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Lyapunov-Based Continuous-Time MPC for DC-DC Boost Converter Control in Photovoltaic Systems

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Abstract. The objective of the current work is to enhance the performance of a grid-connected photovoltaic (PV) system by creating a dependable continuous-time model predictive control (CT-MPC) method. The suggested controller uses a Lyapunov-based formulation within the model predictive control (MPC) framework, and the photovoltaic (PV) panel has been meticulously modeled. In the process, dynamic performance is improved, and system stability is guaranteed. To improve power management and guarantee steady performance in a variety of environmental circumstances, this control strategy is used to a DC-DC boost converter. The simulation findings from this study provide empirical evidence for the effectiveness of the proposed method. The results demonstrate that the proposed method is more efficient, resilient, and flexible than conventional control methods.

Introduction

As clean energy sources, photovoltaic (PV) systems are widely used in grid-connected applications. The amount of power generated by these systems varies according to the environmental conditions. Optimizing energy extraction necessitates operating at the maximum power point (MPP), which calls for effective and flexible control strategies [1, 2].

Effective management of PV systems is essential, particularly for DC–AC power conversion in grid-connected applications. Advanced control strategies have been adopted as a result of PI controllers' poor performance under rapidly changing conditions, despite their widespread use. By anticipating system behavior and optimizing control actions, model predictive control (MPC) provides better performance. This ensures stable operation and maximum power point (MPP) tracking, even when there are variations in irradiance [3][4].

To further enhance performance, this study presents a Lyapunov-based model predictive control (MPC) approach that ensures system stability while minimising computational complexity. When applied to a boost converter connected to a three-phase grid, the proposed method achieves a faster transient response, improved energy efficiency and greater robustness. Simulation results confirm that the proposed strategy is superior to conventional methods, highlighting its suitability for practical PV applications [5][6].

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Modelling of the PV panel

Figure 1 shows the topology of the standalone PV system that is the focus of this study. This system consists of a photovoltaic generator, which is controlled by an MPPT-based PWM signal, and a DC/DC boost converter, which is regulated according to solar irradiance and load conditions

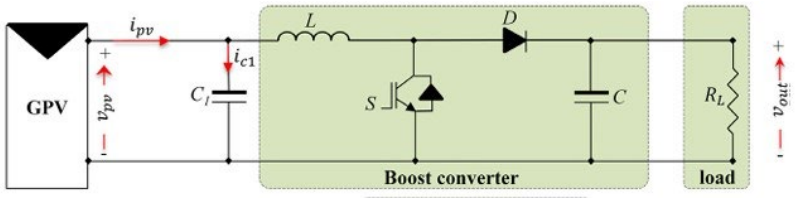


Fig. 1 Plan for a stand alone photovoltaic system

The photovoltaic (PV) panels' maximum power point has been established [7, 8]. As shown below, the averaging technique may be used to define the dynamic model of the boost converter in terms of duty cycle, "D":

$$\begin{cases} \frac{di_L}{dt} = \frac{v_{pv}}{L} - \frac{V_{out}}{L} + \frac{V_{out} \cdot D}{L} \\ \frac{dv_{pv}}{dt} = -\frac{i_L}{C} + \frac{i_p}{C} \end{cases}$$

Model Predictive Control (MPC) is an effective power electronics strategy based on predicting future system behavior using a dynamic model and real-time measurements. At each sampling instant, MPC selects the optimal control action by minimizing a cost function. Only the first input is applied before the process is repeated at the next step.

Active power:

$$\mathrm{P} = \mathrm{v_{pv}} \mathrm{i_L} \cos(\phi) \quad (1)$$

Reactive power:

$$\mathrm{Q} = \mathrm{v_{pv}} \mathrm{i_L} \sin(\phi) \quad (2)$$

Reference power is given by:

$$P_{ref} = P - P_{loss} \quad (3)$$

Where

$$P_{loss} = i_L^2 R \quad (4)$$

The expression for the cost function is:

$$\mathrm{g} = |P_{ref} - \mathrm{P}| + |Q_{ref} - \mathrm{Q}| \quad (5)$$

The complex power error is given by:

$$S_e = S - S_{ref} \quad (6)$$

In discrete time, this error can be expressed as:

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$$S_e = v_{pv} i_L - S_{ref} \tag{7}$$

The lyapunov function is defined as :

$$LF\{S_e\} = \frac{1}{2}(S_e^2) \tag{8}$$

$$\Delta LF\{S_e\} = \frac{1}{2}\left(V_{pv}\left(\frac{T_s d_i}{dt} + I_L\right) - S_{\text{ref}}\right)^2 - \frac{1}{2}S_e^2 \tag{9}$$

Derivative expression :

$$\frac{dI_L}{dt} = \frac{I_L^{\text{new}} - I_L}{T_s} \tag{10}$$

Lyapunov stability theorem:

A system is stable if its Lyapunov function diminishes over time, according to Lyapunov's stability theorem. A Lyapunov-based control algorithm requires that the function's change (ΔLF) be negative. If the first term in equation (9) is zero, the system is stable because the second term is negative. This results in the following limitation:

$$V_{pv}\left(\frac{T_s d_i}{dt} + I_L\right) - S_{\text{ref}} = 0 \tag{11}$$

Thus

$$v_{pv} = \frac{S_{ref}}{i_L} \tag{12}$$

To choose the appropriate switching vector and minimize the cost function, the estimated voltage vpv in equation (11) is compared with the ideal converter output vpv,opt.

$$g = |vpv - vpv,opt| \tag{13}$$

In this work, we use a Lyapunov-based method to examine the system's robustness. A common tool in stability studies, the Lyapunov function is defined as follows:

$$V = \frac{1}{2}S_e^2 \tag{14}$$

where Se is the complex power error. In order to assess the stability of the system, we calculate the Lyapunov function's time derivative:

$$\frac{dV}{dt} = S_e \frac{dS_e}{dt} = S_e\left(v_{pv}\dot{i_L} + \dot{v_{pv}} i_L\right) \tag{15}$$

It is possible to simplify this derivative as follows:

$$\frac{dV}{dt} = -k_e S_e \text{sign}(S_e) \tag{16}$$

In this case, sign(Se) is the sign of the error Se, and ke is a constant. This guarantees that whenever Se is non-zero, the Lyapunov function falls, bringing the system to a stable state.We reduce the cost function g, which is defined as follows, in order to assess the system's resilience further:

$$g = |vpv - vpv,opt|$$

To ensure reliable operation under changes in input and load, the cost function minimizes the discrepancy between the actual and ideal voltages. Converter signals are produced by Lyapunov-based predictive control to offer reliable and effective PV power regulation.

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Simulations

The following figures illustrate the dynamic performance of the proposed Lyapunov-based continuous-time MPC approach applied to the DC–DC boost converter in a photovoltaic system. The behavior of the controller is evaluated under realistic operating conditions, with a focus on voltage regulation, system stability, and control signal evolution. It is essential to keep in mind that all control variables, including the duty cycle, are shown within their actual operating ranges. This ensures that the results of the simulation will be interpreted consistently and meaningfully.

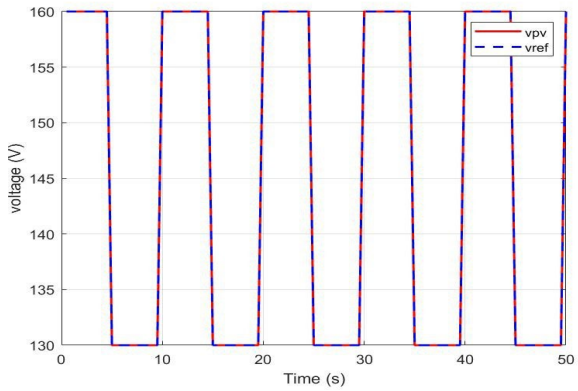


Fig. 2 PV output voltage response

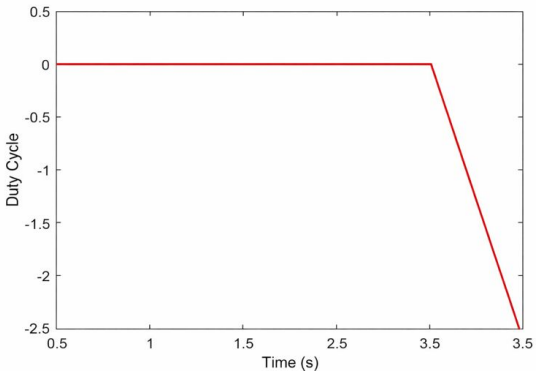


Fig. 3 System Duty Cycle Using the Suggested Approach

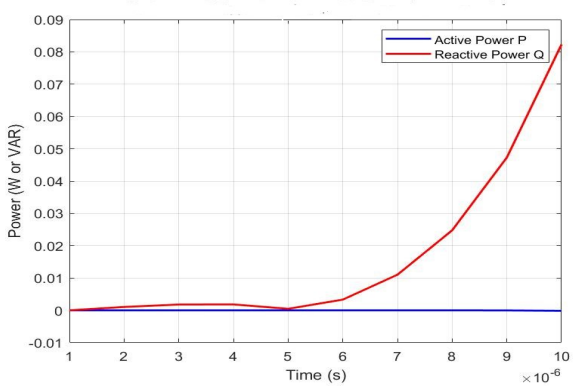


Fig. 4 Active and Reactive Powers in Response to Voltage Changes.

Conclusion

Based on a DC–DC boost converter, this study suggested a hybrid control approach for a grid-connected photovoltaic system. A combined Lyapunov-based and continuous-time model predictive control (MPC) methodology was created to enhance grid stability and voltage regulation after examining the drawbacks of traditional techniques.

The outcomes of the simulation demonstrate enhanced DC-link voltage regulation, quick dynamic response, and efficient active and reactive power control. The proposed method reduces voltage fluctuations, enhances power conversion efficiency, and ensures stable operation under changing irradiance.

However, the validation was limited to simulations under ideal assumptions. To lessen computing complexity for real-time applications, future work should incorporate experimental

implementation, take into account parameter uncertainties and non-ideal effects, and further optimize.

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