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Five-level Cascaded H-Bridge Inverter with Predictive Current Control

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Abstract:

This paper presents different kinds of grid-tied cascade H-bridge inverter and has a look to predictive current control technique. Finally the simulation result will show a Model predictive current control of a five-level cascaded H-bridge (CHB) inverter indifferent sampling times by using MATLAB Simulink software. And this Model Predictive current controller (MPC) for the five-level CHB inverter times has been created to display Total Harmonic Distortion (THD) level of the load and reference current pursuing for a step change with different sampling frequencies.

Keywords: Cascaded H-bridge, CHB, multilevel inverter, predictive current control, total harmonic distortion, THD.

1. INTRODUCTION

As we know nowadays using renewable energy sources is increasing, hence we should find the best way to transfer it to the power grid. One of the most important renewable energy sources is the energy from the sun or also we can call it solar energy. Photovoltaics (PV) is a system to convert energy from the sun into electrical energy.

We need to convert the DC power from the photovoltaic to the AC source. Therefore the conversion of DC power from the photovoltaic module to the AC source allows the system to connect to the existing power grid which is one of the major parts of the PV system. And this conversion will be happened by one type of power electronic devices called the inverter [1].

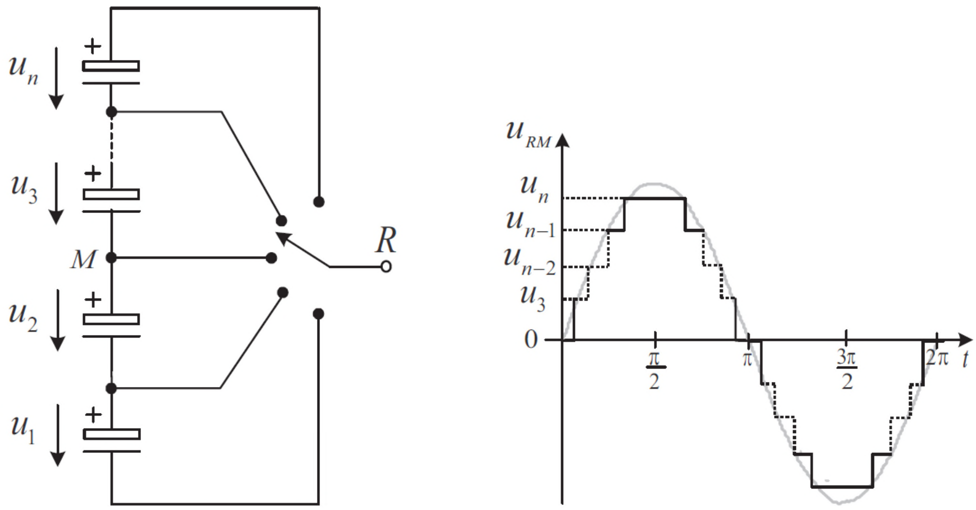
According to the topology, we can see different types of PV inverters. However, there are not lots of experiments with regard to the alternative inverter topologies [1]. At the present time, full-bridge (H-bridge) voltage source inverters are the most widely used topology in Industry [2]. This paper describes the cascade H-bridge inverter which can be used for photovoltaic applications.

2. Multilevel Inverters

In the last decades, using multilevel power converters have been increased because they were picked up as a choice in many high voltage and high power applications, as a result of the benefits in high quality waveforms, low switching losses, high voltage capability and low electromagnetic compatibility (EMC) concerns [3], [4].

Combining several levels of voltage and making a sinusoidal voltage is the general idea of multilevel converters. By increasing in number of levels, the synthesized output waveform adds more steps, producing a set of wave steps which access the sinusoidal wave with minimum harmonic distortion [5]. For example, the generalized n-level inverter (Fig. 1(a)) is able to switch among n voltage levels (Fig. 1(b)).

Although there will exist various kinds of multilevel topologies, usually are classified into four main groups, each having a unique topological layout. The four types are prevalently referred to as diode-clamped, flying capacitor, cascaded H-bridge and hybrid multilevel inverters.



(a) n-level

(b) n-level Voltage

Fig. 1: Simplified circuit(a) and generated output voltage(b) of a n-level converter.

3. Cascaded H-bridge

The Cascaded H-Bridge Inverter first introduced in 1990 to stabilize plasma. This was a basic idea for series connection between the single phase H-Bridge inverters and the multiple isolated DC supplies to make multilevel waveforms [6]. In other words**,** the topology is established in relation with the series of n individual cells, comprise of a single-phase H-bridge inverter with a dedicated DC source. In general, cascade converter with n-full-bridge inverter cells can synthesize m voltage levels at the output voltage of each phase structure. For instance, in a five-level cascaded inverter there are two individual cells, each one containing the own H-bridge inverter and isolated DC source [7].

The number of output phase voltage levels m is defined by:

$$m = (2n + 1) \tag{1}$$

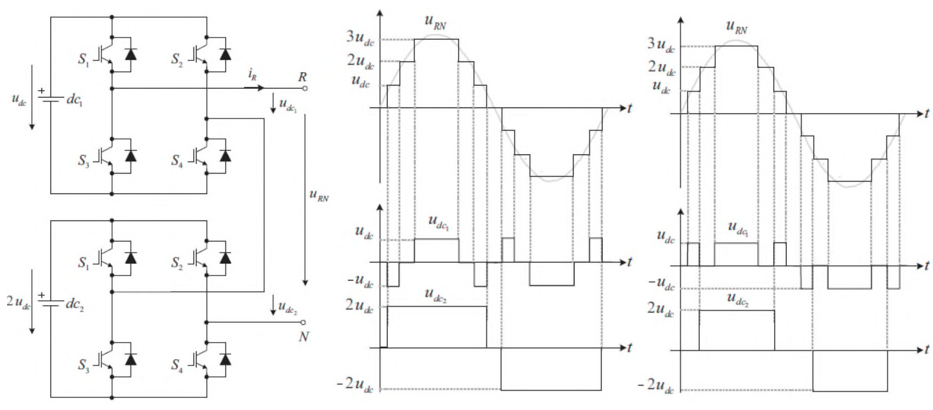
Where n is the number of separated DC sources.

4. Asymmetric Cascaded H-bridge

In cascaded H-bridge inverters if there is at least one DC voltage source used different from the others, this kind of multilevel topology is mentioned as Asymmetric Multilevel Inverters [8]. So it is possible to increase voltage levels at the output of the cascade inverter by the same number of DC power supplies to reduce THD of the output voltage. Hence we only need to use unequal DC voltage sources [9]. The number of output voltage levels can increase to:

$$m = (2^{n+1} - 1) \tag{2}$$

Each H-bridge inverter can create positive, negative or zero voltage at its output with a magnitude equals to the DC voltage source. Therefore there are 7 possible combinations for the cascade H-bridge inverter with 2 separated DC sources (Fig. 2 (a)). Essentially, based on the combination of the H-bridge inverters output voltages, a seven-level output waveform can be performed using two separate switching models (Fig. 2 (b) and (c)). The output voltageu_{dc1} can be equaled to $+u_{dc1}$, 0 and $-u_{dc1}$, and the output voltage u_{dc2} can be supposed equal to $+2u_{dc2}$, 0 and $-2u_{dc2}$. Hence, the sum of the two cascaded inverters output voltages ($u_{RN} = u_{dc1} + u_{dc2}$) can be presented by seven different output voltage levels: $\pm 3u_{dc}$, $\pm 2u_{dc}$, $\pm u_{dc}$ and 0.



(a) Asymmetric cascaded H-bridge (b) Switching states 1 (c) Switching states 2

Fig. 2: Asymmetric cascaded H-bridge (a) topology, (b) switching states 1 and (c) switching states 2.

5. Current Control Techniques

If we suppose a DC/DC converter acts as a voltage source at the inverter input, therefore it must be a voltage source inverter (VSI). According to vary in the manner to control the power flow, there are two principal control strategies for voltage source inverter: the voltage control (VCVSI) and the current control (CCVSI). Controlling the power flow in the CCVSI is in accord with the decoupling inductor current, and the VCVSI regulates the power flow by the control of the decoupling inductor voltage. Notwithstanding the CCVSI is faster and it can control active and reactive power flows independently, it cannot prepare the voltage prop to the load and manage it without the grid. Also based on a comparison between the VCVSI and the CCVSI, the CCVSI has a limited short circuit current and it can be used as a power factor correction [2]. The current control plays one of the most important roles among the multiple functions of the grid connected systems, so the current control strategy has to accomplish basic requirements, such as low harmonic distortion of the output current, high dynamic response, regulation of the DC-link voltage and, in a number of cases, providing bi-directional power flow [9]. Frequently modulating inverter output voltage is obtained depending upon the comparison of the actual measured current $i_{g,i}$ to the desired reference $i_{g,i,ref}$ (Fig. 3).

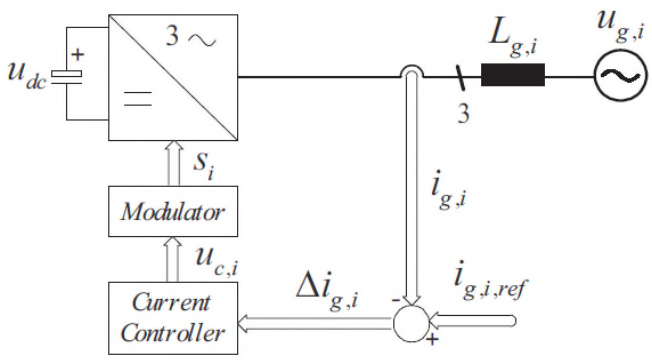


Fig. 3: Basic current control system.

6. Predictive Current Controllers

In a conceptual manner, the Model Predictive current control is a new access to the non-linear current control in three-phase inverters. The predictive control regulates the inverter's output current and voltage with high dynamics and there is no need to face the problem of non-linear nature of the semiconductor power converters. The creation of some limited numbers of voltage levels at the cascade H-bridge inverter’s output is the fundamental doctrine of using the predictive control technique [10].

The changeable concern is the current supplied to the grid I. This current will be affected by the inverter voltage V. The goal is to predict the behavior of the load current I for each possible voltage vector generated by the inverter. The system shown in Fig. 4 can be described by:

$$v = Ri + L\frac{di}{dt} + e \tag{3}$$

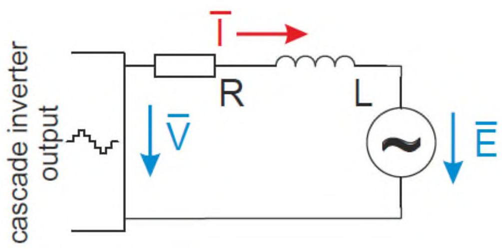


Fig. 4: The L filter between the inverter output and the grid used to decouple the output voltage and the grid and to filter higher harmonics

The derivative in (3) can be replaced by its discrete approximation (T_s is the sampling time):

$$\frac{di}{dt} \approx \frac{i(k+1) - i(k)}{T_s} \tag{4}$$

By replacing (4) in (3), the discrete model of the system is obtained:

$$v(k) = Ri(k) + L\frac{i(k+1) - i(k)}{T_s} + e(k) \tag{5}$$

From (5), the future value of the load current predicted form the model of thy system is:

$$i(k+1) = \frac{T_s}{L}\big(v(k) - e(k)\big) + i(k)(1 - \frac{RT_s}{L}) \tag{6}$$

For the trajectory based predictive control, there is a need to create the trajectory which will be followed by the controlled variable. Anyway, the future value of the reference current $i^*(k+1)$ is unknown. In order to define the next value of the reference current, we apply Lagrange quadratic extrapolation which uses Lagrange polynomials that are polynomials of the least degree assumed as the corresponding value of the function at each point [2].

A possible solution is to calculate the one-step-ahead prediction using the actual current reference in the nth-order formula of the Lagrange extrapolation by:

$$i^*(k+1) = \sum_{l=0}^{n}(-1)^{n-1}\binom{n+1}{l} i^*(k+1-n) \tag{7}$$

For sinusoidal references, n = 2 or higher is recommended [11].

Using this extrapolation formula, the future reference $i^*(k+1)$ can be predicted, for n = 2, with:

$$i^*(k+1) = 3i^*(k) - 3i^*(k-1) + i^*(k-2) \tag{8}$$

For predictive control, we need to determine the cost function which will be appraised in each sampling time and will clarify the behavior of the system. It can be chosen in a way that it can minimize the switching frequency or the higher order harmonics. The function can be chosen as a filter to remove certain harmonics and so on [2].

$$g = \left| i^*(k+1) - i(k+1) \right| \tag{9}$$

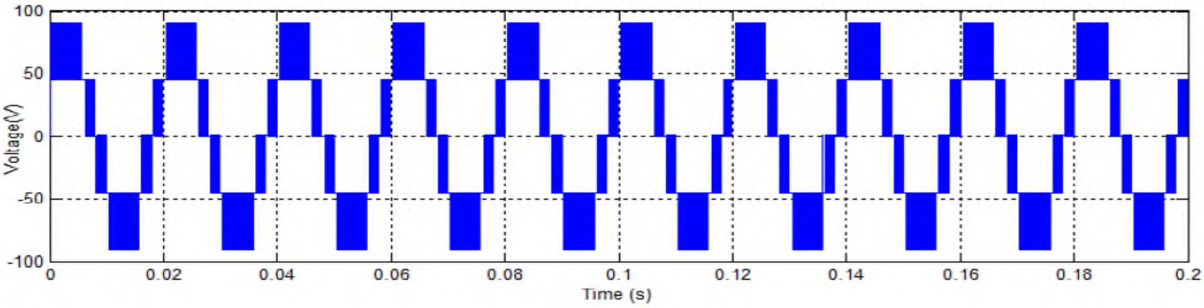
7. Simulation Results

The submitted controller was at fist simulated in MATALB/Simulink. Hence we will use the MATLAB/Simulink software to perform the simulation of the model predictive current control of the CHB inverter with different sampling times. The simulation parameters are shown in table 1. The input DC voltage is the same for all cells. The *RL* load is used as a load for the simulation results [12].

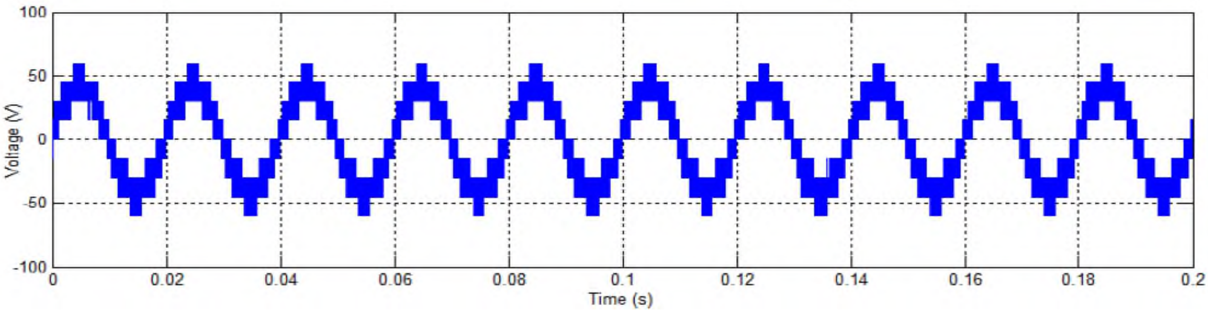
Table l: Simulation parameters

Parameters	Values
Input voltage (Vdc)	45 V
Load resistance (R)	47 Ω
Load inductance (L)	15 mH
Reference current	0.95 A

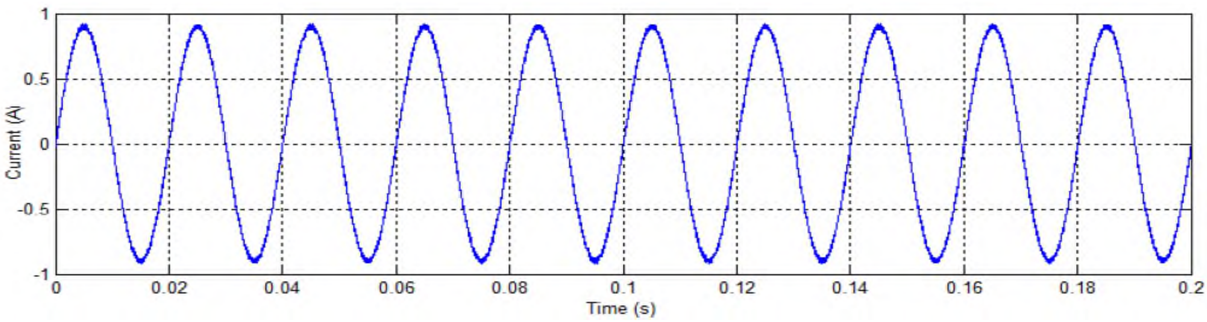
Fig. 5, 6 and 7 illustrate the inverter phase to neutral voltage, load voltage and load current waveforms with sampling times of 25µs, 100µs and 200µs, respectively.



(a)

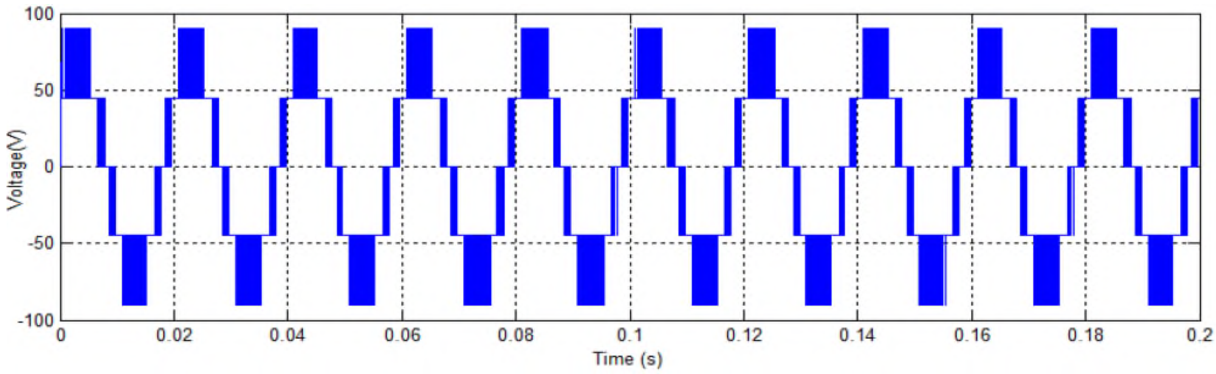


(b)

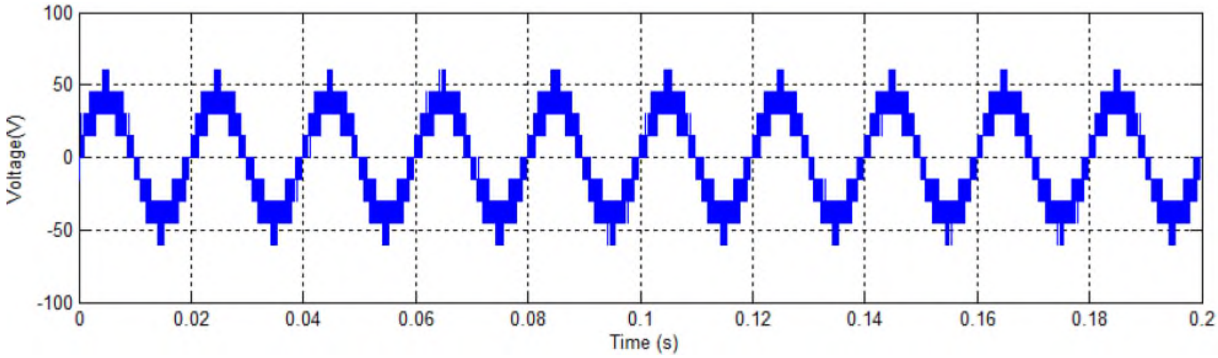


(c)

Fig. 5: (a) Inverter Phase to Neutral Voltage, (b) Load Voltage and (c) Load Current Waveforms for Predictive controller with sampling frequency of 25µs



(a)



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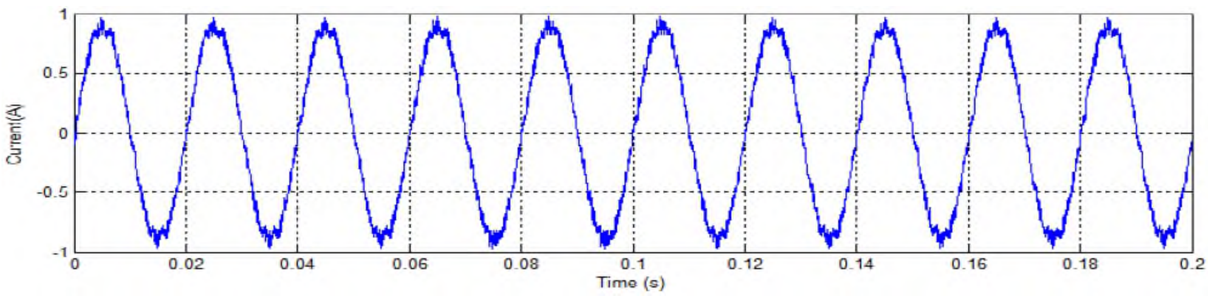
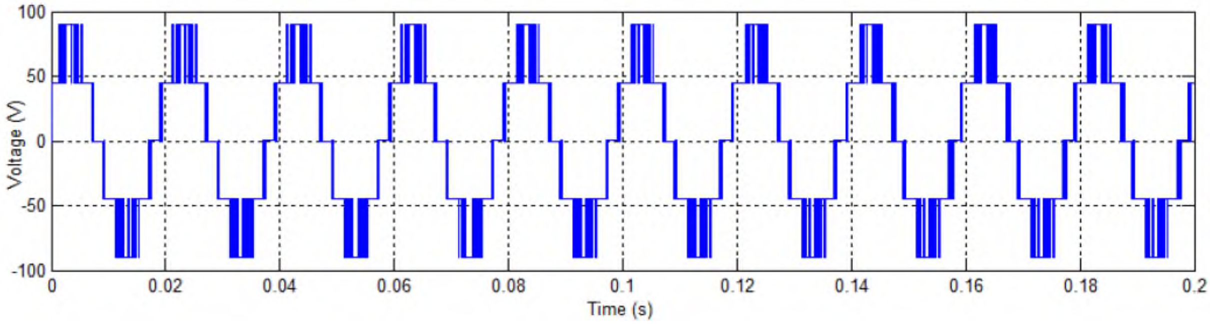
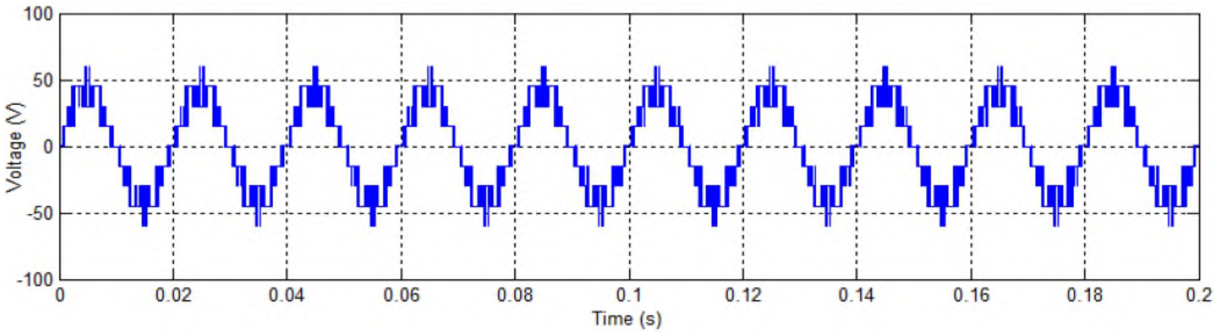


(c)

Fig. 6: (a) Inverter Phase to Neutral Voltage, (b) Load Voltage and (c) Load Current Waveforms for Predictive controller with sampling frequency of 100µs



(a)



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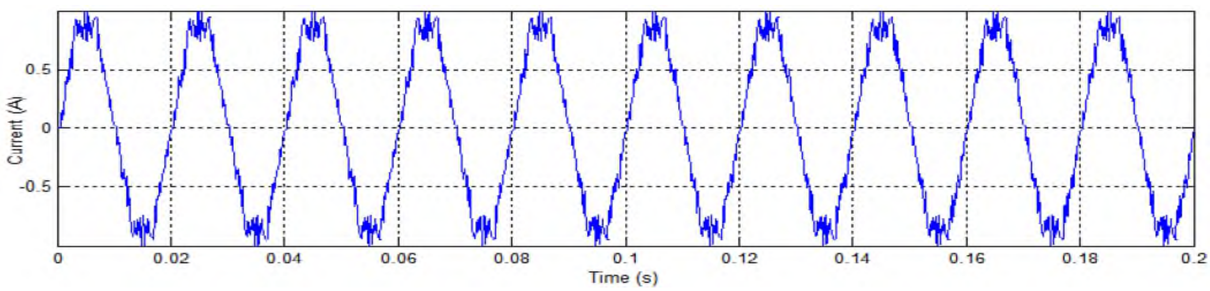
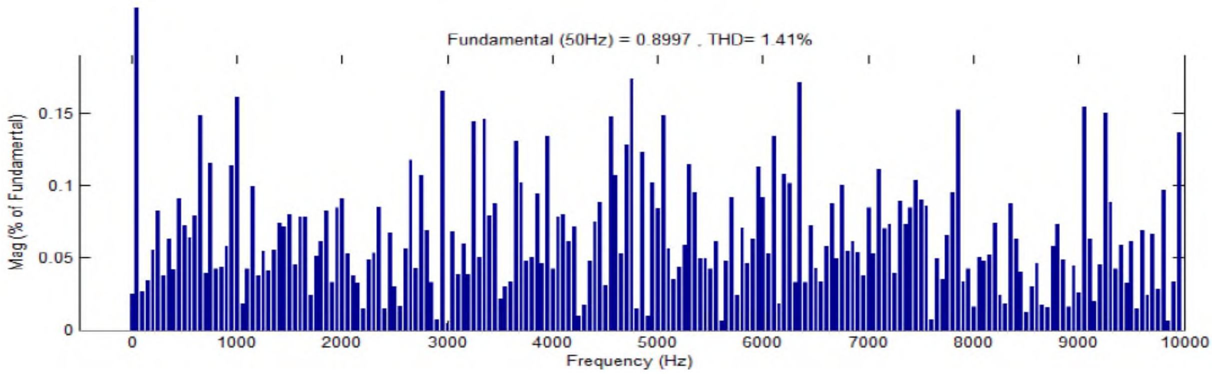


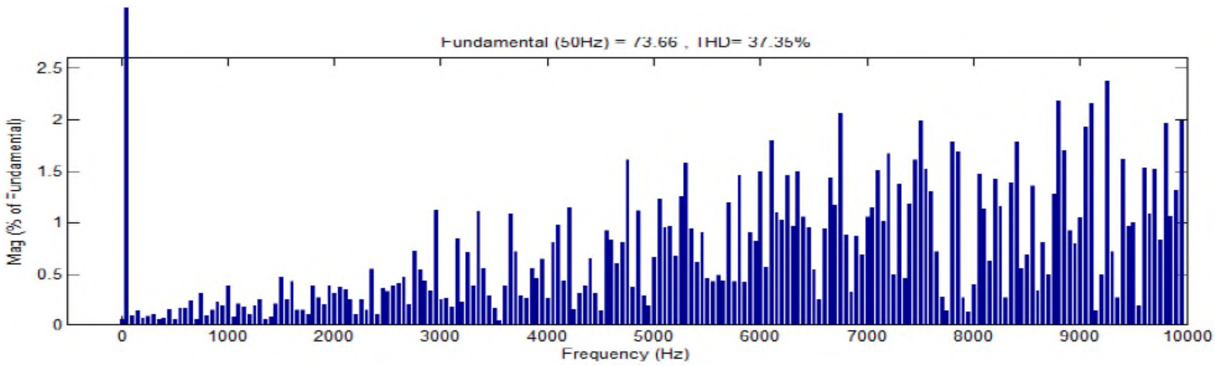
(c)

Fig. 7: (a) Inverter Phase to Neutral Voltage, (b) Load Voltage and (c) Load Current Waveforms for Predictive controller with sampling frequency of 200µs

Fig. 8, 9 and 10 disclose the harmonic spectrum for load current and inverter voltage with sampling times of 25µs, 100µs and 200µs, respectively.

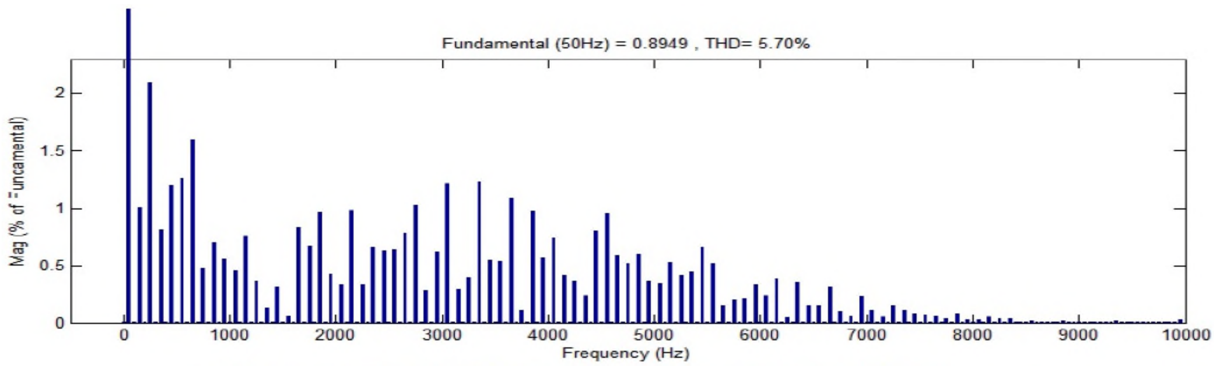


(a)

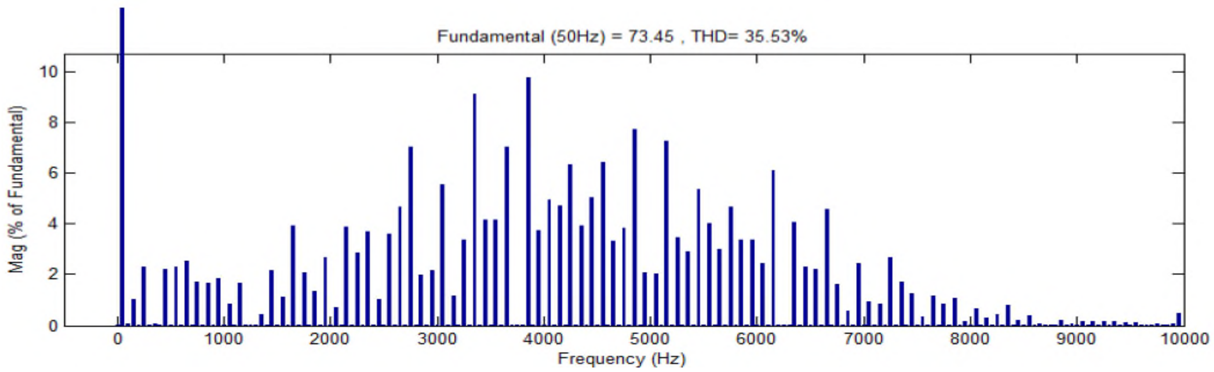


(b)

Fig. 8: (a) Harmonic spectrum for Load Current, (b) Harmonic spectrum for inverter voltage with a sampling time of 25µs

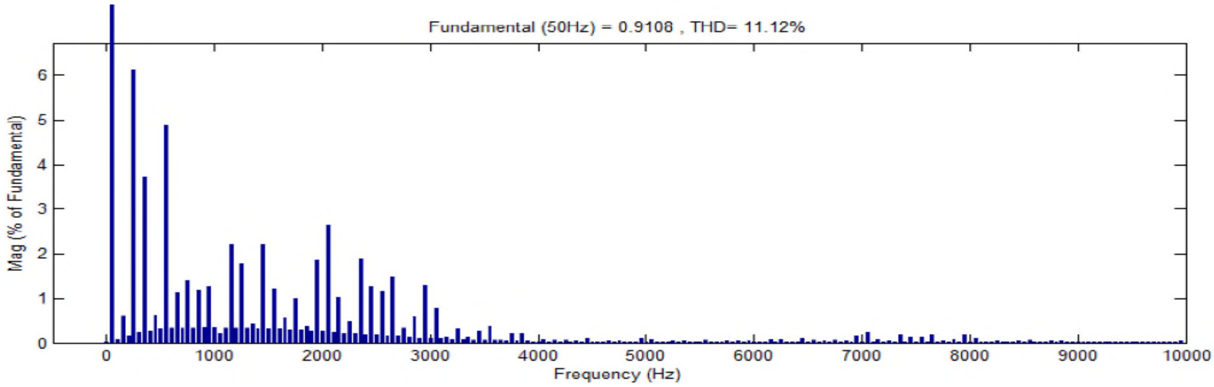


(a)

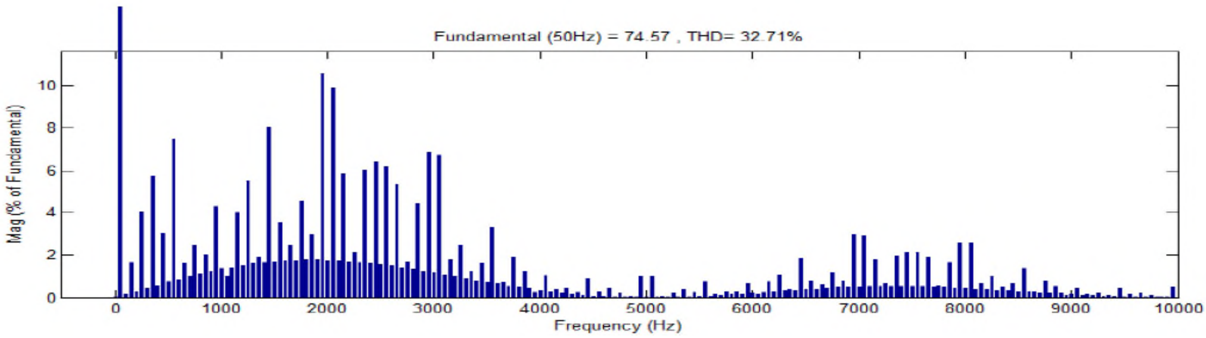


(b)

Fig. 9: (a) Harmonic spectrum for Load Current, (b) Harmonic spectrum for inverter voltage with a sampling time of 100µs



(a)



(b)

Fig. 10: (a) Harmonic spectrum for Load Current, (b) Harmonic spectrum for inverter voltage with a sampling time of 200μs

The load current THD and the inverter voltage THD are observed to determine the various values of the sampling times, and are shown in table 2. The harmonic spectrum of load current and inverter voltage waveforms are analyzed by using the Fast Fourier Transform (FFT). It is remarked that the voltage THD progressively reduces with augment in the sampling time and the current THD raises with increasing in the sampling time [12].

Table 2: Load Current THD and Inverter Voltage THD for different sampling times

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Sampling Times	Current THD	Voltage THD
25µs	1.41%	37.35%
50 µs	2.95%	36.88%
75 µs	4.15%	36.61%
100 µs	5.70%	35.53%
125 µs	6.49%	35.33%
150 µs	7.62%	34.38%
175 µs	9.84%	33.52%
200 µs	11.12%	32.71%

Therefore the sampling time has a significant impact on the ripple of the current and the switching frequency of the CHB inverter. So we need to find an optimal value in this case.

8. Conclusions

In this paper, we surveyed different kinds of the Cascaded H-bridge and presented a Predictive Current Control of Grid-tied Cascade H bridge Inverters without PLL and PWM. The model predictive current control of a Five-level CHB inverter with RL load for different values of the sampling times has been shown. It is supervised the current and voltage harmonic spectrum for various sampling times as well. Finally, there is a major separation between the fundamental and switching harmonics achieved by using a smaller sampling time. And it will improve the overall performance of the model predictive current controller.

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