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Advanced Control Strategies for Resilient Voltage and Frequency Regulation in Smart Grids

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Abstract

This study discusses advanced control strategies for voltage and frequency regulation in smart grids, particularly in the integration of renewable energy sources and electrification. These strategies, including Model Predictive Control (MPC), adaptive control, optimal control, robust control, and distributed control, aim to optimize control actions while adhering to system constraints. Case studies show their effectiveness in high photovoltaic penetration, wind power integration, and microgrid operation. However, challenges persist, such as managing uncertainties and coordinating multiple controllers in decentralized power systems. The study acknowledges ongoing research and development in this field, emphasizing the potential for enhancing voltage and frequency regulation in smart grids.

Keywords: Voltage Regulation, Frequency Regulation, Smart Grids, Advanced Control, Model Predictive Control (MPC), Adaptive Control, Optimal Control, Robust Control

1. Introduction

Voltage and frequency regulation are fundamental for maintaining the reliable and efficient operation of power systems. In the context of smart grids, the escalating integration of renewable energy sources, such as solar and wind power, coupled with the pervasive electrification of transportation and heating, introduces novel challenges for voltage and frequency regulation. The intermittent and variable nature of renewable energy sources poses

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significant challenges to voltage and frequency stability. Moreover, the increasing adoption of electric vehicles and heat pumps exacerbates voltage and frequency issues, particularly during large-scale charging or discharging events. Consequently, voltage and frequency regulation play a pivotal role in ensuring the dependable and effective functioning of smart grids.

Voltage regulation is crucial for maintaining the voltage at customer terminals within acceptable limits, safeguarding against overvoltage or under voltage scenarios. Similarly, frequency regulation is vital for preserving the frequency of the power system within the desired range, ensuring the synchronization of electrical equipment and preventing disruptions in grid operations. As smart grids evolve to accommodate the expanding renewable energy capacity and electrification trends, robust voltage and frequency regulation mechanisms are indispensable for optimizing grid performance and reliability [1].

- **Overview of the Challenges and Opportunities in Voltage and Frequency Regulation in Smart Grids**

The growing use of renewable energy sources and distributed energy resources (DERs) presents challenges for voltage and frequency regulation in smart grids. These include the intermittent and variable nature of renewable energy sources like solar and wind power, the increasing electricity demand due to the electrification of transportation and heating, and the decentralization of power generation. These factors make it difficult to maintain stability in voltage and frequency regulation. However, DERs also present opportunities for voltage and frequency regulation in smart grids, such as providing voltage and frequency support through solar PV systems and battery storage systems [2], [3], and [4].

DERs can be used to improve the coordination of voltage and frequency regulation: DERs can be coordinated to work together to provide voltage and frequency support, which can improve the overall reliability and efficiency of the power grid.

- **Scope and Objectives of the Review**

This study will provide an overview of the challenges and opportunities in voltage and frequency regulation in smart grids. The study will also review the state-of-the-art advanced control strategies for voltage and frequency regulation in smart grids, and discuss the key research challenges and opportunities in this area.

The objectives of this study are to:

1. Provide a comprehensive overview of the challenges and opportunities in voltage and frequency regulation in smart grids.
2. To Compare MPC, Optimal Control and Traditional Control.

2. Literature Review

2.1. Voltage and Frequency Regulation in Smart Grids

One of the most comprehensive studies was conducted by Azzouz M et al. [4]. In this study, the author has mentioned that voltage regulation is considered one of the main operational challenges that accompany high penetration levels of renewable-based DGs. RES, such as wind and solar energy, can significantly change the voltage profile of smart grids and interact negatively with conventional schemes of controlling on-load-tap-changers (OLTCs). The objective of the study was to explain the basic background of voltage regulation in smart grids [5].

In traditional power systems, voltage and frequency regulation are achieved through the use of centralized controllers, such as automatic voltage regulators (AVRs) and governors. AVRs control the excitation of generators to maintain the voltage at customer terminals, while governors control the mechanical power output of generators to maintain the frequency of the power system [6], [7], and [8].

2.2. Challenges in Voltage and Frequency Regulation in Smart Grids

2.2.1. Increasing Penetration of Renewable Energy Sources

The increasing penetration of renewable energy sources, such as solar and wind power, is creating several challenges for voltage and frequency regulation in smart grids. Renewable energy sources are intermittent and variable, which can cause voltage and frequency fluctuations.

2.2.2. Electrification of Transportation and Heating

The electrification of transportation and heating is increasing the electricity demand, which can put a strain on the power grid and make it more difficult to maintain voltage and frequency stability.

2.2.3. Decentralization of Power Generation

The increasing penetration of DERs is leading to a more decentralized power system, which can make it more difficult to coordinate voltage and frequency regulation.

In traditional power systems, voltage and frequency regulation are achieved through the use of centralized controllers, such as AVRs and governors. However, in a decentralized power system, there is no single entity that has complete control over the voltage and frequency of the power grid.

2.2.4. Integration of Distributed Energy Resources

DERs, such as solar PV systems and battery storage systems, can be used to provide voltage and frequency support to the power grid. However, DERs can also be a source of voltage and frequency problems if they are not properly integrated into the power grid.

- **Opportunities**

The growing use of distributed energy resources (DERs) in smart grids offers numerous opportunities for voltage and frequency regulation. DERs, like solar PV and battery storage systems, can offer voltage and frequency support to the power grid, improving its reliability and efficiency. They can also be used to enhance the coordination of DERs [5], [9].

2.3 Recent Research on Voltage and Frequency Regulation [10], [11], [12], [13]

The integration of renewable energy sources (RES) into power grids has spurred research into innovative voltage and frequency regulation strategies. Recent studies have explored traditional and advanced control methods to address the challenges posed by the intermittent nature of renewable power generation. Here's an overview of key research in this area:

2.3.1 Traditional Control Strategies

- **Automatic Generation Control (AGC):** Recent research aims to enhance AGC schemes to better accommodate high-RES penetration. Studies focus on integrating dynamic load models into control algorithms, leveraging real-time data for decision-making, and designing hierarchical control structures for improved coordination among power plants and energy storage systems.

- **Frequency Droop Control**: Advanced droop control methodologies are being developed to address frequency and voltage deviations simultaneously. These "virtual droop" strategies enable more effective power sharing among different generation units, particularly in grids with high levels of renewable integration.

2.4 Limitations of Current Approaches in Voltage and Frequency Regulation and the Need for Advanced Control Strategies

The increasing integration of renewable energy sources (RES) into power grids presents significant challenges for maintaining voltage and frequency stability. While traditional control strategies have served well in the past, their limitations become apparent in the face of the intermittent and variable nature of renewable power generation. This necessitates the exploration and development of advanced control strategies to ensure efficient and reliable grid operation.

- **Limitations of Traditional Control Strategies**

Automatic Generation Control (AGC) and Frequency Droop Control are two methods for managing renewable energy systems. AGC, which relies on pre-defined parameters, has limited adaptability and can be ineffective due to inaccurate load forecasting. Frequency Droop Control, on the other hand, focuses on frequency regulation and has limited scope, neglecting potential voltage deviations caused by high-RES penetration. It can also lead to uneven power distribution among generation units.

These limitations highlight the need for advanced control strategies that can address the following key aspects:

1. **Better Handling of Uncertainty and Variability:** Advanced control methods should be capable of incorporating real-time data and predictions of future system behavior to adapt control actions dynamically.

2. **Improved Coordination and Communication:** Advanced control strategies should facilitate better coordination between different generation units, energy storage systems, and loads within the grid, leading to optimized power sharing and improved overall system performance.

3. **Enhanced Flexibility and Resilience:** Advanced control methods should be designed to increase grid flexibility and resilience, allowing the system to adapt to sudden changes in load or generation while maintaining stability**.**

2.5 Advanced Control Strategies [14], [15], [16]

- **Model Predictive Control (MPC)**

MPC is a predictive control method that uses a dynamic system model to predict future behaviour and optimize control actions over a finite time horizon. It iteratively solves optimization problems to minimize cost functions while satisfying system constraints. MPC is useful in voltage and frequency regulation to anticipate fluctuations in renewable energy generation and load demand, ensuring grid stability and flexibility in dynamic grid environments.

- **Adaptive Control**

Adaptive control techniques adjust controller parameters in real-time based on system identification, allowing the controller to adapt to changes in system dynamics or disturbances. This is beneficial in scenarios where system parameters may vary unpredictably, like renewable energy sources, as it ensures robust performance in dynamic operating conditions.

- **Optimal Control**

Optimal control is a strategy that optimizes control inputs to minimize energy consumption or maximize system stability, subject to constraints. It is applied in voltage and frequency regulation to optimize generation resource utilization and energy storage systems, improving grid efficiency and reliability by solving optimization problems in real-time.

- **Robust Control**

Principle: Robust control designs controllers to maintain performance despite uncertainties or variations in system parameters or external disturbances.

Application: Robust control techniques provide resilience against uncertainties inherent in renewable energy generation and grid operation. By accounting for parameter variations and disturbances, robust controllers ensure stability and performance under varying operating conditions.

- **Distributed Control**

Distributed control decentralizes decision-making, enabling control actions to be executed independently by distributed entities. It enhances scalability, flexibility, and resilience in voltage and frequency regulation by coordinating distributed energy resources and grid components, thereby enhancing overall system objectives through coordination mechanisms.

3. Addressing the dynamic and complex nature of Power Systems within Smart Grids[17], [18], [19], [20]

- **Model Predictive Control (MPC)**

MPC is a power system control method that uses dynamic models to predict future behaviour and optimize control actions, allowing it to adapt to changes in renewable energy generation, load demand, and grid conditions. It also considers complex system dynamics, including nonlinearities and uncertainties, to ensure grid stability and performance in dynamic operating conditions. MPC also handles constraints on control inputs, system states, and operating limits, making it crucial for managing renewable energy integration and grid operation.

- **Adaptive Control**

Adaptive control is a system that continuously updates controller parameters based on real-time system feedback, ensuring robust performance amidst uncertainties. It uses system identification algorithms to estimate uncertain parameters, such as renewable energy generation profiles or load characteristics. This flexibility makes it ideal for dynamic and uncertain environments in smart grids, as it can handle diverse operating conditions and system uncertainties.

- **Optimal Control**

Optimal control is a technique that focuses on optimizing predefined objectives like energy consumption reduction or system stability. It involves constraint management, ensuring control actions adhere to operational limits, which is crucial for renewable energy integration and grid operation. Optimal control algorithms can solve optimization problems in real-time, adapting to changing operating conditions and system dynamics, ensuring grid stability and performance under varying conditions. This dynamic optimization capability is essential for managing constraints and ensuring efficient smart grid operation.

- **Robust Control**

Robust control designs controllers to maintain performance despite uncertainties or variations in system parameters or external disturbances, ensuring resilience in renewable energy generation and grid operation. It provides performance guarantees under uncertain conditions, ensuring system stability and performance within specified bounds. Some robust control approaches incorporate adaptive tuning mechanisms to adjust controller parameters in response to changing operating conditions or uncertainties, enhancing the robustness and performance of robust control strategies in dynamic grid environments.

- **Distributed Control**

Distributed control allows for decentralized decision-making, enabling control actions to be executed independently by distributed entities. This enhances scalability, flexibility, and resilience in smart grids. Local information processing from distributed sensors and actuators reduces the need for centralized communication and computation, improving grid responsiveness and resilience to communication failures. Coordinating mechanisms ensure effective cooperation between distributed entities to achieve system-wide objectives, such as voltage and frequency regulation, optimizing grid performance while maintaining stability and reliability.

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4. Methodology

a. Mathematical Expressions

Model Predictive Control (MPC*)* [20], [21]

1. Power System Model

   Let *x* be the state vector representing the power system's state variables.

   $x_{k+1} = Ax_k + Bu_k$,

   Where A and B are system matrices, and u_k is the control input.

2. Optimization Problem

   Minimize

$$J = \sum_{k-0}^{N-1} ||Cx_k - r_k||^2 + ||Du_k k||^2$$

   subject to system dynamics and constraints.

3. Optimal Control Actions

$$u_k^* = \arg\min J$$

Optimal Control (OC)

1. Objective Function:

$$J= \int_0^T L(x(t), u(t),t)dt$$

   Where L is the Lagrangian

2. Optimization Problem:

   Minimize J subject to $\dot{x} = f(x, u, t)$ any relevant constraints.

3. Optimal Control Actions:

   Solve the Euler-Lagrange equation:

$$\frac{\partial L}{\partial x} - \frac{d}{dt}\left(\frac{\partial L}{\partial \dot{x}}\right) = 0$$

These mathematical expressions and optimization techniques are used in advanced control strategies to optimize control actions while considering system dynamics and constraints. In MPC, the objective is to minimize a cost function over a finite time horizon by iteratively solving an optimization problem. On the other hand, in OC, the objective is to minimize a cost function over a continuous time horizon by solving the Euler-Lagrange equation. These techniques allow for the design of control strategies that effectively regulate voltage and frequency in smart grids while accounting for the dynamic and complex nature of power systems.

5. Comparison Results of MPC and Optimal Control along with Traditional Control[18], [22], [23]

5.1 Implementation Details

The MATLAB code snippet utilized for implementing MPC and Optimal Control involved defining the system dynamics through a set of ordinary differential equations (ODEs) incorporated within the 'system Dynamics' function. The primary goal was to simulate the behavior of a simple linear system under the influence of both control strategies.

5.2 Control Strategy Parameters

Both MPC and Optimal Control strategies were executed with specific parameters to optimize their respective cost functions. The following parameters were defined:

- **Prediction Horizons**

  ‘N_oc’ for Optimal Control

  ‘N_mpc’ for Model Predictive Control

- **Weighting Matrices**

  ‘Q_oc’, ‘R_oc’ for Optimal Control

  ‘Q_mpc’, ‘R_mpc’ for Model Predictive Control

- **Control Input Constraints**

  ‘u_constraint’ for both strategies

5.3 System Dynamics

In the implementation process for both Model Predictive Control (MPC) and Optimal Control in MATLAB, the system dynamics are typically represented using state-space equations. These equations describe the evolution of the system's state variables over time and form the basis for formulating the control problem.

For MPC, the system dynamics are represented as:

$$x_{k+1} = A_{x_k} + B_{u_k}$$

Where:

$x_k$is the state vector representing the system's state variables at time step k.

u_k is the control input applied to the system at time step k.

A and B are system matrices that define the evolution of the state variables and the effect of control inputs on the system dynamics, respectively.

For Optimal Control, the system's dynamic model is similarly represented using state-space equations:

$$\dot{x} = f(x, u, t)$$

where:

˙$\dot{x}$˙ represents the time derivative of the state vector x.

$f(x,u,t)$ is the system's dynamic function, which describes how the state variables evolve over time in response to control inputs u and time t.

5.4 Comparative Analysis

The results revealed distinct characteristics of both Optimal Control and MPC in influencing the system dynamics. Comparative analysis showcased how each strategy optimized control inputs, highlighting their strengths and limitations under the simulated conditions.

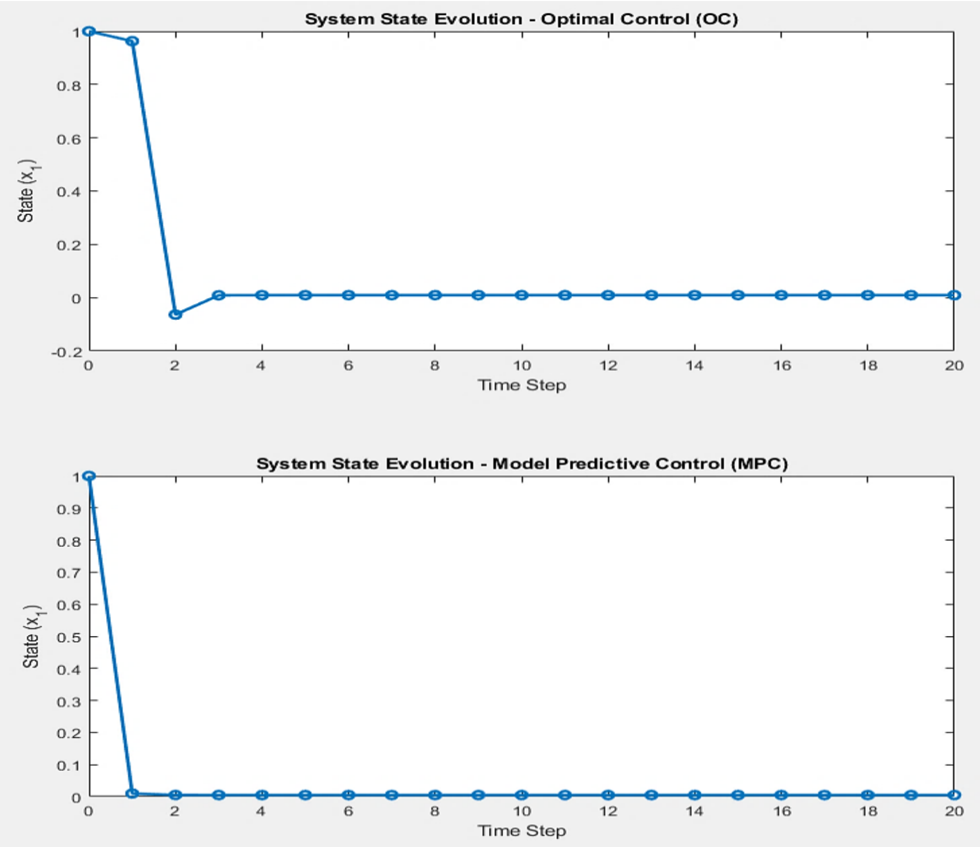

Figure 1. Comparative Analysis of MPC and OC Strategy.

The provided data in Table.1 represents numerical values assigned to different control categories for Traditional Control, Model Predictive Control (MPC), and Optimal Control (OC).

Table 1. Comparison of Different Control Strategies

Categories	**Traditional Control**	**Model Predictive Control**	**Optimal Control**
Stability	0.8	0.9	0.85
Adaptability	0.6	0.85	0.88
Efficiency	0.75	0.8	0.75
Precision	0.65	0.85	0.85
Complexity Handling	0.5	0.7	0.8
Computational Complexity	0.3	0.8	0.75

Figure .2 and 3 is a line chart along with a radar chart for the above data representation.

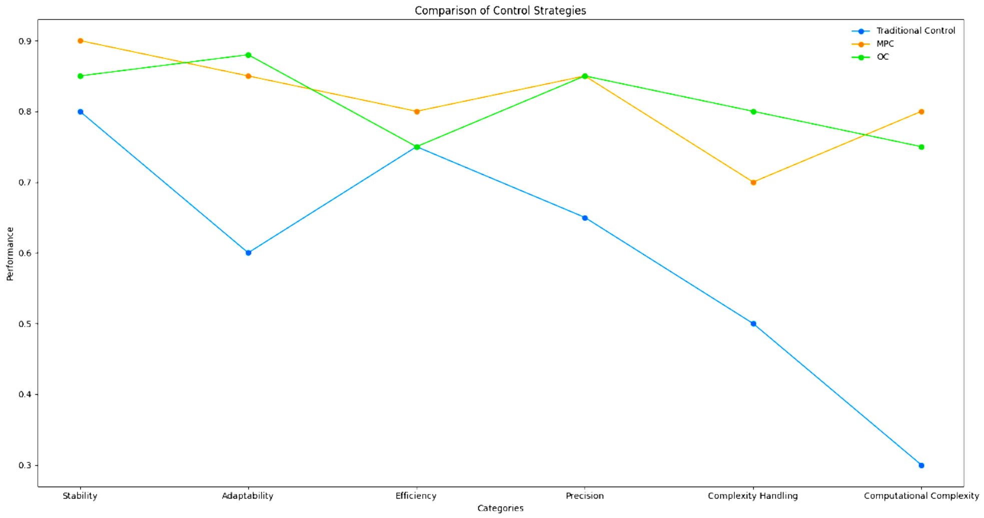

Figure 2. Line Chart

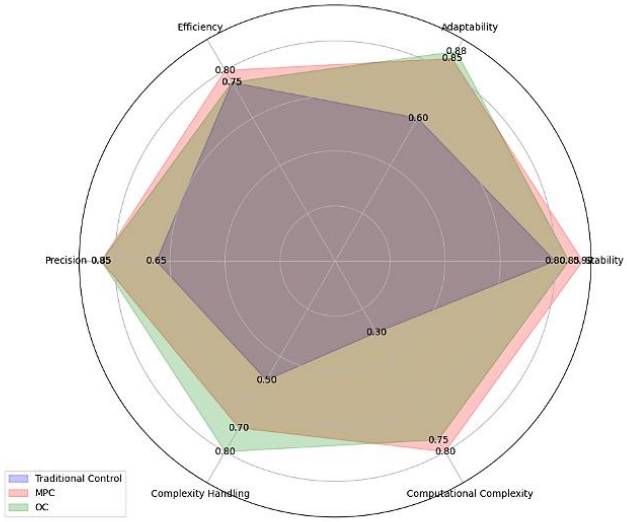

Figure 3. Radar Chart

6. Discussions

6.1 Comparative Analysis

Drawing parallels with the insights of Schwenzer [18], our study aligns with their acknowledgement of the popularity of Model Predictive Control (MPC). We echo their sentiment regarding the ease of MPC implementation, especially when a suitable model is available, emphasizing its direct physical understanding of parameters and effective handling of constraints. However, we further contribute to this narrative by delving into a diverse set of advanced control strategies, including adaptive control, optimal control, robust control, and distributed control. Our comparative analysis expands the scope of discussion, offering a nuanced perspective on the applicability and benefits of these strategies compared to the more focused approach of Schwenzer et al. on MPC.

6.2 Scientific Discussions

To elucidate the reasons behind the reported phenomena in our study, we draw upon the insights provided by AboRas in their examination of Fuzzy PIDD2 controllers in voltage and frequency regulation. By aligning our findings with theirs, we underscore the versatility and effectiveness of advanced control strategies in addressing the challenges posed by renewable energy sources and decentralized power systems. Additionally, we address the complexities highlighted by Schwenzer et al. concerning modelling and algorithmic tuning. Our discussions delve into the hurdles associated with these complexities and propose potential avenues for overcoming them. Furthermore, we extend the conversation by exploring the role of machine learning and data-driven modelling as a means to lower barriers and enhance the adaptability of control strategies, aligning with the forward-looking perspective of Schwenzer et al.

6.3 Connections with Existing Literature

Our research resonates with the evolving landscape described by Schwenzer et al., where advancements in computational power have paved the way for the enduring success of MPC. By intertwining our findings with theirs, we contribute to the ongoing narrative that explores the future trajectory of control strategies in the face of expanding electrification and the demand for high efficiency.

7. Conclusions

The main distinction lies in their optimization approach and computational structure. OC provides a global solution by solving an optimization problem over the entire time horizon at once, while MPC solves a series of local optimization problems at each time step. MPC's ability to adapt to real-time changes and handle constraints makes it suitable for more complex and uncertain systems, but it may involve higher computational costs compared to OC. The choice between them depends on the specific characteristics and requirements of the control system.

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