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Conceptions de controle prédictive Dead-beat appliqué a l' onduleur NPC à trois niveaux

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Appreciation

First of all, we start by addressing our most sincere thanks to our research promoter., who has proposed this very interesting topic. This achievement could not be carried out in large part due to his kindness and cooperation. We are also grateful to him for his unfailing availability and dynamism during the entire duration of this thesis and to the scientific and pedagogical skills of its frame without which this work would not have emerged.

Our thanks also go to our colleagues with whom we shared the section, finally many thanks to our parents and our families for their support.

Dedication

We dedicate this modest work:

To Our parents. May god give them good health and long life.

To our brothers and sisters,

For all family members and friends,

And to all those who contributed to the realization of this theses, we say

thank you.

Abstract

Model predictive control has been considered as a powerful alternative control method in power converters and electrical drives recently. Using Neutral-Point clamped Three-Level NPC Converters this approach relies on the use of space vector modulation (SVM) with deadbeat (DB) predictive controller compared to the conventional MPC in order to achieve optimal performance in the form of maximum productivity, maximum profit, minimum cost, or minimum energy use.

3 vectors method is applied for calculating the desired voltage vector which minimizes the cost function, the total execution time reduces considerably so that the selected voltage vector can be applied immediately without delay compensation. This method improves the dynamic responses and steady-state performance of the system and improve the current total harmonic distortion (THD)

Keywords: Model predictive, Neutral-Point clamped, space vector modulation, deadbeat, total harmonic distortion

Résumé

Le contrôle prédictif des modèles a été récemment considéré comme une méthode de contrôle alternative puissante dans les convertisseurs de puissance et les entraînements électriques. En utilisant des convertisseurs NPC à trois niveaux à point neutre, cette approche repose sur l'utilisation de la modulation vectorielle spatiale (SVM) avec contrôleur prédictif deadbeat (DB) par rapport au MPC conventionnel afin d'obtenir des performances optimales sous la forme d'une productivité maximale, d'un profit maximal, un coût minimum ou une consommation d'énergie minimale. La méthode des 3 vecteurs est appliquée pour calculer le vecteur de tension souhaité qui minimise la fonction de coût, le temps d'exécution total réduit considérablement de sorte que le vecteur de tension sélectionné peut être appliqué immédiatement sans compensation de retard. Cette méthode améliore les réponses dynamiques et les performances en régime permanent du système et améliore la distorsion harmonique totale (THD) actuelle

Mots clés: *Modèle prédictif, point neutre verrouillé, modulation vectorielle spatiale, deadbeat, distorsion harmonique totale*

ملخص

تم اعتبار التحكم التنبئي النموذجي كطريقة تحكم بديلة قوية في محولات الطاقة والمحركات الكهربائية مؤخرًا. باستخدام محولات NPC ثلاثية المستويات المحايدة ذات النقاط المحايدة، يعتمد هذا النهج على استخدام تعديل متجه الفضاء (SVM) مع وحدة التحكم التنبؤية الثابتة (DB) مقارنةً بـ MPC التقليدي من أجل تحقيق الأداء الأمثل في شكل أقصى إنتاجية، وأقصى ربح أو الحد الأدنى من التكلفة أو الحد الأدنى من استخدام الطاقة. يتم تطبيق طريقة 3 متجهات لحساب متجه الجهد المطلوب الذي يقلل من دالة التكلفة، ويقلل وقت التنفيذ الإجمالي بشكل كبير بحيث يمكن تطبيق ناقل الجهد المحدد على الفور دون تعويض التأخير. تعمل هذه الطريقة على تحسين الاستجابات الديناميكية وأداء الحالة المستقرة للنظام وتحسين التشوه التوافقي الكلي الحالي (THD)

الكلمات المفتاحية :

التحكم التنبئي النموذجي ، النقاط المحايدة ، تعديل متجه الفضاء ، وحدة التحكم التنبؤية الثابتة ، التشوه التوافقي الكلي

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Abbreviations and acronyms

AC : Alternating current

CHB : Cascaded H-bridge

COP : coefficient of performance

CSI : : current-source inverter

DB : Deadbeat

DBPC : Deadbeat predictive control

DC : Direct current

GMV : Generalised Minimum Variance

IS : supply an Inverter

MPC : Model Predictive Controller

MV : Minimum variance

NPC : Neutral Point Clamped

PI : Proportional integral

PP : Pole Placement

PV : process variable

PWM : Pulse width modulation

RHC : receding horizon control

SHE : Selectetive harmonic elimination

SP : SET POINT

SPC : Smith Predictor control

SVM : Space vector modulation

VSI : Voltage source inverter

Introduction

In recent years, the multilevel inverters gave the benefits of changing the voltage level and power ratings drastically. This makes the system compact which leads to the advantages of implementing such a topology. The multilevel inverters have three different topologies dictated as neutral point clamped H-bridge and flying capacitors inverters. Among these inverters, the NPC inverters have gain the attention and became the mostly implemented inverter in various industries.

The use of power electronics converters and microcontrollers has increased considerably in a wide range of applications such as wind turbines, driving electrical machines and energy storage systems. This increment of using power converters is due to the features brought by the power converters to these systems, such as an improved performance and a higher efficiency together with a better control of different variables. As a result, power electronic converters have become one of the main actors in industry. In order to contribute to increment the benefits of power, new control strategies for power electronic devices, including certain fault tolerant topologies, have been developed.

Many control systems are used today in a large number of industries consisting of applications from all kinds. The common factor of all control types is to sustain a desired outcome that may change during a process. There are a lot of control strategies such as linear and hysteresis controllers and predictive controls. the classical controllers, like linear PI and nonlinear hysteresis. Model predictive control (MPC) is an advanced method of process control that has been enormously used in industry. In recent years, there has been a rapid increase in the use of digital controllers in control systems. Digital controls are used for achieving optimal performance in the form of maximum productivity, maximum profit, minimum cost, or minimum energy use.

A well-known type of predictive controller is the deadbeat controller. This approach uses the model of the system to calculate. The idea behind predictive control is to use

a model of the system to calculate predictions of future controlled variables. Deadbeat control is a discrete-time model based control scheme, which uses the machine model to calculate the voltages that eliminate the current errors after one sampling period. The voltages are subsequently synthesized to the machine terminals using an inverter controlled by PWM.

The First Chapter: brief definition of the inverter and its types mainly the three-level Neutral Point-Clamped, also a description of the control methods (classic and linear), in the end the main Advantages and disadvantages of predictive controls

The second chapter: consecrated on the study of the predictive controller specially the dead-beat controller and its modulation

The Third chapter: In this chapter we presented the schema of three multilevel NPC inverter, using Matab LAB we obtained different variables using two different control system method (Control predictive, Dead-Beat control).

Chapter I

Overview of digital control techniques

I.1 Introduction:

The use of power converters has become very popular in the last decades for a wide range of applications, including drives, energy conversion, traction and distributed generation. The control of power converters has been extensively studied and new control schemes are presented every year, hysteresis control and linear control with pulse width modulation are the most established in the literature

Predictive control presents several advantages that make it suitable for the control of power converters: concepts are intuitive and easy to understand, it can be applied to a variety of systems, constraints and nonlinearities can be easily included, multivariable case can be considered, and the resulting controller is easy to implement

I.2 Inverter:

I.2.1 Defention:

A DC – AC converter, also known as an inverter, generates an AC output from a DC source. There are different types of inverters. According to the type of the DC supply, an Inverter IS known as a current-source inverter (CSI) if the supply is a current source and a voltage-source inverter (VSI) if the supply is a voltage source.

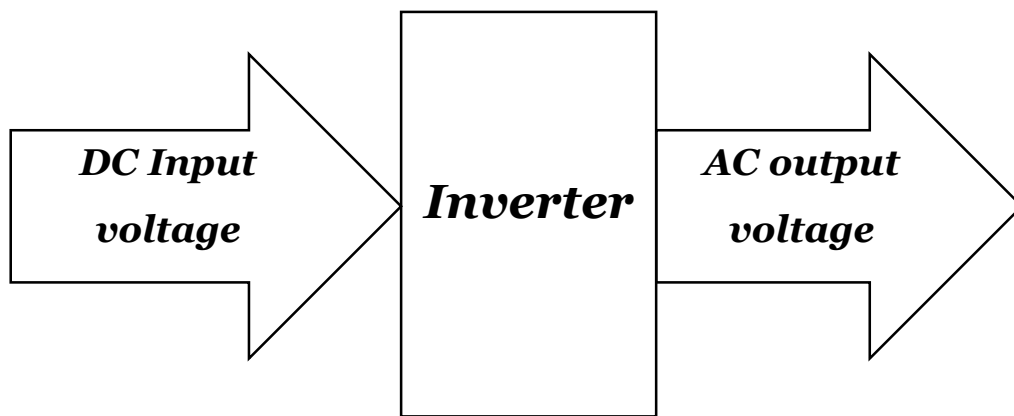


Figure I.1: *inverter*

There are different basis of classification of inverters. Inverters are broadly classified as current source inverter and voltage source inverters (vsi). Moreover, it can be classified on the basis of devices used (SCR or gate commutation devices), circuit configuration (half bridge or full bridge), nature of output voltage (square, quasi square or sine wave), type of circuit (switched mode PWM or resonant converters) etc. [1]

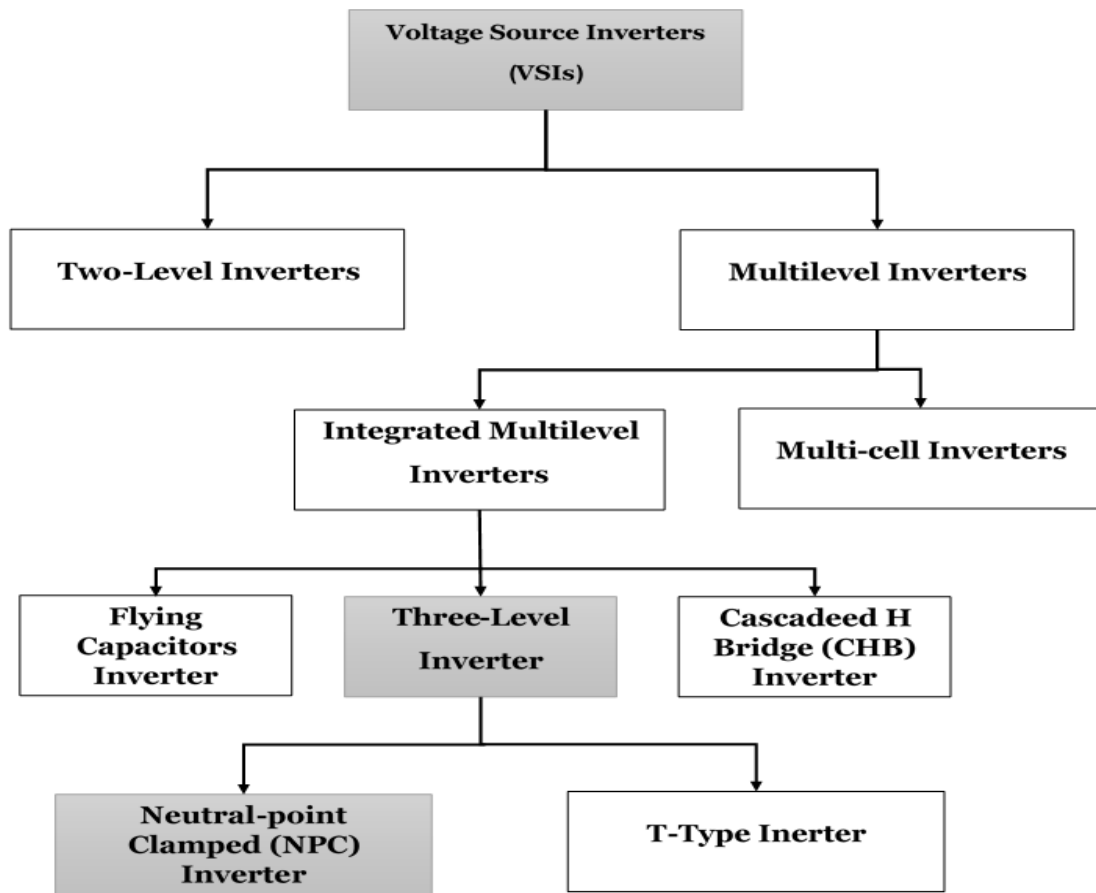


Figure I.2: Voltage source inverter types.

I.2.2 Triple phase:

A three-phase inverter can be made by grouping three universal cells. It suffices to shift the commands of the three phases by a third of a period. [2]

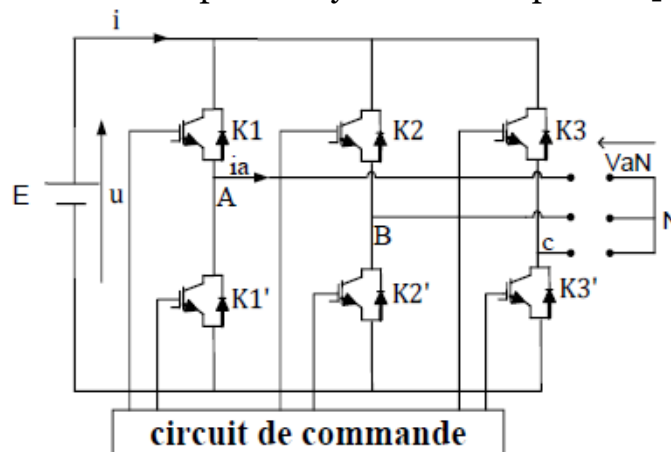


Figure I.3: Three-phase voltage inverter

I.2.3 Three-phase bridge inverter:

The three-phase bridge inverter consists of three switching cells as shown in Figure I.4. There is obviously a differential structure in which the three-phase voltages are obtained in a composite manner on the three output terminals.

The three-phase inverter must obviously, in nominal mode, deliver a voltage system whose fundamental components form a balanced system [2].

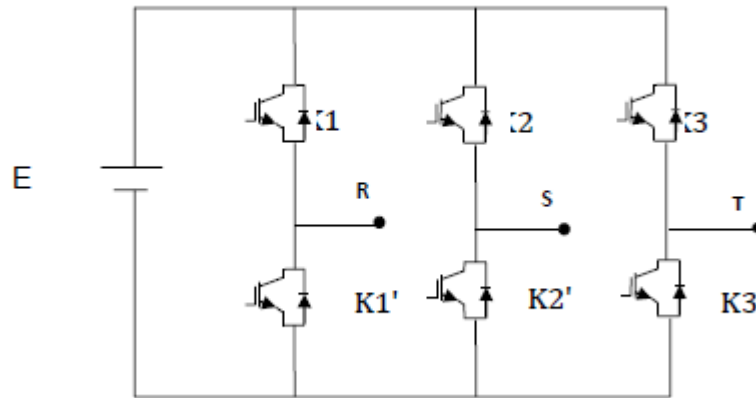


Figure I.4: Three-phase bridge inverter

I.3 The three-level Neutral Point-Clamped:

The so-called Neutral- Point-Clamped (NPC) inverter topology. It guarantees that the voltage across the non-conducting switches is clamped by diodes and a string of series connected capacitors.

The three-level Neutral Point-Clamped inverter is as shown in Figure I.5. There are four switching devices, in this case IGBT's, per phase in a three level Neutral Point-Clamped inverter and the blocking voltage per switch required in case of a three-level inverter is halved when compared to a two-level inverter. Henceforth, in this thesis, a three-level inverter would represent a three-level Neutral Point-Clamped inverter. Each phase has a pair of clamping diodes by virtue of which the DC-bus voltage can be increased beyond the voltage rating of each switch. [3]

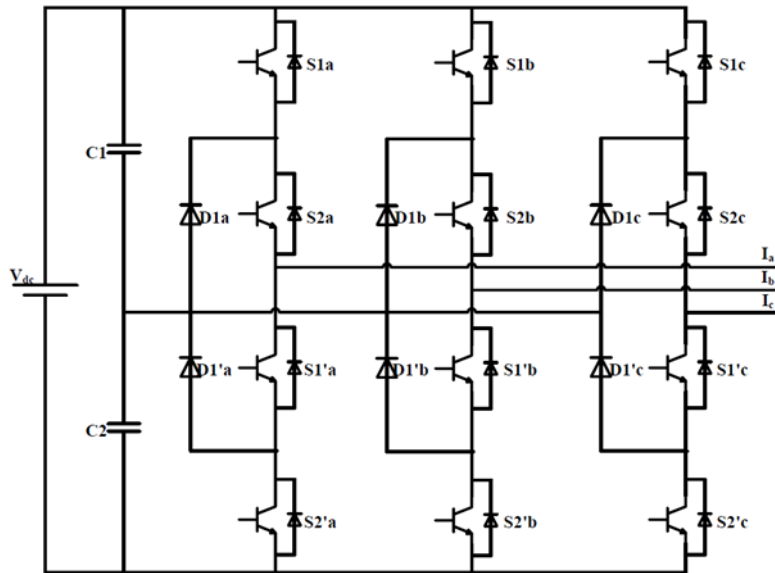


Figure I.5: Three-level Neutral Point-Clamped Inverter

I.3.1 Advantages and Disadvantages:

Advantages:

- Availability of switching redundancy for capacitor voltage balance.
- Increased number of capacitors allows the inverter to ride through short duration outages.

Disadvantages:

- Increased number of capacitors makes the system very bulky with increased losses.
- Capacitor voltage levels have to be maintained at all times; the capacitors require a separate pre-charge circuit. Cost increases manifold due to the increased number of capacitors in the Capacitor-Clamped topology when compared to the clamping diodes in the Diode-Clamped topology. [4]

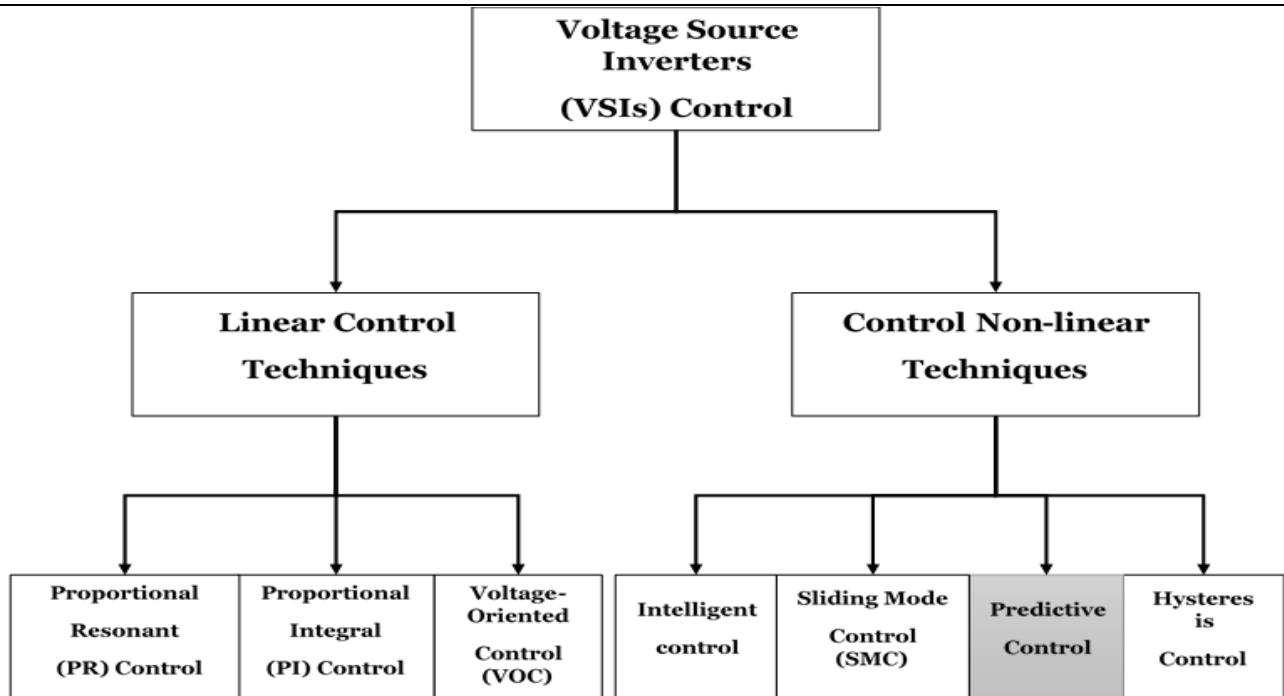


Figure I.6: Classification of control techniques used in voltage source converters

I.4 Classic control méthodes for power transformers and drives :

I.4.1 Classical Current Control methods :

1. Hysteresis Current Control:

The hystérésis current control technique is a simple and effective technique to achieve fast dynamics within the current control loop. The inherent current limiting capability, robustness, and model-free implementation are some of the main benefits of the hysteresis control approach. In this technique, a “hysteresis band” is defined around the reference current that the controller needs to track. The switches of the inverter are then controlled in such a manner that the output current of the inverter always stays within this band ; hence, there is no need for a PWM modulator. [4]

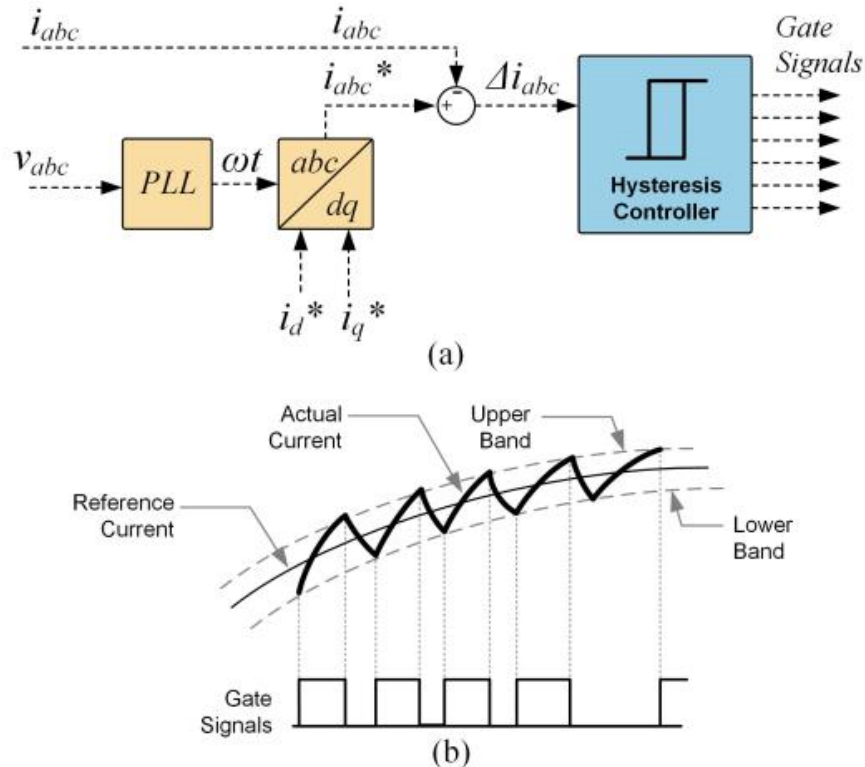


Figure I.7 : Hysteresis current controller. (a) Schematic diagram. (b) gate signal generation.

This greatly improves the transient response time of this control approach, but this also means that the switching frequency is variable, depending largely on the selected hysteresis band and load/operating conditions, making the design of the output filter difficult. Alternate techniques to keep the switching frequency constant are proposed in. In, a method of using a sinusoidally-varying hysteresis band is proposed to reduce the output current and power ripple. However, for simplicity, a generic hysteresis current controller as shown in Figure I.7 is discussed in this paper.[4]

Linear Control with Pulse Width Modulation or Space Vector Modulation PWM:

Considering a modulator stage for the generation of control signals for the power switches of the converter allows one to linearize the nonlinear converter. In this way, any linear controller can be used, the most common choice being the use of proportional–integral (PI) controllers.

2.1 Pulse Width Modulation :

The PWM modulators are open-loop voltage controllers, and the commonly used techniques for PWM modulation is carrier based PWM, space vector modulation and random PWM. However, other methods of PWM are included in the classification below. The only technique to be described here will be sinusoidal carrier based PWM, since only this PWM is used in this work.

2.2 PWM CLASSIFICATION :

There are various techniques of PWM proposed in literature, namely ;Sinusoidal :

- Random PWM.
- Minimum ripple current PWM.
- *Space-Vector PWM (SVM)*.
- *Selective harmonic elimination (SHE) PWM*.
- *Sigma-delta modulation*.
- *Sinusoidal PWM with instantaneous current control*.
- *Delta modulation*.
- *Hysteresis band current control PWM*.

2.3 Linear Control with Space Vector Modulation:

A variation of PWM is called space vector modulation (SVM), in which the application times of the voltage vectors of the converter are calculated from the reference vector. It is based on the vectorial representation of the three-phase voltages, defined as:

$$v = \frac{2}{3}(v_{aN} + \mathbf{a} v_{bN} + \mathbf{a}^2 v_{cN}) \quad (I.1)$$

where v_{aN} , $\mathbf{a} v_{bN}$, and v_{cN} are the phase-to-neutral (N) voltages of the inverter and $\mathbf{a} = e^{i2[\pi]/3}$. The output voltages of the inverter depend on the switching state of each phase and the DC link voltage, $v_{xN} = s_x v_{dc}$, with $x = \{a, b, c\}$. Then, taking into account

the combinations of the switching states of each phase, the three-phase inverter generates the voltage vectors listed in Table 1.1 and depicted in Figure I.8. Considering the voltage vectors generated by the inverter, the $\alpha - \beta$ plane is divided into six sectors, as shown in Figure I.8. In this way, a given reference voltage vector [5]

S_a	S_b	S_c	Voltage vector V
0	0	0	$V_0 = 0$
1	0	0	$V_1 = (2/3)V_{dc}$
1	1	0	$V_2 = (1/3)V_{dc} + j(\sqrt{3}/3)V_{dc}$
0	1	0	$V_3 = (-1/3)V_{dc} + j(\sqrt{3}/3)V_{dc}$
0	1	1	$V_4 = (-2/3)V_{dc}$
0	0	1	$V_5 = (-1/3)V_{dc} - j(\sqrt{3}/3)V_{dc}$
1	0	1	$V_6 = (1/3)V_{dc} - j(\sqrt{3}/3)V_{dc}$
1	1	1	$V_7 = 0$

Table I.1 : Switching states and voltage vectors

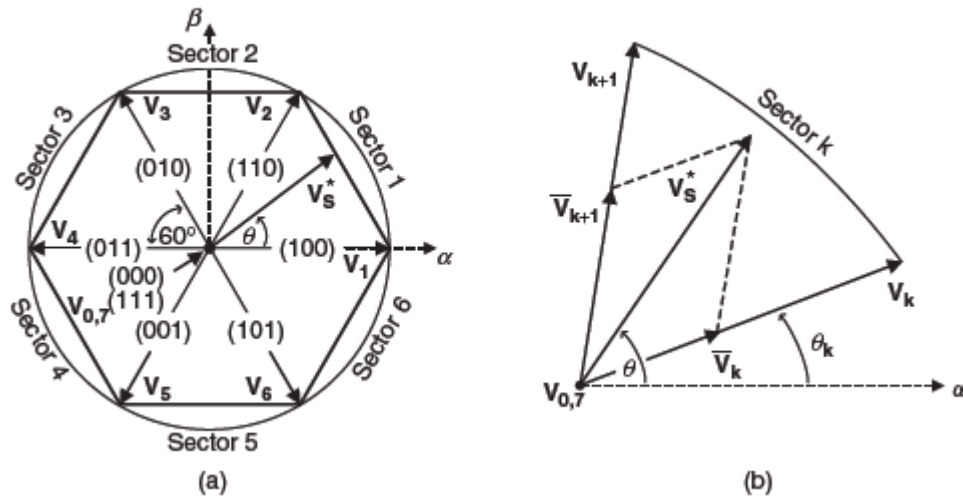


Figure I.8 Principles of space vector modulation (SVM). (a) Voltage vectors and sector definition. (b) Generation of the reference vector in a generic sector

I.5 Model Predictive Controller:

I.5.1 Definition:

MPC is an advanced control technique used to control power electronic systems. The ease in including system non-linearities with an intuitive control design is the main attraction of the MPC technique. MPC uses a model of the system to predict the future behavior of the controlled variables. The prediction in turn is used by the controller to generate near-optimal control actions by minimizing a cost function.

I.5.2 Advantages and Disadvantages [4]:

Advantages:

- Cost effective and enhanced energy saving.
- Disturbance robustness and shifting in performing conditions.
- Control of multiple variables within bounds.
- Steady state response improvement (decrease in offset error).
- Prediction on upcoming disturbance.
- Upcoming control actions prediction.
- Enhanced transient response.
- Using time postponements to control slow moving processes.
- Peak load shifting capability.
- Reduction in fluctuations from a set-point (better regulation).
- Efficiency and coefficient of performance (COP) improvements.
- Indoor air quality and thermal comfort improvement.
- Computation time reduction.

Disadvantages:

- In demand of identifying a proper model of the system.
- Possibility of costly installation.

I.6 Conclusion:

The use of inverter is not enough therefor the multi inverter are used widely in the power energy industries, using The- Neutral- Point-Clamped (NPC) inverter topology to achieve voltage outsource by Classical Current Control methods (SVM) and (PWM), but with the advanced technologies in the industries the use to control the system in every aspect needed , one of the most successful control system is the Model predictive control (MPC) that can reduced the consumption and improve the performance of the system efficiency.

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Chapter II

Dead beat predictive controller without weighting factor

II.1 Introduction:

Inverters are widely used in many power conversion applications, electrical drives, renewable energy systems. Model-based predictive control (MPC) has become the most popular advanced control technology industries in this chapter we presented the study of MPC and focusing on the Dead-beat predictive control, going through 3 Vectors-based DB Predictive Controller and it's switching state.

II.2 Principle and basic structure of MPC

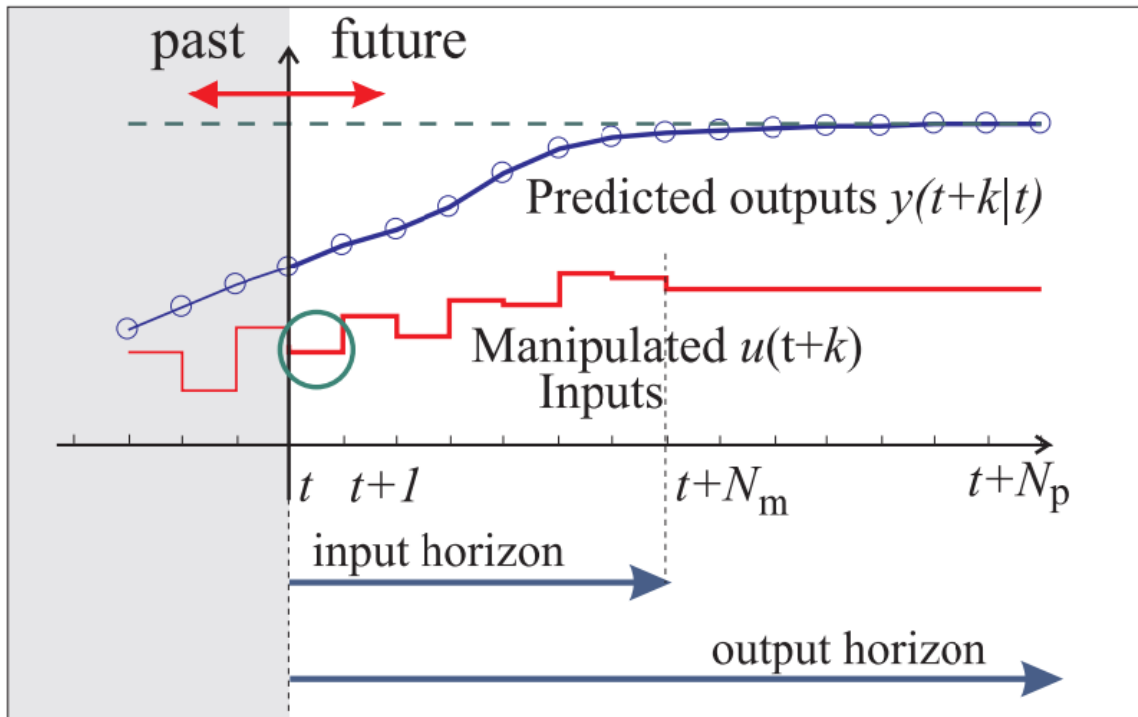


Figure II.1: MPC strategy

A typical MPC strategy is illustrated in Figure II.1. It proposes a sequence of candidate future input moves which are expected to give the best predicted performance, where performance is assessed using a defined performance index. Usually, MPC utilises only the first move of the control candidate sequence, while ongoing measurement and optimization are used continually to improve the planning for each sample. This philosophy is called receding horizon control (RHC). [1]

II.2.1 MPC structure

A typical MPC implementation structure is shown in Figure II.2. The MPC is based on an internal model which is used to predict the future process outputs. This controller manipulates the difference between the set point (SP) and the feedback process variable (PV) to provide manipulated variables (MV) to the controlled object. The disturbance is rejected by disturbance cancellation inside the controller. [1]

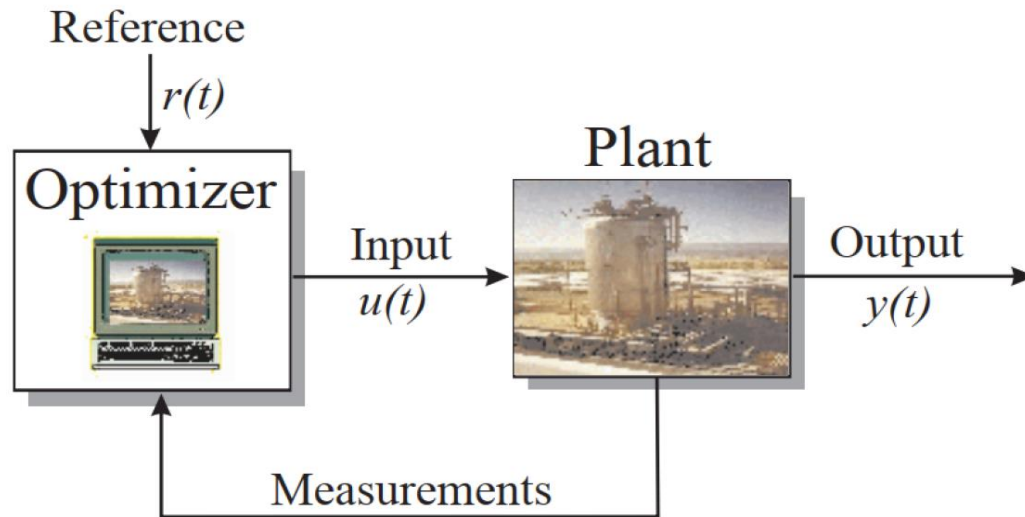


Figure II.2: Basic MPC structure

II.3 Predictive control methods:

Predictive control is a very wide class of controllers that have found rather recent application in power converters. The classification proposed in this paper for different predictive control methods is shown in Figure II.3. [2]

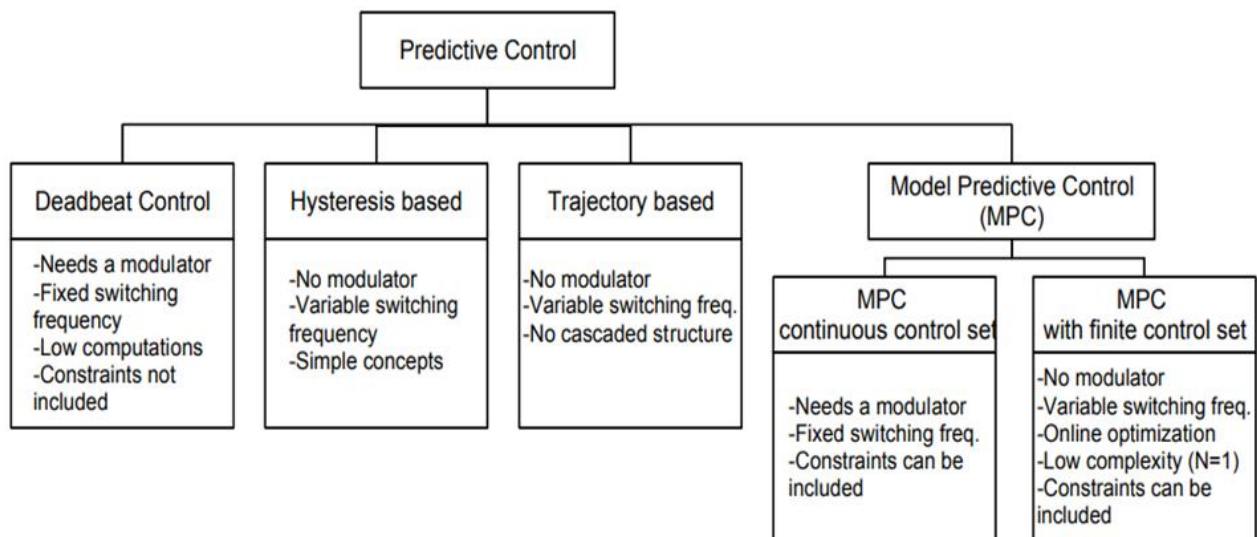


Figure II.3. Classification of predictive control methods used in power electronics

II.3.1 Deadbeat predictive control:

The deadbeat predictive control was presented in 1980 as the first type of predictive controls for power converters and now is a very popular strategy among

various types of predictive controls The block diagram of this type of predictive control is shown in Figure II.4. In each sampling period, the reference voltage is estimated according to the load and the converter model, in order to have a zero-reference tracking in the next sampling instant. In this strategy, the future performance of the system is predicted, and the optimal voltage is generated. Later on, this reference voltage will be employed by the modulation stage. In this method the dynamic response is fast, and the switching frequency is fixed due to the use of SVM or PWM modulation. Nevertheless, the deadbeat predictive control is very sensitive to the system parameters variations.

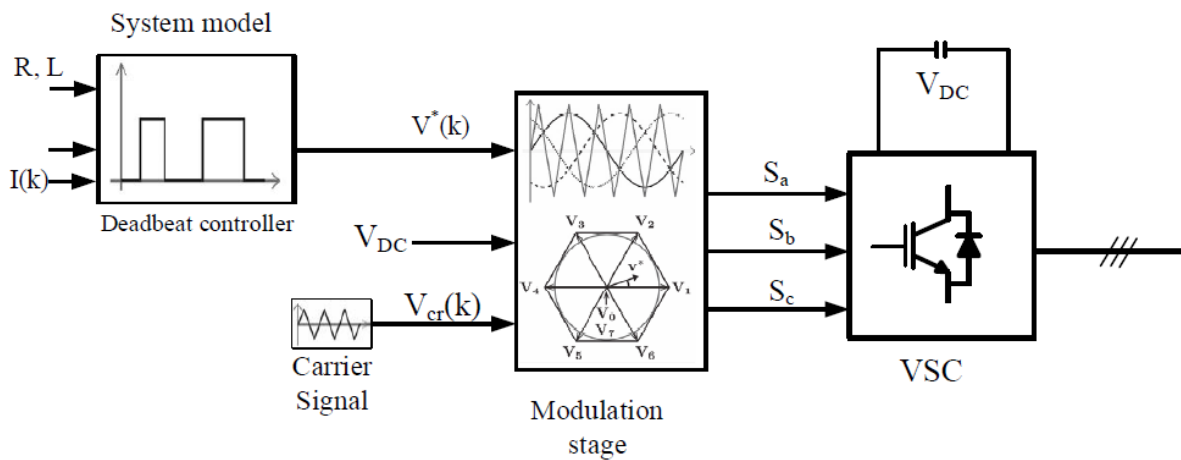


Figure II.4. Overall block diagram of the deadbeat predictive control.

The deadbeat control is very simple to be implemented and does not need any cost function and optimization process or any tuning like the classic PI controllers. Nonetheless, the measurement noises, the delays in the control and the perturbation have a negative influence in this strategy which can lead to instability problems. Moreover, if the parameters are not correctly estimated, there will be an error in tracking the references during the SteadyState. Many investigations have been done to remove some of these problems and to make the control be more robust during noises and parameters variations. [3]

II.4 Vectors-based Deadbeat (DB):

The effect of the number of effective vectors considered for the cost function evaluation on steady-state and dynamic performance is investigated. To do that, three

DB predictive controllers with different numbers of effective vectors, namely, 19 vectors-based, 6 vectors-based, and 3 vectors-based DB, are compared beside the conventional current-based model predictive control (MPC). [4]

II.4.1 3 Vectors-based DB Predictive Controller:

To further reduce the computational burden, especially the cost function calculation, while effectively maintaining the balance of the capacitor voltages, the voltage vectors were distributed over four regions for each sector. Thus, the number of voltage vectors associated with the cost function evaluation can be reduced to 3 vectors. From Figure II.5, the triangular regions for each sector can be obtained by using the position of the $\alpha\beta$ components of the reference voltage vectors $V_{\alpha n}^*$ and $V_{\beta n}^*$ in the space vector diagram as follows:

$$\begin{cases} V_{\alpha n}^* = m_n \frac{2}{\sqrt{3}} \sin\left(\frac{\pi}{3} - \left(\theta - (S_n - 1)\frac{\pi}{3}\right)\right) \\ V_{\beta n}^* = m_n \frac{2}{\sqrt{3}} \sin\left(\theta - (S_n - 1)\frac{\pi}{3}\right) \end{cases} \quad (\text{II.1})$$

The values estimated in (1) are used to identify the relevant triangle according to the rules given in **Table II.1**. Where S_n is the sector number, θ is the phase of the reference voltage vector, V_n^* is the complex notation of the reference voltage vector $V_n^* = V_{\alpha n}^* + jV_{\beta n}^*$, and m_n is modulation index, which can be expressed as follows:

$$m_n = \sqrt{3} \frac{|V_n^*|}{V_{dc}} \quad (\text{II.2})$$

Regions	Working conditions
1	$V_{\alpha n}^* < 0.5m_n$ $V_{\beta n}^* < 0.5m_n$ and $V_{\alpha n}^* + V_{\beta n}^* < 0.5m_n$
2	$V_{\alpha n}^* < 0.5m_n$ $V_{\beta n}^* < 0.5m_n$ and $V_{\alpha n}^* + V_{\beta n}^* > 0.5m_n$
3	$V_{\beta} > 0.5m_n$
4	$V_{\alpha} > 0.5m_n$

Table II.1 region selection criteria

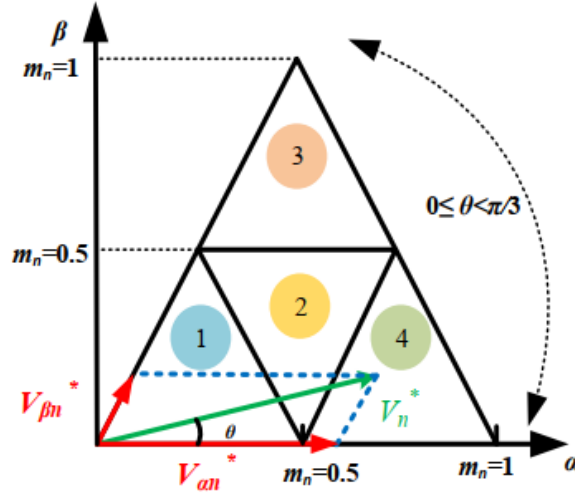


Figure II.5. Triangular regions for sector I

$$\theta = \tan^{-1} \left(\frac{V_{\beta n}^*(k)}{V_{\alpha n}^*(k)} \right) \quad (\text{II.3})$$

According to θ , the candidate voltage vectors participating in the cost function evaluation was distributed over 3 sectors as summarized in Table II.2. It can be seen clearly that the 3 vectors-based DB predictive controller requires one reference voltage prediction and 6 cost function evaluations, which requires only 4 iterations in each sampling period.

In the case of the reference voltage vector located in the fourth region in the first sector, as illustrated in Figure II.6, the small voltage vectors (V_3 or V_4) are selected for NP voltage balancing using the principle explained in Section II.4.2. Furthermore, 3 vectors-based DB predictive controller involves one reference voltage prediction and three cost function evaluations. Thus, this algorithm requires only four iterations in each sampling period. Table II.2 lists the candidate voltage vectors for all sectors and regions under different conditions. [4]

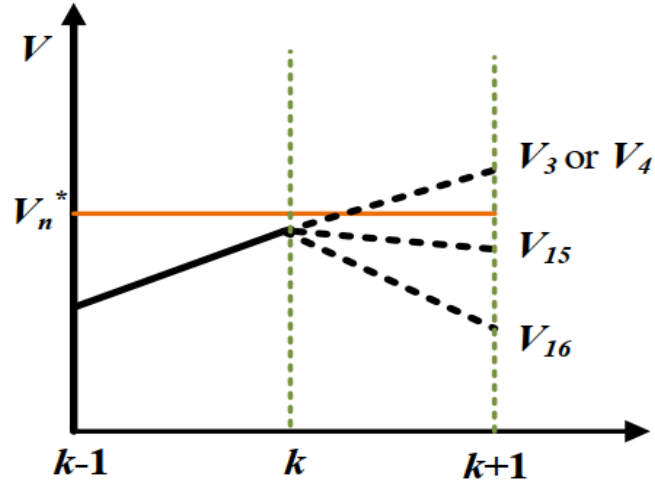


Figure II.6: The candidate voltage vectors using the 3 vectors-based DB predictive controller for sector I, region

Sector number	Candidate Voltage Vectors	Sector number	Candidate Voltage Vectors
I-1	$(V_3, V_4), (V_5, V_6), V_1$	IV-1	$(V_9, V_{10}), (V_{11}, V_{12}), V_1$
I-2	$(V_3, V_4), (V_5, V_6), V_{16}$	IV-2	$(V_9, V_{10}), (V_{11}, V_{12}), V_{22}$
I-3	$(V_5, V_6), V_{16}, V_{17}$	IV-3	$(V_{11}, V_{12}), V_{22}, V_{23}$
I-4	$(V_3, V_4), V_{15}, V_{16}$	IV-4	$(V_9, V_{10}), V_{21}, V_{22}$
II-1	$(V_5, V_6), (V_7, V_8), V_1$	V-1	$(V_{11}, V_{12}), (V_{13}, V_{14}), V_1$
II-2	$(V_5, V_6), (V_7, V_8), V_{18}$	V-2	$(V_{11}, V_{12}), (V_{13}, V_{14}), V_{24}$
II-3	$(V_7, V_8), V_{18}, V_{19}$	V-3	$(V_{13}, V_{14}), V_{24}, V_{25}$
II-4	$(V_5, V_6), V_{17}, V_{18}$	V-4	$(V_{11}, V_{12}), V_{23}, V_{24}$
III-1	$(V_7, V_8), (V_9, V_{10}), V_1$	VI-1	$(V_{13}, V_{14}), (V_3, V_4), V_1$
III-2	$(V_7, V_8), (V_9, V_{10}), V_{20}$	VI-2	$(V_{13}, V_{14}), (V_3, V_4), V_{26}$
III-3	$(V_9, V_{10}), V_{20}, V_{21}$	VI-3	$(V_3, V_4), V_{26}, V_{15}$
III-4	$(V_7, V_8), V_{19}, V_{20}$	VI-4	$(V_{13}, V_{14}), V_{25}, V_{26}$

Table II.2: Candidate voltage vectors of 3 vectors-based DB predictive controller for all sectors

Finally, the voltage-based DB predictive controllers method is more attractive from the computational point of view compared with the conventional MPC method, supporting the feasibility of the real-time implementation. The overall system of the proposed control strategy is shown in Figure II.7.

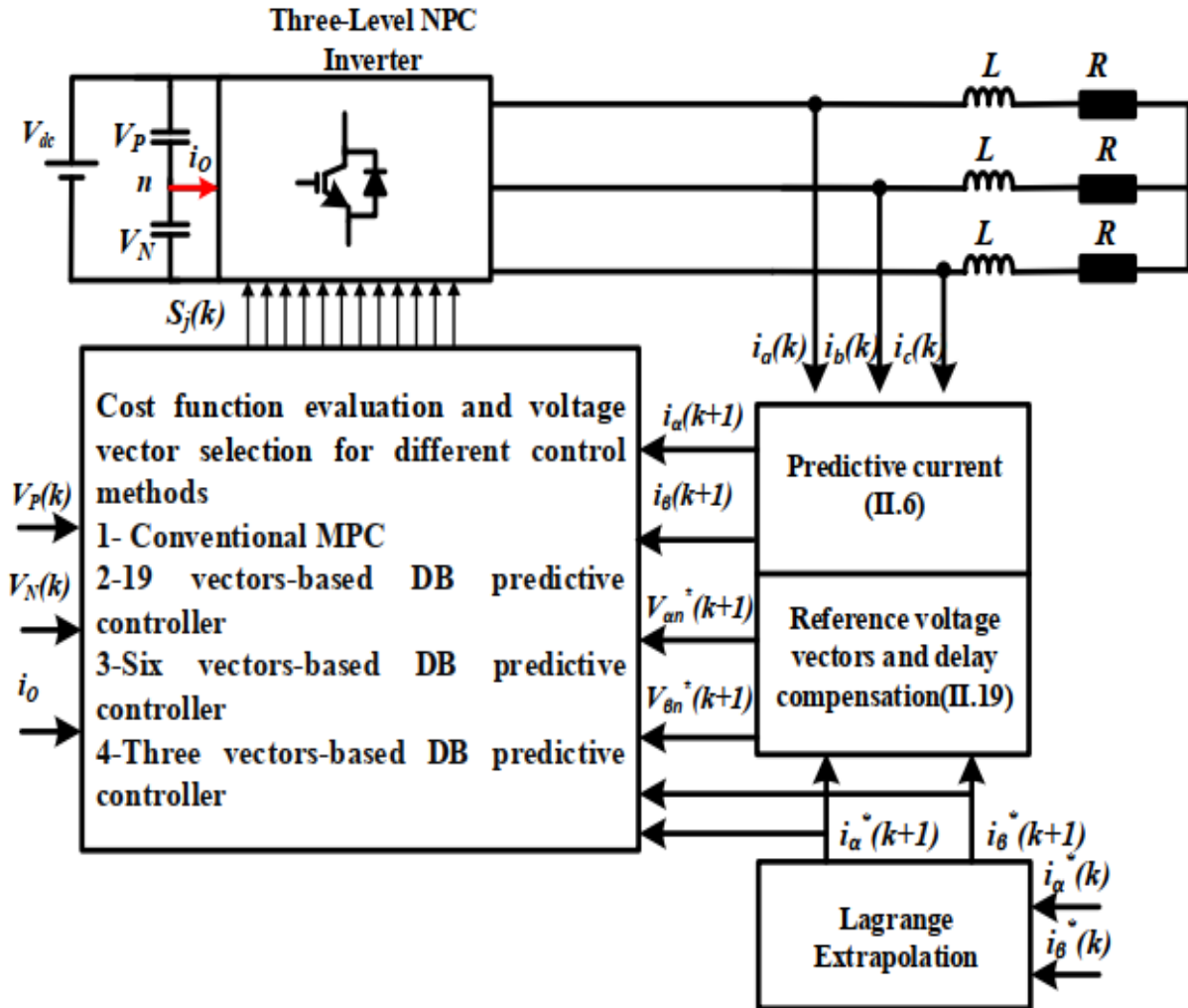


Figure II.7: Block diagram of the studied voltage-based DB predictive controllers.

II.5 The three level NPC

The main reasons to use three-level over two-level topologies are lower harmonic distortion, better efficiency, half of voltage rating of main components and less stress on motor windings isolation.

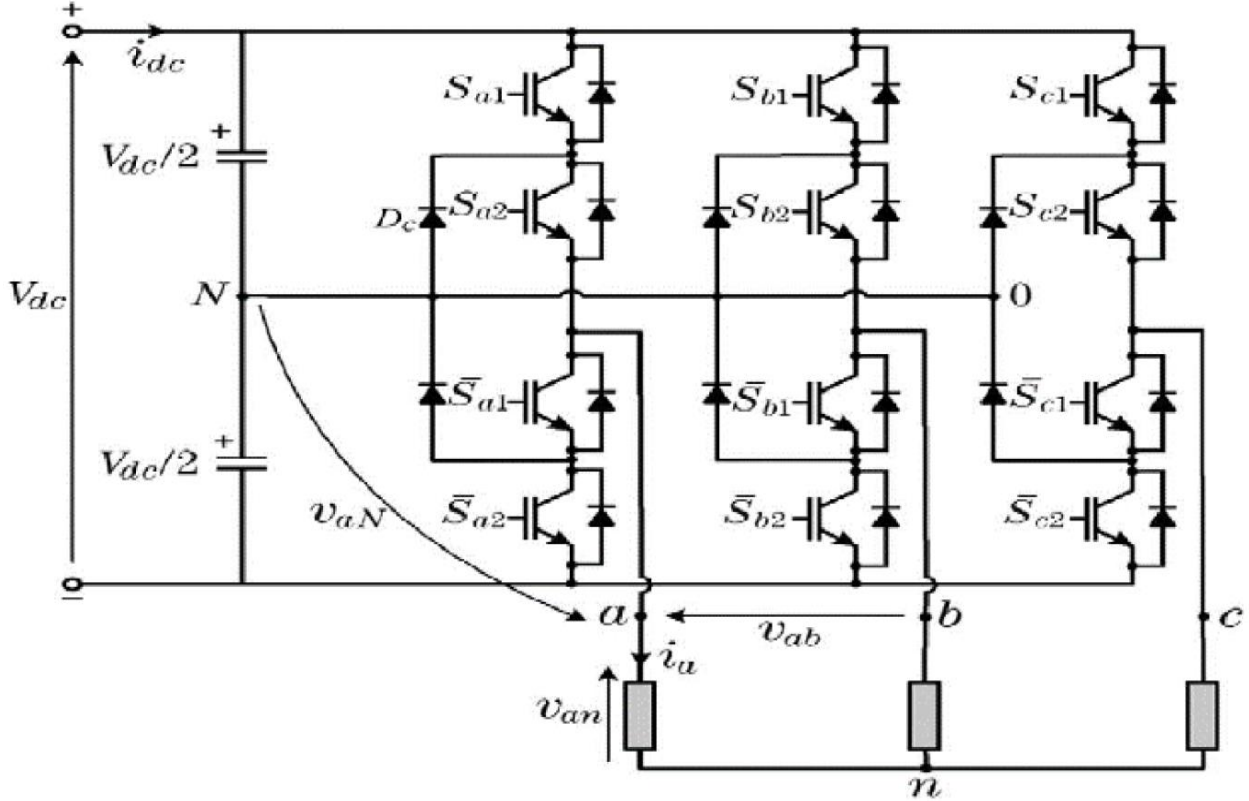


Figure II.8 Three level NPC inverter

The three level NPC topology consist of 12 switches including 6 diodes. It is necessary to connect two capacitors in series both charged with V_{dc} . Each phase led contains 4 series switches with two diodes clamped in series. The main function of the diodes is to clamp the upper switches at higher potential to the zero dc-link point. A particular switching pattern will give the output of three level NPC inverter

The circuit diagram shown above in Figure II.8 gives idea about the arrangement of the power circuit required for the three level NPC inverter. In this circuit, the diodes are arranged in such a way that it yields different stages of voltages with respect to neutral point N. The splitting of the voltage level is considered according capacitors C_1 and C_2 arranged in series with each other having neutral point N in between them.

The division of voltages are obtained as $V_{dc}/2, 0, -V_{dc}/2$. So it is named as three level topology. [5]

II.5.1 Switching state

The switching states of each inverter phase $X \in \{a,b,c\}$ are summarised in Table II.3. During the switching state [P], both switches S_{a1} and S_{a2} are turned ‘ON’ while S_{a3} and S_{a4} are ‘OFF’, and the output voltage is equal to $V_{dc}/2$. As well, the switching state [O] means that the two internal switches S_{a2} and S_{a3} are ‘ON’ while S_{a1} and S_{a4} are ‘OFF’, and Vdc is clamped to zero. The switching state [N] signifies that the two switches S_{a3} and S_{a4} are turned ‘ON’ while S_{a1} and S_{a2} are ‘OFF’, and the output voltage is equal to $-V_{dc}/2$. These switching states generate 19 non redundant vectors and eight redundant vectors in the $\alpha\beta$ frame. According to their length, these 27 vectors are divided into four groups as shown in Figure II.9. Finally, the 27 voltage vectors with their switching states are summarized in Table II.4.

- Zero vectors (from V_0 to V_2) are represented by three switching states: (OOO), (PPP) and (NNN). The magnitude of these vectors is equal to 0.
- Small vectors (from V_3 to V_4). Each small vector has two switching states, one containing P and the other containing N, and therefore can be further classified into P or N type small vector.
- Medium vectors ($V_{16}, V_{18}, V_{20}, V_{22}, V_{24},$ and V_{26}).
- Large vectors ($V_{15}, V_{17}, V_{19}, V_{21}, V_{23},$ and V_{25}).

S_x	S_{x1}	S_{x2}	S_{x3}	S_{x4}	V_{xn}
P	1	1	0	0	$V_{dc}/2$
O	0	1	1	0	0
N	0	0	1	1	$-V_{dc}/2$

Table II.3: Possible switching combinations of each phase $x = \{a, b, c\}$

S_a	S_b	S_c	V_i
O	O	O	$V_0 = 0$
P	P	P	$V_1 = 0$
N	N	N	$V_2 = 0$
P	O	O	$V_3 = (1/3)V_{dc}$
O	N	N	$V_4 = (1/3)V_{dc}$
P	P	O	$V_5 = (1/6)V_{dc} + j(\sqrt{3}/6)V_{dc}$
O	O	N	$V_6 = (1/6)V_{dc} + j(\sqrt{3}/6)V_{dc}$
O	P	O	$V_7 = (-1/6)V_{dc} + j(\sqrt{3}/6)V_{dc}$
N	O	N	$V_8 = (-1/6)V_{dc} + j(\sqrt{3}/6)V_{dc}$
O	P	P	$V_9 = (-1/3)V_{dc}$
N	O	O	$V_{10} = (-1/3)V_{dc}$
O	O	P	$V_{11} = (-1/6)V_{dc} - j(\sqrt{3}/6)V_{dc}$
N	N	O	$V_{12} = (-1/6)V_{dc} - j(\sqrt{3}/6)V_{dc}$
P	O	P	$V_{13} = (1/6)V_{dc} - j(\sqrt{3}/6)V_{dc}$
O	N	O	$V_{14} = (1/6)V_{dc} - j(\sqrt{3}/6)V_{dc}$
P	N	N	$V_{15} = (2/3)V_{dc}$
P	O	N	$V_{16} = (1/2)V_{dc} + j(\sqrt{3}/6)V_{dc}$
P	P	N	$V_{17} = (1/3)V_{dc} + j(\sqrt{3}/3)V_{dc}$
O	P	N	$V_{18} = j(\sqrt{3}/3)V_{dc}$
N	P	N	$V_{19} = (-1/3)V_{dc} + j(\sqrt{3}/3)V_{dc}$
N	P	O	$V_{20} = (-1/2)V_{dc} + j(\sqrt{3}/6)V_{dc}$
N	P	P	$V_{21} = (-2/3)V_{dc}$
N	O	P	$V_{22} = (-1/2)V_{dc} - j(\sqrt{3}/6)V_{dc}$
N	N	P	$V_{23} = (-1/3)V_{dc} - j(\sqrt{3}/3)V_{dc}$
O	N	P	$V_{24} = -j(\sqrt{3}/3)V_{dc}$
P	N	P	$V_{25} = (1/3)V_{dc} - j(\sqrt{3}/3)V_{dc}$
P	N	O	$V_{26} = (1/2)V_{dc} - j(\sqrt{3}/6)V_{dc}$

Table II.4: The switching states S_x and the voltage vectors V_i of the three-level NPC inverter

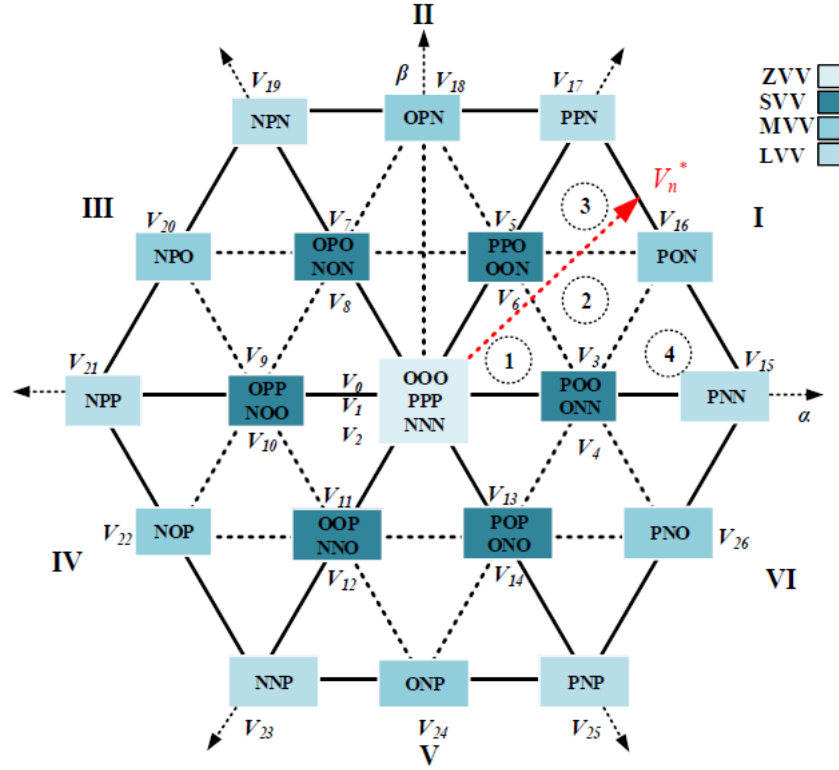


Figure II.9: Basic voltage vectors of three-level NPC inverter: zero voltage vectors (ZVV), small voltage vectors (SVV), medium voltage vectors (MVV), and large voltage vectors (LVV).

II.6 Discrete-time model of the system:

As shown in Figure II.8, the model of the three-level NPC inverter with a three-phase resistive-inductive load is expressed as [6]:

$$\begin{cases} L \frac{di_a}{dt} = V_{an} - Ri_a \\ L \frac{di_b}{dt} = V_{bn} - Ri_b \\ L \frac{di_c}{dt} = V_{cn} - Ri_c \end{cases} \quad (II.4)$$

Applying the Clarke transform, the three-level NPC inverter model in the $\alpha\beta$ stationery frame is expressed as:

$$\begin{cases} L \frac{di_\alpha}{dt} = V_{\alpha n} - Ri_\alpha \\ L \frac{di_\beta}{dt} = V_{\beta n} - Ri_\beta \end{cases} \quad (II.5)$$

According to the relationship between the DC-link bus voltage and the output switching states of the inverter, the terminal voltage of the inverter can be written as:

$$\begin{cases} V_{an} = V_{dc} (2S_a - S_b - S_c)/6 \\ V_{bn} = V_{dc} (-S_a + 2S_b - S_c)/6 \\ V_{cn} = V_{dc} (-S_a - S_b + 2S_c)/6 \end{cases} \quad (\text{II.6})$$

The equation (3) can be transformed into the stationary $\alpha\beta$ reference frame as follows:

$$\begin{cases} V_\alpha = V_{dc}(2S_a - S_b - S_c)/6 \\ V_\beta = \sqrt{3}V_{dc}(S_b - S_c)/6 \end{cases} \quad (\text{II.7})$$

where V_{an} and V_{bn} are the α and β components of the voltage vector, S_a , S_b , and S_c are the switching states of three inverter legs, respectively.

The derivative of load current can be replaced by forward Euler formula as follows:

$$\frac{d_i(t)}{dt} = \frac{i(k+1) - i(k)}{T_s} \quad (\text{II.8})$$

By using (2) and (5), the predictive current of the inverter at the $(k+1)^{th}$ instant can be expressed as follows:

$$\begin{cases} i_\alpha(k+1) = \frac{T_s}{L} (V_\alpha(K) - Ri_\alpha(k)) + i_\alpha \\ i_\beta(k+1) = \frac{T_s}{L} (V_\beta(K) - Ri_\beta(k)) + i_\beta \end{cases} \quad (\text{II.9})$$

where k is the sampling period, i_α and i_β are the measured currents at k^{th} sampling instant.

From Figure II.8, the neutral point current i_o of the three-level three-phase NPC inverter can be calculated by using the combination of the output currents and switching states as follows:

$$i_o = i_{c1} - i_{c2} = -(S_{a1} + S_{a4})i_a - (S_{b1} + S_{b4})i_b - (S_{c1} + S_{c4})i_c \quad (\text{II.10})$$

The capacitor voltages dynamics are described by the capacitor differential equations:

$$\begin{cases} i_{c1} = \frac{i_o}{2} = C \frac{dV_P}{dt} \\ i_{c2} = -\frac{i_o}{2} = C \frac{dV_N}{dt} = C \frac{d(V_{dc} + V_N)}{dt} = -C \frac{dV_P}{dt} \end{cases} \quad (\text{II.11})$$

Then, the discrete-time model of the dc-link capacitor voltages are obtained by applying the forward Euler approximation as follows:

$$\begin{cases} V_P(k+1) = V_P(k) + \frac{1}{C} i_{c1}(k) T_s = V_P(k) + \frac{1}{2C} i_o(k) T_s \\ V_N(k+1) = V_N(k) + \frac{1}{C} i_{c2}(k) T_s = V_N(k) - \frac{1}{2C} i_o(k) T_s \end{cases} \quad (\text{II.12})$$

II.7 Conventional MPC based on Reference Current Prediction:

For the three-level NPC inverter, the conventional MPC scheme has two objectives, the first is to achieve a fast and accurate current tracking, and the second is to realize the inverter NP voltage balancing by using weighting factors. Thus, the cost function of the conventional MPC based on the current predictive model is expressed as:

$$g_1(\mathbf{k}) = |i_\alpha^*(\mathbf{k}+1) - i_\alpha(\mathbf{k}+1)| + |i_\beta^*(\mathbf{k}+1) - i_\beta(\mathbf{k}+1)| + \lambda_{dc1} |V_P(\mathbf{k}+1) - V_N(\mathbf{k}+1)| \quad (\text{II.13})$$

where λ_{dc1} is the weighting factor, which sets the relative importance of the phase current tracking and the NP voltage balancing [6]

From (9), (12), and (13), it can be seen that the selection of an optimal switching state for the three-level-NPC inverter by using conventional MPC requires 27 current predictions, 27 NP voltages predictions, and 27 cost function evaluations. This means that a total of 81 iterations are required in each sampling period, which increases the computational burden. Further, the heuristic selection of the weighting

Chapter II: Dead beat predictive controller without weighting factor

factor required to maintain the relative importance of these multiple control objectives between the current tracking and the NP voltage balancing is an intricate and time-consuming task [6].

II.8 conclusion

One of the most model predictive control is dead-beat control and one of the most modulation is the Vectors-based DB Predictive Controller which can affect the switching state by using discrete-time model of the system to achieve the capacitor voltages.

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Chapter III

Results and discussion

III.1 Introduction:

Many methods have been developed and published in order to improve THD and reduce transducer losses, and these technologies differ in many aspects and among these technologies, Deadbeat predictive control is the most popular. In this chapter, we will compare the results of the MATLAB simulation between dead-beat predictive control technology and model predictive control.

III.2 The aim of this study:

In order to validate the effectiveness of deadbeat predictive control for three-level NPC inverter, the control scheme has been simulated using MATLAB software with the parameters shown in Table II.2. Moreover, to verify the steady-state and the dynamic performance, we perform a comparison between the Model predictive classique and the 3Vectors-based DB predictive controllers with the same parameter

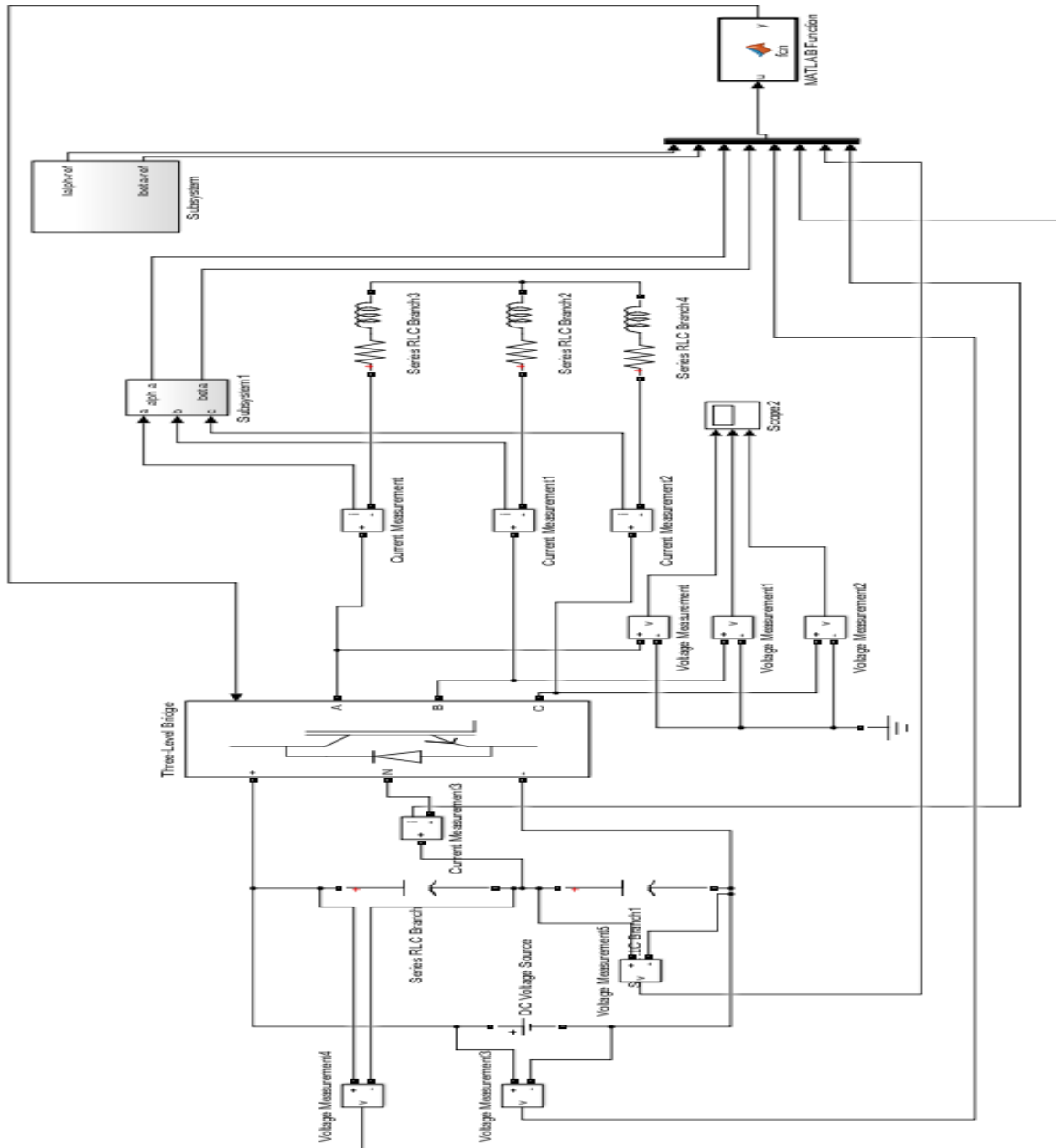
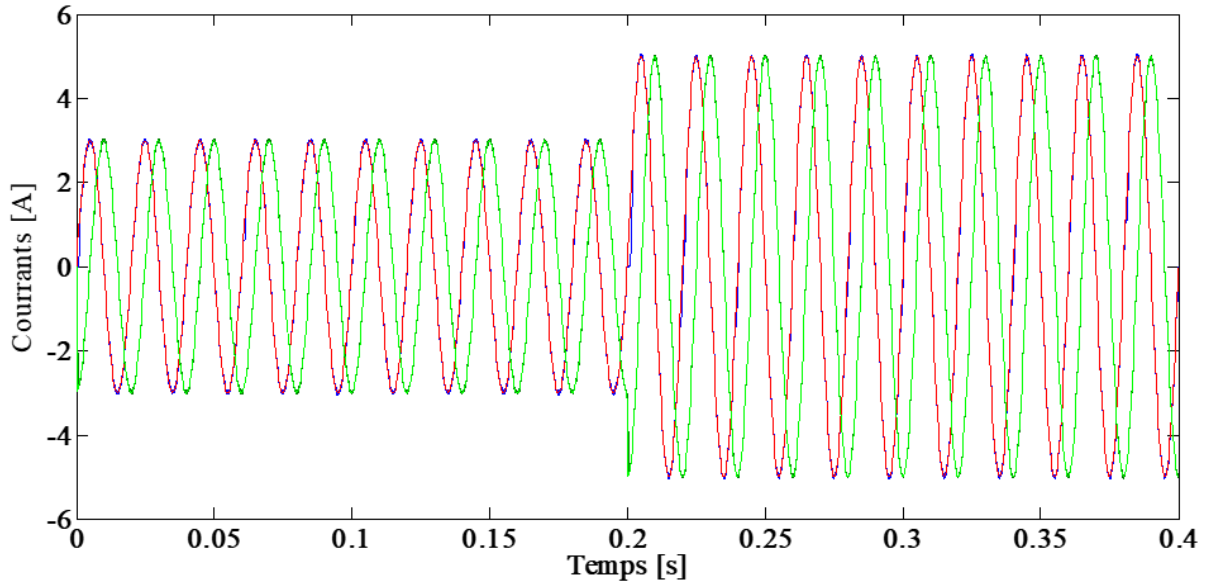


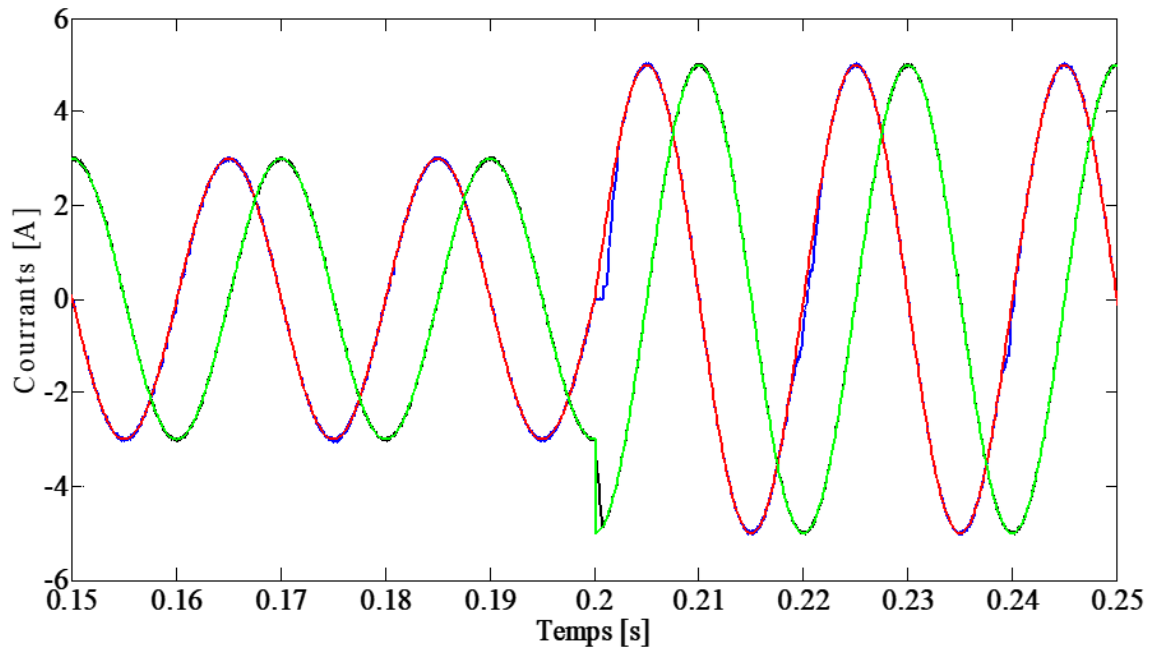
Figure III .1: Simulink system diagram

III.3 Simulation results

III.3.1 3Vectors-based DB Predictive Controller

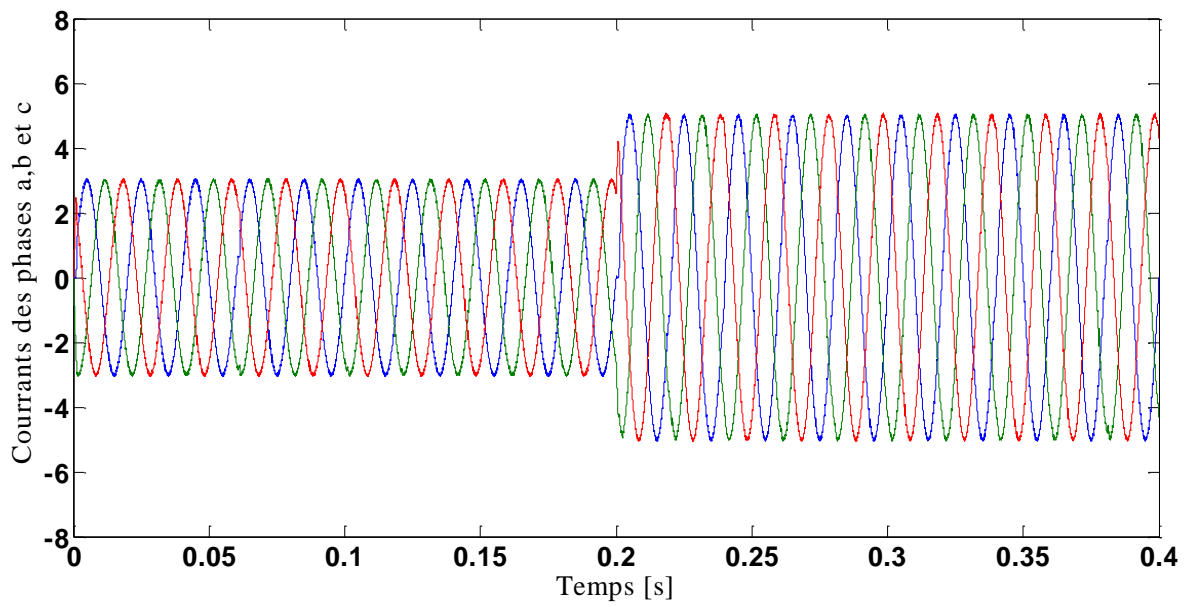


(a)

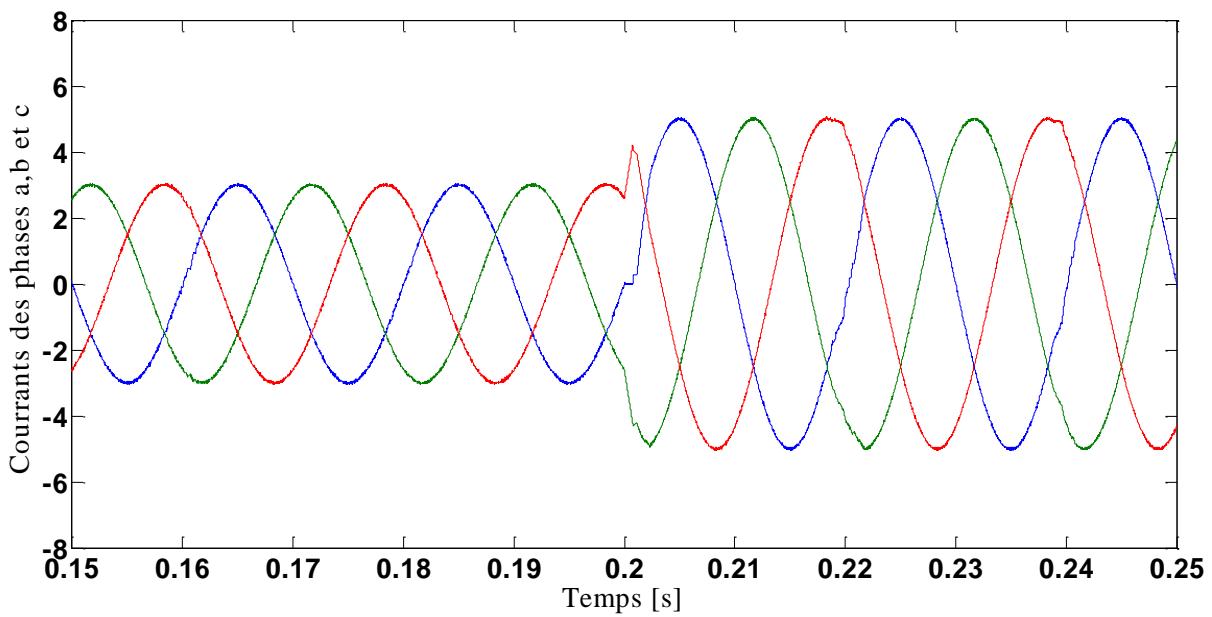


(b)

Figure III .2: Output currents a and b (A)

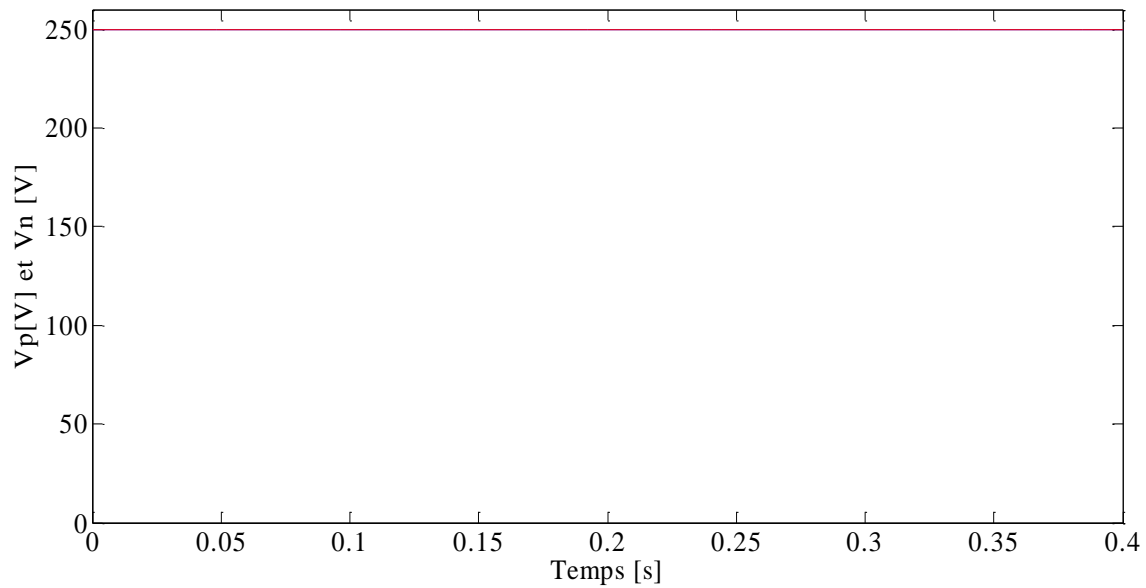


(a)

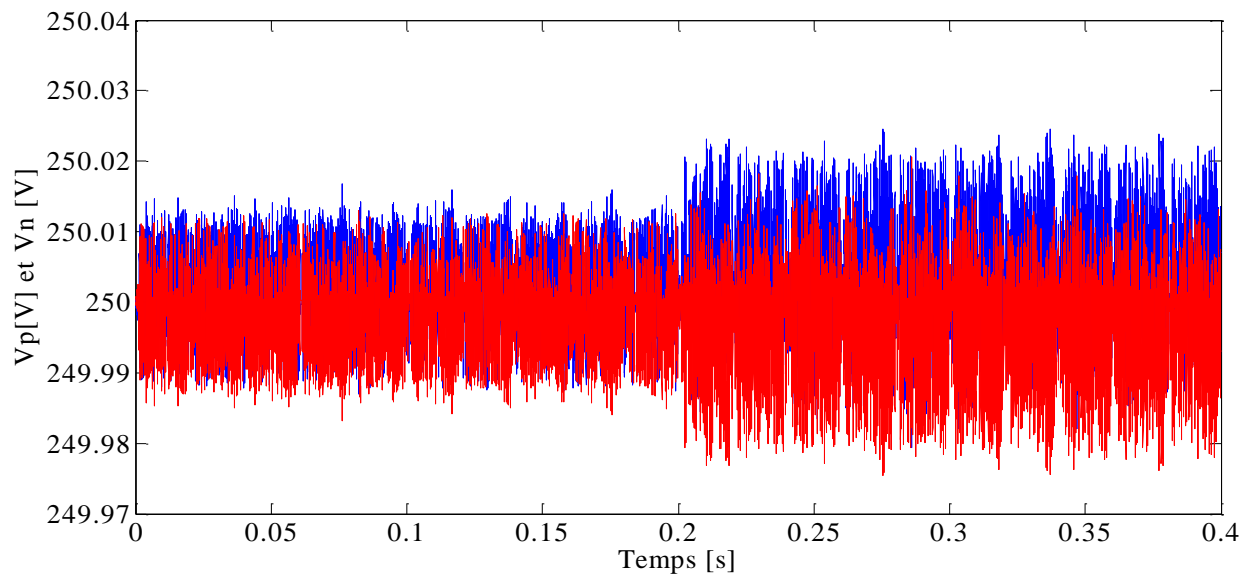


(b)

Figure III.3 : currents a,b and c (A)

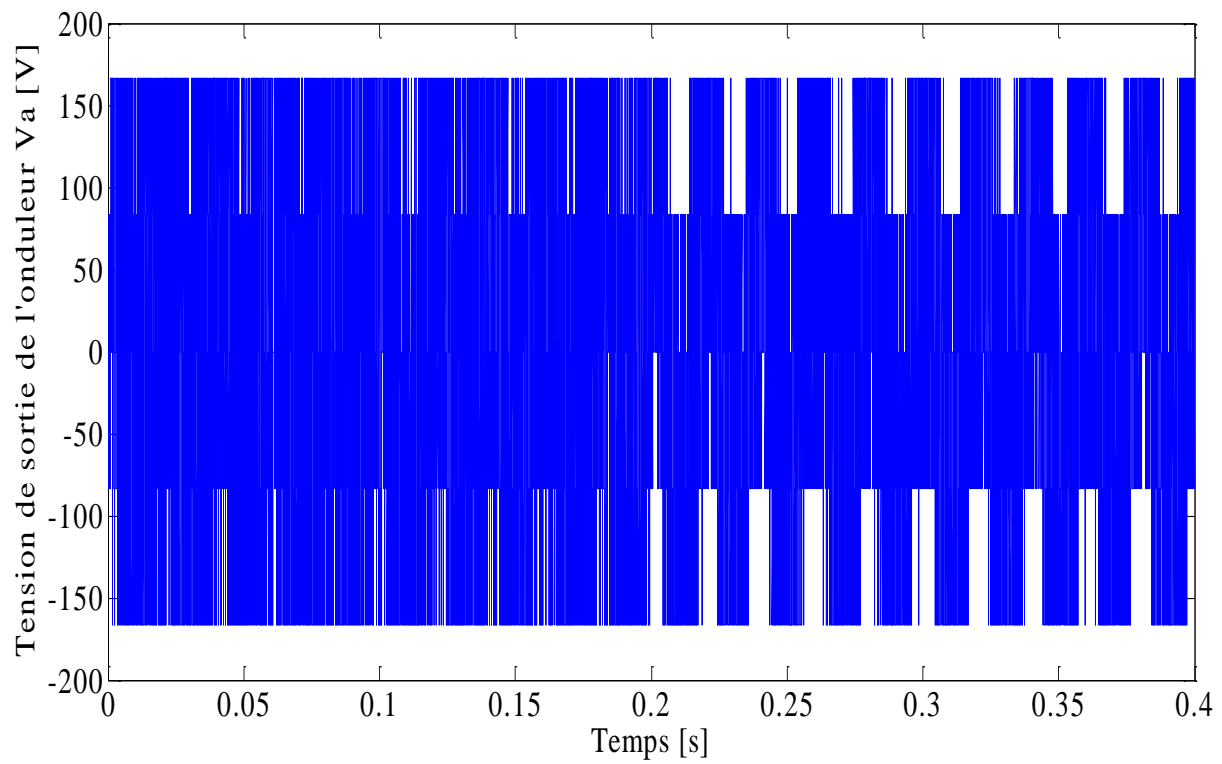


(a)

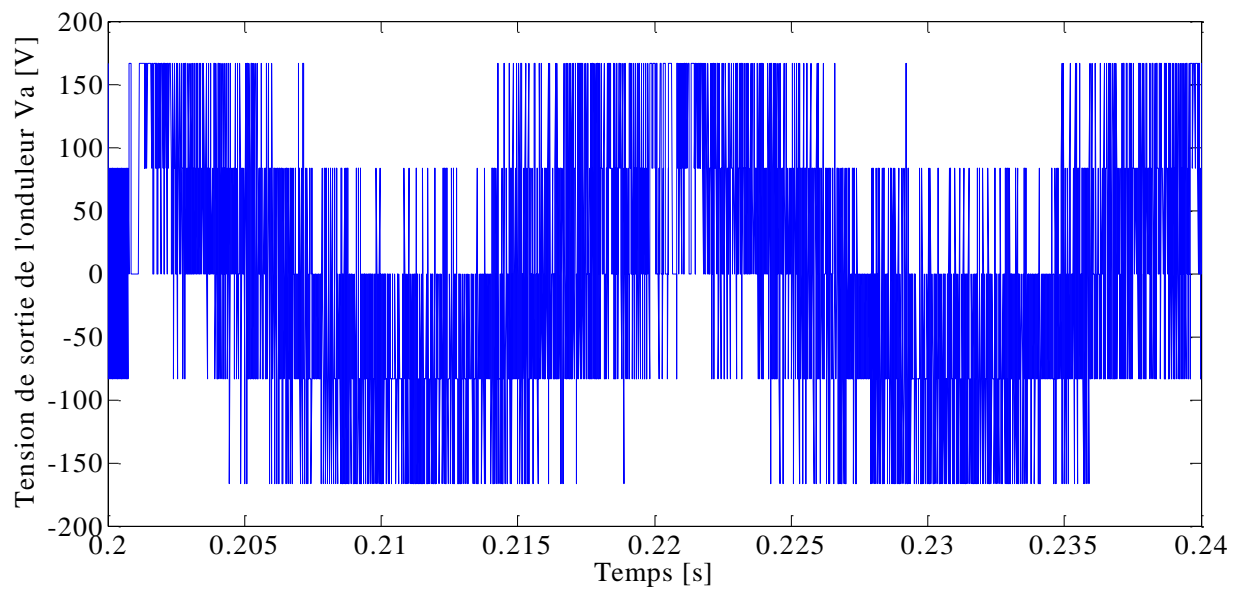


(b)

Figure III .4 : Simulation results the capacitor voltages V_p and V_n (v)



(a)



(b)

Figure III.5: Output voltage Inverter V_a (v)

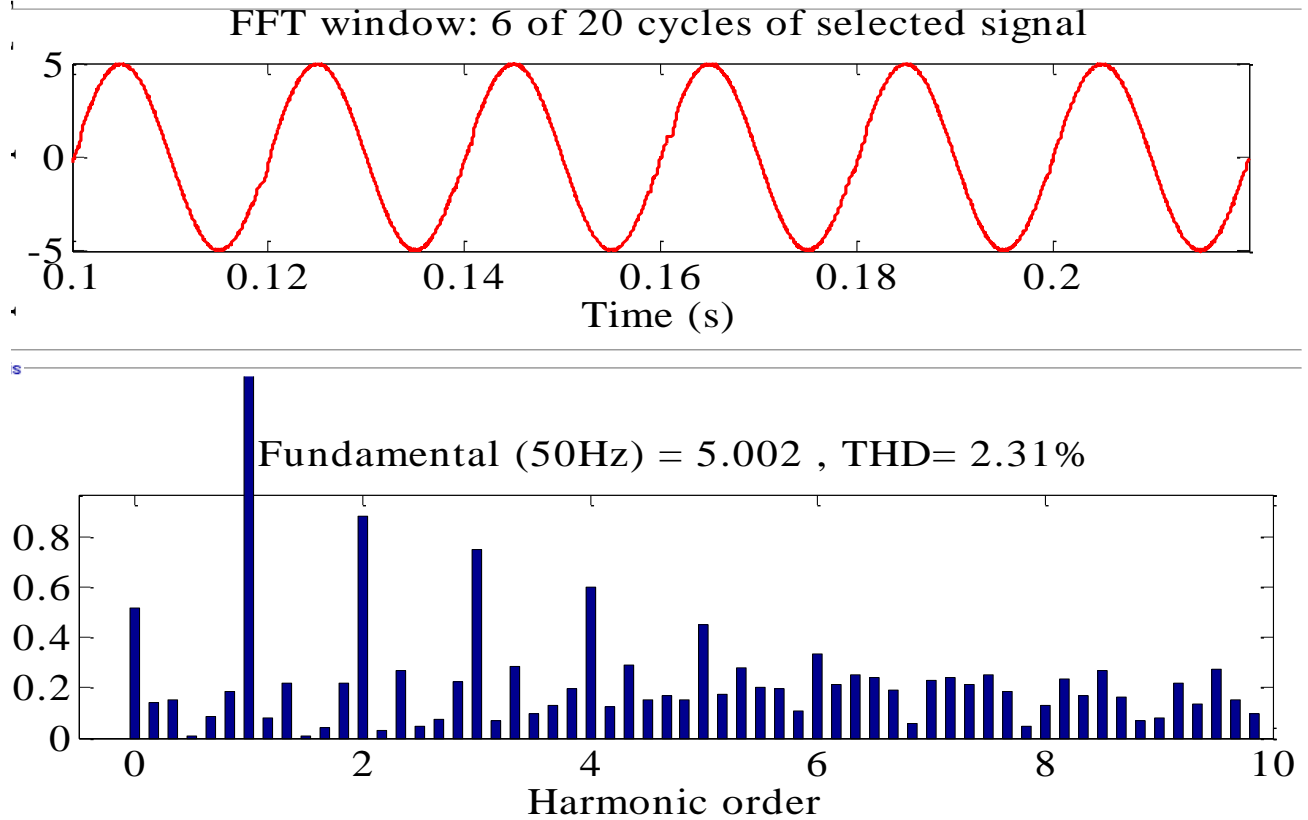
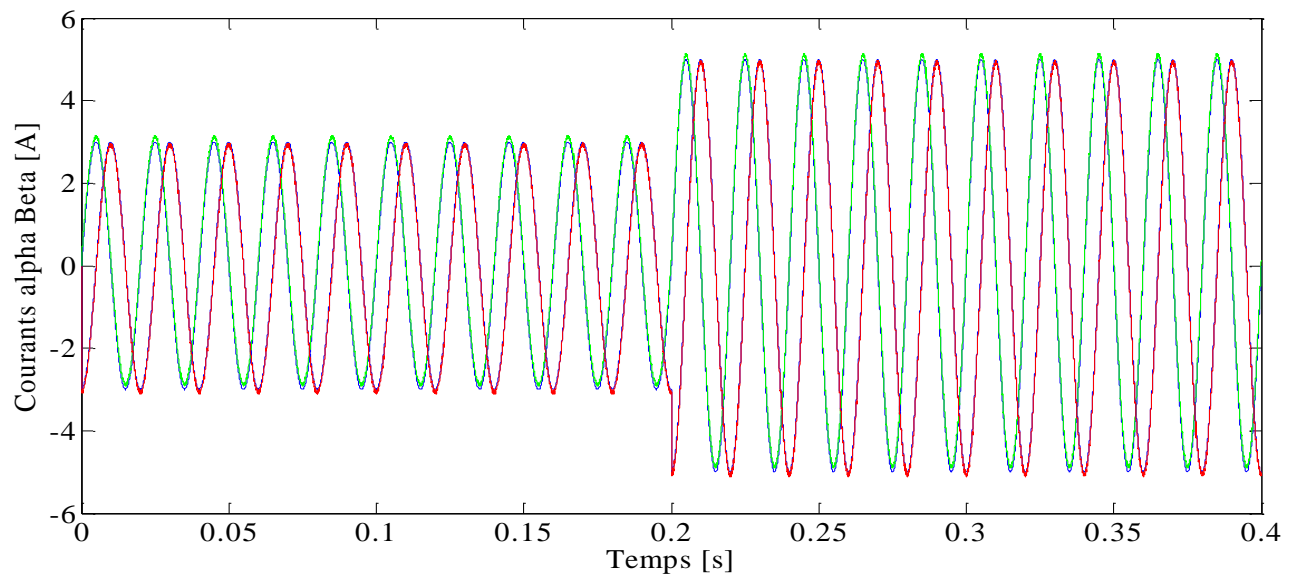
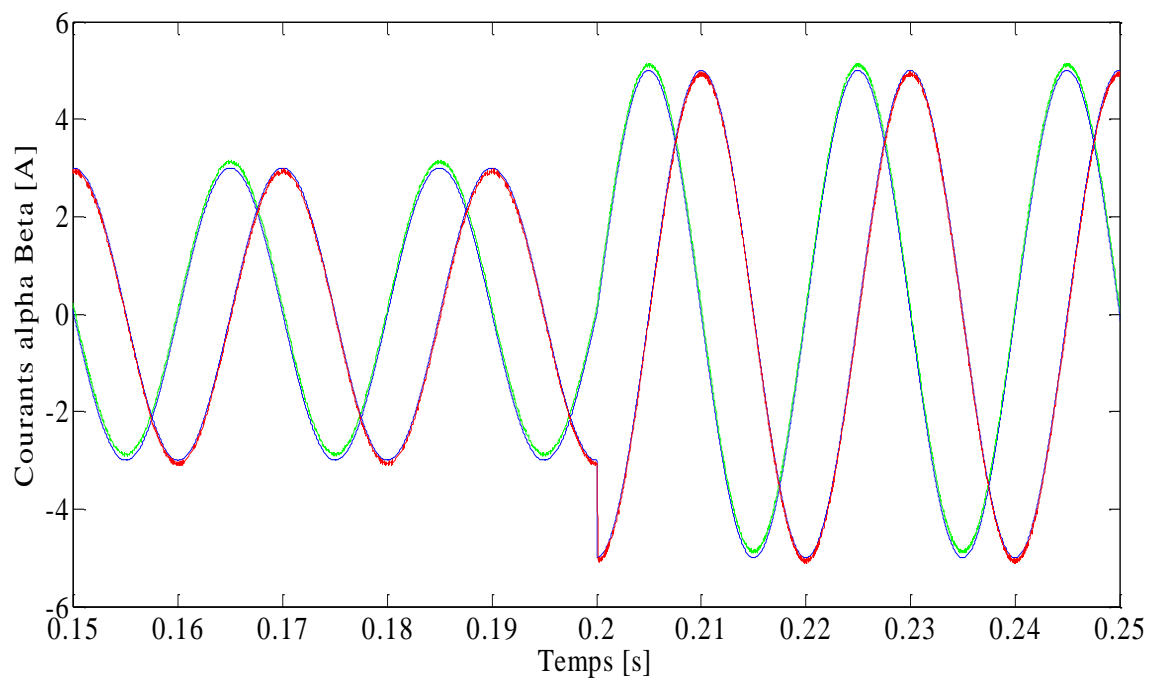
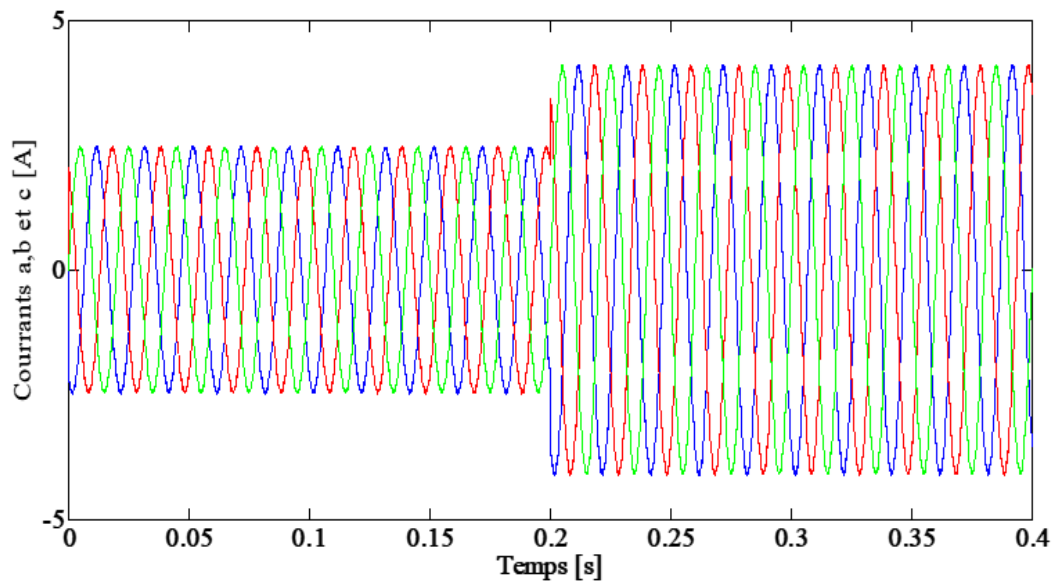


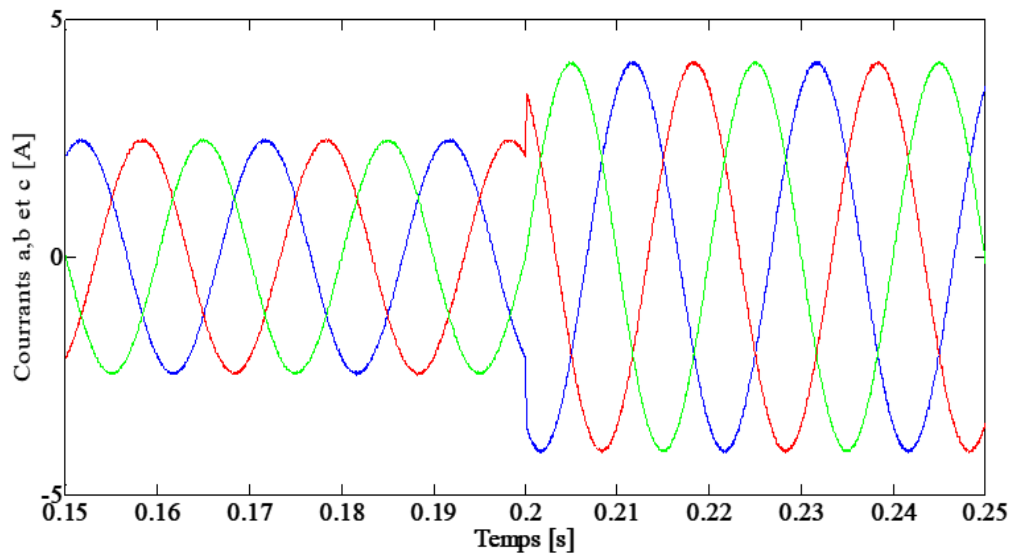
Figure III.6: Harmonics spectrum of phase-a current

For more clarification, it is clear that the 3 vectors-based DB predictive controller method obtains an accurate current tracking ability with a low THD and low current ripple. Moreover, this simulation clearly demonstrated the ability of the proposed 3 vectorsbased DB predictive control algorithm to track reference currents with a fast dynamic response.

III.3.2 Model predictive control (MPC) :**(a)****(b)****Figure III.7: Output currents (A)**

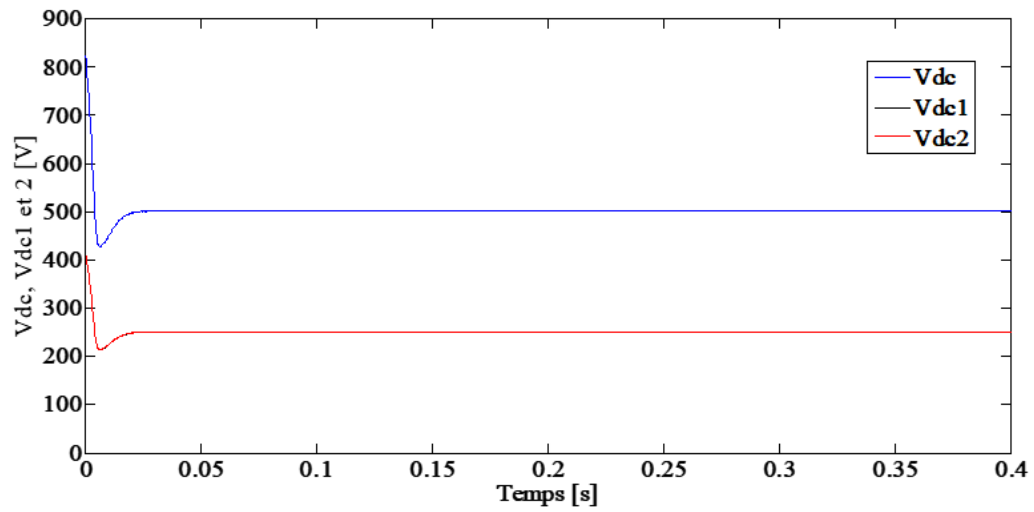


(a)

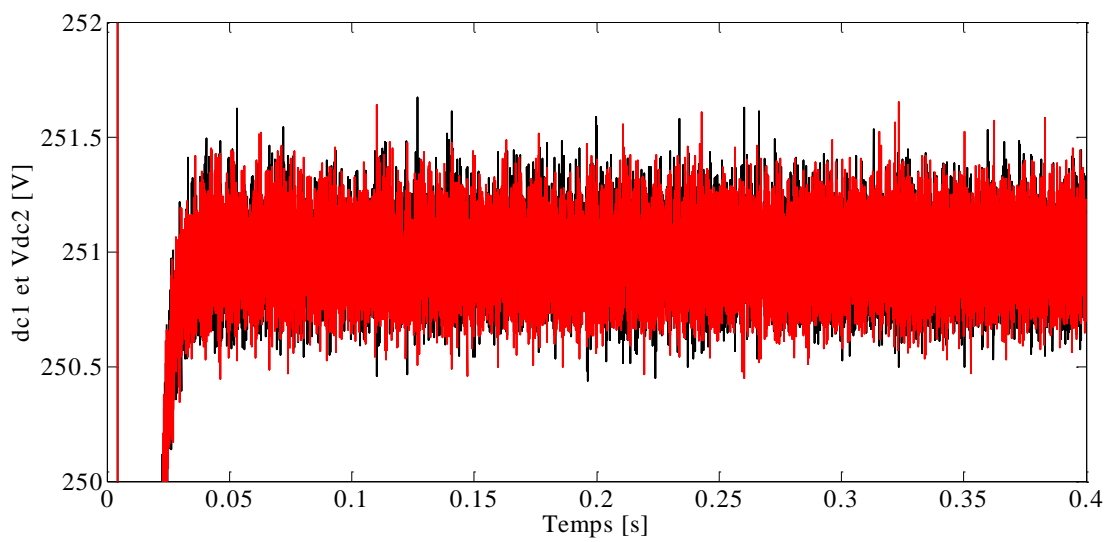


(b)

Figure III.8: three phase currents a , b and c (A)

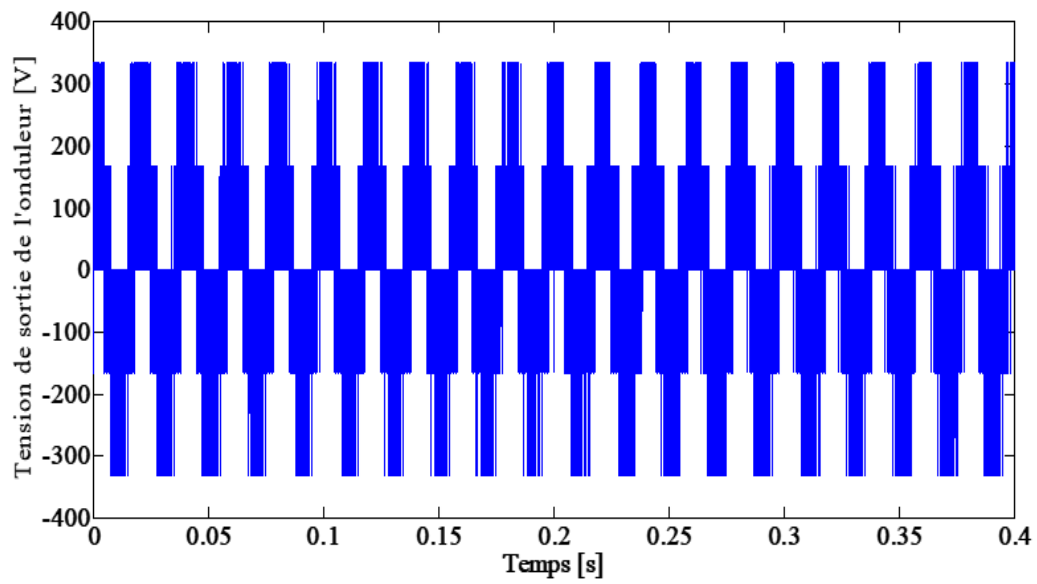


(a)

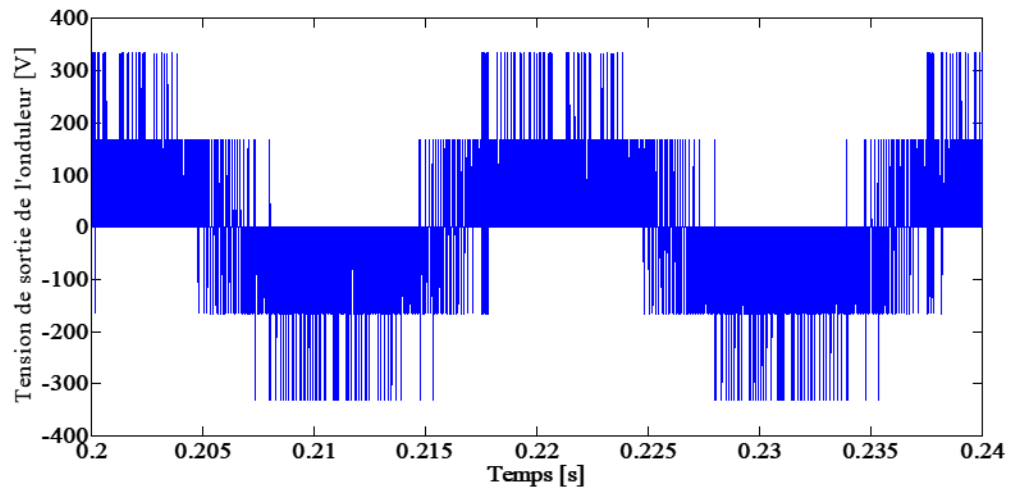


(b)

Figure III.9: Output DC voltages (V)



(a)



(b)

Figure III.10: Output voltage Inverter (v)

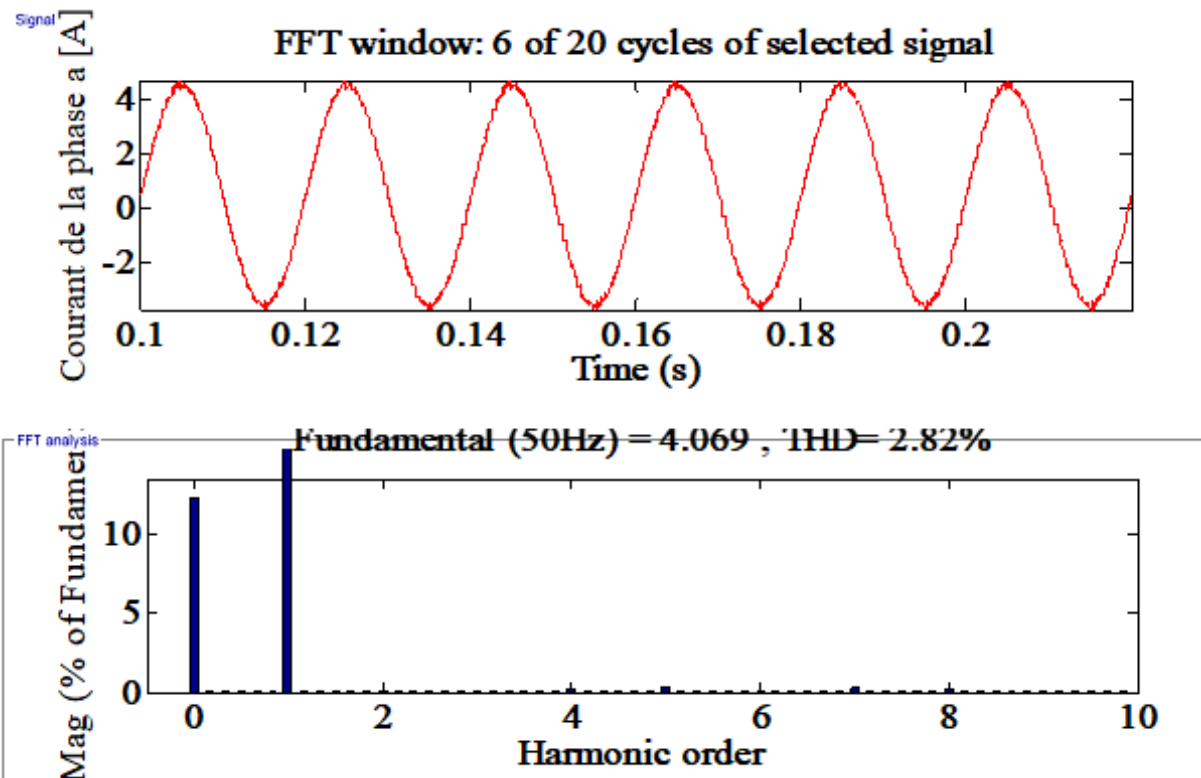


Figure III.11: Harmonics spectrum of phase-a current

The results for the model predictive classique show that the stator current contains high order harmonics, they are difficult to remove by means of filters. In two voltage vectors MPC .

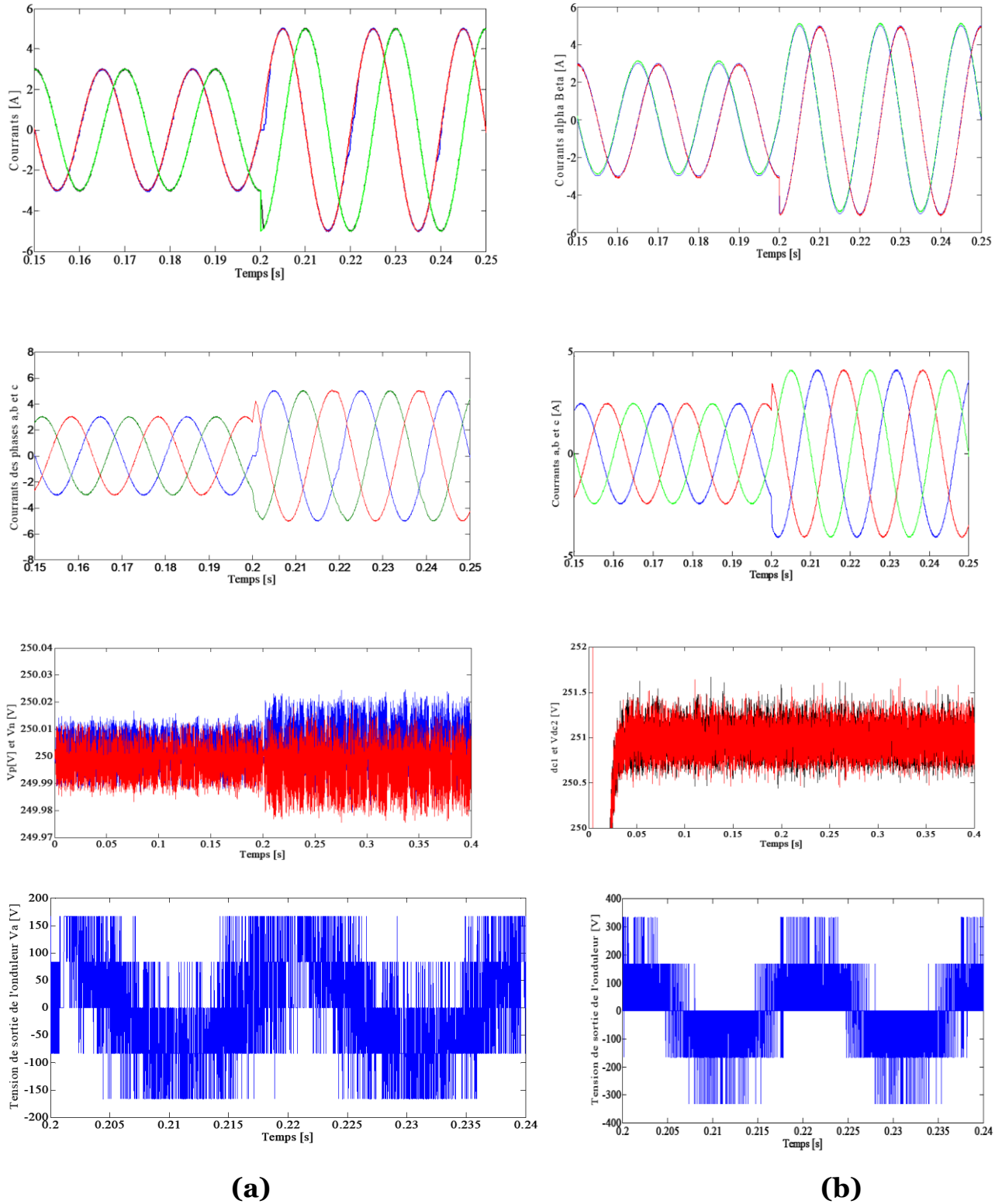


Figure III.12: Simulation results of (a) 3 Vectors-based DB Predictive Controller. (b) Model predictive classique

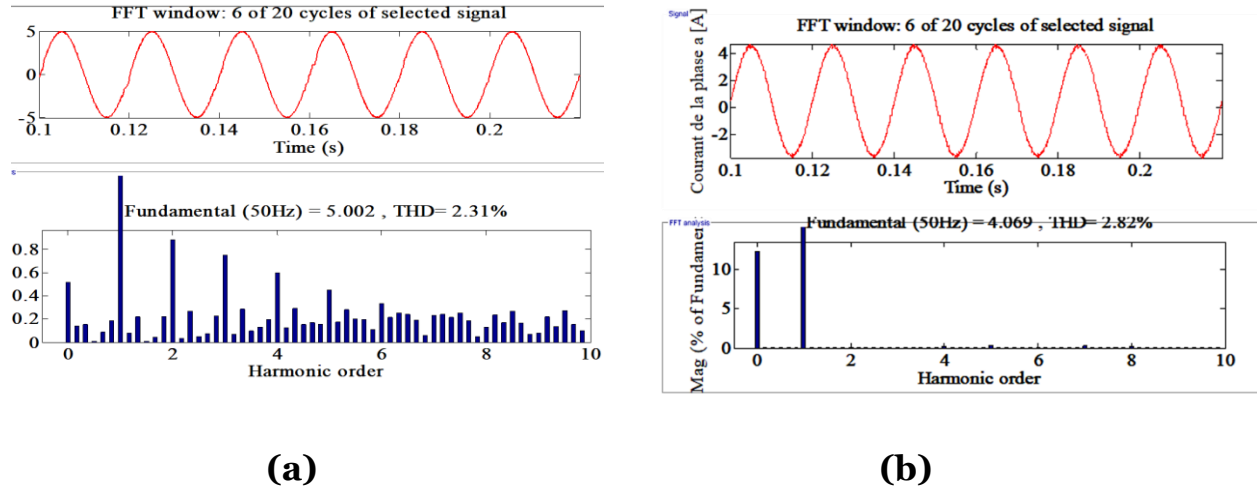


Figure III.13: Harmonics spectrum of phase-a current. (a) 3 Vectors-based DB Predictive Controller. (b) Model predictive classique

III.3.3 The simulation results presented:

Figure III.12 shows that the 3 vectors-based DB predictive controller has the fastest dynamic response with the lowest settling time compared to the other algorithms. and note the 3 vectors-based DB predictive controller method obtains an accurate current tracking ability with a low THD and low current ripple. Compared to the way Model predictive classique you notice that the response time is slower by based on DB predictive and it shows a lot of Harmonics spectrum and stream distortion .

III.4 Conclusion

Using the three-level NPC inverter with the DB predictive controllers with the conventional MPC has been conducted, current THD, NP voltage balancing, average switching frequency, and dynamic response. The conventional MPC method suffers from a long response and the 3 vectors-based DB predictive controller and has the lowest THD value (2.31%) .

Conclusion

With efficiency becoming increasingly important in Power Electronics, it is the goal of every industry to take up initiatives for reduced energy consumption and improve the performance.

DB predictive controllers applied to a three-level NPC inverter are investigated. A comprehensive comparison study of the DB predictive controllers with the conventional MPC has been conducted, current THD, NP voltage balancing, average switching frequency, and dynamic response. The conventional MPC method suffers from a long computation burden and tedious tuning of weighting factors.

Using the 3 vectors-based DB predictive controller, it can be seen that the execution time is reduced by nearly 60% compared with conventional predictive controller, which significantly reduces the computational resources for implementation. The improved DB predictive controllers show less sensitivity concerning the mismatch in the filter inductance and have the lowest power losses than conventional MPC methods. The 3 vectors-based DB predictive controller is the best in the output current quality of the inverter, low computational burden, less average switching frequency, and has the lowest THD value (2.31%). The 3 vector-based DB predictive controllers show the lowest power losses.