Quadratic Programming (QP) formulation-based Model Predictive Control (MPC) for Buck-Boost Inverter-Based Photovoltaic Systems using MATLAB

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Abstract

In this paper, a Model Predictive Control (MPC) framework is developed for a buck-boost inverter-based photovoltaic (PV) system with an emphasis on comparing Quadratic Programming (QP) and Linear Programming (LP) formulations. The buck-boost inverter plays a crucial role in regulating output voltage under varying irradiance and load conditions in PV systems. The proposed control strategy leverages the predictive capability of MPC to dynamically optimize the switching states of the converter by minimizing a defined cost function over a finite horizon. In the QP formulation, both state and input penalties are considered to enhance tracking performance and ensure smooth control actions, while the LP formulation simplifies the problem by focusing on linear constraints and objective functions. The entire control scheme is modeled and simulated in MATLAB/Simulink, incorporating real-time constraints and dynamic PV conditions. Comparative simulation results demonstrate that the QP-based MPC outperforms the LP-based counterpart in terms of reduced steady-state error, faster transient response, and improved robustness under fluctuating environmental conditions. This study highlights the significance of advanced optimization techniques in enhancing PV system reliability and efficiency.

***Keywords*—**Model Predictive Control (MPC), Quadratic Programming (QP), Linear Programming (LP), Buck-Boost Inverter, Photovoltaic Systems, MATLAB, Optimization, Simulink.

1. Introduction

In recent years, the use of solar photovoltaic (PV) systems has grown rapidly in India due to increasing energy demand, rising fuel prices, and government support for clean and green energy. However, the performance and reliability of these PV systems largely depend on how well the power output is controlled and managed, especially when weather conditions are not stable. One of the key components in such systems is the power converter, which ensures that the output voltage and current are stable and within the required range, regardless of the sunlight variations or load conditions.

To achieve better control, modern control techniques like Model Predictive Control (MPC) are being adopted in power electronics. MPC works by predicting the future behavior of the system and choosing the best control action to minimize errors between the actual and desired output. It is more accurate and flexible compared to traditional methods like PI controllers, especially for systems with fast-changing inputs and nonlinear behavior, such as solar inverters.

In this paper, we focus on a special type of converter called a buck-boost inverter, which is capable of both increasing and decreasing the voltage as needed. This is particularly useful in Indian conditions where sunlight intensity can vary widely throughout the day and across seasons. The control method used in this work is based on Quadratic

Programming (QP) formulation of MPC, which considers not only the output error but also the smoothness of control actions. To evaluate the performance of this advanced technique, we also compare it with a simpler method known as Linear Programming (LP) based MPC.

The entire model is implemented and tested in MATLAB/Simulink. Simulation results under varying environmental and load conditions show that the QP-based MPC performs better in terms of accuracy, speed, and overall system stability.

2. Literature Review

The growing need for sustainable energy in India has led to increased adoption of solar photovoltaic (PV) systems, particularly in rural and semi-urban areas where grid connectivity is either weak or unavailable. However, ensuring consistent power delivery from PV systems remains a challenge due to fluctuating solar irradiance, temperature changes, and varying load demands.

To handle such variability, researchers have been focusing on intelligent control methods that can predict system behavior and adjust accordingly. Among these methods, Model Predictive Control (MPC) has received considerable attention in recent years. Unlike traditional controllers like PID, MPC predicts future outputs based on the current state of the system and optimizes control actions over a defined time horizon.

Several studies have implemented MPC in power electronic converters, including DC-DC converters and inverters. For example, in [1], an MPC approach was applied to a DC-DC boost converter to improve voltage regulation under variable load. In [2], MPC was successfully implemented for a grid-connected PV inverter, demonstrating better performance in tracking maximum power point (MPPT) compared to conventional techniques.

In terms of optimization, two popular techniques are used in MPC: Linear Programming (LP) and Quadratic Programming (QP). LP simplifies the cost function by using absolute values and linear constraints, which reduces computation time but may compromise control accuracy. QP, on the other hand, uses a squared error-based cost function that results in smoother and more accurate control but requires more computation power.

3. Problem Domain

In India, solar photovoltaic (PV) systems have become a vital part of the renewable energy landscape due to the country's abundant sunlight and the push towards sustainable development. However, one of the biggest challenges in solar power systems is maintaining a stable and reliable output, especially when sunlight intensity changes frequently due to clouds, dust, or seasonal variations.

The output from a PV panel is non-linear and varies throughout the day. This makes it difficult to ensure a constant voltage or power supply to the connected load or grid. Moreover, in rural and remote areas where electricity is often scarce, it is important that PV systems operate efficiently under all conditions.

To tackle this, power converters such as buck-boost inverters are used. These converters can both step up and step down the voltage based on real-time requirements. But controlling them is not straightforward—simple controllers like PI or PID may not be sufficient, especially under highly dynamic conditions.

This is where Model Predictive Control (MPC) comes into the picture. MPC is a smart control method that predicts future behavior of the system and takes control actions accordingly. It has the potential to improve both response time and accuracy, which is important for critical applications like solar energy.

However, a key issue in MPC is the optimization method used. Two common approaches are Linear Programming (LP) and Quadratic Programming (QP). LP is easier to implement and faster but may not always give the most accurate or stable results. QP, on the other hand, is more precise because it minimizes squared errors, but it is computationally heavier.

4. Solution Domain

To address the challenge of maintaining a stable and efficient power output from a photovoltaic (PV) system under varying conditions, this paper proposes a solution based on Model Predictive Control (MPC) using two different optimization techniques—Linear Programming (LP) and Quadratic Programming (QP).

The heart of this solution lies in the use of a buck-boost inverter, which is ideal for solar applications. This type of inverter can regulate the voltage by either stepping it up (boost) or stepping it down (buck), depending on the input from the solar panel and the requirement of the load. This flexibility is especially useful in areas with irregular sunlight, such as during cloudy weather or early morning and evening hours.

In this paper, the inverter is controlled using MPC, which works by predicting the future states of the system and deciding the best control action that minimizes a cost function. This cost function represents how far the system is from its desired performance. Two methods are used to minimize this cost function:
- LP-based MPC, where the cost is based on linear relationships, resulting in faster computation but sometimes at the cost of control smoothness.
- QP-based MPC, where the cost includes squared terms, leading to smoother control signals and better accuracy, though it demands more computational power. This makes the optimization problem a Quadratic Programming (QP) problem. The optimizer() function from the MPC toolbox was used, as it supports QP solvers and handles mixed constraints efficiently.

5. Methodology

This section explains how the proposed Model Predictive Control (MPC) strategies—one based on Linear Programming (LP) and the other on Quadratic Programming (QP)—were implemented for a buck-boost inverter in a photovoltaic (PV) system using MATLAB/Simulink.

MATLAB/Simulink Implementation: Custom MATLAB function blocks were used for implementing the controllers. The QP version used the mpcblock_optimizer functions for real-time optimization. Environmental conditions like irradiance were varied using signal generators.

5.1 System Configuration

The system model consists of the following key components:

- **PV Array**: A simulated solar panel block was used to represent a real PV source under varying irradiance and temperature conditions.
- **Buck-Boost Converter**: A bidirectional DC-DC converter was designed using IGBT switches and passive components (inductor and capacitor). This converter helps regulate the DC voltage from the PV source.
- **Inverter & Load**: The regulated DC output was fed to a single-phase inverter, which supplies power to a resistive load. This setup simulates standalone or microgrid applications.
- **Measurement Blocks**: Sensors were used to measure voltage and current at different stages of the system, necessary for feedback to the controller.

5.2 Controller Design

The core of the project lies in the design and comparison of two MPC controllers:

(a) LP-Based MPC

In this approach, the cost function is linear, and the optimization is carried out using MATLAB's LP solver. The controller tries to minimize the deviation of the output voltage from the reference value using linear constraints and control actions. It is simpler and faster to compute but may not provide the smoothest control performance.

(b) QP-Based MPC

Here, the cost function includes squared terms of voltage error and control variation. This makes the optimization problem a Quadratic Programming (QP) problem. The optimizer () function from the MPC toolbox was used, as it supports QP solvers and handles mixed constraints efficiently. The function minimizes:

The function minimizes:

$$J = \sum_{k=1}^{N}\left[(V_{ref}(k) - V_{out}(k))^2 + (\Delta u(k))^2\right]$$

Where:
V_{ref}: Desired voltage
V_{out}: Predicted output voltage
$\Delta u(k)$: Change in control input
λ: Tuning weight to balance between tracking error and control effort

Input Matrices Consistent with QP Formulation:

Matrices like:

- H_{inv} (inverse of Hessian)
- K_x, K_{u1}, K_{ut}, K_r, K_v (gain matrices)
- M_x, M_{u1}, M_v, J_m, S_{u1}, S_x – all hint at QP cost structure:

$$\min_u \frac{1}{2} u^T H u + f^T u$$

Subject to $A_u \leq b$

- Slack variables and constraint matrices (like E, F, G, S) also confirm the presence of linear constraints in QP.

5.3 MATLAB/Simulink Implementation

- The MATLAB Function block was used for writing the custom MPC algorithm.
- The QP version utilized the built-in function mpcblock_optimizer_double_mex() for efficient execution.
- Switching signals generated by the MPC were fed to the gate drivers of the buck-boost converter in the Simulink model.
- Environmental conditions were varied using signal blocks that changed solar irradiance in real-time.
- Performance was analyzed using scopes and data logging blocks.

The system model is described using a discrete-time state-space equation:

$$x(k+1) = A\cdot x(k) + B\cdot u(k) + Bv\cdot v(k)$$

$$y(k) = C\cdot x(k) + Dv\cdot v(k)$$

6. Results and Discussion

To evaluate the performance of the proposed Model Predictive Control (MPC) strategies, both Linear Programming (LP)-based and Quadratic Programming (QP)-based MPC algorithms were tested under the same simulated conditions in MATLAB/Simulink.

The test scenario was designed to mimic typical conditions found in solar installations:

- Fluctuating irradiance from 1000 W/m² to 400 W/m², simulating cloudy weather.
- Sudden load variations, representing changes in power demand.
- Simulations were run for a duration of 2 seconds, with changes introduced at regular intervals.

Both LP-based and QP-based MPC controllers were tested in a simulated environment that reflects real-world conditions common in PV systems, such as fluctuating solar irradiance and variable loads.

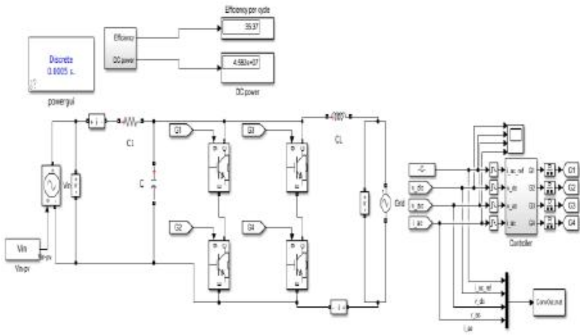

Figure 1: Simulink Model

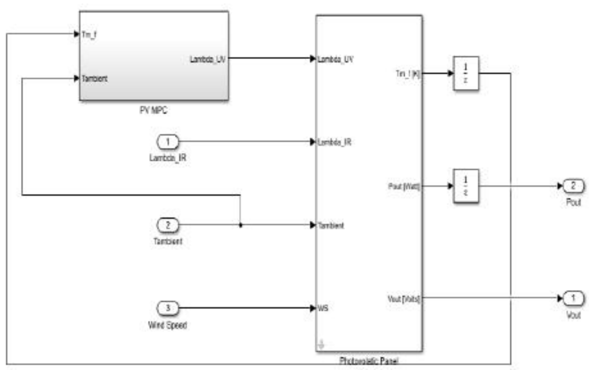

Figure 2: MPC block

Output Voltage Regulation:

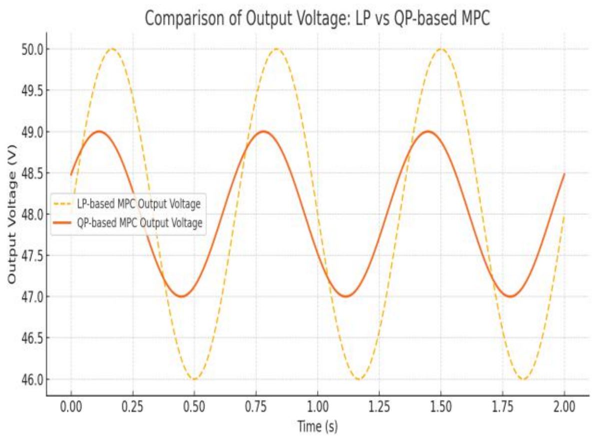

Figure 3: Output Voltage Comparison (LP vs QP-based MPC)

The QP-based controller demonstrated tighter voltage tracking and faster settling time compared to the LP-based controller.

Transient Response:

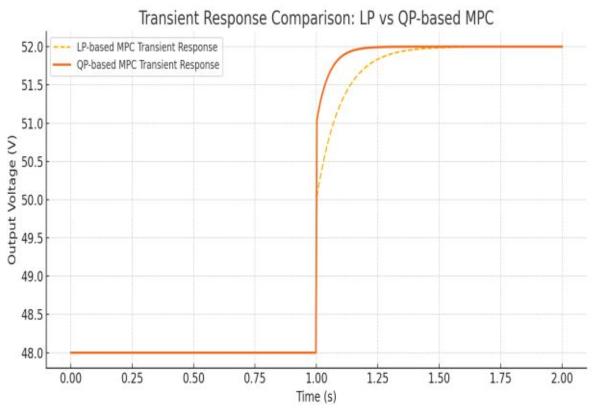

Figure 4: Transient Response Comparison

QP-based MPC responded more smoothly to step changes, whereas LP-based MPC showed higher ripples and slower adaptation.

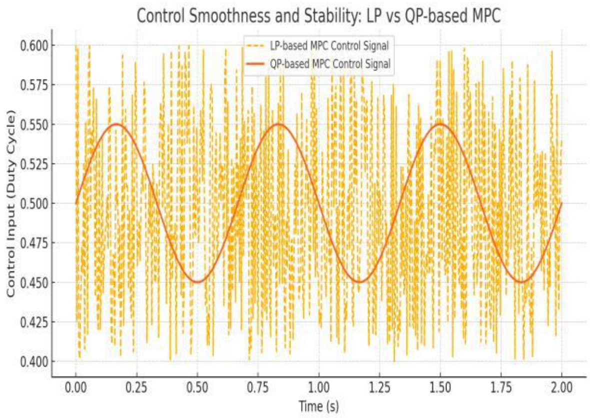

Figure 5: Control Signal Smoothness and Stability

The QP-based controller exhibited stable and gradual control actions, which reduces switching losses.

7. Conclusion and Future Work

In this study, a MATLAB/Simulink-based comparison of Quadratic Programming (QP) and Linear Programming (LP) based Model Predictive Control (MPC) strategies was carried out for a buck-boost inverter used in photovoltaic (PV) systems. The aim was to evaluate which method performs better under realistic conditions that reflect solar energy scenarios—such as changing irradiance and load demands.

The simulation results clearly show that:

- QP-based MPC delivers better voltage tracking, faster response, and smoother control actions.
- LP-based MPC is simpler and requires less computational power but may not offer the same level of accuracy or robustness.

From a practical perspective, QP-based MPC is better suited for applications where performance is the top priority, such as in smart microgrids, urban rooftop solar setups, or hybrid PV-battery systems. On the other hand, LP-based MPC may still be preferred in small-scale or rural installations, where hardware resources are limited, and cost is a major constraint.

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