Study of Voltage Stability Continuous Multilevel Inverter Voltage Applied to the Induction Machine

M. S. Djebbar and H. Benalla

Abstract—This work presents an analysis of fluctuating input voltages of the DC source of voltage three-phase inverter at three levels. Indeed, the two voltages have an imbalance between it. We obtain an output voltage of the inverter at three levels asymmetric and whose non-zero means value. To minimize this imbalance we propose a solution that involves inserting the terminals of each capacitor, a bridge balancing said bridge clamping. The simulation results are quite satisfactory

Index Terms—Neutral-Point-Clamped-(NPC), three level inverter, Pulse-Width-Modulation (PWM), clamping bridge, three level rectifiers.

I. INTRODUCTION

The field of application of asynchronous machines is today important changes. They are due to the development of new structures involving machines and static converters. Indeed these structures is required in applications necessitate high dynamic performance. The induction machine is usually fed by inverters at two levels. For applications of high voltage and high power, the inverter voltage three-level NPC structure is becoming increasingly used [1] -[2]-[3]. Nevertheless, the two voltages delivered by the three-phase rectifier at three levels, have an imbalance, thus obtained, the output of the inverter, an unbalanced system voltage. To remedy this problem, we propose to use a balancing bridge called bridge clamping. For this we first present the modelling and control of converters PWM three-level NPC structure, next we discuss the modelling of the induction machine in d-q reference park, its simulation empty and loaded and see the behaviour of the machine through the deferent's parameters namely speed and electromagnetic torque. At the end we finish by showing the role of bridge clamping in stabilizing voltages delivered by the rectifier at three levels.

II. MODELING AND CONTROL

A. Rectifier Three Level [1], [4], [5], [6].

Fig.1 shows the structure of the NPC rectifier current three levels.

Fig. 1. Structure of the NPC rectifier three levels

Three orders are possible for this rectifier. The most optimal is given by the relationship (1)

$$\begin{aligned} B_{K1} &= \overline{B_{k4}} \\ B_{K2} &= \overline{B_{K3}} \end{aligned} \quad (1)$$

With B_{KS} control of the base of the transistor T_{KS} .

In command mode, the voltages for the rectifier expressed to the functions of half-arm connections, depending on the system (2)

$$\begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix} = 1/3 \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \left\{ \begin{bmatrix} F_{11}^b \\ F_{21}^b \\ F_{31}^b \end{bmatrix} U_{c1} - \begin{bmatrix} F_{10}^b \\ F_{20}^b \\ F_{30}^b \end{bmatrix} U_{c2} \right\} \quad (2)$$

The output currents, I_{red1} , I_{red2} and I_{red0} the rectifier at three levels using the connect function switches are given by the following system (3).

$$\begin{cases} I_{red1} = F_{11}F_{12}I_{res1} + F_{21}F_{22}I_{res2} + F_{31}F_{32}I_{res3} \\ I_{red2} = F_{13}F_{14}I_{res1} + F_{23}F_{24}I_{res2} + F_{33}F_{34}I_{res3} \\ I_{red0} = F_{11}F_{13}I_{res1} + F_{21}F_{23}I_{res2} + F_{31}F_{33}I_{res3} \end{cases} \quad (3)$$

B. Inverter Three Level [5],[6],[7]

The structure of the NPC inverter phase voltage at three levels is shown in Fig. 2. To ensure continuous operation of the inverter, it must be completely controllable. [6]

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Fig. 2. Structure of the NPC voltage inverter at three levels.

Modeling the three-phase inverter voltage at three levels is described by the following system of equations (4).

$$\begin{bmatrix} V_{AM} \\ V_{BM} \\ V_{CM} \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \left\{ \begin{bmatrix} F_{11}^b \\ F_{21}^b \\ F_{31}^b \end{bmatrix} U_{c1} - \begin{bmatrix} F_{10}^b \\ F_{20}^b \\ F_{30}^b \end{bmatrix} U_{c2} \right\} \quad (4)$$

C. Strategies of Command PWM

The rectifier and inverter are controlled by the same strategy PWM triangular-sinusoidal natural sampling two carriers triangular bipolar. [1],[7],[8]

 Fig. 3. Different signals the strategy triangular-sinusoidal two carriers Triangular bipolar ($m = 6$, $r = 0.8$).

The general principle is to compare a reference voltage to a triangular carrier. This strategy is characterized by two parameters:

- The modulation index (m) is defined as the ratio of the modulation frequency (f_p) of the carrier at the frequency (f) of the reference voltage

$$m = \frac{f_p}{f} \quad (5)$$

- The degree of modulation (r) is the ratio of the amplitude (V_m) of the reference voltage (V_p) to the amplitude of the carrier

$$r = \frac{V_m}{V_p} \quad (6)$$

Triangular carriers are given by the following equations (7).

$$\begin{cases} V_{p1}(t) = V_{pm} \left(4 \cdot \frac{t}{T_p} - 1 \right) & 0 \leq t \leq \frac{T_p}{2} \\ V_{p1}(t) = V_{pm} \left(-4 \cdot \frac{t}{T_p} + 3 \right) & \frac{T_p}{2} \leq t \leq T_p \\ V_{p2}(t) = V_{p1}\left(t + \frac{T_p}{2}\right) \end{cases} \quad (7)$$

 Fig. 4. The pulse control of the an arm of the three-phase rectifier at three levels ($m = 6$, $r = 0.8$)

D. Machine à Induction [2]

The general equations describing the operation of cage induction machine in a referential park d-q are defined by the following system (8).

$$\begin{aligned} V_{sd} &= R_s I_{sd} + \frac{d\Phi_{sd}}{dt} - \omega_s \Phi_{sq} \\ V_{sq} &= R_s I_{sq} + \frac{d\Phi_{sq}}{dt} + \omega_s \Phi_{sd} \\ V_{rd} &= R_r I_{rd} + \frac{d\Phi_{rd}}{dt} - \omega_r \Phi_{rq} \\ V_{rq} &= R_r I_{rq} + \frac{d\Phi_{rq}}{dt} + \omega_r \Phi_{rd} \end{aligned} \quad (8)$$

The machine rotor cage is closed on itself (shorted), we take V_{rd} and V_{rq} equal zero.

By rewriting the equations in a referential precedents stationary d-q ($\omega_s = 0$), we obtain the model of the electric part of the induction machine.

$$\begin{aligned} V_{sd} &= R_s I_{sd} + \frac{d\Phi_{sd}}{dt} \\ V_{sq} &= R_s I_{sq} + \frac{d\Phi_{sq}}{dt} \\ V_{rd} &= R_r I_{rd} + \frac{d\Phi_{rd}}{dt} - \omega_r \Phi_{rq} \\ V_{rq} &= R_r I_{rq} + \frac{d\Phi_{rq}}{dt} + \omega_r \Phi_{rd} \end{aligned} \quad (9)$$

The flow equations coupled stator and rotor are obtained from own inductors L_s , L_r and mutual M_{sr}

$$\begin{aligned}
 \Phi_{sd} &= L_s I_{sd} + M_{sr} I_{rd} \\
 \Phi_{sq} &= L_s I_{sq} + M_{sr} I_{rq} \\
 \Phi_{rd} &= L_r I_{rd} + M_{sr} I_{sd} \\
 \Phi_{rq} &= L_r I_{rq} + M_{sr} I_{sq}
 \end{aligned} \quad (10)$$

The equation of the electromagnetic torque of the machine is:

$$T_{em} = \frac{3}{2} p (\Phi_{sd} I_{sq} - \Phi_{sq} I_{sd}) \quad (11)$$

The equation of motion connecting the electrical and mechanical parts is written as follows:

$$J \frac{d\Omega}{dt} = T_{em} - T_r \quad (12)$$

Knowing that the rotor angular velocity ω is connected with pulsations ω_s stator and ω_r rotor as follows (13).

$$\begin{aligned}
 \omega_r &= \omega_s - \omega' \\
 \omega' &= p\Omega
 \end{aligned} \quad \text{p: number of pole pairs} \quad (13)$$

III. CASCADE RECTIFIER NPC A THREE LEVELS - NPC INVERTER A THREE LEVELS-THREE PHASE INDUCTION MOTOR

The input bridge of this cascade consists of a rectifier at three levels associated with the three-phase voltage inverter at three levels, the two converters are controlled by the same strategy with two PWM carrier triangular ($m = 36$, $r = 0.8$). The structure of this cascade is shown in Fig.5. The cascade powers a three-phase motor considered a balanced three-phase load leading a load imposed a resistive torque T_r .

A. Application and Simulation Results

The following figures show the simulation results of the cascade shown in Fig.5.

Fig. 5. Cascade rectifier current three level- inverter voltage three-level- three phase asynchronous motor.

Fig. 6. Tensions intermediate the filter and their differences the rectified voltage Ured

Fig. 7. Ired1, Ired2, Ired0 the three-level three-phase rectifier

Fig. 8. Id1, Id2, Id0 absorbed by the inverter at three levels

Fig. 9. Speed Ω and torque T_e couple of the machine was empty and loaded

Fig. 10. The stator currents I_s and I_r of rotor phase a, empty and loaded

Fig. 11. Rotor and stator flux in the d-q repere

Fig. 12. Van simple voltage at the entrance of the rectifier and the inverter output

Fig. 13. Voltage and current source and THDI the current absorbed by the rectifier at three levels

Fig. 14. Voltage and current source and THDI the current absorbed by two rectifiers in series at two levels

Fig. 15. Voltage and current source and THDI the current absorbed by rectifier at two levels

B. Interpretation

The voltages U_{C1} and U_{C2} illustrated in Fig. 6 are very close and the voltage difference ($U_{C1} - U_{C2}$) oscillates around the values small compared to that of U_{C1} and U_{C2} . This difference is larger for low capacity value, which causes instability of the input voltage to the inverter, and this affects the power of the machine. The decrease in the voltage difference ($U_{C1} - U_{C2}$) is possible by increasing the carrying capacity. Figure 7 shows the shapes of the currents I_{red1} , I_{red2} who the same appearance but inverted with respect to each other, the current I_{red0} to a mean value near zero. This is very important for a balanced capacitive bridge. The inverter currents I_{d1} , I_{d2} have the same shape but reverses and the average value is practically nule I_{d0} (Fig. 8). Note the increase of these currents at time $t = 0.3s$ caused by the load torque.

It can be seen from Fig.9 the evolution of speed and the electromagnetic torque is empty and loaded. Speed attains a value very similar synchronism (157rad / s, sliding almost zero), with an almost linear increase.

Torque is highly pulsating regime transitoir hang on, it has at the time of starting of major beats, but it vanishes at steady state. The stator and rotor currents are stabilizing a necessary constant in the Magnetization of the empty machine at a nominal voltage. A perturbation torque $T_e = 50$ Nm applied to the shaft of the machine at time $t = 0.3$ s. Joined the electromagnetic torque value to offset this oxillation with virtually instantaneous response, before stabilizing at the nominal value resistant torque. It can be seen in the same figure the decrease in rotor speed Ω with augmentation load resulting in slippage, which very obvious. Note it after-grading of the Fig.10, which the stator and rotor currents change depending on the load applied to the machine. The values of the stator flux and rotor Φ_{sd} , Φ_{rd} evolve proportionally to empty and loaded, but still a difference between the two flows is due to failure of the rotor relative to the stator (Fig.11)

We see the three voltage levels, $2U_{red}/3$, $U_{red}/2$, $U_{red}/3$, presented let be the input of the rectifier to the inverter output, thus validating the simulation results well (Fig.12). It can be seen from Fig.13. That the use of three levels rectifier improves the THD much more network-side current around 4.11%. Harmonics that exist are very small in magnitude compared to the harmonic spectrum to two rectifier bridges in series at two levels (Fig. 14, THDI = 9.86), or a single bridge rectifier two levels (Fig. 15, THDI = 28.27). These results strongly justify the choice of the rectifier at three levels to generate the DC voltages to the inverter.

IV. REGULATION OF SOURCE CONTINUOUS INVERTER

We observed that during the simulation of the cascade that previous input voltages of the DC source (U_{C1} and U_{C2}) are unstable and different values and the difference $U_{C1} - U_{C2}$ is considerable (see Fig. 6).

To minimize the imbalance between the two input voltages of the continuous source of three-level inverter is proposed to insert a bridge balancing, said clamping bridge, consisting of a transistor and a resistor the terminals of each capacitor

The transistors are controlled in such a way to maintain equal tensions U_{C1} and U_{C2} . [9], [10]. Thus the new intermediate filter between the rectifier and the inverter voltage is shown in Fig. 16.

Fig. 16. Structure of the cascade rectifier at three levels - clamping bridge - three-level inverter - induction machine

A. Modeling of the Bridge Clamping – Filter

The structure of intermediate filter is as follows

Fig. 17. Bridge structure of clamping

The model of these filters is defined by the system following (14).

$$\begin{cases} C1 \frac{dU_{C1}}{dt} = I_{C1} = I_{red1} - I_{d1} - I_{r1} \\ C2 \frac{dU_{C2}}{dt} = I_{C2} = I_{d2} - I_{red2} - I_{r2} \end{cases} \quad (14)$$

With

$$\begin{cases} I_{r1} = \frac{U_{C1}}{R_p} \\ I_{r2} = \frac{U_{C2}}{R_p} \end{cases} \quad (15)$$

The control algorithm of the transistors is defined as follows:

$$\begin{aligned} \Delta U_{12} > 0 &\Rightarrow I_{r1} = 0 \text{ et } I_{r2} \neq 0 \Rightarrow B_1 = 0 \text{ et } B_2 = 1 \\ \Delta U_{12} < 0 &\Rightarrow I_{r1} \neq 0 \text{ et } I_{r2} = 0 \Rightarrow B_1 = 1 \text{ et } B_2 = 0 \end{aligned} \quad (16)$$

With: B_K the control commands of the two transistors

$$\Delta U_{12} = U_{C1} - U_{C2} \quad (17)$$

B. Application and Simulation Results

Fig. 18. Forms of continuing voltage and bridge differences without clamping

To improve the tensions U_{C1} and U_{C2} minimizing the imbalance and the difference between these voltages, we will

simulate the same cascade but this time we use a clamping bridge.

Fig. 19. Forms of continuing voltage and bridge differences with clamping

C. Interprétation

Figure 19 shows the shapes of the voltages supplied by balancing the bridge with a value of $R_p = 30\Omega$ and capacitance values $C_1 = C_2 = 20\text{mF}$. As we can see the difference between the input voltages of the inverter at three levels dropped considerably and reaches zero at steady state. And the voltages become equal. The results obtained are very promising for the use of this cascade in the fields of high power.

V. CONCLUSION

In this work we presented the modeling and control of PWM converters for three-level control of the induction machine. The latter has been modeled mathematically in referential Park d-q and controlled a-v and in charge. The results obtained in the simulation are very satisfactory side machine or side converters.

We presented as a contribution to the study of the stability of input voltages of the inverter at three levels which allows the proper functioning of all rectifier at three levels - voltage inverter at three levels-machine induction.

We showed that these strains have an imbalance between them. This gives us a system of unstable voltage at the terminals of the machine. While the insertion of a clamping bridge across each capacitor decreases considerably the fluctuation of the input voltages of the inverter at three levels. The results were satisfactory using the filter capacitor values high enough. To reduce the value of these capacitors, while maintaining system stability, the enslavement of the voltages at the input of the inverter is recommended.

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