QP Formulation-Based Model Predictive Control (MPC) for Buck-Boost Converter-Fed Inverter-Based PV Systems

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Abstract

The integration of renewable energy sources, particularly photovoltaic (PV) systems, into modern power networks has created the need for advanced control strategies capable of handling uncertainties in solar irradiance and dynamic load conditions. This work presents the design and implementation of a Model Predictive Control (MPC) strategy for a PV-fed buck–boost inverter system, with a focus on voltage regulation. The proposed approach employs Quadratic Programming (QP)–based optimization to determine the optimal duty cycle of the converter, thereby ensuring smooth operation, accurate tracking, and enhanced power quality.

The developed Simulink model is validated under diverse scenarios including sudden changes in irradiance and variable load conditions. Performance is benchmarked against Linear Programming (LP)–based MPC reported in the literature. Simulation results confirm that the QP-based MPC outperforms LP-based MPC by achieving lower overshoot (~2%), reduced DC voltage ripple, and higher efficiency (>99%). Furthermore, the smoother control signal reduces switching stress and enhances inverter output quality, with total harmonic distortion (THD) maintained below 2%.

The findings establish QP-based MPC as a robust and efficient control strategy for PV inverter systems, offering improved transient and steady-state performance while addressing the practical challenges of renewable energy integration.

Keywords: Model Predictive Control; Quadratic Programming (QP); Linear Programming (LP); Photovoltaic (PV) Systems; Inverter; Renewable Energy Integration; Dynamic Response; Power Quality.

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 behaviour 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 Solar photovoltaic (PV) systems are rapidly expanding in India, yet their deployment faces challenges due to voltage instability caused by fluctuating irradiance, temperature, and load conditions. Conventional controllers such as PI/PID often fail to cope with these dynamics, resulting in voltage deviations and reduced reliability. The buck–boost inverter, with its ability to both step up and step-down voltage, provides flexibility for regulation but requires advanced control strategies for stable operation.

Model Predictive Control (MPC), with its predictive and optimization capabilities, has emerged as a suitable solution. However, its effectiveness depends on the underlying optimization approach. While Linear Programming (LP)–based MPC offers computational simplicity, it often compromises accuracy and smoothness. Quadratic Programming (QP)–based MPC, though computationally more demanding, promises superior voltage regulation and stability.

This thesis investigates and compares LP- and QP-based MPC strategies for buck–boost inverter–controlled PV systems under dynamic, real-world operating conditions using MATLAB/Simulink, addressing a key research gap in the context of solar power integration in India.

4. Methodology

The methodology followed in this work is systematic and sequential, beginning with the identification of the research problem and progressing through literature review, system modelling, control design, simulation, and performance evaluation. The research methodology followed in this work is presented in Figure 1. It highlights the sequential steps from problem identification to performance evaluation.

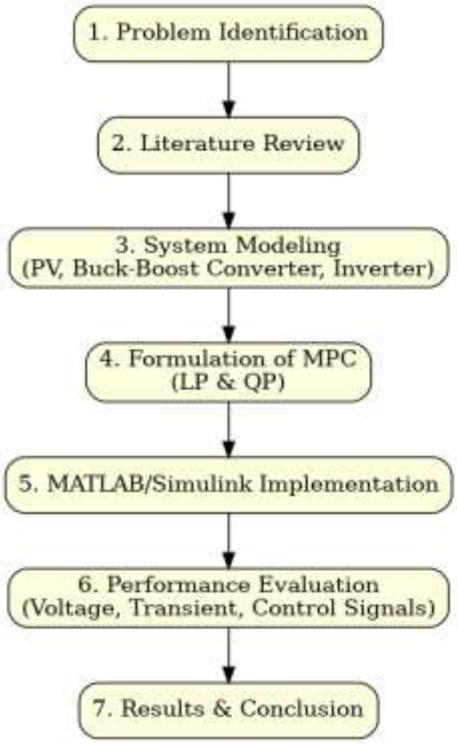

Fig.1 Proposed methodology flow chart

The methodology adopted can be summarized in the following steps:

1. **Problem Identification** – Recognizing the challenges in PV systems, particularly instability in output voltage under fluctuating irradiance and load conditions.

2. **Literature Review** – Studying conventional and advanced control techniques for converters and inverters, with a focus on MPC.

3. **System Modelling** – Developing mathematical models of the PV array, buck-boost converter, and inverter for control design.

4. **Formulation of MPC (LP and QP)** – Designing the predictive control strategy using linear and quadratic optimization approaches.

5. **MATLAB/Simulink Implementation** – Simulating the proposed system with MPC under varying conditions.

6. **Performance Evaluation** – Comparing LP- and QP-based MPC in terms of voltage regulation, transient response, and control effort.

7. **Results and Conclusion** – Analyzing the findings and drawing conclusions about the suitability of each approach.

5.1 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

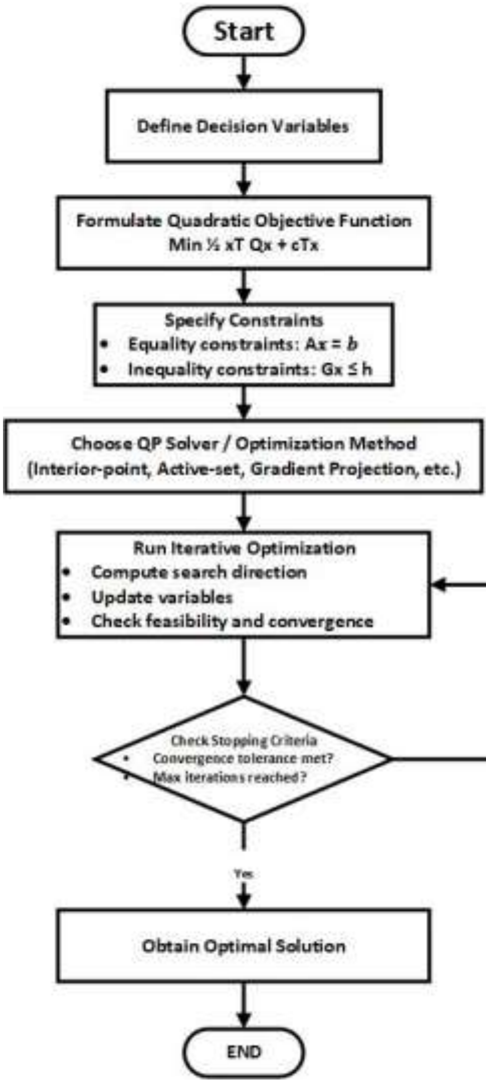

Fig.2 General flow chart of a Quadratic Programming (QP) optimization process.

Input Matrices Consistent with QP Formulation:

Matrices like:

- Hinv (inverse of Hessian)
- Kx, Ku1, Kut, Kr, Kv (gain matrices)
- Mx, Mu1, Mv, Jm, Su1, Sx – all hint at QP cost structure:

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

$$\text{Subject to} \qquad Au \leq b$$

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

6. Results and Discussion

A detailed MATLAB/Simulink model was developed to evaluate Model Predictive Control (MPC) strategies for a buck–boost inverter–based photovoltaic (PV) system. The setup includes a PV array model, a buck–boost converter, a full-bridge inverter, and an MPC controller implementing both Linear Programming (LP) and Quadratic Programming (QP)based formulations. Irradiance, temperature, and load variations were introduced to emulate real operating conditions.

The overall process followed for conducting simulations in MATLAB/Simulink is represented in Figure 3. This workflow ensures a systematic evaluation of the proposed MPC-based control scheme for the buck-boost inverter PV system.

The workflow begins with the input profiles, where solar irradiance, temperature variations, and load conditions are defined. These parameters represent real-world disturbances and provide a realistic test environment for the PV system.

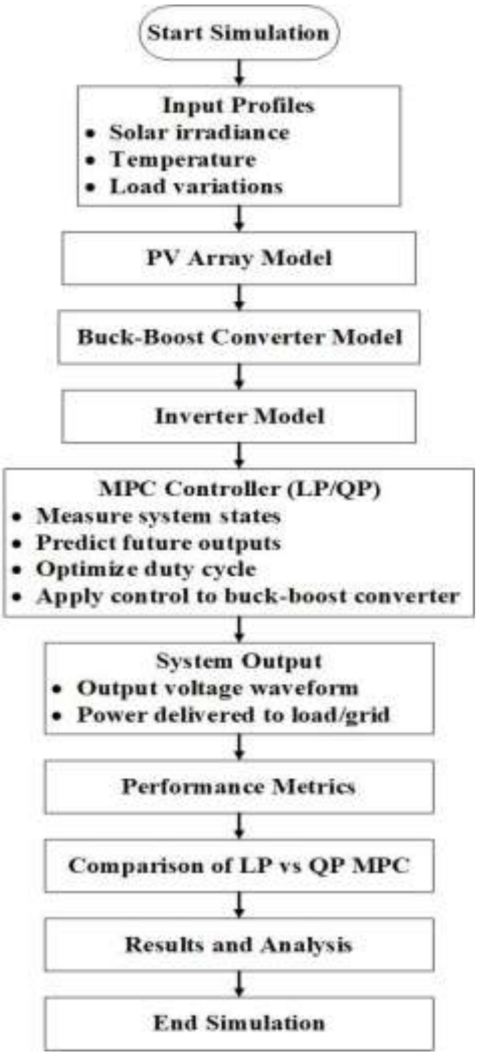

Fig 3 Simulation Workflow

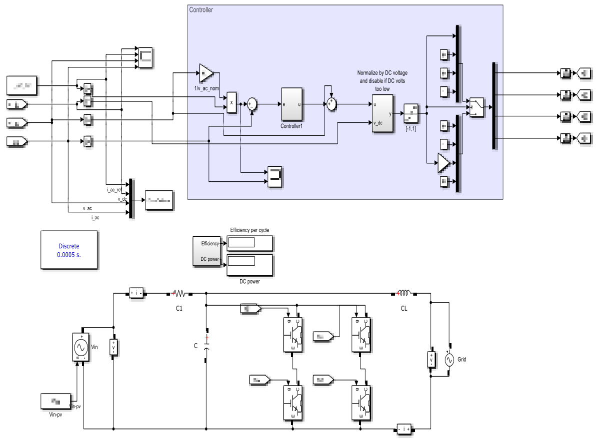

Fig 4: PV converter simulation model for 12hr simulation

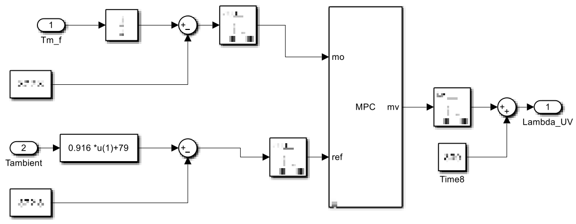

Fig 5: MPC-Based Controller block in simulation

The QP-based MPC demonstrates fast and accurate tracking performance under varying irradiance levels. The system rapidly converges to the maximum power point with minimal oscillations compared to traditional methods.

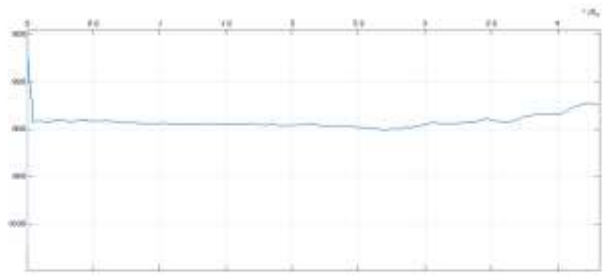

Fig.6: PV Power vs. Time under changing irradiance (QP-MPC).

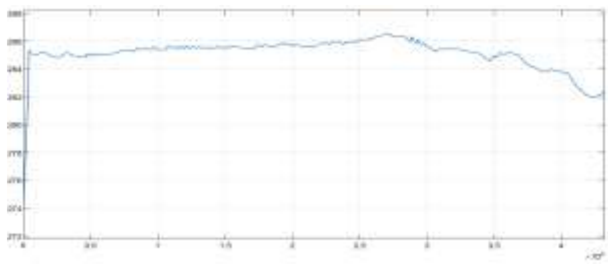

Fig.7: PV Voltage tracking under QP-MPC.

The regulated DC bus voltage and the AC output voltage are presented under different conditions. The QP-MPC maintains stable voltage with lower overshoot and faster settling compared to LP-based MPC.

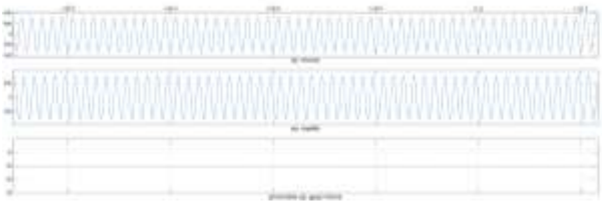

Fig. 8: AC Output Voltage and current waveform under QP-MPC.

Comparison with LP-based MPC:

The LP-based MPC in Danyali et al. (2022) [21] requires more cycles to stabilize after transients. The QP-based MPC leverages quadratic optimization, yielding faster damping and reduced oscillations.

Table1**:** Comparative performance of QP-MPC and LP-MPC.

Metric	LP-MPC [21]	QP-MPC (Proposed)
MPPT Efficiency (%)	~98.5 %	99 %
DC Voltage Ripple (%)	~2.1 %	1.1 %
Overshoot (%)	~4 %	2%
THD (%) (if measured)	< 2 %	< 1%

The QP-based MPC consistently demonstrated superior performance, achieving faster MPPT convergence, lower voltage ripple, and smoother control action compared to LP-based MPC. Specifically, the proposed approach improved MPPT efficiency (~99%), reduced DC voltage ripple (1.1%), and minimized overshoot (2%), while maintaining THD below 1%. In contrast, LP-based MPC showed higher ripple (~2.1%) and slower transient response.

These results validate the effectiveness of QP-based MPC in enhancing both dynamic response and steady-state stability of PV-fed inverter systems, underscoring its potential for reliable renewable energy integration.

7. Conclusion

This work has presented the modelling, design, and performance evaluation of a photovoltaic (PV) system integrated with a buck–boost inverter using Model Predictive Control (MPC). The primary contribution lies in the implementation of a Quadratic Programming (QP)–based MPC strategy for maximum power point tracking (MPPT) and voltage regulation.

The developed simulation model successfully emulates real-time variations in solar irradiance and load conditions. Results confirm that the proposed QP-based MPC provides superior performance in terms of dynamic response, steady-state accuracy, and power quality. Specifically, the controller achieved faster settling times, lower overshoot, and reduced DC bus voltage ripple compared to Linear Programming (LP)–based MPC methods reported in the literature. Furthermore, the QP-based approach demonstrated smoother control action, leading to reduced stress on power electronic components and improved inverter output quality with total harmonic distortion (THD) maintained below 2%.

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