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JOURNAL OF UNIVERSITY OF BABYLON

For ENGINEERING SCIENCES (JUBES)

Vol.30, No.3.| 2022

Analysis of Five Level Neutral Point Clamped Inverter Fed from 18 Pulse Output Multiphase Rectifier for Grid Tied Applications

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Received:	**22/6/2022**	**Accepted:**	**19/7/2022**	**Published:**	**8/8/2022**

Abstract

Power electronics converters play a major role in various energy processing applications. In many instances the need arises to use two converters to achieve power processing, conditioning or both. In this work, two converter systems are studied, which is based on two multiphase/multilevel converters. The main objective is to process AC power from a source which can be a distributed energy source (DER) by converting it to DC before injecting it into another AC system. An 18 pulse multiphase rectifier is used for the first objective. The second processing task, which involves converting the DC power back to AC is achieved by five level neutral point clamped converter (NPC). Results verify the benefits of the multiphase rectifier in producing a smooth DC voltage. On the other side, the five level NPC revels an interesting feature of high fundamental voltage.

Keywords: Neutral point clamped converter, Injected power, Pulse width modulation, Distributed energy source.

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1. Introduction

Multi-pulse rectifiers (MPR) are adopted when high DC output voltage is required to be produced from three-phase power source. In comparison with the conventional 6-pulse rectifier, MPR can produce higher average DC output voltage with lower ripple content, they are also capable of reducing the harmonic distortion in the input current. Therefore, MPRs are used as front-end converters in various applications. MPR can be configured as 12-, 18-, and 24-pulse rectifier fed by phase-shifting transformer [1-3].

In many industrial applications, 18-pulse rectifier system is considered as cost-effective solution for reducing the harmonic distortion in the input current and fulfilling the IEEE standard [4]. Eighteen pulse rectifier has better rectification characteristics with simple structure in comparison with 12 and 24-pulse rectifiers [5].

In most existing literatures, 18-pulse front end rectifier feeds a two level voltage source inverter (VSI) for various applications, including drive systems. [6] introduced 18-pulse autotransformer rectifier unit (ATRU) to drive permanent magnet synchronous machine (PMSM) under direct torque control (DTC) strategy. It is also used to drive an induction motor in adjustable speed drive system with lower value of current total harmonic distortion (THD) [7-9]. More electric aircraft (MEA) also employs an 18-pulse rectifier to supply DC load while maintaining the current harmonic within the regulatory limits. [10] provided a guideline for optimal selection of 18-pulse ATRU configuration by comparing six types of autotransformer units (ATU) based on their kVA rating and current harmonic distortion. A differential delta /fork ATR connection for 18-pulse rectifier with no interphase transformer is presented in [11]. This configuration was able to maintain the quality of current within the aircraft industry requirements. A model for MPR system to serve aircraft applications is introduced in [5,12].

In this paper, 18-pulse rectifier is employed to feed grid-tied five-level neutral point clamped (NPC) inverter to improve the quality of inverter line current. Multi-level inverters (MLI) are characterized by their ability to generate staircase output waveform with low distortion, reduction in device stresses, common mode (CM) voltage with low input current distortion in addition to high efficiency due to its ability to operate at fundamental switching frequency[13]. In high power application, NPC inverter is considered as the most attracting topology of MLI. In this work, the NPC inverter is used as one of the MLI topologies due to its advantages over other types of MLI such as sharing a common DC bus between all phases which reduces the capacitor numbers, pre-charging the capacitors as a group and high efficiency [13,14]. This paper aims to the following objectives:-

1. A study of the output voltage of the 18 pulse rectifier in terms of the voltage spectrum and DC content. The 18 pulse rectifier is chosen as a compromise between 12 and 24 pulse rectifier.
2. Analyse the behaviour of the five level converters when supplied from a non-battery source and the effect (s) on the output voltage in terms of the levels, shape and content of the fundamental voltage.

3. Evaluate the effectiveness of the multiphase/multilevel converters in injecting real and reactive powers into a balanced utility grid.

2. The 18 Pulse Multiphase Rectifier

Multiphase rectifiers are available with output pulses that are multiple of three. As the pulse number increases, so does the ripple frequency which results in an insignificant ripple content compared to the zero frequency DC output voltage. Figure 1 shows the basic building block of the 18 pulse rectifier, which is the 6 pulse rectifier with output voltage, V_{o1}. Therefore, the 18 pulse rectifier is composed from the cascaded connection of three of these rectifiers [15].

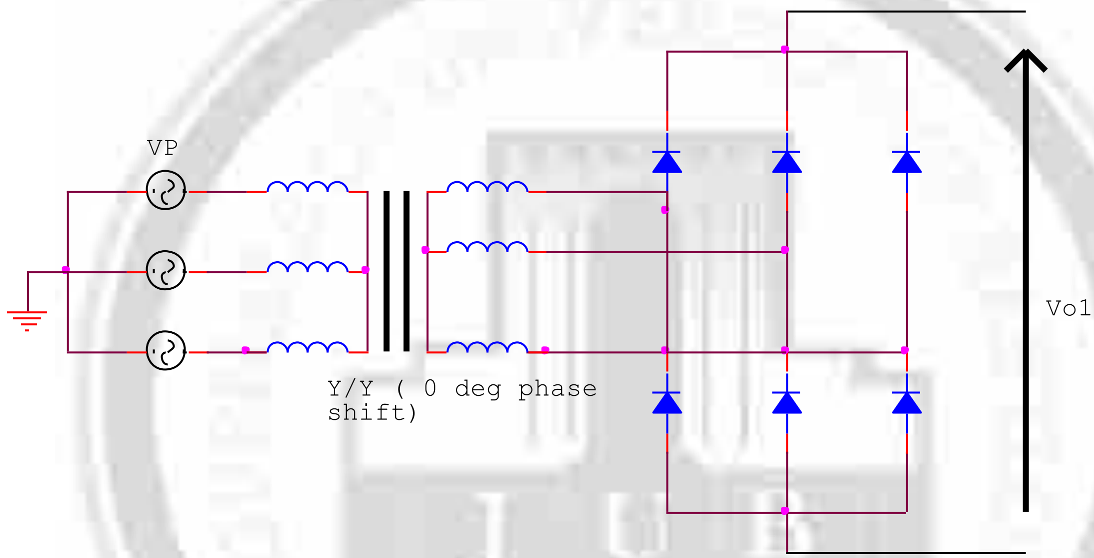

Figure 1 circuit diagram of 6 pulse rectifier building block of 18 pulse rectifier

Since the voltage of the three subsystem rectifiers add up to compose the total output voltage, a phase shift is introduced between each output. In general the phase shift between cascaded subsystems is given by [15,16],

$$\alpha = \frac{360^o}{n} \text{-------------------------------} (1)$$

Where, n is the number of pulses in the output voltage.

Hence, according to Eq. (1), for the 18 pulse rectifier considered in this study, the required phase shift is 20^o.This phase shift can be organized in different collections and can be either leading or lagging [15]. The mean voltage obtained from this rectifier is higher than that of

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the 6 and 12 pulse output. In general, for n pulse output rectifier, the mean voltage is given by [16],

$$V_{dc} = \frac{nV_p}{2\pi}\left(2\sin\frac{\pi}{n}\right) \text{-------------------------}(2)$$

Where V_p is the peak voltage of the line-line input at the transformer primary. The average current obtained from this converter is expressed as,

$$I_{dc} = \frac{nV_p}{2\pi R_{eq}}\left(2\sin\frac{\pi}{n}\right) \text{--------------------------}(3)$$

Here, R_{eq} is the equivalent resistance seen at the terminals of the rectifier output terminals. The root mean square (rms) content in the output voltage of a rectifier in its general form is expressed as [16],

$$V_{rms} = V_p\left[\frac{n}{2\pi}\left(\frac{\pi}{n}+\frac{1}{2}\sin\frac{2\pi}{n}\right)\right]^{1/2} \text{-----------------------}(4)$$

Also, the Fourier expression of the general n pulse output rectifier is expressed for the output instantaneous voltage as [16],

$$v_o(t) = \frac{nV_p}{2\pi}\left(2\sin\frac{\pi}{n}\right) - \sum_{m=n,2n,\ldots}^{\infty} \frac{2nV_p}{\pi(m^2-1)}\left(\cos\frac{m\pi}{n}\sin\frac{\pi}{n}\right)\cos m\omega t \text{----------}(5)$$

Equation (5) is for a general multiphase rectifier. The analyses can be easily adapted to the rectifier considered in this study. This is simply implemented by substituting $n = 18$. However, the harmonics order in the output of the rectifier is expressed as $m = 18k \pm 1, k = 1,2,3,..$ [15]. Therefore, eq. (5) is modified for the 18 pulse rectifier by substituting, $n = 18$,

$$v_o(t) = 0.99V_p - \sum_{m=18k\pm1}^{\infty} \frac{2V_p}{(m^2-1)}\left(\cos\frac{m\pi}{18}\right)\cos m\omega t \text{-------------}(6)$$

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The 18 pulse rectifier was simulated at no-load and the harmonic amplitudes are evaluated as per unit relative to the average component. Table 1 shows the numerical values of amplitude harmonic voltages. Results from the spectrum analyses show that the AC content are small in magnitude and oscillate at high frequency. Hence this input voltage will have a small contribution to the ripple at the NPC input, which is discussed in the next section.

Table 1 Harmonic amplitudes for 18 pulse rectifier, for m=17, 19, 35 and 37.

Harmonic order	Percentage of average value	Actual value (V)
17	0.02%	0.2576
19	0.01%	0.1288
35	0.01%	0.1288
37	0.01%	0.1288

3. The Five Level Neutral Point Clamped Converter

The NPC converter has a main advantage of using one DC source rather than multiple sources. With this type of converter, the capacitors are clustered at the input of the converter. Moreover, these capacitors act as voltage dividers of the input voltage which produce the required levels in the output voltage at the AC side. Figure 2 shows a three level NPC which consists of 4 IGBT switches per phase [13]. The upper four switches which can be viewed as half bridges in series, produce the positive voltage levels, whereas the lower bridge are responsible for the negative levels of the AC output. The above converter can be extended to build a five level NPC which consists of eight IGBTs per phase [17]. The output voltages are defined as follows;

$$v_o(t) = \left\{V_{dc}, \frac{3}{4}V_{dc}, \frac{1}{2}V_{dc}, \frac{1}{4}V_{dc}, 0, -\frac{1}{4}V_{dc}, -\frac{1}{2}V_{dc}, -\frac{3}{4}V_{dc}, -V_{dc}\right\} - - - - - - - - - - (7)$$

It is clear from eq. (7), for the positive side there are five levels with the zero voltage.

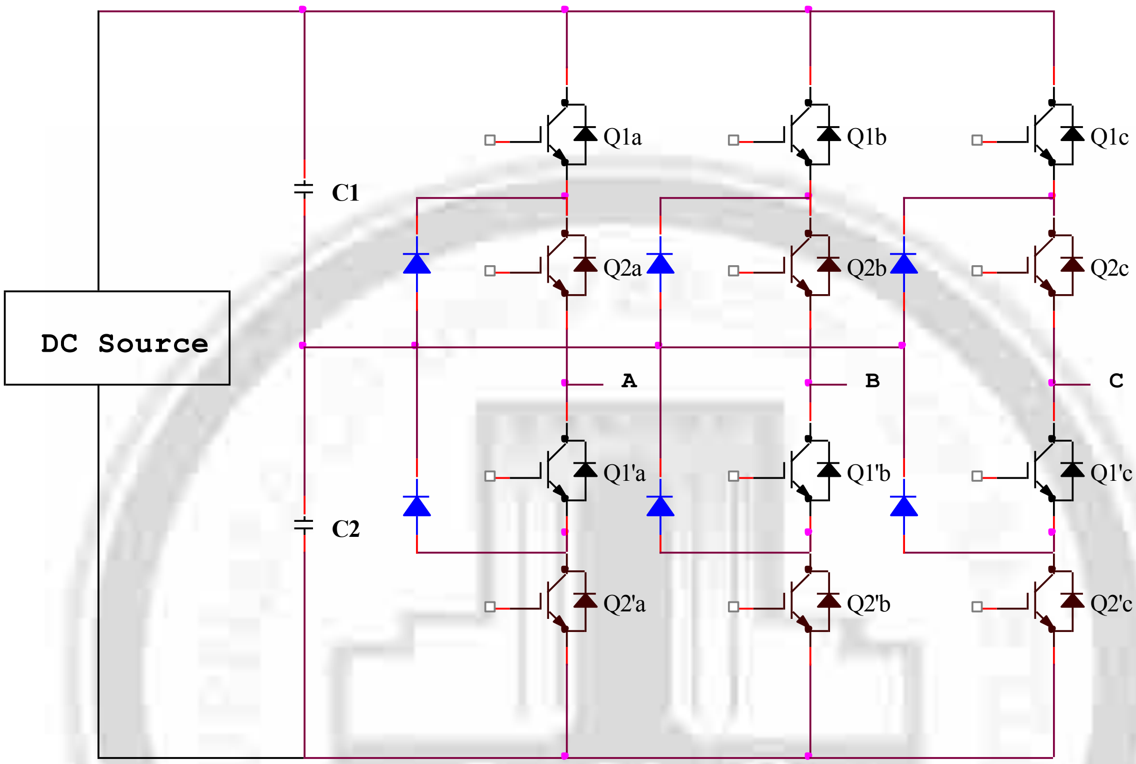

Figure 2. Three-level NPC diagram

This type of converter can be controlled by different modulation technique such as Phase Disposition-Pulse Width Modulation (PD-PWM), Alternative Phase Disposition-Pulse Width Modulation (APD-PWM), Phase Opposition Disposition-Pulse Width Modulation (POD-PWM) and Alternative Phase Opposition Disposition-Pulse Width Modulation (APOD-PWM) [18]. This type of converter usually supplies stand-alone loads or drives. However, in this work the converter is utilized in injecting power into a balanced grid.

The system under study in this paper consists of an 18 pulse output three phase rectifier, a 5 level NPC and a utility grid. Here, the rectifier output terminals supply the NPC. The latter converter injects real and reactive power into the grid. The two converter system with the balanced grid is shown in fig.3.

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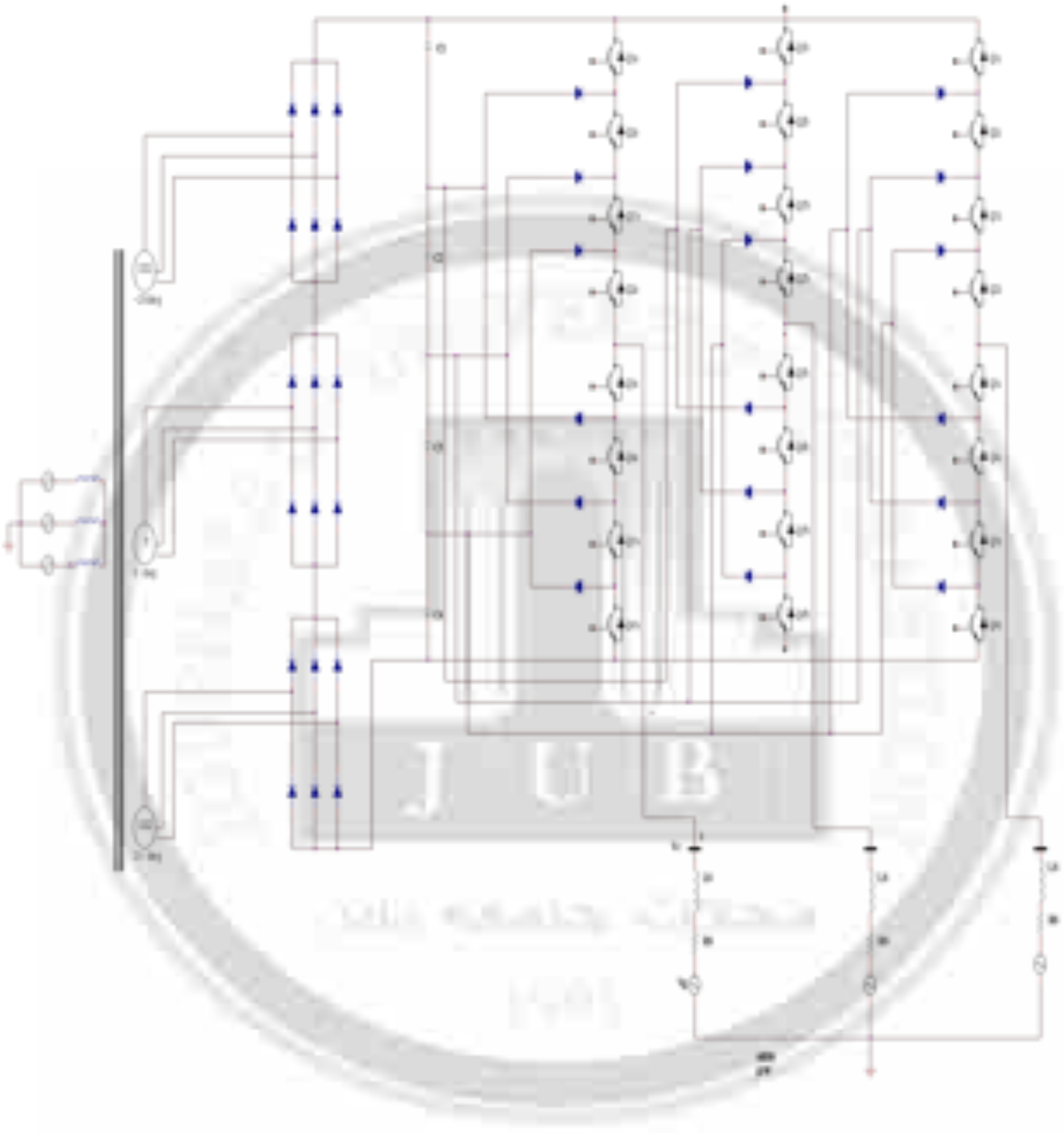

Figure 3 Circuit of three phase five level NPC fed by 18 pulse multiphase rectifier

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4. Simulation of Five Level Neutral Point Converter Behavior Fed from a Multi-phase Rectifier

In this part of the paper, simulation of the system under study is carried out. The simulation platform used is the MATLAB/SIMULINK. For this part, it is assumed that the NPC is coupled to a grid of high short circuit level which means a very low Thevenin's equivalent impedance. Figure 4 shows the block diagram of the system in SIMULINK. Parameters of the simulated system are shown in table 2.

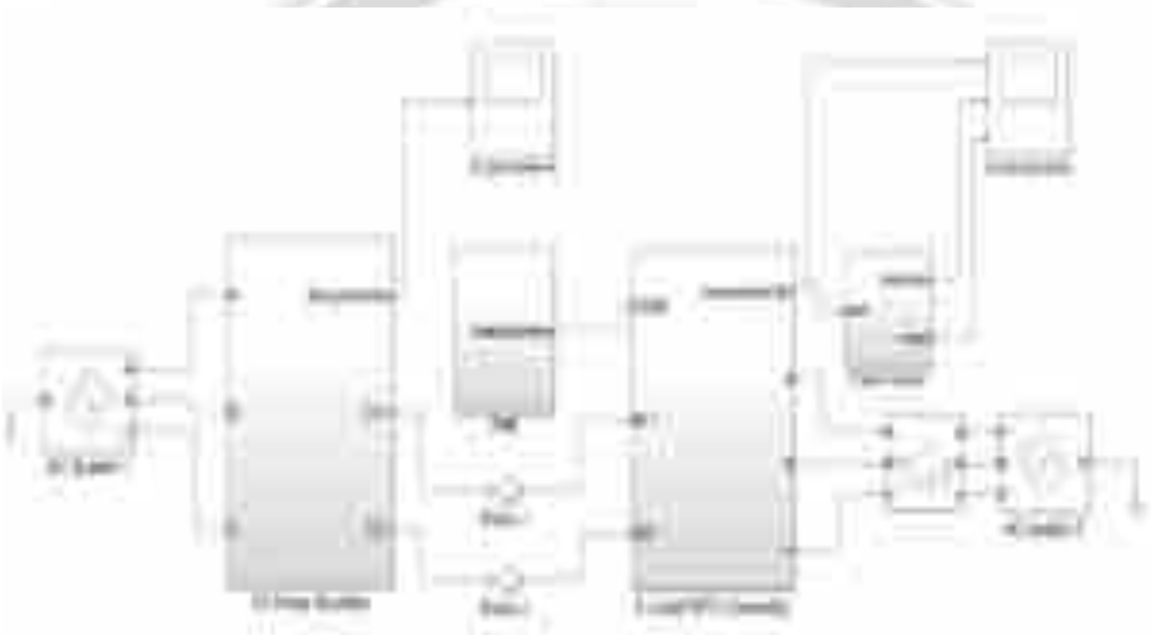

Figure 4 Simulink block diagram

Table 2. Parameters of Simulations

Parameter	Value
Main AC line-line voltage input,	1000 V
Nominal DC output of rectifier,	1288 V
AC line-line voltage of utility grid	250 V
NPC converter, C1, C2,C3 and C4	5 mF
Filter resistance, inductance	50 mΩ,10 mH [17]
ESR for capacitor	1 mΩ
Nominal frequency of converter output voltage	$f = 60\ Hz$
Amplitude modulation index	A=0.8
Carrier frequency of NPC	5000 HZ [17]

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4.1 Simulation of the 18 Pulse Rectifier

The multiphase rectifier is simulated under no-load condition. The multi-winding transformer, which provides a phase shift of 20^o, is implemented according to the following pattern [15],

$$Phase\ shift = \{-20^o, 0^o, +20^o\} ----------------(8)$$

For the -20^o & $+20^o$ phase shift, a zig-zag formation is used at the secondary side. The zero phase shift is implemented simply by a star winding. Figure 5 shows the output voltage.

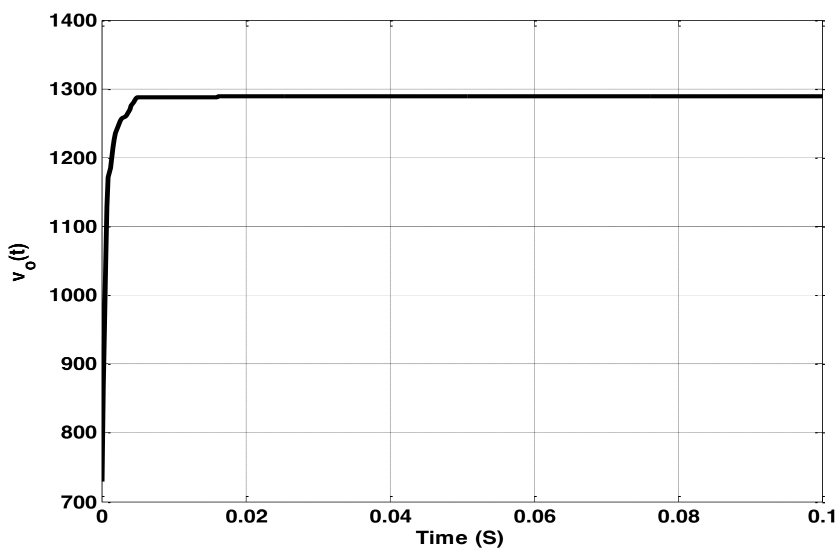

Figure 5 output voltage (in volts) of rectifier only

It is clear that the rectifier produces a voltage that highly mimics a battery. A look at the frequency spectrum confirms that the DC component has a value of 1288 V versus a 0.7061 V rms content. The spectrum of the 18 pulse output rectifier for voltage is shown in figure. 6. Clearly the 18 pulse rectifier produces a high amount of DC voltage, since AC components are small.

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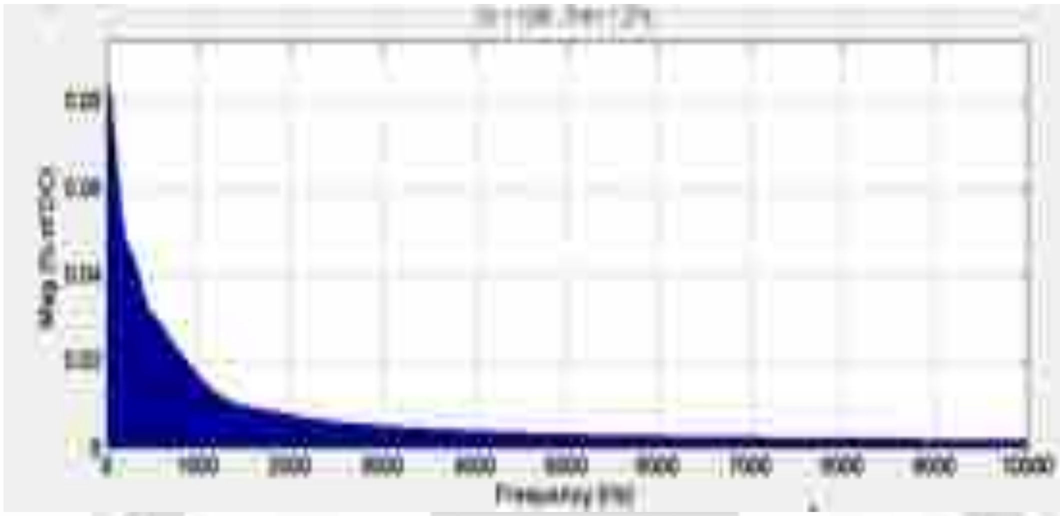

Figure 6 spectrum of rectifier output voltage at no-load.

4.2 Simulation of the Neutral Point Clamped Converter and Multiphase Rectifier

The above rectifier output in this case is coupled to the five level NPC converter. For the purpose of analyzing the converter behavior in steady state, the rectifier is switched to the NPC converter 20 cycles later based on the 60 Hz system. This allows the voltage in rectifier enough time to reach steady state. Figure 7 shows the output line-line voltage of the NPC for each phase.

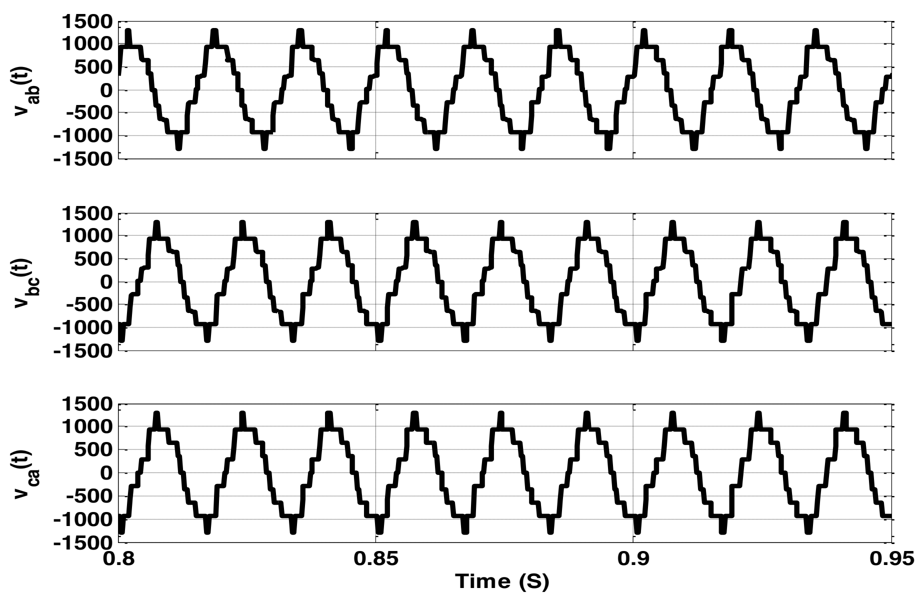

Figure 7 the output line-line voltage (in volts) of the NPC converter.

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Here, the levels are clearly defined which are composed of 4 positive levels in addition to the zero level. It is worth mentioning that the NPC converter switching pulses are generated

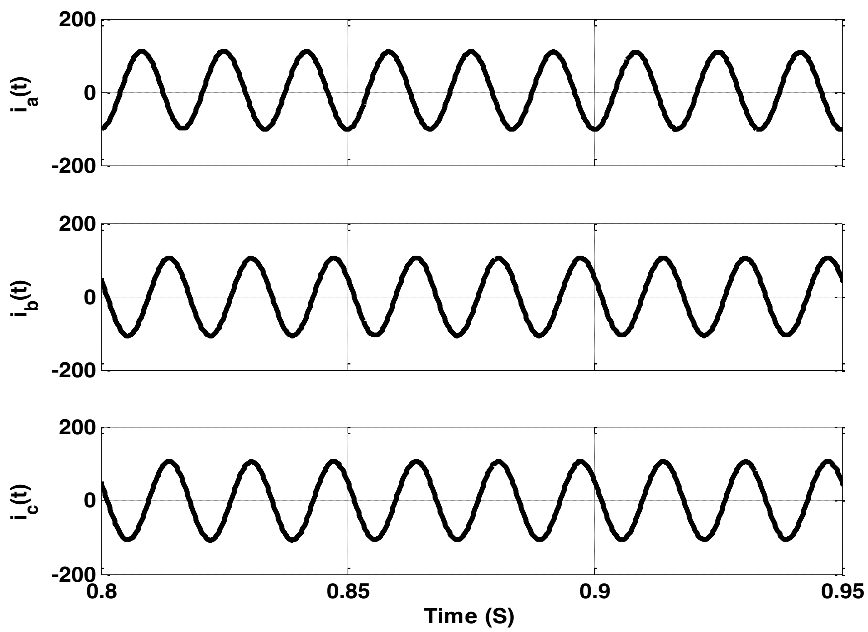

Figure 8 the current injected (in A) into the grid per phase

using the PD-PWM [18]. With this scheme, four high frequency carriers are required which are compared with the naturally sampled sinusoidal modulating signal. Figure 8 depicts the three phase current injected into the grid side of the converter.One of the important points in analyzing NPC converters is to examine the voltage waveform of the capacitors at the input terminals. Figure 9 shows the individual capacitor voltage. The waveforms show an acceptable amount of ripple which in turn confirms the superiority of the 18 pulse rectifier.

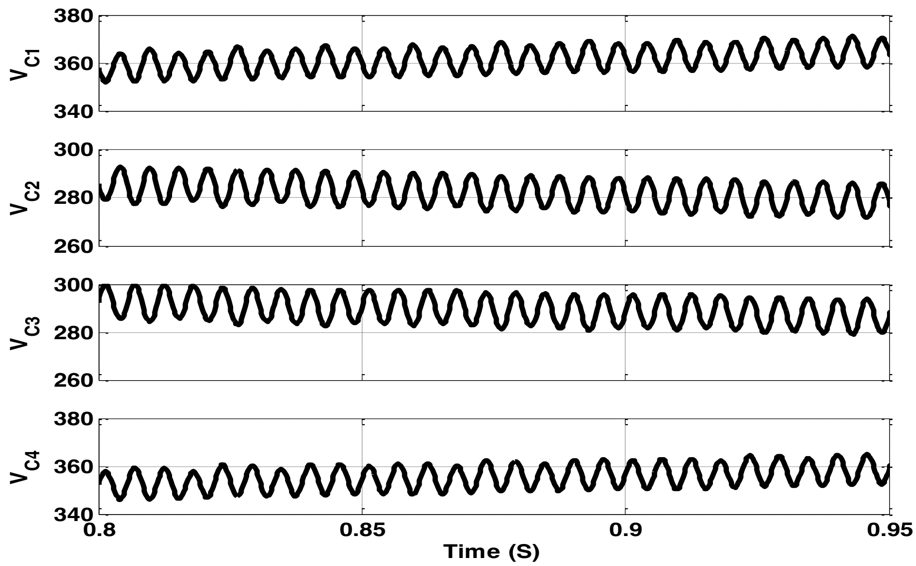

Figure 9 the individual capacitor voltage (in volts)

Since the main objective of the NPC converter is to inject active and reactive power, figure 10 shows these powers. The onset of the power injected is at $t = 0.3334\,sec$ which corresponds to 20 cycles of the nominal 60 Hz. Both active and reactive powers reach steady state at around $t \approx$

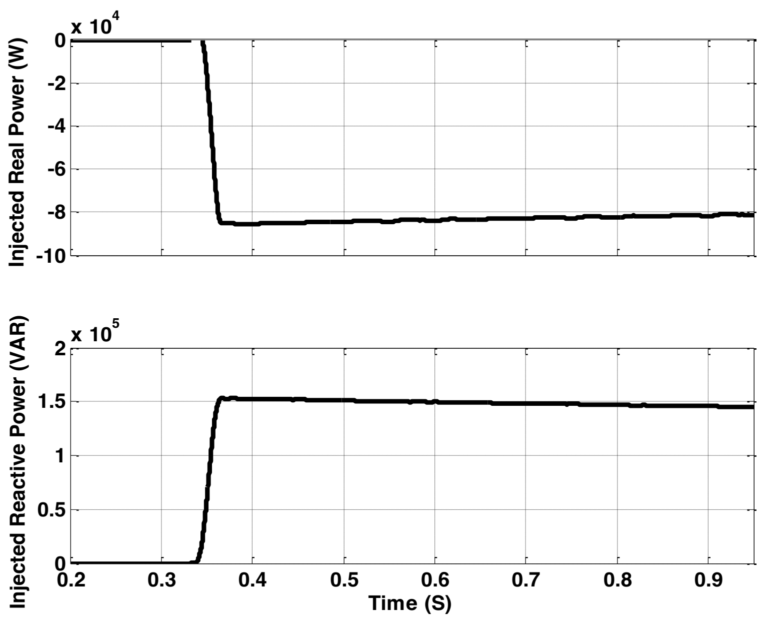

Figure 10 real and reactive powers injected into the grid from the five level NPC inverter

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It is worth mentioning that this work is focusing only on the analysis of rectifier-inverter system operation and its characteristics with no power control scheme.

5. Conclusion

The system studied in this work is composed from two converters, which are multiphase/multilevel converters. Results show that the DC voltage produced by the rectifier is almost ripple free with harmonics amplitudes that are insignificant compared to the obtained average component. On the other side, the AC converter shows an output voltage that has high fundamental value with a waveform that highly resembles a sine behavior. One interesting conclusion is that the quality of the AC voltage is highly acceptable even without a balancing mechanism for the capacitors which are clustered at the input terminals of the converter. Therefore, based on the results presented, the system studied in this work can be a potential candidate for many applications that involves power electronics converters especially in power systems where standards must be fulfilled.

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JOURNAL OF UNIVERSITY OF BABYLON

For ENGINEERING SCIENCES (JUBES)

Vol.30, No.3.| 2022

تحليل عاكس ذو نقطة محايده مثبته لخمس مستويات مغذى من مقوم ذو 18 نبضة متعددة الأطوار لتطبيقات الارتباط بالشبكات الكهربائية

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الخلاصة:

تلعب محولات إلكترونيات الطاقة دورًا رئيسيًا في تطبيقات معالجة الطاقة المختلفة. في كثير من الحالات ، تنشأ الحاجة إلى استخدام محولين لتحقيق معالجة الطاقة أو التكييف أو كليهما. في هذا العمل ، تمت دراسة نظام محولين يعتمد على محولين متعدد الأطوار / متعدد المستويات. الهدف الرئيسي هو معالجة طاقة التيار المتناوب من مصدر يمكن أن يكون مصدر طاقة موزع (DER) عن طريق تحويله إلى تيار مستمر قبل حقنه في نظام تيار متردد آخر. يتم استخدام مقوم متعدد الأطوار ذو 18 نبضة للهدف الأول. يتم تحقيق مهمة المعالجة الثانية ، والتي تتضمن تحويل طاقة التيار المستمر إلى التيار المتناوب من خلال محول محايد ذو خمسة مستويات مثبتة (NPC). النتائج المبينة تحقق فوائد المعدل متعدد الأطوار في إنتاج جهد تيار مستمر سلس. ومن جانب أخر ، تتميز NPC ذات المستويات الخمسة بميزة مثيرة للاهتمام وهي ان الجهد الأساسي ذو قيمة عالية.

الكلمات ادالة: المحول المثبت بنقطة محايدة ، الجهد المحقون ،تضمين بعرض النبضة ، مصدر الطاقة الموزع.

ISSN: 2616 - 9916 | www.journalofbabylon.com | Journal.eng@uobabylon.edu.iq | info@journalofbabylon.com