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BEHAVIOR ANALYSIS OF A DUAL STARS INDUCTION MOTOR SUPPLIED BY PWM MULTILEVEL INVERTERS

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Key words: Dual stars induction machine, Multilevel PWM voltage source inverter, Dynamical modelling, Behavior analysis, Current quality, Torque ripples.

This paper deals with a dynamical modelling in view of behavior analysis of double stars induction machine (DSIM) supplied by voltage source PWM inverter. Two modelling approaches are elaborated. In the first one the stator armatures of the DSIM are described by two coupled circuits in Concordia's frame. In the second approach the stator armatures of the DSIM are described by two decoupled circuits. One is equivalent to the model of three phase machine in Concordia's frame. And the other is equivalent to a passive circuit and does not produce torque. Based on the established electrical circuits, the effect of supply mode and the increasing of the inverter level on the current quality and the torque ripples are analyzed.

1. INTRODUCTION

Today no one can doubt the interest of the use of ac machines in the industry. Of course, three phases machine associated to power electronics converters are widely explored in the electrical energy conversion field. For some applications such as in the field transport or renewable energy exploitation [1–3], it is necessary to increase the power while ensuring the reliability of the energy conversion chain. Thus to obtain the required level of power and reliability, multiphase machine seems to be an interesting solution. These considerations have led researchers to study new electrical drives constituted of multiphase machines fed by PWM inverters [4–8]. Hence, modeling and vector control approaches are developed. These first studies [7] showed that, despite the feeding of the machine by two levels PWM inverters, not sequential current depending on the leakage inductance degrade the quality of the phase current and the electromagnetic torque. To solve this problem, one solution needs to exploit the emf's harmonics [8].

Looking at the side of power electronic converters, multi-level power electronics converter are widely investigated in many applications as electrical drive, flexible alternating current transmissions (FACTS) [9], active filters [10, 11]. Their use allows the segmentation of power while improving harmonic distortion.

This paper investigates and analyzes the behaviour of a double star induction machine (DSIM) supplied by two multi level voltage sources (PWM) inverters. This solution in addition to the segmentation of power and redundancy of the structure should help improve the quality of the supply voltage and reduce non-sequential currents. The paper is organized in four sections. After a short description of the electrical drive, more focus is accorded to dynamical modeling of the DSIM in various frames. Then, several simulations are carried and the results are analyzed based on the electrical equivalent circuits.

2. DESCRIPTION OF ELECTRICAL DRIVE

Figure 1 shows the electrical drive under study. It is composed by a dual stars induction machine. Each one is supplied by its own dc link voltage and controlled by a PWM unit. Two topologies of inverters are considered: two-level inverter and three-level neutral point clamped (NPC) inverter.

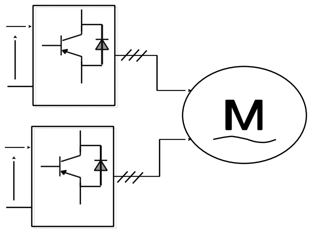

Fig. 1– Description of electrical drive.

3. MODELING OF DUAL STAR INDUCTION MACHINE

The dual star induction machine is composed by a stator with two identical three-phase windings, the first denoted (a_1, b_1, c_1) the second denoted (a_2, b_2, c_2) and shifted by an electrical angle γ and a squirrel cage (Fig. 2). When the rotor denoted (a_r, b_r, c_r) rotates at different speeds, the rotor cage becomes the seat of a system for generating three-phase electromotive forces, leading to induced rotor currents which manifest themselves by the development of a pair of electromagnetic forces on the rotor such that away speed is reduced [1–3].

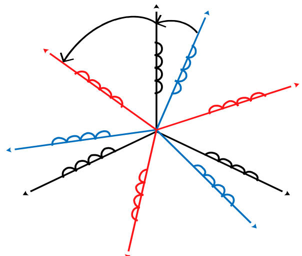

Fig. 2 – Configuring dual stars induction machine.

The modeling approach is based on the following assumptions: Magnetic saturation, hysteresis, eddy current, the temperature effect and the effect of skin are neglected. The magneto-motive forces created by each phase of the two plates have sinusoidal distribution, the inductances are

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constant, the mutual inductances between two windings are sinusoidal functions of the angle between their magnetic axes, and the machine has balanced constitution.

3.1. BASIC MODEL

Knowing that each star is a three phase winding and the rotor is modeled by an equivalent three phase winding, the DSIM can be considered as three magnetically coupled three phase windings.

3.1.1. VOLTAGE EQUATIONS

In the real reference called natural frame, the voltage equations can be written in the following matrix form:

$$\begin{cases} [\boldsymbol{v}_{s1}] = r_s[\boldsymbol{i}_{s1}] + \dfrac{d}{dt}\left([\boldsymbol{L}_{1,1}][\boldsymbol{i}_{s1}] + [\boldsymbol{L}_{1,2}][\boldsymbol{i}_{s2}] + [\boldsymbol{L}_{1,r}][\boldsymbol{i}_r]\right) \\ [\boldsymbol{v}_{s2}] = r_s[\boldsymbol{i}_{s2}] + \dfrac{d}{dt}\left([\boldsymbol{L}_{1,2}]^t[\boldsymbol{i}_{s1}] + [\boldsymbol{L}_{2,2}][\boldsymbol{i}_{s2}] + [\boldsymbol{L}_{2,r}][\boldsymbol{i}_r]\right), \\ [\boldsymbol{v}_r] = r_r[\boldsymbol{i}_r] + \dfrac{d}{dt}\left([\boldsymbol{L}_{1,r}]^t[\boldsymbol{i}_{s1}] + [\boldsymbol{L}_{2,r}]^t[\boldsymbol{i}_{s2}] + [\boldsymbol{L}_{r,r}][\boldsymbol{i}_r]\right) \end{cases} \quad (1)$$

with: $[\boldsymbol{v}_{s1}] = [\boldsymbol{v}_{as1} \quad \boldsymbol{v}_{bs1} \quad \boldsymbol{v}_{cs1}]^t$,

$[\boldsymbol{v}_{s2}] = [\boldsymbol{v}_{as2} \quad \boldsymbol{v}_{bs2} \quad \boldsymbol{v}_{cs2}]^t$, $[\boldsymbol{v}_r] = [\boldsymbol{v}_{ar} \quad \boldsymbol{v}_{br} \quad \boldsymbol{v}_{cr}]^t$;

$[\boldsymbol{i}_{s1}] = [\boldsymbol{i}_{as1} \quad \boldsymbol{i}_{bs1} \quad \boldsymbol{i}_{cs1}]^t$, $[\boldsymbol{i}_{s2}] = [\boldsymbol{i}_{as2} \quad \boldsymbol{i}_{bs2} \quad \boldsymbol{i}_{cs2}]^t$,

$[\boldsymbol{i}_r] = [\boldsymbol{i}_{ar} \quad \boldsymbol{i}_{br} \quad \boldsymbol{i}_{cr}]^t$.

The stator inductance matrix of each star is:

$$[\boldsymbol{L}_{1,1}] = [\boldsymbol{L}_{2,2}] = \begin{bmatrix} (L_{fs}+L_{ms}) & L_{ms}\cos\left(\frac{2\pi}{3}\right) & L_{ms}\cos\left(\frac{4\pi}{3}\right) \\ L_{ms}\cos\left(\frac{4\pi}{3}\right) & (L_{fs}+L_{ms}) & L_{ms}\cos\left(\frac{2\pi}{3}\right) \\ L_{ms}\cos\left(\frac{2\pi}{3}\right) & L_{ms}\cos\left(\frac{4\pi}{3}\right) & (L_{fs}+L_{ms}) \end{bmatrix}. \quad (2)$$

The rotor inductance matrix is:

$$[\boldsymbol{L}_{r,r}] = \begin{bmatrix} (L_{fr}+L_{mr}) & L_{mr}\cos\left(\frac{2\pi}{3}\right) & L_{mr}\cos\left(\frac{4\pi}{3}\right) \\ L_{mr}\cos\left(\frac{4\pi}{3}\right) & (L_{fr}+L_{mr}) & L_{mr}\cos\left(\frac{2\pi}{3}\right) \\ L_{mr}\cos\left(\frac{2\pi}{3}\right) & L_{mr}\cos\left(\frac{4\pi}{3}\right) & (L_{fr}+L_{mr}) \end{bmatrix}. \quad (3)$$

The mutual inductance matrix between the two stars is:

$$[\boldsymbol{L}_{1,2}] = L_{ms}\begin{bmatrix} \cos(\gamma) & \cos\left(\gamma+\frac{2\pi}{3}\right) & \cos\left(\gamma+\frac{4\pi}{3}\right) \\ \cos\left(\gamma-\frac{2\pi}{3}\right) & \cos(\gamma) & \cos\left(\gamma+\frac{2\pi}{3}\right) \\ \cos\left(\gamma-\frac{4\pi}{3}\right) & \cos\left(\gamma-\frac{2\pi}{3}\right) & \cos(\gamma) \end{bmatrix}. \quad (4)$$

The mutual inductance matrix between each star and the rotor is:

$$[\boldsymbol{L}_{i,r}] = L_{sr}\begin{bmatrix} \cos(\theta-(i-1)\gamma) & \cos\left(\theta-(i-1)\gamma+\frac{2\pi}{3}\right) & \cos\left(\theta+\frac{4\pi}{3}-(i-1)\gamma\right) \\ \cos\left(\theta-(i-1)\gamma-\frac{2\pi}{3}\right) & \cos(\theta-(i-1)\gamma) & \cos\left(\theta+\frac{2\pi}{3}-(i-1)\gamma\right) \\ \cos\left(\theta-\frac{4\pi}{3}-(i-1)\gamma\right) & \cos\left(\theta-\frac{2\pi}{3}-(i-1)\gamma\right) & \cos(\theta-(i-1)\gamma) \end{bmatrix} \quad (5)$$

In this study we considered that $L_{ms} = L_{mr} = L_{sr} = \frac{2}{3}L_m$.

3.1.2. TORQUE EQUATION

The torque equation can be deduced from the derivate of the co-energy as follow:

$$\Gamma_{em} = \frac{P}{2}\left(\left[[\boldsymbol{i}_{s1}]^t [\boldsymbol{i}_{s2}]^t \quad [\boldsymbol{i}_r]^t\right] \frac{\partial}{\partial\theta}\begin{bmatrix} [\boldsymbol{L}_{1,1}] & [\boldsymbol{L}_{1,2}] & [\boldsymbol{L}_{1,r}] \\ [\boldsymbol{L}_{1,2}]^t & [\boldsymbol{L}_{2,2}] & [\boldsymbol{L}_{2,r}] \\ [\boldsymbol{L}_{1,r}]^t & [\boldsymbol{L}_{2,r}]^t & [\boldsymbol{L}_{r,r}] \end{bmatrix}\begin{bmatrix} [\boldsymbol{i}_{s1}] \\ [\boldsymbol{i}_{s2}] \\ [\boldsymbol{i}_r] \end{bmatrix}\right) \quad (6)$$

where P is the number of poles of the machine. Knowing that only the mutual inductance matrices stator/rotor depends on θ, the torque expression can be simplified and become:

$$\Gamma_{em} = \frac{P}{2} \cdot \left([\boldsymbol{i}_{s1}]^t \frac{\partial}{\partial\theta}[\boldsymbol{L}_{1,r}] + [\boldsymbol{i}_{s2}]^t \frac{\partial}{\partial\theta}[\boldsymbol{L}_{2,r}]\right) [\boldsymbol{i}_r]. \quad (7)$$

3.2. MODEL OF DSIM IN CONCORDIA'S FRAMES $(\alpha_1\beta_1, \alpha_2\beta_2)$

Equation (1) shows that the voltage equations of the basic model depend on the rotor position θ. So its numerical resolution requires the matrix inversion at each step on simulation. Hence, in order to solve this problem, the electrical equations of DSIM will be written in Concordia's frames.

3.2.1 VOLTAGE EQUATIONS

Each three phase armature is described in its own Concordia's frame. In order to reduce the coupling terms between the two stars, the frame of the second star (α'_2, β'_2) will be turned with an angle γ Fig. 3 to (α_2, β_2).

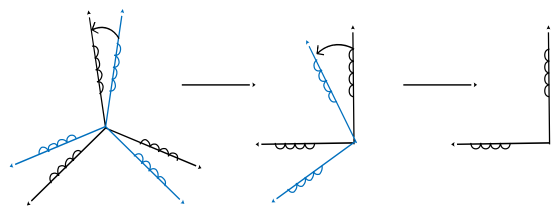

Fig. 3 – Transformation of double three phases system into dual diphase system.

Hence, two matrix transformation $T_{32}(\gamma)$ and T_{32} are defined as follow:

$$[\boldsymbol{T}_{32}] = \sqrt{\frac{2}{3}}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \text{ and } [\boldsymbol{T}_{32}(\gamma)]^t = [\boldsymbol{T}_{32}]^t\,[\boldsymbol{p}(\gamma)],$$

with $[\boldsymbol{p}(\gamma)] = \begin{bmatrix} \cos(\gamma) & -\sin(\gamma) \\ \sin(\gamma) & \cos(\gamma) \end{bmatrix}$.

To establish the new model, these transformations are applied to the voltage equations given by (1). After development of the calculations, the voltages equations in the new frame $(\alpha_1\beta_1, \alpha_2\beta_2)$ become:

$$\begin{cases}\left[\mathbf{v}_{\alpha\beta1}\right]=r_s\left[\mathbf{i}_{\alpha\beta1}\right]+\dfrac{d}{dt}\left(\begin{bmatrix}L_{fs}+L_m & 0\\ 0 & L_{fs}+L_m\end{bmatrix}\left[\mathbf{i}_{\alpha\beta1}\right]+ \atop +L_m\begin{bmatrix}1 & 0\\ 0 & 1\end{bmatrix}\left[\mathbf{i}_{\alpha\beta2}\right]+L_m\left[p(\theta)\right]\left[\mathbf{i}_{\alpha\beta r}\right]\right)\\ \left[\mathbf{v}_{\alpha\beta2}\right]=r_s\left[\mathbf{i}_{\alpha\beta2}\right]+\dfrac{d}{dt}\left(\begin{bmatrix}L_{fs}+L_m & 0\\ 0 & L_{fs}+L_m\end{bmatrix}\left[\mathbf{i}_{\alpha\beta2}\right]+ \atop +L_m\begin{bmatrix}1 & 0\\ 0 & 1\end{bmatrix}\left[\mathbf{i}_{\alpha\beta1}\right]+L_m\left[p(\theta)\right]\left[\mathbf{i}_{\alpha\beta r}\right]\right)\\ \left[\mathbf{v}_{\alpha\beta r}\right]=r_r\left[\mathbf{i}_{\alpha\beta r}\right]+\dfrac{d}{dt}\left(\begin{bmatrix}L_{fr}+L_m & 0\\ 0 & L_{fr}+L_m\end{bmatrix}\left[\mathbf{i}_{\alpha\beta r}\right]+ \atop +L_m\left[p(\theta)\right]\left[\mathbf{i}_{\alpha\beta1}\right]+L_m\left[p(\theta)\right]\left[\mathbf{i}_{\alpha\beta2}\right]\right).\end{cases} \quad (8)$$

The resulting model is equivalent to two three phase machine, with a coupling between the two stars in addition to the standard coupling between rotor and stator of an induction machine. This model is therefore strongly coupled and highlights the magnetic coupling between the two stars.

3.2.2. TORQUE EQUATION

By applying the transformation $T_{32}(\gamma)$ and T_{32} to torque expression given by equation (7), the torque expression becomes:

$$\Gamma_{em}=PL_m\left(i_{\alpha r}\left(i_{\beta1}+i_{\beta2}\right)-i_{\beta r}\left(i_{\alpha1}+i_{\alpha2}\right)\right). \quad (9)$$

3.3. MACHINE MODEL IN THE $\left(\alpha^+,\beta^+,\alpha^-,\beta^-\right)$FRAME

From equation (9) it can be seen that the torque expression depend on the sum of currents $\left(i_{\alpha1}+i_{\alpha2}\right)$ and $\left(i_{\beta1}+i_{\beta2}\right)$. Therefore the electrical model may be rewritten by making a change of variables using the sum of currents; and for reasons of bijectivity, the difference between currents, too. The following standardized transformation is defined [7]:

$$\begin{bmatrix}X_\alpha^+\\ X_\beta^+\\ X_\alpha^-\\ X_\beta^-\end{bmatrix}=\frac{1}{\sqrt{2}}\begin{bmatrix}1 & 0 & 1 & 0\\ 0 & 1 & 0 & 1\\ 1 & 0 & -1 & 0\\ 0 & 1 & 0 & -1\end{bmatrix}\begin{bmatrix}X_{\alpha s1}\\ X_{\beta s1}\\ X_{\alpha s2}\\ X_{\beta s2}\end{bmatrix}. \quad (10)$$

By applying this transformation to electrical equations (8), the following model is obtained

$$\begin{cases}\left[\mathbf{v}_{\alpha\beta^+}\right]=r_s\left[\mathbf{i}_{\alpha\beta^+}\right]+\dfrac{d}{dt}\left(\begin{bmatrix}L_{fs}+L_m & 0\\ 0 & L_{fs}+L_m\end{bmatrix}\left[\mathbf{i}_{\alpha\beta^+}\right]+ \atop +\sqrt{2}L_m\left[p(\theta)\right]\left[\mathbf{i}_{\alpha\beta r}\right]\right)\\ \left[\mathbf{v}_{\alpha\beta^-}\right]=r_s\left[\mathbf{i}_{\alpha\beta^-}\right]+\dfrac{d}{dt}\left(\begin{bmatrix}L_{fs} & 0\\ 0 & L_{fs}\end{bmatrix}\left[\mathbf{i}_{\alpha\beta^-}\right]\right)\\ \left[\mathbf{v}_{\alpha\beta r}\right]=r_r\left[\mathbf{i}_{\alpha\beta r}\right]+\dfrac{d}{dt}\left(\begin{bmatrix}L_{fr}+L_m & 0\\ 0 & L_{fr}+L_m\end{bmatrix}\left[\mathbf{i}_{\alpha\beta r}\right]+ \atop +L_m\left[p(\theta)\right]\left[\mathbf{i}_{\alpha\beta^+}\right]\right).\end{cases} \quad (11)$$

The major advantage of this model given in equation (11) is the decoupling between a first part which provides torque, and a second part which is the image of the leakages and losses of the machine. Thus the first part is equivalent of the three phase machine model.

4. RESULTS AND ANALYSIS OF THE DSIM BEHAVIOR DEPENDING ON THE SUPPLY MODE

In order to show the influence on the supply mode of DSIM on the phase current quality and electromagnetic torque ripples, several simulations were conducted. Fig. 4 shows the results obtained when DSIM is fed directly by two ideal three phase voltage sources. The two sources are sinusoidal and shifted by 30°. Consequently the torque is constant.

Indeed, as shown in Fig. 5, for this supply mode the voltage vector has a constant radius in the $\left(\alpha^+,\beta^+\right)$ plan and equal to zero in $\left(\alpha^-,\beta^-\right)$ plane. Hence the current vector in the plan $\left(\alpha^-,\beta^-\right)$ is zero. Therefore the phase current is perfectly sinusoidal and the couple does not oscillate.

Figures 6–9 show the results obtained when DSIM is supplied by PWM inverters phase voltage sources. Figs. 6 and 7 give the results with two level inverters. The phase currents are polluted by the switching effect of PWM unit, and torque undulates with switching frequency. These results allow us to highlight the problem related to this feeding mode. Unlike at the ideal voltage source supply case, voltage vectors of the two stars in Concordia's frame are not equal at any time. This gives a current flow between the two stars. Referring to the mathematical model in the equation (8), it is shown that the slope of this current is linked to the low leakage inductance. These results are confirmed by those obtained in Fig. 7. Indeed, as shown in Fig. 7, for this supply mode the voltage vector in $\left(\alpha^-,\beta^-\right)$ plan is different from zero. Hence a circulating current between the two stars appears. Therefore the phase current quality is degraded and the torque is oscillating. Now, as shown in Figs. 8 and 9 by increasing the level of the inverter, the supply voltage of the DSIM approximates the ideal sinusoidal voltage source. As shown in Figs. 8 and 9 by increasing the level of the inverter, the supply voltage of the DSIM approximates the ideal sinusoidal voltage source.

Hence the current filtering and reducing torque ripples are highlighted in the fig.8, the reduction of leak current $\left(i_{\alpha\beta^-}\right)$ leads to a decreasing torque ripples.

5. CONCLUSION

Based on dynamical modeling approaches, the temporal behavior of DSIM supplied by PWM voltage source inverters is investigated. The model in Concordia's frames ($\alpha_1\beta_1,\alpha_2\beta_2$) explains the origin of current flow between the two stars when are supplied by PWM inverters. As shown in the equivalent circuit, this current depends on the leakage inductance. It is zero if the supply voltages are sinusoidal and goes to zero if the inverter levels is increased. The second model in $(\alpha^+, \beta^+, \alpha^-, \beta^-)$ frame shows that the DSIM is equivalent to two parts, one equivalent to the classical three phase machine in Concordia frame, and the other equivalent to a passive circuit.

Hence only the first one produces a torque and the second is the origin of degradation of the current quality and torque ripples.

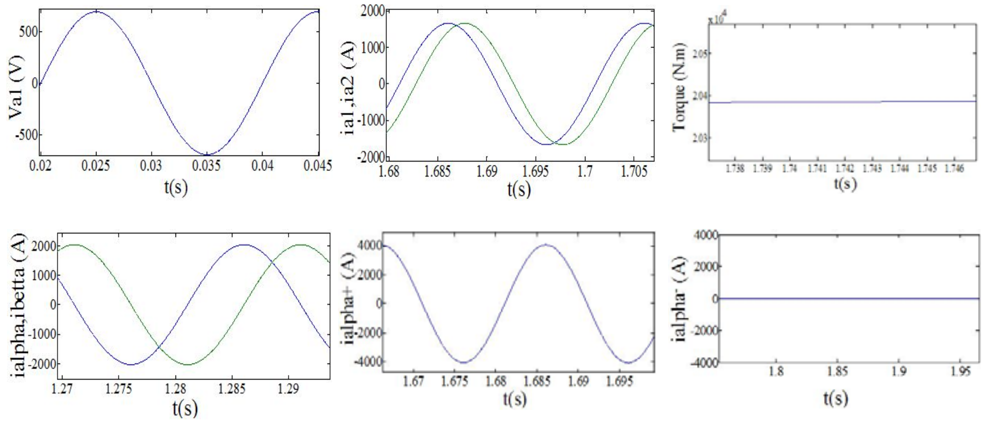

Fig. 4 – Simulation results with ideal voltage source.

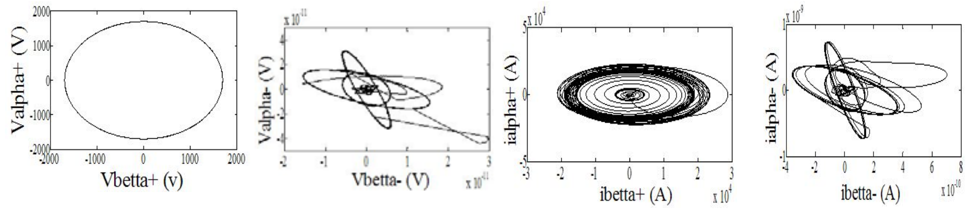

Fig. 5 – Simulation results in $(\alpha^+, \beta^+, \alpha^-, \beta^-)$ frame with ideal voltage source.

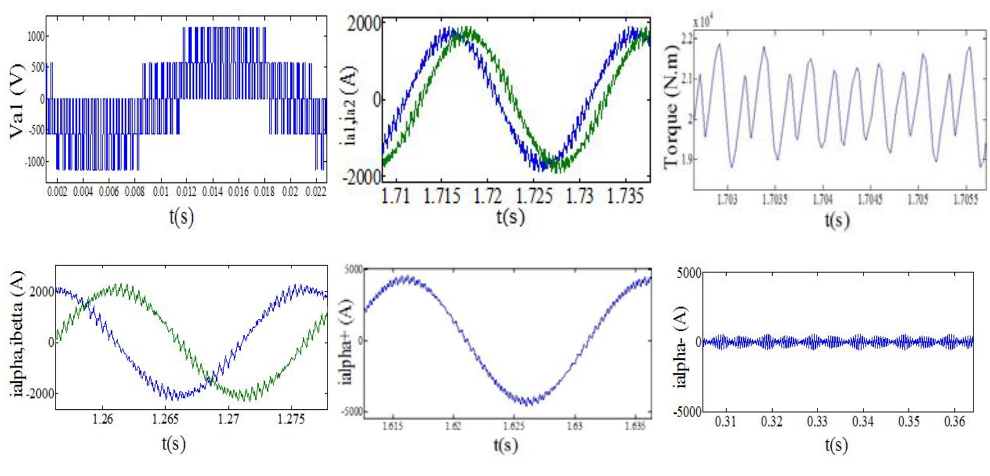

Fig. 6 – Simulation results with two levels inverter.

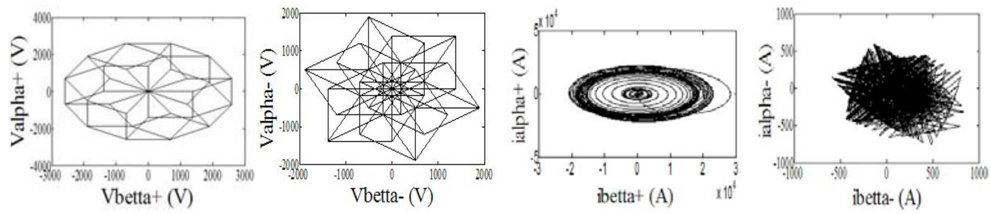

Fig. 7 – Simulation results in $(\alpha^+, \beta^+, \alpha^-, \beta^-)$ frame with two levels inverters.

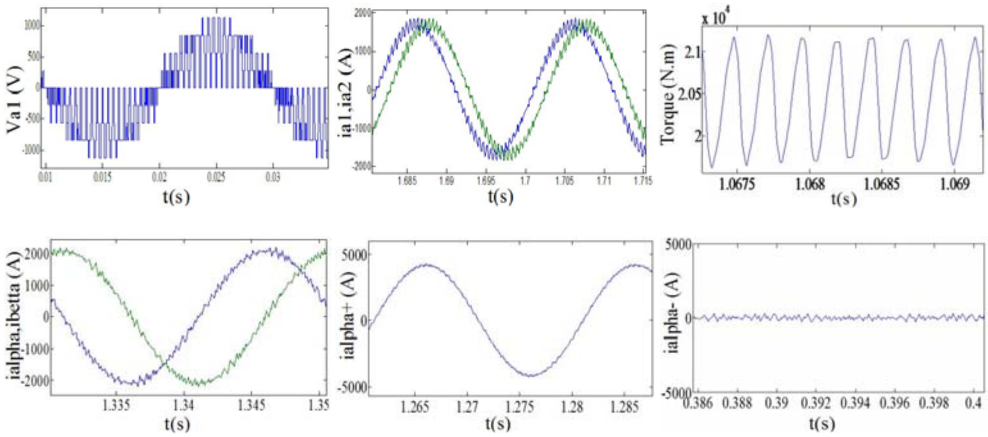

Fig. 8 – Simulation results with three levels inverter.

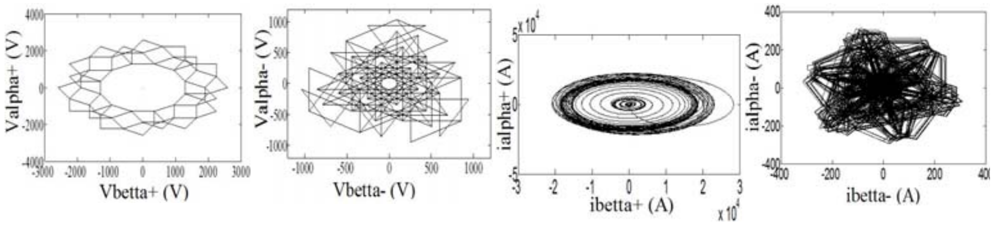

Fig. 9 – Simulation results in $\left(\alpha^{+}, \beta^{+}, \alpha^{-}, \beta^{-}\right)$ frame with three levels inverters.

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