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Maximum Power Point Tracking Using Constrained Model Predictive Control for Photovoltaic Systems

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A B S T R A C T

Photovoltaic (PV) systems offers clean source for the generation of electricity, which is however costly today. Due to the variable and stochastic behavior of the solar energy resource, Maximum Power Point Tracking (MPPT) of photovoltaic systems is required to ensure continuous operation at the maximum power point to generate the most electrical energy. This paper presents the use of a model predictive controller (MPC) considering constraints for safe operation in order to maximize the power output from a PV system. Analysis and simulation of the proposed system is discussed in details through the paper. The simulation results show that the designed controller can track Maximum Power Point quickly, accurately and effectively.

1. Introduction

The increasing demand for energy and the limited capacity of fossil fuel resources have motivated numerous studies on alternative renewable energy resources in recent decades. Among the different renewable energy resources, photovoltaic (PV) solar energy, has attracted considerable interests because of its availability, low maintenance demand, and environment friendliness. Despite all its benefits, the high investment cost required by this technology makes extracting a large amount of available power from PV panels necessary. Hence, tracking the maximum power of the PV arrays at real time is very important to increase the whole system performance; the interest in this area is significantly growing focusing mainly on the MPPT efficiency improvement. As a result, maximum power point tracking (MPPT) strategies should be deployed to ensure the tracking of the maximum power point (MPP) of nonlinear PV characteristics. The major challenges of MPPT lie in its dependence on the environmental parameters of the PV curve (i.e., temperature and insolation dependence) [1].

In order to overcome the undesired effects on the output PV power and draw its maximum power, it is possible to insert a DC/DC converter between the PV generator and the batteries, which can control the seeking of the MPP, besides including the typical functions assigned to controllers. These converters are normally named as maximum power point trackers [2].

Many MPPT methods have been suggested over the past few decades; the relative merits of these various approaches are discussed in [3]. Considering the MPPT methods discussed in [3], candidate techniques considered include Incremental Conductance (INC) [4], Perturb-and-Observe (P&O) [5, fractional Open-Circuit Voltage (VOC) [6], and Best Fixed Voltage (BFV) [7]. The difference of these algorithms is related to their performance, convergence speed and hardware complexity each approach has certain advantages and disadvantages for the present application. The MPPT using artificial neural network proposed can reduce the noises and oscillations generated by classical methods and can be competitive against other MPPT algorithms [8]. Other researchers presented a method for the control of the PV system through the MPPT using a Fuzzy Logic controller. This method succeeded to reduce the PV array area and increase their output, and used for control of MPPT for stand-alone PV system giving a minimum economic cost. Developed controller can be improved by changing the form of the functions of memberships as well as the number of subsets [9] Intelligent control technique using fuzzy logic control is associated with an MPPT controller in order to improve energy conversion efficiency and this fuzzy logic controller is then improved by using genetic algorithms (GA) and (PSO) [10].

Model predictive control (MPC) is an attractive alternative to the classical control methods, due to its fast dynamic response, simple concept, and ability to include nonlinearities and constraints in the design of a controller [11]. MPC presents several advantages over the conventional control Techniques such as easy implementation which is expected to improve PV system utilization efficiency under continuous changes in solar irradiation overcoming disturbances and uncertainties [12]. The implementation of a PV array MPPT using MPC combines two keys of vital importance, speed, and reliability, avoiding unacceptable oscillations despite the increased speed. Improved perturb and observe MPPT algorithm and MPC model is developed to control the output current of the boost converter in order to extract maximum solar power from the solar panel [13].

Duty cycle may change between (0,1) range, this constraint cannot be taken into consideration for another controller. That is the reason why classical controllers may generate false commands and lose accuracy and efficiency in the system. Model Predictive controller is a highly efficient and strong method to control processes with constraints and complicated dynamics. In this paper, constrained model predictive control algorithm is presented for Maximum Power Point Tracking of photovoltaic systems. At last, the simulation results verify the validity of the model and the effectiveness and accuracy of the proposed controller.

2. Material and Method

2.1. Modeling of the PV system

Photovoltaic module is built with connecting many solar cells in series and parallel. Therefore, studying about one cell might be a guide to understand the behavior of PV module. Although there are some equivalent circuits for modeling of a PV cell, the most common equivalent circuit is a one-diode model because of its simplicity. On the other hand, it has an acceptable level of accuracy to model the actual PV cell [14].

One-diode model: An ideal solar cell is a combination of a diode in parallel with a photo current source, but to have a more accurate model a parallel resistance, R_P, and a series resistance, R_s, is considered in the ideal model, Figure 1 illustrates the equivalent circuit. To have a simpler model in some calculation R_P has been omitted, as a result the output loses its accuracy [15].

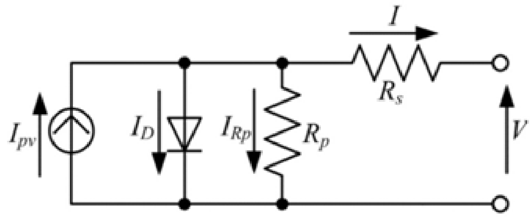

Figure 1. The equivalent circuit for one-diode model

According to Figure 1, the output current is computed from subtraction of diode and parallel resistance current from produced current of PV $I = I_{PV} - I_D - IR_P$. If the equation of current for the ideal diode is considered and current of parallel resistance is calculated the output current will be stated in the following equation.

$$\boldsymbol{I = I_{PV} - I_0\left(e^{\left(\frac{V+IR_S}{\alpha V_T}\right)} - 1\right) - \frac{V + IR_S}{R_P}} \quad (1)$$

$$\boldsymbol{V_T = \frac{N_s KT}{q}} \quad (2)$$

Where I_{PV} is the current producing by light radiation, I_0 is reverse saturation current, α is diode ideality factor, V_T is thermal voltage of PV module, N_s is number of cells in series, K is Boltzmann constant(=1.381 e-23 $J/°K$), q is electron charge(=1.602 e-19 Coulomb) , and T is the temperature of p-n junction in °Kelvin [14].

2.2. Constrained model predictive control for MPPT

As known that, the photovoltaic module has a maximum power point. This point is continuously changing with the change of the module temperature and irradiation. The MPPT controller tracks this power point as long as it changes. In this section, a maximum power point by using model predictive control will be presented. The main concept of the MPC is to predict the future value of the PV module output voltage and current (inductor current and capacitor voltage).

Model Predictive controllers are referred to a family of controllers which use explicitly a model to predict the process output at future time instants (horizon), calculation of a control sequence minimizing a certain objective function subject to constraints and receding strategy so that at each instant the horizon is shifted toward the future, which involves the application of the first control signal of the sequence calculated at each step [16].

The general aim is that the future output (y) on the considered horizon should follow a determined reference signal (w) and, at the same time, the control effort necessary for doing so should be penalized. The general expression for such an objective function will be:

$$J(N_1, N_2, N_3) = \sum_{j=N_1}^{N_2} \|\hat{y}(t+j|t) - w(t+j)\|_Q^2 + \sum_{j=1}^{N_3} \|\Delta u(t+j-1)\|_R^2 \tag{3}$$

where $\hat{y}(t+j|t)$ is an optimum j step ahead prediction of the system output on data up to time t; that is, the expected value of the output vector at time t if the past input and output vectors and the future control sequence are known. N_1 and N_2 are the minimum and maximum prediction horizons N_2 are control horizon and $w(t+j)$ are a future setpoint or reference sequence for the output vector. R and Q are positive definite weighting matrices.

In order to implement this strategy, the basic structure shown in Figure 2 is used [16].

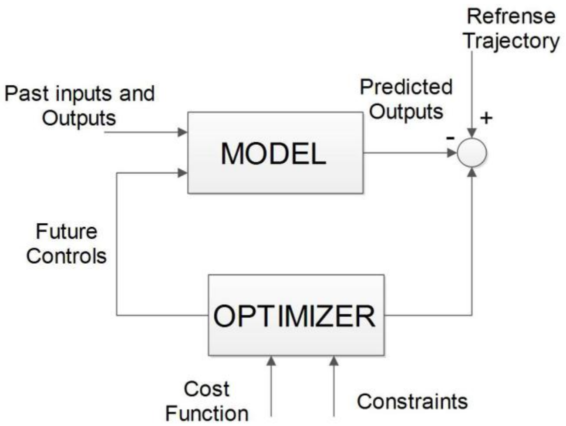

Figure 2. Block diagram of a model-based predictive controller (MPC)

A model is used to predict the future plant outputs, based on the past and current values and on the proposed optimal future control actions. These actions are calculated by the optimizer taking into account the cost function (where the future tracking error is considered) as well as the constraints [14].

The model predictive controller is able to consider all constrains over the inputs, outputs and states of the system. Therefore, the control signal obtained from this controller is much practical and can be implemented in experiments easily. In fact, the controller has knowledge of input limitation, like being saturated, and do not generate the control signal against these limitations. As MPC considers all constraints of the system it can be one of the best and most suitable controllers for these types of systems [17].

The constraint acting on a process can originate from amplitude limits in the control signal and slew rate limits of the actuator can be described by:

$$\begin{gathered} u_i^{min} \leq u_i(t) \leq u_i^{max} \\ \Delta u_i^{min} \leq \Delta u_i(t) \leq \Delta u_i^{max} \end{gathered} \tag{4}$$

These constraints can be considered as inequality constraints in the optimization algorithm.

Figure 3 shows the structure of the proposed control system. MPC has been used to track the reference voltage provided by the algorithm for maximum power point tracking.

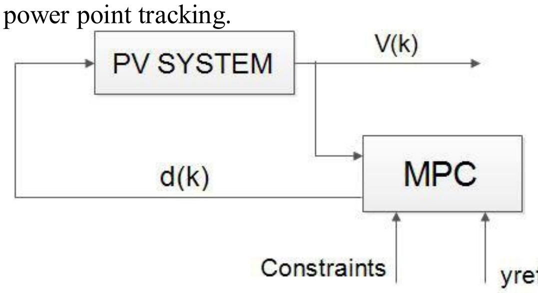

Figure 3. MPC implementation block diagram

The implementation of the MPC was performed by means of the Matlab Toolbox, in which is possible to insert the model, cost function and constraints, following the block diagram presented in figure 3. The inputs of the MPC are the PV voltage, the constraints (range of duty cycle), and the reference for V_{PV} given by the MPPT. The output of the MPC is the input of the PV system (duty cycle d).

3. Results and Discussion

This paper proposes the use of a model-based predictive controller (MPC) designed using the state space representation of the PV system. In this section, the proposed MPPT will be evaluated using a simulation. Figure 4 shows the satisfactory behavior of the output voltage and output current of the PV. Figure 5 demonstrates output power and duty cycle of the system. The power is converged to the maximum value as desired. As can be seen, the duty cycle of the system remains in the interval of (0,1) as desired.

4. Conclusions

In the recent decades, Photovoltaic (PV) power generation system has been paid more and more attention. To make output power of photovoltaic system most, energy converter should track Maximum Power Point (MPP) which is very important in order to ensure the efficient operation of the solar panel. This paper proposes a constrained model predictive controller designed using the state space representation of the PV system. MPC benefits from advantages of simplicity, high flexibility, imposing the constraint of the duty cycle, and less fluctuation around the maximum power point, which increases the efficiency of the PV system. The simulation results showed the effectiveness of the proposed controller and the accuracy of maximum power point tracking for PV system. Finally, the model predictive controller can be improved by considering a nonlinear model of the PV system instead of the linearized model.

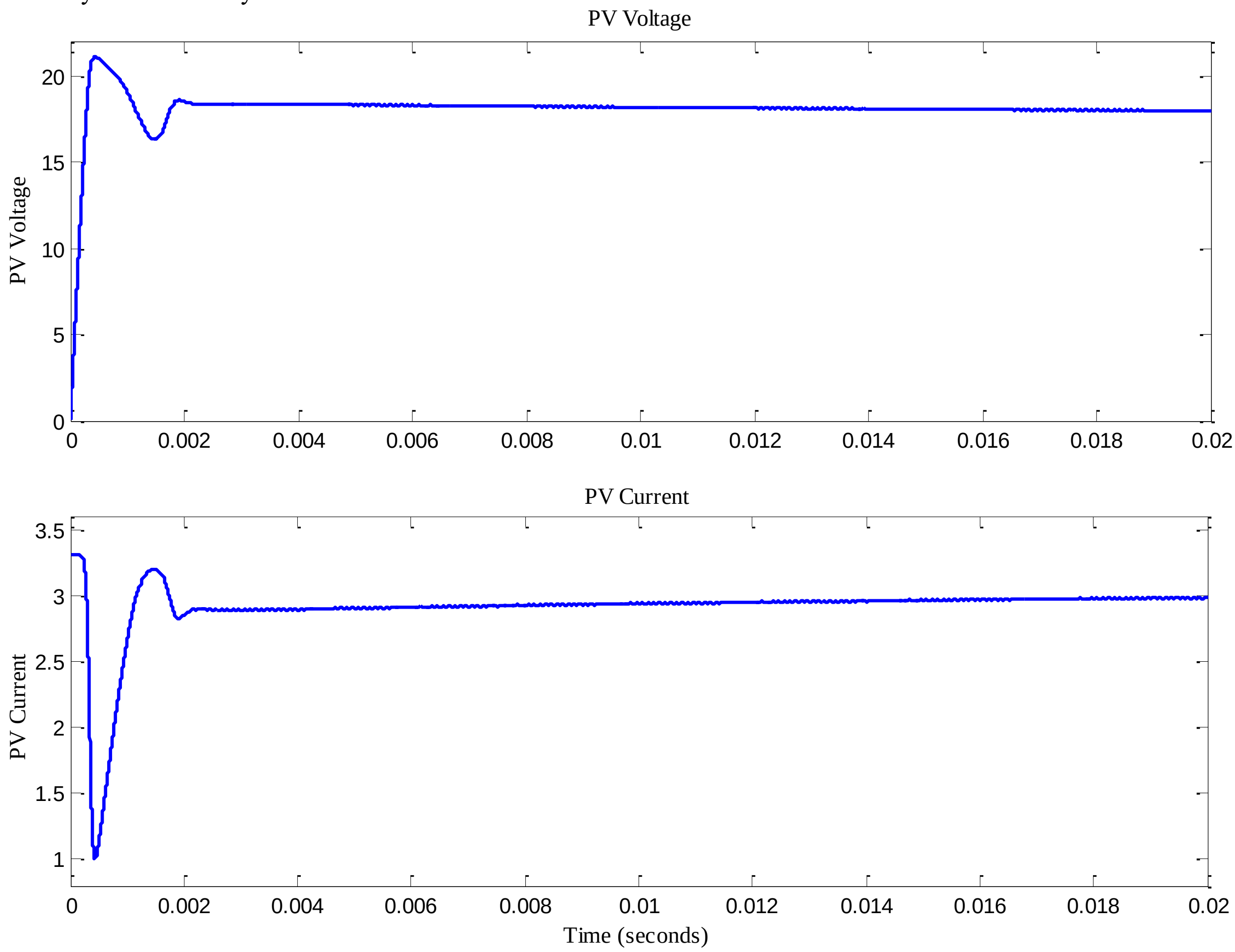

Figure 4. The output current and output voltage of PV

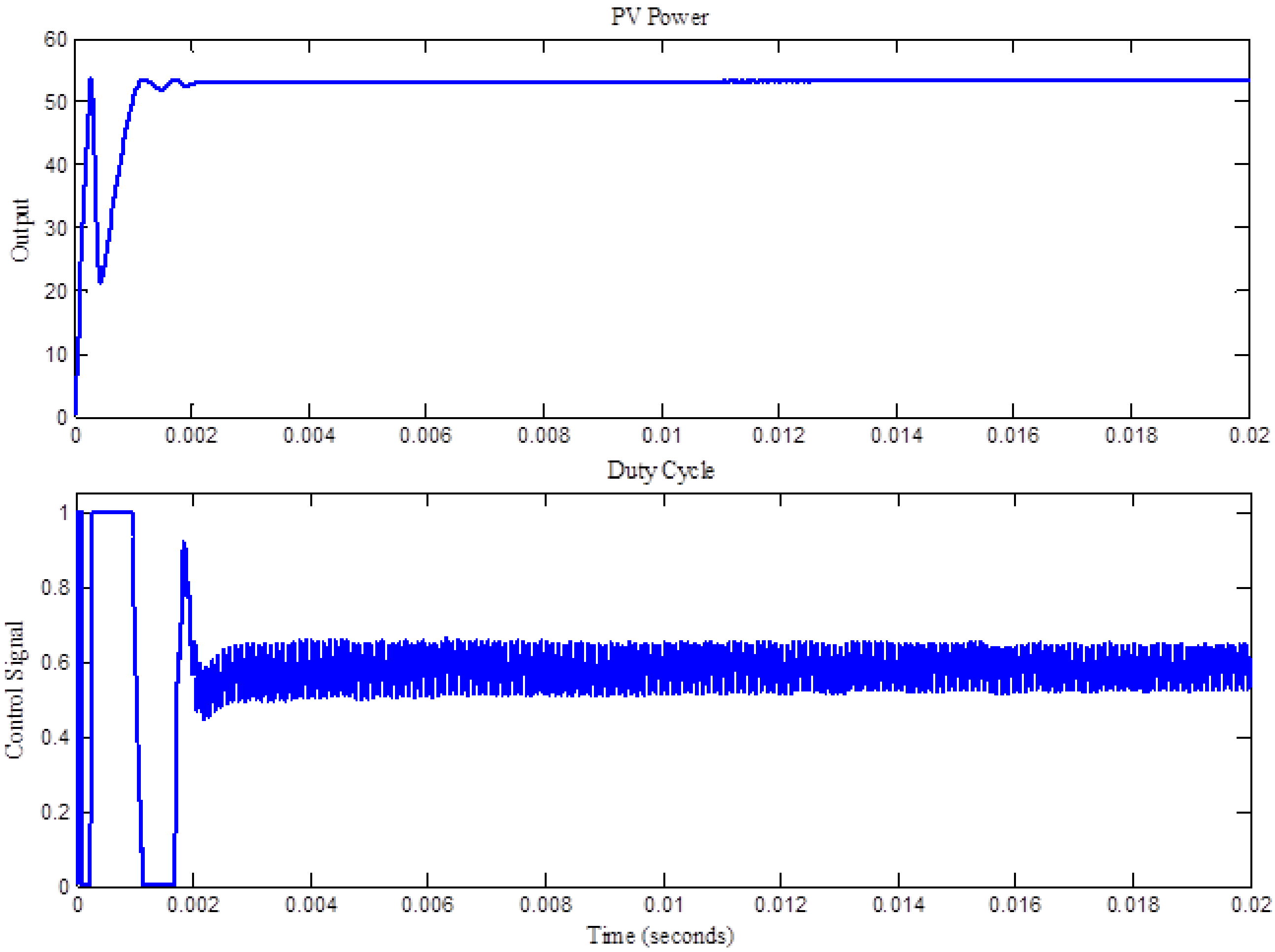

Figure 5. PV output power and duty cycle

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