Model Predictive Control for Regulating the Inverter in a Standalone Mode

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***Abstract*— The integration of renewable energy sources (RES) into microgrid systems has received considerable interest because of its potential to improve the dependability and sustainability of power grids. To make the renewable energy penetrate the microgrid we use inverters to convert the DC to AC. Inverter based Microgrids can help penetrate the power from the renewable sources and which in turn also increasing the reliability of the grid connection regulate the AC bus voltage and frequency in the presence of the load variability inherent in microgrids, robust, rapid, and precise control system algorithms are required. In the recent times Model Predictive Control (MPC) has risen up as a phenomenal control approach for handling the power flow in microgrid systems. This paper presents a literature survey on recent developments in the MPC of inverters in microgrid systems. The survey discusses the challenges and opportunities of using MPC to regulate voltage and frequency, share power among inverters, and improve the power quality in microgrid systems. This review also highlights the importance of accurate modelling of system dynamics and uncertainties in RES and load demand for effective MPC control. Finally, the survey identifies the need for further research on the integration of MPC with energy management systems to optimize the operation of parallel inverters and energy storage systems in microgrids.**

Keywords—MPC, inverters, switching states, LC filter, cost function, reference values.

I. INTRODUCTION

A. Motivation

There is a problem with the consistency of the power supply in places that are far from the power plant or the grid, but this problem can be partially resolved by incorporating locally accessible energy resources (such as solar, wind, etc.) into the grid and meeting local energy needs. This can be done by using microgrid systems, which make it easier for renewable energy to enter the system. Droop control, model predictive control (MPC), and other reliable, economical, and robust control techniques were developed because microgrid systems needed them to maintain supply reliability [1]. The objective of this report is to study and discuss the designing of model predictive control of an inverter.

B. Predictive Controls

Predictive control views the system as a mathematical model and taking the help of the same mathematical model the predictive control strategy predicts its future behavior and optimize a performance criterion over a finite time horizon. The purpose of predictive control is to identify the optimal control inputs that result in the lowest possible performance criterion, considering the limitations of the system.

However, predictive control can be difficult to perform because it requires considerable computation and accurate models of the system, which can be difficult to implement in practice [2-6]. Deadbeat controller is a well-known term in the field of predictive controllers. It has been used to control the flow of electricity in three phase inverters, uninterruptible power sources, and dc-dc converters. The nonlinearities and system variable constraints cannot be met by deadbeat control methods.

Model Predictive Control with the help of the system’s mathematical model tries to forecast how the system will behave in the nearby future time horizon and determine the best way to control it [7-12]. At each time step, the model is used to mimic how the system responds to different control inputs, and an optimization algorithm is used to choose the best control action that minimizes a given cost function while meeting constraints. The system then takes the chosen control action, and the process loops back to the starting stage for the next time step. MPC is extensively used in process control, robotics, and self-driving systems because it can handle complicated systems, constraints, and changes in the dynamics and disturbances of the system.

The inverter can be treated as a system with a set number of switching states, which makes the application of MPC much simpler. Additionally, only one step in time must be considered to achieve optimal performance for a much simpler calculation. This allows all possible switching states to be checked live, and the next instant is used to choose the state with the lowest cost function.

C. Basic Principle of MPC

MPC with the help of the system’s mathematical model tries to predict how the system will behave in the nearby future time horizon and optimize a performance criterion. The basic principles of MPC are as follows. MPC is a mathematical model-based control strategy that uses the mathematical model to predict its future behavior [13-16]. The model could be a physical-rules-based first-principles model or an empirical model based on experimental evidence.

MPC may concurrently optimize a performance criterion across a specific time horizon while anticipating how a system will behave in the future for a finite amount of time. The optimization problem is constrained by limitations on the system's inputs and outputs, and the performance criterion is often a cost function which describes the system's intended nature.

At each time step, this process is repeated, with the prediction horizon advancing forward by one time step after each iteration. MPC can work with both strict and lax limits on the system's inputs and outputs. There are two types of restrictions: hard constraints that must be met at all times and soft constraints that can be temporarily ignored as long as they are eventually satisfied.

Because MPC can be delivered through the internet, it can be used for real-time system administration. This provides advantages over more traditional methods of control. However, due to the need to find an optimization issue at each time step, the online implementation of MPC may necessitate a significant amount of computational work. MPC is a powerful control strategy that is widely used in a range of applications including process control, automotive control, and robotics. However, MPC requires a mathematical model of the system, which can be challenging to develop in practice, and can be computationally intensive, particularly for large-scale systems [17-19].

Regarding the common control structure, MPC comprises three essential components: a predictive model, cost function, and solving algorithm. In contrast, the typical design procedure begins with the development of a predictive model, followed by defining the cost function, and finally, configuration of the solution algorithm.

II. SYSTEM DESCRIPTION

Our system model contains a 3-phase inverter coupled to an LC filter at output side that converts DC to AC is shown in Fig. 1. The components of this system are the inverter, LC filter, and load. The system used in this study is described as follows.

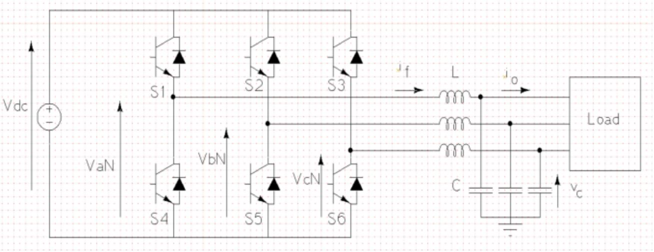

Fig. 1. The 3-phase inverter

The gate signals S_x, S_y, and S_z determine the switching states of the inverter as follows:

$$S_x = \begin{cases} 1, & \text{S}_1\text{: ON, S}_4\text{: OFF} \\ 0, & \text{S}_1\text{: OFF, S}_4\text{: ON} \end{cases} \tag{1}$$

$$S_y = \begin{cases} 1, & \text{S}_2\text{: ON, S}_5\text{: OFF} \\ 0, & \text{S}_2\text{: OFF, S}_5\text{: ON} \end{cases} \tag{2}$$

$$S_z = \begin{cases} 1, & \text{S}_3\text{: ON, S}_6\text{: OFF} \\ 0, & \text{S}_3\text{: OFF, S}_6\text{: ON} \end{cases} \tag{3}$$

The vector is specified by Eq. (4)

$$S = \frac{2}{3}(S_x + aS_y + a^2 S_z) \tag{4}$$

where $a = e^{j(2\pi/3)}$.

Here, the switches are considered to be ideal; therefore, the turning on and turning off operations is not considered. The definitions of the space vectors for the voltage at output is produced by the inverter as follows:

$$V_i = \frac{2}{3}(v_{aN} + av_{bN} + a^2 V_{cN}) \tag{5}$$

The switching state vector S can be connected to the load voltage vector v_i by using the following formula:

$$v_i = V_{dc} S \tag{6}$$

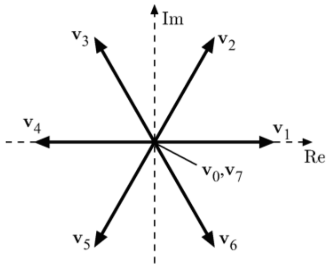

Fig. 2. All eight possible inverter voltage vectors

After taking all of the gating signal combinations, eight voltage vectors were obtained which is shown in Fig. 2. Table I shows the state vectors.

TABLE I. THREE-PHASE INVERTER'S POSSIBLE SWITCHING STATES AND VOLTAGE VECTORS

S_x	S_y	S_z	v_i
0	0	0	v_0
1	0	0	v_1
1	1	0	v_2
0	1	0	v_3
0	1	1	v_4
0	0	1	v_5
1	0	1	v_6
1	1	1	v_7

where, the voltage vectors $v_0 = 0$, $v_1 = \frac{2}{3}V_{dc}$, $v_2 = \frac{V_{dc}}{3} + j\frac{\sqrt{3}}{3}V_{dc}$, $v_3 = -\frac{V_{dc}}{3} + j\frac{\sqrt{3}}{3}V_{dc}$, $v_4 = \frac{-2}{3}V_{dc}$, $v_5 = -\frac{V_{dc}}{3} - j\frac{\sqrt{3}}{3}V_{dc}$, $v_6 = \frac{V_{dc}}{3} - j\frac{\sqrt{3}}{3}V_{dc}$, $v_7 = 0$. The inverter model used in this study is considered to be a nonlinear discrete system. However, using PWM techniques, we can display the model as a continuous system.

$$i_f = \frac{2}{3}(i_{fa} + ai_{fb} + a^2 i_{fc}) \tag{7}$$

$$v_c = \frac{2}{3}(v_{oa} + av_{ob} + a^2 v_{oc}) \tag{8}$$

$$i_o = \frac{2}{3}(i_{oa} + ai_{ob} + a^2 i_{oc}) \tag{9}$$

III. THE FILTER MODEL

Next, we discuss the LC filter used in this study. The LC filter presented in Fig. 3 used here is of a 2nd order type filter and provides significantly better damping characteristics than a simple L or C filter. The LC filter can be represented as a transfer function as

$$F(s) = \frac{1}{1+s^2LC} \tag{10}$$

The LC filter has the cut-off frequency, denoted by f_c, as shown below

$$f_c = \frac{1}{2\pi\sqrt{LC}} \tag{11}$$

An LC filter is used to balance the capacitance and inductance. A larger volume is the direct cause of higher voltage. This filter is a good choice for the suggested system because it requires a larger inductance value to achieve the desired cut-off frequency.

In particular, nonlinear loads can cause the inverter's output voltage waveform to be very different from a sinusoidal waveform and add unwanted harmonics. An inverter with an output LC filter can generate sine-wave output voltages with minimal damage from harmonics. In this setup, the LC filter was a low-pass filter. High-frequency signals are slowed down by the inductors, whereas low-frequency signals pass through the capacitors. Low-pass filters restrict low-frequency signals more than high-frequency ones and lower the output voltage harmonics by passing the signal via an inductor or a capacitor connected to the ground. High-pass filters restrict high-frequency signals to a greater extent than low-frequency ones. The control bandwidth of the converter system can be restricted by changing the LC filter at the inverter output. This results in a reduction in the voltage fluctuations caused by the switching operations of the inverter. For any given output LC filter cut-off frequency, there is an endless number of possible L-C combinations.

Two equations can be used to describe the continuous-time model of an LC filter. The first equation describes the dynamics of the inductor, and the second equation describes the dynamics of the capacitor.

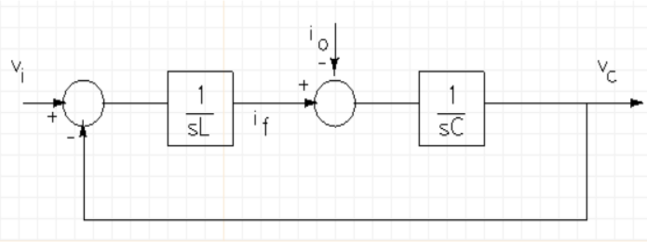

Fig. 3. The model of LC filter

The dynamics revolving the inductance parameters, written in vector form, is as follows:

$$L\frac{di_f}{dt} = v_i - v_c \tag{12}$$

where, L denotes the inductance of the LC filter circuit. Similarly, equation for the capacitor dynamics, written in vector form, is as follows:

$$C\frac{dv_c}{dt} = i_f - i_o \tag{13}$$

where, C denotes the capacitance of the LC filter circuit. The equations (12) and (13) can be represented in a state space system as shown below

$$\frac{dx}{dt} = MX + Nv_i + N_d i_o \tag{14}$$

where,

$$X = \begin{bmatrix} i_f \\ v_c \end{bmatrix} \tag{15}$$

$$M = \begin{bmatrix} 0 & \text{-}1/L \\ 1/C & 0 \end{bmatrix} \tag{16}$$

$$N = \begin{bmatrix} 1/L \\ 0 \end{bmatrix} \tag{17}$$

$$N_d = \begin{bmatrix} 0 \\ -1/C \end{bmatrix} \tag{18}$$

In this instance, the value of V_{dc} is known and does not change. Filter current, i_f and output voltage, v_c are the variables to be measured, while v_i can be computed using $v_i = V_{dc}S$, and the output current i_o is the unknown parameter that we have to find out. As a state equation, the value of the system voltage, denoted by v_c, can be expressed as:

$$v_c = [0 \;\; 1]\,\mathrm{X} \tag{19}$$

A discrete time mode of LC filter can be expressed as:

$$X(k+1) = M_q X(k) + N_q v_i(k) + N_{dq} i_o(k) \tag{20}$$

Where,

$$M_q = e^{AT_s} \tag{21}$$

$$N_q = \int_0^{T_s} e^{A\tau} B d\tau \tag{22}$$

$$N_{dq} = \int_0^{T_s} e^{A\tau} B_d d\tau \tag{23}$$

With the help of the output current, one can figure out what the voltage at output. So, the following Eq. can be used to estimate it:

$$i_0(k-1) = i_f(k-1) - \frac{C}{T_s}(v_c(k) - v_c(k-1)) \tag{24}$$

IV. THE PROPOSED MPC

In this study, we focused on the proposed MPC in view of only one prediction step, N=1. Then, we choose a particular cost function that minimizes the difference between the reference voltage and the predicted output voltage. Finally, a comprehensive simulation model of the inverter system of each controller is presented. The forthcoming behavior of the elements of the system is predicted using a model, and the optimum course of action is selected using a cost function.

During the controller design phase, MPC's adaptability makes it possible to include several of the system restrictions and non-linearities. In MPC, the cost function can be expressed in several ways, each of which accounts for a unique set of criteria, variables, and weights. In addition, other forecasting time frames can be considered. By applying the optimal voltages via a modulator as described, the inputs to the system can be treated as continuous.

As presented for a three phase inverter, the inverter is modeled as a system with a finite possible switching-states and we only consider a single time step horizon to facilitate the implementation of MPC. An online evaluation of all conceivable switching states is feasible. Then, the option with the lowest cost function was chosen.

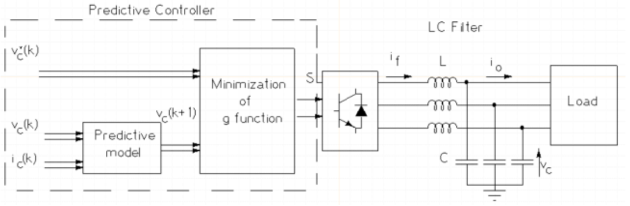

Fig. 4. One prediction step of MPC system.

The MPC algorithm proposed in this study employs a discrete-time inverter model with an output LC filter. Discrete-time models portray the system as a collection of different equations, in which the state of the system at any given time is determined solely by its state at the preceding time step. A state-space model is a particular system’s mathematical representation in which the behavior of the system is characterized by a set of differential equations and the state of the system is defined as a set of variables that fully describe the system's behavior at a given moment.

The state-space model of the proposed MPC of the inverter system covers the dynamics of the inverter and the LC filter as well as the load dynamics. To identify the ideal control signal, the technique additionally employs an optimization problem that is addressed at each control interval. The optimization problem is addressed using a numerical optimization approach that considers the voltage and current limits as well as the performance objectives. The control cycle of the MPC is defined as follows at sampling time *k*. The value of the filter current $i_f(k)$ and the output voltage $v_c(k)$ at sampling time *k* were obtained. Now, for the next sampling instant the output voltage value at for all the probable voltage vectors that the inverter generates was predicted. The cost function g_1 was compared to the seven predictions obtained.

A. The Cost Function

The performance criterion is typically expressed as a cost function, which is a mathematical expression that enumerates the intended behaviour of system. The cost function of a MPC problem is defined as the sum of the individual costs associated with the control inputs and the system outputs over a finite time horizon. The cost function’s objective is to determine the optimal values of the control inputs that can minimize the function over the time horizon, subject to the constraints of the system. These constraints may include limitations on control inputs, state variables, and reference signals. The optimization problem is usually solved using mathematical solving techniques. The cost function can be described as: The cost function plays a crucial role in Model Predictive Control because it enables the control engineer to specify the desired behaviour of the system in terms of a quantitative measure. By adjusting the weighting matrices and the reference signals, the control engineer can tune the performance of the system to achieve the desired objectives. To minimise the output voltage's error

$$g = (v^*_{c\mathrm{Re}al} - v_{c\mathrm{Re}al})^2 + (v^*_{c\mathrm{Im}} - v_{c\mathrm{Im}})^2 \tag{25}$$

Where, $v_{c\mathrm{Re}al}$ is real part of voltage prediction $v_c(k+1)$. $v_{c\mathrm{Im}}$ is voltage prediction imaginary part, $v_c(k+1)$.

And similarly, $v^*_{c\mathrm{Re}al}$ is real part of the reference voltage $v_c^*(k)$. $v^*_{c\mathrm{Im}}$ is voltage reference imaginary part, $v_c^*(k)$.

The cost function plays a crucial role in MPC because it enables the control engineer to specify the system’s preferred specifications in terms of a quantitative measure. By adjusting the weighting matrices and reference signals, the control engineer can tune the system performance to achieve the desired objectives. To minimize the output voltage's error

$$g_N = (v^*_{c\mathrm{Re}al} - v_{c\mathrm{Re}al}(k+N))^2 + (v^*_{c\mathrm{Im}} - v_{c\mathrm{Im}}(k+N))^2 \tag{26}$$

This cost function calculation is then applied to each seven voltage vectors of the inverter. The reference voltage in this work is held constant at k until time M, at which point it is set to $v^*_c(k)$.

For N = 1, the MPC cost function is:

$$g_1 = (v^*_{c\mathrm{Re}al} - v_{c\mathrm{Re}al}(k+1))^2 + (v^*_{c\mathrm{Im}} - v_{c\mathrm{Im}}(k+1))^2 \tag{27}$$

The entire process can be described using the flowchart shown below. The flowchart can be described as follows. The first phase of the method comprises initializing the system's current state and the prediction horizon, which refers to the span of time over which the system's future behavior may be forecasted. The next step is to estimate the system's future behavior over the single step time horizon using the inverter system's state-space model. To calculate the prediction error, the predicted output voltage and current values were compared to the target values. An issue is expressed as an optimization problem in order to minimize prediction error while also satisfying system restrictions. Finding the appropriate control signal that minimizes both performance criteria and prediction horizon constraints is part of the optimization problem that must be solved. After analyzing the results of the optimization procedure, the most effective control signal is produced and employed to operate the inverter. The system's current state is revised based on measurements of the output voltage and current of system. The altered state serves as the starting point for subsequent prediction cycle rounds. The algorithm repeats the middle steps of a closed-loop approach to manage the inverter system's output voltage and current. The proposed MPC’s flowchart is shown in Fig. 5.

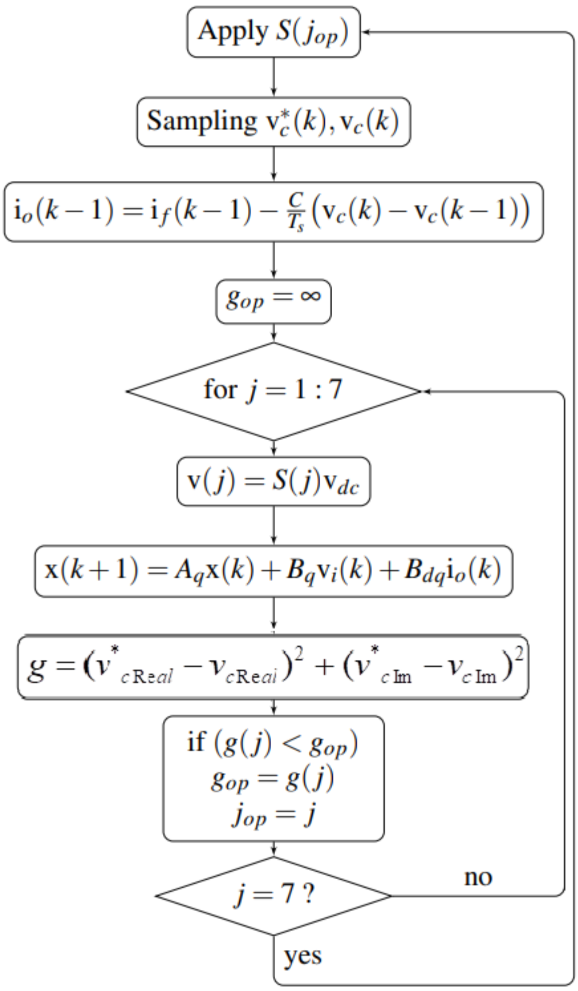

Fig. 5. The proposed predictive control algorithm's flowchart

V. SIMULATION RESULTS AND DISCUSSION

The simulation model schematic consists of a 3-phase inverter connected in a standalone mode and is used as an interface of the DC source. The inverter is linked to a three-phase load. The parameter values of simulation are presented in Table II. The voltage and current in linear-load are illustrated in Fig. 6 and 7, respectively. The voltage and current in nonlinear load are shown in Fig. 9 and 10, respectively. The load voltage THD in linear load is revealed in Fig. 8. The load voltage THD in nonlinear load is illustrated in Fig. 11.

TABLE II. SIMULATION PARAMETERS

Parameter	**Value**
V_{dc}	500V
Output Voltage (RMS)	200V
Filter Parameters	$C_f = 45 \times 10^{-6} F$ $L_f = 4 \times 10^{-3} H$
Linear Load	400W+ 400W (For time t = 0.2 to 0.4 s)
Nonlinear Load	R= 100Ω $C = 500 \times 10^{-6} F$
Time of simulation	0.6 sec
Frequency	50Hz
Sampling Time (Ts)	30 μsec

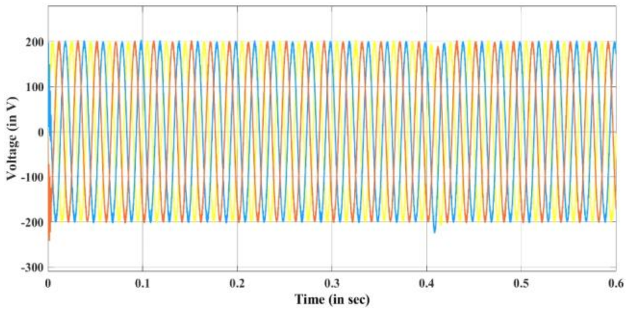

Fig. 6. Load voltage (Linear load)

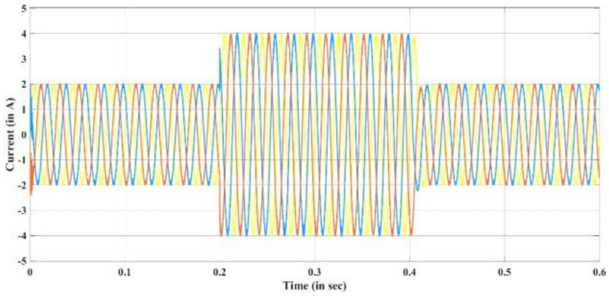

Fig. 7. Current in linear load

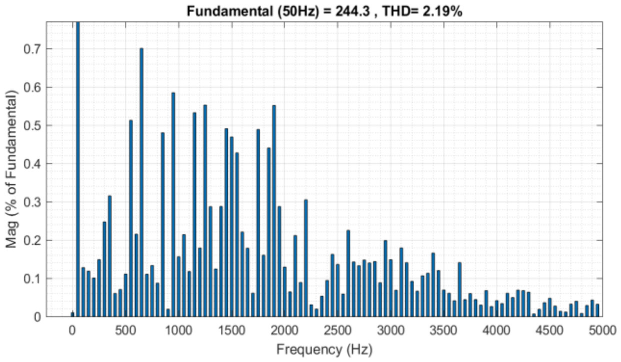

Fig. 8. Voltage THD in linear load

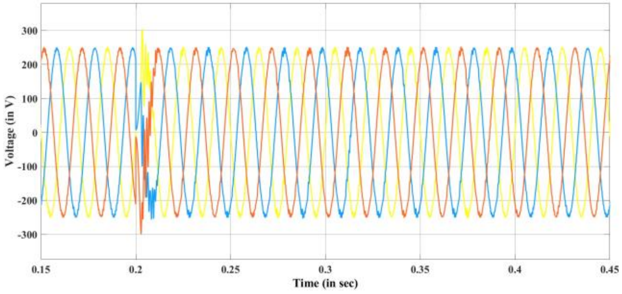

Fig. 9. Load voltage (Nonlinear load)

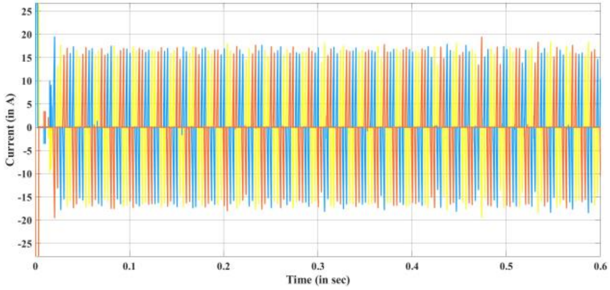

Fig. 10. Current in nonlinear load

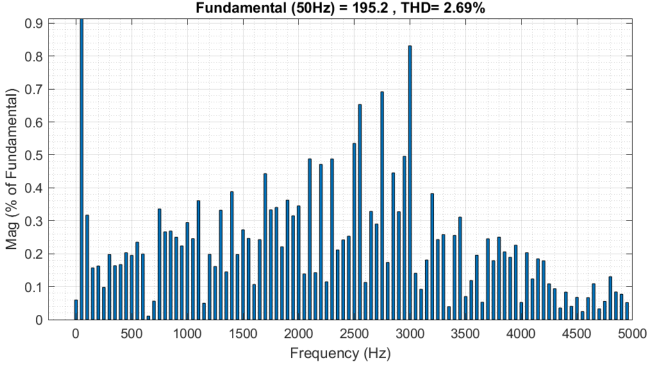

Fig. 11. Voltage THD in nonlinear load

VI. CONCLUSION

In this work, three-phase full-bridge inverters were controlled with the help of MPC. The technique is built on predicting the current in load at the next sample period based on different instances of inverter output voltage. The scenario with the smallest margin of error was chosen. Thus, the reference wave is accurately monitored. The thesis has highlighted the advantages of MPC over traditional control techniques, such as its ability to handle non-linearities, constraints, and uncertainties effectively. According to the simulation results, MPC has an accurate tracking capability, which considerably optimizes the load-current quality. As a result, MPC has demonstrated to be an ideal inverter control method. The MPC is a popular control strategy used in microgrids to optimize the operation of distributed energy resources and ensure reliable and efficient power supply.

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