Palestine Polytechnic University

College of Engineering

Electrical Engineering Department

Model Predictive Current Control with Duty Ratio Optimization for Three Phase Grid Tie Micro Inverter Based on Runge Kutta Approximation

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Submitted to the College of Engineering

in partial fulfillment of the requirements for the degree of

Bachelor degree in Electrical Engineering

Palestine Polytechnic University

Hebron, Palestine

2nd Jun, 2021

Abstract

In conventional model predictive current (MPCC) only one voltage vector is chosen and applied through one control cycle by using the discrete time system model. The selection of the voltage vector is based on minimizing a cost function. However, due to the restricted number of switching states which produced by three phase micro inverters, this will produce high current harmonics and limit the steady state performance. To enhance the effectiveness of the conventional MPCC, this research proposed an improved MPCC with duty ratio optimization for three phase grid tie micro inverter. The proposed strategy divides the one control period into two sub periods for two voltage vectors. This strategy uses the current error minimization principle to obtain the duration of the chosen voltage vectors. The simulation results prove the performance of the proposed MPCC in obtaining better steady state performance and reducing the total harmonic distortion of current to 0.77%.

الملخص

في طريقة MPCC التقليدية يتم اختيار متجه جهد واحد فقط ويطبق خلال دورة تحكم واحدة ويحدث هذا باستخدام نموذج النظام الزمني المنفصل ، وتعتمد طريقة اختيار متجه الجهد على تقليل دالة التكلفة (Cost Function) . ومع ذلك نظرًا للعدد المحدود من حالات التبديل التي تنتجها المحولات الصغيرة ثلاثية الطور فإن هذا سينتج توافقيات تيار عالية ، ويحد من أداء الحالة المستقرة ، ولتعزيز فعالية MPCC التقليدية اقترح هذه البحث تحسين لطريقة MPCC مع تحسين نسبة العمل لعاكس صغير متصل مع شبكة ثلاثية الطور، و تقسم الإستراتيجية المقترحة فترة التحكم الواحدة إلى فترتين فرعيتين لمتجهين للجهد. تستخدم هذه الإستراتيجية مبدأ تقليل الخطأ للتيار للحصول على مدة متجهات الجهود المختارة ، وقد أثبتت نتائج المحاكاة لأداء MPCC المقترح في الحصول على أداء أفضل للحالة المستقرة وتقليل التشوه التوافقي الكلي للتيار إلى 0.77٪.

Acknowledgements

To Allah, thank you for the opportunity and ability you have given me, and how you have always strengthened me during my hardest times. I give you all the thanks and glory.

To our supervisor, Professor Sameer Hana. Thank you for your patience, understanding, guidance and the sharing of your knowledge during this thesis. We would not have had the opportunity to do a Bachelor's degree without your support.

To all our teachers at Palestine Polytechnic University, thank you for your scientific and educational support, and for sharing your knowledge during the study phase.

Our parents, you have always given a hundred-and-ten per cent of yourselves to your children. We realize now how much you have sacrificed so that we can grow and excel. Thank you very much for your generous support and prayers. We would not have had the opportunity to do anything without your support.

Thanks to all of our families and friends who kept us in their prayers and provided support and understanding.

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Chapter 1

Introduction

1.1 Background

Recently, The Photovoltaic (PV) micro inverter has become the future trend of the development of PV system due to its advantages such as converting the PV DC voltage directly into AC signal, increasing energy production by implementing MPPT for each PV panel, simple installation and design and enhance the scalability of the PV system [1].

The classical approach for the micro inverter is single-phase which can be used in small size applications such as residential applications. In order to extend the usage of micro inverter to large size applications, there is a need to modify the classical approach to be three-phase with high efficiency [1].

There are many control techniques can be used to improve the efficiency and current harmonic control for PV converters such as the model predictive current control (MPCC) which has classified as promising technique in enhancing current control and efficiency. This is because its advantages such as simple concept, easy to control different variables, precise control ability and good dynamic performance. The MPCC with duty ratio optimization can be implemented by several techniques such as Forward Euler and Runge Kutta approximation [2-4].

1.2 Literature Review

There are several studies that have addressed the topic of the MPCC, among the most recent are the following:

• Jose R. and Patricio C., showed in their book the concept and principle of the MPCC method and how to implement it for three phase inverters [5].

• Ricardo PG., Marco R., Nicolas V. and Patrick W., published experimental results which verify the performance of the MPCC in improving the quality of the output power of three-phase inverter [6].

• Shahrouz E., Qihong C. and Liyan Z., published a detailed analysis about how to implement the MPCC with duty cycle optimization for a three-phase inverter based on Forward Euler approximation [7].

• Patricio C., Gabriel O., Juan Y., Jose R., Sergio V. and Leopoldo F., published a detailed analysis about the implementation of the MPCC for three-phase inverter with output LC filter for UPS applications [8].

• Jingang H., Zhiyuan M. and Dongkai P., published a detailed analysis about the MPCC for voltage source inverter with experimental results allowed to show the good performances of the current tracking ability in both steady and transient state [9].

1.3 Research Statement

This research proposed a MPCC with duty ratio optimization method based on the Runge Kutta approximation, to study its effectiveness in improving efficiency and reducing current harmonics for three phase grid tie micro inverter with output LCL filter.

1.4 Research Objectives

This research aimed to achieve the main objective which provides a specific detailed analysis and mathematical modeling of the MPCC with duty ratio optimization of three phase grid tie micro inverter using Runge Kutta approximation. In addition to optimization procedure.

This research also aimed to achieve the following sub-objectives:

- Designing a three-phase grid tie micro-inverter with efficiency over 90%.
- Reducing current THD to be less than 3%.

1.5 Research Motivation

The PV micro inverter has become widely used in many countries of the world due to its many advantages. Hence, there is a need to enhance its efficiency. There are several control methods to make this, including the MPCC method which has been classified as one of the best techniques in reducing switching losses and controlling current harmonics. [10-11].

Therefore, this research proposed the implementation of the MPCC for The PV micro inverters. In order to open a new era of micro inverters and increase the reliability of PV system in Palestine.

1.6 Research Importance

- Improve energy harvesting.
- Opening new aspects for micro inverter utilization in Palestine.
- Increase the reliability of PV system.
- Increase the efficiency of three phase grid tie the micro-inverter.

1.7 Research Methodology

- Understanding the Concept of the MPCC.
- Building a mathematical module of the MPPC with duty ratio optimization of three phase grid tie micro inverter using Runge Kutta approximation by using Matlab-Simulink software.
- Conduct the required simulator process.
- Optimization and data processing.

1.8 Brief Overview of The Research

Chapter 2 The components of the system, which are: PV panel, MPPT controller, DC to DC converters (Buck-Boost chopper), and DC to AC converter (Three phase grid tie micro-inverter), are presented in order to provide the main concepts and theory involved in the thesis.

Chapter 3 The model predictive current control with duty ratio optimization based on Runge Kutta approximation are presented with all explanation of the concept and principles.

Chapter 4 Implementation and Simulation of the system are presented using Matlab-Simulink software. Then the results, which are found out, are analyzed and compered. After that, future works are suggested.

1.9 Summary

This chapter discussed the theoretical side of the research in which the importance of micro-inverter was explained and how to improve the quality of output power produced from it, by using the MPCC method. This chapter also discussed some previous studies that dealt with the use of the MPCC. This research focused on one main objective which is providing a detailed analysis and mathematical modeling of MPCC with duty ratio optimization for three phase grid tie micro inverter using Runge Kutta approximation. The following results are expected to be obtained: designing a three-phase grid tie micro-inverter with efficiency over 90% and reducing current THD to be less than 3%.

Chapter 2

The System Components

2.1 Introduction

The fundamental part of the PV system is solar cell which acts as a DC source. The difference between the solar cell and the DC source is that the output power produced by the solar cell changes by changing the environmental changes as well as based on its characteristics. Hence, the solar cell must operate at the maximum power point (MPP) during operation to ensure that it produces its maximum power. To implement this, there is a technique called maximum power point tracking (MPPT) and it can be performed using several methods such as: perturb and observe method and incremental conductance method [12].

DC/DC converters at a module level can convert each module from a current source into a power source thus allowing each module to deliver its maximum power to the load despite any mismatches in the system. There are several topologies and algorithms available to achieve this. The most common topologies are: buck, boost and buck-boost [13].

To convert the DC power produced by the PV system, DC/AC converters can be used. There are several topologies and types available to achieve this. The two most common topologies are: voltage source inverter (VSI) and current source inverter (CSI). They can be classified as single phase and three phase inverters with different ranges of output power. In recent times, the power converters used in the PV systems have undergone great development, and this has led to the innovation of DC/AC inverter, with output power ranging from (300-1000) watts which is called micro-inverter [10].

2.2 Solar Cell and Module

The solar cell is a p-n semiconductor junction fabricated in a thin layer of semiconductor. When photons with energy greater than the band gap energy hits it, electrons are knocked loose from the atoms creating an electron-hole pair. The internal electric fields of the p-n junction lead these carries to swept apart which will produce a DC current proportional to causative radiation. In the dark, the solar cell works as diode. It creates neither a voltage nor a current.

The ideal solar cell can be modeled by a current source in parallel with a diode as shown in figure (2.1). A series and shunt resistance component are added to the module because an ideal solar cell does not exist [4].

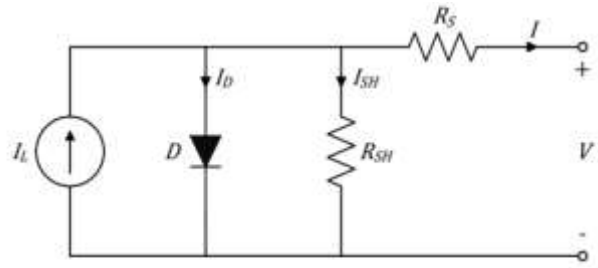


Figure 2.1: The equivalent circuit of a solar cell.

The solar cell does not produce enough power to do much work as its power is usually in watts. In order to gain the desired output power, the solar cells can be connected in series and/or parallel. The PV Module is combination of two or more solar cells in parallel or in series to give a desired output voltage, current and power [4].

2.3 MPPT Technique

The output power of the module changes along with environmental changes as temperature and solar irradiation. To ensure a module produce its maximum power, the maximum power point (MPP) must be kept during operation. A technique is performed for solar module to track the MPP is called maximum power point tracking (MPPT).

The principle of the MPPT technique is matching load impedance with module impedance so the MPPT technique can be considered as impedance matching problem. The two most common of MPPT techniques are: perturb and observe (P&O) and incremental conductance (IC). The P&O is widely used in PV applications due to its advantages such as lesser time to track the MPP, simple implementation and other economic reasons.

It is an algorithm by periodically perturbing the module terminal current and voltage and comparing the output power with that of the pervious perturbation cycle. If the power and operating voltage of the module increase ($dp/dv > 0$), the control system moves the operating point of the module in that direction. If they decrease ($dp/dv < 0$), the control system moves the operating point of the module in the opposite direction. This algorithm continues in the next perturbation cycles in the same way [5]. The flowchart of the P&O algorithm is shown in figure (2.2).

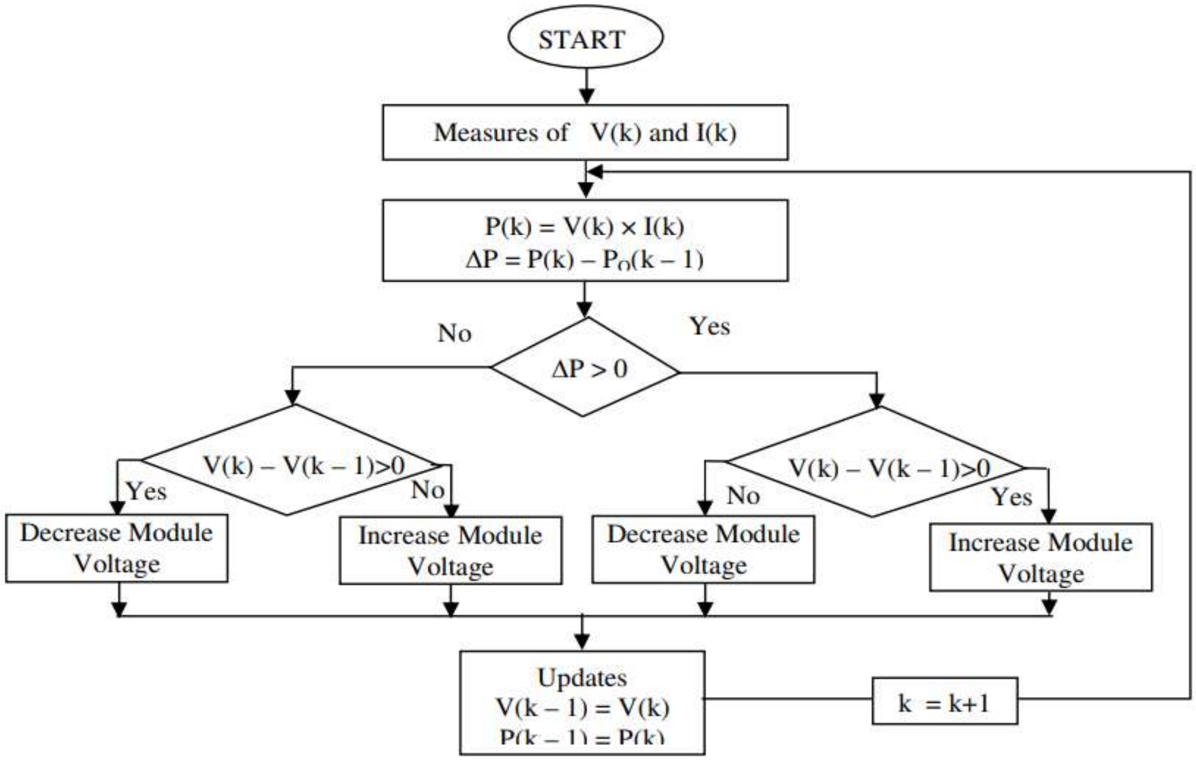


Figure 2.2: The flowchart of P&O algorithm.

2.4 DC-DC Converter

The DC-DC converters is used to convert DC voltage from one form to another. There are three common topologies which are: buck, boost and buck-boost converter. They are widely used in solar photovoltaic system as an interface between the module and load to manage the power delivered to the load. In order to produce maximum PV output power at any circumstances.

It is found that the buck-boost converter is the best choice [14]. The output voltage of buck-boost converter is either greater than or less than the input voltage with reverse polarity. The buck-boost converter circuit consists of four elements as shown in figure (2.3), which are: switch, inductor, diode and capacitor, that combines the principles of the boost and buck converters. It will work as boost converter if the duty ratio is greater than 0.5, otherwise it will work as buck converter [6].

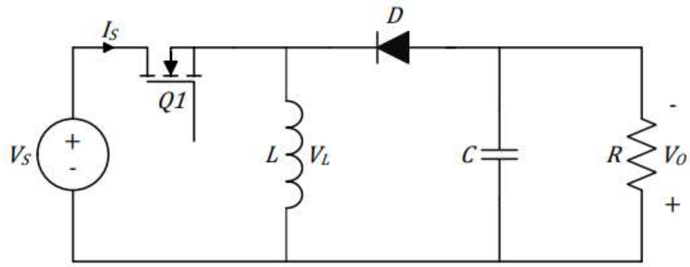


Figure 2.3: Buck-Boost converter circuit.

2.5 DC-AC Converter

The DC-AC converters, is also known as inverters, is used to convert DC power to AC power at grid level. This converter consists of switching devices, thus the switching pattern applied in them gives the desired output. There are many pulse width modulation (PWM) techniques can be used to control it, but the most common PWM techniques are: third harmonic PWM, sinusoidal PWM, space vector PWM [7]. By making comparison between them, SVPWM is the best because it gives less THD, better PF and less switching losses [22].

In solar application, there are two most common topologies which are: single-phase and three phase inverters with various range of output power. The low output power inverter usually in the range of (300-1000) watts is called micro inverter. Recently, it has become the most widely used in PV system due to its advantages as enhanced energy production, friendly ‘plug and play’ operation, simple design and installation and enhanced flexibility and expandability [8].

The classical topologies for micro inverters are mainly in the form of single phase which are used in the residential applications. It would be advantageous to extend the uses of micro inverters to many applications where three phase connections are required [1]. There are many circuit topologies for three phase micro inverters, this research focuses on the standard two-level three phase micro inverter as shown in figure (2.4).

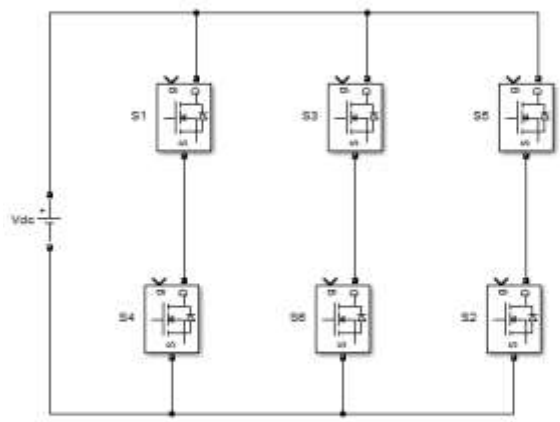


Figure 2.4: The two level three phase micro-inverter.

The three-phase micro inverter is built of six switching devices arranged in the form of three legs. The most common switching devices are MOSFETs and IGBTs switches. In order to avoid short circuiting of the DC input source, the two switches in each leg must operate in a complementary mode. The switching states of the switches can be represented by gating signals, also known as switching signals, S_a, S_b and S_c as follows [9]

$$Sa = \begin{cases} 1 \text{ If S1 on and S4 off} \\ 0 \text{ if S1 off and S4 on} \end{cases}$$

$$\text{Sb} = \begin{cases} 1 \text{ If S3on and S6 off} \\ 0 \text{ if S3 off and S6 on} \end{cases}$$

$$\text{Sc} = \begin{cases} 1 \text{ If S5 on and S2 off} \\ 0 \text{ if S5 off and S2 on} \end{cases} \qquad \textbf{(2.1)}$$

The total number of switching states which can be obtained by all possible combinations of the switching signals is eight. The switching state vector can be defined by

$$\boldsymbol{S} = \frac{2}{3}(\text{Sa}+ \text{ a Sb} + a^2\ Sc) \qquad \textbf{(2.2)}$$

Where **a** = $e^{\frac{j2\pi}{3}} = \frac{-1}{2} + \text{j}\,\frac{\sqrt{3}}{2}$, which represents the 120-phase displacement between the adjacent. The output voltages of three phase micro inverter (V_{aN}, V_{bN} and V_{cN}) can be defined by these gating signals as follow

$$v_{aN} = Sa\ V_{dc}$$

$$v_{bN} = Sb\ V_{dc}$$

$$v_{cN} = Sc\ V_{dc} \quad \textbf{(2.3)}$$

According to (2.2), the output voltage vector of three phase micro inverter can be defined by

$$V = \frac{2}{3}\left(v_{aN} + a\ v_{bN} + a^2\ v_{cN}\right) \quad \textbf{(2.4)}$$

Depending on (2.2) to (2.4), The equation describes the relationship between the switching state vector and the output voltage vector of three phase micro inverter can be defined by

$$V = V_{dc}\,\vec{\boldsymbol{S}} \quad \textbf{(2.5)}$$

In order to reduce total harmonic current distortion (THD_C) of three phase micro inverter, the filters can be used. The three most common topologies of filters are: L, LC and LCL. The LCL filter is found to be the most effective filter in reducing THD_C [10]. This research proposes the two level three phase grid tie micro inverter with output LCL filter.

2.6 Micro-Inverter Protection

The protection techniques are a major factor to increase the micro-inverter reliability. The micro-inverter uses six switches to generate AC voltage from an input-side DC voltage. These switches are switched on and off according to a specific pattern which is applied in them. Hence, they generate the desired voltage which they are designed to produce it during normal operation. If there is any error occurred during the operation, these switches may generate low or over voltage in compered with the desired voltage. Also, in case of grid tie micro inverter, the voltage of grid can be over or low in compered with the normal voltage.

During operation of the micro-inverter, the system may be affected by any disturbance which may lead to damage the system. There are many disturbances may be occurred such as increasing temperature, short circuit and grid outage. Hence, the micro-inverter protection usually include: short circuit, over temperature, anti-islanding, over voltage, low voltage and reverse polarity.

2.7 Summary

This chapter discussed 3 stages of three-phase grid-tie micro-inverter system as follows:

- Stage one: converting solar energy to DC power using solar cells which they can be connected in series or/and parallel, to form a module, in order to achieve the desired voltage and current. The output of PV module changes with environmental changes. In order to increase the PV module efficiency, MPPT can be used to track the MPP. There are several MPPT techniques such as P&O which is most widely used due to its simple implementation and lesser time to track the MPP and also other economic reasons.
- Stage two: converting DC power generated from PV System to the desired DC power by using DC-DC converters. There are three most common topologies are: buck, boost and buck-boost. The buck-boost chopper is found to be the most effective solution in producing maximum PV output power at any circumstances.
- Stage three: converting DC power generated from buck-boost chopper to AC power by using DC-AC converters. There are two most common topologies which are: single phase and three phase inverters. This research proposed three- phase grid tie micro-inverter with output power is around 1000 watts.

Chapter 3

Model Predictive Current Control

3.1 Introduction

The demand for solar energy in Palestine is increasing very rapidly due to growing human population. In recent years, solar energy systems have greatly developed due to the huge technological development that has occurred to power electronics. Hence, photovoltaic (PV) micro inverter becomes most popular for PV system development due to its advantages such as simple design and installation, improved energy harvesting and easy operation. Therefore, it is important to increase the efficiency and reliability of this inverter [1]. To achieve that, MPCC can be applied to optimize the switching pattern applied in micro inverter aiming at decreasing THD_C and switching losses .

Due to its advantages such as easy inclusion of system nonlinearities restriction, good dynamic performance and accurate control capability [4]. The MPCC method uses a discrete time system model to predict the future value of output current. There are many discretization techniques can be applied to obtain it such as Runge Kutta and Forward Euler approximations. It is noticed that, applying Forward Euler approximation gives higher THD_C and more current ripples as compared to Runge Kutta approximation [20]. After the predicted currents are obtained, the MPCC controller applies the optimal switching state which achieves minimal cost function.

This research proposes a MPCC with duty ratio optimization depend on Runge Kutta method, to study its performance in reducing THD_C and enhancing the steady state performance for three phase grid tie micro inverter. The design approach has been divided into four stages which are: convert solar energy generated from solar modules to DC power, then convert DC power generated from PV System to the desired DC power by using buck-boost chopper, after that convert DC power generated from buck-boost chopper to AC power by using three phase grid-tie micro inverter with output power is around (1000 watts), finally build the model of the proposed MPCC in MATLAB/Simulink.

The system block diagram is illustrated in figure (3.1) where components are PV modules, buck boost Dc choppers, three-phase inverters, AC filters, maximum power point tracking module using P& O approach are well known modules and described briefly in chapter 2.

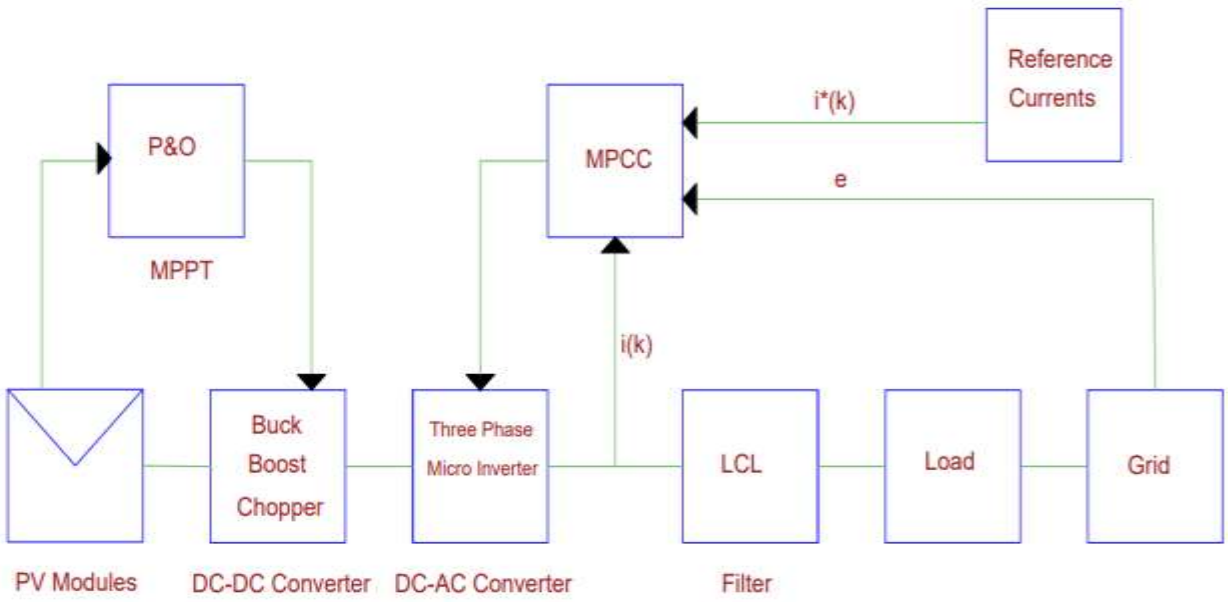


Figure 3.1: The proposed system block diagram of MPCC with duty ratio optimization.

3.2 Mathematical Modeling of MPCC

3.2.1 Principle of MPCC

Basically, MPCC strategy is depended on only eight switching states which can be produced by three phase micro inverters. The output current can be predicted by using the system model for each switching state. This strategy selects the appropriate switching state based on minimizing the cost function. The load current future value will be predicted from measured currents by using the system discrete time model. In this research the discrete time model of the system will be obtained by performed Runge Kutta approximation, as illustrated in figure (3.2).

Refer to fig. (3.3) where three-phase inverter energizing symmetrical resistive load throughout LCL filter, the voltage balance equation is presented in (3.1).

$$V_{an} = L\frac{di_a}{dt} + Ri_a + e_a$$

$$V_{bn} = L\frac{di_b}{dt} + Ri_b + e_b$$

$$V_{cn} = L\frac{di_c}{dt} + Ri_c + e_c \qquad \textbf{(3.1)}$$

where R and $L=L_1+L_2$ are the load resistance and filter inductance, respectively.

Equation (3.1) can be stated in vector form as follows:

$$V = L\frac{di}{dt} + Ri + e \qquad \textbf{(3.2)}$$

where $e = \frac{2}{3}(e_a + ae_b + a^2e_c)$, and $i = \frac{2}{3}(i_a + ai_b + a^2i_c)$ are the voltage and current of the grid, respectively.

According to (3.2), the expression of current of the grid side is a differential equation can be expressed as

$$\frac{di}{dt} = \frac{V - Ri - e}{L} \qquad \textbf{(3.3)}$$

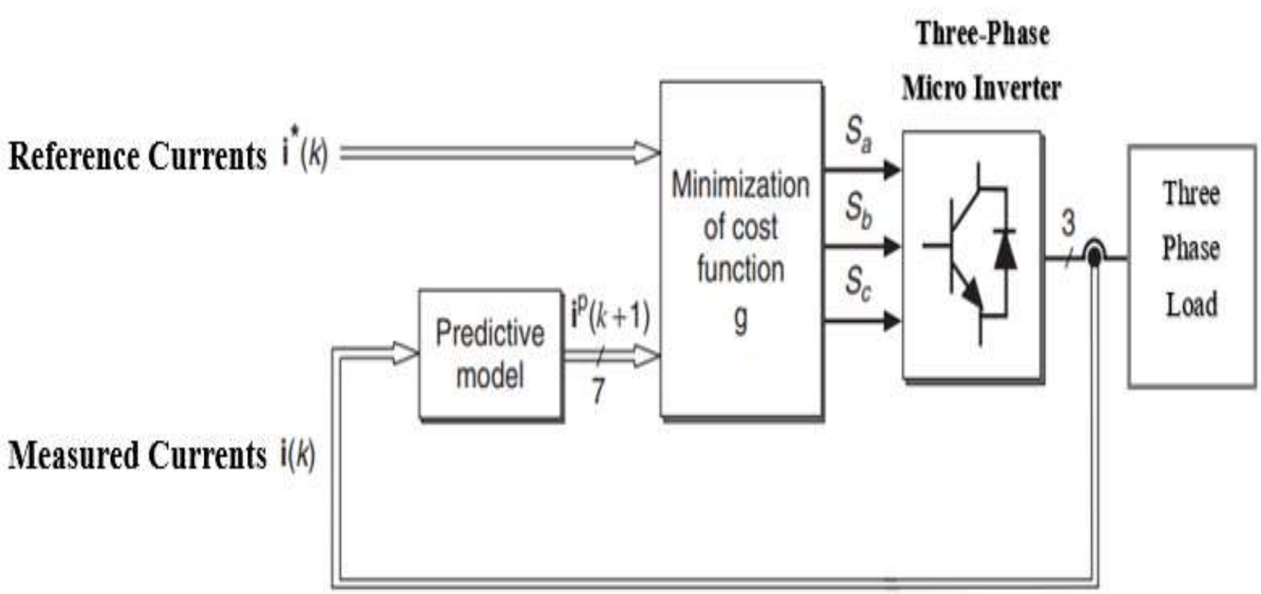


Figure 3.2: MPCC block diagram.

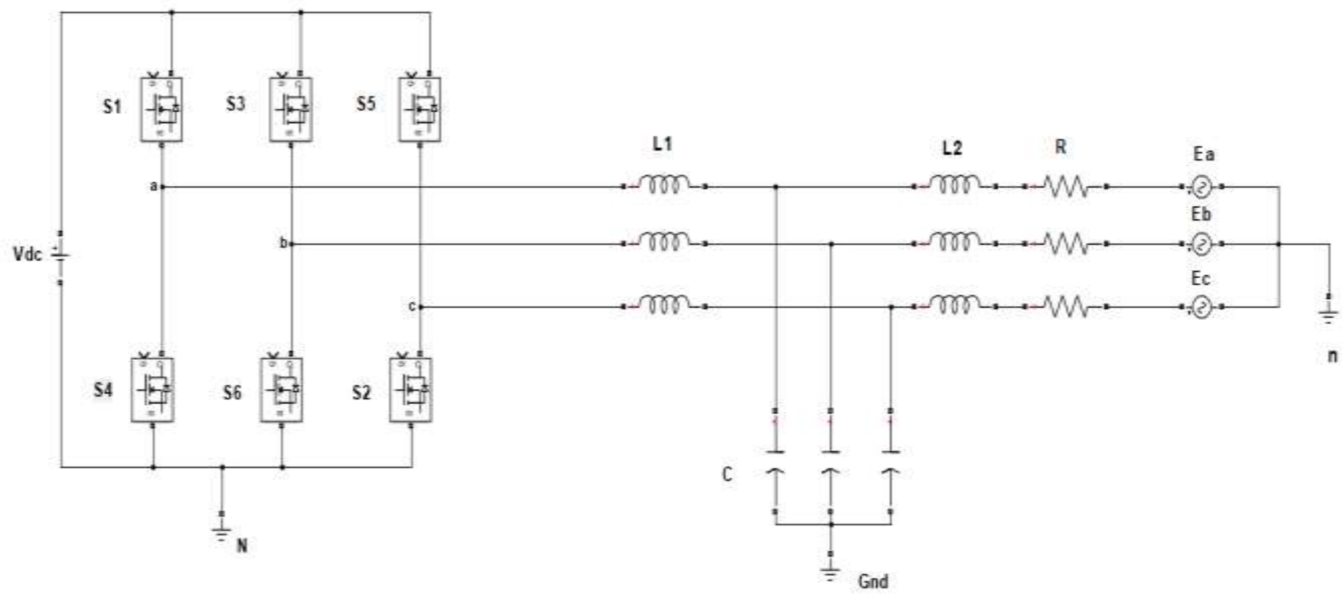


Figure 3.3: Three Phase Grid Tie Micro-Inverter With output LCL Filter.

3.2.2 Discrete Time Model

According to (3.3), the output currents future value will be predicted by using Runge Kutta method at the kth sampling instant. Hence, it can be performed by substituting the system state space representation in discrete time as follows [20]

$$x(k+1) = x(k) + \frac{1}{6} T_{sp}.\ (\dot{x}_o + 2\,\dot{x}_A + 2\,\dot{x}_B + \dot{x}_C) \qquad \textbf{(3.4)}$$

where Tsp is the sampling time and ẋo, ẋA, ẋB and ẋC are the state variables which can be written as

$$\dot{x}_o = \frac{V-e-Ri}{L}$$

$$\dot{x}_A = \frac{V-e-R(\,i+\frac{1}{2}Tsp\ \dot{x}o)}{L}$$

$$\dot{x}_B = \frac{V-e-R(\,i+\frac{1}{2}Tsp\ \dot{x}A)}{L}$$

$$\dot{x}_C = \frac{V-e-R(\,i+Tsp\ \dot{x}B)}{L} \qquad \textbf{(3.5)}$$

Therefore, by performed Runge Kutta approximation, the future output current can be predicted as follows

$$i\,(k+1) = i(k) + \frac{1}{6}\,Tsp\,\left(\frac{V(k)-e(k)-Ri(k)}{L}\right) x\,\left(6 - \frac{3R}{L}Tsp + \frac{R^2}{L^2}Tsp^2 - \frac{R^3}{4L^3}Tsp^3\right) \quad \textbf{(3.6)}$$

In addition to that Forward Euler approximation can be used to predict the future output current as follows

$$i(k+1) = i(k) + \frac{Tsp}{L}\,[\,V(k) - e(k) - Ri(k)] \quad \textbf{(3.7)}$$

3.2.3 Cost Function

Minimizing the error between the reference and measured currents is the objective of MPCC which expressed as cost function. It measures the error absolute value between the predicted and reference currents which can be defined by

$$g = |Re\,[i_{ref} - i\,(k+1)]\,| + |Im\,[i_{ref} - i\,(k+1)]\,| \quad \textbf{(3.8)}$$

where $i_{ref} = \frac{2}{3}\,(ia_{ref} + a\,ib_{ref} + a^2\,ic_{ref})$ and i(k+1) are the reference and predicted current vectors, respectively.

After the calculation of the predicted currents for each switching state, the cost function is calculated. The state, that minimizes it is selected and being applied for the next sampling period [7].

$$Vopt = V\,(\min\,[gn]) \quad \textbf{(3.9)}$$

where n = 0, 1, 2, 3, 4, 5, 6, 7.is the number of vectors.

3.3 Principle of MPCC with Duty Ration Optimization

In classical MPCC, only one voltage vector is picked out and put through one control period. For three phase micro inverters with only eight switching states, this is a cause for increasing current harmonics and voltage ripples and limiting the steady state performance [7]. To enhance the performance of the classical MPCC, this research proposes a new technique which can be used to facing its problems.

The technique is dividing the one control period into two sub periods for a non-zero and an appropriate zero voltage vectors. Hence, MPCC can be applied with this technique to decrease the errors between the reference and measured currents as illustrated in figure (3.4).

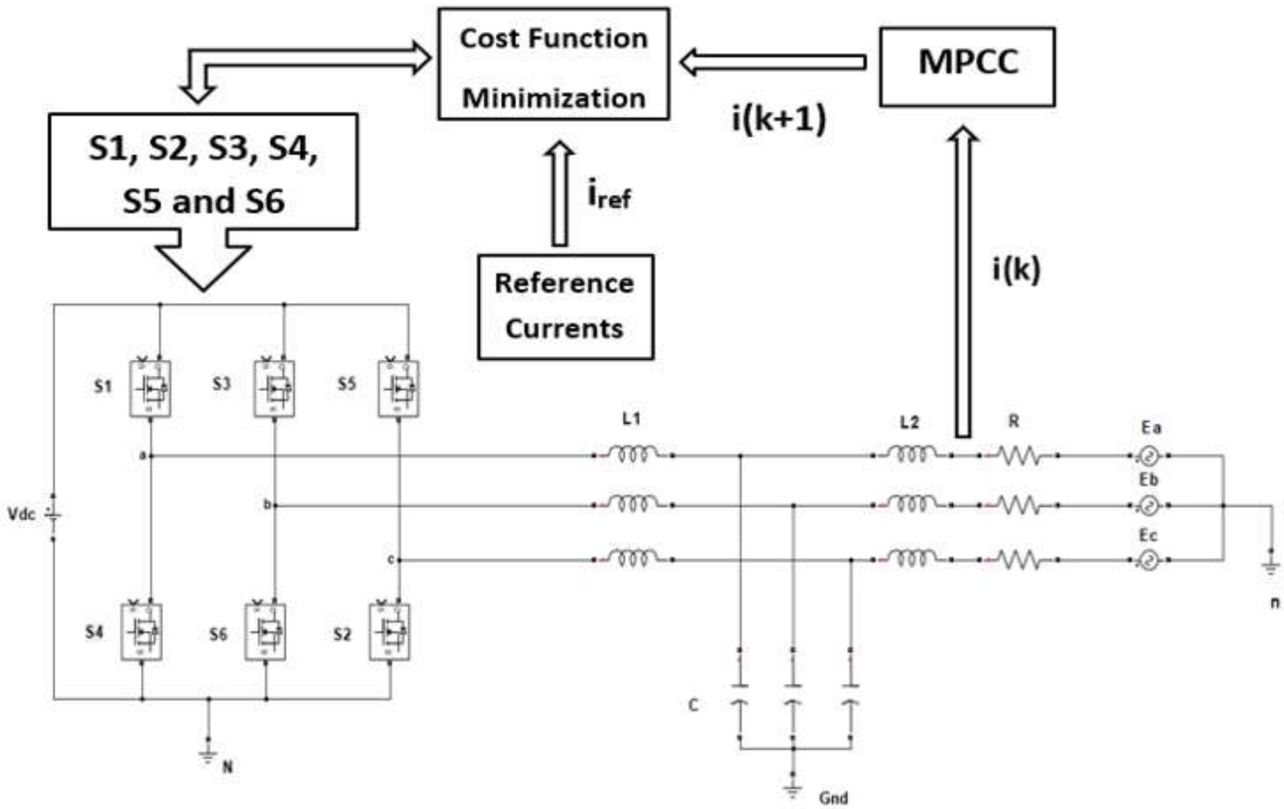


Figure 3.4: MPCC with Duty Ratio and the inverter.

3.3.1 Vector Selection

In the proposed MPCC with duty ratio optimization, two voltage vectors, will be applied during one control cycle. For three phase micro inverters, there are eight voltage vectors: six active and two non-active voltage vectors. Hence, the selection of the non-zero voltage vector is depending on minimizing the cost function to be as close as possible to zero [7].

According to (3.9), the active voltage vector with minimum cost function is with numbers n = 1, 2, 3, 4, 5, and 6. While for selection of the zero-voltage vector, it is selected as one of the two vectors. The selection criterion is decreasing the switching frequency. Therefore, the zero-voltage vector with lowest switching jumps is selected [20],[7], and [23].

3.3.2 Optimal Duty Ratio

The control period duration will be split into two sub durations for the active and zero voltage vectors. According to (3.2), the output current slopes for the active (S1) and non-active (So) voltage vectors can be used to define the duration of the active and zero voltage vectors as follows [20]

$$So = \frac{-e-Ri}{L}$$

$$S_1 = \frac{V(n-z)-e-Ri}{L} \qquad \textbf{(3.10)}$$

where V_{n-z} is the best active voltage vector. By performed Runge Kutta technique, the future value of the predicted current will be expressed by

$$i\,(k+1) = i(k) + \frac{1}{6}\,T_{sp}\left(\frac{\text{Topt}\,(\text{V(n−z)−ek−Rik})+\text{Tz}\,(\text{Vz−ek−Rik})}{L}\right)x\left(6 - \frac{3R}{L}\text{Tsp} + \frac{R^2}{L^2}Tsp^2 - \frac{R^3}{4L^3}Tsp^3\right) \qquad \textbf{(3.11)}$$

With $V_{n-z} + V_z = V(k)$ and $T_{opt} + T_z = T_{sp}$, where T_z and T_{opt} are the best non-active and active voltage vector durations, respectively. Hence, by substituting (3.8) in (3.9), the predicted current can be written as follows

$$i\,(k+1) = i(k) + \frac{1}{6}\,(S_1.\,\text{Topt} + S_o\,(T_{sp} - T_{opt}))x\left(6 - \frac{3R}{L}\text{Tsp} + \frac{R^2}{L^2}Tsp^2 - \frac{R^3}{4L^3}Tsp^3\right) \qquad \textbf{(3.12)}$$

During the control period, the best active voltage vector duration T_{opt} satisfies the following condition

$$\frac{dg}{dTopt} = 0 \qquad \textbf{(3.13)}$$

Therefore, the optimal active voltage vector duration can be defined by substituting (3.12) in (3.8) and solving (3.13) as follows

$$T_{opt} = \frac{\left|\frac{6[\,iref-i(k)]}{\left(6-\frac{3R}{L}Tsp+\frac{R^2}{L^2}Tsp^2-\frac{R^3}{4L^3}Tsp^3\right)}-So\ x\ Tsp\,\right|}{|S1-So|} \qquad \textbf{(3.14)}$$

Also, if Forward Euler approximation used, the optimal active voltage vector duration will be defined as follows

$$T_{opt} = \frac{|\,iref-i(k)-So\ x\ Tsp|}{|\,S1-So|} \qquad \textbf{(3.15)}$$

It is necessary to observe that the value of Topt can be substituted by Tsp if its value is greater than Tsp, and it is substituted by zero if its value is less than zero [20],[7].

3.3.3 Vector Sequence

The switching frequency can be controlled by the sequence of the two voltage vectors which will be applied during one control cycle. In general, the first voltage vector, which will be applied, is the non-zero voltage vector. After that the appropriate zero voltage vector with lowest switching jumps is applied.

However, if the zero-voltage vector is the same in the present and previous vector sequences, then, it will be employed firstly to minimize the switching frequency [23].

3.4 Summary

In this chapter the concept and principle of the conventional MPCC were presented. The selection criterion for a voltage vector is defined as the cost function, which minimizes the error between the reference and measured currents. For micro inverter, this a cause for increasing THD_C and limiting the steady state performance. To improve the performance of the conventional MPCC, this chapter presented the proposed MPCC with duty ratio optimization based on Runge Kutta approximation where two voltage vectors will be applied during one control period. Hence, the active and non-active voltage vector durations are defined depend on the current error minimization.

Chapter 4

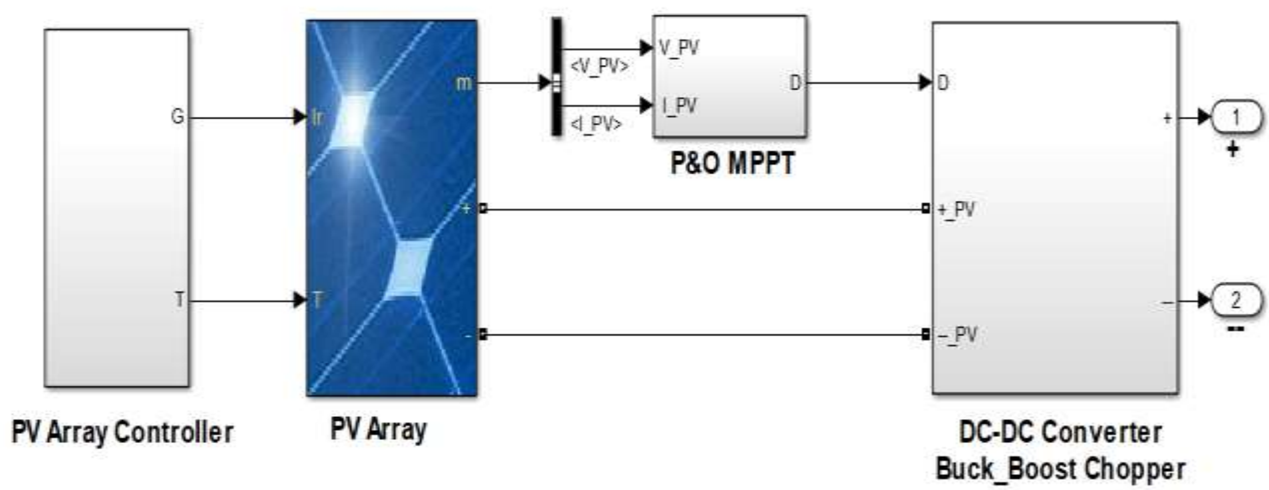
Implementation and Results

4.1 Introduction

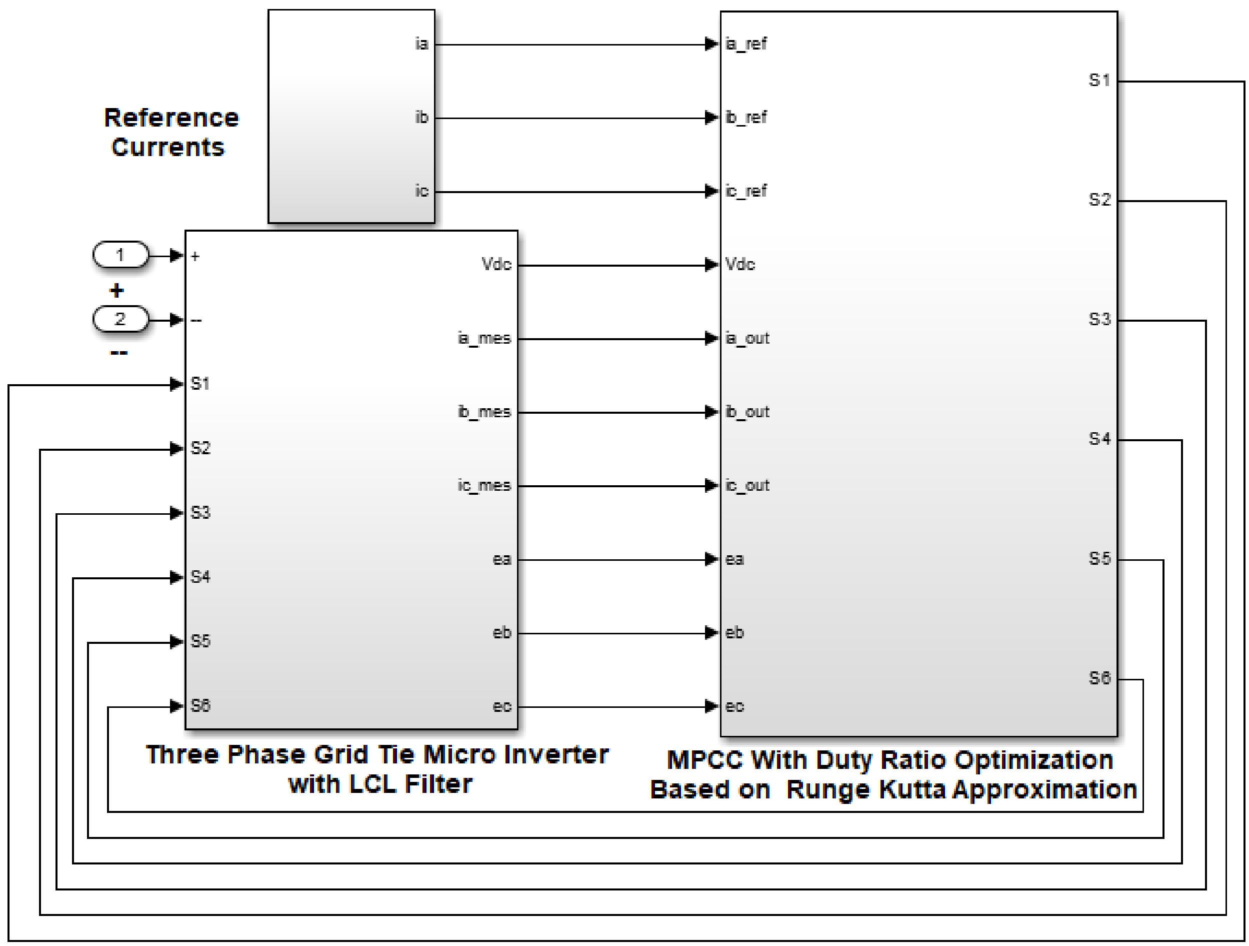
In this chapter the conventional and proposed MPCC with duty ratio optimization based on Runge Kutta and Forward Euler approximation for three phase grid tie micro inverter is implemented using MATLAB / Simulink. Firstly, the simulation diagram shows how the system is implemented in simulation. Secondly, the simulation results which obtained from the simulation diagram are presented and analyzed. Thirdly, the conclusion provides a summary of the findings. Finally, the research recommends three topics as future works.

4.2 Simulation Platform

To verify the effectiveness of the improved MPCC with duty ratio optimization depended on Runge Kutta method simulation of the three-phase grid tie micro inverter with output LCL filter was implemented using MATLAB/Simulink, as shown in figure (4.1). The parameters of the system are mentioned in Table 4.1.



a) Main PV-Chopper circuit



b) Inverter Circuit with respected switching signals.

Figure 4.1: Diagram of MPCC with Duty Ratio Optimization for Three-Phase Grid Tie Micro Inverter Based on Runge Kutta and Forward Euler approximation in MATLAB/Simulink.

Table 4.1: Simulation Parameters.

Variable	System Parameters	Value
P_{max}	PV Module Peak Power	315 W
V_{mpp}	PV Module Rated Voltage	54.7 V
I_{mpp}	PV Module Rated Current	5.76 A
V_{oc}	PV Module Open Circuit Voltage	64.6 V
I_{sc}	PV Module Short Circuit Current	6.14 A

V_{dc}	DC-Link Voltage	540 V
e	Grid Voltage (RMS)	220 V
F	Grid Frequency	50 Hz
i_{ref}	Reference Current Peak Amplitude	2 A
L_1	Filter Inductance	30 mH
L_2	Filter Inductance	0.68 mH
C_f	Filter Capacitance	1 μF
R_f	Damping Resistance	8.6 Ω
T_{sp}	Sampling Time	50 μs

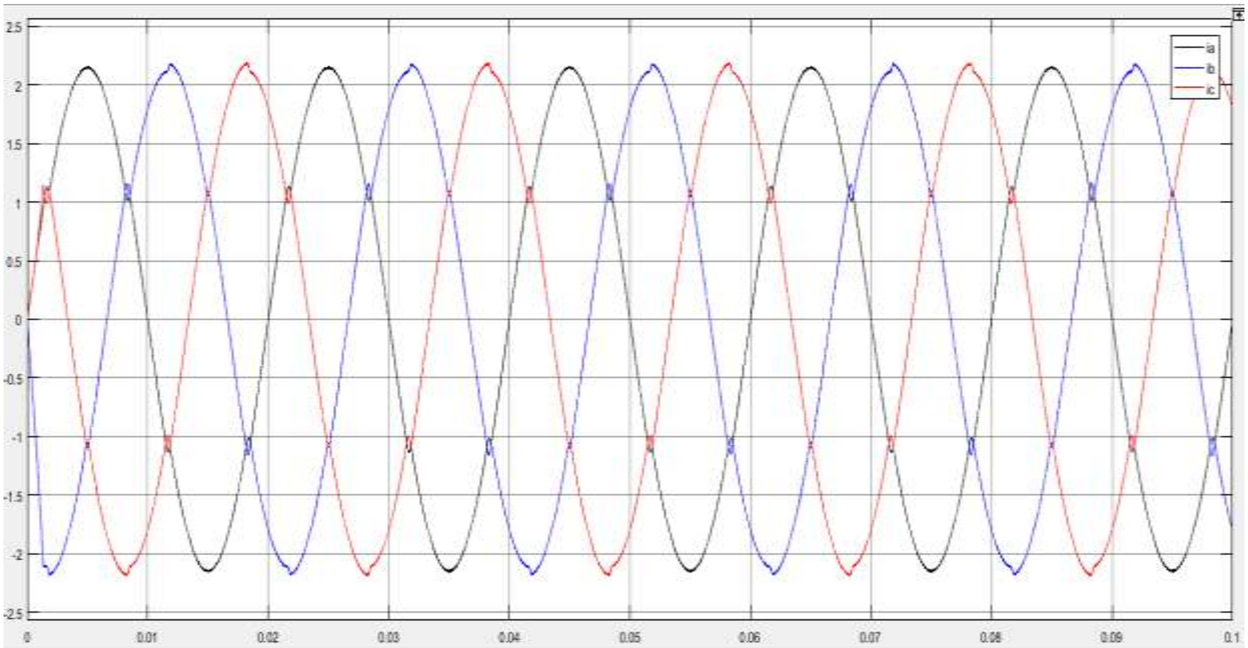
4.3 Comparison Analysis

To prove the accuracy and effectiveness of proposed control method, three phase current is investigated for conventional MPCC method and modified MPCC method using Runge Kutta and Forward Euler approximation.

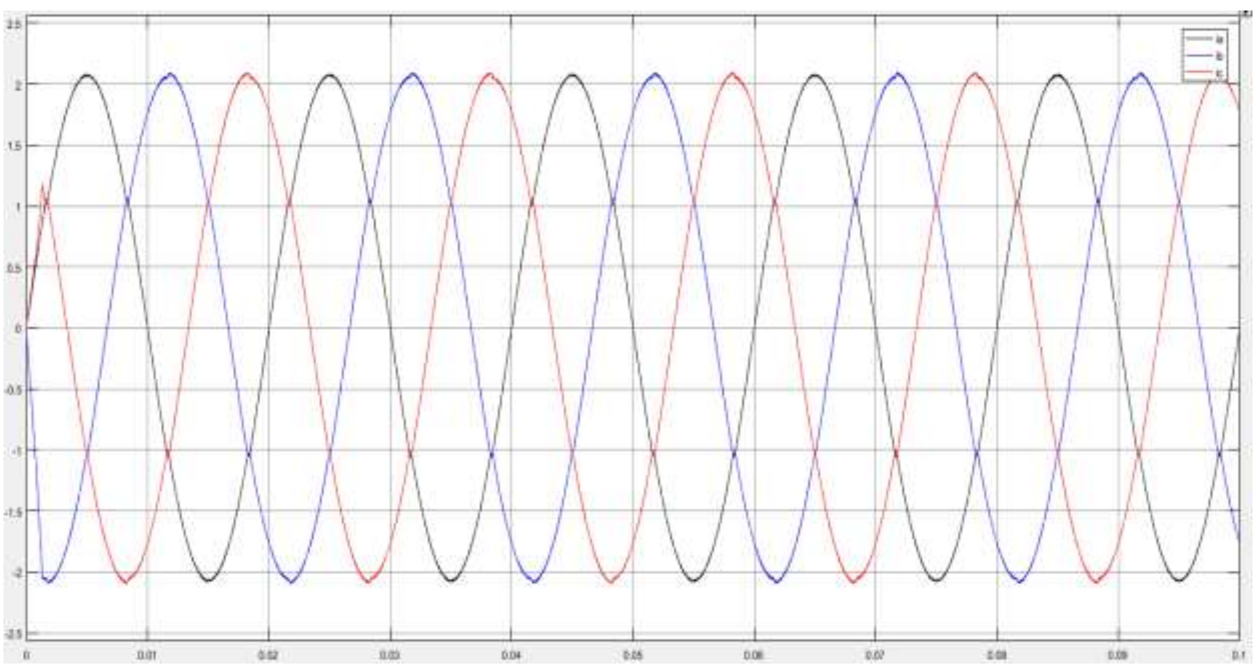
Figure (4.2) illustrates the obtained three phase currents for conventional MPPC, and modified MPCC based on Runge Kutta and Forward Euler approximation at 50 μs sampling time. While figure (4.3) illustrates the harmonic decomposition using Fast Fourier Transformer (FFT) and the obtained total harmonic distortion factors for them.

By conducting brief comparison between the conventional and the proposed MPCC with duty ratio optimization depend on Runge Kutta and Forward Euler approximation, it is clear that the THD_C of the proposed MPCC based on Runge Kutta and Forward Euler approximation are 0.77% and 1.31% respectively, which far less than the THD_C of the conventional MPCC with value of 2.80%, as shown in figure (4.3).

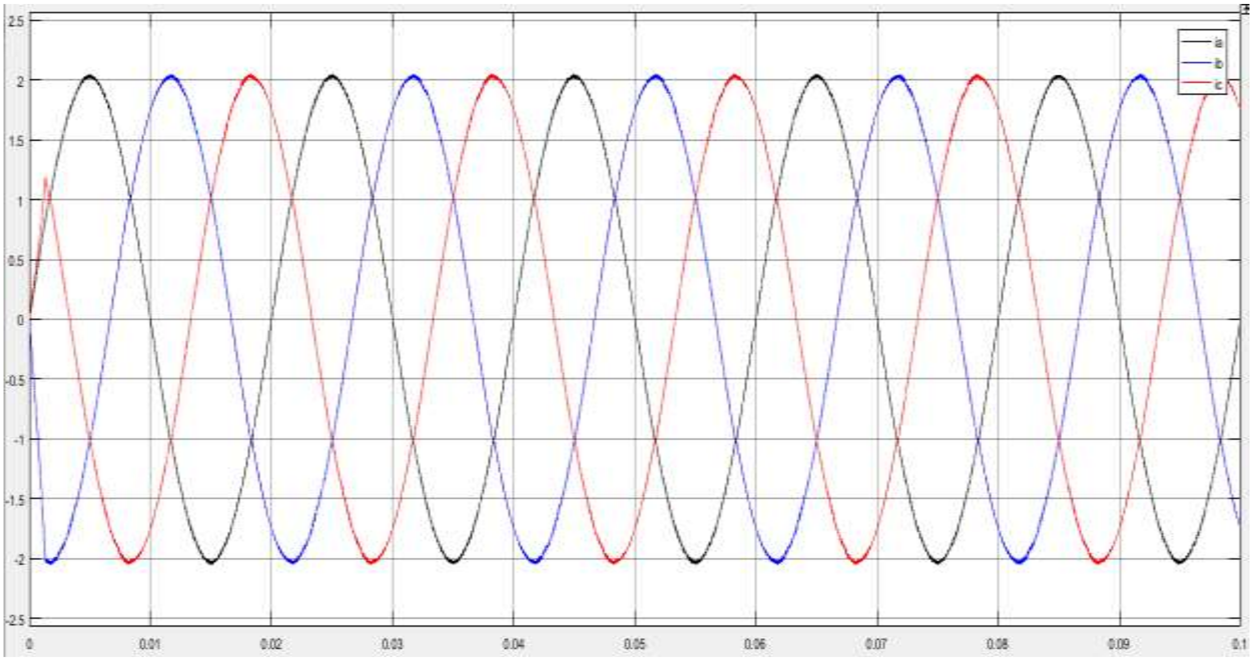
Furthermore, the output current waveform in the proposed MPCC with duty ratio optimization is very closed to sinusoidal waveform which justified the accuracy and effectiveness of the proposed method resulting in getting better steady state performance. In addition to that reducing the total harmonic distortion enhances the true power factor of the system.



a) Conventional MPCC.

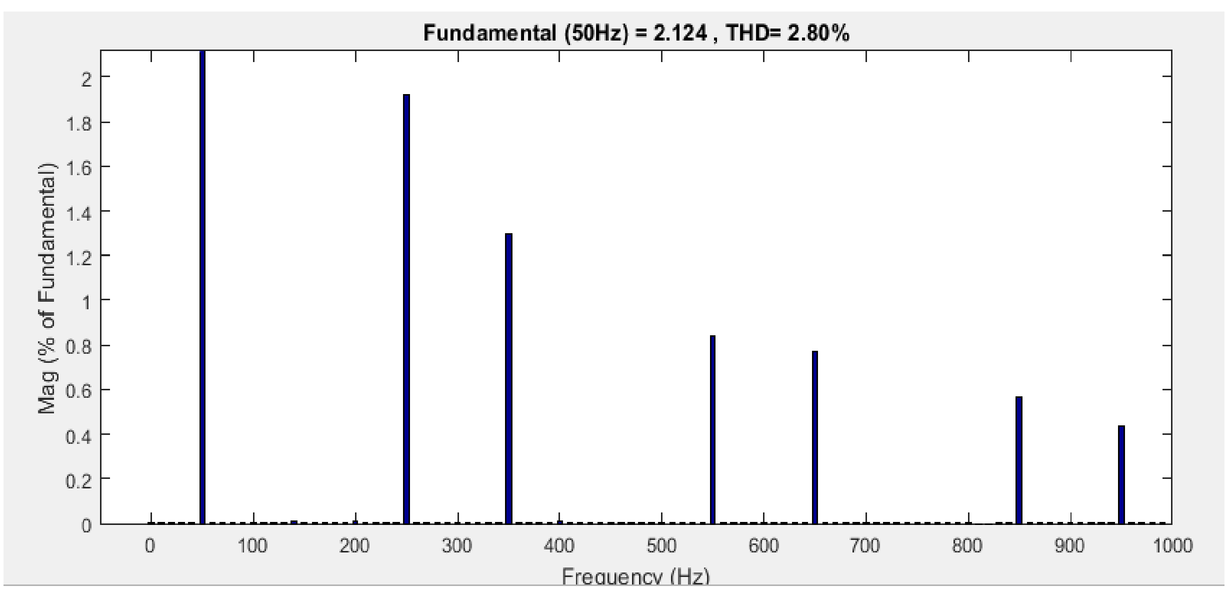


b) Proposed MPCC Based on Forward Euler Approximation.

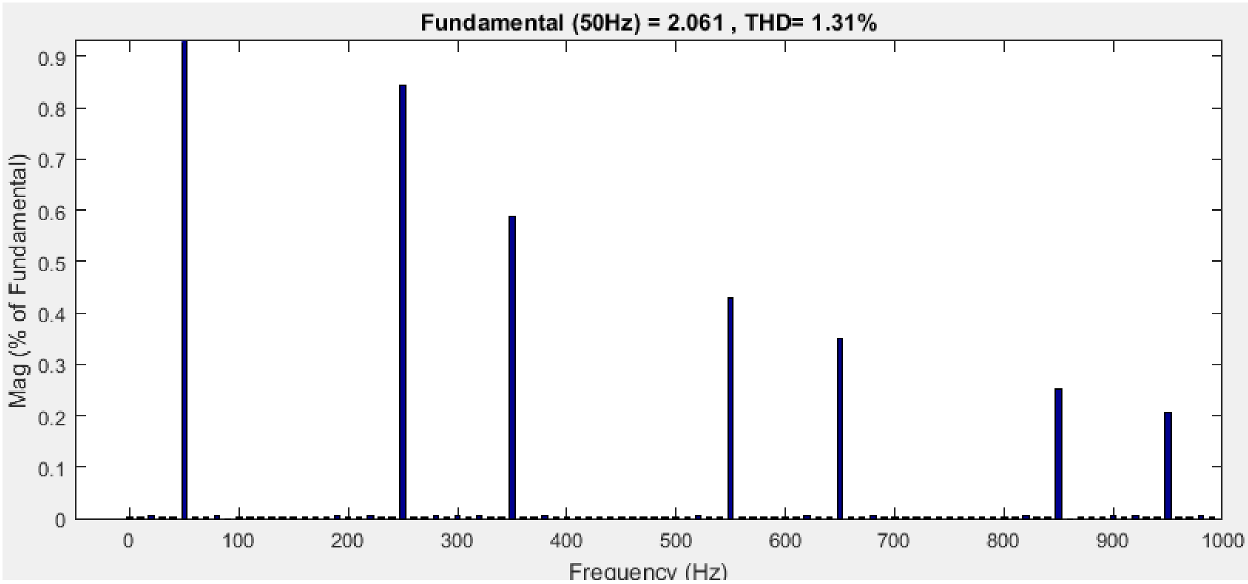


c) Proposed MPCC Based on Runge Kutta Approximation.

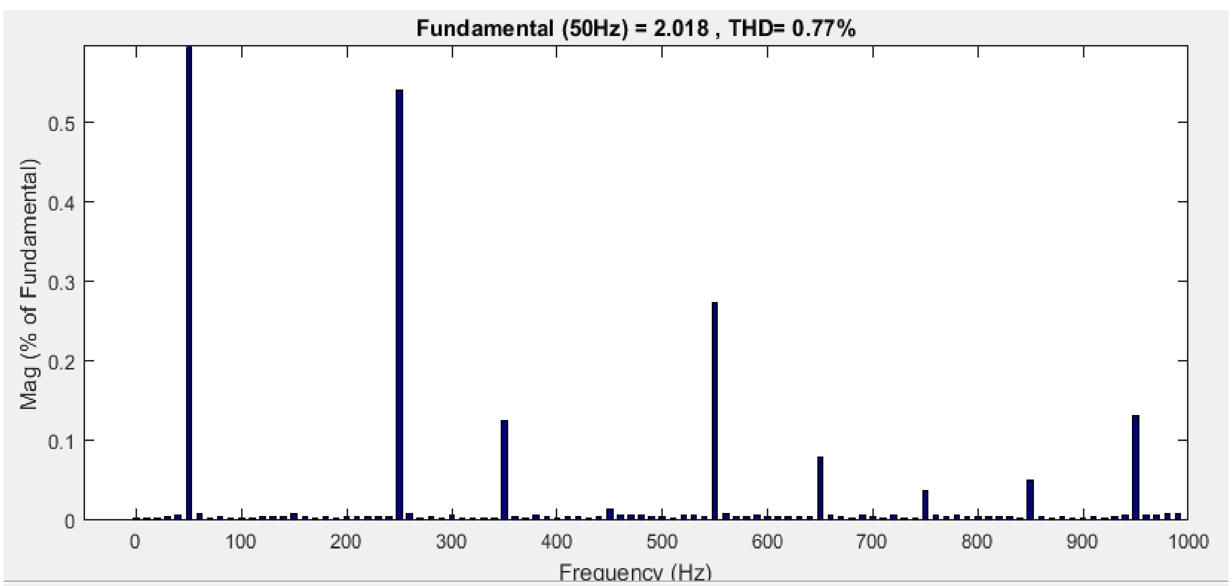
Figure 4.2: Simulation results for conventional and proposed MPCC Based on Runge Kutta and Forward Euler Approximation. Three phase output current waveforms, at 50 µs sampling time.



a) Conventional MPCC



b) Proposed MPCC Based on Forward Euler Approximation.



c) Proposed MPCC Based on Runge Kutta Approximation.

Figure 4.3: Load current harmonic spectrum of conventional and proposed MPCC Based on Runge Kutta and Forward Euler Approximation.

The following table (4.2), illustrated the comparisons of the three methods between: THDc, system efficiencies, switching losses and steady state performance.

Table (4.2): Comparison of the three methods.

Method	Steady State Performance	THDc	Efficiency	Switching Losses
Conventional MPCC	Less	2.80%	95.68%	40.6 w
MPCC based on Forward Euler Approximation	Better	1.31%	97.1%	27.6 w
MPCC based on Runge Kutta Approximation	Best	0.77%	99.17%	7.8 w

4.4 Conclusion

The proposed MPCC with duty ratio optimization depended on Runge Kutta approximation for three phase grid tie micro inverter with output LCL filter has been studied and showed in this research. The simulation results are demonstrated to verify its performance in obtaining lower current total harmonic distortion THD_C, decreasing the transistors switching losses, increasing the system efficiency and improving the steady state performance of the inverter. Therefore, this strategy can be used to enhance the quality of the output power of converters used in Solar PV applications.

4.5 Future Works

In this research the MPCC with duty ratio optimization strategy was implemented for three phase voltage source micro inverter and it is clear that its effectiveness in reducing THD_C and obtaining better steady state performance. Hence, it can be applied for other applications such as current source inverter.

The effectiveness of the MPCC strategy depends on the discretization technique which is used. In this research two discretization techniques are used and it is noticed that Runge Kutta approximation is better than Forward Euler approximation. Therefore, the MPCC with duty ratio optimization can be performed based on advanced discretization techniques.

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