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Assessment of field oriented induction machine control strategy using new generation of inverters in BB36000 locomotive

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ABSTRACT

Due to their excellent characteristics; Reaching high voltage inverters by using lower voltage switches, reduced output current distortion, dv/dt, and switching losses decrease, efficiency rise, multilevel inverters are an interesting alternative to the two-level inverters especially in traction applications. Many studies compared both topologies, but this work compare performances of Field oriented control strategy using two levels and neutral point piloted three levels inverter supplied by space pulse width modulation. Based on real parameters, this work shows that this efficient multilevel inverter reduces current distortion and torque ripples in a manner to reduces the size and cost of all railway traction systems chosen for this work.

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1. INTRODUCTION

In the United States, more than 25% of total greenhouse emissions are due to the transportation sector 50% reduction in this ratio will give an important reduction in total greenhouse gas emissions [1]-[3]. Due to their reduced greenhouse emissions and reduced reliance on fossil fuels, electric vehicles (EVs) are the best alternative vehicles in this critical environmental context. Even, EVs do not produce any emissions; the generation of electricity can still produce emissions. However, compared to internal combustion engine vehicles (ICEVs), EVs still produce 50% lower of greenhouse emissions. EVs are offering many opportunities, but they also face many challenges, particularly concerning the battery of EVs. The unavailability of chargers and their high cost compared to the ICEVs, the limited energy density of batteries, slow recharging compared to the refueling of ICEVs are the major limitations to a huge expansion of that environmentally friendly transportation mean [4]. To reduce the recharging time, many works try to increase the Evs' battery voltage. Higher DC-link voltage enables extreme fast charging and decreases the cable size and weight [5]-[7]. However, it needs new requirements regarding the inverter, devices or structure needs to be improved in such a manner to withstand high voltages [8]. Because of its higher electromagnetic interference, the use of two levels inverter can damage the electric motor. Although, its reduced conduction losses, two levels inverter presents important switching losses. Hence, the inverter efficiency decreases [9]. Numerous industrials used higher input voltages inverters by moving to 1200 V and 1700 V IGBTs and

MOSFETS [6], [7], [10], [11]. Even though high voltages switch inverters could attain high voltages, high switching losses and high dv/dt are maintained in two levels inverter. Due to their excellent characteristics, the multilevel inverter can be a very attractive alternative to the two levels inverter for traction applications. Reaching high voltage inverters by using lower voltage switches, reduced output current distortion, dv/dt and switching losses decrease, and efficiency rise are the main opportunities offered by multilevel inverters to the new traction applications [12]-[14]. Many comparisons between two levels and multilevel inverters have been made in the literature. Thanks to the multilevel inverter, efficiency is improved in standard driving cycles [15], [16], costs of the two systems are compared [13], [15]. Thanks to the lower filter and battery cost in the case of multilevel drive, the overall system is cheaper even if the cost of a multilevel inverter is softly higher than two levels inverter. The previous studies have studied topologies. Anyway, another aspect of multilevel traction drives that need to be investigated and compared: Performances of control strategies. This work aims to show the performances improvement of a conventional Field oriented induction machine control strategy in both steady-state and transient conditions by using neutral point piloted three levels inverter NPP, instead of two levels inverter controlled by space pulse width modulation. Very used in Moroccan railways, BB 36000 is the locomotive chosen to be improved in this work. Using real parameters, very interesting simulations results are obtained and discussed after explaining the principle off field-oriented control (FOC) and net primary production (NPP) inverter.

2. PRINCIPLE OF DFOC STRATEGY FOR INDUCTION MACHINE USING TWO LEVELS INVERTER

FOC is a method of controlling a rotating field machine in such a manner to attain independent control over the torque and the flux components of the stator current [17]. It makes it possible to control the induction machine like the control of a separately excited DC machine, and hence it enables the use of induction motors in applications requiring high-dynamic performance, where traditionally only DC drives were applied. The concept of FOC applied to induction motor drives, allows us to perform fast and fully decoupled control of torque and flux [18]. To obtain such a decoupled control, FOC algorithms need to know the rotor flux angular position to correctly align the stator current vector. As a consequence, it is possible to control torque and rotor flux in a DC machine control fashion, by acting on two separated components of the stator current i_{sd} and i_{sq}in (1).

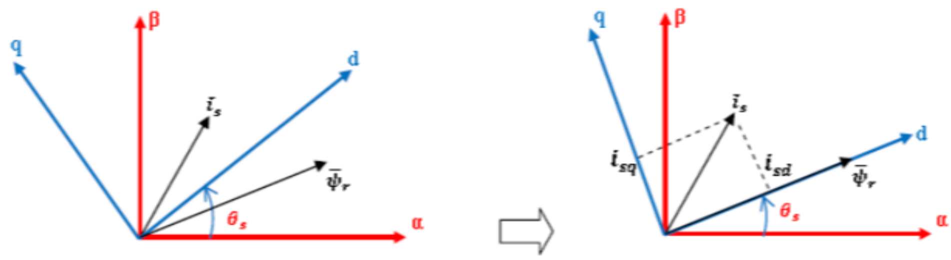


Figure 1. Orientation of the rotor field to d axis of the (d,q) reference

After applying the rotor field rotation, Figure 1, $\hat{\psi}_{rd} = \hat{\psi}_r$ and$\hat{\psi}_{rq} = 0$. Induction machine (IM) relations becomes then:

$$\begin{cases} \psi_{rd} = \frac{M}{1+pT_r} i_{sd} \\ T_e = n_p \frac{M}{L_r} \psi_r i_{sq} \end{cases} \quad (1)$$

before the determination of rotor flux, angular position is required before applying this orientation. Direct field-oriented control (DFOC) and indirect field-oriented control (IFOC) are the two methods used to obtain this position.

Using (2), $\hat{\psi}_r$ and$\hat{T}_e$ are estimated using $i_{sd}$and i_{sq} respectively, and are compared to ψ_r^* and T_e^* . As shown in Figure 2 torque and flux are directly controlled in DFOC.

$$\begin{cases} v_{sd} = \left[(R_s + p\sigma\mathfrak{L}_s)\frac{(1+T_r p)}{\mathcal{M}} + \frac{\mathcal{M}}{\mathfrak{L}_r p}\right]\psi_{rd} - w_s\mathfrak{L}_s\sigma i_{sq} \\ v_{sq} = (R_s + p\sigma\mathfrak{L}_s)\frac{T_e}{p\frac{M}{L_r}\psi_{rd}} + w_s\mathfrak{L}_s\sigma i_{sd} + w_s\frac{\mathcal{M}}{\mathfrak{L}_r}\psi_r \\ \psi_r = \frac{M}{1+pT_r} i_{sd} \\ T_e = n_p\frac{M}{L_r}\psi_r i_{sq} \\ \theta_s = \int(n_p\Omega + \frac{M}{T_r}\frac{i^*_{sq}}{\psi^*_{rd}})dt \end{cases} \quad (2)$$

Figure 2 shows the control strategy scheme of DFOC.

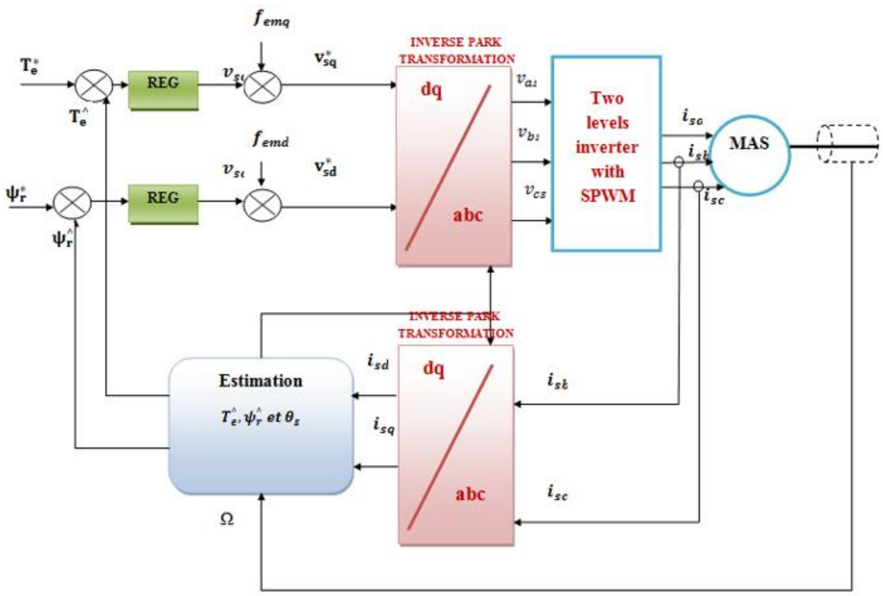


Figure 2. Direct Field oriented control strategy scheme of IM using two levels inverter

To ensure decoupled control for torque and flux, compensation terms f_{emd} and f_{emq} (3) are added to obtain a d and q axes completely independent.

$$\begin{cases} f_{emd} = w_s\mathfrak{L}_s\sigma i_{sq} \\ f_{emq} = w_s\mathfrak{L}_s\sigma i_{sd} + w_s\frac{\mathcal{M}}{\mathfrak{L}_r}\psi_r \end{cases} \quad (3)$$

In (2) shows that how position θ_s and voltages v_{sq}, v_{sd} are calculated. Using Park position θ_s, v_{sq}, and v_{sd} are transformed and injected to the two levels inverter. A sinusoidal pulse width modulation is used to control this inverter Figure 3. In SPWM modulation, pulses resulting from the comparison between a sinusoidal reference signal and triangular carrier are injected to the switches, to obtain two voltage levels [19].

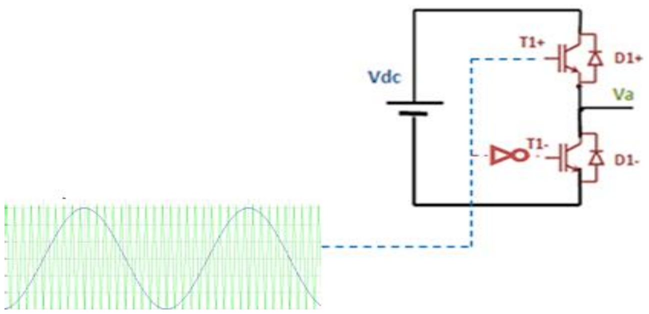


Figure 3. Principle of the SPWM two levels control strategy

3. IMPROVEMENT OF DFOC STRATEGY FOR IM

To improve performances given by the classical structures with two voltages levels, multilevel conversion structures constitute an interesting solution. For medium voltage high power applications such as railway traction, the cost of semiconductor devices is increased. Multilevel structures offer a reduction of the voltage stress that compensates for the increased number of devices. Also, by lowering the total harmonic content, these structures offer the advantage of reducing the size of the output filter and then the cost of the overall system. Moreover, torque ripples for motor drive applications will be reduced. Even if, NPC inverters have a wide industrial spread mostly in medium voltage applications. They have disadvantages; like unequal switches losses distribution. To solve this problem, three levels NPP (3L_NPP) inverter is the multilevel inverter chosen to be used to replace the two levels inverter [20]-[23].

3.1. Principle of the 3L_NPP inverter

As shown in Figure 4, two capacitors that have the same capacitance are used to divide equally the voltage and obtain two voltage levels. Each leg of the 3L-NPP inverter contains two head-to-tail connected and clamped IGBTs and four other vertical IGBTs, each IGBT has an antiparallel connected diode. To obtain the three voltage levels, switches are following switching states as shown in Table 1. Figure 5 shows the two carriers sinusoidal pulse width modulation (SPWM) control strategy used for one leg of the NPP inverter [24], [25].The following Figure6 shows the output voltages of the inverter simulated in MATLAB/Simulink where the three voltage levels are observed.

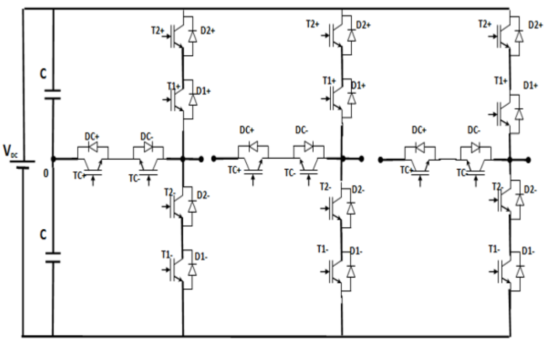


Figure 4. Structure of a 3L_NPP inverter brush

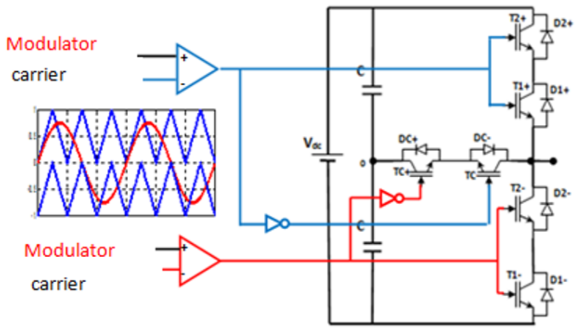


Figure 5. SPWM of the 3L_NPP inverter

Table 1. Basic switching of the three levels NPP inverter

Voltage Va	T2+	T1+	TC+	T2-	T1-	TC-
Vdc/2	1	1	1	0	0	0
0	0	0	1	0	0	1
-Vdc/2	0	0	0	1	1	1

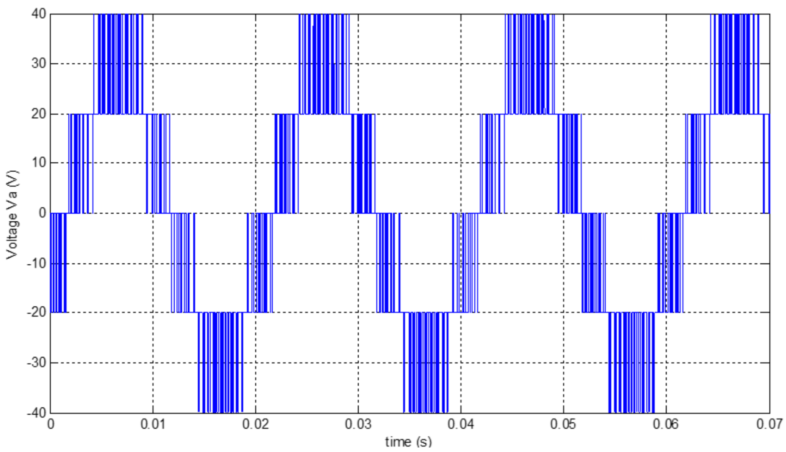


Figure 6. Output voltages of the five levels NPC inverter

3.2. Improvement of DFOC strategy 3L_NPP inverter

To improve the transient and steady-state performances of DFOC strategy for IM, to reduce voltage stress in semiconductors and to avoid unequal junction temperature distribution which confines the inverter maximum output power especially for high power applications, instead of the two levels inverter and 3L_NPC inverter a 3L_NPP inverter is used with an appropriate SPWM control strategy. As shown in Figure 7, all the other blocks of the DFOC strategy scheme are still unchangeable.

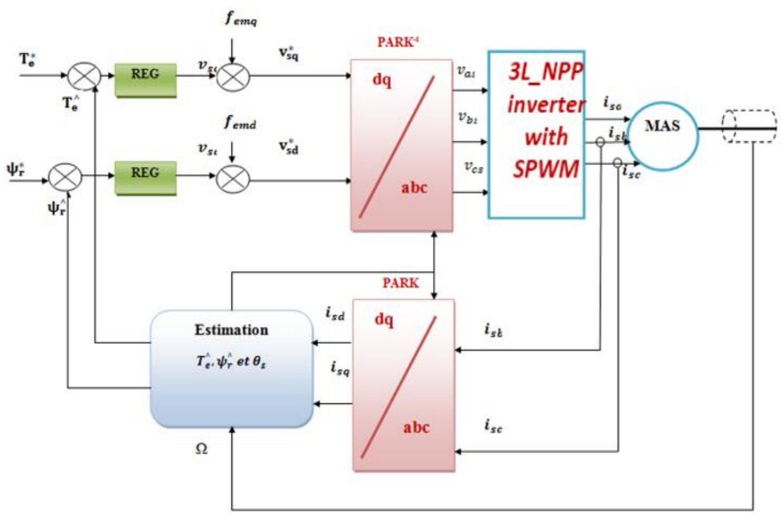


Figure 7. Field oriented control strategy scheme of IM using 3L_NPP inverter

4. SIMULATION RESULTS AND DISCUSSION

To verify the effectiveness of using a 3L_NPP inverter, simulations are made for a high-power medium voltage application which is a railway traction application. A simulation test on the BB 36000 locomotive induction machine has been performed. In this section the two strategies: DFOC of IM supplied by two levels inverter 2L_DFOC and DFOC of IM supplied by 3L_NPP inverter 3L_DFOC are compared following method as shown below:

- In open-loop conditions
  a. Steady-state performance: The two strategies are compared in terms of current and torque ripples.
  b. Transient performance: The two Strategies are compared in terms of Time response to a step variation of the torque command.
- In closed-loop conditions

  Using two regulators: proportional-integral PI and integral proportional IP:
  a. The two strategies are compared in terms of the pursuit of the rotor speed to the speed reference for different speed variations.
  b. The two strategies are compared in terms of the behavior of speed under perturbations.
  c. The behavior of the two regulators is compared for the two strategies

4.1. Open loop conditions

4.1.1. Steady state performance

The steady-state performance of 2L_ DFOC and 3L_DFOC schemes has been compared evaluating current distortions and torque ripples. Table 2 presents a comparison between the two strategies in terms of current THD in different torque values: 100%, 50%, and -50% of the rated torque. As shown in this table THD is still the same for 2L_DFOC for the three torque values, but it is reduced to half for the 3L_ DFOC control strategy, Three levels of NPP used in the 3L_DFOC reduce current distortions. Thereby, torque ripples are reduced to the third of 2L_DFOC torque ripples value as shown in Table.3.

Table 2. Current THD for 2L_DFOC and 3L_DFOC at different torque value

THD	2L_DFOC	3L_DFOC
3,000	21.81%	12.05%
1,500	21.7%	12.3%
-1,500	21.72%	12.2%

Table 3. Torque ripples for 2L_DFOC and 3L_DFOC at different speed value

Torque (N.m)	2L_DOC	3L_DFOC
3,000	10%	12.05%
1,500	10%	12.3%
-1,500	10%	12.2%

4.1.2. Transient performance

For 3,000 (N.m), 1,500 (N.m) and -1,500 (N.m) torque values, time response still the same and equal to 5.6 ms. For both 2L_DFOC and 3L_DFOC. This result shows that transient performances still the same even if two levels inverters is replaced by a 3L_NPP inverter Table 4.

Table. 4. Time response for 2L_DFOC and 3L_DFOC at different torque value

Torque (N.m)	2L_DFOC	3L_DFOC
3,000	5.6 ms	
1,500	5.6 ms	
-1,500	5.6 ms	

4.2. Closed loop conditions

The rotor speed closed loop DFOC system is presented in Figure 8. IP and PI controller schemes are presented in Figure 9(a) and Figure 9(b). Their coefficients are presented in (4) and (6). In order to have an aperiodic of the above presented system, we found for IP speed controller.

$$K_{iip} = \frac{1}{4g\tau} \text{ and } K_{pip} = \frac{J-\tau f}{\tau} \quad (4)$$

Where:

$$\tau = \frac{J}{K_{pip}+f} \text{ and } g = \frac{K_{pip}}{K_{pip}+f} \quad (5)$$

In order to have an aperiodic of the above presented system, we found for PI speed controller.

$$K_{ipi} = J\omega_0^2 \text{ and } K_{ppi} = 2J\omega_0 - f\,J\omega_0^2 \quad (6)$$

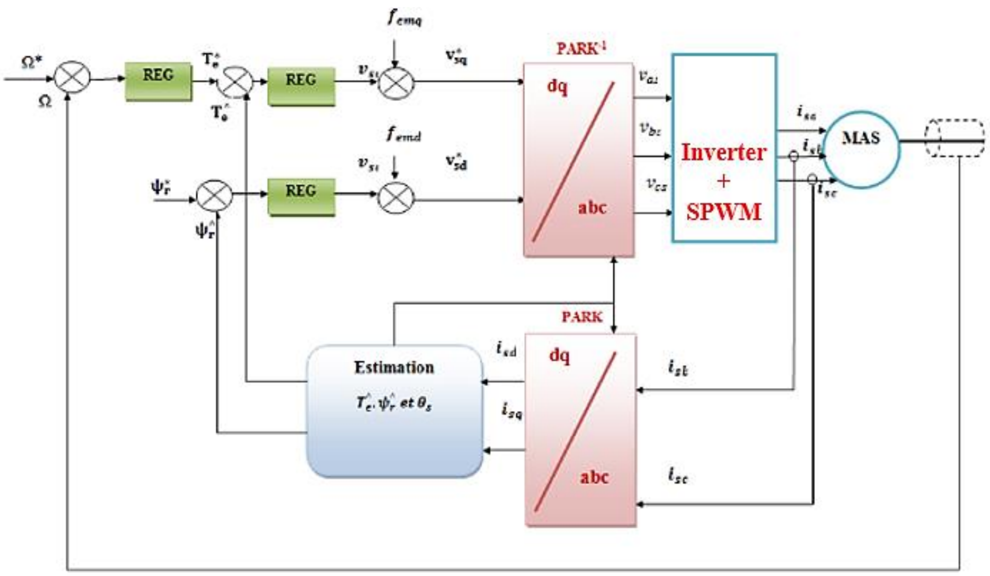


Figure 8. The rotor speed closed loop 3L_DFOC system

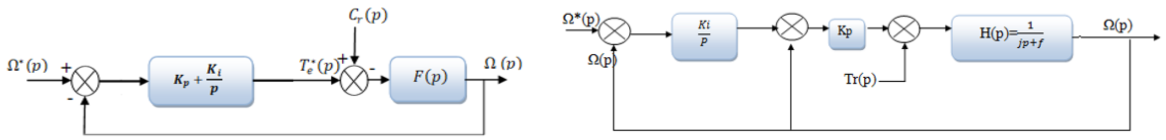


Figure 9. Closed loop: (a) PI speed controller and (b) IP speed controller

As shown in Figures 10(a) and 10(b) (see Appendix), for both 2L_DFOC and 3L_DFOC strategy, the rotor speed reference is varying from 430 rd.s-1 (rated speed) to -430 rd.s-1, and from 100 rd.s-1 (rated speed) to -200 rd.s-1; rotor speed is following the rotor speed reference for high, medium, and small speed. Even with applying a torque load variation from 0N.m to 1,500 N.m at the 30s to the two closed-loop systems, this perturbation is directly rejected. Then, for 2L_DFOC and 3L_DFOC, rotor speeds follow again their references after 10s. Both IP and PI controller presents good steady-state performances, but IP controller presents better transient performance especially in the pursuit of reference. Finally, a detailed comparison between 2L_DFOC and 3L_DFOC is summarized in Table 5.

4.3. Results discussion

Using real parameters of BB 36000 locomotive, simulation results presented below show performances improvement of the FOC using NPP inverter. As presented in Figures 10(c) and 10(d) (see Appendix), 3L_FOC reduces noticeably torque ripples in a manner to offer quiet and more relaxed journeys. Also, in addition to his interesting efficiency compared to two levels inverter, Figures 10(e) and 10(f) (see Appendix) shows that the use of three levels NPP inverter decreases current distortion to half, hence the size and then the cost of the output filter and the overall system is reduced. Finally, as shown in the Table 5, 3L_NPP inverter is reaching high voltage inverters by using two times lower voltage switches $\frac{Vdc}{2}$ instead of V_{dc} for two levels inverter. Table 6 gives values of all coefficients and simulation parameters.

Table 5. Detailed comparison between 2L_DFOC and 3L_DFOC

Performances	2L_DFOC	3L_DFOC
Structure	simple	complex
Off-state voltage	V_{dc}	$\frac{Vdc}{2}$
Complexity of implementation	simple	complex
Current distortions	Not good (Around21.94%)	Good (Around 12.05%)
Torque ripples	More (ΔTe=300 Nm)	Less((ΔTe=100 Nm)
Response to a torque step variation	Fast(5.6 ms)	Fast(5.6 ms)
Pursuit of the rotor speed	Very good	Very good
Behavior ofspeed under perturbations	Good	Good

Table 6. Induction machine and simulation parameters

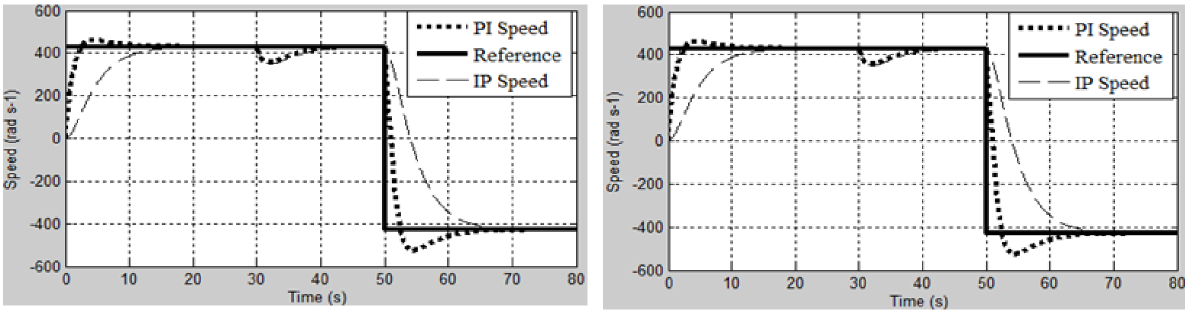
Parameter		Signification
Machine parameters	Rs=0.029	Stator resistance (Ω)
	Rr=0.022	Rotor resistance (Ω)
	M=0.035	Mutual inductance (H)
	Ls=0.00059	Stator inductance (H)
	Lr=0.00059	Rotor inductance (H)
	J= 63,87	Factor of inertia (Kg.m^2)
	f=0.0000155	Coefficient of friction
	p=2	Number of pole pairs
Simulation parameters	P=1.5	Rated power (MW)
	V_{dc}=4391	DC bus voltage (V)
	F_{pwm}=2000	Pulse width modulation frequency (Hz)
	C_{nom}=3000	Rated torque (N.m)
	Ω_{nom}=435	Rated speed (rad/s)
	Kppi=9,6, Kipi=4,6	Integral and proportional coefficients

5. CONCLUSION

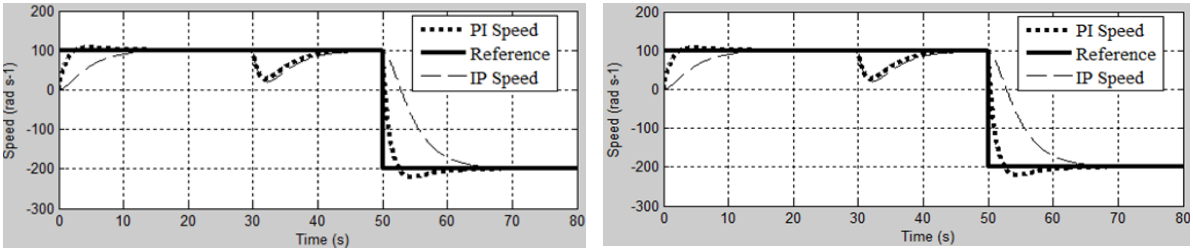
This work presents a detailed comparison between 2L_DFOC and 3L_DFOC using an NPP inverter. The two strategies used a high power application: railway traction with real parameters of BB 36000, to present performances in both open and closed-loop conditions. As presented 3L_FOC reduces noticeably torque ripples in a manner to offer quiet and more relaxed journeys. Also, the use of three levels of NPP inverter decreases current distortion to half, hence the size and then the cost of the output filter and the overall system is reduced. The aim of our future work is to improve 3L_DFOC by using space vector modulation instead of SPWM control of the NPP inverter.

APPENDIX

Closed Loop

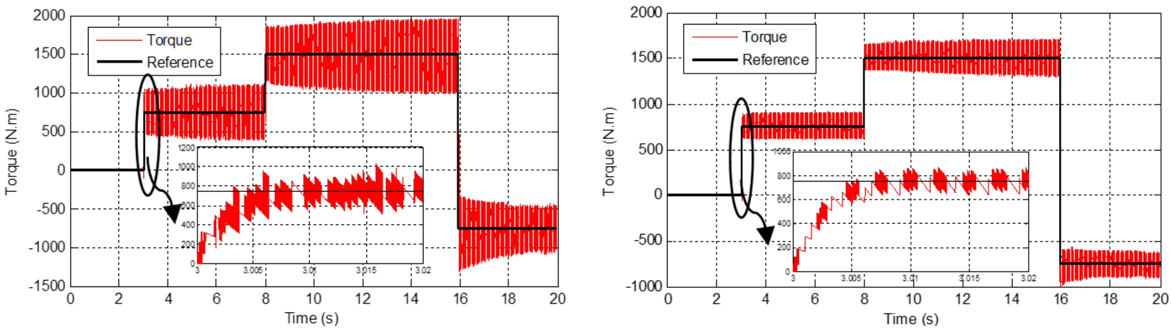


(a)

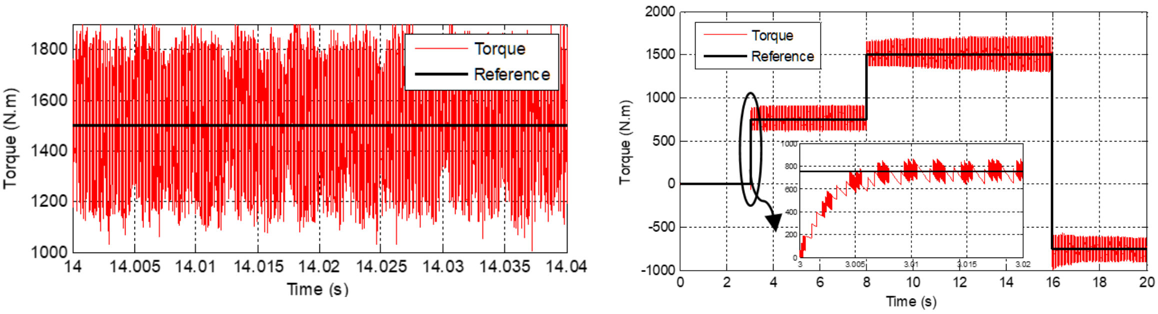


(b)

Open Loop System

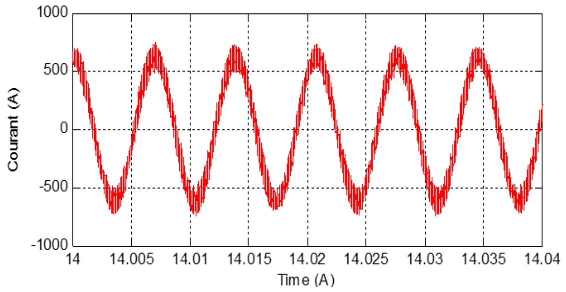


(c)

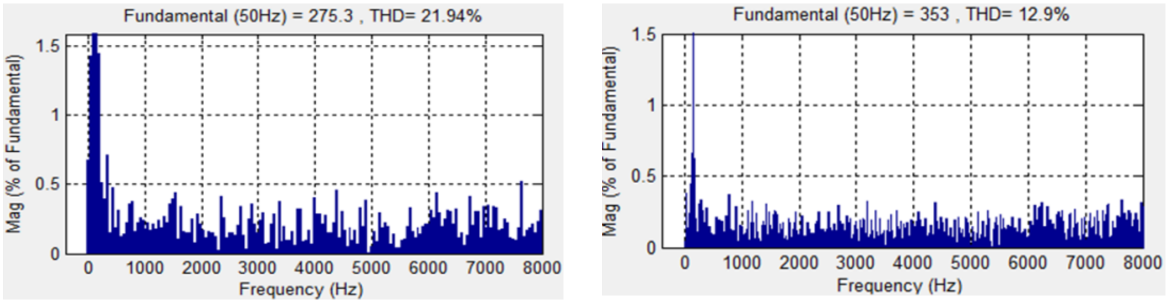


(d)

Figure 10. Comparison between 2L_DFOC and 3L_DFOC in (a) closed and open loop conditions in term of speed response (high speeds), (b) speed response medium and small speeds, (c) torque response, and (d) torque ripple



(e)



(f)

Figure 10. Comparison between 2L_DFOC and 3L_DFOC in (e) current distortions and (f) THD current (continue)

REFERENCES

[1] M. Muratori *et al.*, "The rise of electric vehicles-2020 status and future expectations," *IOP Science*, vol. 3, no. 2, Jan. 2021, doi: 10.1088/2516-1083/abe0ad.

[2] M. Broy, "Challenges in automotive software engineering," in *ICSE'06:Proceedings of the 28th international conference on Software engineering*, May 2006 pp. 33-42, doi: 10.1145/1134285.1134292.

[3] J. Cao, X. Chen, R. Qiu, and S. hou, "Electric vehicle industry sustainable development with a stakeholder engagement system," *Technoloy in Society*, vol. 67, Nov. 2021, doi: 10.1016/j.techsoc.2021.101771.

[4] A. Tomaszewska *et al.*, "Lithium ion battery fast charging: A review," *eTransportation*, vol. 1, Aug. 2019, doi: 10.1016/j.etran.2019.100011.

[5] M. Mosaraf , A. Hossain , A. Ullah, M. Shahad , S. Shahnewaz, M. Shafiul, T. Jamal, H. Ahmed, "Integration of Large-Scale Electric Vehicles into Utility Grid: An Efficient Approach for Impact Analysis and Power Quality Assessment," *Sustainability*, vol. 13, no. 19, pp. 1-18, Oct. 2021, doi: 10.3390/su131910943.

[6] O. Heidrich, G.nHill, M. Neaimeh, Y. Huebner, P. Blythe, R. Dawson, "How do cities support electric vehicles and what difference does it make?," *Technological Forecasting and Social Change*, vol. 123, pp. 17-23, Oct. 2017, doi: 10.1016/j.techfore.2017.05.026.

[7] C. Jung, "Power Up with 800-V Systems: The benefits of upgrading voltage power for battery-electric passenger vehicles," in *IEEE Electrification Magazine*, vol. 5, no. 1, pp. 53-58, Mar. 2017, doi: 10.1109/MELE.2016.2644560.

[8] D. Ronanki, A. Kelkar, and S. S. Williamson, "Extreme fast charging technology-Prospects to enhance sustainable electric transportation,"*Energies*, vol. 12, no. 19, p. 3721, Sep. 2019, doi: 10.3390/en12193721.

[9] N. Soualhi, A. Makouf, N. Nait-Said, and S. Hamada, "Comparison between a Two-Level and Three-Level Inverter fed Induction Motor including Losses and Efficiency,"in *4th International Conference on Advanced Systems and Emergent Technologies (IC_ASET)*, 2020, pp. 89-94, doi: 10.1109/IC_ASET49463.2020.9318310.

[10] H. Tu, H. Feng, S. Srdic, and S. Lukic, "Extreme Fast Charging of Electric Vehicles: A Technology Overview," in *IEEE Transactions on Transportation Electrification*, vol. 5, no. 4, pp. 861-878, Dec. 2019, doi: 10.1109/TTE.2019.2958709.

[11] K. Zhang, J. Yang, C. Liu, J. Wang, and D. Yao, "Dynamic Characteristics of a Traction Drive System in High-Speed Train Based on Electromechanical Coupling Modeling under Variable Conditions," *Energies*, vol. 15, Feb. 2022, doi: 10.3390/en15031202.

[12] A. Choudhury, P. Pillay and S. S. Williamson, "Comparative Analysis Between Two-Level and Three-Level DC/AC Electric Vehicle Traction Inverters Using a Novel DC-Link Voltage Balancing Algorithm," in *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 2, no. 3, pp. 529-540, Sep. 2014, doi: 10.1109/JESTPE.2014.2310140.

[13] R. Teichmann and S. Bernet, "A comparison of three-level converters versus two-level converters for low-voltage drives, traction, and utility applications," in *IEEE Transactions on Industry Applications*, vol. 41, no. 3, pp. 855-865, May-June 2005, doi: 10.1109/TIA.2005.847285.

[14] L. Dorn-Gomba, J. Ramoul, J. Reimers, and A. Emadi, "Power Electronic Converters in Electric Aircraft: Current Status, Challenges, and Emerging Technologies," in *IEEE Transactions on Transportation Electrification*, vol. 6, no. 4, pp. 1648-1664, Dec. 2020, doi: 10.1109/TTE.2020.3006045.

[15] F. Chang, O. Ilina, M. Lienkamp, and L. Voss, "Improving the Overall Efficiency of Automotive Inverters Using a Multilevel Converter Composed of Low Voltage Si mosfets," in *IEEE Transactions on Power Electronics*, vol. 34, no. 4, pp. 3586-3602, April 2019, doi: 10.1109/TPEL.2018.2854756.

[16] M. Quraan, P. Tricoli, S. D'Arco and L. Piegari, "Efficiency Assessment of Modular Multilevel Converters for Battery Electric Vehicles," *in IEEE Transactions on Power Electronics*, vol. 32, no. 3, pp. 2041-2051, March 2017, doi: 10.1109/TPEL.2016.2557579.
[17] K. Hasse, "On the dynamics of speed control of a static AC drive with squirrel cage induction machine," Ph.D. dissertation, Tech. Hochschule Darmstradt, Germany, 1969.
[18] R. Garg, P. Mahajan, N. Gupta, H.Saroa, "A comparative study between field oriented control and direct torque control of AC traction motor," *in International Conference on Recent Advances and Innovations in Engineering,* May. 2014, doi: 10.1109/ICRAIE.2014.6909201.
[19] H. Chaikhy, M.Khafallah, A. Saad, M. Es-Saadi, and K. Chikh, "Evaluation des performances des commandes vectorielles de la machine à induction,"*Revue de génie industriel*, vol. 6, pp. 23-32, Jan. 2011.
[20] V. Guennegues, B. Gollentz, F. Meibody-Tabar, S. Rael, and L. Leclere, "A converter topology for high speed motor drive applications," *2009 13th European Conference on Power Electronics and Applications*, 2009, pp. 1-8.
[21] J. I. Leon, S. Vazquez and L. G. Franquelo, "Multilevel converters: Control and modulation techniques for their operation and industrial applications", *Proc. IEEE*, vol. 105, no. 11, pp. 2066-2081, Nov. 2017, doi: 10.1109/JPROC.2017.2726583.
[22] V. Gennegues, "Contribution à l'étude des convertisseurs multiniveaux destinés aux applications moteurs rapides," M.S. thesis, Univ. Lorraine, Lorraine, Suisse, 2009.
[23] V. Guennegues, B. Gollentz, L. Leclere, F. Meibody-Tabar, and S. Raël, "Selective harmonic elimination PWM applied to H-bridge topology in high speed applications", in *International Conference on Power Engineering, Energy and Electrical Drives*, May. 2009, doi: 10.1109/POWERENG.2009.4915189.
[24] W. Brumsickle, D. Divan, and T. Lipo, "Reduced switching stress in high-voltage IGBT inverters via a three-level structure," in *APEC 98 Thirteenth Annual Applied Power Electronics Conference and Exposition,* Aug. 1998, doi: 10.1109/APEC.1998.653944.
[25] H. Akagi, "Multilevel Converters: Fundamental Circuits and Systems ," in *Proceedings of the IEEE*, vol. 105, no. 11, Nov. 2017, doi: 10.1109/JPROC.2017.2682105.

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