DMA2 90L4, 15 kg

cos φ = 0.78,

50Hz; 1410 rpm; 1.5KW;

400V, I = 3.49A;

380V, I = 3.65A;

420V, I = 3.42A

Fig. 6. Experimental prototyping of open-end winding induction machine

V. Feeding of Open-End Winding Induction Machine Prototype by Sinusoïdal Voltage

To verify the operation of realized prototype, the open-end stator winding induction machine is fed by sinusoidal voltage using the three-phase transformer with two secondary in phase opposition (m = 1/2). The obtained experimental results are presented by the following figures.

Figures 7 and 8 show respectively the evolution of voltages between phases of each inverter $(Vs_{11}-Vs_{12})$, $(Vs_{21}-Vs_{22})$ and the stator current Is1 of phase.

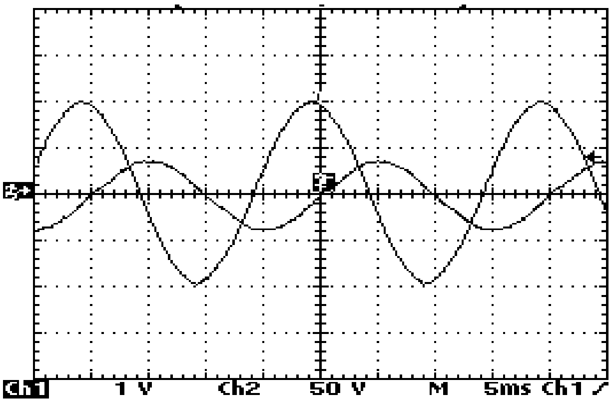

Fig. 7. Evolution of voltage Vs_{11}-Vs_{12} and stator current Is_1

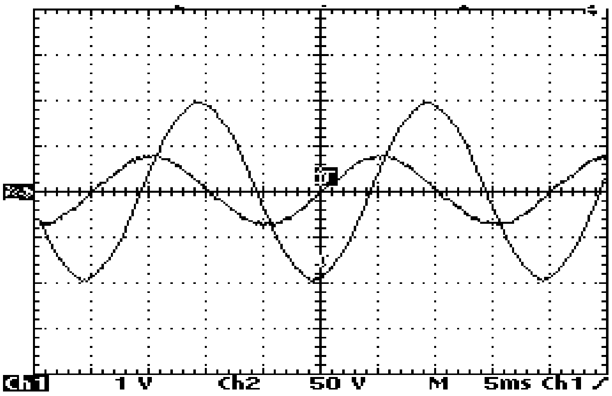

Fig. 8. Evolution of voltage Vs_{21}-Vs_{22} and stator current Is_1

VI. Feeding of the open-end winding induction machine by two voltage source inverters based on V/F law

In figure 9, the picture of the experimental platform represents an open-end stator induction machine of power P = 1.5 kW fed by two voltage source inverters of type Semikron based on the scalar control using the three-phase transformer with two secondary voltages in phase opposition (m = 1/2) for isolated.

The scalar control controlled the inverters for supply the machine, whose controller is embedded into Xilinx Spartan-3E FPGA board.

The program of scalar control is realized and validated in the MATLAB/Simulink environment using the Xilinx System Generator. It is implemented the program on the Xilinx FPGA Spartan-3E board. The experimental results of the different command signals for each inverter are visualized and verified the dead time between command signals of the switches [16].

The different experimental results of the voltage between phases to each entry of the three-phase stator winding as well the stator current of phase are shown in starting and permanent mode by the following figures.

The figure 10 shows the validation of the V/f law applied for the feeding machine by the results of the voltage between phases (Vs_{11}-Vs_{12}) and stator current of phase in starting mode.

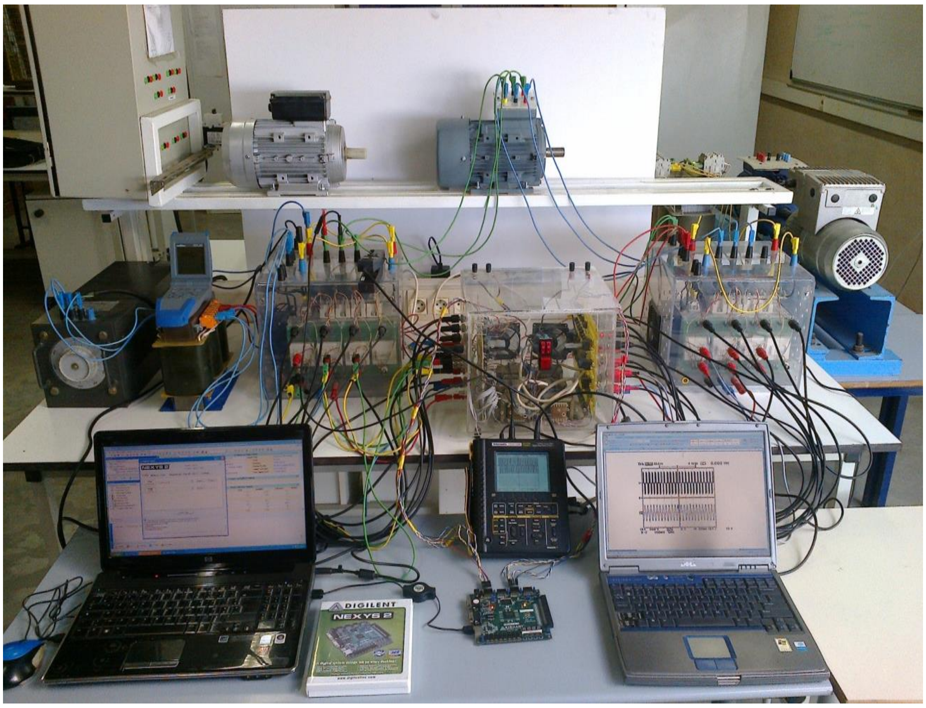

Fig. 9. Experimental plaform of the feeding open-end winding induction machine by two voltage source inveters based on V/f law

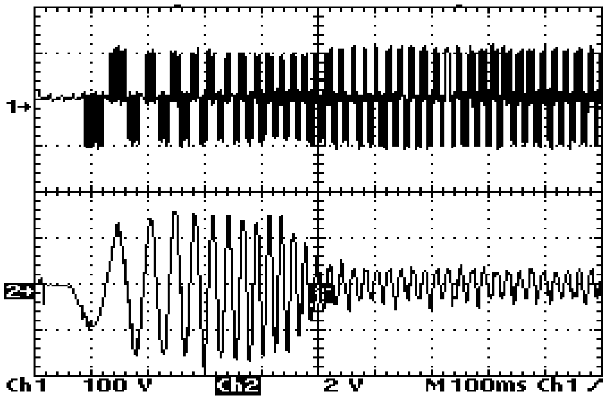

Fig. 10. Evolution of the voltage and stator current of the «OEWIM » conttrolled by V/f law

In permanent mode, the figures 11 and 12 show respectively the voltage between phases of each inverter and stator current of phase.

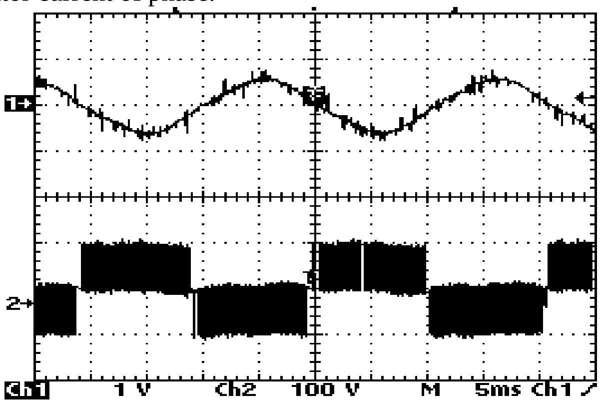

Fig. 11. Stator current and voltages between phases in entry 1.

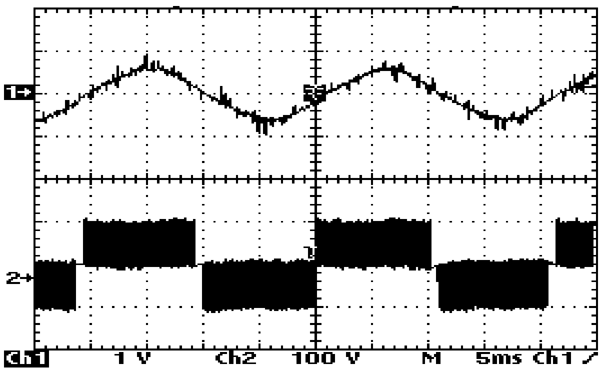

Fig. 12. Stator current and voltages between phases in entry 2

VII. Conclusion

The experimental plaform of proposed prototype for the power P = 1.5 kW, which is three-phase open-end stator winding induction machine is realized in our Laboratory. This prototype is fed by sinusoidal voltage using a three-phase transformer with two secondary voltages in phase opposition. Thereafter, the machine is supplied by two 2-level inverters of type Semikron with half Dc-link (E/2) of each inverter, where each inverter is dimensioned to a half power of machine.

Each inverter is controlled by scalar control implemented on FPGA Spartan 3E board. The validation of scalar control with controlled the open-end winding induction machine is shown by the obtained experimental results.

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