DIFFERENT FEEDING CONFIGURATIONS OF THE OPEN-END WINDING IM BY 2-LEVEL INVERTERS IN DEGRADED MODE

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Abstract: *The objective of this paper is presenting the different feeding configurations of the open-end stator winding induction machine in degraded mode. This machine is fed by two 2-level inverters which each inverter is dimensioned to half power of the machine. Such machine topology ensures the power segmentation in order to improve the reliability and availability of the drive system, since the loss of one inverter does not cause the machine to stop. indeed, if the operating conditions are respected, the exploitation of the machine under redundancy mode can be ensured. Simulation results are carried out to show the two configurations for the degraded mode.*

Key words: *Degraded mode, open-end winding induction machine, power segmentation, two levels inverter.*

1. Introduction

The improvement of the reliability and the availability of the machines-inverters association became essential purpose in many applications of drive system such as the railways domain, electrical propulsion of ships, aeronautics and electrical vehicles system [1-2]. In order to achieve this reason, one of the solutions is the power segmentation of the electric machines and the inverter structures. Indeed, it is the replacement of converter of high power by combining several converters of lower powers. For example, the feeding of the double star machine by two 2-level inverters where each inverter is dimensioned to half power of the machine ensures the power segmentation for the improvement the reliability of drive system. It offers multiple redundancy degrees in degraded mode [3-4]. The double star machine can ensure the operation with active redundancy, where the two inverters operate simultaneously and the failure of a converter does not alter system operation. In addition, the double star machine provides the passive redundancy, when only one inverter is functional and the second is at hold, in case of failing of the main inverter, the second one will take over [5-6]. Then, several researches have been developed in machine structures including the poly-phase machines [7-11], or the multi star machines [12-18] and three-phase open-end stator winding machine “OEWIM” [19-25].

The paper purpose is presenting the different feeding configurations of the open-end winding IM by 2-level inverters in degraded mode and organized as follow:

The first section describes the operation of the feeding of the “OEWIM” for voltage source supply. The second section is devoted to the analysis of the operation of the open-end winding induction machine in degraded mode. Then, two configurations of the supply of the machine in degraded mode are treated:

In first configuration, the two inverters, dimensioned for half of machine power, ensure the power supply of the machine in the case of failure in one of the two inverters (caused by open circuit or short circuit); the faulty inverter is configured in such way to ensure the star connection of the stator winding, the remaining operational inverter keep providing the power supply of the machine but the speed must be reduced depending on the load type.

In the second configuration, one of the two inverters ensure the power supply of the machine at its adequate entry, whereas the second inverter ensures the star coupling of the stator winding, in the case of switch fault (open switch or short-circuited switch), the roles between inverters are reversed. If the two inverters are dimensioned for half of machine power, then the speed is reduced depending on the load type. Else, if the two inverters are sized at full power, then the machine can operate at nominal speed. The obtained results highlight the effectiveness of the last proposed configuration.

2. Operation of the supply of the open-end winding induction machine by two 2-level inverters

The mathematical model of the open-end stator winding induction machine is presented in [21-23] and validated in the environment of « Matlab simulink ».

The figure 1 represents the feeding of the proposed machine by supply voltages.

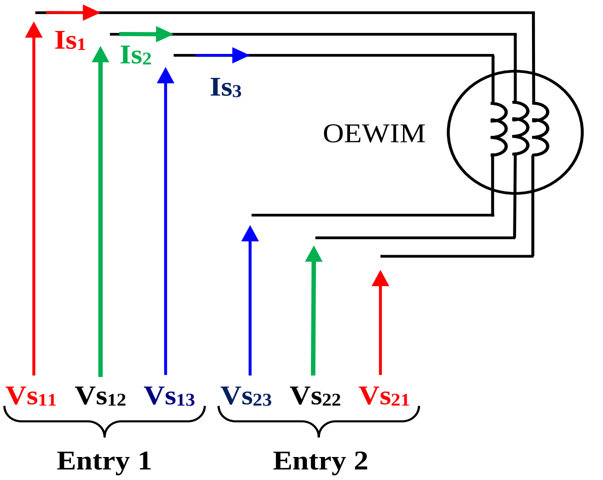


Fig. 1. Supply of the open-end winding induction machine

Vs_{1n} : Supply voltage of entry 1 of machine.
Vs_{2n} : Supply voltage of entry 2 of machine.
With: n = {1, 2, 3}

The open-end winding induction machine is fed by two PWM voltage source inverters with half DC-link (E/2) of each inverter based on V/f law. This supply structure is represented by figure 2. Each inverter is dimensioned to a half power of machine.

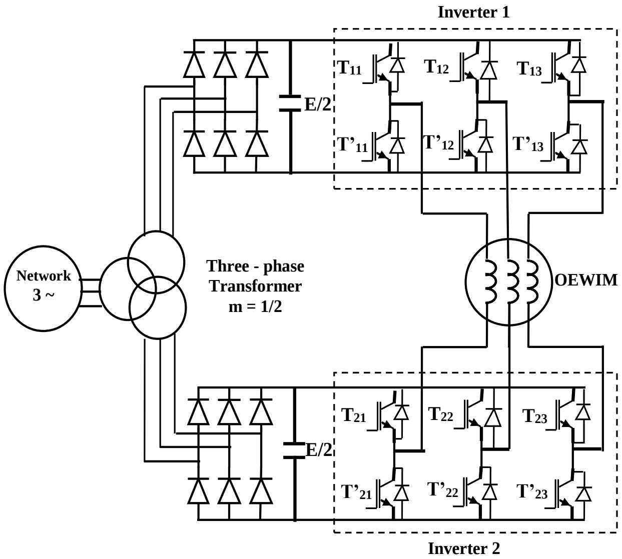


Fig. 2. Open-end winding IM supplied by two 2-levels inverters

To control each inverter, the strategy PWM involves the use of six reference voltages of frequency fs = 50Hz, the three reference voltages (Vs_{11}, Vs_{12} and Vs_{13}) shifted by 120° between them for feeding the entry 1 of stator and also three other (Vs_{21}, Vs_{22} and Vs_{23}) shifted by 120 ° between them but the last three are shifted from to the first reference voltages by an angle 180° for feeding the entry 2 of stator. These reference voltages are compared with carrier frequency fp = 5000HZ for control each inverter. The principal of the PWM sine triangle is shown by the figure 3.

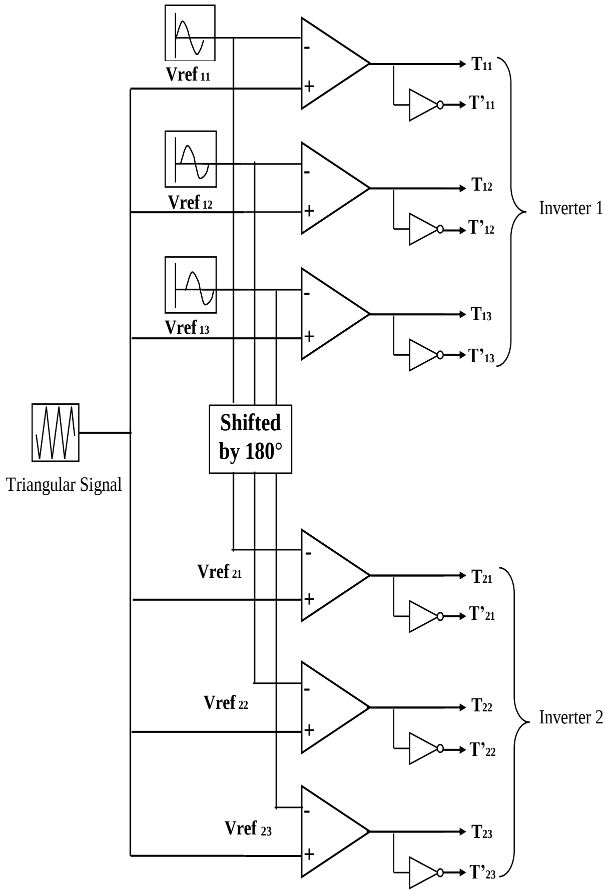


Fig. 3. Principal of the PWM technique

Figure 4 represents the simulation results of the PWM technique principal.

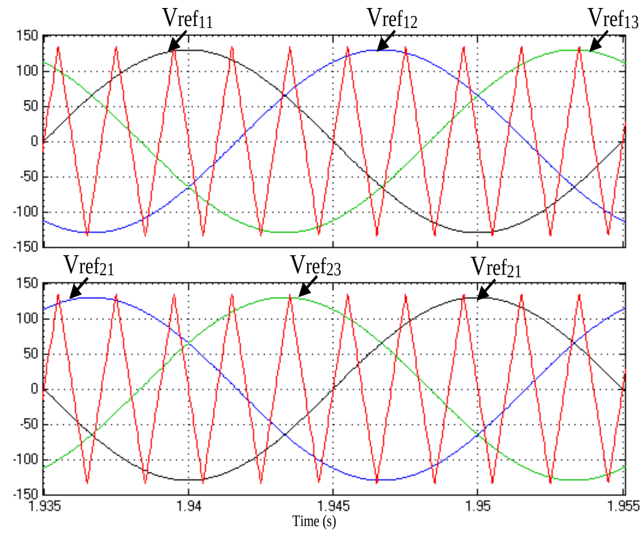


Fig. 4. Reference voltages with triangular signal

Figure 5 shows the voltage of each inverter (Vs_{11}-Vs_{12}), (Vs_{21}-Vs_{22}) and phase-to-phase machine voltage U_1 which obtained 3 levels of voltage to supply by two 2-level inverters.

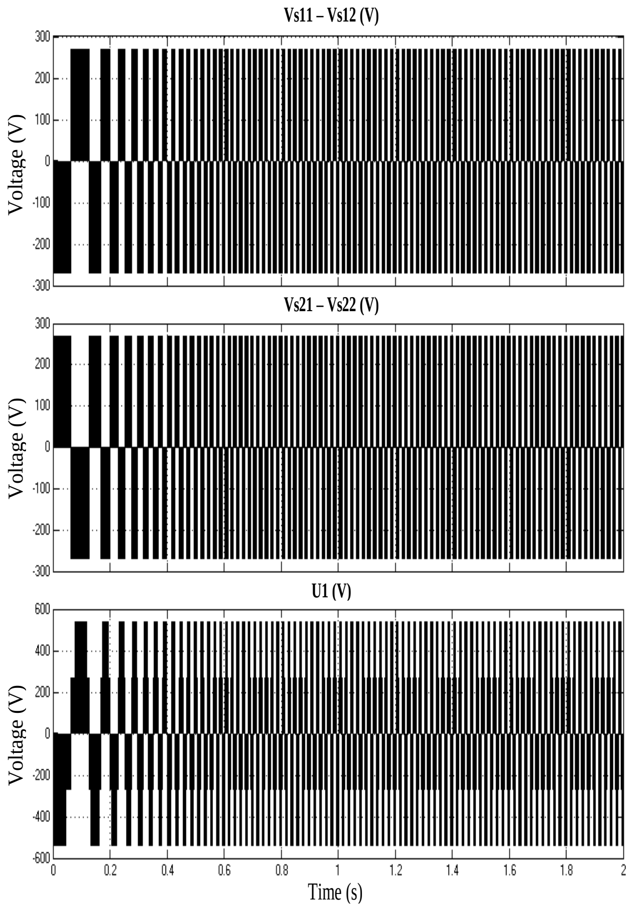


Fig. 5. Evolution of the voltages for inverter and machine.

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.

The figure 6 shows the simulation results of the evolution of the speed, stator currents and torques for the operation of the open-end winding induction machine for a load torque of the type Tr = kn².

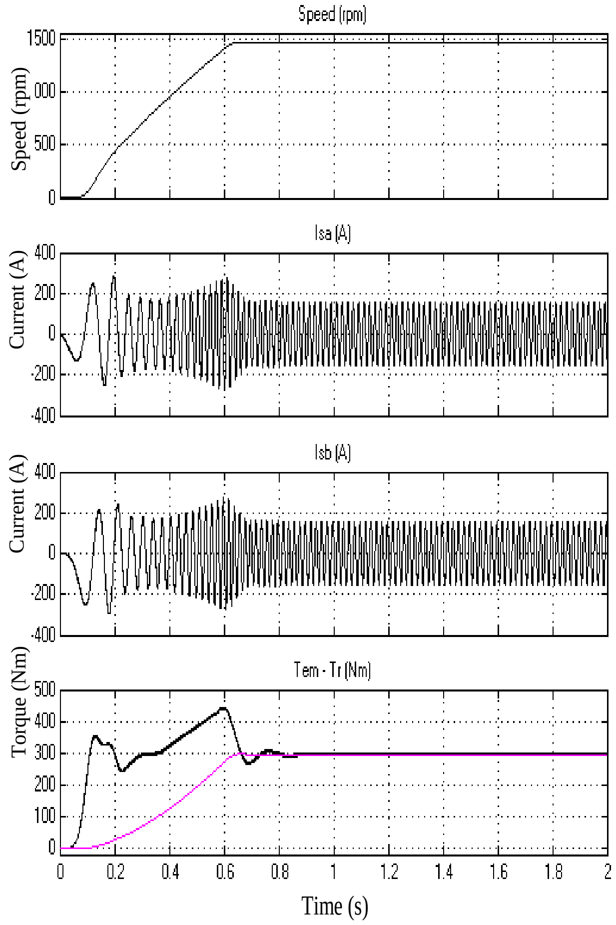


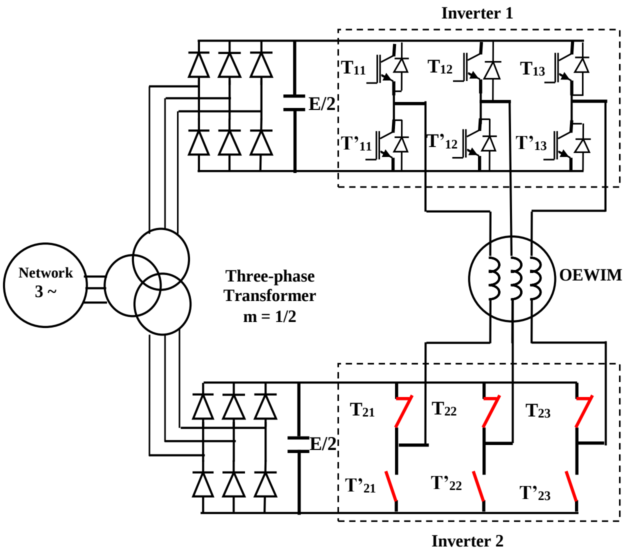
Fig. 6. Evolution of the speed, stator current and torques for load torque kn²

3. Operation in degraded mode of the open-end winding induction machine supplied by VSI

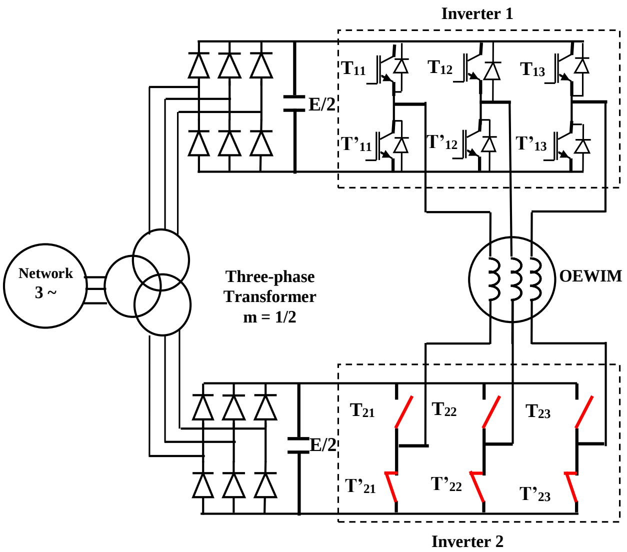
3.1. First configuration

In the event of failure detection of one of the switches of the lower-stage (T'_{21} or T'_{22} or T'_{23}), figure 7 (a) or one of the switches of the upper-stage (T_{21} or T_{22} or T_{23}), figure 7 (b), two approaches are possible:

during open-switch, the other stage is reconfigured by the control of the switches so that the switches ensure a star coupling for the machine at entry 2. During short-circuited switch, the faulty switch is isolated and the two other switches of the faulty stage are opened. The switches of the other stage are reconfigured to obtain a star coupling of the machine. In this case, the inverter 1 ensure the supply of the machine and the inverter 2 is configured in a way to ensure the star coupling of the stator windings at entry 2 as shown by figure 7.



(a) Failure of one switch of the lower-stage



(b) Failure of one switch of the upper-stage

Fig. 7. Power supply of the "OEWIM" with reconfiguration of the inverter 2 following a failure

The condition of the operation must be respected. Indeed, the speed will be reduced to 70% or 50% of its nominal value for a load torque respectively $Tr = kn^2$ or kn. The inverters are dimensioned to a half power (P/2) of the machine.

The figures 8 and 9 show the simulation results of the voltages of inverters, speed, stator current and torque for a load torque $Tr = kn$.

At t = 1.2s, we reconfigured the inverter 2 following a default, the power supply of the machine is then ensured by inverter 1.

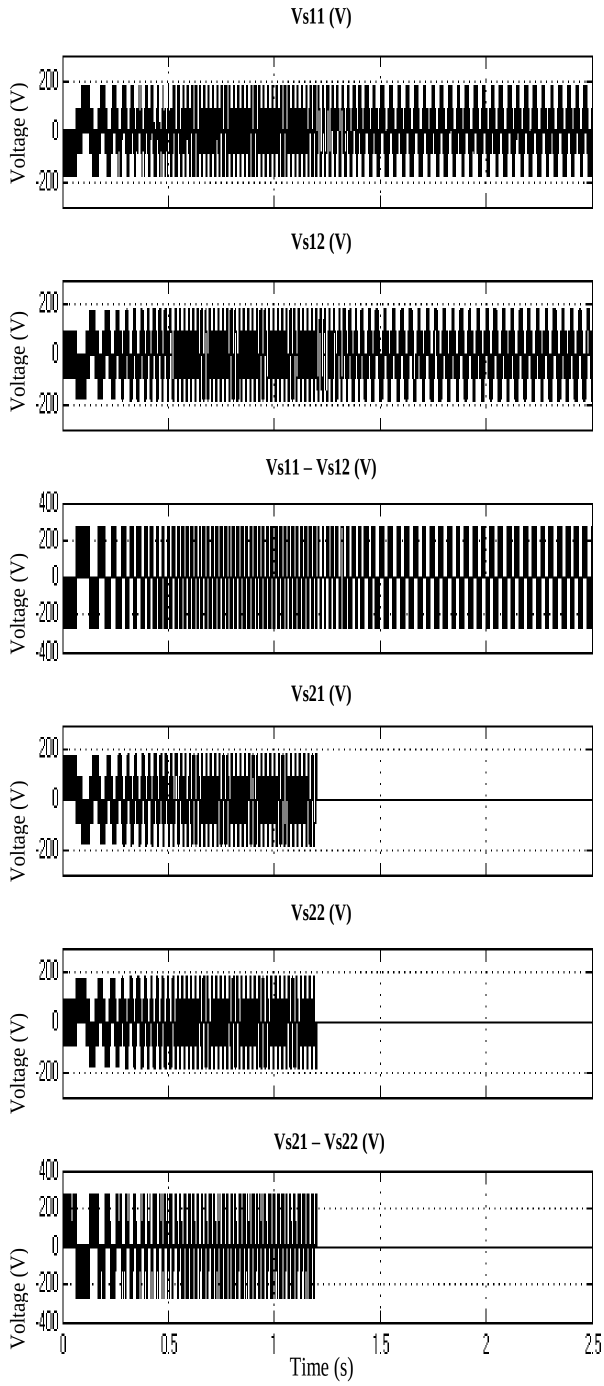


Fig. 8. Evolution of the simple voltages and the pole voltages with failure of the inverter 2

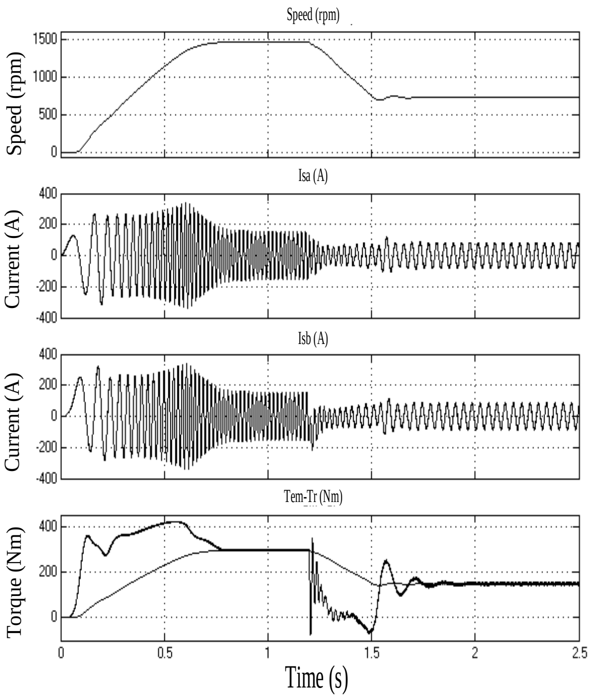


Fig. 9. Evolution of speed, stator current and torque with failure of inverter 2 and reduced speed at 50% for Tr = kn.

The figure 10 shows the simulation results of speed, stator current and torque for a torque of load of the form Tr = kn². We keep the same operating conditions as previously but without rise in the voltage DC, on the other hand the speed is limited to 70% of nominal value.

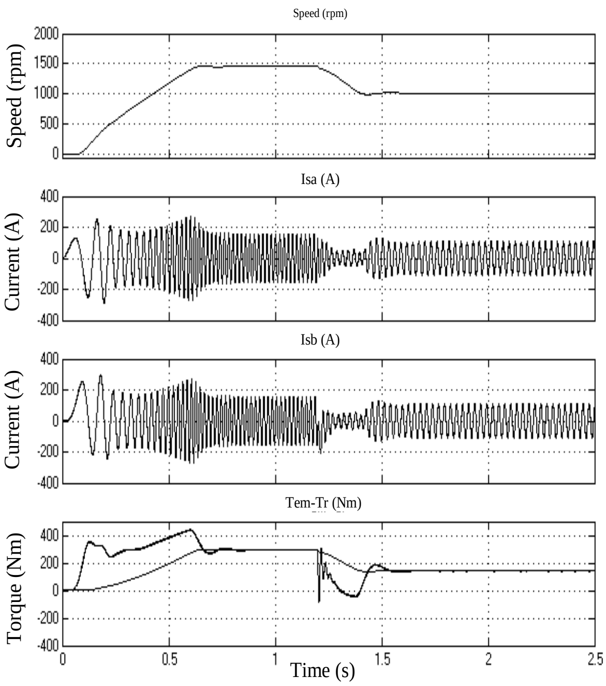


Fig. 10. Evolution of speed, stator current and torque with reduced speed at 70% for Tr = kn²

3.2. Second configuration

For the second configuration, one of the two inverters supply the machine, and the other inverter ensure the star coupling of the stator winding.

In case of the inverter failure, the adopted reconfiguration technique reverse the role of the two inverters

Figure 11 represents the case where inverter 1 ensures the supply of machine, and inverter 2 ensures the star coupling of the stator winding.

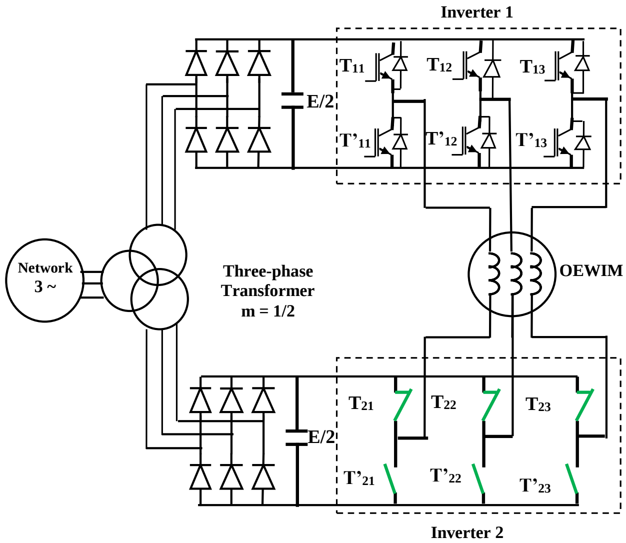


Fig. 11. Supply of the “OEWIM” by the inverter 1 and the inverter 2 ensuring the star coupling of the machine.

Figure 12 shows the exchanging roles between the two inverters, in case of fault incident (in T'_{11} or T'_{12} or T'_{13}), in order to provide the machine supply by the inverter 2 and the star coupling of the stator winding by inverter 1.

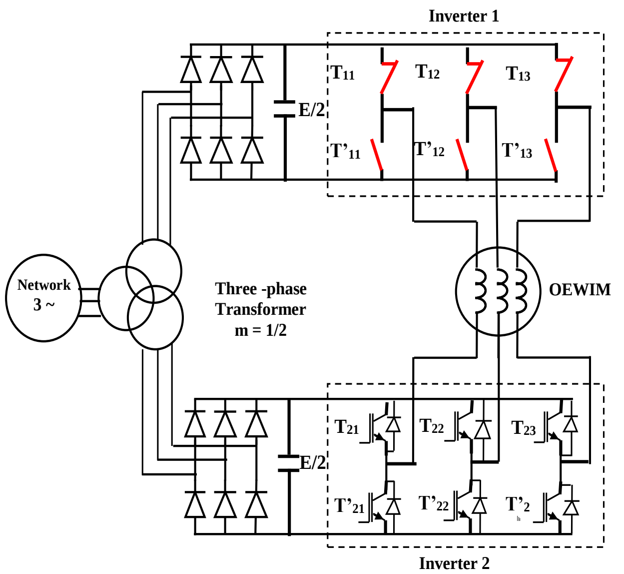


Fig. 12. Supply of the “OEWIM” by inverter 2 following a failure of the inverter 1.

To keep the power segmentation at the level of the power supply of the machine, the dimensioning of each inverter must be at half power (P/2) of the machine. Indeed, the speed is reduced to 70% of the nominal value for a load torque kn².

Figure 13 shows the simulation results of the voltages between phases of each inverter, stator currents, speed and torques for load torque Tr = kn² with reducing speed of 70% of the nominal value. The starting of the open-end winding induction machine by inverter 1 and inverter 2 ensuring the star coupling of the stator winding. At the moment t = 1.8s, the fault of the inverter 1 is simulated and consequently the reconfiguration of its command to ensure star of the stator winding, and the instantaneous entry in service of inverter 2 thus ensuring the continuity of operation of the machine.

In this second configuration, it is also possible to operate at nominal speed, to do so, the two converters can be dimensionned for the P power of the machine. This advantage is not possible for double star machines because the cross section of the conductor wire is divided by two.

The figure 14 shows the simulation results of the operation of the open-end winding induction machine at nominal value of the speed with increase of the continuous bus for a load torque Tr = kn². At the moment t = 1.2s, the failure of the inverter 1 is simulated and consequently the reconfiguration of its command to ensure the star coupling of the stator winding, and the instantaneous entry in service of inverter 2 thus ensuring the continuity of operation of the machine in nominal mode.

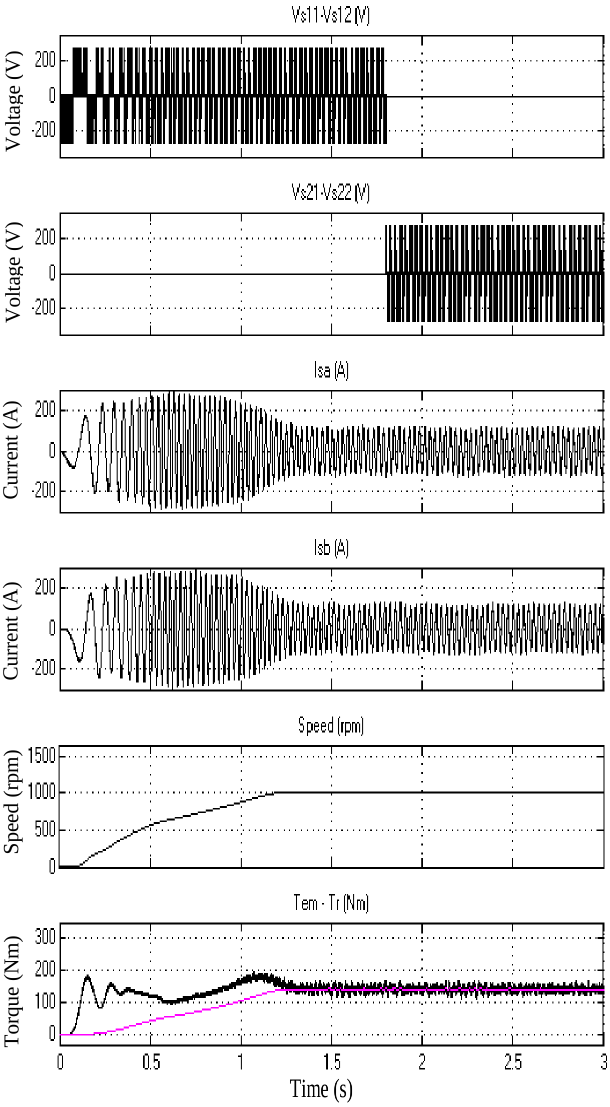


Fig.13. Evolution of the voltages, the stator currents, speed and the torques for Tr = kn² with speed limit at 70%

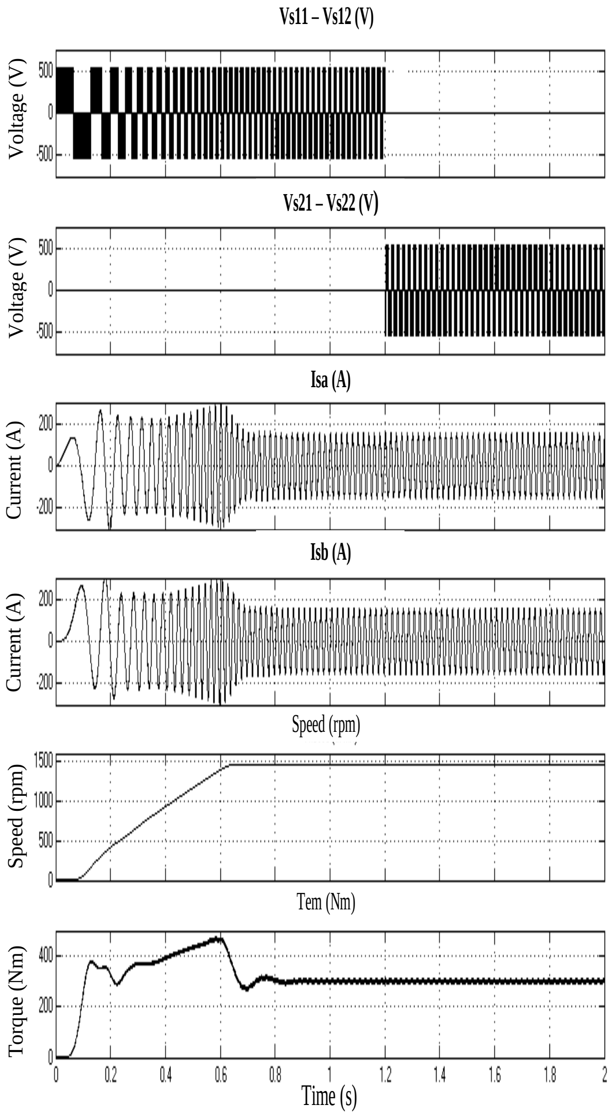


Fig.14. Evolution of the voltages, the stator currents, speed and the torque for Tr = kn² with nominal speed

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

4. Conclusion

In this work, the study of the operation of the open-end winding induction machine supplied by two 2-level inverters in degraded mode for different configurations.

In the first configuration, the two inverters dimensioned by half machine power ensure the power supply of the machine in the event of failure of one of the two inverters, the machine operate with one inverter, the other inverter ensure the star coupling of the stator winding, but the speed must be reduced to 50% or 70% of nominal value for the load torque with type kn or kn².

In the second configuration, one inverter ensures the supply and the other ensures the star coupling of the stator winding, in the event of failure inverter that supply machine the roles of the two inverters are reversed. Furthermore, our system can operate at reduced speed by sizing it for the half of the power. However, it is possible to obtain the nominal speed operating, in this case, the two inverters can be dimensioned for full power.

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

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