Table 2. 5-levels MMC inverter switching states and voltage levels

M	L	ua1	ua2	ua
2	2	2Vc	2Vc	0
1	3	Vc	3Vc	Vc
0	4	0	4Vc	2Vc
3	1	2Vc	2Vc	-Vc
4	0	2Vc	0	-2Vc

2.2 Circuit configuration and mathematic model of a 5-level NPCVSI

The Figure 2 represents one leg of five level neutral point clamped, it consists of eight switches that are called B_{kj}.

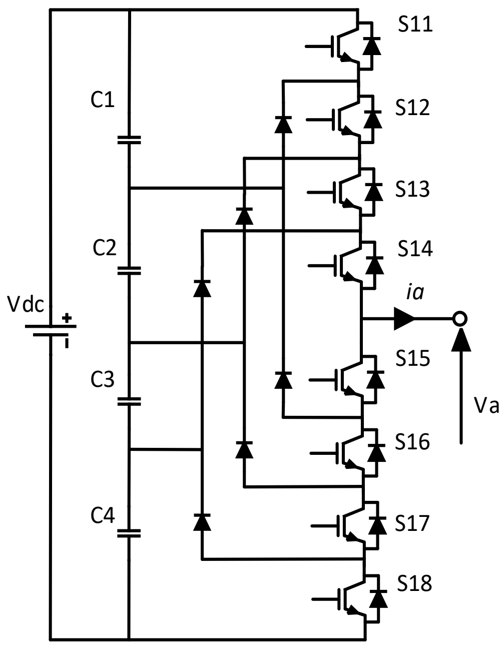

Figure 2. Schematic representation one leg of a 5-level NPCVSI

For each switch, S_{ij} $(i=\overline{1-8},\ j=\overline{1-3})$ we define a commutation function as:

$$F_{ij}=\begin{cases}1 & \text{When } S_{ij} \text{ is opened}\\ 0 & \text{When } S_{ij} \text{ is opened}\end{cases}$$

The optimal control low of a five level inverter is, [7]:

$$F_{ij}=1-F_{(i-4)} \quad (i=\overline{5-8},\ j=\overline{1-3}) \tag{12}$$

Each leg of the inverter is associated with five-connection functions (Eq. 13), who are associated to the states of the leg (Table 3):

$$\begin{cases}F_{c1j}=F_{1j}\cdot F_{2j}\cdot F_{3j}\cdot F_{4j}\\ F_{c2j}=F_{2j}\cdot F_{3j}\cdot F_{4j}\cdot F_{5j}\\ F_{c3j}=F_{3j}\cdot F_{4j}\cdot F_{5j}\cdot F_{6j}\\ F_{c4j}=F_{4j}\cdot F_{5j}\cdot F_{6j}\cdot F_{7j}\\ F_{c5j}=F_{5j}\cdot F_{6j}\cdot F_{7j}\cdot F_{8j}\end{cases} \tag{13}$$

Table 3. Five level neutral point inverter switching states and voltage levels

S_{k1}	S_{k2}	S_{k3}	S_{k4}	S_{k5}	S_{k6}	S_{k7}	S_{k8}	V_k
1	1	1	1	0	0	0	0	Vdc/2
0	1	1	1	1	0	0	0	Vdc/4
0	0	1	1	1	1	0	0	0
0	0	0	1	1	1	1	0	-Vdc/4
0	0	0	0	1	1	1	1	-Vdc/2

The output voltage is given by Eq. (14)

$$\begin{pmatrix}V_a\\ V_b\\ V_c\end{pmatrix}=\begin{pmatrix}2 & -1 & -1\\ -1 & 2 & -1\\ -1 & -1 & 2\end{pmatrix}\cdot\begin{pmatrix}2(B_{11}-B_{12})+(B_{17}-B_{18})\\ 2(B_{21}-B_{22})+(B_{27}-B_{28})\\ 2(B_{31}-B_{32})+(B_{37}-B_{38})\end{pmatrix}\cdot\frac{V_{dc}}{2} \tag{14}$$

3. PHASE DISPOSITION PULSE WIDTH MODULATION (PD-PWM)

Several modulation techniques are used for multilevel converter, based in high and fundamental frequency, in high frequency there are the PWM techniques (Phase shifted, Level shifted, Phase disposition and Phase opposite disposition) and in fundamental frequency, the most known modulation techniques are nearest level control (NLC) and the selective harmonic elimination (SHE). In this work, a carrier based Phase Disposition Pulse Width Modulation (PD-PWM) is used to control the two inverters, for a five level inverter four triangular carriers with the same frequency and amplitude so that they occupy a contiguous band over the range +0.5. V_{dc} to -0.5. V_{dc}. A reference waveform for each phase is then compared against the carriers to determine how the phase leg should be switched (Figure 3).

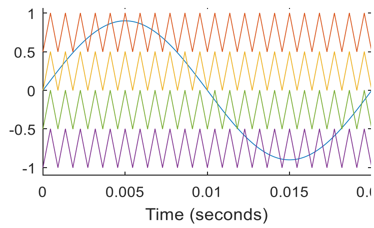

Figure 3. Phase Disposition PWM (m = 0.9, f_c = 1100 Hz)

If the reference is greater than a carrier signal, then the active device corresponding to that carrier is switched ON, and if the reference is less than the carrier signal, then the active device corresponding to that carrier is switched OFF.

4. SIMULATION RESULTS AND INTERPRETATION

The results presented in this section are obtained from a five-level modular and neutral point clamped multilevel inverter fed a three-phase induction motor in Matlab/SimPowerSystem, the phase disposition pulse width modulation (PD-PWM) is used to control the switching devices of both inverters. The switching frequency of the carriers is 1100 Hz. The simulation parameters of the induction motor used in this work are carried in appendix. The torque load varies as follow:

At t = 0.8 s vary from 0 to 31.83 N.m (The nominal value);
At t = 1.5 s vary from 31.83 to 0 N.m;
At t = 2.2 s vary from 0 to - 31.83 N.m;
At t = 3 s vary from - 31.83 to 0 N.m.

Figures 4 and 5 show the electromagnetic torque and its zoom, we can see that is identical for both converter, figures 6 and 7 show the stator current and its zoom, then figures8 and 9 present the harmonic analysis of the stator current. Figures 10 and 11 show the line-to-line voltage and his harmonic analysis for the NPCVSI and, finally, figures 13 and 14 show the line-to-line voltage and his harmonic analysis for the MMVSI. From this figure, we can see that the simulation results are nearly identical in both systems. All the simulation results are synthesized in Table 4.

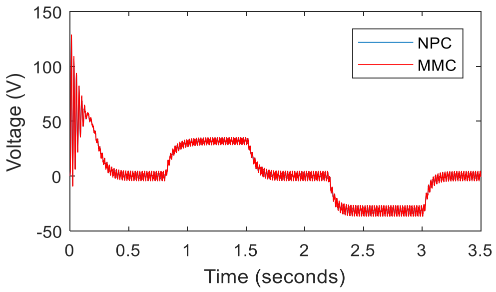

Figure 4. Electromagnetic torque

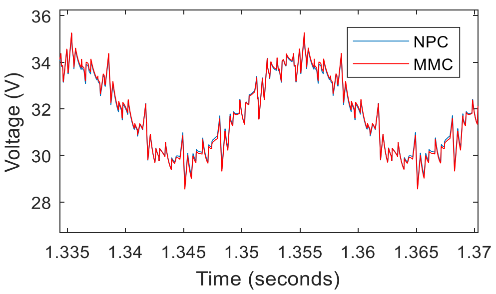

Figure 5. Electromagnetic torque's zoom

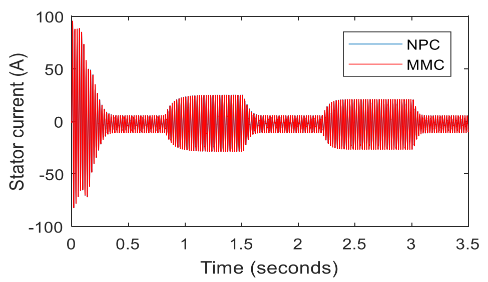

Figure 6. Stator current with NPCVSI and MMVSI

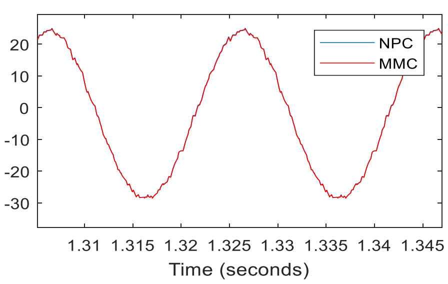

Figure 7. Zoom of stator currents with NPCVSI and MMVSI

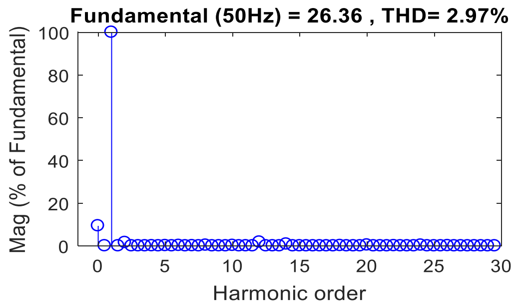

Figure 8. Stator current harmonic analysis of NPCVSI

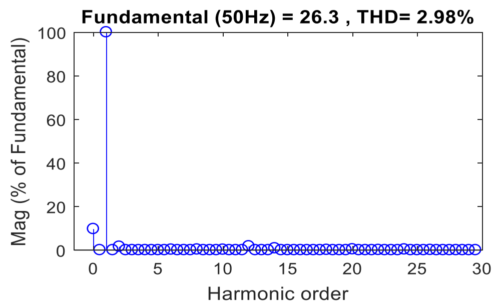

Figure 9. Stator current harmonic analysis of MMVSI

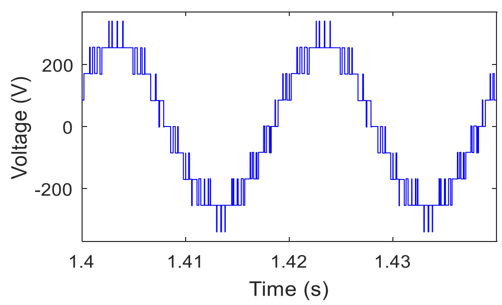

Figure 10. Stator line-to-line voltage for NPCVSI

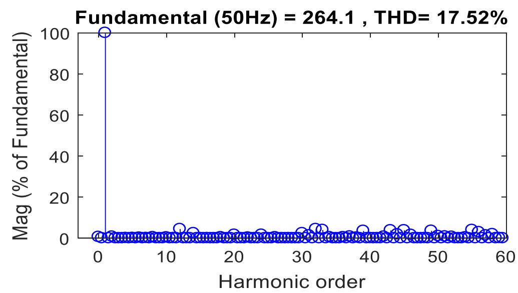

Figure 11. Harmonic analysis Stator line-to-line voltage for NPCVSI

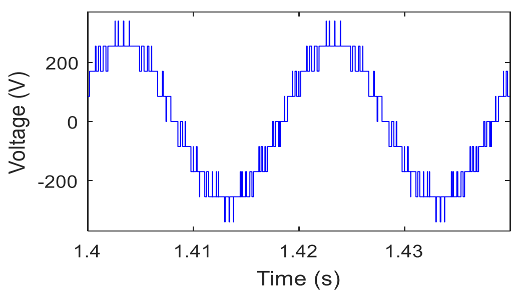

Figure 12. Stator line-to-line voltage for MMVSI

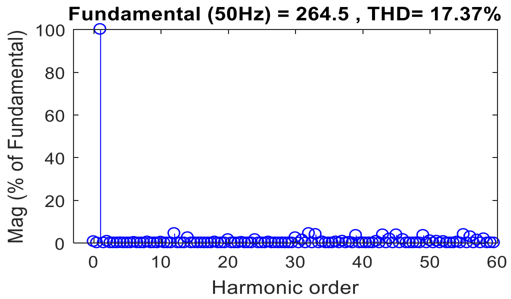

Figure 13. Harmonic analysis Stator line-to-line voltage for MMVSI

Table 4. MMVSI-5L and NPCVSI-5L Comparison

	MMVSI-5 L	**NPCVSI -5 L**
Voltage fundamental amplitude (V)	264.5	264.1
Voltage THD %	17.37	17.52
Current fundamental amplitude (A)	26.3	26.36
Current THD %	2.98	2.97
Number of power switches	**48**	**24**

5. CONCLUSIONS

In this paper, a five-level modular multilevel source voltage inverter (MMSVI) is used to drive an induction motor. Indeed, this converter is compared to a classical neutral point clamped source voltage inverter (NPCSVI), where the two multilevel inverters topologies are used to drive the induction motor and numeric simulations are carried in Matlab/SimPowerSystem, the both inverters are piloted by a Phase Disposition Pulse width modulation (PD-PWM). The results obtain are the same for both topologies. Nevertheless, the modular multilevel inverter presents some disadvantages, as the high number of switches required compared to the neutral point clamped inverter for the same level of output voltage (Table 4). Indeed, for twice the number of power switches we got the same results, and an additional control of voltage balancing of SM's capacitor is required. Hence, the modular multilevel converter is not recommended in case of motor drive compared to the neutral point clamped. By increasing the number of power switches, the failure rate increases, which reduces the reliability of MMC in traction systems and despite the quality of energy provided by this latter. Another study of the cost may seem interesting in this sense. However, the modular multilevel converter is highly desirable for medium and high voltage applications for the reasons mentioned above.

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NOMENCLATURE

dc	Direct current
F	Friction factor
IM	Induction motor
HVDC	High Voltage Direct Current
J	Moment of inertia
L	Leakage inductance
M	Mutual inductance

MMC	Modular Multilevel Converter
MMVSI	Modular Multilevel Voltage Sourse Inverter
N	Number of SM in arm
NLC	Nearest Level Control
NPC	Neutral Point Clamped
NPCVSI	Neutral Point Clamped Voltage Source Inverter
p	Number of pole pairs
PDPWM	Phase Disposition Pulse Width Modulation
S	Power switch
SHE	Selective Harmonic Elimination
V	Voltage

Greek symbols

Γ	Torque N.m
φ	Flux leackage wb
Ω	Mechanical speed rad/s

Subscripts

f	fluid (pure water)
nf	Nanofluid
s	Stator
r	Rotor
d	Direct axis
q	Quadratic axis
em	Electromagnetic
dc	Direct current side
ac	Alternative current side
u	Upper arm
l	Lower arm
circ	Circulating current