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The Dual Open-End Winding Induction Machine Fed by Quad Inverters in Degraded Mode

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Abstract— In this paper, the different failed inverters for the feeding dual open-end stator winding induction machine is proposed. Each input of open-end stator winding is supplied by one three phase voltage source inverter. The different conditions must be respect after first, second and third failure in four inverters feeding the machine are presented.This study shows the advantage of the dual open-end stator winding induction machine to improve the availability of service of a variable speed drive.

Index Terms— Availability, Dual open-end stator winding induction machine, Failed inverter, Operation degraded mode, Three phase 2-level inverter.

1 Introduction

THe improvement availability, reliability and the power segmentation of the speed drive application became an essential purpose for the industrialization of the high power equipment.

The concept of PEBB (Power Electronic Bulding Block) initiated by the ONR (Office of Research Noval) and CPES (USCenter of Power Electronics System), aims to improve reliability, modularity, standardization, reconfigurability scalability and the cost of electrical systems in many fields such as railways applications, aeronautics, electrical propulsion of ships and electrical vehicles systems…[1], [2],[3].

A considerable interest is given for multiphase machines [4], or the multi star Asynchronous machines [5],[6],[7] and open-end winding asynchronous machine [8],[9],[10],[11] ,[12],[13].

The use of the multi-open-end stator winding asynchronous machine offers multiple redundancy degrees [14].

The dual open-end stator winding induction machine is composed by two sets of stator windings spatially shifted by 0 or 30 degrees angle. Each input is fed by one voltage inverters that offer more degrees of liberty in degraded mode which can be utilized to enable the operation with faulty inverter.

In the first part of the paper, the authors devote the simulation model of dual open-end winding induction machine for voltage supply by four three-phase inverters.

In the second part, they proposed the operation of feeding machine in degraded mode; indeed several respective failure inverters are treated.

The conditions must be respected to guarantee the performances of the drive system are presented.

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2 Simulation Model For Voltage Supply

The dual open-end stator winding induction machine is fed by four voltage inverters as shown by the figure 1. Each inverter is dimensioned to a quarter power of the machine.

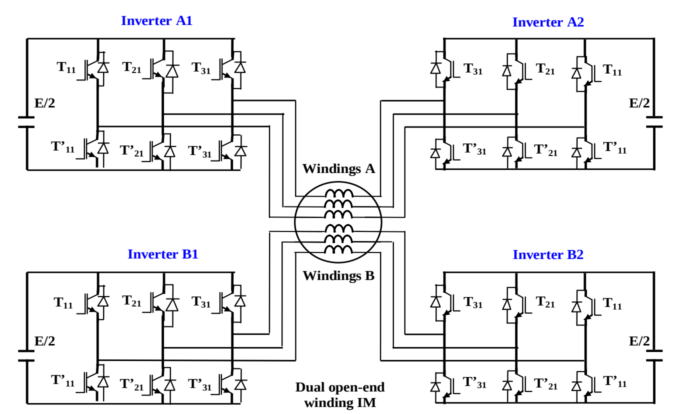

Fig. 1. The dual open-end winding induction machine is supplied by four 2-level inverters.

The voltage supplies of the dual open-end stator winding induction machine are represented by the figure 2.

With:

V_{SA11}, V_{SA12} and V_{SA13} simple voltage of inverter A1
V_{SA21}, V_{SA22} and V_{SA23} simple voltage of inverter A2
V_{SB11}, V_{SB12} and V_{SB13} simple voltage of inverter B1
V_{SB21}, V_{SB22} and V_{SB23} simple voltage of inverter B2
(V_{SA11}-V_{SA12}) pole voltage of inverter A1
(V_{SA21}-V_{SA22}) pole voltage of inverter A2
(V_{SB11}-V_{SB12}) pole voltage of inverter B1
(V_{SB21}-V_{SB22}) pole voltage of inverter B2
U_A= (V_{SA11}-V_{SA12}) - (V_{SA21}-V_{SA22}) pole voltage of the machine (stator windings A).
U_B = (V_{SB11}-V_{SB12}) - (V_{SB21}-V_{SB22}) pole voltage of the machine (stator windings B).

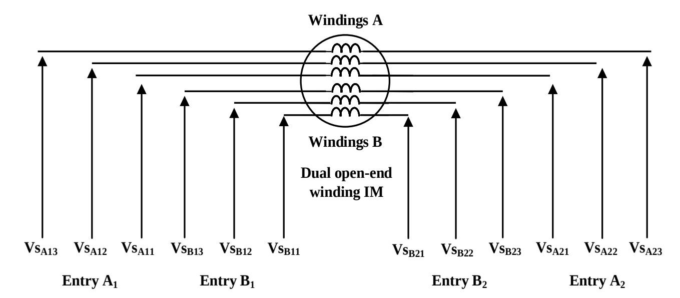

Fig 2. Feeding dual open-end winding induction machine

The functional diagram of the dual open-end stator winding induction machine model is given by figure 3.

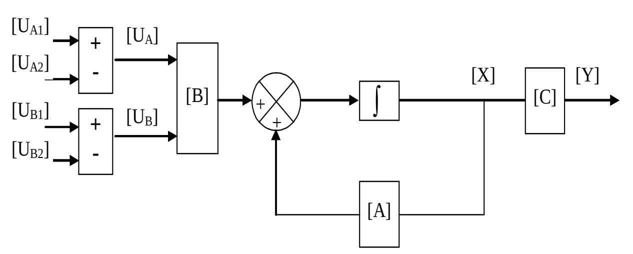

Fig 3. Functional diagram of the open-end winding machine.

The mathematical flux model is written in (d,q) reference frame, and described by the following state equation representation.

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

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

$$X(t) = \left[\Phi s_{d1}, \Phi s_{q1}, \Phi s_{d2}, \Phi s_{q2}, \Phi r_d, \Phi r_q\right]^t \qquad (2)$$

$$U(t) = [\ UA\ UB\ ]t$$

$$= \left[Vs_{dA1} - Vs_{dA2} \quad Vs_{qA1} - Vs_{qA2} \quad Vs_{dB1} - Vs_{dB2} \quad Vs_{qB1} - Vs_{qB2}\right]^t \qquad (3)$$

$$Y(t) = \left[Is_{d1}, Is_{q1}, Is_{d2}, Is_{q2}\right]^t \qquad (4)$$

X(t): State vector
U(t): Control vector
Y(t): Ouput vector

The state matrix is determined by the following expression:

$$\left[A(\omega(\omega_{dq})\right] = -\left(\left[R\right]\left[L_{d,q}\right]^{-1} + \left[\omega\right]\right) \qquad (5)$$

[A]=

$$\begin{bmatrix} -k_4(Rs+\frac{k_1 Ms_1 r}{\tau r}) & 0 & k_4(\frac{k_3}{\sigma_2\tau s}-\frac{k_1 Ms_2 r}{\tau r}) & 0 & \frac{k_4 k_1}{\tau r} & k_4 k_1\omega \\ 0 & -k_4(Rs+\frac{k_1 Ms_1 r}{\tau r}) & 0 & k_4(\frac{k_3}{\sigma_2\tau s}-\frac{k_1 Ms_2 r}{\tau r}) & -k_4 k_1\omega & k_4\frac{k_1}{\tau r} \\ k_5(\frac{k_3}{\sigma_1\tau s}-\frac{k_2 Ms_1 r}{\tau r}) & 0 & -k_5(Rs+\frac{k_2 Ms_2 r}{\tau r}) & 0 & \frac{k_5 k_2}{\tau r} & k_5 k_2\omega \\ 0 & k_5(\frac{k_3}{\sigma_1\tau s}-\frac{k_2 Ms_1 r}{\tau r})) & 0 & -k_5(Rs+\frac{k_2 Ms_2 r}{\tau r}) & -k_5 k_2\omega & k_5\frac{k_2}{\tau r} \\ \frac{Ms_1 r}{\tau r} & 0 & \frac{Ms_2 r}{\tau r} & 0 & -\frac{1}{\tau r} & -\omega \\ 0 & \frac{Ms_1 r}{\tau r} & 0 & \frac{Ms_2 r}{\tau r} & \omega & -\frac{1}{\tau r} \end{bmatrix}$$

(6)

With:

Msr_1: Mutual maximal cyclic inductance between winding A and rotor.

Msr_2: Mutual maximal cyclic inductance between winding B and rotor.

$\tau_s = \frac{L_s}{R_s}$: Constant of time for the stator

$\tau_r = \frac{L_r}{R_r}$: Constant of time for the rotor

$\sigma_1 = 1 - \frac{Ms_1 r^2}{LrLs}$: coefficient of dispersion relatively winding A

$\sigma_2 = 1 - \frac{Ms_2 r^2}{Ls.Lr}$: coefficient of dispersion relatively winding B

$$K_1 = \frac{Ms_1 r}{Lr} - \frac{K_3\, Ms_2 r}{\sigma_2 LsLr},$$

$$K_2 = \frac{Ms_2 r}{Lr} - \frac{K_3\, Ms_1 r}{\sigma_1 LsLr},$$

$$K_3 = Mss - \frac{Ms_1 r\, Ms_2 r}{Lr}$$

$$K_4 = \frac{\sigma_2\, Ls}{\sigma_1\sigma_2 Ls^2 - K_3{}^2},$$

$$K_5 = \frac{\sigma_1\, Ls}{\sigma_1\sigma_2 Ls^2 - K_3{}^2}.$$

$$[R] = \begin{bmatrix} Rs & 0 & 0 & 0 & 0 & 0 \\ 0 & Rs & 0 & 0 & 0 & 0 \\ 0 & 0 & Rs & 0 & 0 & 0 \\ 0 & 0 & 0 & Rs & 0 & 0 \\ 0 & 0 & 0 & 0 & Rr & 0 \\ 0 & 0 & 0 & 0 & 0 & Rr \end{bmatrix} \qquad (7)$$

$$[\omega] = \begin{bmatrix} 0 & -\omega_{dq} & 0 & 0 & 0 & 0 \\ \omega_{dq} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -\omega_{dq} & 0 & 0 \\ 0 & 0 & \omega_{dq} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & -(\omega_{dq}-\omega) \\ 0 & 0 & 0 & 0 & (\omega_{dq}-\omega) & 0 \end{bmatrix} \qquad (8)$$

$$[L_{(d,q)}] = \begin{bmatrix} Ls & 0 & Mss & 0 & Ms_1 r & 0 \\ 0 & Ls & 0 & Mss & 0 & Ms_1 r \\ Mss & 0 & Ls & 0 & Ms_2 r & 0 \\ 0 & Mss & 0 & Ls & 0 & Ms_2 r \\ Ms_1 r & 0 & Ms_2 r & 0 & Lr & 0 \\ 0 & Ms_1 r & 0 & Ms_2 r & 0 & Lr \end{bmatrix} \qquad (9)$$

In case of failure in inverters A_1 and A_2, it could be disconnected from stator windings A.

In the inductance matrix is:

$[L_{d,q}]_{faultA}$ the terms involving Msr_1 and Mss can be ignored

$$[L_{(d,q)}]_{faultA} = \begin{bmatrix} Ls & 0 & 0 & 0 & 0 & 0 \\ 0 & Ls & 0 & 0 & 0 & 0 \\ 0 & 0 & Ls & 0 & Ms_2 r & 0 \\ 0 & 0 & 0 & Ls & 0 & Ms_2 r \\ 0 & 0 & Ms_2 r & 0 & Lr & 0 \\ 0 & 0 & 0 & Ms_2 r & 0 & Lr \end{bmatrix} \qquad (10)$$

Similarly, in the inductance matrix $[L_{d,q}]_{fault2}$ the terms involving Msr_2 and Mss can be ignored in case of the disconnection of stator windings B.

$$[L_{(d,q)}]_{faultB} = \begin{bmatrix} Ls & 0 & 0 & 0 & Ms_1r & 0 \\ 0 & Ls & 0 & 0 & 0 & Ms_1r \\ 0 & 0 & Ls & 0 & 0 & 0 \\ 0 & 0 & 0 & Ls & 0 & 0 \\ Ms_1r & 0 & 0 & 0 & Lr & \\ 0 & Ms_1r & 0 & 0 & 0 & Lr \end{bmatrix} \quad (11)$$

$$[C]=\left[L_{d,q}\right]^{-1} \quad (12)$$

$$[B]=\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \quad (13)$$

3 Modeling Validation

The simulation model is validated in the Matlab simulink environment. The dual open-end winding induction machine is fed by four PWM voltage source inverters based on V/f law.

The following cycle of the operation, of t = 0 to t = 0.6 s, the system has a starting cycle, from t = 0.6 s to t = 1s, the machine is working in no-load conditions. At time t = 1s, a load torque Tr = 300mN is applied.

Figure 4 shows the pole voltage machine $U_A = (V_{SA11}-V_{SA12}) - (V_{SA21}-V_{SA22})$, the pole voltage machine $U_B = (V_{SB11}-V_{SB12}) - (V_{SB21}-V_{SB22})$, the stator currents, the speed and the torque.

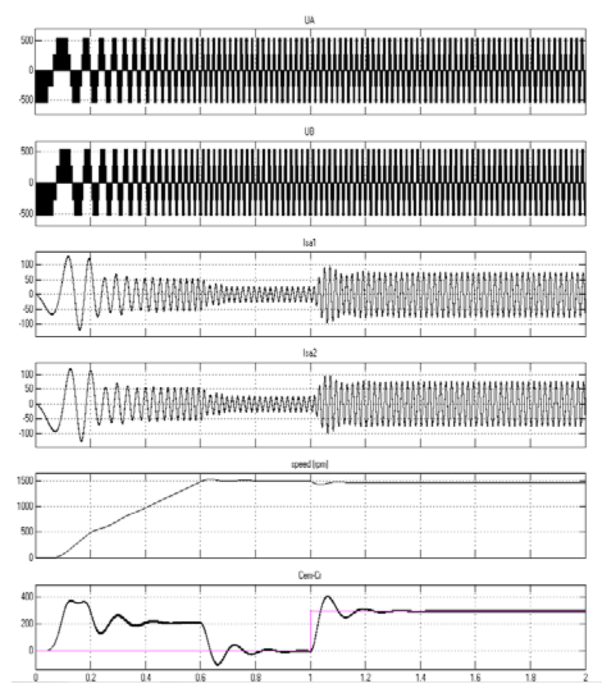

Fig 4. Pole voltage, stator currents, speed and torque for a machine starting between 0 and 0.6s, then the nominal torque impact at t = 1 s

4 Operation Machine In Degraded Mode

We are interested to supply the dual open-end winding induction machine by four voltage source inverters in degraded mode, and then several failure in inverters are treated.

4.1 First failed inverter

In the first case we considered the first failed inverter exemple A2 as shown by the figure 5.

Thus the three inverters ensure the supply machine, indeed the inverter A2 is reconfigured that it ensures the star coupling of the stator windings A.

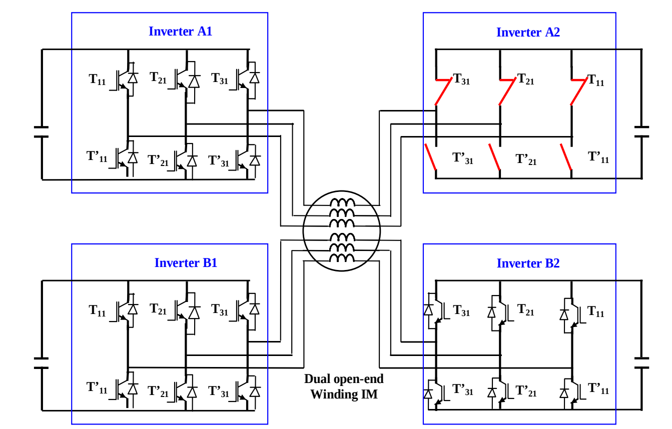

Fig 5. Feeding Dual open-end winding IM by four inverters then failed inverter A2

To avoid an imbalance between the two operating stator windings, one solution is to reduce the DC bus of the windings B. The speed will be reduced to 70% of its nominal value for a load torqueTr = kn^2.

Figure 6 shows the simulation results for a load torque Tr = kn^2. At t = 1.2 s we reconfigured the ordering of the inverter A2 following a default.

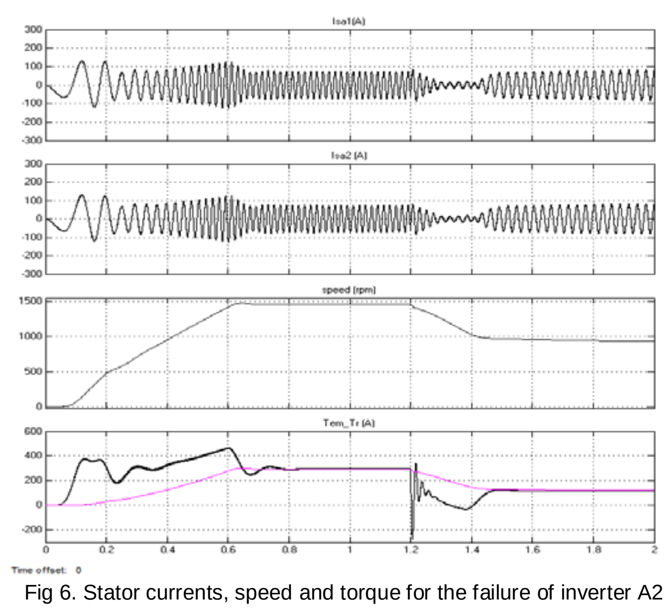

Fig 6. Stator currents, speed and torque for the failure of inverter A2 with speed limited at 70%

Figure 7 shows the evolution of the phase to phase volage inverters (Vs_{A11}-Vs_{A12}) of entry A1, (Vs_{A21}-Vs_{A22}) of entry A2 that equal to zero of failed inverter A2, (Vs_{B11}-Vs_{B12}) of entry B1 and (Vs_{B21}-Vs_{B22}) of entry B2. Thus machine voltage U_A = (Vs_{A11}-Vs_{A12}) - (Vs_{A21}-Vs_{A22}) of winding A and U_B = (Vs_{B11}-Vs_{B12}) - (Vs_{B21}-Vs_{B22}) of winding B.

Fig 7. Simulated waveforms of the phase to phase voltage inverters and machine for the failure inverter A2 at t = 1.2s

Also, it is possibole to operate the machine at nominal speed after the failure A2 inverter, however the inverters must be dimensioned by the half power of the machine, and the DC bus of the inverter A1 must be double. This solution although it is very effective, it is difficult to achieve. Thereafter the first solution is considered.

Figure 8 shows the pole voltage of the A1 inverter after the failed A2 inverter, we note at moment the level decrease of the pole voltage machine UA.

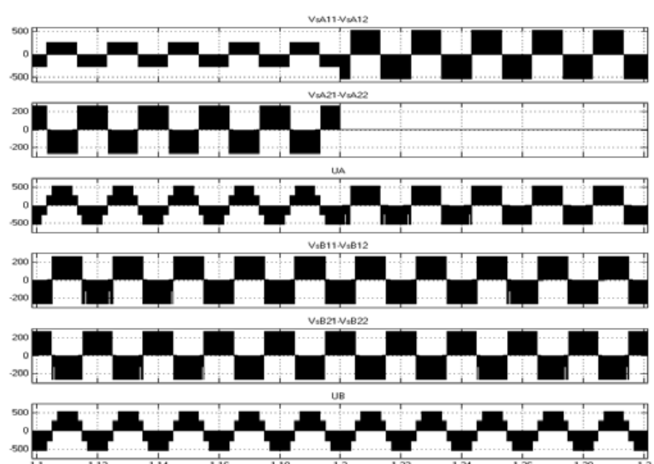

Fig 8. Enlarging effect of the phase to phase voltage inverters and machine before and after the failure inverter A2 at t = 1.2s

Figure 9 shows the stator currents, the speed and the torque with the DC bus of the A1 inverter is double, when the A2 inverter is failed at t = 1.2s

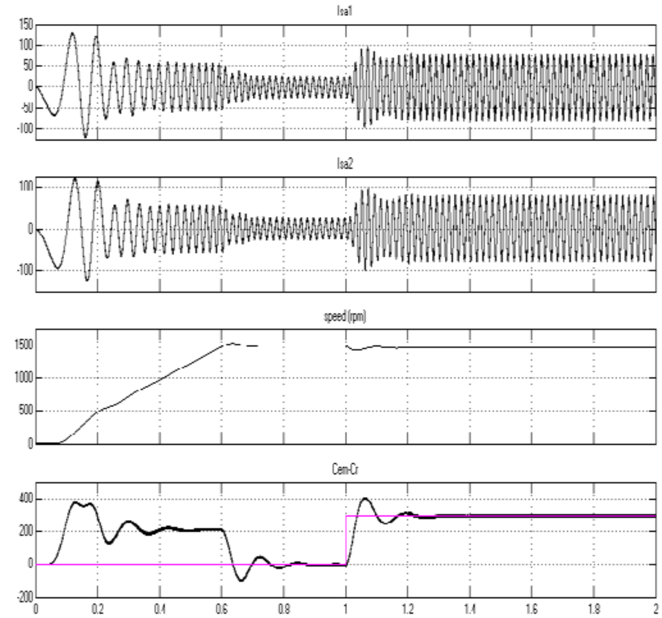

Fig 9. Stator currents, speed and torque for the failure A2 inverter with nominale speed and DC bus of the A1 inverter is double

4.2 Second failed inverter

4.2.1 First configuration

If we considered that the failure inverter A2, then it ensures the star of the winding A and the second failure occurred at the inverter A1 as shown by figure 10.

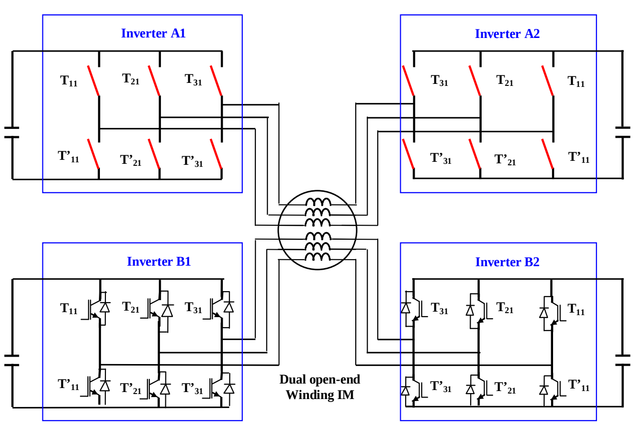

Fig 10.Feeding the machine for the failure of inverters A1 then A2

We have an equivalent operation to the open-end winding induction machine is supplied by two 2-level inverters, compulsorily speed reduced to 70% of nominal value for the load torque Tr = kn², as shown by the figure 11.

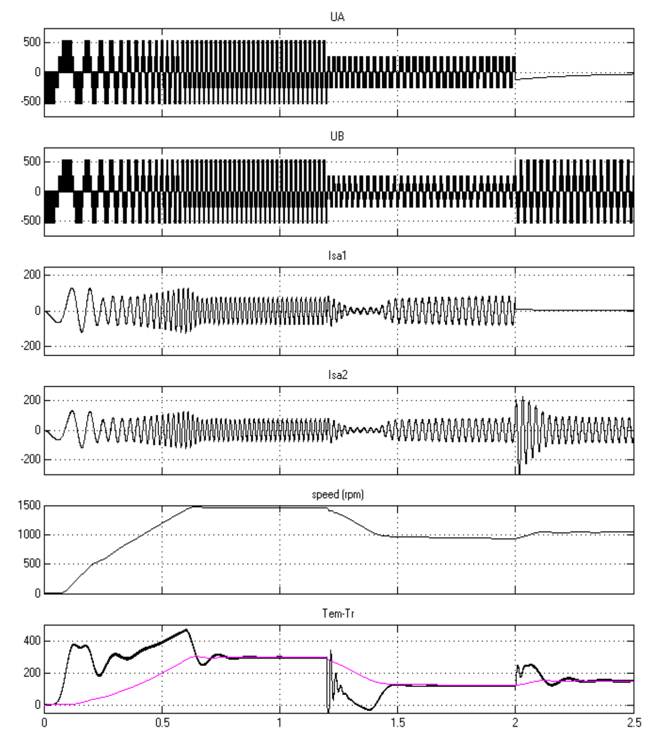

Fig 11. Pole voltage of the machine, stator currents, speed and torque for the failure of inverters A1 then A2

4.1.2 Second configuration

If we considered that the failure inverter A2 and the second failure occurred at the inverter B2 or inversely, similary for inverters A1 and B1; as shown by the figure 12.

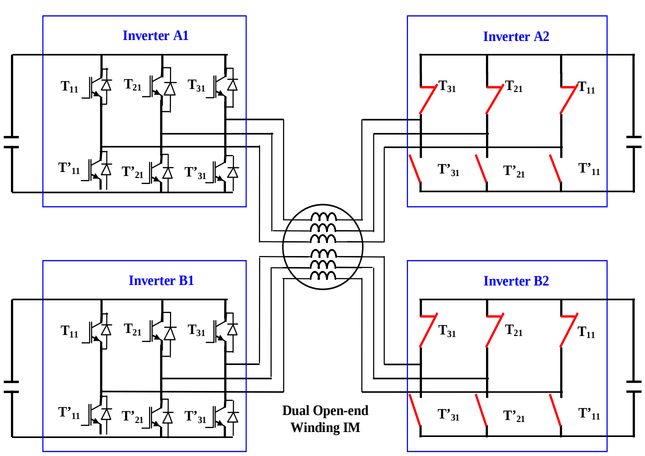

Fig 12.Feeding the machine for the failure of inverters A2 then B2

Then, we have an equivalent operation to the double star asynchronous machine is fed by two three phase 2-level inverters, which must be reduced to 70% of nominal value for the load torque $T_r = kn^2$. The two failure inverters A2 and B2 must ensure the star of the two windings A and B.

The simulation results of the evolution phase to phase-machine voltage, stator currents, speed and the torqueis shown by the figure 13.

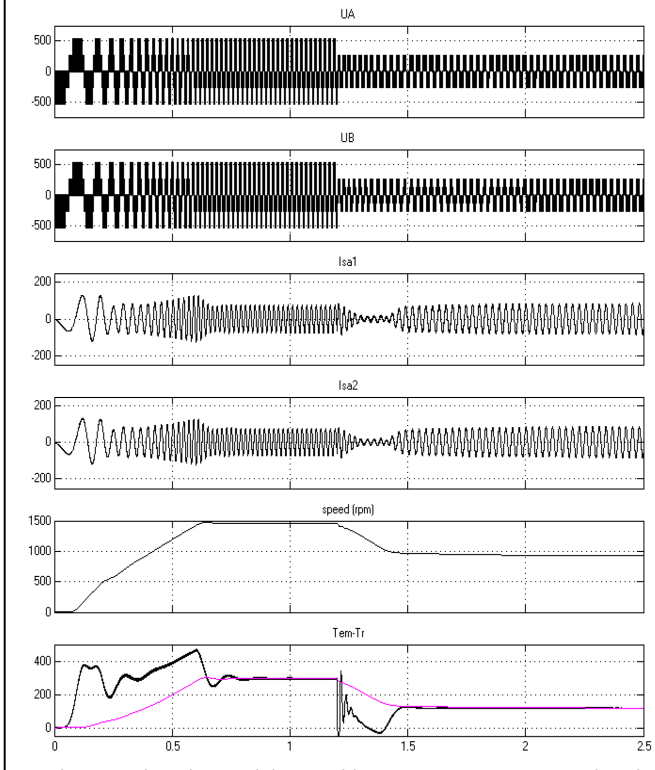

Fig 13. Pole voltage of the machine, stator currents, speed and torque

4.3 Third failed inverter

4.3.1 First configuration

In the second case we considered third failed inverter. We considered primarily, first configuration of the second failure Figure 10. That is to say when one winding is supplied by the two inverters B1 and B2.

The third failure will be at the inverter B1 or B2 as shown in Figure 14, This will ensure the star of the winding B.

Similarly if the winding A is fed, the third failure will be at the inverter A1 or A2.

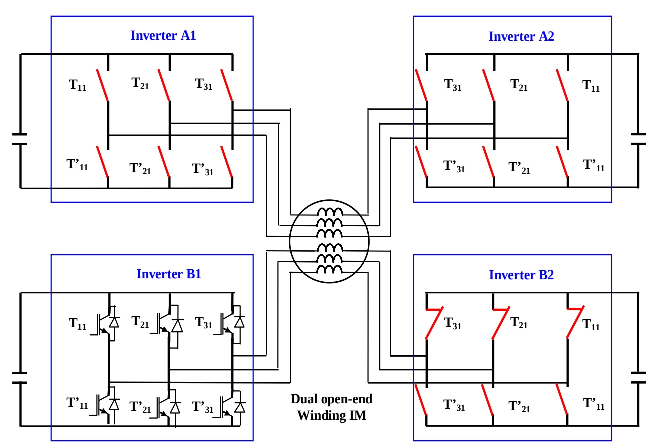

Fig 14. Feeding the machine for the failure of inverters A2, B2 then A1

We will have an equivalent to the conventional induction machine with speed reduced to 50% of its nominal value operation.

Figure 15 shows the machine operation with the first failure inverter A2 at t = 1.2s, the second failure inverter A1 at t = 2s, and third failure inverter B2 at t = 2.5s.

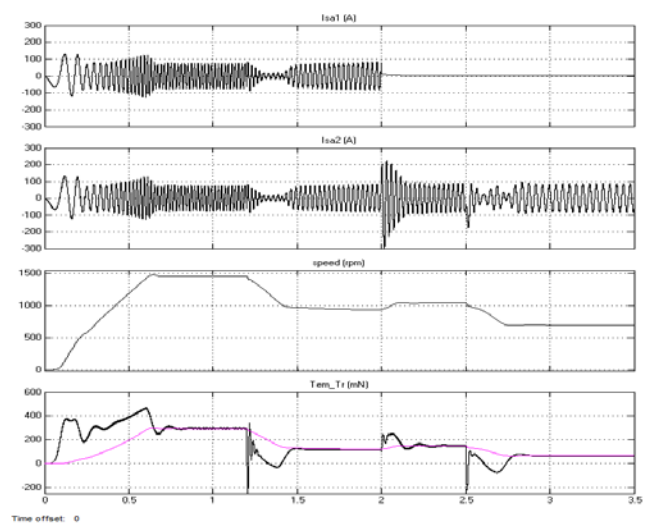

Fig 15. The stator currents, speed and torque for the failure of inverters A2, A1 then B2

Figure 16 shows simulation results of the evolution voltage for the different failed inverters.

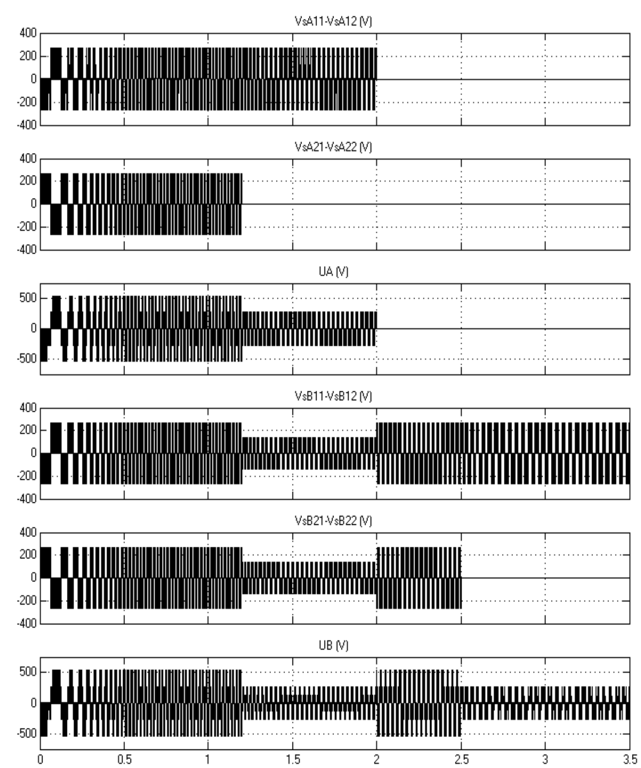

Fig 16. Simulated waveforms of the phase to phase voltage inverters and machine for the failed inverters A2, A1 then B2

The phase to phase volage inverters (Vs_{A21} - Vs_{A22}) of entry A2 that equal zero at t = 1.2 s, (Vs_{A11} - Vs_{A12}) of entry A1 equal zero at t = 2 s , (Vs_{B11} - Vs_{B12}) of entry B1 and (Vs_{B21} - Vs_{B22}) of entry B2 equal zero at t = 2.5 s. Thus machine voltage U_A = (Vs_{A11}-Vs_{A12}) - (Vs_{A21}-Vs_{A22}) of winding A and U_B = (Vs_{B11}-Vs_{B12}) - (Vs_{B21}-Vs_{B22}) of winding B.

4.3.2 Second configuration

In the second case we considered the configuration of the second failure Figure 12. That is to say when the two windings are supplied by the two inverters A1 and B1.

Third failure will be at the inverter A1 or B1 feeding one of the two windings.

In this case you must open the ends of the winding, the two converters are down, the third inverter B2 will continue to ensure the star of the winding operation such a configuration is shown in Figure 14.

We will have an equivalent to the conventional induction machine with speed reduced to 50% of its nominal value operation.

Figure 17 shows the machine operation with the first failure inverter A2 at t = 1.2s, the second failure inverter B2 at t = 2s, and third failure inverter B1 at t = 2.5s.

Figure 18 shows the evolution voltage for the different successive failed inverters.

The phase to phase volage inverters (Vs_{A11}-Vs_{A12}) of entry A1, (Vs_{A21}-Vs_{A22}) of entry A2 that equal to zero of failed inverter A2, (Vs_{B11}-Vs_{B12}) of entry B1 and (Vs_{B21}-Vs_{B22}) of entry B2that equal to zero of failed inverter B2 at t = 2s. Thus machine voltage U_A = (Vs_{A11}-Vs_{A12}) - (Vs_{A21}-Vs_{A22}) of winding A and U_B = (Vs_{B11}-Vs_{B12}) - (Vs_{B21}-Vs_{B22}) of winding B,that equal to zero of failed inverters B1 and B2.

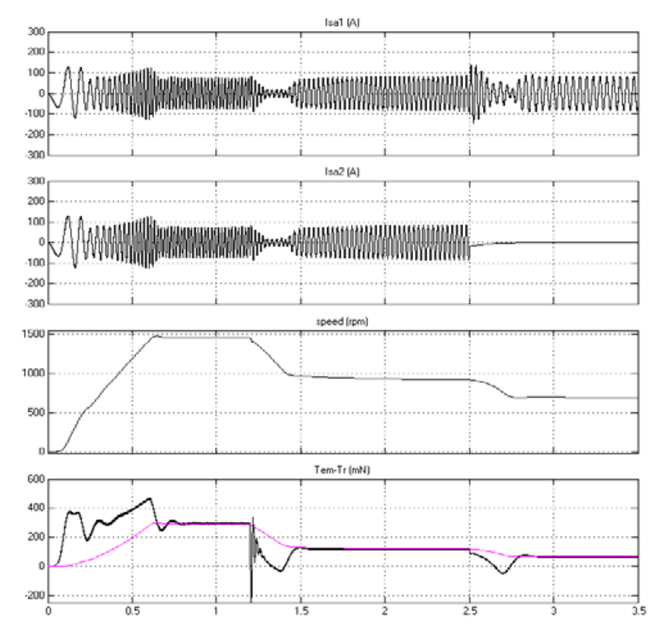

Fig 17. The stator currents, speed and torque for the failed inverters A2, B2 then B1

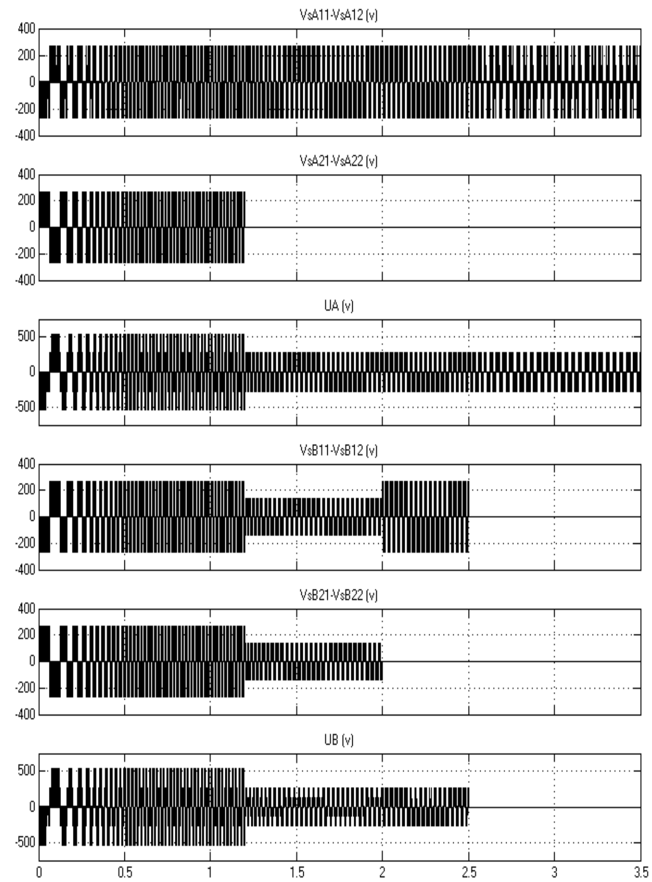

Fig 18. Simulated waveforms of the phase to phase voltage inverters and machine for the failed inverters A2, B2 then B1.

The characteristics of the machine used:

Power nominal P = 45 KW.
Speed n = 1450 tr/min.
Resistance of stator Rs = 0.3 Ω.
Resistance of rotor Rr = 0.046 Ω.
Inductance of stator Ls = 17.9 mH.
Inductance of rotor Lr = 18.6 mH.
Mutual inductance Msr = 17.2 mH.

5 Conclusion

We implemented the simulation model of the dual open-end stator winding induction machine for voltage supply in the Matlabsimulink environment.

We have presented the operation of dual open-end stator winding is supplied by four three phase 2-level inverters in degraded mode; different successive failed inverters for feeding machine are studied.

The advantage of the machine in degraded mode is that it can continue to operate when a default appears in one, two or three of the four inverters.

This study shows the importance that presents such a machine structure, for power segmentation, improved reliability and continuity of service of the system.

The simulation results show that It would be very interesting to use the field oriented control strategy to reduce the currents peaks when the failures inverters.

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