



## **Supplying Three Phase, Four Wire, Unbalanced and Non-Linear, Asymmetric Ohmic-Inductive Load by NPC Inverter Based on Method Predictive Control**

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### **Abstract**

In this paper, unbalanced, nonlinear and asymmetric ohmic-inductive three-phase load are supplied by the NPC inverter based on the model named Model Predictive Control (MPC). The MPC is designed for the compensator. The basic principles of MPC as well as MPC model are described in this paper. The design of the proposed controller along with the MPC control steps for controlling the power converter and modeling the power converter are provided to determine all possible switching conditions. Also, the cost function that describes the optimal behavior of the system is formulated. Further, discrete models are defined when future behavior predicts controlled variables. Then the switching modes of the NPC inverter are presented and the control scheme is described based on the control schema for the MPCs with the purpose of power converters and drives, variables prediction and cost function definition. The system performance is evaluated based on the proposed method in various loads including symmetric load and symmetric reference flow, unbalanced load, and symmetric phase voltage. The simulation results indicate the optimal performance of the proposed method in supplying three-phase load demand with optimal quality so that the current distortion is low and the inverter output voltage is also multi-level. In addition, considering asymmetric ohmic-inductive load and step variation in load, the harmonic distortion of the flow is 0.5% in a phase and the output voltage of inverter is also extracted multilevel. The best advantage of the proposed approach compared to SVM methods is controlling without the use of 3D Space Vector. This makes it easier to compute and implement easier than the 3D-SVM.

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## 1. INTRODUCTION

This is especially true for critical loads such as hospitals, telecommunication and communication systems, security systems, process control systems, the Internet industry, and IT technology. The existing power grid is not able to provide high-reliability, high-quality electrical power for these loads, and cause problems such as shortages and overvoltages, voltage fluctuations, voltage and voltage harmonics, and off-grid with program and without network power program. This requirement is met. It affects. Therefore, uninterruptible power supplies (UPS) are used to feed sensitive loads with high reliability and good quality [1-2]. A significant portion of the load of the single-phase load distribution network is required to supply them with the fourth wire to provide the required non-equilibrium return path. On the other hand, non-linear loads, such as single-ended diodes, can process current THDs up to 150% of the network. The harmonic currents generated by nonlinear three-phase voltages, resulting in the harmonic voltage produced by the flow through the lines, can be divided into three components of the harmonic positive sequence, namely, the harmonics of the coefficient  $(6n + 1)$ , the negative harmonic sequence, or, in other words, the harmonics. The coefficient  $(6n-1)$  and the harmonic zero sequence, or, in other words, the harmonics of the coefficient  $(6n-3)$ , were analyzed. Zero-current sequence harmonics, due to their coherency and unlike the positive and negative sequence harmonics, they are not removed, and the fourth wire must be used to

provide the zero-sequence harmonic return path.

So far, there are four solutions for feeding these three-phase loads using inverters. 1) use of three single-phase inverters, 2) use of three-phase three-phase inverters with trans-star triangle, 3) use of a four-phase inverter with a separate capacitor, 4) use of a four-speed inverter. The first solution is less attractive due to the need for three separate dc sources and the lack of integrity and reduced system reliability. The second solution has a big weakness due to the large volume and weight of the transformer than the other two solutions. The third solution, owing to the use of large capacitors to prevent unbalanced voltage dc linking volume and weight compared to the fourth solution, and also for the same dc link voltage, about 15% is less than the fourth solution of the output voltage [3-5]. The need for a high-quality power source has led to the rapid development of power inverters with the latest technology of semiconductor switches. The most popular and easiest is, of course, the inverter of the three-phase voltage source, the six-socket (VSI). Until now, VSI has been used in industrial drives [1-3], uninterrupted power supplies [4-5], active power filters [6-7], and many other uses. But these applications were limited to low voltages and powers due to the lack of suitable switches. This issue, plus its limited two-level switch, has led to the creation of NPC neutral point inverters. Although the NPC inverter can be considered as an adult technology, it still evolves like the inverters examined in [8-12].

NPC active inverters have the same arrangement as the old NPC inverters, but instead of two clamped diode, clamped switches are used. In this way, the NPC inverters use 6 switches per phase, which allows for proper adjustment. There will be no single point of error in this way. In addition, the active NPC inverters have no distinct output performance with older NPC inverters. This means that they still use three levels of output voltage whose output voltage is always lower than the input voltage [13-15].

In this paper, an NPC three-phase three-phase inverter for supplying three-phase quasicide based on model predictive control (MPC) [16-17] has been used. The purpose of the study is to investigate the nonlinear and non-linear quasi-three-phase charging of the NPC inverter. In this research, simulation for three-level NPC converters based on predictive control method using MATLAB / Simulink software and in different scenarios of different loads including symmetric load and symmetric reference flow, unbalanced load and symmetric phase voltage are presented. The proposed method is optimally evaluated.

In Section 2, the design of the precautionary control method for the compensator is described. In Section 3, the implementation of prediction models and prediction of the control strategy are presented, and in Section 4, the simulation results and conclusions are presented in Section 5.

## 2. PREDICTIVE CONTROL METHOD

Between advanced control methods, standard PID control and MPCs are successfully used

in industrial applications [30-29]. Although the ideas of MPC are developed in the 1960s as the application of optimal control theory, its industrial fields began in the late 1970s. Since then, MPC has been successfully used in the chemical industry with long-standing constraints to perform computations. The MPC theory is presented in field of power electronics by the 1980s, considering high-power systems with low-frequency switching. The application of the high switching frequency at that time is not possible to the high-level calculation for control algorithms. However, with the rapid development of high-power microprocessors, the field for the use of MPC in power electronics has doubled over recent decades. The MPC controls are widely used for those controllers that were recently used for power electronic converters [17-16]. The main feature of the prediction control is the use of a model of the system to predict the future behavior of controlled variables. This information is used by the controller for optimal operation in accordance with the predefined optimization criterion. The optimization criterion in the MPC hysteresis control [17] is to maintain control variables in the band of the hysteresis region. While controlling the path, the variables must track the predefined path [17-16]. In dead bead control, the optimal performance is when the error reaches zero at the next sampling time. In the prediction control model, a suitable criterion is used which is specified as the minimum target function in reference [18]. The other advantage of the prefix controller is its simple and understandable structure. Depending on the type of forward control, implementation can be simple. However,

some of the MPC implementations can be complicated by considering continuous control settings. The deadbeat control changes for controlling the controller type can be complicated and incomprehensible. Using MPC, there is no need for a series structure that is used in a linear control schema and provides quick transient response. For example, speed control using routing preflight control. Basic structure of MPC is illustrated in Figure 1. Figure 1 shows the basic structure used to implement this strategy. A model is used to predict the future plant outputs, based on past and current values and on the proposed optimal future control actions. The optimizer calculates these actions taking into account the cost function as well as the constraints [18].

## 2.1 Controller Designing

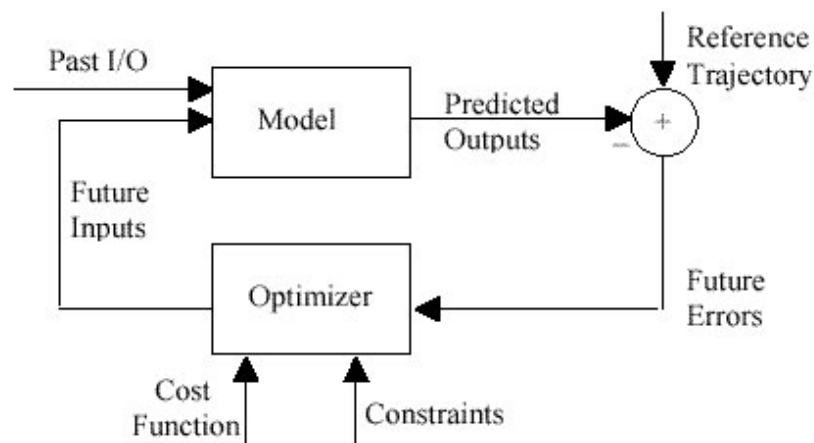
In the design of MPC control stages for controlling the power converter, the following steps must be defined [22-20]:

- Modeling the power converter to

determine all possible switching conditions and its relation to the voltages / inputs and outputs

- Defining the cost function that describes the system's optimal behavior.
- Create discrete models when future behavior predicts controlled variables.

When the converter is modeled, it is the basic element of the power switch that can include the IGBT, thyristor. The simple model of these power switches includes an ideal switch with two on / off modes. Therefore, the total number of switching modes of the power converter is equal to the number of combinations of two switching modes of each switch. By constructing a model for prediction, controlled variables should be considered in order to be compatible with discrete-time models that can be used to predict the same variables. It is also important to determine which variables are measured. In some cases, the variables required for the prediction model are not measured and only those estimates are required. Figure 2 illustrates the Voltage vectors for a three-level NPC inverter.



*Fig. 1. Basic structure of MPC [18].*

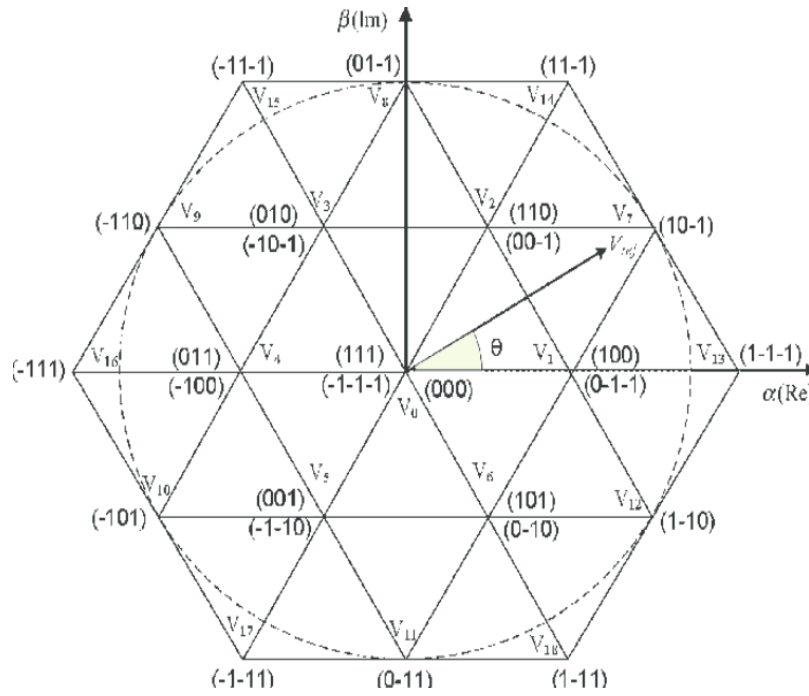


Fig. 2. Voltage vectors for a three-level NPC inverter [21-20].

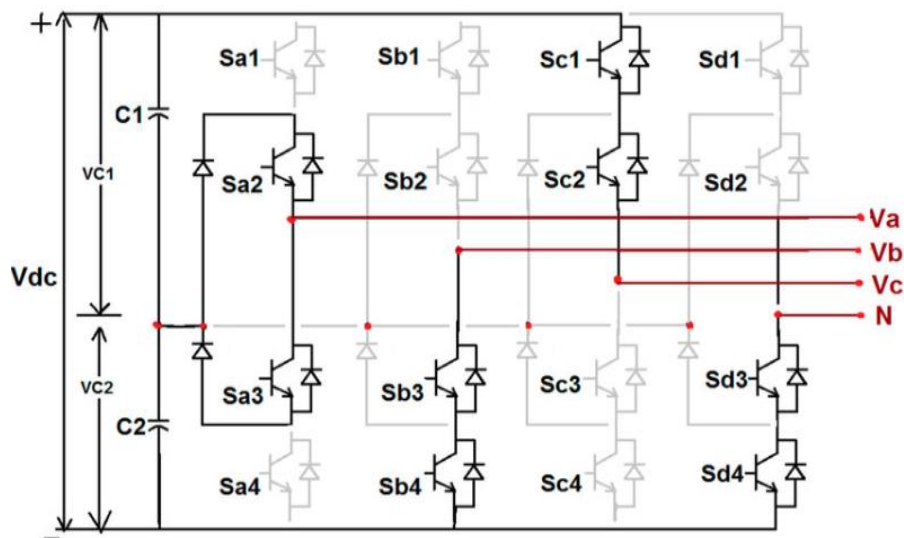


Fig. 3. Multilayer inverter NPC four legs [23].

**2.1.1 Investigating the Switching States of the NPC Inverter**

Figure 3 shows a simple display of an NPC inverter. Phase U inverter contains 4 switches

$S_{a1}$  to  $S_{a4}$ , 4  $D_{a1}$  to  $D_{a4}$  diode and 2 Diode  $D_1$  and  $D_2$ . The  $C_1$  and  $C_2$  capacitors divide the voltage DC link into two parts and create a neutral point (NP). Clamp Diodes  $D_1$  and

D2 provide the connection of the U phase to the neutral point [23-25].

When the Sa1 and Sa2 switches are on, the phase U is connected to the positive terminal of the DC (P) link, and the phase voltage a is  $+V_{dc} / 2$ . And with Sa3 and Sa4 switches turned on, phase a is connected to the negative terminal of the DC (N) link and the phase voltage U is equal to  $-V_{dc} / 2$  relative to NP. Finally, with Sa2 and Sa3 switches turning on the U phase, one of the bright switches and one. The switch phases of phase U are shown in Table 1.

In Fig. 4, two modes for the sample for calculating the U phase voltage are illustrated.

But in the inverter, which legstating into account the NP point and the voltage of each phase is not applicable to this point. The voltage on each phase (for example,  $V_{Un}$ ) depends on the position of that leg and leg. Given that the NPC inverters for each phase

of the three states and for the three phases, we have a total of 81 switches modes. In Table 2, the output voltage is expressed for 81 switching modes. In this table, with the order of PP, NN and OO, the voltage of the Vin phase is zero, PO and ON, the voltage of the Vin phase is equal to  $V_{dc} / 2$ , in PN states equal to  $V_{dc}$ , NP is  $-V_{dc}$ , and NO and OP are equal to  $V_{dc} / 2$ - ( $i = u, v, w$ ).

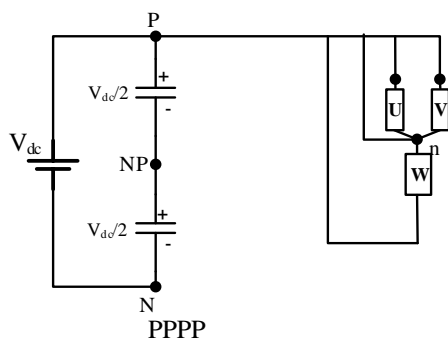
### 3. IMPLEMENTATION OF FORECASTING MODELS AND PREDICTION OF CONTROL STRATEGY

When the system is implemented, the controller should take the following steps:

- Predict the behavior of controlled variables for all possible switching states.
- Assess the cost function for each forecast.
- Select the switching mode as long as the target function fails.

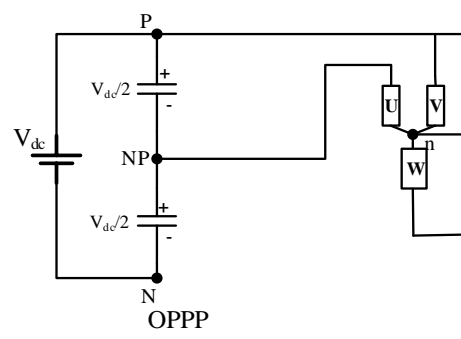
**Table 1. Phase U switching states.**

Switch status	Sa1	Sa2	Sa3	Sa4	Phase voltage U ( $V_{u-NP}$ )
P	On	on	off	off	$+V_{dc}/2$
O	Off	on	on	off	0
N	Off	off	on	on	$-V_{dc}/2$



[PPPP] mode

(a)



[OPPP] mode

(b)

**Fig. 4. Two modes for the sample for calculating the U phase voltage.**

**Table 2. Space vectors of NPC inverter.**

Phase state n	P			O			N		
UVW phase mode	V <sub>un</sub>	V <sub>vn</sub>	V <sub>wn</sub>	V <sub>un</sub>	V <sub>vn</sub>	V <sub>wn</sub>	V <sub>un</sub>	V <sub>vn</sub>	V <sub>wn</sub>
[PPP]	PP	PP	PP	PO	PO	PO	PN	PN	PN
[OOO]	OP	OP	OP	OO	OO	OO	ON	ON	ON
[NNN]	NP	NP	NP	NO	NO	NO	NN	NN	NN
[POO]	PP	OP	OP	PO	OO	OO	PN	ON	ON
[ONN]	OP	NP	NP	OO	NO	NO	ON	NN	NN
[PPO]	PP	PP	OP	PO	PO	OO	PN	PN	ON
[ONN]	OP	NP	NP	OO	NO	NO	ON	NN	NN
[OPO]	OP	PP	OP	OO	PO	OO	ON	PN	ON
[NON]	NP	OP	NP	NO	OO	NO	NN	ON	NN
[OPP]	OP	PP	PP	OO	PO	PO	ON	PN	PN
[NOO]	NP	OP	OP	NO	OO	OO	NN	ON	ON
[OOP]	OP	OP	PP	OO	OO	PO	ON	ON	PN
[NNO]	NP	NO	OP	NO	NO	OO	NN	NN	ON
[POP]	PP	OP	PP	PO	OO	PO	PN	ON	PN
[ONO]	OP	NP	OP	OO	NO	OO	ON	NN	ON
[PON]	PP	OP	NP	PO	OO	NO	PN	ON	NN
[OPN]	OP	PP	NP	OO	PO	NO	NN	PN	NN
[NPO]	NP	PP	OP	NO	PO	OO	NN	PN	ON
[NOP]	NP	OP	PP	NO	OO	PO	NN	ON	PN
[ONP]	OP	NP	PP	OO	NO	PO	ON	NN	PN
[PNO]	PP	NP	OP	PO	NO	OO	PN	NN	ON
[PNN]	PP	NP	NP	PO	NO	NO	PN	NN	NN
[PPN]	PP	PP	NP	PO	PO	NO	PN	PN	NN
[NPN]	NP	PP	NP	NO	PO	NO	NN	PN	NN
[NPP]	NP	PP	PP	NO	PO	PO	NN	PN	PN
[NNP]	NP	NP	PP	NO	NO	PO	NN	NN	PN
[PNP]	PP	NP	PP	PO	NO	PO	PN	NN	PN

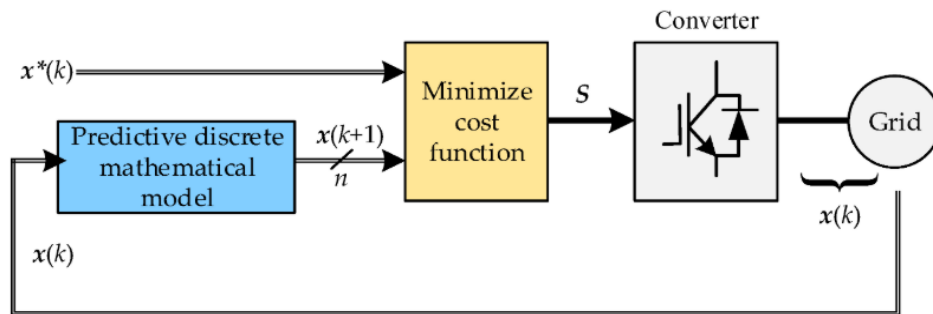
Implementing forward models and forecasting control strategies may have different issues depending on the type of processor used. When implemented using a fixed-point processor, special attention should be given to precise programming in introducing the fixed point of the variables. However, if the implementation is performed using a floating point processor, roughly the same programming for simulation can be used in the lab. In order to select the switching mode

that minimizes the cost function, all possible scenarios are evaluated and the optimal values are applied to the next mode. The number of calculations is directly related to the number of switching states. In the case of a three-phase dual-level inverter, the prediction for eight possible modes of switching is not complicated, but in the case of multi-level multi-axial systems, different optimization methods should be considered in order to reduce the number of calculations.

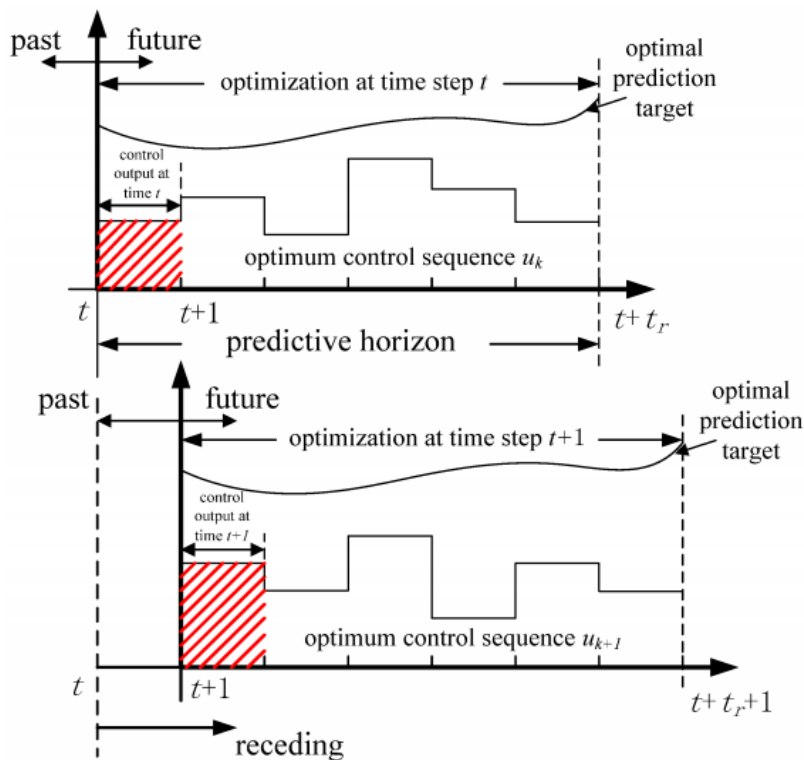
### 3.1 Overall Control Plan

The schematic control for MPC and operation basis of MPC method is shown in Figure 5 for power converters and drives. The power converter can be constructed from a topology and a number of phases, while the overall load shown in the figure can be presented in electrical machines, networks or any other active or passive components. In

this scheme, the variables measured in  $X(k)$  in the model are used for calculating the  $X(k+1)$  predictions of the control variables for each of the possible  $n$  operators, which are switching states, voltages, and flows. These predictions are then evaluated using the cost function that considers reference values ( $k$ ) and constraints. The optimal  $S$  operator is selected and applied to the converter.



(a)



(b)

Fig. 5. a) MPC schema for various converters, b) Operation basis of MPC method [26].



**Table 3. Simulation parameters.**

Parameter	Value
Input Voltage Source $V_{dc}$	300 V
Inverter output inductor	15 mAh with a resistance of 0.75 ohms
Sampling frequency	5 microseconds

The controller must select the best switch vector at any moment  $K$  in such a way that the defined cost function is minimized at the instant  $K + 1$ . Control variables should be foreseen for future moments. Therefore, it is possible to select the best vector for minimizing the cost function. The cost function ensures that the control variables follow their reference values. However, the prediction of control variables requires time spent on sampling time. Therefore, this delay may need to be compensated.

### 3.1.1 Forecasting Variables

MPC helps to estimate the future behavior of control variables. The proposed control method has the potential for digital implementation. Therefore, in the analysis, it can solve the equations in a discrete way as well as approximating them.

We have a discrete inverter model [19-21]:

$$\begin{aligned}
 C_{vu} &= T_s / (L_f + (R_f + R_u) * T_s) \\
 C_{vv} &= T_s / (L_f + (R_f + R_v) * T_s) \\
 C_{vw} &= T_s / (L_f + (R_f + R_w) * T_s) \\
 C_{iu} &= L_f / (L_f + (R_f + R_u) * T_s) \\
 C_{iv} &= L_f / (L_f + (R_f + R_v) * T_s) \\
 C_{iw} &= L_f / (L_f + (R_f + R_w) * T_s)
 \end{aligned} \tag{1}$$

$$\begin{aligned}
 i_u &= (C_{iu} * i_{ou}) + (C_{vu} * V_{un}) \\
 i_v &= (C_{iv} * i_{ov}) + (C_{vv} * V_{vn}) \\
 i_w &= (C_{iw} * i_{ow}) + (C_{vw} * V_{wn})
 \end{aligned} \tag{2}$$

where  $T_s$  is the sampling period,  $L_f$  is the output filter output,  $R_f$  is the output filter strength, and  $R_u$  and  $R_v$  and  $R_w$  are the load resistance.

### 3.1.2 Definition of Cost Function

The control algorithm contains the following steps:

*Step 1)* Measure some of the required parameters, such as dc link voltage, injector flow and production voltage

*Step 2)* Use the switch vector

*Step 3)* Estimate the flow at the instant  $K + 1$

*Step 4)* Calculate the cost function of each vector and then select the optimal one.

The cost function is defined as:

$$J = |i_u^* - i_u| + |i_v^* - i_v| + |i_w^* - i_w| \tag{3}$$

## 4. SIMULATION RESULTS

In this section, simulation results for the three-level NPC converter are presented. The simulation results were performed using MATLAB/Simulink software and the results were analyzed in two simulation scenarios. In

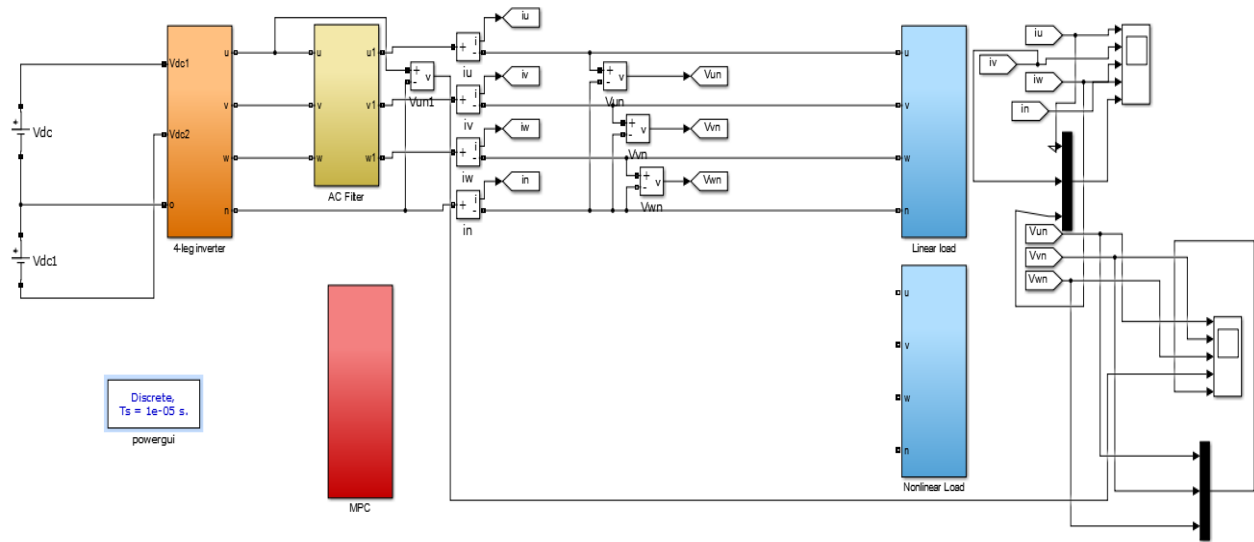


Fig. 6 The system implemented in MATLAB / Simulink software.

the first scenario, the ohms are balanced and the reference phase of the three phases is balanced. This scenario is used to check the performance of the system without the needle flow. In the second scenario, the load is unbalanced but it is balanced by creating unbalanced currents of the three-phase voltage. In Table 3, simulation parameters are presented. An inverter output is used to filter the harmonic components of an inductor.

Figure 6 illustrates the block diagram of the simulated system in MATLAB software. It is observed that two sources of 150 volts are used in the DC link. An NPC inverter is also shown in Fig. 7.

#### 4.1 Simulation Results for Symmetric Load and Symmetric Reference Current

In this section, the performance of an NPC inverted in symmetric load conditions and symmetric reference flow is investigated. The load in each phase is 10 ohms. The reference current in each phase is determined by the following relationships:

$$\begin{aligned} i_u^* &= 15 \sin(120t) \\ i_v^* &= 15 \sin\left(120t + \frac{2\pi}{3}\right) \\ i_w^* &= 15 \sin\left(120t + \frac{4\pi}{3}\right) \end{aligned} \quad (4)$$

Therefore, in this situation, the simulation is not expected due to the balanced load and the reference currents, and no need for the presence of the fourth leg. Fig. 8 and Fig. 9 respectively show the load feed current and its harmonic spectrum. It is observed that at each phase of the current is 15 amps (with an error of 0.03 amps) and with a distortion less

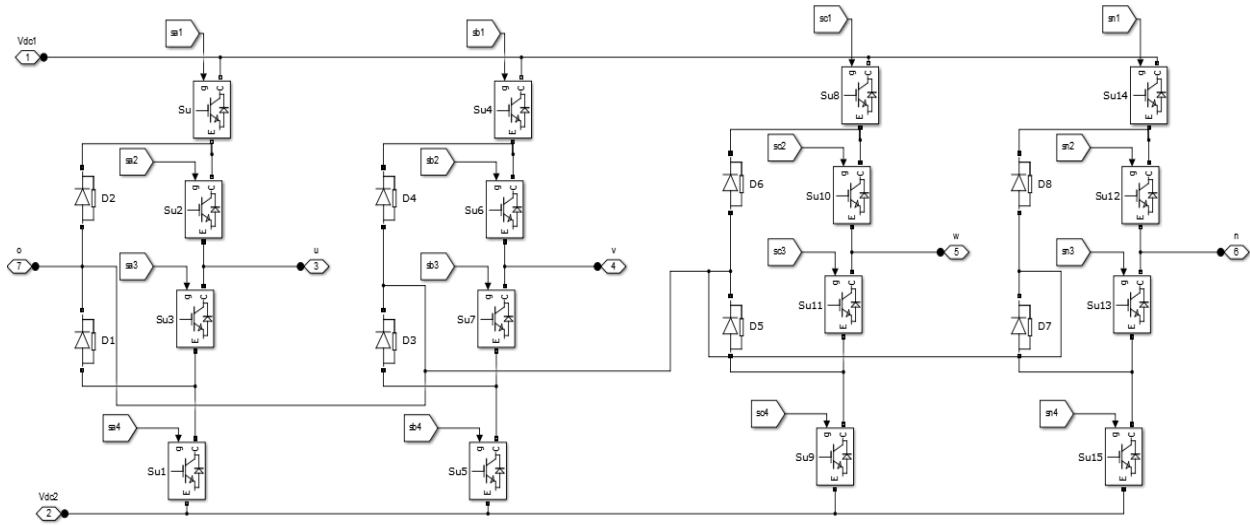


Fig. 7. NPC Inverter implemented in MATLAB software.

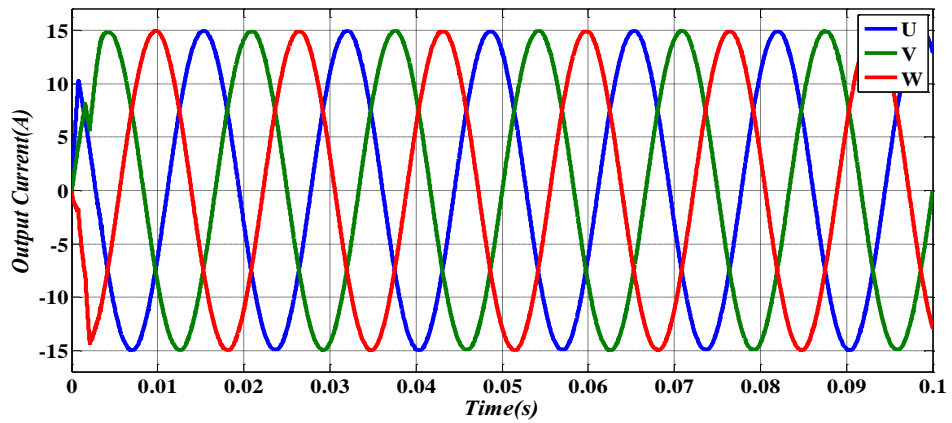


Fig. 8. Load feed current.

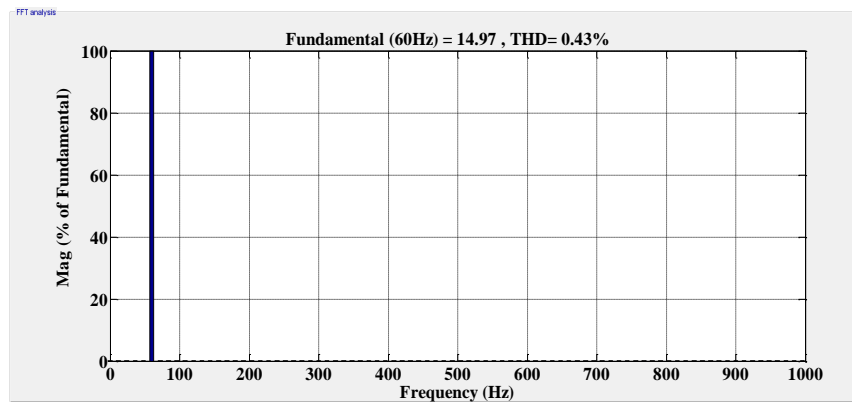


Fig. 9. Distortion and harmonic spectrum of load current in a phase.

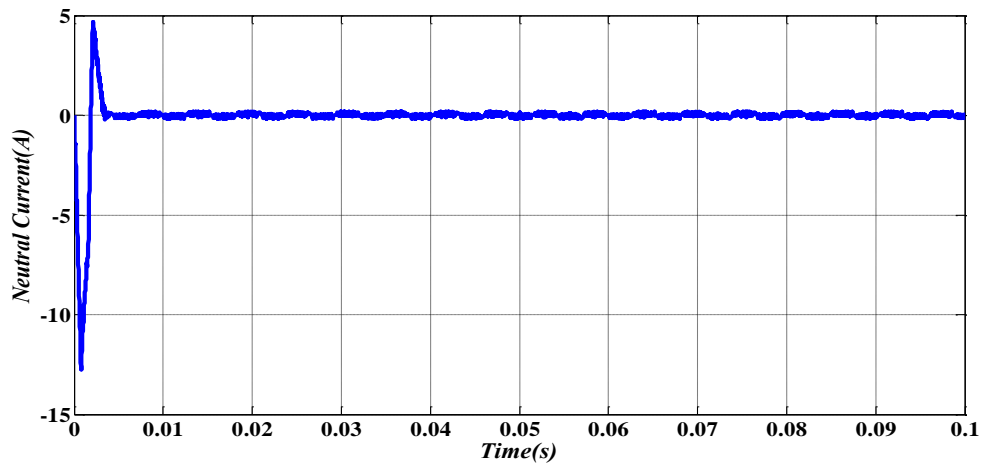


Fig. 10. Null current.

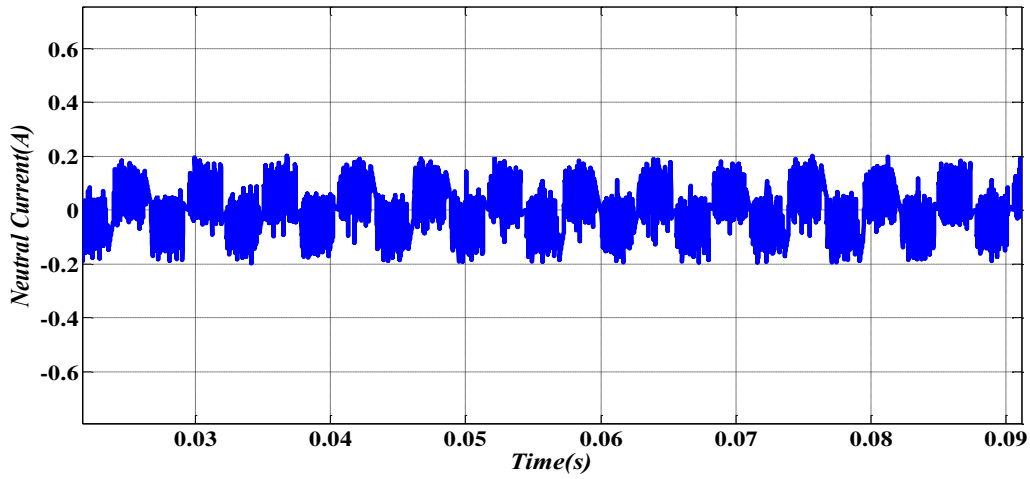


Fig. 11. Null current (magnified).

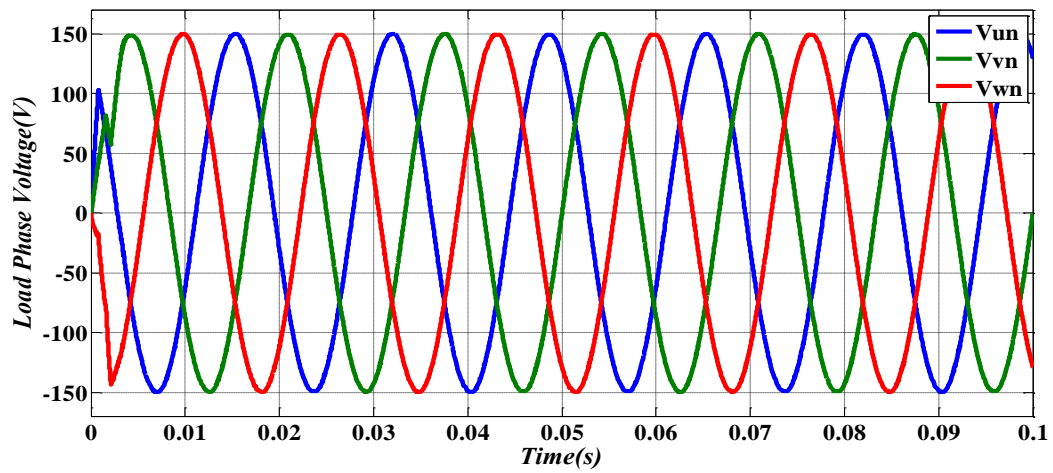
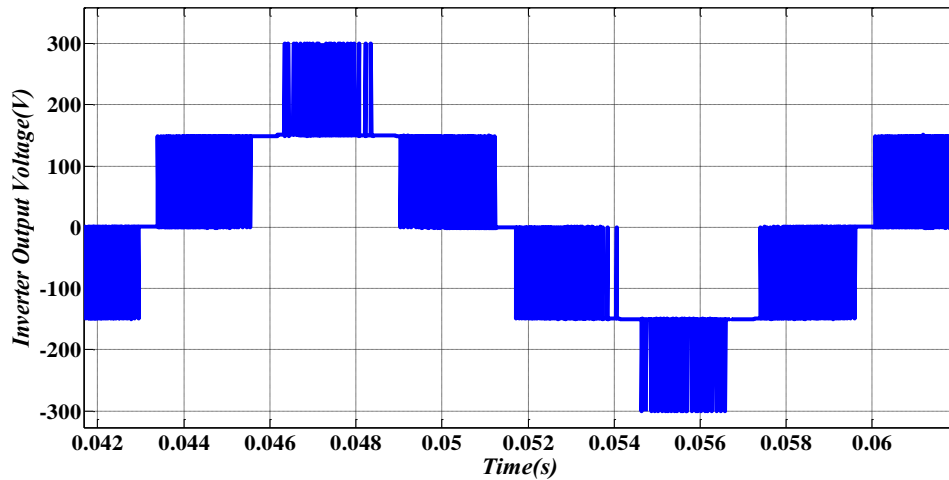


Fig. 12. Load Phase Voltage.



*Fig. 13. Inverter output voltage.*

than half a percent. It has been shown that the flows are balanced, and therefore, according to Fig. 10 and Fig. 11, the Null current is zero.

Figure 12 shows the voltages of each phase. Regarding the use of 10 ohms in load and 15 amp peak flow in each phase, the peak voltage of each phase will be equal to 150 volts. Figure 13 shows the output voltage of the inverter before filtering. It can be seen that the voltage is 300, 150, 0, 150, and 300, and has five levels. Of course, this voltage can be produced in two levels when the output current decreases and no high levels are produced.

#### 4.2 Simulation Results for Unbalanced Load and Symmetric Phase Voltage

In this section, the results of the simulation of the performance of the NPC inverted in unbalanced load conditions and symmetric phase voltage have been evaluated. In this scenario, the load resistance in phase U is equal to 14 ohms and in phase V and W is 7 ohms. To generate the symmetric voltage in the load, the reference voltages should be as follows:

$$\begin{aligned} i_u^* &= 10 \sin(120t) \\ i_v^* &= 20 \sin\left(120t + \frac{2\pi}{3}\right) \\ i_w^* &= 20 \sin\left(120t + \frac{4\pi}{3}\right) \end{aligned} \quad (5)$$

In fact, the reference current of the two phases V and W is twice that of the reference phase of the U phase. Figure 14 and Figure 15 show the load current and its harmonic spectrum. The phase difference of 120 degrees and twice the amplitude of the two-phase current in this form is clear. The phase current of U is also produced with a frequency of 0.07 amps, relative to the reference current with a distortion of about 1%.

Figure 16 shows the flow of the null having a range of about 10 amps and at each instant the total phase flows pass through the null path. Figure 17 shows the load phase voltage. It is observed that about 140 volts in each phase are produced in a balanced manner. Figure 18 also shows the output voltage of the inverter, which is multi-level.

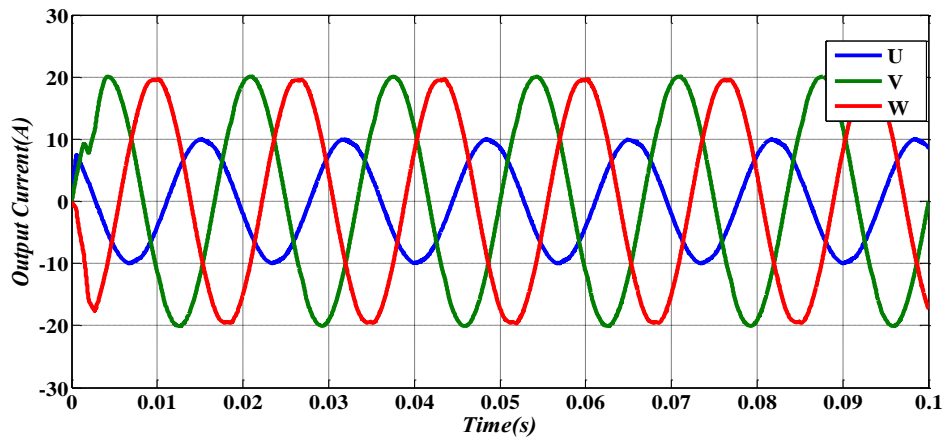


Fig. 14. Load feed current.

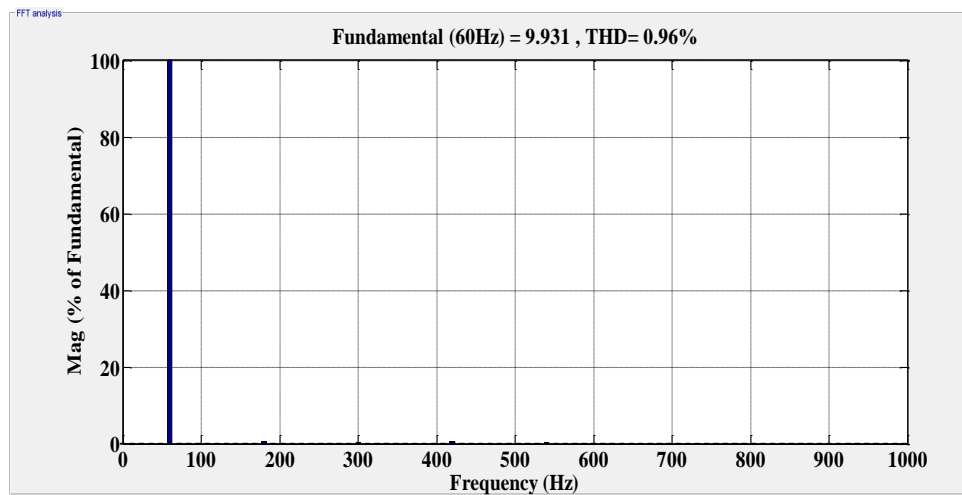


Fig. 15. Distortion and Harmonic voltages in a phase.

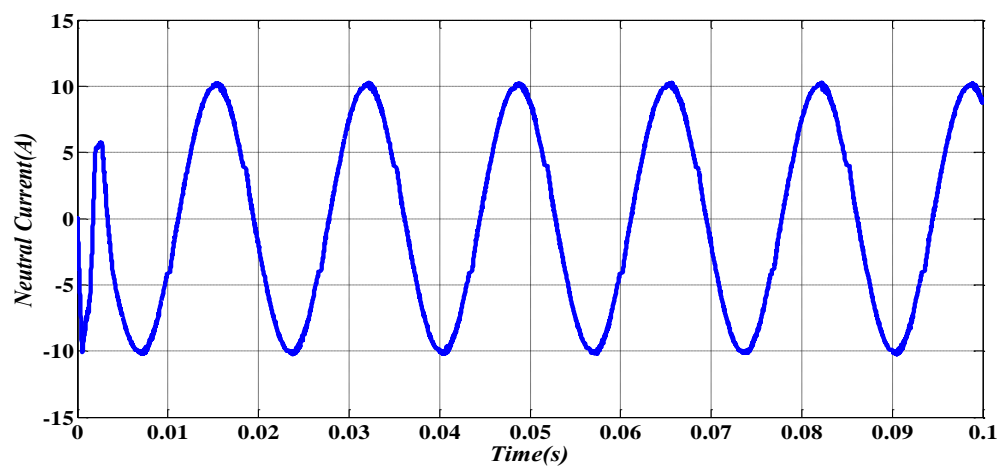


Fig. 16. Null current.

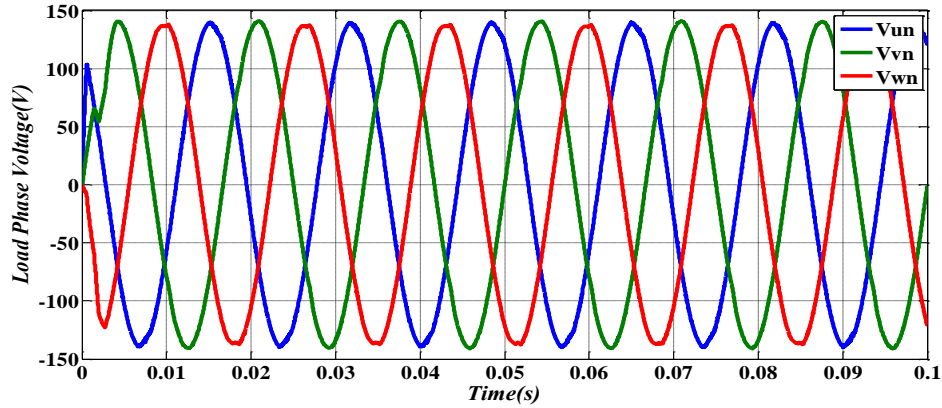


Fig. 17. Load Phase Voltage.

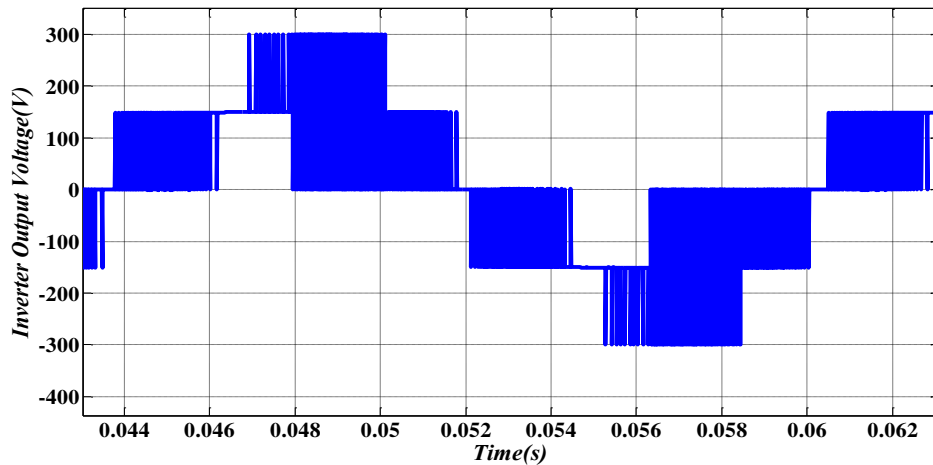


Fig. 18. Inverter output voltage.

### 4.3 Simulation Results for Asymmetric Ohmic-Inductive Load and Step Variation in Load

In this section, the performance of the NPC inverter with the proposed control method is presented considering asymmetric ohmic-inductive load and step variation in load. In this scenario, the resistance of the U phase is 15, the phase of V is 3 and the phase of W is 5 ohms. The inductance with 1 mH in the phase after the instant of 0.5 seconds is connected in series instantaneously with

resistance. The reference currents in phases are as follows:

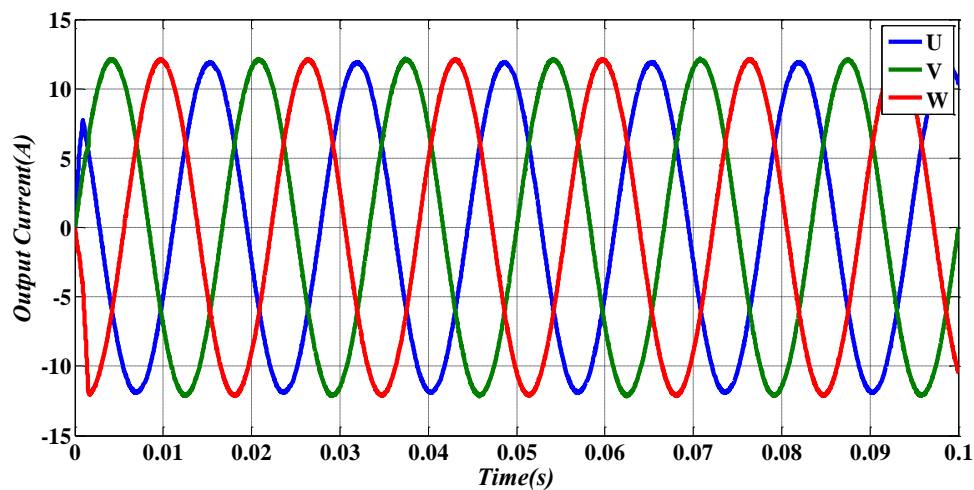
$$\begin{aligned} i_u^* &= 12 \sin(120t) \\ i_v^* &= 12 \sin\left(120t + \frac{2\pi}{3}\right) \\ i_w^* &= 12 \sin\left(120t + \frac{4\pi}{3}\right) \end{aligned} \quad (6)$$

Fig. 19 shows the load supply current and Fig. 20 shows distortion and its harmonic spectrum. It is observed that a 12 A current is generated with a 0.1 A error at the output. Total harmonic distortion is also 0.5%.

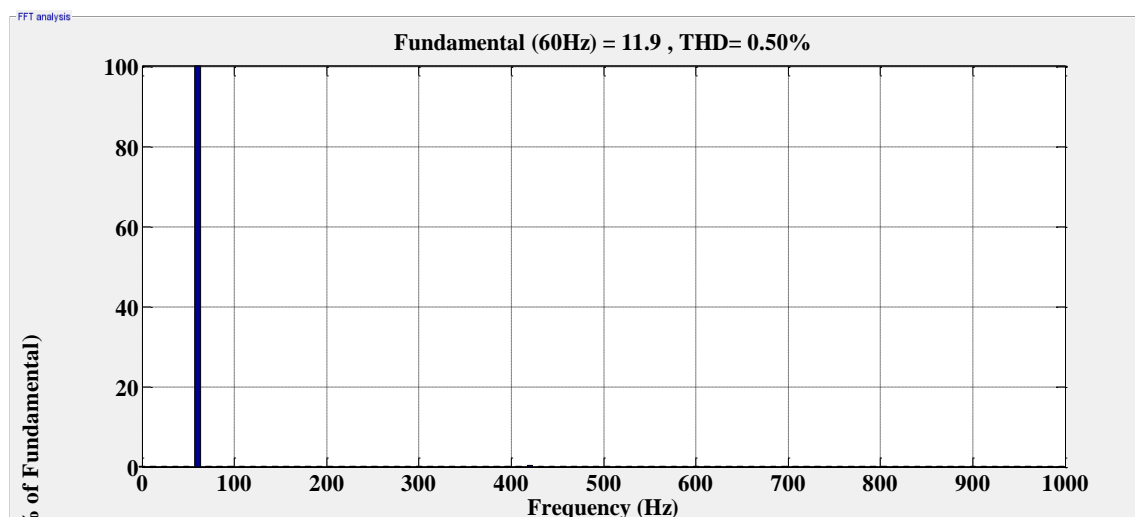
Fig. 21 shows the null current, which is due to the symmetric current in the output, the null current is zero. Fig. 22 shows the load voltage. It is observed that the voltage in the three phases is asymmetric and shows suitable dynamic voltage and current due to the step variation in load. Fig. 23 also shows the 5-level output voltage.

In previous studies of the three-phase load supply by the NPC inverters were mostly based on the Space Vector

Modulation (SVM), and this method has a lot of computational and complexity. In the proposed method based on the MPC, the reference current is simply calculated and then, by modeling the behavior of the inverter, the switching is done so that the current reaches to its reference value. The MPC presented in this article does not need to adjust the parameter, and only it needs to the filter output information of the inverter and dc link capacitor. As a result,



*Fig. 19. Load feed current.*



*Fig. 20. Distortion and Harmonic spectrum of load current in a phase.*



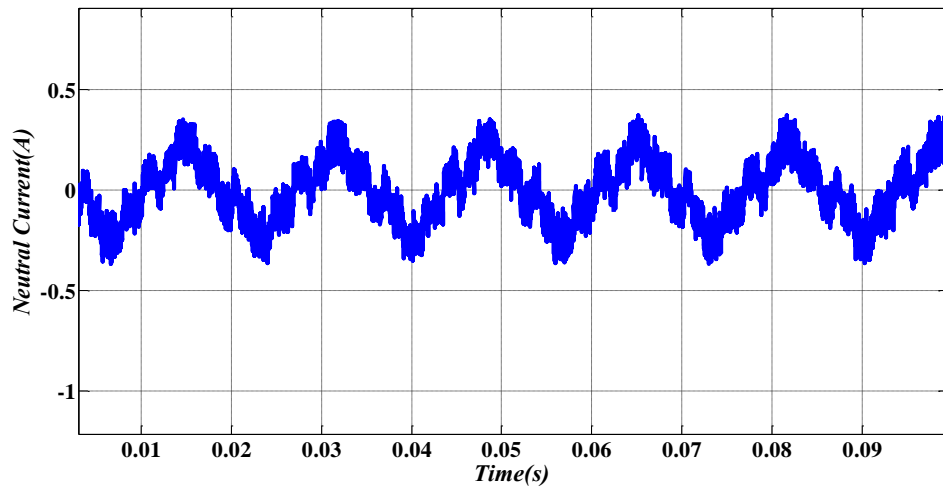


Fig. 21. Null current.

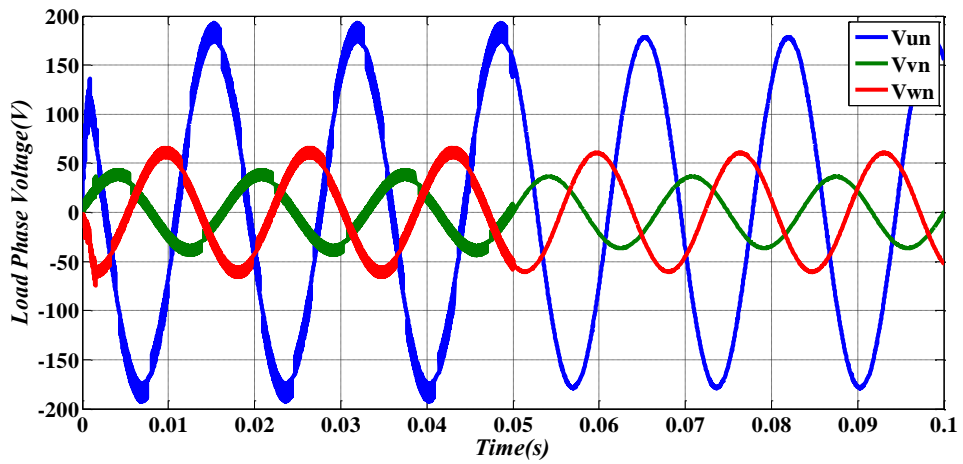


Fig. 22. Phase voltage of load.

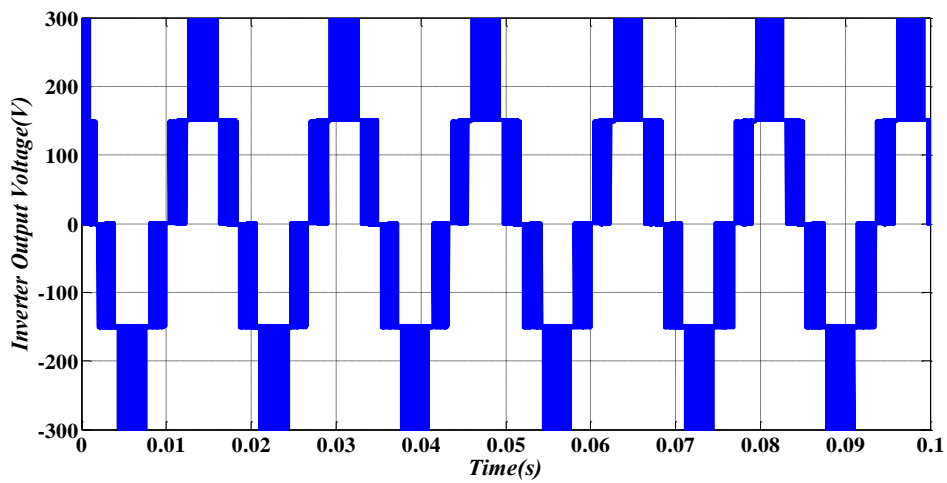


Fig. 23. Output voltage of inverter.

implementing this proposed method is much simpler than similar methods, such as 3D-SVM procedures [27-30]. The best advantage of the proposed approach compared to SVM methods is: controlling without the need to 3D Space Vector. This makes it easier to compute and implement compared to the 3D-SVM.

## 5. CONCLUSION

In this paper, a new method for supplying unbalanced three-phase load to the neutral point clamping inverter NPC was proposed based on the MPC method. In this study, three-phase NPC three-phase inverter was used to feed the four-phase three-phase load. In this paper, proposed controller design with MPC control steps for controlling the power converter and modeling the power converter to determine all possible switching conditions were presented. Then the NPC inverter switching modes were presented and the control scheme was described based on the control schema for the MPCs for power converters and drives, variables prediction, and cost function definition. The performance of the NPC inverted in symmetrical load conditions and symmetrical reference flow was investigated, in which case the flow of the null was not created, and the presence of the fourth leg was not necessarily required, and the current distortion was less than half a percent, that is, the flows were balanced. The inverter output voltage is also multi-level. In addition, the performance of the NPC inverted in unbalanced load conditions and symmetric phase voltage were investigated. The results showed that the phase current was generated

by about 1% relative to the reference current with distortion, and at the same time, the total phase flows passed through the null path and the inverter output voltage Multi-level generation. Also, the performance of the NPC inverters is evaluated using the proposed control method considering asymmetric ohmic-inductive load and step variation in load. The results showed that the harmonic distortion of the flow is 0.5% in a phase. Also, due to the symmetrical current in the output, the zero null current is achieved. In addition, the voltage is asymmetric in three phases and has good dynamic of current and voltage with step variation in the load. Moreover, the output voltage of inverter is also extracted multileveled. The best advantage of the proposed approach compared to SVM methods was controlled without the need to 3D Space Vector. This makes it easier to compute and implement in comparison with the 3D-SVM.

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