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RESEARCH ARTICLE

Enhanced the Hosting Capacity of a Photovoltaic Solar System Through the Utilization of a Model Predictive Controller

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ABSTRACT The global expansion of solar-powered within distribution networks with Low Voltage (LV) is experiencing substantial expansion. Despite the various advantages offered by solar photovoltaic generation, surpassing the constraints on Hosting Capacity (HC) within these networks persist a significant technical problem in system operation, especially in relation to voltage operation. This research delves into the effectiveness of improving the Hosting Capacity (HC) of a photovoltaic (PV) system within an LV distribution system. It utilizes a Model Predictive Controller (MPC) to achieve this enhancement and contrasts its performance with reactive power control. The study examines scenarios encompassing both linear and non-linear loads to assess the impact of these control strategies on the PV system's harmonic current in the LV distribution network. Through detailed analysis, the MPC controller demonstrates superior adaptability and responsiveness, maintaining stable active power at 95.5 kW before accommodating a 100% PV system penetration and experiencing a substantial increase to 192 kW. The hosting capacity, thereby, sees a notable 101.05% improvement under MPC control. Additionally, the study reveals that MPC optimizes reactive power utilization, resulting in a 17.9% reduction in reactive power and an 18.3% enhancement in bus voltage compared to reactive power control. Notably, MPC exhibits superior adaptability to both linear and non-linear loads, emphasizing its potential as an effective solution for optimizing the performance of PV systems within LV distribution grids. This research underscores the significance of advanced control strategies in facilitating the integration of renewable energy systems while ensuring grid stability and reliability.

INDEX TERMS Model predictive controller, hosting capacity, solar power, distribution network, grid constraints.

NOMENCLATURE

PV	Photovoltaic.
LV	Low- voltage.
HC	Hosting Capacity.
PCC	Point of Common Coupling.
PQ	Power Quality.
DG	Distributed Generation.
SLD	Single Line Diagram.
DER	Distributed Energy Resources.
MPC	Model Predictive Controller.
DN	Distribution Network.
DSR	Distribution System Reconfiguration.
MPPT	Maximum Power-Point Tracking.
PQE	Power Quality Enhancement.

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AC	Alternating Current.
DC	Direct Current.
S_{rated}	Rated apparent power at PCC.
D	The operational cycle of a boost converter.
V_{in}	The voltage input of the boost converter.
P_{PV}	Real energy from the PV array.
V_{d-ref}	Voltage reference for active control.
THD	Total Harmonic Distortion.
TDD	Total Demand Distortion.
I_{d-ref}	PV smart inverter's reference active current.
I_{Q-ref}	The reactive current reference of a smart inverter in a photovoltaic (PV) system.
V_{q-ref}	Reference Reactive Voltage.
V_0	voltage produced by the boost converter.

I. INTRODUCTION

The increasing energy consumption has led to the exploration of sustainable and sources of renewable energy that remain abundant over time. These sources not only provide a solution to rising energy needs but also contribute to environmental conservation by reducing carbon emissions. Projections indicate that by 2050, renewable forms of energy are anticipated to make up 86% of the power produced, meeting Two-thirds of global energy requirements [1], [2]. The popularity of resources for distributed generation, including PV systems, is on the rise as renewable energy sources. Solar power stations, equipped with numerous photovoltaic panels, have been successfully integrated into diverse distribution networks. Furthermore, such solar power plants can also be connected, via different power transformers, to high-voltage systems. When conventional fossil fuel-powered generators are gradually replaced, equivalent power generation is transitioning to renewable resources [3]. Introducing PV panels to a network for low-voltage distributed may cause voltage elevation issues at the feeder link and within the low-voltage architecture, consequently imposing effectiveness limitations and compromising overall system dependability [4]. Establishing and adhering to a defined limit for violations is crucial to prevent the ability to accommodate solar panels in a feeder from being exceeded [5], [6].

The HC of a PV solar system denotes the highest level of solar power that can be incorporated into a particular electrical grid or distribution system without negatively impacting the system's stability and dependability. Put more simply, it signifies the grid's capability to handle extra solar generation without compromising its operational robustness [7]. This explanation is contingent on various elements, encompassing voltage surges leading to the reversal of the network's power flow, heating overloads that impact conductors and transformers, and imbalanced voltage. The assessment of a solar photovoltaic (PV) system's impact on an actual network takes into account multiple elements including topology, feeder properties, and system load conditions, and the specific installation locations of PV systems [8]. The primary issues that often limit the maximum capacity of connected photovoltaic (PV) arrays involve voltage escalation in practical low-voltage (LV) distribution network and the resulting breach of legal constraints [9].

Intelligent inverters, previously known as clever inverters, have caused an essential change in the application of Distributed Energy Resources (DER) [10]. These inverters can handle a variety of duties, including either (Volt-Var) and (Volt-Watt) management. Furthermore, processes such as controlling voltage, power factor management, actual power constraints, ramp-rate enforcement, failure ride-through, and frequency regulate are presently being demonstrated with smart inverters on actual distribution as well as transmission networks in several countries changing from DC to AC energy sources. This presentation includes many grid support routines [11].

The paper in [12] examines three different hosting capacity strategies: deterministic, stochastic, and time series. These methodologies look primarily at the impacts of a major fraction of photovoltaic PV on voltage values and the load in the lines, cables, and transformers in these networks. However, their attention is restricted to other network abnormalities. The deterministic, stochastic, and time series techniques are meant for assessing and assess the consequences of growing integration of solar electricity production on voltage ranges and load distribution [12].

The smart inverter simulation was validated utilising MATLAB SIMULINK, which included a variety of Volt-Var and Volt-Watt control functions. A Volt-Watt-Var control was developed using Model Predictive Control (MPC), and the results were compared to those obtained with a PID controller. The planned MPC control was implemented on the IEEE-9 bus, which had incorporated controllers. The study investigates the effects of various connection requirements on Photovoltaic Hosting Capacity (PVHC) to determine optimal connection solutions for managing voltage encroachment difficulties. Furthermore, the article delves deeper into the development of HC using complex inverter management functions in a low-voltage converter distribution network. Furthermore, it investigates the impact of overvoltage and low voltage on network variables [13]. When evaluating control approaches, several options merit consideration, including real power, reactive power control, and a combination of both real and inactive regulation. In comparative designed to improve solar power HC, it is evident that Volt-Var regulation outperforms coupled Volt-Var -Watt control in terms of both effectiveness and cost efficiency [4]. The hosting capacity control is greatly influenced by the smart inverter, it evaluates the enhancement of HC via control systems included in the two smart inverter and the Energy Storage System (ESS). While this system proves to be the most efficient method for enhancing hosting capacity, it comes with elevated costs attributed to challenges related to the battery system [14]. Furthermore, the enhancement of Photovoltaic Hosting Capacity (PVHC) in PV systems is achieved by incorporating a harmonic filter. A harmonic filter that is passive was specifically created to improve PVHC in low-voltage distribution networks, tackling optimization difficulties associated with problems with excess and undervoltage, transmission cable lost energy, distortion from harmonics induced by non-linear loads (such as a six-pulse rectifier), and present capabilities of the line. The outcomes demonstrate an improvement in PVHC and an rise in the system's PF, achieved by diminishing THD and TDD [15]. In [16], A unique method for harmonic filtering, particularly involving the utilization of the passive C-type filter, is introduced to enhance HC in minimal voltage electrical distribution systems. Reducing distortion values in the voltage and current outputs at a terminal associated with energy from renewable sources is the main goal of the method described in this source, with the objective of attaining the maximum HC through an innovative optimization process. This exhaustive review encompasses every facet associated with Hosting Capacity (HC), encompassing its diverse terms, references, restricting limitations within the studied systems, location categorizations, and the methodologies employed for their determination. Additionally, the review succinctly lists the elements influencing hosting capability across several systems and elucidates the structures utilized to augment it [17]. Evaluating the optimal arrangement of a distribution system with regards to its ability to integrate solar power production [10]. This passage provides an overview of research conducted on evaluating the HC for PV in LV systems. It delineates a feeder-oriented methodology devised for appraising solar PV hosting capacity, especially under constraints related to overvoltage problems in the LV systems [18].

Earlier studies in this field have predominantly focused on employing Volt-reactive and Volt-active regulation to determine the HC of a LV distribution system incorporating PV panels. However, the Model Predictive Controller is employed to ascertain the maximum level of PV integration into the grid at the Point of Connection without affecting any normal system operation.

The research gap in ascertaining a PV system's ability to host in a low-voltage distribution network via the utilization of Model Predictive Control (MPC) is twofold. Firstly, there exists a void in comprehending the performance of MPC when contrasted with well-established techniques like reactive power control or other classical control strategies. This lack of understanding impedes the ability to gauge the relative strengths and weaknesses of MPC in the specific context of hosting capacity determination. Secondly, there is a deficiency in the exploration of criteria for selecting the optimal grid performance as the penetration of PV systems increases within a minimal voltage distribution utility. The absence of a clear framework for decision-making hinders stakeholders in determining when MPC is the most suitable choice for enhancing hosting capacity under these evolving conditions.

Addressing these research gaps requires focused investigations that systematically compare the performance of MPC with traditional methods, delve into the intricacies of MPC's effectiveness, and establish decision-making criteria for optimizing grid performance amidst increasing PV penetration in low-voltage distribution grids. Such endeavors are essential for advancing the knowledge base and guiding the practical application of Model Predictive Control in this specific domain.

There are various obstacles with integrating sustainable energy resources such PV panels, wind generator, and other technologies into the electrical utility. These problems include increased harmonic distortion, voltage spikes, overheating, protection malfunctions, backward power flow, and possible network improvement. There are several ways to handle these issues, such as using harmonic filters for reduction, implementing a Model Predictive Controller (MPC), and smart inverter management (which involves reactive power, PF, real energy, and combined real and reactive management). The research introduces the utilization of Model Predictive Controllers (MPCs) to augment the integration of PV solar systems. This augmentation is aimed at increasing the Hosting Capacity (HC) of the utility, ensuring that it does not adversely impact the regular operations of the grid. The study focuses on the seamless incorporation of PV solar systems into the utility infrastructure, with MPCs serving as a tool to enhance their penetration without causing disruptions to the normal grid operations. The research also includes a comparative study between reactive power control and Model Predictive Control (MPC) in PV systems across Low Voltage (LV) distribution networks. The investigation delves into the effectiveness of employing MPC to optimize the Hosting Capacity (HC) of photovoltaic solar power. It provides insights into the performance of MPC in contrast to conventional reactive power control methods within the framework of low-voltage distribution grids.

The continuing portions of the research can be arranged as follows: After a brief overview, Part 2 outlines the steps involved in building a PV solar energy system that is linked to the utility. Part 3 investigates the fulfilment of several inverter control methods, including MPC control. Part 4 emphasises HC calculations. In Part 5, the evaluation of hosting capacity resultant for the PV system is displayed using MPC control, alongside a comparative study between inverter control techniques and MPC control. Lastly, Part 6 concluded the research and discusses possible future study paths.

II. PV SOLAR SYSTEM

Building a grid-connected PV system comprises various essential components and steps. The typical construction process includes the following key elements: Photovoltaic Modules (Solar Panels), Mounting Structure, Inverters, Electrical Wiring and Components, Grid Connection, Monitoring and Control Systems, Safety and Compliance measures, and optional Battery Storage. The construction process may vary based on the type of PV system (residential, commercial, or utility scale) and the specific requirements of the project. Professional installers, engineers, and electricians are typically involved in the construction and commissioning of PV systems to ensure safety, efficiency, and compliance with

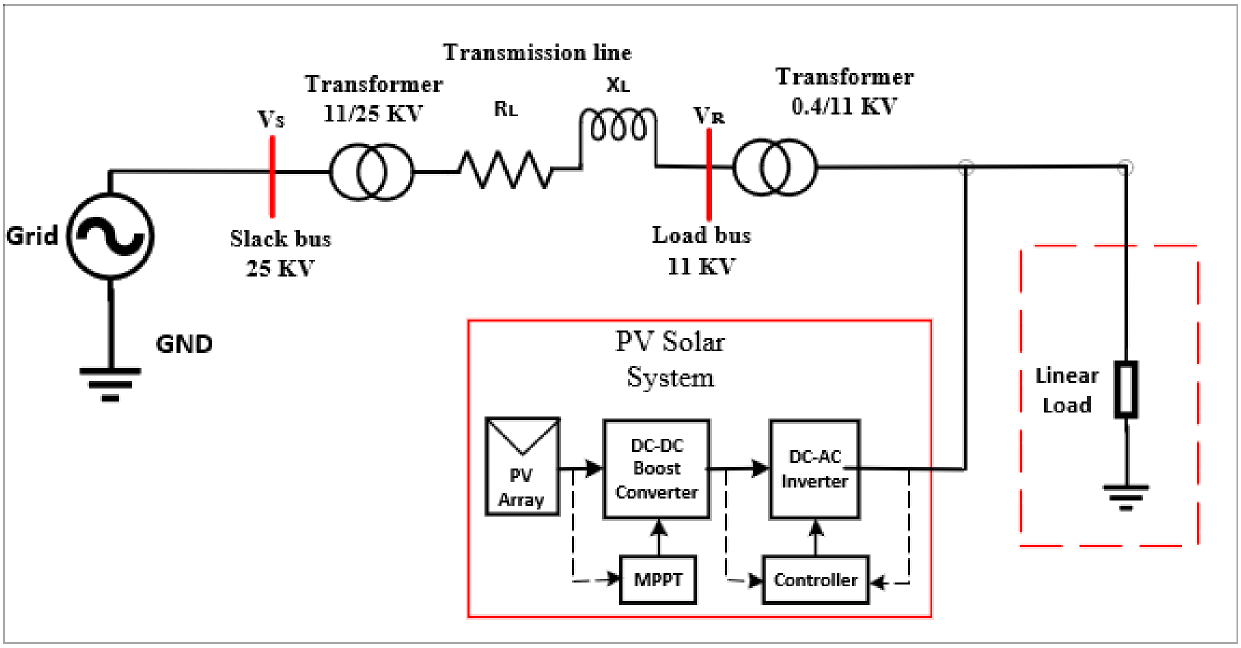

FIGURE 1. The configuration of the investigated model for the PV power system.

regulations [10]. The proposed control method will undergo validation using the system depicted in Fig. 1. This system comprises a straightforward LV distribution system that provides power to a 100 kVA PV system and a 100 kVA loading situated 5 km in a distance from the feeder. Table 1 outlines the detailed specs of the PV network, operating at its maximum capacity. The PV structure includes a suitable combination of series and parallel photovoltaic panels to provide the needed PV capacities. The operational parameters for the PV system adhere to criterion, with an irradiation level of 1000W/m^2 and a temperature of 25°C. The temperature and irradiance are maintained at specific values based on the deterministic method.

The boost converter illustrated in Fig. 2 employs a chopper topology to amplify the entry DC to a higher DC value determined by the cycle of duties. The cycle of duties, variable from zero to slightly below unity, establishes the relationship between the input and output, as described in equation (1) [19].

$$v_o = \frac{1}{1-D} * v_{in} \tag{1}$$

where, v_o represents the output voltage of the boost converter, D signifies the duty cycle, and v_{in} denotes the supplied voltage of the boost conversion.

The primary interface components connecting the PV panels and the network consist of a DC/DC conversion and a DC/AC inverter. To ensure optimal power production from the PV resource, the perturbation and observation MPPT procedure is employed to regulate the DC/DC chopper. The electricity generated is then conveyed to the AC side through an inverter. Various aspects of inverter regulate involve utility synchronicity, DC link voltage equilibrium, and real inactive power requirement. A standard approach involves adjusting the inverter current for the simultaneous regulation of both real and reactive energy [20].

The DC/DC converter is regulated by the MPPT algorithm to ensure optimal power production from the PV source. Electric power generated is then converted to the AC edge using an inverter. Examples of inverter regulation tasks encompass network synchronization, Voltage balancing for DC links, and the regulation of real/inactive power. Modifying the inverter current is a conventional practice for simultaneously controlling both active and reactive power [20].

III. TYPES OF CONTROL

Different controlling techniques are available to augment the HC of solar power in LV distribution systems. This section illustrates the application of reactive power regulation and model predictive control for enhancing the hosting capacity.

A. CLASSIC CONTROL AND VOLT-VAR CONTROL

Classic control generally denotes traditional or conventional control methods established prior to the emergence of modern control theory and digital control systems. It is commonly linked with linear control systems and methods that do not extensively depend on sophisticated mathematical tools such as state-space analysis. In the context of this study, classic control is specifically represented by the PI controller. This involves the adjustment of proportional and integral components to regulate the system response.

In this operating mode, the photovoltaic (PV) inverter is utilized to either way, inject or absorb reactive surpasses the preset upper limit (*V4*), the inverter absorbs reactive power to mitigate the voltage at the PCC [20].power based on the

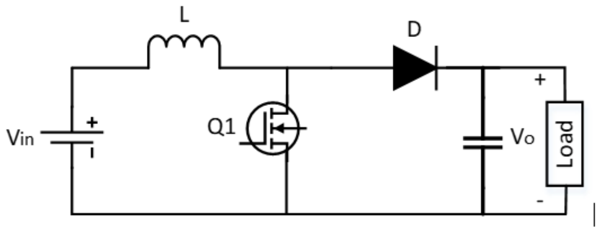

FIGURE 2. Boost converter.

TABLE 1. Parameters of a photovoltaic (PV) solar system.

Characteristic	Magnitude
PV Capacity	100 KW
PV Power Panel	305 W of solar energy
Current of Panel at MPP	5.58 A
Voltage of Panel at MPP	54.7 V
Limitations on Brightness	1000 W/m2
Quantity of Series Modules	5
Quantity of Parallel Strings	66
Weather	25^0C
Transformer for Distribution	100KVA(0.4/11)kV
Supply Distance	5 km
Step up transformer	47 MVA (25/125)kV
Line resistance	0.754Ω/km
Line inductance	0.25 mH/km
Static Load	10 kVA

voltage at the point of common coupling (PCC) [21]. The compensated reactive power is determined by the user/utility-defined Volt-Var setpoints. Fig. 3 depicts a generic Volt-Var curve. According to the curve, when the terminal voltage falls below the predefined lower bound (*V3*), the inverter injects reactive power to bolster the voltage at the connection point. Conversely, if the terminal voltage

The mathematical expression for the injection of reactive power through Volt-Var control is represented in Equation (2).

$$Q(t) = \begin{cases} Q_{\max(t)} & V_{(t)} \leq V_2 \\ \dfrac{V_3 - V_{(t)}}{V_3 - V_2} * Q_{\max(t)} & V_2 < V_{(t)} \leq V_3 \\ 0 & V_3 < V_{(t)} \leq V_4 \\ -\dfrac{V_4 - V_{(t)}}{V_4 - V_5} * Q_{\max(t)} & V_4 < V_{(t)} \leq V_5 \\ -Q_{\max(t)} & V_{(t)} > V_5 \end{cases} \tag{2}$$

where, $V_{(t)}$ denotes the terminal voltage, and $Q_{(t)}$ represents the reactive energy injection determined by the Volt-Var regulation.

The block diagram in Figure 4 illustrates the fulfilment of reactive energy regulation in a low-voltage distribution network, aiming to develop the HC of the PV model. The DC voltage measurement is contrasted with the DC benchmark, and the outcome an error indicator undergoes amplification through a gain. The PI regulator is utilized to rectify the malfunction indicator and make *Id-ref*. For reactive energy

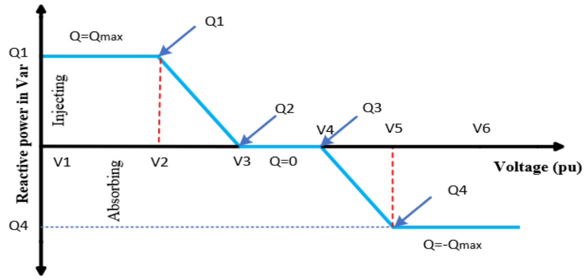

FIGURE 3. Reactive power control curve.

control, a comparison is made between the measured voltage at the busbar (Bus) and the reference AC voltage. A suitable controller rectifies the erroneous signal, resulting in the production of *Iq-ref*. The controller operates within specified highest and lowest Values. To evaluate the effectiveness of the devised reactive power management approach to increase capacity for hosting, simulation experiments are conducted using MATLAB/Simulink.

B. MODEL PREDICTIVE CURRENT CONTROL (MPCC)

Model Predictive Control (MPC) stands out as a widely adopted approach for addressing challenges related to constrained control utilising multiple parameters. The MPC controller is conceptualized as a supervisor generating a sequence of making decisions parameters with the aim of optimizing a cost function over a future time span referred to as the control horizon. Once the optimal control is identified, the collection of command windows is shifted to the next stage, where the command action is executed. Subsequently, a new observation is introduced to modify the control action over the subsequent control horizon.

The MPC control scheme is typically depicted in the model for a power converter, as illustrated in Figure 5.

In grid-connected photovoltaic (PV) systems, a standard three-level, three-phase converter is employed. The primary function of MPC is to assess the disparity between the requirements of reference and the actual values of the output currents through the control strategy in use today. Consequently, a cost function is working to compute the discrepancy between the anticipated and reference currents over a defined range, as depicted below.

$$G = \left| i_{dref}\,(k+1) - i_d\,(k+1) \right| + \left| i_{qref}\,(k+1) - i_q\,(k+1) \right| \tag{3}$$

where; $i_d\,(k+1)$, and $i_q\,(k+1)$ are the actual and imaginary constituents' respective predicting currents in a similar vein, $i_{dref}\,(k+1)$ and $i_{qref}\,(k+1)$ The reference currents pertain to both real and imaginary components. The correlation between the voltages of grid-connected inverters and line currents relies on Equation (4).

$$\begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} = \mathrm{R_f} * \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \mathrm{L_f} * \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \tag{4}$$

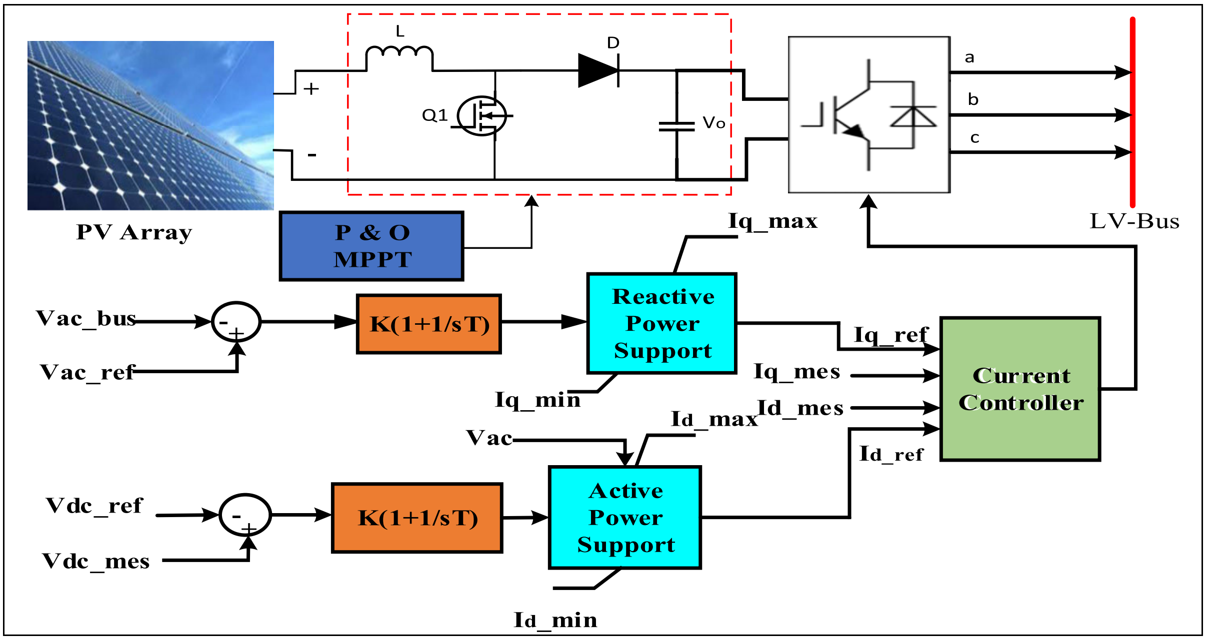

FIGURE 4. The schematic diagram illustrating reactive power control.

where e_a, e_b, and e_c represent inverter output voltages, v_a, v_b and v_c represent utility voltages, i_a, i_b, and i_c depict three-phase currents, and L_f and R_f depict inductance and resistance of the filter, respectively. Eqs. (5) and (6) describe the rotating reference frame synchronized with the grid voltage vectors.

$$V_d = e_d - R_f * i_d - l_f * \frac{di_d}{dt} - \omega * l_f * i_q \quad (5)$$

$$V_q = e_q - R_f * i_q - l_f * \frac{di_q}{dt} - \omega * l_f * i_d \quad (6)$$

Here, e_d and e_q denote the d-axis and q-axis components of the inverter voltage, vd and v_q represent the d-axis and q-axis elements of the grid voltage, id and iq stand for the d-axis and q-axis currents injected into the grid, and omega represents the angular frequency of the utility.

IV. HOSTING CAPACITY CALCULATION

The term "hosting capacity" generally refers to the ability of an electricity grid or power system to integrate and accommodate additional distributed energy resources (DERs) such as solar panels, wind turbines, and other forms of renewable energy. The hosting capacity is essentially the maximum amount of distributed generation or load that can be added to a specific location on the grid without causing reliability issues or exceeding certain technical limits.

The calculation of hosting capacity involves various technical factors and considerations, and it can vary depending on the specific characteristics of the grid and the location in question. Some key factors that are typically taken into account in hosting capacity calculations include voltage Limits, load Levels, line and transformer capacity, grid configuration, and power quality constraints [22], [23].

The calculation for determining the HC of a LV distribution system can be expressed through the following formula [17].

$$HC(\%) = \frac{P_{PV}}{S_{rated}} * 100 \quad (7)$$

where, P_{PV} represents the quantity of solar PV production, and S_{rated} corresponds to the nominal apparent energy of the load connector.

The HC equation, whether juxtaposed with two controls or in comparison with a single control [4].

$$Hosting\ Capacity\ Equation\% = \frac{HC\ (with) - HC\ (without)}{HC\ (without)} \quad (8)$$

In equation (8), HC (with) represents the watt value when control is applied, while HC (without) denotes the watt value without control.

The system's hosting capacity is constrained by different performance indicators, including voltage constraints at the connected bus, thresholds for Total Harmonic Distortion (THD) for voltage as same as current, the line of current capabilities, the maximum penetration of the photovoltaic (PV) connected to the load bus, and the scope of PF constraint. This can be succinctly condensed follows:

A. VOLTAGE BUS LIMITATION

The bus of the voltage at the PCC is restricted by two possibilities of values, with the lower limit set at 0.95 per unit (pu) and the higher limit at 1.05 pu [24], [25]. The constraints on the root mean square (rms) magnitude the difference in electric

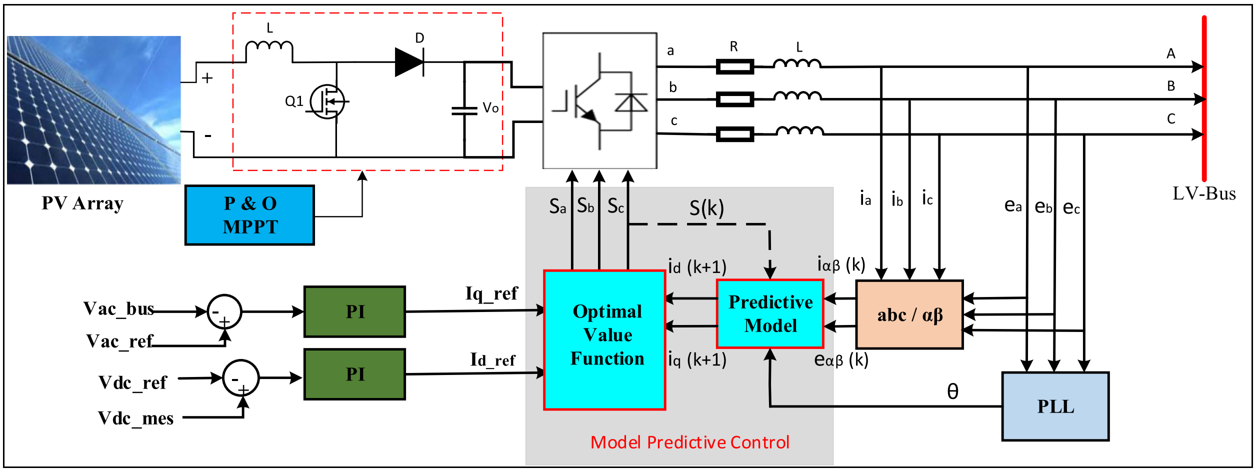

FIGURE 5. The diagram depicts the application of model predictive control in a photovoltaic (PV) system.

potential can be expressed as:

$$0.95 \leq \sqrt{\sum_{h=1}^{h=\infty} V_{S2}(h)} \geq 1.05 \tag{9}$$

B. TOTAL HARMONIC DISTORTION (THD)

In accordance with IEEE Std. 519 [26], the maximum allowable total voltage of harmonic distortion at the PCC is 5%. The THD voltage formula is detailed in formula (10) as:

$$THD(\%) = \frac{\sqrt{\sum_{h=2}^{\infty} |V_{S2}(h)|^2}}{V_S(1)} \leq 5\% \tag{10}$$

C. TOTAL DEMAND DISTORTION (TDD)

This measure is used to assess the harmonic properties of transmission cables, considering the attendance or lack of distributed generators (DGs). Compliance with IEEE Std. 519 sets the permissible level of TDD in a system. The determination involves factors like the maximum load current (Is_2), fault limit, and the specific DG scheme, encompassing distributed generation, network distribution producing machine, or a customer net [24]. The TDD percentage within the system should not exceed 8%, as specified in Equation(11).

$$TDD(\%) = \frac{\sqrt{\sum_{h=2}^{\infty} |I_{S2}(h)|^2}}{I_{S2}(1)} \leq 8\% \tag{11}$$

D. INDIVIDUAL TOTAL HARMONIC DISTORTION

In accordance with IEEE Std. 519, the harmonic distortion for each individual order of voltage at the PCC should not exceed 3% when operating at voltages less than or equal to 69 kV. The harmonic content for each unique order of current is constrained to different magnitudes, as illustrated in Table (2). Equations (12 and 13) delineate the individual voltage and current, respectively.

$$IHDV(\%) = \left[|\frac{V_{S2}(h)}{V_{S2}(1)}| \right] \leq 3\% \tag{12}$$

$$IHDC(\%) = \left[|\frac{I_{S2}(h)}{I_{S2}(1)}| \right] \leq according\ table\ (2) \tag{13}$$

E. POWER FACTOR (PF) LIMITS

The improvement in power change quality from the source to the load is achieved by maintaining the Power Factor (PF) at the PCC within a specified range, as defined by minimum and maximum limits [27]. This range is articulated in Equation (14).

$$PF = \frac{P}{S} = \frac{\sum_{h=1}^{\infty} P(h)}{\sum_{h-1}^{\infty} S(h)} \tag{14}$$

$$\text{where, } 0.9 \leq PF \leq 1 \tag{15}$$

The flow chart of determine the hosting capacity in low voltage distribution utility are show in fig.6.

V. RESULTS FROM THE SIMULATION

The outcomes of the hosting capacity investigation for PV scheme can be categorized into triple segments. The initial segment assesses the situation in the PV scheme is linked to the grid with classic control. The second segment investigates the application of Volt-Var regulation to tackle concerns such as voltage rise, power factor, Total Harmonic Distortion (THD), and Total Demand Distortion (TDD) at the PCC. Finally, the third segment delves into the application of model predictive control (MPC) to enhance the hosting capacity of the system.

A. THE PHOTOVOLTAIC SYSTEM EMPLOYING TRADITIONAL CONTROL

Fig. 7 illustrates the outcome of a 100-kW photovoltaic (PV) system linked to the network, employing conventional regulation. The real power of the PV system rose from zero to 100 kW within the first 6 seconds, reaching a penetration level of 100% by the 6th second. However, it did not surpass 200 kW due to the utilization of classic control. Throughout this period, reactive power remained consistently at zero.

TABLE 2. The highest particular degree harmonic of current, as defined by IEEE Standard 519 [26].

Harmonic degree	IHDC%
h <11	7
$11 \leq h < 17$	3.5
$17 \leq h < 23$	2.5
$23 \leq h < 35$	1
$35 \leq h$	0.5

The system exhibits a unity power factor since it neither absorbs nor injects reactive power. However, it's important to note that the bus voltage was initially set at 1 per unit (pu) before integration. Despite this, raising the bus voltage to 1.43 pu led to an increase in THD, TDD, higher losses, and reversed power flow.

B. THE PHOTOVOLTAIC SYSTEM INCORPORATING REACTIVE POWER CONTROL

The results concerning the real power, reactive energy, and bus voltage of a photovoltaic (PV) system linked to a network with reactive power control are illustrated in fig (8). The real power registers at 98.5 kW prior to the 6-sec. By the 6th second, the PV penetration surges by 100%, yet the system falls short of reaching 200 kW. Additionally, the reactive power draws 39 kV from the grid, lowering the bus voltage from 1.43 pu to 1.2 pu also out of range or voltage limitations according to the code. Consequently, the bus voltage experiences a 16% improvement. The HC of PV scheme in LV distribution interconnect stands at 48.5%. The PF of the system is lower to 0.966 compared to classic control, but there is an improvement in the voltage profile.

C. THE PV SYSTEM WITH MPC CONTROL

Fig. 9. illustrates the results pertaining to the actual power, inactive power, and linked voltage of a photovoltaic (PV) system linked to a utility employing a model predictive controller. The active power remains constant at 95.5 kW for the initial 6 seconds. At the 6-sec, the PV system penetration increases by 100%, elevating the actual power from 95.5 kW to 192 kW. Consequently, the HC of the PV system sees a notable 101.05% increase.

The reactive power drawn from the grid decreases from 39 kVar under volt-var control to 32 kVar with the MPC controller, marking a reduction of 17.9%. Additionally, the bus voltage improves from 1.2 pu in volt-var control to 0.98 pu with the MPC controller, indicating an 18.3% enhancement. The PF of the system at low voltage bus is equal to 0.986 is improve by 2.11% comparative to reactive power regulation.

Fig. 10 illustrates the voltage bus and line current of the system. The voltage at the bus remains almost constant both prior to and following the integration of the PV solar system into the LV distribution network. However, there is an increase in current after integration, resulting in a subsequent rise in active power generated by the PV system.

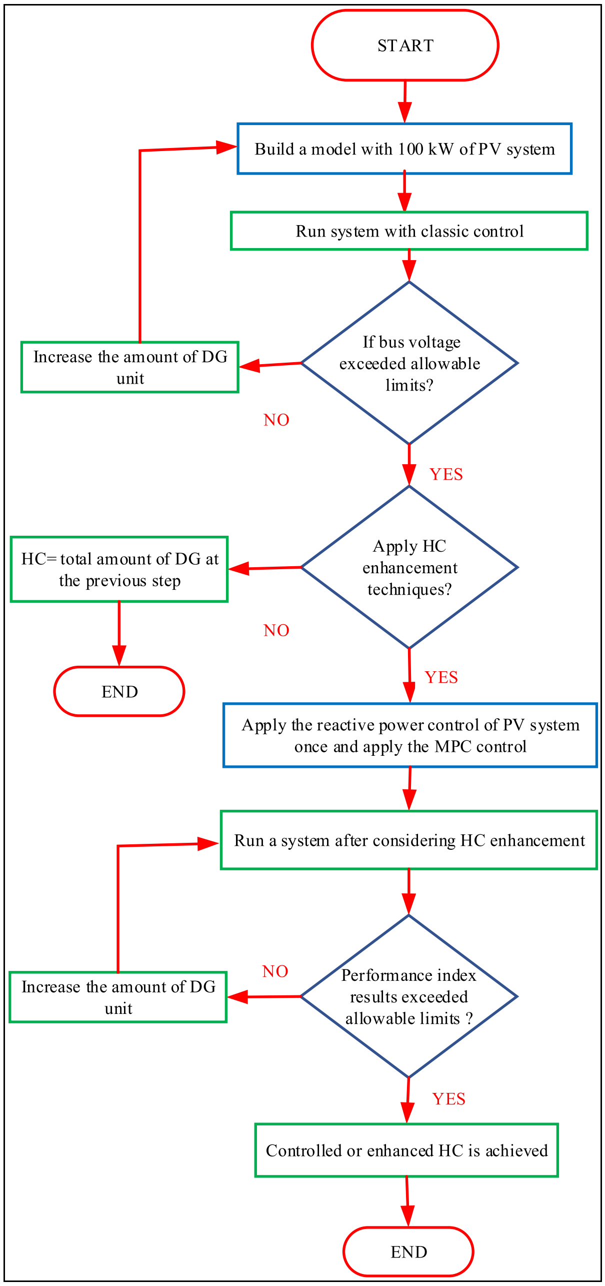

FIGURE 6. The organizational chart depicting the process of the system.

D. THE SYSTEM WITH NON-LINEAR LOAD

The initial segment of this section examines the system under various controls, including classic control, volt-var control, and MPC control, exclusively employing linear loads. The subsequent part of this section explores the impacts of both non-linear and linear loads on the low-voltage distribution system, employing various inverter controls.

Non-linear loads are electrical loads characterized by the absence of a linear correlation between voltage and current. To put it differently, the current waveform deviates from a proportional alignment with the voltage waveform. Non-linear loads draw current in a distorted or nonlinear manner when compared to the sinusoidal voltage waveform. This

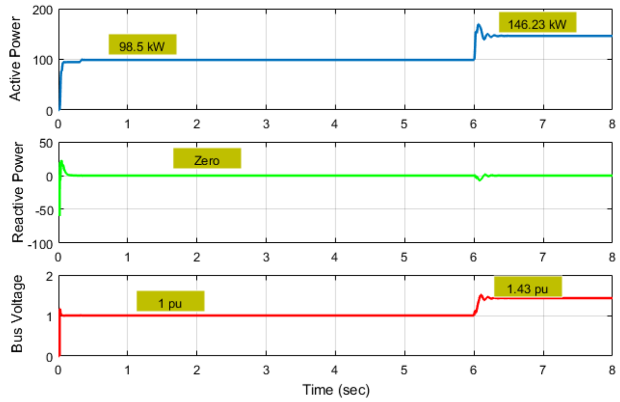

FIGURE 7. Displays the outcomes pertaining to the real power, reactive power, and voltage of the bus of a photovoltaic (PV) system related to a grid under classic control.

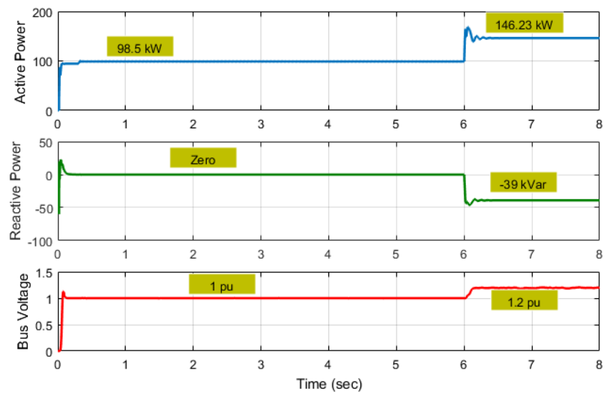

FIGURE 8. Displays the outcomes pertaining to the real power, inactive energy, and the voltage at bus of a photovoltaic (PV) system tied to a network under reactive power control.

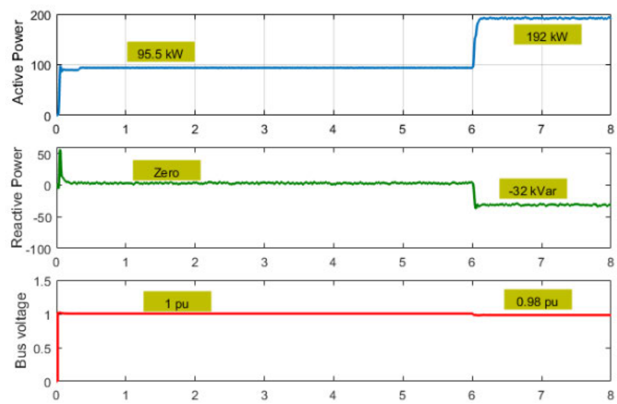

FIGURE 9. Displays the outcomes pertaining to the actual power, inactive energy, and bus voltage of a photovoltaic (PV) system tied to a grid under MPC control.

distortion commonly arises from electronic devices housing nonlinear elements, including rectifiers, power converters, and other equipment incorporating semiconductor devices. The non-linear load of the system is consisted of six pulse rectifiers. The non-linear load is equal to 10 kVA.

Fig 11 depicts the real power, inactive power, and bus voltage in a PV system connected to the grid using various controllers. In Fig 11(a), the real power is illustrated under classic control, Volt-Var control, and MPC control, considering both linear and non-linear loads. It is noteworthy that active power remains constant with MPC control but decreases with Volt-Var or classic control. This suggests that MPC enhances the active power profile, irrespective of load type.

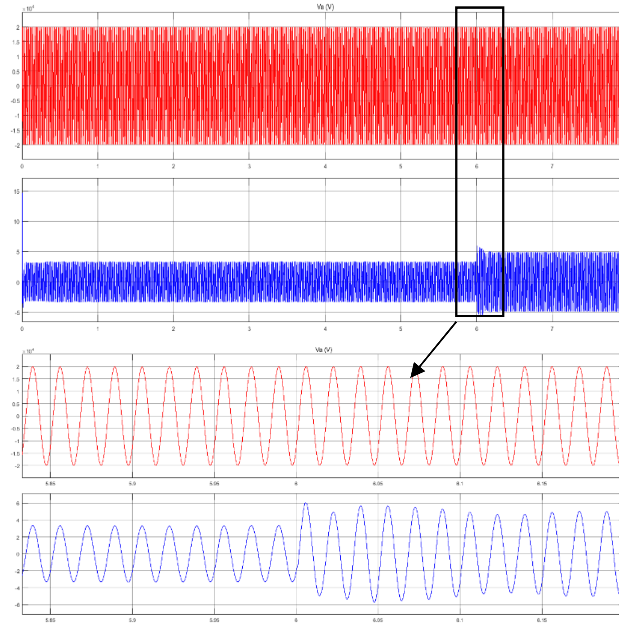

FIGURE 10. The bus voltage and line current within the system.

TABLE 3. The THD and TDD with different controls.

	THD	TDD
Classic Control	20.33%	12.4%
Volt-Var Control	8.17%	5.23%
MPC Control	7.36%	4.8%

Fig 11(b) details the reactive power under the three different controllers. The reactive power of MPC control shows lower absorption from the grid compared to the other two controller types. Additionally, fig 11(c) presents the bus voltage under different controller types. The voltage remains constant when using non-linear loads.

Table 2 presents a comprehensive overview of the total harmonic distortion (THD) and total demand distortion (TDD) across various control methods. In the context of classic control, both THD and TDD surpass the established system limits, underscoring inherent limitations associated with this control approach. Despite the positive influence of reactive power control on improving THD and TDD, it falls short of bringing these parameters within the acceptable range.

Furthermore, the implementation of MPC control results in additional enhancements to both THD and TDD. This suggests a substantial impact of MPC control on the distortion characteristics of the system. For a more intricate analysis, Fig. 12 visually represents individual harmonic distortion,

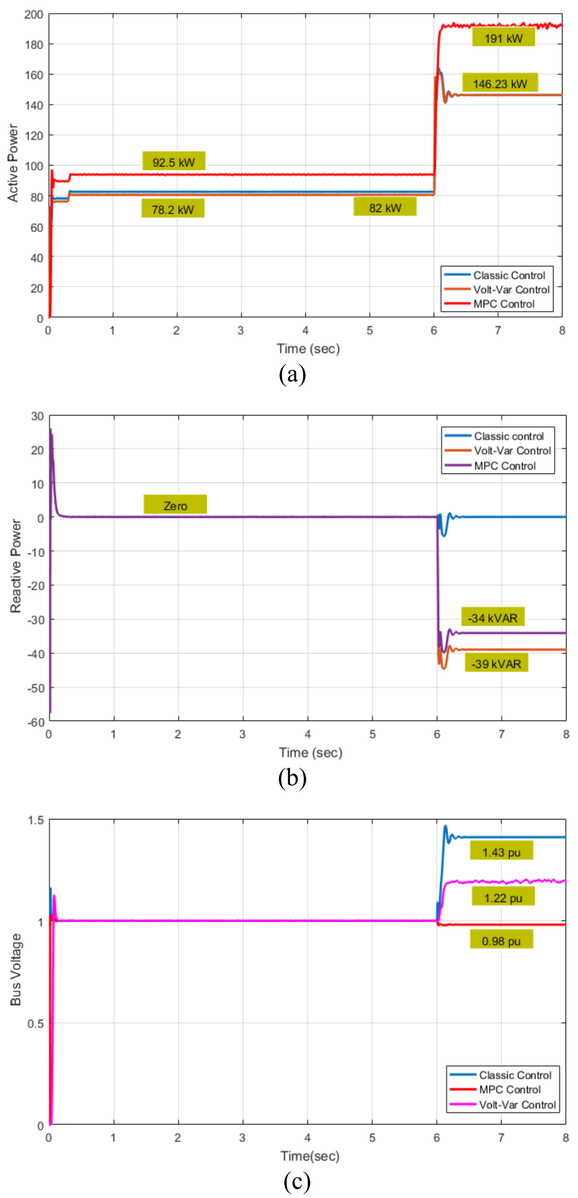

FIGURE 11. Illustrates the variations in actual power, inactive power, and bus voltage under different control scenarios when non-linear loads are employed.

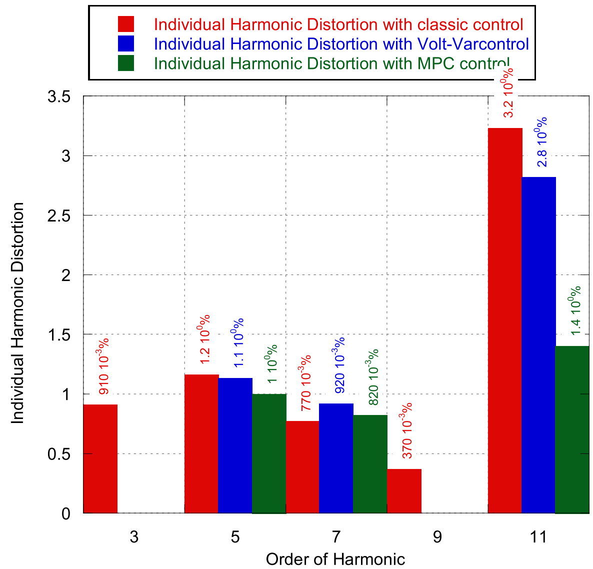

FIGURE 12. Individual harmonic distortion.

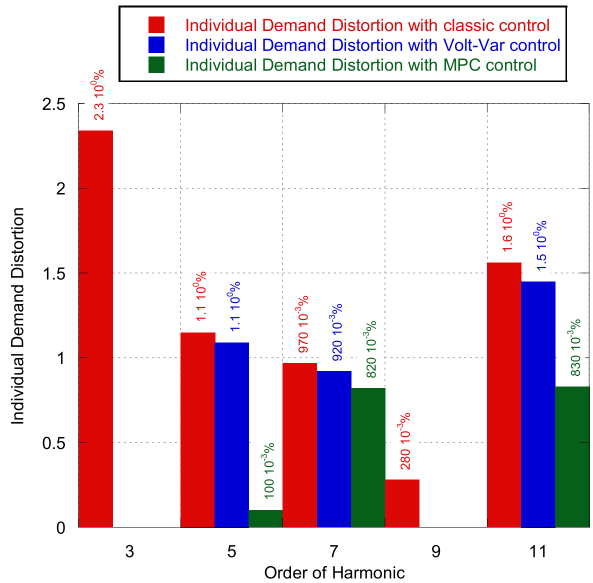

FIGURE 13. Individual demand distortion.

providing insights into the specific harmonic components contributing to the overall distortion. Similarly, Fig. 13 illustrates individual demand distortion, offering a visual representation of the factors influencing the total demand distortion in the system. These visualizations contribute to a more nuanced understanding of the distortion characteristics under different control strategies.

VI. CONCLUSION

In conclusion, the application of a model predictive controller (MPC) has demonstrated remarkable effectiveness in improving the hosting capacity (HC) of a photovoltaic (PV) system within a low-voltage (LV) distribution network. A thorough examination comparing MPC with reactive power control and traditional control reveals that MPC notably enhances crucial performance indicators, particularly when dealing with both linear and non-linear loads.

The stability exhibited by the active power under MPC control, maintaining constancy at 95.5 kW before experiencing a substantial increase to 192 kW with a 100% PV system penetration, demonstrates the remarkable adaptability and responsiveness of the MPC controller. This surge in active power translates into a notable 101.05% increase in hosting capacity, showcasing the potential for accommodating higher levels of PV system integration.

Furthermore, the transition from volt-var control to MPC control manifests tangible benefits in terms of reactive power management. The reduction in reactive power from 39 kVar to 32 kVar, a 17.9% decrease, signifies the MPC controller's ability to optimize reactive power utilization efficiently. The concurrent enhancement in bus voltage, from 1.2 pu to 0.98 pu, reflects an 18.3% improvement, contributing to a more stable and resilient low voltage distribution grid.

When considering both linear and non-linear loads, the MPC controller outperforms reactive power control, showcasing its adaptability in diverse operating conditions. The MPC controller not only meets but surpasses expectations in terms of efficiency, stability, and hosting capacity, making it a promising solution for the effective integration of PV systems into low voltage distribution grids. This study underscores the significance of advanced control strategies, such as MPC, in optimizing the performance of renewable energy systems and ensuring the sustainable and reliable operation of distribution grids.

DECLARATIONS

ETHICAL APPROVAL

Not Applicable

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The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

AVAILABILITY OF DATA AND MATERIALS

"not applicable"

AUTHOR CONTRIBUTIONS

We declare that the manuscript entitled " Highly Efficient Machine Learning Approach for Automatic Disease and Color Classification of Olive Fruits" is original, has not been full or partly published before, and is not currently being considered for publication elsewhere.

We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order updating of authors listed in the manuscript has been approved.

We understand that the Corresponding Author is the sole contact for the editorial process. The corresponding author "M. Mourad Mabrook" is responsible for communicating with the other authors about process, submissions of revisions, and final approval of proofs.

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CONFLICTS OF INTEREST

Not Applicable (NA)

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