International Journal of Research and Review
Vol. 10; Issue: 7; July 2023
Website: www.ijrrjournal.com
E-ISSN: 2349-9788; P-ISSN: 2454-2237

Case Study

Development of an Advanced Optimization and Optimal Control Mathematical Model for Energy-Efficient Operations of Renewable Energy

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DOI: https://doi.org/10.52403/ijrr.20230735

ABSTRACT

The potential for developing energy-efficient operations for renewable energy systems has increased with the expansion of renewable energy sources. As a result, creating advanced optimization and optimum control mathematical models will be necessary to handle the difficulties related to their integration into the grid. This study develops an enhanced optimization and optimal control model for the energy-efficient operation of renewable energy systems based on photovoltaic (PV) and hydropower. The created model takes into account the economic element while integrating an optimization method to address the energy management issue of PV systems. PV system operation is optimized taking into account a variety of operational restrictions using economic objectives like profit maximization and cost minimization. To further simplify energy balancing and lower risk, a hydropower energy system is also taken into consideration. Furthermore, by forecasting the ideal PV output and hydropower generation for various economic purposes, a dynamic optimum control approach is created to discover the best operational strategy for the systems. Case studies are used to evaluate this sophisticated optimization and optimum control model, and the findings show how effective it is at lowering operating expenses for the operation of renewable energy systems in an energy-efficient manner.

Keywords: Advanced Optimization, Optimization Techniques, Control Strategies, Energy Management, Optimal control, Mathematical model, Energy-efficient operations, Renewable energy

INTRODUCTION

A paradigm shift in the energy landscape has recently been ushered in by the emergence and quick spread of renewable energy sources, such as solar, wind, and hydropower (Scheer, 2012; Cloke et *al*., 2017). These sources present a compelling and sustainable alternative to conventional fossil fuel-based power generation. To fully realize their potential, these renewable energy sources must be integrated into the current electrical system, which presents numerous problems. These difficulties include the intermittent nature of renewable energy sources, the inherent difficulties in managing their production, and the high operating expenses connected to their use (Liserre et al., 2010; Rehman et al., 2015; Chen et *al*., 2007).

Deploying innovative optimization and optimal control approaches that can successfully handle these issues and guarantee the smooth and efficient operation of renewable energy systems is therefore urgently needed (Ishaq et *al.*, 2022; Hannan et *al*, 2020; Roslan et al., 2019). The core of this endeavor is the creation of complex mathematical models because they give us the tools to improve and fine-tune the performance of these systems, allowing them to function at their highest levels of efficacy and efficiency (Shaikh et al., 2014; Machlev et *al*., 2020).

It is possible to maximize the use of renewable energy resources by maximizing their generation, storage, and distribution by using advanced optimization techniques and optimal control strategies (Ishaq et *al*., 2022).These techniques enable for comprehensive and dynamic optimization of renewable energy systems by taking into consideration a variety of variables, including energy costs, storage capacity, and battery state of charge (Abdulla et *al*., 2016; Wang et *al*., 2015). These models can calculate and optimize the optimal energy storage capacity, battery state of charge, and renewable energy resource levels through the complex interaction of mathematical equations, all of which are essential in achieving energy-efficient operations and lowering costs (Meliani et *al*., 2021; Absulla et *al*., 2016; LI et *al*., 2014).

The way we harvest and use renewable energy could be completely changed by the incorporation of such cutting-edge optimization and optimal control approaches (Iris et al., 2021; Oree et *al*., 2017). These techniques pave the way for the seamless integration of renewable energy sources into existing power grids by successfully addressing the issues posed by intermittency, control restrictions, and operating costs (Fathima et *al*., 2015; Ouramdane et *al*., 2021). Additionally, they help to improve the entire energy infrastructure's stability, dependability, and sustainability, bringing us one step closer to a cleaner and greener energy future (Herzog et *al*., 2001; Majid et *al*., 2020).

The introduction and widespread use of renewable energy sources have ushered in a new era of potential in the energy industry. But in order to use these sources to their fullest capacity, integration problems must be resolved. The efficient and successful management of renewable energy systems is made possible by the development of sophisticated optimization and optimal control approaches, in addition to sophisticated mathematical models. By adopting these approaches, we may maximize the advantages of renewable energy, promoting the development of a sustainable energy sector that is both commercially viable and environmentally responsible.

In the context of this research, we provide an original and thorough optimization and optimal control model adapted especially for hydropower and photovoltaic (PV)-based renewable energy systems. Our suggested model takes into account the numerous operational constraints that can be faced in addition to integrating the optimization of PV systems with an economic purpose. We also include a hydropower energy system to enhance the overall performance of the renewable energy system since we recognize the importance of energy balancing and risk reduction. To do this, we create a dynamic optimal control approach that efficiently determines the system's most successful operational strategy.

The subsequent sections of this paper are organized as follows, providing a structured overview of our research and findings. Section 2 presents a comprehensive analysis of the technical and economic considerations associated with the optimization of renewable energy systems, highlighting the key factors that necessitate the development of advanced optimization models. In Section 3, we formulate the optimization problem for energy-efficient operations of renewable energy systems, taking into account the specific requirements and constraints.

On top of that, Section 4 elaborates on the optimization process in depth and introduces the dynamic optimal control strategy created for our proposed model, explaining its theoretical underpinnings and real-world application.

To show the effectiveness and efficiency of the suggested methodology, we offer the outcomes of two interesting case studies that have been simulated in Section 5. These case studies show concretely how our methodology can improve the operational performance of renewable energy systems and contribute to the overall optimization of energy resources. Finally, in Section 6, we suggest opportunities for further study and development in the area of optimization and optimal control for renewable energy systems, review the key findings, and draw illuminating conclusions.

This research intends to shed light on the possibilities and benefits of leveraging advanced mathematical models to promote energy-efficient operations through the presentation of our advanced optimization and optimal control model for hydropower and PV-based renewable energy systems. Our approach has the potential to revolutionize the way renewable energy systems are created, maintained, and improved, leading to a more environmentally friendly and sustainable energy landscape by taking into account technical, financial, and operational variables.

TECHNICAL AND ECONOMIC CONSIDERATION

The basic objective of energy management systems is to keep the supply and demand for energy in balance (Corchero et *al*., 2014). The level of supply reliability, the quality of the power delivered, and the cost of the energy generated are just a few of the technical considerations when developing energy management systems (Lupangu et *al*., 2017; Ribeiro et *al*., 2001]. The possibility for profit maximization or the reduction of operational costs, such as fuel and maintenance costs, are the focus of the economic consideration. To achieve this, both technical and financial goals should be met while optimizing the operation of renewable energy systems (Ma et *al*., 2018; Olatomiwa et *al*., 2016).

PROBLEM FORMULATION

The suggested model's goal is to operate renewable energy systems based on photovoltaic (PV) technology and hydropower as efficiently as possible. The model is specifically designed to maximize profit or reduce operating expenses while taking into account a variety of operational restrictions.

In this regard, the optimization problem can be expressed as follows:

$$min_{p_h,p_p} c_p(p_h, p_p) + c_s(p_h, p_p) + c_t(p_h, p_p)$$

Subject to:

<u>Generation constraints:</u>

$$p_p + p_h = P$$
$$0 \le \mathrm{p_p} \le \mathrm{P_p}$$
$$0 \le \mathrm{p_h} \le \mathrm{P_h}$$

<u>Operation constraints:</u>

<u>PV constraints:</u>

$$0 \le \dot{\mathrm{p}}_\mathrm{p} \le \dot{\mathrm{P}}_\mathrm{p}$$
$$0 \le \dot{\delta}_\mathrm{p} \le \dot{\Delta}_\mathrm{p}$$

<u>Hydropower constraints:</u>

$$0 \le \dot{\mathrm{p}}_\mathrm{h} \le \dot{\mathrm{P}}_\mathrm{h}$$
$$0 \le \dot{\delta}_\mathrm{h} \le \dot{\Delta}_\mathrm{h}$$

Where c_p ,c_s and c_t represent the unit costs for, respectively, obtaining electricity from the grid, solar energy, and the cost of fuel and maintenance; P, P_p and P_h represent the total available capacity, photovoltaic capacity, and hydropower capacity; $\dot{\mathrm{P}}_\mathrm{p}$, and $\dot{\mathrm{P}}_\mathrm{h}$ are the maximum allowable ramp-up and ramp-down rates of PV and hydropower, respectively; $\dot{\Delta}_\mathrm{p}$ and $\dot{\Delta}_\mathrm{h}$ represent the maximum allowable changes in, PV and operating points of hydropower respectively

OPTIMIZATION PROCEDURE AND DYNAMIC OPTIMAL CONTROL

The suggested strategy involves incorporating financial goals, including maximizing profit or minimizing overhead, into optimization techniques for running renewable energy plants. The objective function of the optimization problem, which represents the cost of purchasing from the grid, the cost of solar radiation, and the cost of fuel and maintenance, is composed of three cost functions using a mathematical programming approach in order to do this. Additionally, the optimization issue takes into account numerous operational restrictions, including constraints on hydropower ramp rate and capacity as well as constraints on generating capacity and PV smoothing.

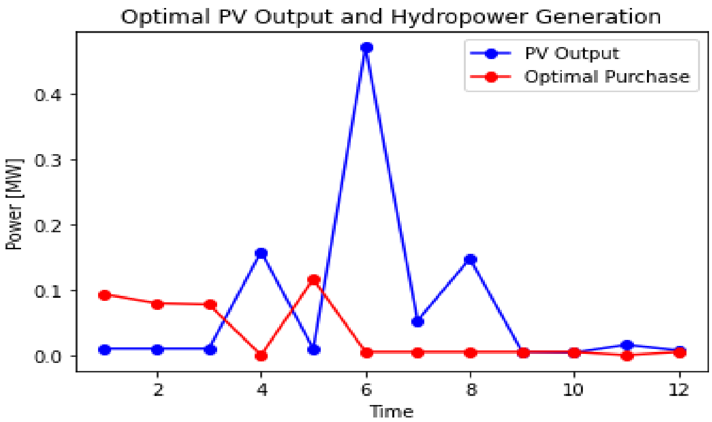
A genetic algorithm is used to address the optimization problem and provide the best operating strategy for renewable energy systems. The suggested model also incorporates a dynamic optimal control strategy to forecast the best hydropower and PV output for various economic goals. The ramp up and ramp down restrictions of the PV and hydropower systems are taken into account when formulating the dynamic optimum control problem as a constrained optimal control problem, with the economic objective of minimizing the overall cost of generating.

The dynamic optimum control problem's essential elements are a prediction model to forecast the system's future state and an optimization technique to produce the ideal control variables. An approach called discrete-time model predictive control is utilized to get the best power set points.

CASE STUDY RESULT

Two case studies are simulated using the Python program to show the effectiveness of the suggested model. The first case study simulates a PV system for 12 hours with a 10 MW rated capacity and a 0.20 USD/kWh billing rate. The assumed electricity demand is 5 MW.

Figure 1 displays the case study's findings.

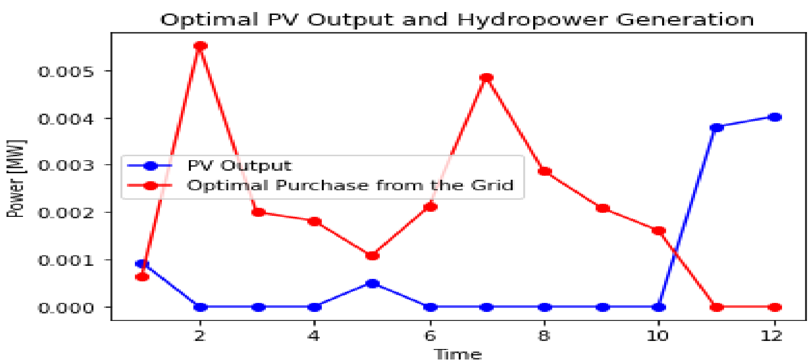


Both the best grid purchase (green curve) and the best PV production (blue curve) against time are presented.

The outcomes of the simulation shows that the suggested paradigm significantly reduces operational costs.

In the second case study, a PV-hydropower system with a total rated capacity of 15 MW and a billing rate of 0.30 USD/kWh is simulated throughout the course of 12 hours. The projected electricity demand is 8 MW.

Figure 2 displays the case study's findings.



Where the ideal hydropower production (red curve) and photovoltaic (PV) output (blue curve) against time are plotted. According to the simulation results, the suggested model significantly reduces costs.

The results of the two Case Studies conclusively demonstrate that the system was successfully optimized using the suggested model, taking into account a variety of restrictions and other factors. The model was able to optimize the system's power production while taking into account many considerations, including cost and technical limits.

The results show the effectiveness of mathematical model and imply that it can offer a practical and efficient solution for RESs' energy-efficient functioning.

CONCLUSION

An innovative optimization and optimal control model for the operation of hydropower and photovoltaic (PV)-based renewable energy systems was proposed in this research. The suggested methodology combines PV system optimization with an economic goal while accounting for operational restrictions. In order to simplify energy balance and lower risk, a hydropower energy system is also implemented. To determine the system's ideal operational strategy, a dynamic optimum control approach is also created. Two case studies are used to test the suggested model, and the results show how effective it is at lowering operational expenses for running renewable energy systems efficiently. Future work should concentrate on putting the suggested model into practical applications. Additionally, more investigation is required to pinpoint potential dangers and create mitigation solutions.

Declaration by Authors

Acknowledgement: None

Source of Funding: None

Conflict of Interest: The authors declare no conflict of interest.

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How to cite this article: Venant Niyonkuru. Development of an advanced optimization and optimal control mathematical model for energy-efficient operations of renewable energy. *International Journal of Research and Review*. 2023; 10(7): 268-273.
DOI: *https://doi.org/10.52403/ijrr.20230735*

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