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

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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 inverter, this will produce high current harmonics and limit the steady state performance. To enhance the effectiveness of the conventional MPCC, this paper proposes 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%.**

Index Terms— **Model predictive current control, Forward Euler approximation, Runge Kutta approximation, Cost function, Three phase grid tie micro inverter.**

I. 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, to decrease THD_C and switching losses. Due to its advantages such as easy inclusion of system nonlinearities restriction, good dynamic performance and accurate control capability [2]. 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 less current ripples as compared to Runge Kutta approximation[3]. After the predicted currents is obtained, the MPCC controller applies the optimal switching state which achieves minimal cost function.

This paper 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 (1).

The block diagram components 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 [4-8]

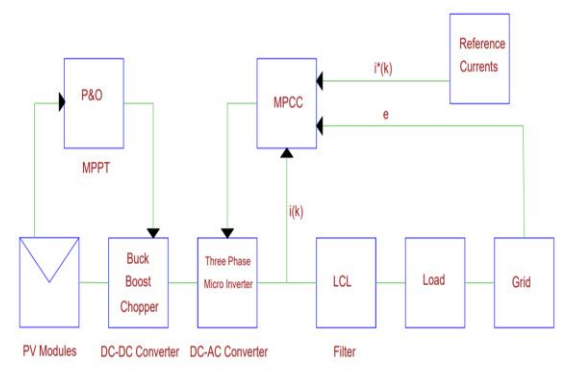


Figure 1: The proposed system block diagram of MPCC with duty ratio optimization.

II. MATHEMATICAL MODELING OF MPCC

II.1 Principle of MPCC

Basically, MPCC strategy is depended on only eight switching states can be produced by three phase micro inverter and 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 paper the discrete time model of the system will be obtained by performed Runge Kutta approximation, as illustrated in figure (2).

Refer to fig. (3) where three-phase inverter energizing symmetrical resistive load throughout LCL filter, where

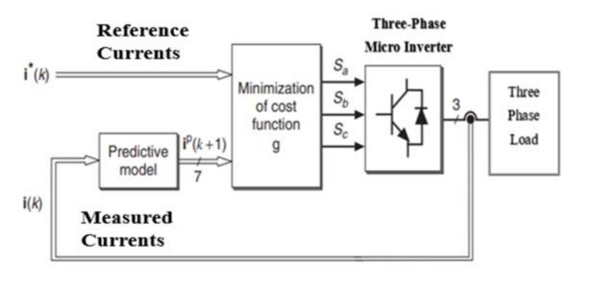


Figure 2: MPCC block diagram.

the voltage balance equation is presented in (1)

$$V_{an} = L\frac{di_a}{dt} + Ri_a + e_a$$
$$V_{bn} = L\frac{di_b}{dt} + Ri_b + e_b$$
$$V_{cn} = L\frac{di_c}{dt} + Ri_c + e_c \quad \textbf{(1)}$$

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

Equation (1) can be stated in vector form as follows:

$$V = L\frac{di}{dt} + Ri + e \quad \textbf{(2)}$$

where, $e = \frac{2}{3}(e_a + ae_b + a^2e_c)$,

and $i = \frac{2}{3}(i_a + ai_b + a^2i_c)$ **(3)**

are the voltage and current of the grid, respectively.

According to (2), the expression of current of the grid side is a differential equation can expressed as

$$\frac{di}{dt} = \frac{V - Ri - e}{L} \quad \textbf{(4)}$$

II.1.2: Discrete time model

According to (4), 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 [3]

$$x(k+1) = x(k) + \frac{1}{6}T_{sp}.(\dot{x}_o + 2\dot{x}_A + 2\dot{x}_B + \dot{x}_C) \quad \textbf{(5)}$$

Where Tsp is the sampling time and $\dot{x}_o$, $\dot{x}_A$, $\dot{x}_B$ and $\dot{x}_C$ are the state variables which can be written as

$$\dot{x}_o = \frac{V - e - Ri}{L}$$
$$\dot{x}_A = \frac{V - e - R(i + \frac{1}{2}Tsp\,\dot{x}o)}{L}$$
$$\dot{x}_B = \frac{V - e - R(i + \frac{1}{2}Tsp\,\dot{x}A)}{L}$$
$$\dot{x}_C = \frac{V - e - R(i + Tsp\,\dot{x}B)}{L} \quad \textbf{(6)}$$

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

$$i(k+1) = i(k) + \frac{1}{6}Tsp\left(\frac{V(k) - e(k) - Ri(k)}{L}\right) x \left(6 - \frac{3R}{L}Tsp + \frac{R^2}{L^2}Tsp^2 - \frac{R^3}{4L^3}Tsp^3\right) \quad \textbf{(7)}$$

II.1.3: 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

$$g = |Re[\,i_{ref} - i(k+1)]| + |Im[\,i_{ref} - i(k+1)]| \quad \textbf{(8)}$$

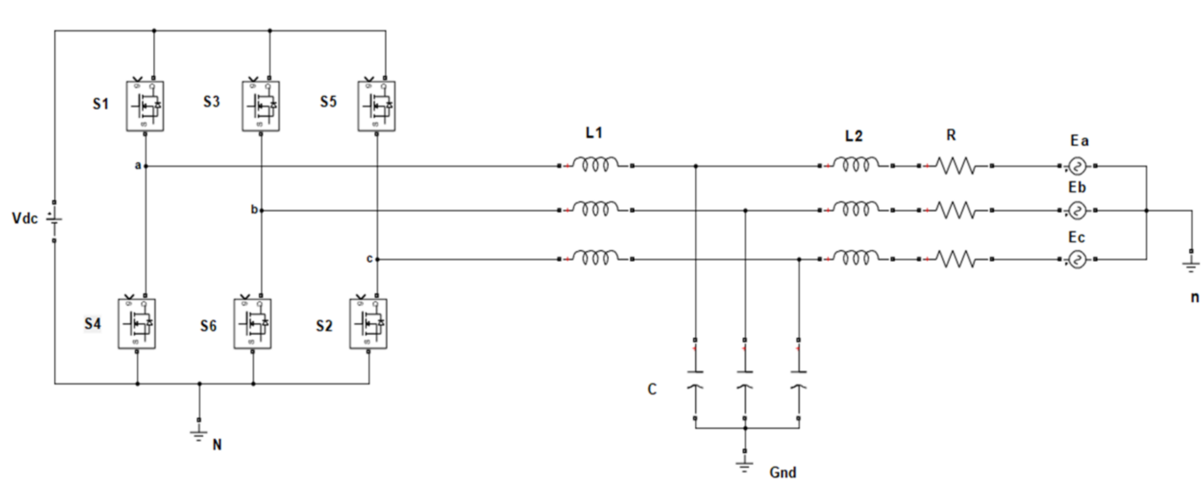


Figure 3: Three Phase Grid Tie Micro-Inverter With output LCL Filter.

where $i_{ref} = \frac{2}{3}(i_{a\_ref} + a\, i_{b\_ref} + a^2\, i_{c\_ref})$ 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 and the state ,that minimizes it, is selected to be applied in the next sampling period. follows [11]

$$V_{opt} = V\ (\min\ [g_n]) \qquad \textbf{(9)}$$

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

II.2 Principle of MPCC with Duty Ratio Optimization

In classical MPCC, only one voltage vector is picked out and put through one control period. For three phase micro inverter with only eight switching states, this is a cause for increasing current harmonics and voltage ripples and limiting the steady state performance [11]. To enhance the performance of the classical MPCC, this paper 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 (4).

II.2.1 Vector Selection

In the proposed MPCC with duty ratio optimization, two voltage vectors, will be applied during one control cycle. For three phase micro inverter, 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 [11].

According to (9), the active voltage vector with minimum cost function are 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 [3,11,12].

II.2.2 Optimal Duty Ratio

The control period duration will be split into two sub durations for the active and zero voltage vectors. According to (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 [3]

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

$$S_1 = \frac{V(n-z)-e-Ri}{L} \qquad \textbf{(10)}$$

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

$$i\ (k+1) = i(k) + \frac{1}{6}T_{sp}\left(\frac{\text{Topt}\ (\text{V(n−z)−ek−Rik})+\text{Tz}\ (\text{Vz−ek−Rik})}{L}\right) x \left(6 - \frac{3R}{L}Tsp + \frac{R^2}{L^2}Tsp^2 - \frac{R^3}{4L^3}Tsp^3\right) \qquad \textbf{(11)}$$

with $V_{n\text{-}z} + V_z = V(k)$ and $T_{opt} + T_z = T_{sp}$. Where T_z and T_{opt} are the best non-active and active voltage vectors durations, respectively. Hence, by substituting (8) in (9), the predicted current can be written as follows

$$i\ (k+1) = i(k) + \frac{1}{6}(S_1.T_{opt} + S_o\,(T_{sp} - T_{opt}))\ x\ \left(6 - \frac{3R}{L}Tsp + \frac{R^2}{L^2}Tsp^2 - \frac{R^3}{4L^3}Tsp^3\right) \qquad \textbf{(12)}$$

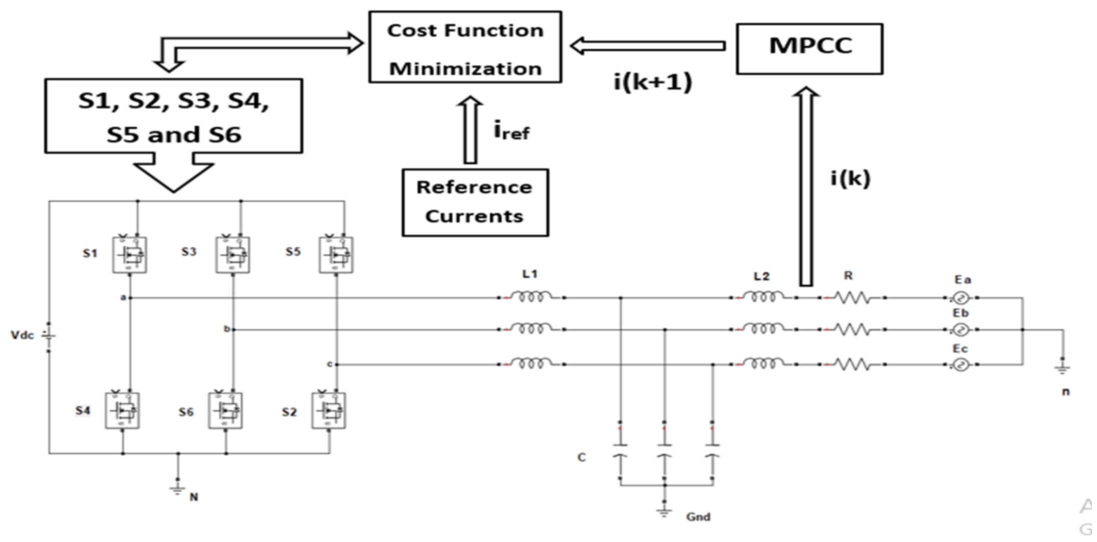


Figure 4: MPCC with Duty Ratio and the inverter.

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

$$\frac{dg}{dTopt} = 0 \qquad \textbf{(13)}$$

Therefore, the optimal active voltage vector duration can be defined by substituting (12) in (8) and solving (13) as follows

$$Topt = \frac{\left| \frac{6[\,iref - i(k)]}{\left(6 - \frac{3R}{L} Tsp + \frac{R^2}{L^2} Tsp^2 - \frac{R^3}{4L^3} Tsp^3\right)} - So \; x \; Tsp \right|}{|S1 - So|} \qquad \textbf{(14)}$$

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 [3,11].

II.2.3 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 [3,12].

III. SIMULATION RESULTS

III.1. Simulation Platform

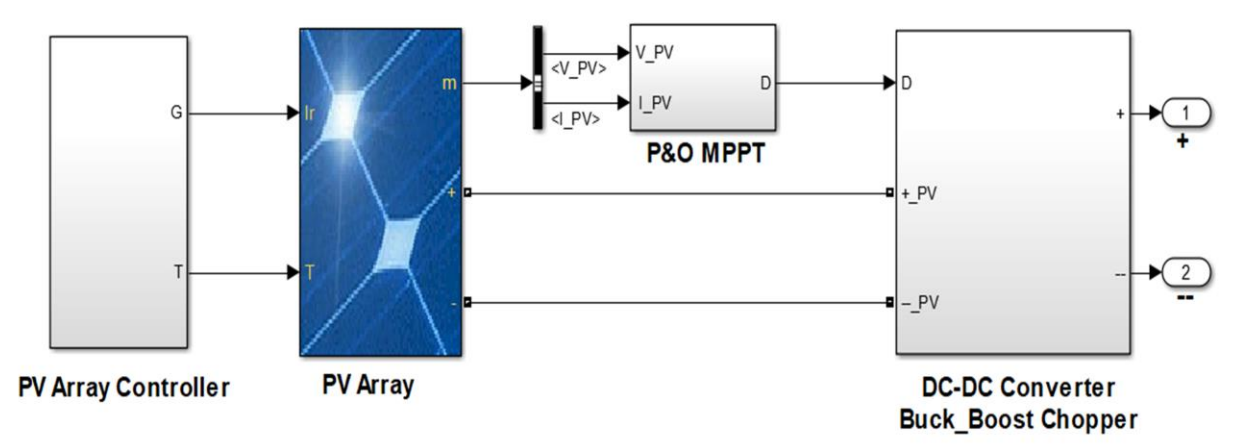
To verify the effectiveness of the improved MPCC with duty ratio optimization depended on Runge Kutta method, simulation of the three-phase grid tie micro inverter with output LCL filter was implemented using MATLAB/Simulink, as shown in figure (5), and the parameters of the system are mentioned in Table 1.

Table 1: Simulation Parameters.

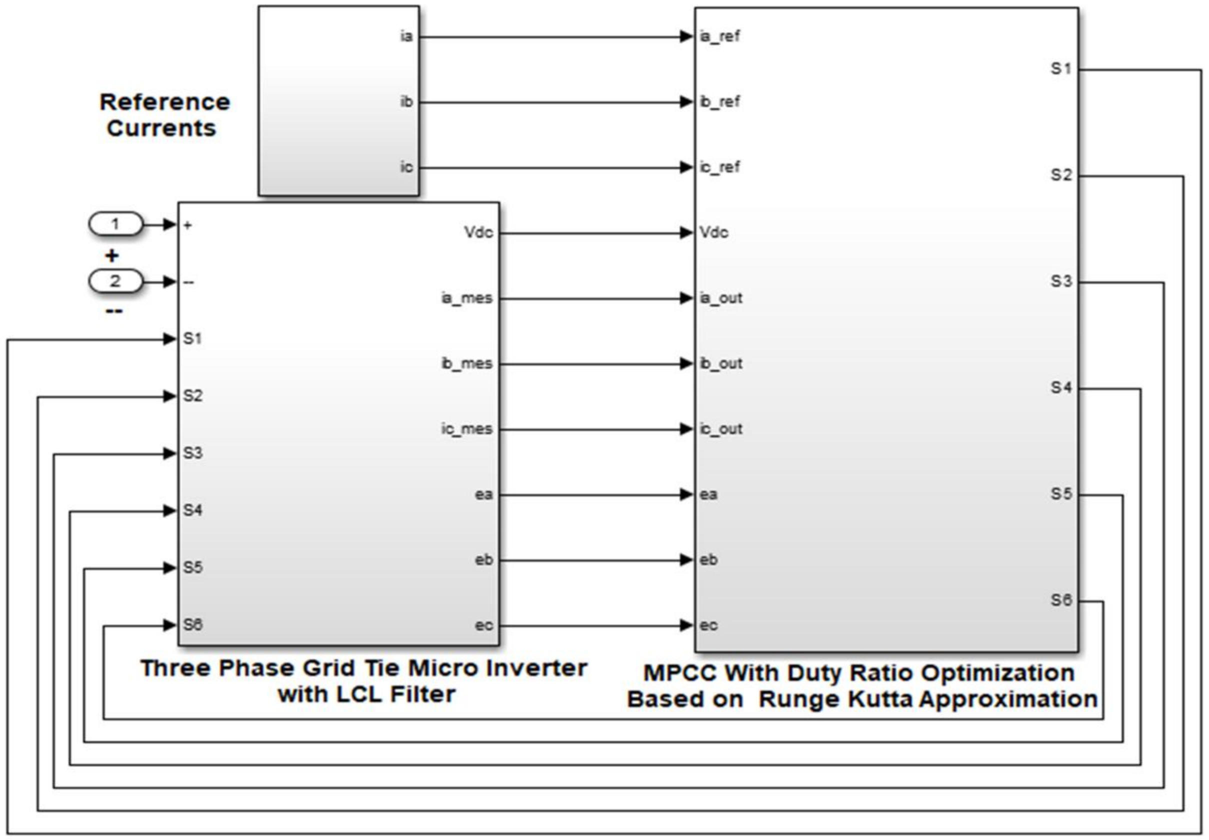
Variable	System Parameters	Value
P_{max}	PV Module Peak Power	315 w
V_{mpp}	PV Module Rated Voltage	54.7 v
I_{mpp}	PV Module Rated Current	5.76 A
V_{oc}	PV Module Open Circuit Voltage	64.6 v
I_{sc}	PV Module Short Circuit Current	6.14 A
V_{dc}	DC-Link Voltage	540 v
e	Grid Voltage (RMS)	220 v
F	Grid Frequency	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

III.2. Comparison Analysis

To prove the accuracy and effectiveness of proposed control method, three phase current is investigated for

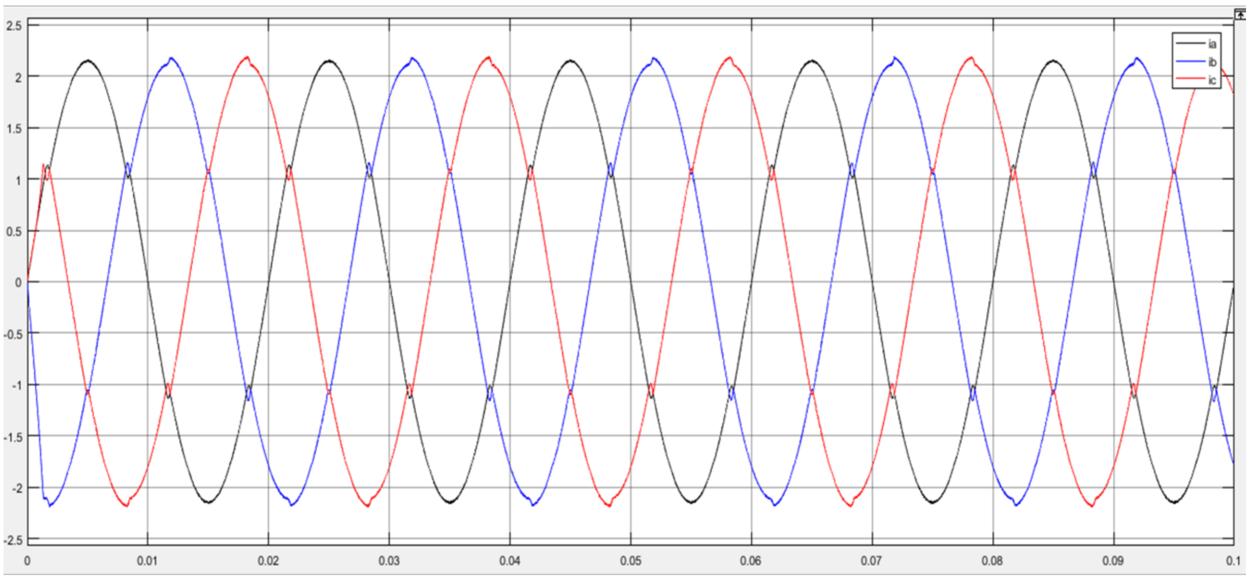


a) Main PV-Chopper circuit

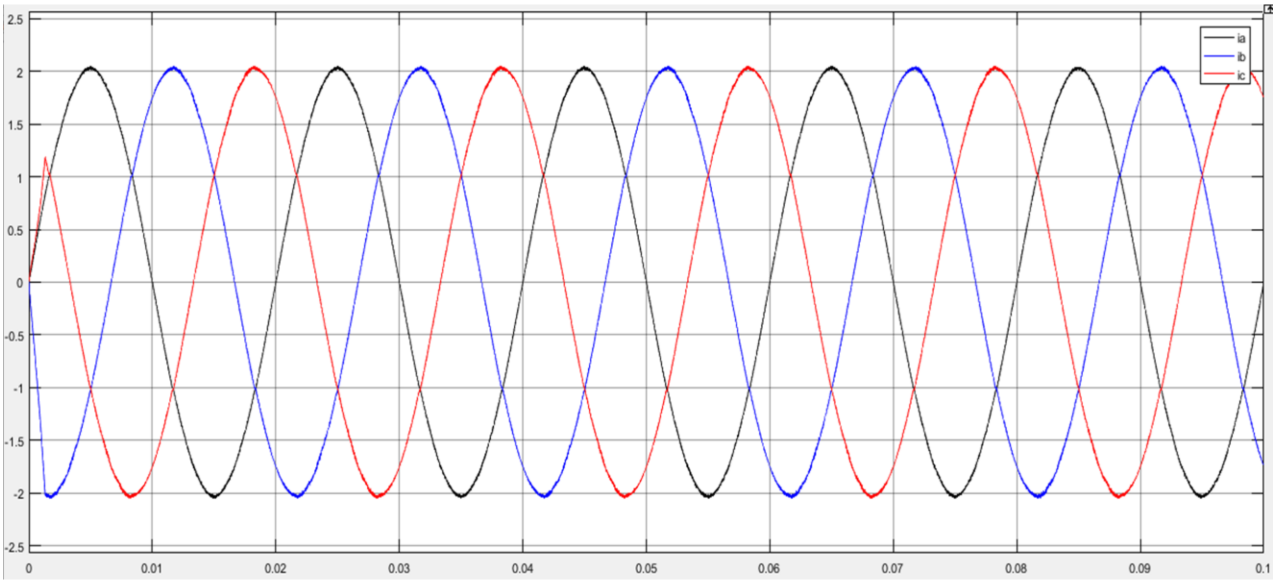


b) Inverter Circuit with respected switching signals

Figure 5: Diagram of MPCC with duty ratio optimization for three-phase grid tie micro inverter based on Runge Kutta approximation in MATLAB/Simulink.



a) Conventional MPCC .



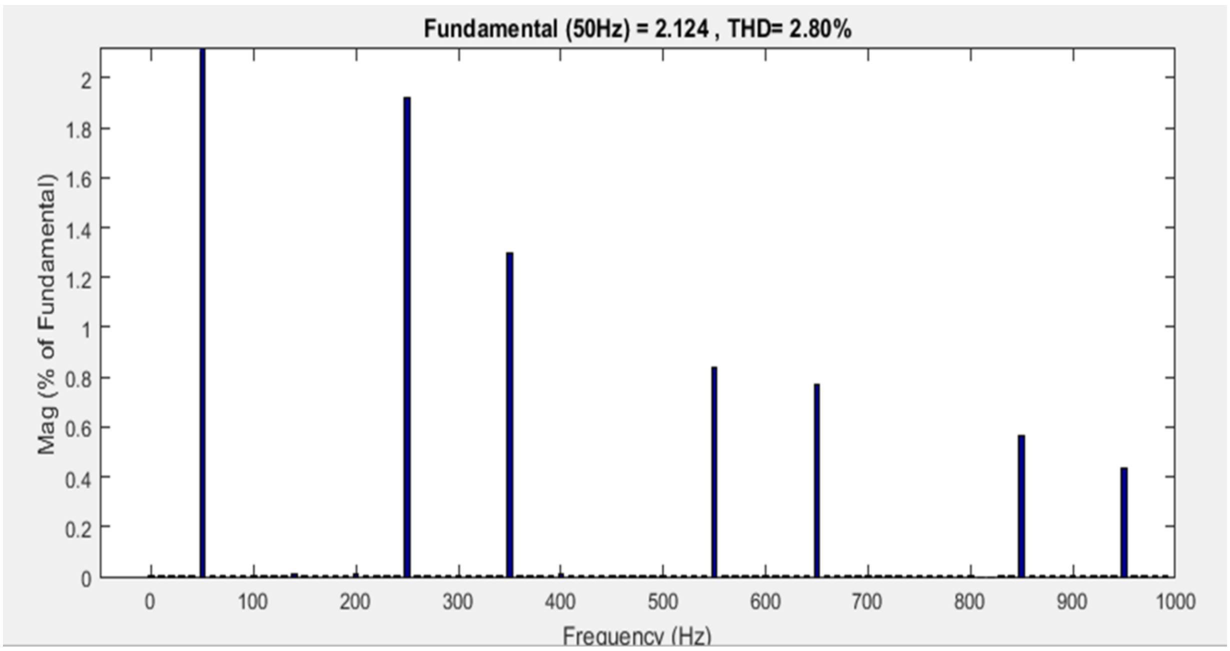
b) Proposed MPCC .

Figure 6: Simulation results for conventional and proposed MPCC. Three phase output current waveforms, at 50 µs sampling time.

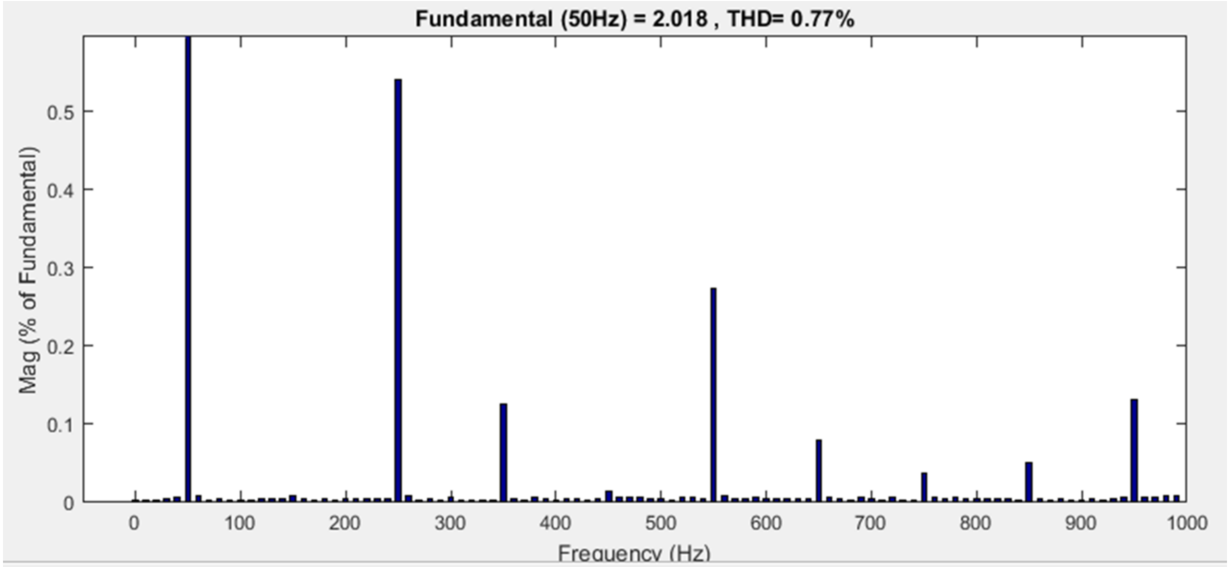
conventional MPCC method and modified MPCC method using Runge Kutta approximation. Figure (6) illustrates the obtained three phase current for conventional MPPC, and modified MPCC at 50 µs sampling time, while figure (7) illustrates the harmonic decomposition using Fast Fourier Transformer (FFT) and the obtained total harmonic distortion factors for both control methods.

By conducting brief comparison between the conventional and the proposed MPCC with duty ratio optimization depend on Runge Kutta approximation , it is clear that the THD_C of the proposed MPCC is 0.77% which far less than the THD_C of the conventional MPCC with value of 2.80%, as shown in figure (7).

Furthermore, the output current waveform in the proposed MPCC with duty ratio optimization is very



a) Conventional MPCC



b) Proposed MPCC

Figure 7: Load current harmonic spectrum of both control methods

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.

IV. 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 paper. The simulation results are demonstrated to verify its performance in obtaining lower current total harmonic distortion THD_C, decreasing the output current ripples, 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.

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