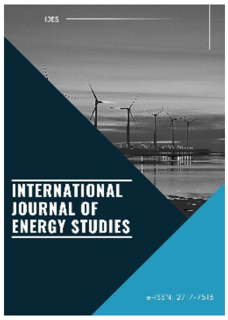
INTERNATIONAL JOURNAL OF ENERGY STUDIES

e-ISSN: 2717-7513 (ONLINE); homepage: https://dergipark.org.tr/en/pub/ijes



Research Article

Int J Energy Studies 2024; 9(3): 543-558

DOI: 10.58559/ijes.1449558

Received : 09 Mar 2024

Revised : 06 May 2024

Accepted : 18 July 2024

Improve LVRT capability of organic solar arrays by using chaos-based NMPC

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Highlights

- Low voltage ride through.
- Organic photovoltaic.
- Chaos theory.
- Non-linear model predictive control.

You can cite this article as: Elmi MMB, Yildirim O. Improve LVRT capability of organic solar arrays by using chaos-based NMPC. Int J Energy Studies 2024; 9(3): 543-558.

ABSTRACT

Electric utilities are continuously scheduling to develop power grids in order to supply the electrical energy demanded by their consumers. The common method is the construction of traditional power plants or development of existing infrastructures. The challenges associated with using fossil fuel, such as environmental pollution and climate changing like glacier melting and rising sea levels, highlight the importance of using green energy sources like photovoltaic systems. In other side, extracting the maximum power under intermittent generated power has a great importance. So, a novel chaotic-based nonlinear model predictive control method is introduced for tracking the maximum power point of organic photovoltaic cells. The proposed approach involves estimating a reference point and adjusting the operating point by using a Lagrangian function. Also, chaotic-based nonlinear model predictive controller is used for controlling the operation of boost converter. According to obtained results, the proposed approach capable of fast tracking as well as improving the ride through capacity.

Keywords: Low voltage ride through, Chaos theory, Non-linear model predictive control, MPP tracking

1. INTRODUCTION

In the past years, the capacity of photovoltaic (PV) arrays used in the power system has grown significantly. According to the report of the European Photovoltaic Industry Association (EPIA), the amount of installed PV system capacity has increased to about 345 GW by 2020 [1]. With the increase in the penetration of clean renewable sources, there are concerns about their effect on power quality indices, reliability, stability against possible faults and network losses [2]. For instance, a sudden drop in the voltage level can activate the islanding mode and lead to the isolation of PV systems from the main grid. In fact, an adaptive control model not only can reduce power quality problems but also provide a reliable performance for transient stability [3]. Although the traditional methods for controlling the performance of solar arrays have a simple implementation, they have disadvantages such as slow tracking, continuous fluctuations even when reaching the maximum power point (MPP), low efficiency and lack of proper control in the transient states [4]. According to the literature review, model predictive controller (MPC) based MPPT methods present a unique performance that increases operational efficiency and improves the speed of convergence for tracking the reference point [5] (Table 1). In [6-7], the MPC as a model-based control method has achieved remarkable success in industrial applications, especially in variable working conditions and the presence of limitations. In addition, these approaches have a fast dynamic response. This controller has been improved in recent decades.

Table 1. Comparison of different MPPT methods

Mppt Method	Speed	Accuracy	Sensor Type	Cost	Status	Complexity	Characteristic
VOC	Medium	Low	Voltage	Low	Offline	Simple	Linear
ISC	Medium	Low	Current	Low	Offline	Simple	Linear
P&O	Medium	Medium	Voltage Current	High	Online	Simple	Linear
INC	High	Good	Voltage Current	High	Online	Medium	Linear
ANN	High	Medium	Voltage Current	High	Online	Complex	Non-linear
Fuzzy	Medium	Medium	Voltage Current	Low	Online	Complex	Non-linear
MPC	High	Medium	Voltage Current	Low	Online	Simple	Linear

A brief overview of predictive model controller applications and techniques can be found in [8]. However, at the presence of severe variations in the environmental conditions and undesired disturbances, using a linear model for approximation can not provide the necessary efficiency. In this situation, the nonlinear model can be used to provide a proper mapping between the current conditions and the future outputs of the system according to the records of the system's past information. Using of chaos theory is also increasing the speed of convergence with improving the exploring ability in search space. The main contributions of this paper are as follows:

- Control the performance of boost converter under normal and fault conditions with using non-linear model predictive controller.
- Managing the injected active and reactive power simultaneously
- Regulating the voltage amplitude of the low voltage network under fault conditions to prevent from isolation of the main grid and inject the reactive power for improving the power quality.
- Control of PWM’s converter performance under fault conditions with using logistic map
- Improving the low voltage ride through capability in the presence of voltage sag condition

In the rest of the article, first, details about organic PVs, nonlinear model preictive controller, chaos-based systems are presented. Then the characteristics of the proposed approach include how to generate reference values, the designed process for regulating the operating point of the converter, The mathematical model of organic PV and Boost converter is stated and the objective function is expressed. Finally, the obtained results are presented in the form of figures and after evaluating the efficiency of the proposed approach, the conclusion is stated.

2. BASIC CONCEPTS

2.1. Organic Photovoltaics

An organic photovoltaic (OPV) cell consists of an absorber-receiver layer connected to transmission layers. Electrical contacts are used on both sides of the absorbent layers. This layer absorbs the incoming photons and if the energy absorbed from the electrons is greater than their band gap, excitation occurs. This excitability causes the occurrence of current between the layers [9]. The specifications of the different models are compared with each other in Table 2.

Table 2. Comparison of organic PV characteristics

Model	No. of Parameters	Complexity	Ref.
One Diode	5	Low	[10]
Two Diodes	7	Medium	[11]
Two Inverted Diodes	8	Medium	[12]
Three Diodes	9	High	[13]

2.2. Nonlinear Model Predictive Controller

Although the traditional methods have a simple implementation, they have disadvantages such as slow tracking, constant fluctuations even when reaching the maximum power point, and low efficiency. In this regard, several solutions have been proposed to overcome the above challenges. But these methods, unlike linear systems modeling methods, did not provide a specific method to identify the system. In this project, the chaotic-based non-linear model predictive controller (CNMPC) approach will be used, which has several advantages, some of which are as follows:

- The ability to explore precisely among various operating states of the system
- Providing the necessary flexibility to control complex systems
- Improving the level of system stability during disturbances

2.3. Chaotic Systems

Chaos is a fundamental concept in modern science, which is observed in many phenomena of the real world, including systems with apparently random and disorderly behavior, as well as systems with definite behavior. The main essence of chaos theory is that there is order in every disorder. In the sense that order should not be sought on a small scale. Excessive sensitivity to initial conditions and having a continuous frequency spectrum are special characteristics of the dynamic behavior of chaotic systems [14]. In recent years, random value generation has been combined with chaotic mappings to use their better dynamic and statistical properties. Indeed, chaotic mapping is applied in the main structure of these proposed algorithms in order to improve the process of generating random numbers for improving the exploring capability [15].

3. PROBLEM MODELLING

3.1. Estimation of Reference Values

In MPC techniques, discrete equations of the system are used to predict the future state of the controlled variable. In the case of the solar array, designing an accurate model of the system at each time step is a very challenging task due to the presence of various effective factors that change continuously. Among these factors, variable solar irradiations, sudden temperature changes, and erosion of PV modules can be mentioned. In order to improve the performance efficiency, a predictor model with Lagrange polynomial transform function is used to model the power-voltage (P-V) curve whose characteristics are stated in Equation (1). Also, the Vandermonde matrix also is used to determine the values of the coefficients, which are defined according to Equation (1) [16]. These coefficients are updated at each step to obtain an accurate estimation for the P-V curve in any weather condition. In fact, it is necessary to model the variations of environmental conditions continuously in predictor model. Then the obtained points are applied to the control system for tracking. Also, in this paper, the logistic map is used to improve the search process of extracting the global optimal point. In this mapping, a second-order polynomial function is used according to Equation (3). In this relation, r is the control parameter ($0 \leq r \leq 4$) and x_0 is the initial value ($0 \leq x_0 \leq 1$).

$$v_{pv}(k) = a_2 . i(k)_{pv}^2 + a_1 . \; i_{pv}(k) + a_0 \tag{1}$$

$$\begin{bmatrix} i(k-2)_{pv}^2 & i_{pv}(k-2) & 1 \\ i(k-1)_{pv}^2 & i_{pv}(k-1) & 1 \\ i(k)_{pv}^2 & i_{pv}(k) & 1 \end{bmatrix} \begin{bmatrix} a_2 \\ a_1 \\ a_0 \end{bmatrix} = \begin{bmatrix} v_{pv}(k-2) \\ v_{pv}(k-1) \\ v_{pv}(k) \end{bmatrix} \tag{2}$$

$$x_{k+1} = r . x_k (1 - x_k) \tag{3}$$

3.2. Regulating the Operating Point

In this project, the combination of chaotic neural network with non-linear MPC system is used to track the reference values according to the conditions created in each time step and received values from predictor model. In this project, the boost converter is used to achieve high voltage gain, and the dynamic model of the converter's behavior is described by Equation (4) to Equation (5). In these equations, s indicates the switching mode, $v_c(t)$ is the capacitor voltage and $v_{pv}(t)$ is the PV array voltage. In other words, the control process in the proposed CNMPC controller can be described as follows:

- Determining the reference for active/reactive powers
- Calculation of the reference current of the controller
- Determination of predicted current
- Apply two currents to the cost function

- Selecting the desired voltage as the controller voltage reference by applying the cost function
- Calculation of switching pattern

$$L\frac{di_L}{dt}(t) = -(1-s)v_c(t) + v_{pv}(t) \tag{4}$$

$$C\frac{dv_c}{dt}(t) = (1-s)i_L(t) + \frac{1}{R}v_c(t) \tag{5}$$

3.3. Organic PV Model

In recent years, several models such as single diode, two and three diode models have been introduced for organic PV cells [17]. Although single-diode and double-diode models are commonly used to model silicon PV cells, they can not provide proper results for describing the behavior of organic cells. So, the model of two inverted diodes is used for this purpose (Figure 1). The related equations are stated in Equation (6) to Equation (10). The current-voltage characteristic of the organic PV is described by Lambert W function. In these equations, V_{D1} and V_{D2} indicate the voltage of diode D_1 and D_2, respectively.

$$V_{D1} = V - IR_s - V_{D2} \tag{6}$$

$$I = \frac{1}{R_s + R_{sH1} + R_{sH2}}[-(I_{ir} + I_{D1})R_s + (I_{D2}.R_{sH2}) - V] \tag{7}$$

$$V_{D2} = (I - I_{D2}).R_{sH2} \tag{8}$$

$$I_{D1} = I_{o1}\left[e^{\frac{V-IR_S-V_{D2}}{n_1V_T}} - 1\right] \tag{9}$$

$$I_{D2} = I_{o2}\left[e^{\frac{V_{D2}}{n_2V_T}} - 1\right] \tag{10}$$

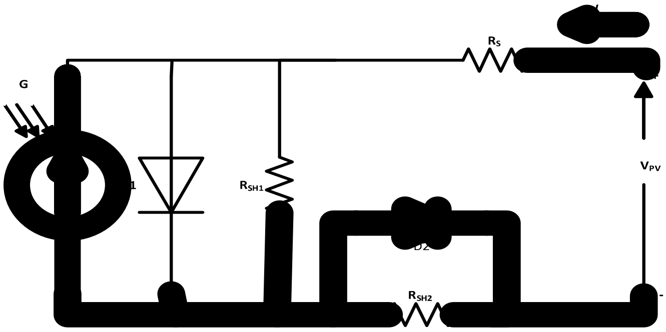

Figure 1. Two diode model of organic PV [18]

3.4. Boost Converter Model

A boost converter is a step-up converter that is usually used to convert voltage from low levels to higher levels. The schematic of this converter is shown in Figure 2. In order to extract the maximum power at each time step, the designed signal commands are applied to this converter. In this project, a discrete-time model is used for modelling of the converter. In this regard, the inductor current is estimated for the next time step and then the obtained results are evaluated. According to the designed model, Equation (11) and Equation (12) are presented the ON state and Equation (13) and Equation (14) are presented the OFF state of the converter.

$$i_{pv}(k+1) = i_{pv}(k) + \frac{T_s}{L}\left(v_{pv}(k) - v_c(k)\right) \tag{11}$$

$$v_c(k+1) = \left[1 - \frac{T}{RC}\right] v_c(k) + \frac{T_s}{C}\left(i_{pv}(k)\right) \tag{12}$$

$$i_{pv}(k+1) = i_{pv}(k) + \frac{T_s}{L}\left(v_{pv}(k)\right) \tag{13}$$

$$v_c(k+1) = \left[1 - \frac{T}{RC}\right] v_c(k) \tag{14}$$

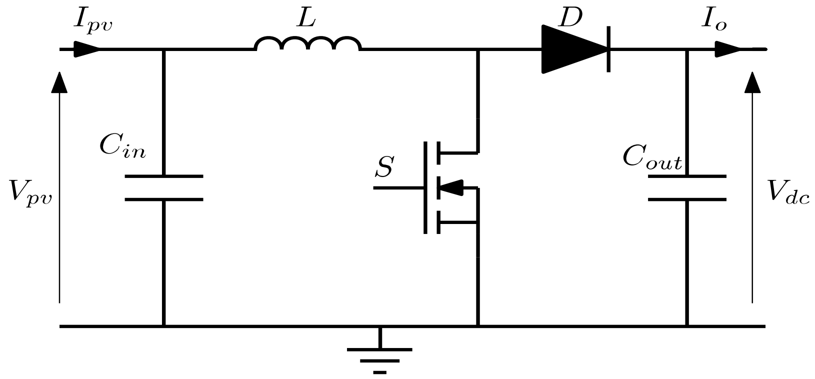

Figure 2. Schematic of boost converter [19]

3.4. Objective Function

In the proposed approach, at the first stage, the voltage and current values of the reference operating point are estimated by model predictor according to the intensity level, ambient temperature, dynamic variations of load and other effecting factors. Then, the switching pattern of the converter is determined by using the chaos-based nonlinear predictive controller. The steps of the proposed approach are as follows:

- Measuring the current/voltage of the panel and sending it to the control unit
- Calculation of current and voltage variations according to Equation (15) and Equation (16).
- Calculation of the reference voltage by using predictor model (Equation (17))
- Regulating the duty cycle of converter (Equation (18))

Equation (18) shows the objective function, which tries to minimize the difference between the current/voltage of the operating point with reference ones in each time step. The coefficients ω_A and ω_B represent the weights for determining the level of voltage and current error's participation in objective function according to operator's point of view. In this simulation, their values are assumed equal to 1 so that both terms have the same importance.

$$\frac{di_L}{dt} = \frac{v_{pv}}{L} - \frac{v_o}{L} \tag{15}$$

$$\frac{dv_{pv}}{dt} = -\frac{i_L}{C_1} + \frac{i_{pv}}{C_1} \tag{16}$$

$$\frac{dv_o}{dt} = \frac{i_L}{C_2} - \frac{v_o}{RC_2} \tag{17}$$

$$\min O.F = \omega_A.|V_o(k+1) - V_{MPP}|^2 + \omega_B.|i_o(k+1) - i_{MPP}|^2 \quad (18)$$

4. SIMULATION RESULTS

In order to evaluate the proposed controller approach, the simulation was done in MATLAB/Simulink environment (Figure 3). In this project, PV arrays are used as green energy equipments for power generation, and the related information about power electronic components are shown in Table 3.

Table 3. Characteristics of regulator, solar panel and inverter

<table>
<tr><td colspan="2">Regulator</td><td colspan="2">Solar Module</td><td colspan="2">Inverter</td></tr>
<tr><td rowspan="2">Rated Current (A)</td><td rowspan="2">30</td><td>Rated Voltage (V)</td><td>12</td><td rowspan="2">Rated Voltage (V)</td><td rowspan="2">48</td></tr>
<tr><td>Rated Power (W)</td><td>150</td></tr>
<tr><td rowspan="3">Rated Voltage (V)</td><td rowspan="3">48</td><td>Short Circuit Current (A)</td><td>8.4</td><td rowspan="2">Short Circuit Current (A)</td><td rowspan="2">2799</td></tr>
<tr><td>Open Circuit Voltage (V)</td><td>21.6</td></tr>
<tr><td>Efficiency Coefficient</td><td>0.74</td><td>Rated Power (W)</td><td>3500</td></tr>
</table>

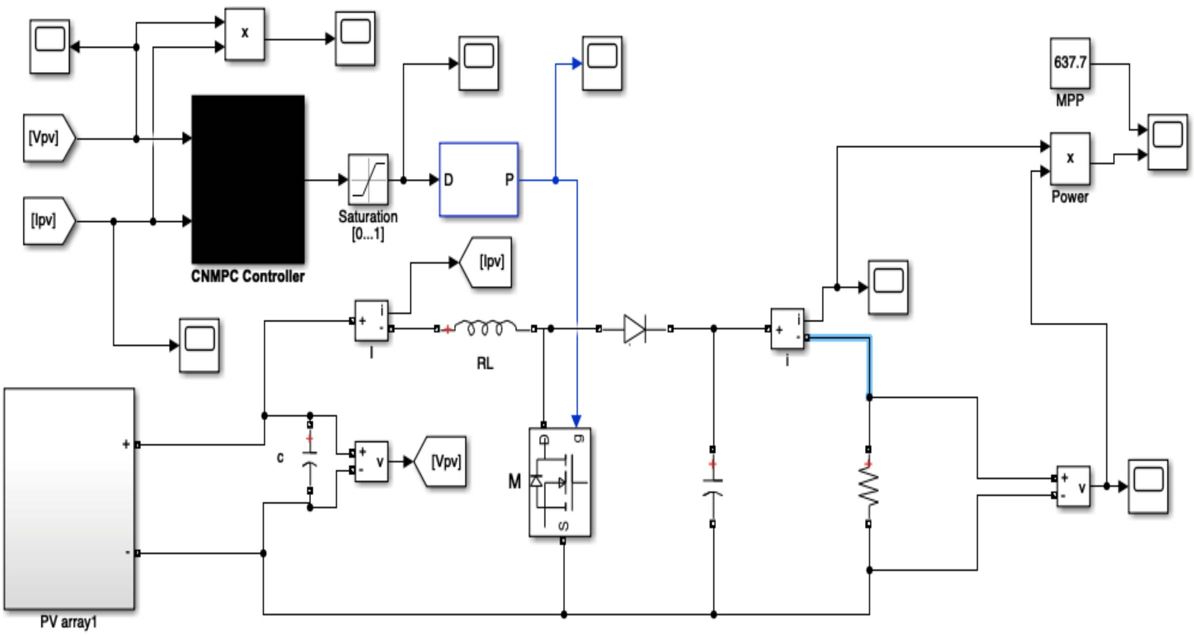

Figure 3. Simulink model of under study system

4.1. Performance Evaluation During Disturbances

Normally, in this situation, a bypass diode is used in parallel with each of the OPV modules to protect the module. The current and power generated in this scenario are shown in Figure 4 and

Figure 5, respectively. In this situation, it can be seen that tracking has been done properly using the proposed approach. The output signal of PWM modulator is shown in Figure 6.

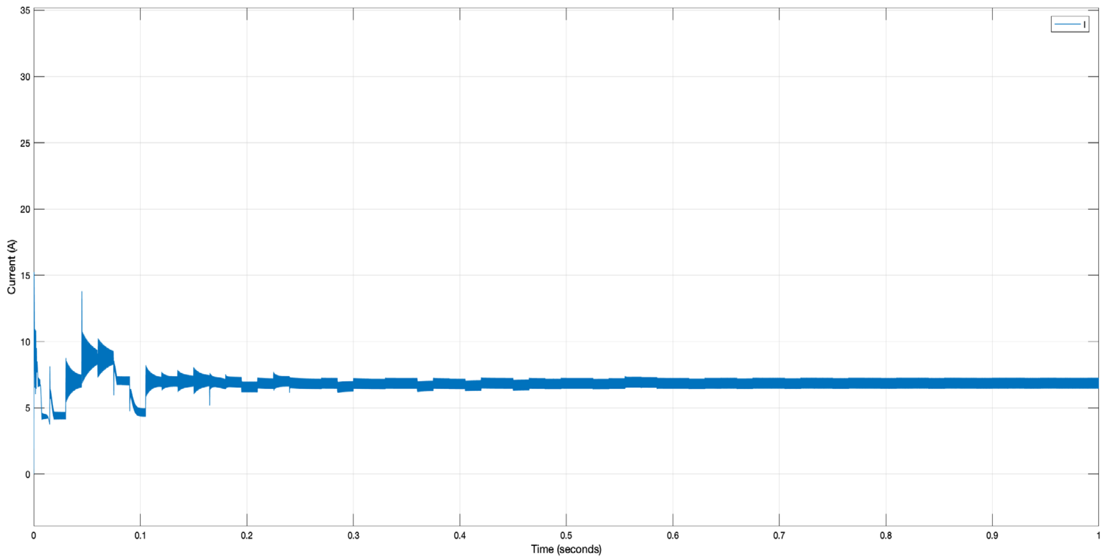

Figure 4. Output current of OPV panel (With disturbance)

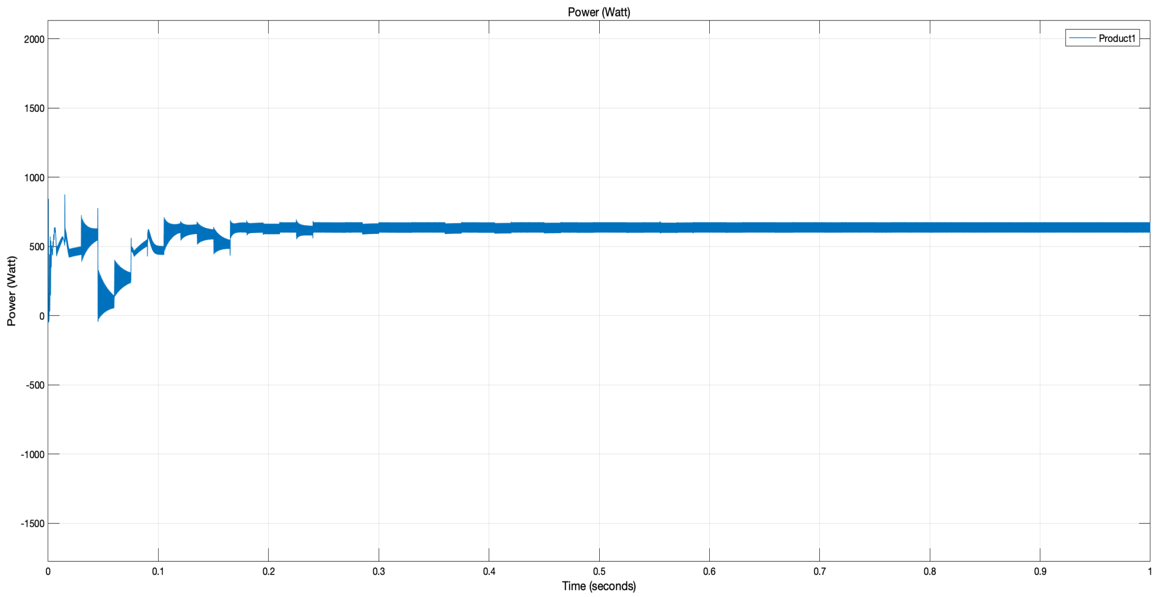

Figure 5. Output power of OPV panel (With disturbance)

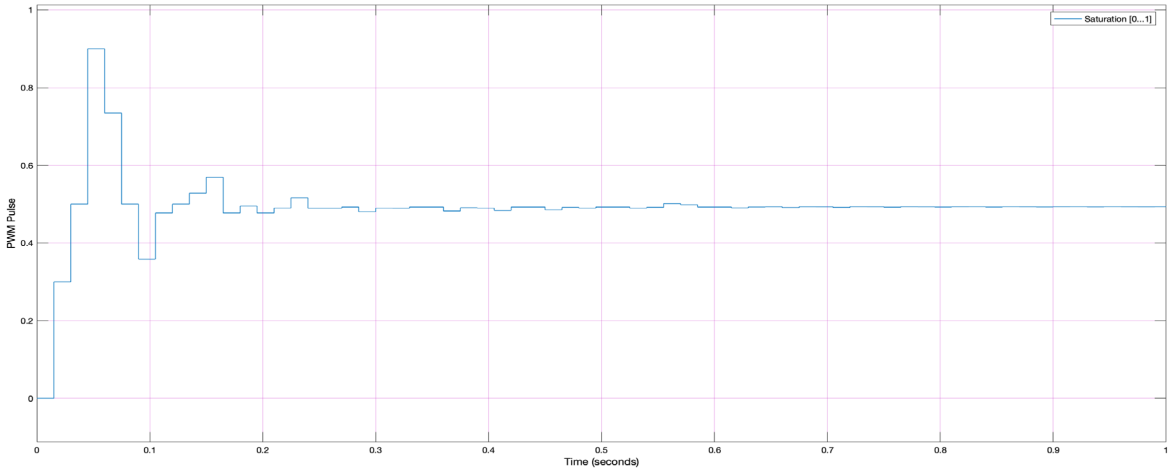

Figure 6. Output signal of PWM converter

4.2. Performance Evaluation at Different Irradiation

To assess the effectiveness of the proposed method, variable irradiation is taken into account. This involves considering changes in intensity levels, as well as variations in the boost converter parameters, photovoltaic voltage/current are shown in Figure 7.

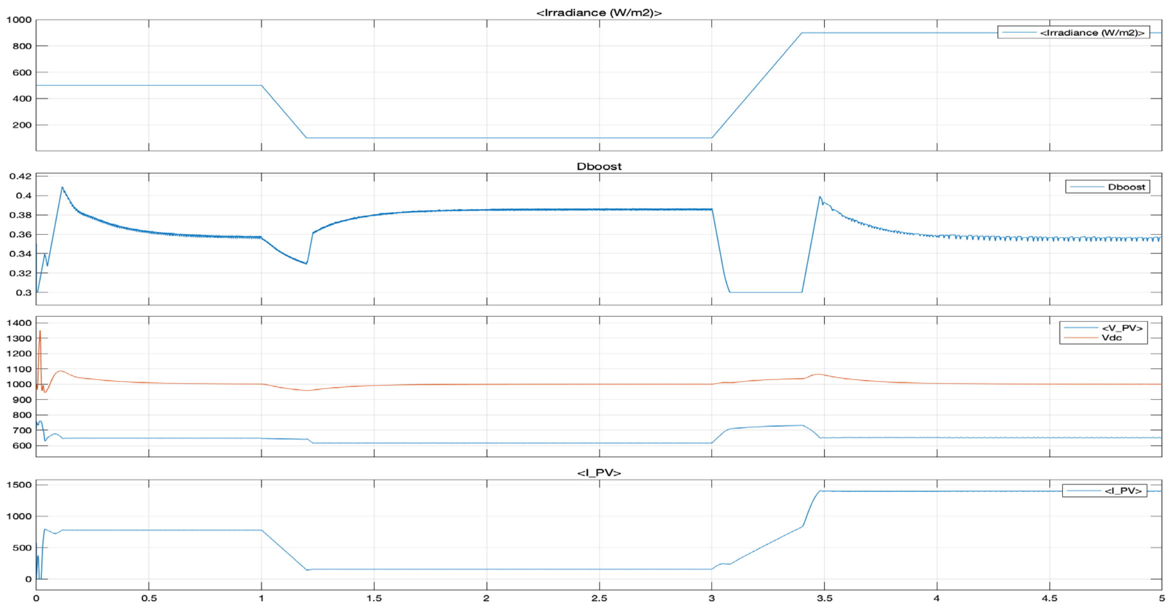

Figure 7: Irradiation variations, boost voltage level, PV voltage and current

4.3. Voltage Recovery in Transient Conditions

To model the dynamic changes of active and reactive power, it is assumed that the grid voltage drops to 0.8 P.U. in 0.5 s and then rises to 1 P.U. in 0.8 s. The compensation effect of reactive power injection by the converter is shown in Figure 8. As can be seen in this figure, by using the

CNMPC method, the amount of voltage drop has been optimally compensated with the injection of reactive power and the reference point has been tracked with appropriate accuracy. The amount of generated reactive power is shown in Figure 9. The output current of the converter is also shown in Figure 12. Subsequently, Figure 10 illustrate variations in active power and frequency during the tracking of predetermined reference values.

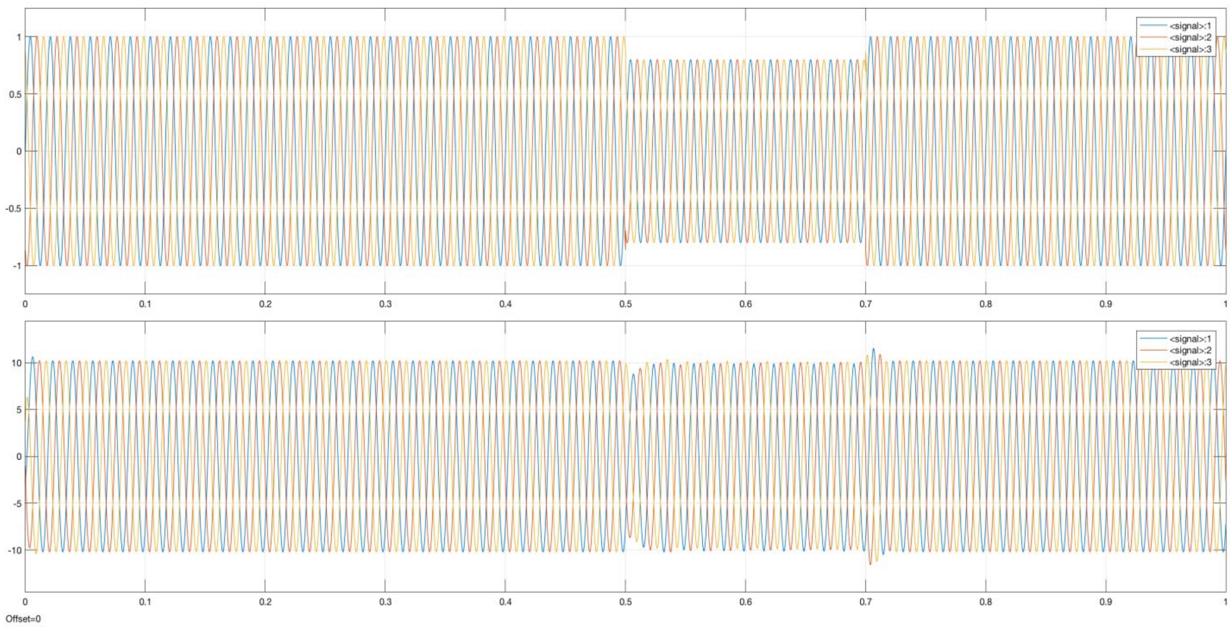

Figure 8. Voltage and Current before using CNMPC controller

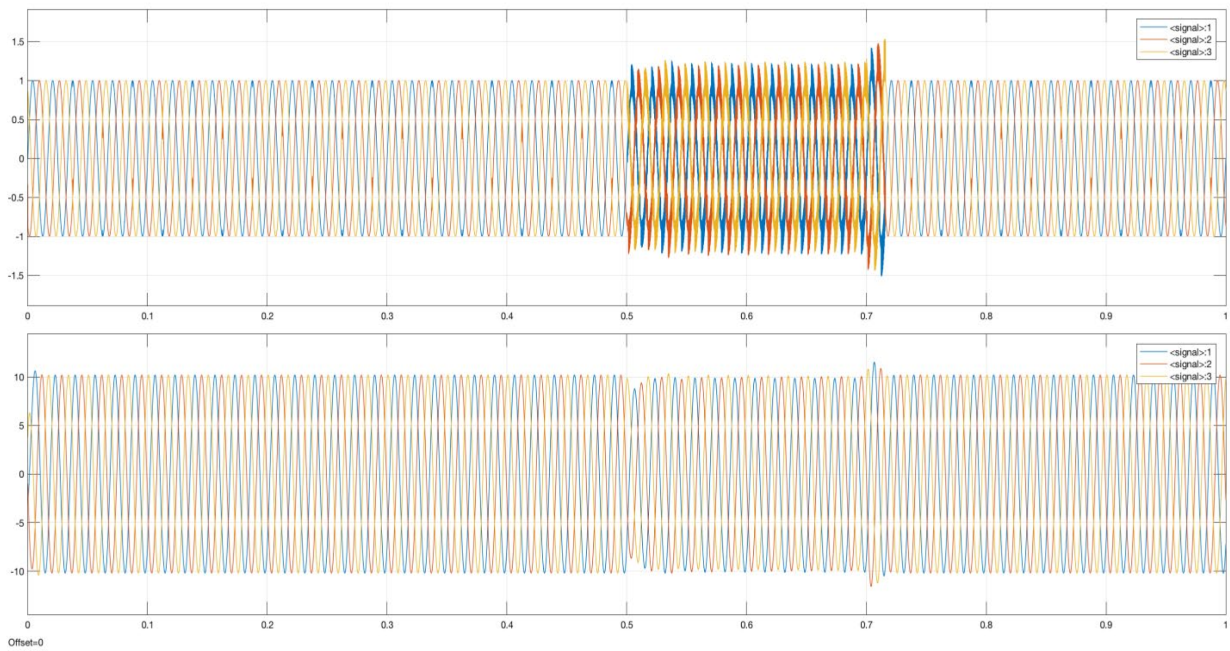

Figure 9. Voltage and Current after using CNMPC controller

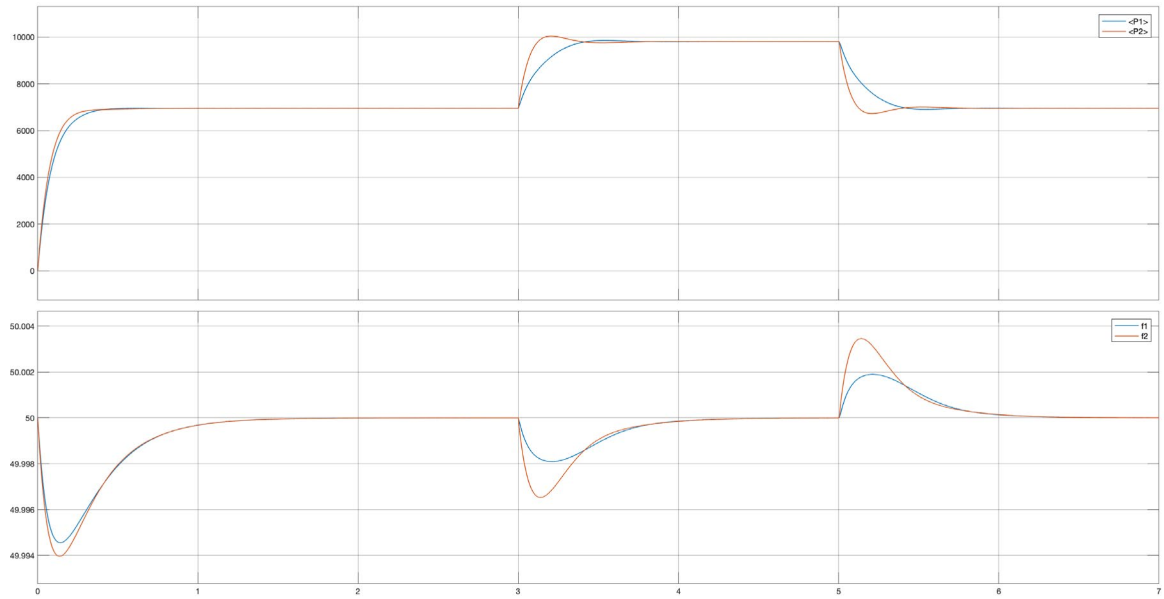

Figure 10. Active power & frequency variations for tracking reference points

5. CONCLUSION

Electric companies are continuously planning for development of electric networks in order to supply the power demanded by their consumers. The classical method used is the construction of new stations or the development of existing infrastructure. With the implementation of new government policies in the field of using new resources, the use of distributed generation resources has gained significant importance. The integration of distributed generation resources with the main grid can expand energy generation resources, improve efficiency, ease of installation and operation, improve security, increase power quality and reliability, and reduce environmental pollution. In other side, the connection of distributed generation (DG) resources to the distribution network causes significant changes in the operation of the network and several effects on its power quality. In this regard, most of the studies conducted in the field of connecting DGs to the main grid have only considered active power exchange and less studies have been conducted on the potential of their participation in improving the voltage level and reducing losses.

In this paper, the non-linear chaotic-based model predictive control method is presented for maximum power point tracking in organic PV panels. The proposed method adopts a two-stage strategy to address non-uniform conditions. Initially, the algorithm analyzes the current characteristics of the panel for determining the reference point. After that, the operating point of the converter is determined by NCMPC method. According to obtained results, this approach could enhance dynamic response, reduce steady-state power ripples, and optimize the extracted power from OPV panels.

NOMENCLATURE

CNMPC:	Chaotic-based Non-linear Model Predictive Controller
DG:	Distributed Generation
MPC:	Model Predictive Controller
MPP:	Maximum Power Point
OPV:	Organic Photovoltaic

DECLARATION OF ETHICAL STANDARDS

The authors of the paper submitted declare that nothing which is necessary for achieving the paper requires ethical committee and/or legal-special permissions.

CONTRIBUTION OF THE AUTHORS

Mohammad Mahdi Borhan Elmi: Perofrmed the experiments and analyse the results.
Osman Yildirim: Wrote the manuscript.

CONFLICT OF INTEREST

There is no conflict of interest in this study.

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