FAULT-TOLERANT CONTROL FOR OPEN-END STATOR WINDING INDUCTION MACHINE SUPPLIED BY TWO THREE PHASE CASCADED INVERTERS WITH ONE FAILED INVERTER

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Abstract: *In this paper the authors propose the degraded mode operation of the open-end stator winding induction machine supplied by two converters on three levels. Each converter is constituted by two three-phase inverters in cascaded. The different conditions that must be respected for the operation mode will be presented.*

Key words: *Cascaded converter, degraded mode, open-end winding induction machine, two levels inverter.*

1. Introduction

The power segmentation 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, scalability, reconfigurability and the cost of electrical systems in many fields such as railways applications, aeronautics, electrical propulsion of ships and electrical vehicles systems…[1-3].

In order to achieve this objective, the operation is based on the replacement of high power large converter by the association of lower power several converters. The power segmentation of the electric machines and inverters is now a major interest in electrical engineering researches. A considerable interest is given for multiphase machines, or the multi star Asynchronous machines and open-end winding asynchronous machine [4-8].

In the first part of the paper, the authors devote the simulation model of open-end winding induction machine for voltage supply by two three-phase cascaded inverters using “Matlab Simulink environment”.

The second part of the paper deals with the dimensioning switches of the three-phase cascaded inverters for given solutions when it is operating in degraded mode.

Finally this paper gives an operation analysis of the open-end winding induction machine supplied by three-phase cascaded inverters in degraded mode. For the operation in degraded mode, the conditions must be respected to guarantee the performance of the drive system. Indeed, four configurations are presented in this research work.

2. Open-end winding induction machine model 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 equations representation:

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

Where:

$X(t) = \left[\Phi\right] = \left[\Phi_{sd} \quad \Phi_{sq} \quad \Phi_{rd} \quad \Phi_{rq}\right]^T$: The State vector

$U(t) = U_1(t) - U_2(t) = \left[V_{sd1} - V_{sd2} \quad V_{sq1} - V_{sq2}\right]^T$: The Control vector

$Y(t) = \left[I\right] = \left[I_{sd} \quad I_{sq} \quad I_{rd} \quad I_{rq}\right]^T$: The output vector

The functional diagram is given by figure 1:

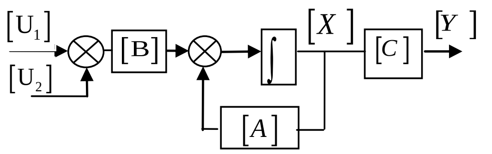

Fig. 1. Functional diagram of the open-end winding machine.

The equation of current vector is:

$$[I]=[L]^{-1}[\Phi] \quad (2)$$

$$[A]=\begin{bmatrix} -\frac{1}{\sigma\tau_s} & \omega_{dq} & \frac{Msr}{\sigma\tau_s L_r} & 0 \\ -\omega_{dq} & -\frac{1}{\sigma\tau_s} & 0 & \frac{Msr}{\sigma\tau_s L_r} \\ \frac{Msr}{\sigma\tau_r L_s} & 0 & -\frac{1}{\sigma\tau_r} & \omega_{dq}-\omega \\ 0 & \frac{Msr}{\sigma\tau_r L_s} & -(\omega_{dq}-\omega) & -\frac{1}{\sigma\tau_r} \end{bmatrix} \quad (3)$$

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

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

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

Rr: Rotor resistance
Rs: Stator resistance
Ls: Stator cyclic Inductance
Lr: Rotor cyclic Inductance
Msr: Mutual Maximal cyclic inductance between stator and rotor.

$$[B]=\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (4)$$

$$[C]=[L]^{-1}=\begin{bmatrix} \frac{1}{\sigma L_s} & 0 & \frac{-Msr}{\sigma L_s L_r} & 0 \\ 0 & \frac{1}{\sigma L_s} & 0 & \frac{-Msr}{\sigma L_s L_r} \\ \frac{-Msr}{\sigma L_r L_s} & 0 & \frac{1}{\sigma L_r} & 0 \\ 0 & \frac{-Msr}{\sigma L_r L_s} & 0 & \frac{1}{\sigma L_r} \end{bmatrix} \quad (5)$$

The drive mechanical equation is given as follows:

$$T_{em} - T_r = j\frac{d\omega}{dt} + f\,\omega \quad (6)$$

$$T_{em} = \frac{3}{2}p(\Phi_{s\alpha} I_{s\beta} - \Phi_{s\beta} I_{s\alpha}) \quad (7)$$

T_{em}: Electromagnetic torque
T_r: Load torque

3. Open-end stator winding induction machine supplied by two 3-levels inverters

The open-end stator winding induction machine is fed by two 2-levels inverters in cascade based on V/f law, is shown in figure 2.

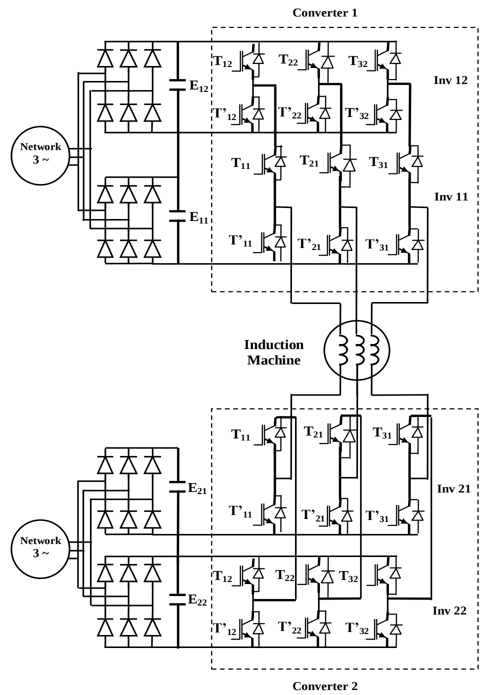

Fig. 2. Open-end stator winding asynchronous machine supplied with two 2-level cascaded inverters.

To control the two three phase cascaded inverters, the three reference signals of frequency fm and amplitude Am are compared with two triangular carriers of frequency fp and amplitude $\frac{A_p}{2}$, as shown by figure 3.

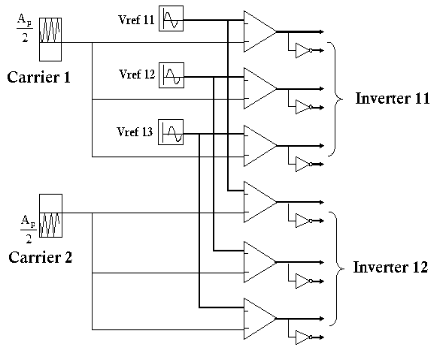

Fig. 3. Principle of the phase-disposition PWM for control two three-phase cascaded inverters.

Figure 4 shows two triangular carriers and a signal reference.

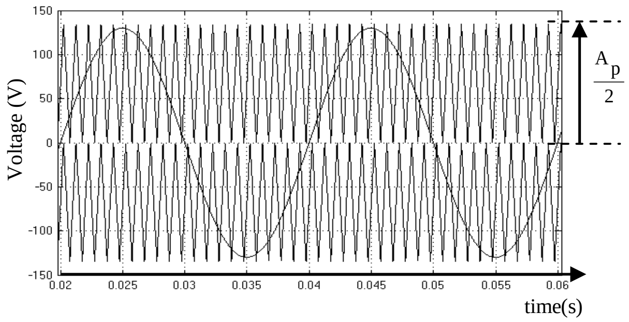

Fig. 4. Signal reference and 2 carriers vertically shifted.

The simulation results of the open-end winding induction machine where each entry is supplied by two 2-level cascaded inverters as shown in the figure 5. The load torque is the type kn².

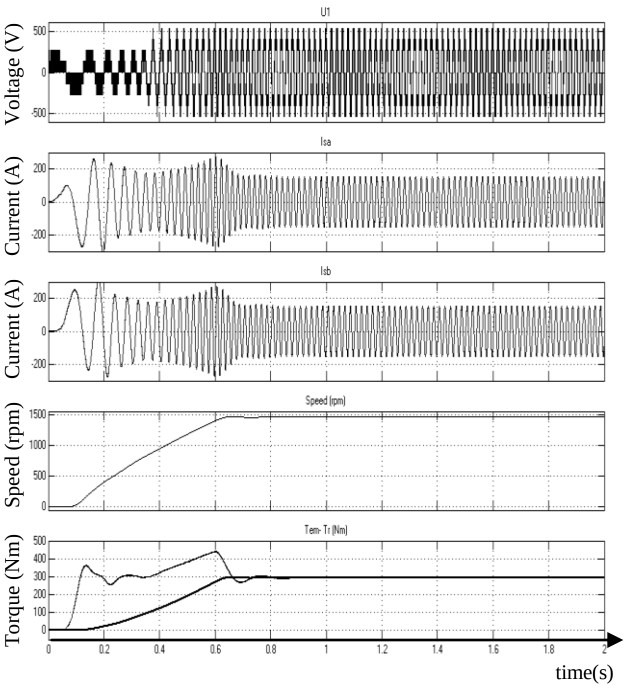

Fig. 5. Pole voltage of the machine, stator currents, speed and torque.

Figure 6 shows the voltage (Vs_{11}-Vs_{12}), (Vs_{21}-Vs_{22}) and phase-to-phase machine voltage U_1 which is 5 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}-Vs_{12}) - (Vs_{21}-Vs_{22}) pole voltage of the machine.

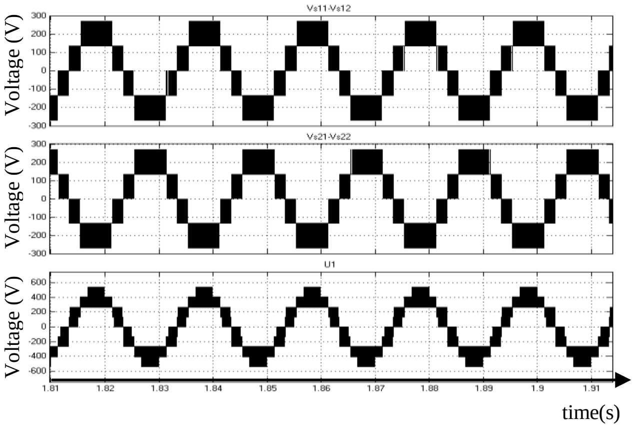

Fig. 6. Pole voltage inverter and phase-to-phase machine Voltage.

4. Operation of the open-end winding induction machine in degraded mode

The operation of the open-end winding induction machine in degraded mode when it is supplied by two 2-level cascaded inverters is interested. We only consider faults inverter in entry 2 and the operation is similar to entry 1. Then four configurations are possible where the operating conditions for each configuration must be respected.

4.1. Dimensioning three phase cascaded inverters

It is essential to know the dimensioning of three phase cascaded inverters to propose solution when the operation in degraded mode. That we will show the case of two three phase cascaded inverters.

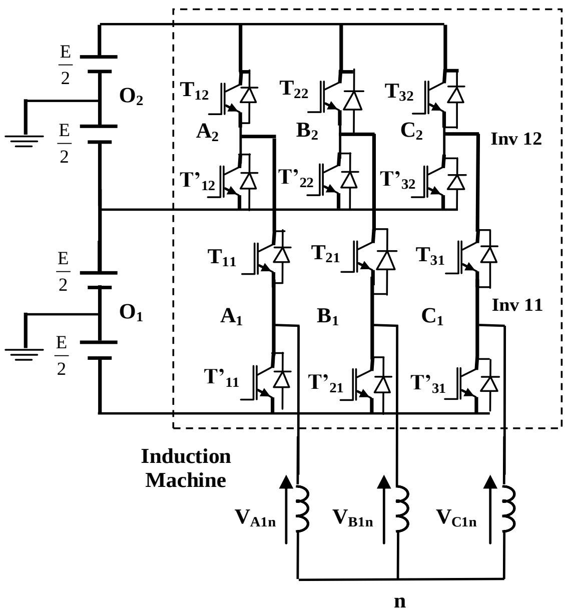

Fig. 7. Asynchronous machine supplied by two 2-level cascaded inverters.

Notations:
n : fictitious neutral.
i : index indicating the number of the phase i, i = {1,2,3}
j : index indicating the number of the switch j, j = [1…p]
T (i,j), T'(i,j) : power switches.
S (i,j) : the corresponding switching signal of the T(i,j)
S'(i,j) : the corresponding switching signal of the T'(i,j).
The S(i, j) and S'(i, j) are complementary signals.
From the structure in figure 7, we assume the DC bus for each inverter is E and it is written by the following relation:
For inverter 12:

$$V_{T'12} = \frac{E}{2} + V_{A_2O_2} = 2S_{12} = E \qquad (8)$$

For inverter 11:

$$V_{T'11} = \frac{3E}{2} + V_{A_2O_2} = \frac{3E}{2} + (2S_{12} - 1)\frac{E}{2} = 2E \qquad (9)$$

In this case, the open-end winding induction machine of power P supplied to each entry by three phase cascaded inverters, there will be two inverters Inv_{11} and Inv_{21} dimensioned for a power $\frac{P}{2}$ also the two other inverters Inv_{12} and Inv_{22} dimensioned for a power $\frac{P}{4}$.

4.2. Configuration 1: Failure at the top floor of the inverter 22

In the first configuration, we consider a short-circuit in one of the switches on the top floor of the inverter 22, which also corresponds to an open circuit on the bottom floor of the same inverter. To entry 2 the DC bus becomes $E_2 = E_{21} + E_{22} = \frac{E}{2}$, any constraint on the inverter Inv_{21} as it is dimensioned for a power $\frac{P}{2}$ then it was operating at the nominal speed. Figure 8 shows this configuration structure.

The simulation results for the first configuration with a load torque Tr = kn², as shown by figure 9 the voltage U_1 between two phases of the machine, the stator currents, speed and the torque. Then we simulated a failure in the inverter 22 to time t = 1.2s.

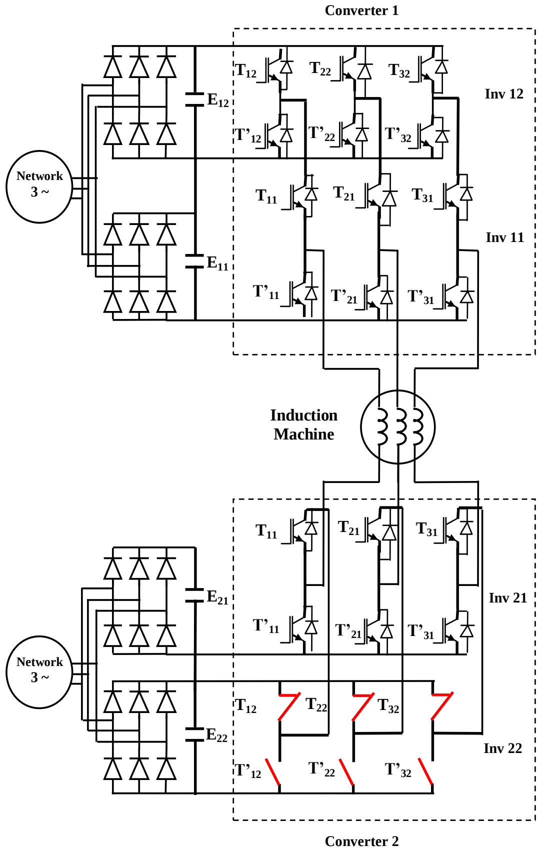

Fig. 8. Open-end stator winding induction machine fed by a short circuit in a switch of the top floor of the inverter 22.

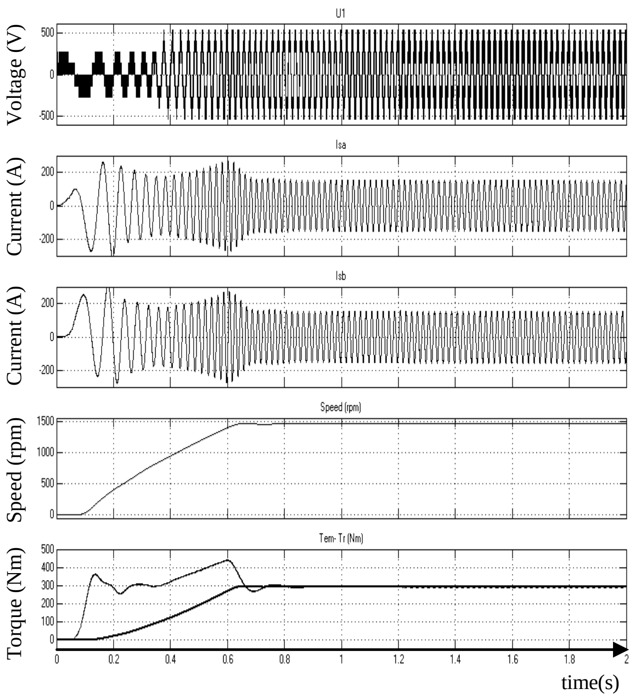

Fig. 9. Machine voltage, stator currents, speed, and torque with a short circuit in a switch of the top floor of the Inv 22.

Figure 10 and 11 respectively, are shown the pole voltage of the two converters and phase-to-phase machine voltage also an enlarging effect of these voltages.

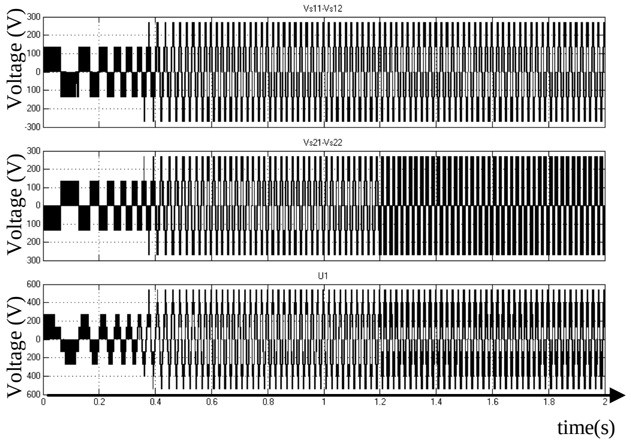

Fig.10. Pole voltage of the two converters and phase-to-phase machine voltage in degraded mode.

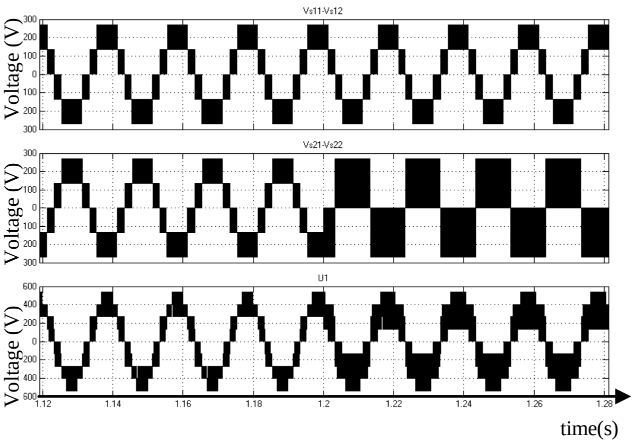

Fig. 11. Enlarging effect of voltage converters and phase-to-phase machine voltage before and after the fault moment.

4.3. Configuration 2: Failure at the bottom floor of the inverter 22

For the second configuration, it is considered a short-circuit in one of the switches on the bottom floor of the inverter 22. Figure 12 shows the scheme of this configuration.

The DC voltage bus to entry 2 becomes $E_2 = E_{21} = \frac{E}{4}$.

The operation of the machine must be reduced speed:
- 86% of the nominal speed for a torque Tn = kn ².
- 75% of the nominal speed for a torque Tn = kn.

The simulation results of the open-end winding induction machine operation in degraded mode with a load torque Tr = kn², as shown by figure 13. Also the simulation time of the failure is t = 1.2s.

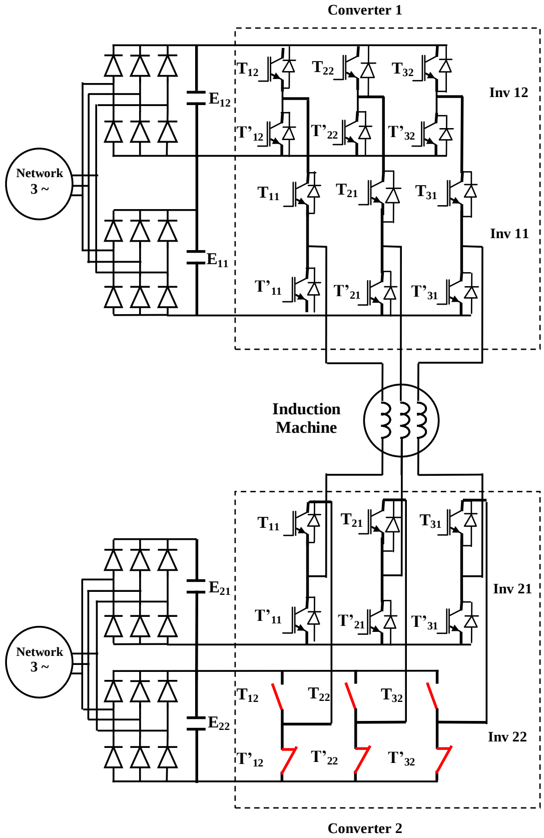

Fig.12. Operation of the machine with a short-circuit in a switch on the bottom floor of the inverter 22.

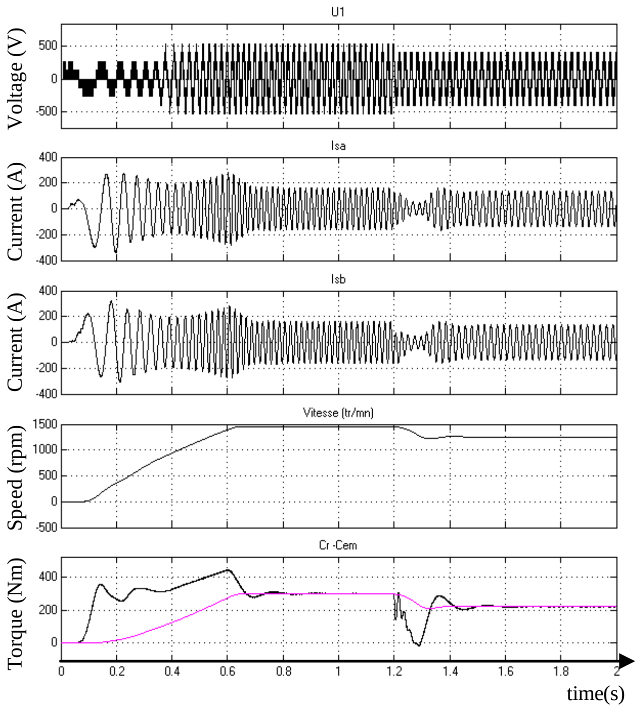

Fig. 13. Machine voltage, stator currents, speed, and torque for a short-circuit in a switch on the bottom floor of the inverter 22, speed reduced to 86 %.

In the figure 14, we show the pole voltage of the two converters and the phase-to-phase machine voltage.

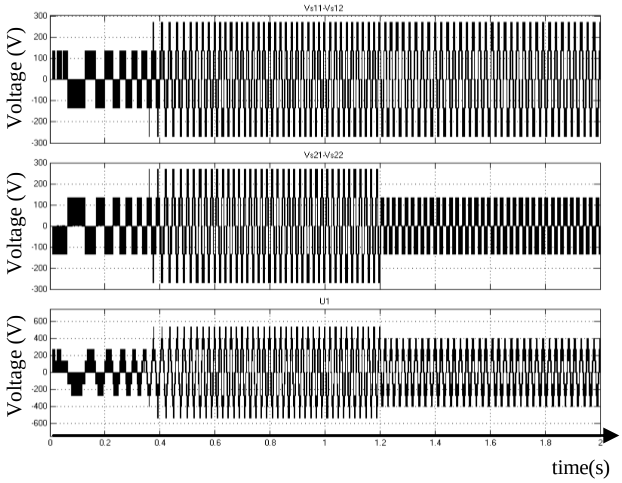

Fig. 14. Pole voltage converter and phase-to-phase machine voltage in degraded mode.

An enlarging voltage effect of the two converters and phase-to-phase machine voltage before and after the failure of the inverter 22 is shown by the figure 15.

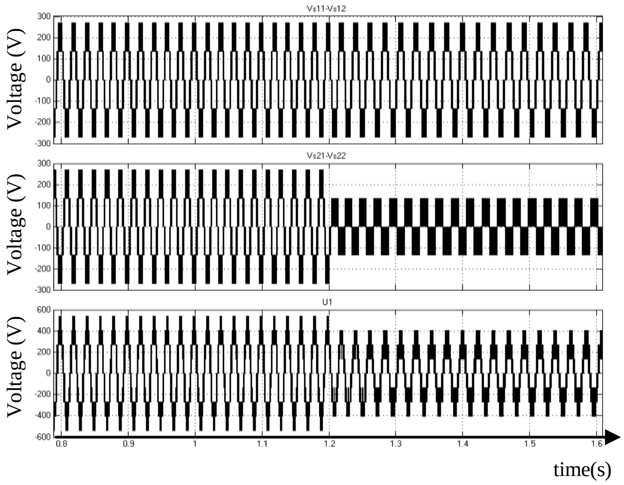

Fig.15.Enlarging effect of the voltage converters and phase-to-phase machine voltage before and after the failure.

4.4. Configuration 3: Failure at the top floor of the inverter 21

For the third configuration, it is considered a short-circuit in one of the switches on the top floor of the inverter 21 as shown by the figure 16.

The DC voltage bus to entry 2 becomes $E_2 = E_{22} = \frac{E}{4}$.

The operation of the machine must be reduced speed:

- 86% of the nominal speed for a torque Tn = kn².
- 75% of the nominal speed for a torque Tn = kn.

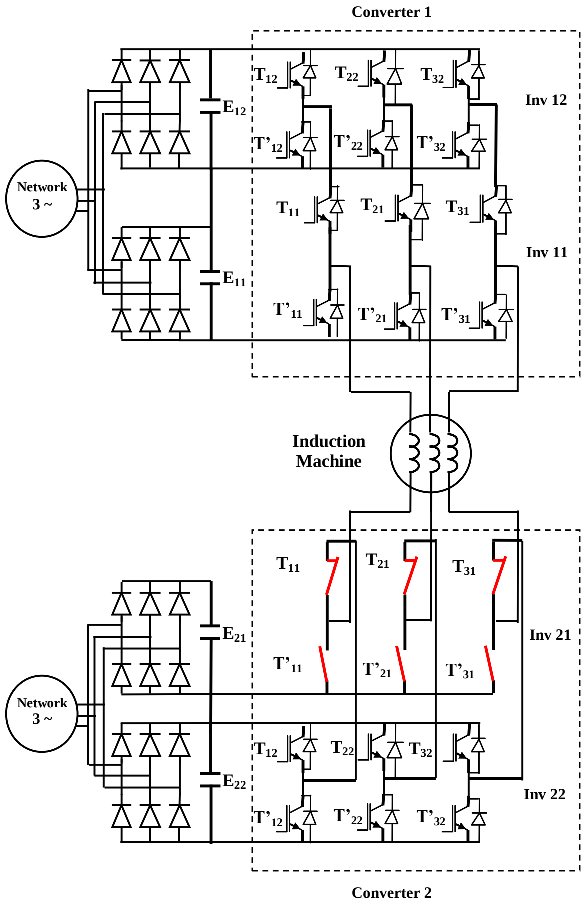

Fig.16. Feeding the machine with short-circuit in a switch on the top floor of the inverter 21.

In this configuration, it is limited to show the simulation results of the two voltage converters and phase-to-phase machine voltage, figure 17. The other obtained results are the same in the second configuration.

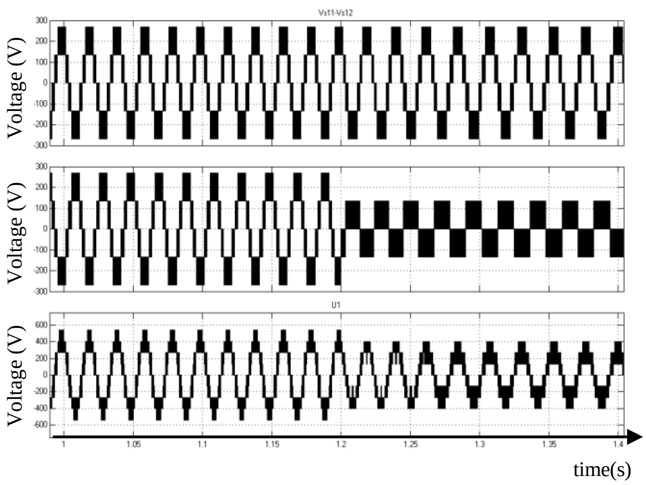

Fig.17. Enlarging effect of the voltage converters and phase-to-phase machine voltage.

4.5. Configuration 4: Failure at the bottom floor of the inverter21

The fourth configuration consists to consider a short-circuit in one of the switches on the bottom floor of the inverter 21, which corresponds to an open circuit on the top floor of the same inverter. The scheme of this configuration is given by the figure 18.

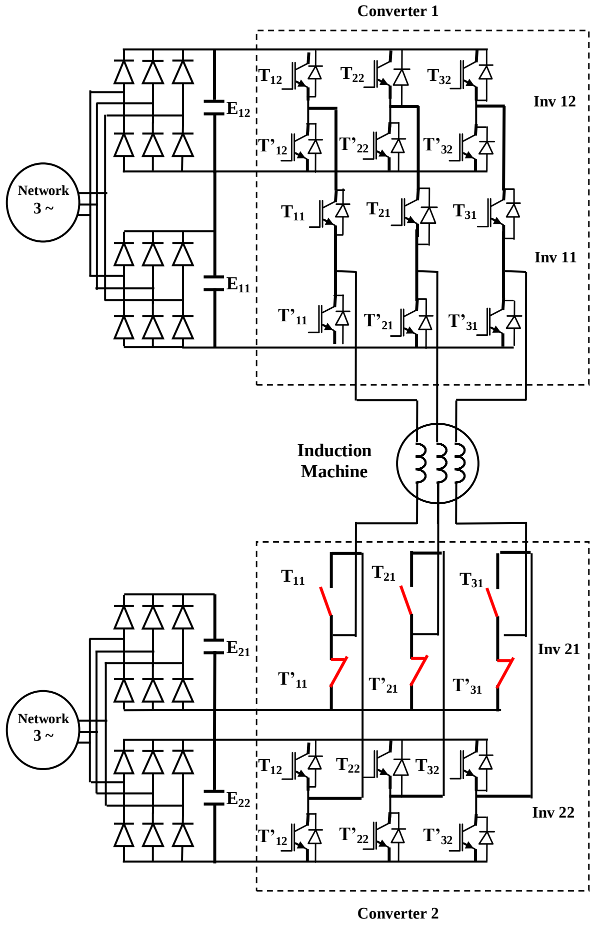

Fig.18. Feeding the machine with short-circuit in a switch on the bottom floor of the inverter 21.

This is the operation of the open-end winding induction machine fed by two 2-level cascaded inverters but reduced speed.

The value of the DC bus $E_{11} = E_{12} = \frac{E}{4}$, the operation of the machine must be reduced speed and consequently no conditions on the dimensioning of inverters:

- 70% of the nominal speed for a load torque Tn = kn².
- 50% of the nominal speed for a load torque Tn = kn.

Figure 19 show the simulation results of the machine operation in degraded mode with reduced speed to 70% of nominal value for a load torque Tr = kn².

Figure 20 and 21 respectively, is shown the pole voltage of the two converters and phase-to-phase machine voltage also an enlarging effect of these voltages before and after the fault.

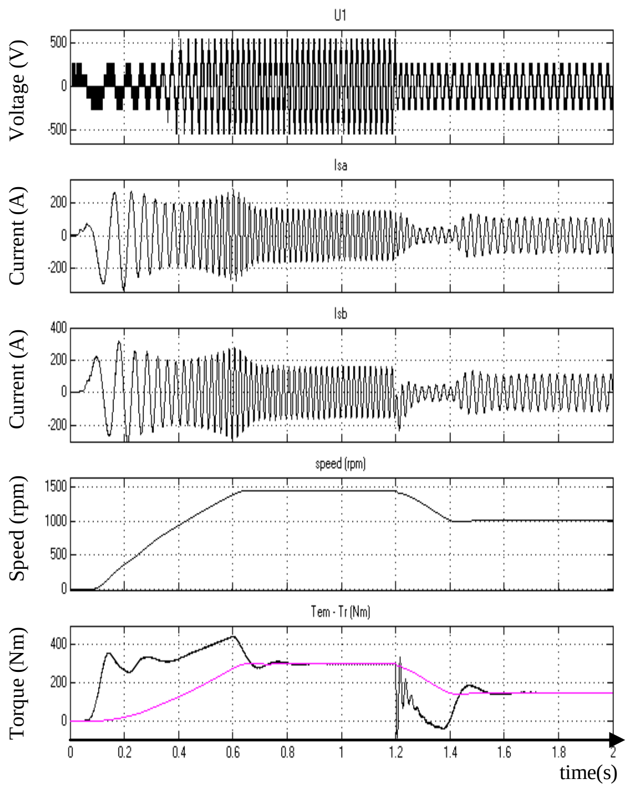

Fig.19. Voltage machine, stator currents, speed, and torque for degraded mode with reduced speed at 70%.

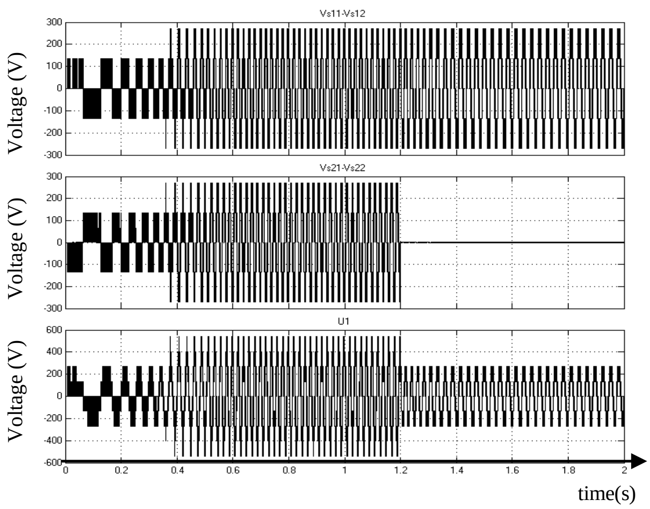

Fig. 20. Pole voltage converters and phase-to phase machine voltage with $E_{11} = E_{12} = \frac{E}{4}$.

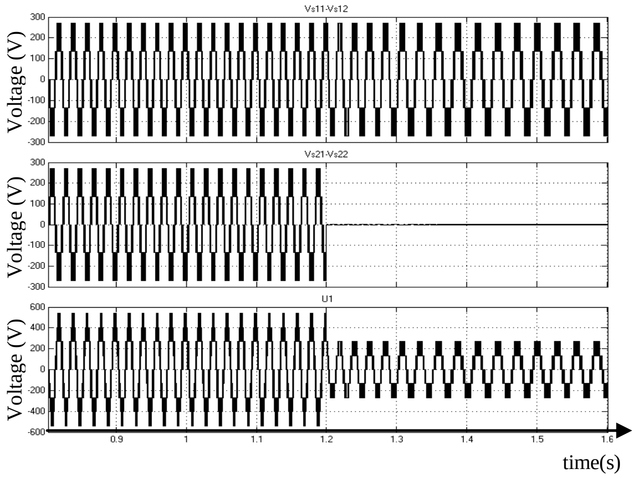

Fig. 21. Enlarging effect of the voltage converters and phase-to-phase machine voltage.

The characteristics of the machine used:

- Nominal power P = 45 KW.
- Speed n = 1450 rpm.
- Resistance of stator Rs = 0.15 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 a simulation model of the open-end winding asynchronous machine supplied by two three-phase cascaded inverters in the Matlab Simulink environment.

We studied the different configurations of the operation in degraded mode for the feeding open-end winding induction machine by 2-level cascaded inverters after the first fails of the switches forming the two cascaded inverters.

Then four configurations are presented as well as different operating condition to be respected for each case.

The simulation results showed the efficiency of control strategy use and consequently the interest of such a structure inverter machine to ensure continuity of system service.

The association of the machine with the cascaded inverters allows a good compromise between the power segmentation and continuity of service.

Finally the feeding of the machine by two three phase cascaded inverters can allows to tolerate the second failure inverter, that improve the reliability of the drive system.

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