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OPTIMIZATION OF ENERGY SYSTEMS THROUGH THE APPLICATION OF BOOLEAN DIFFERENTIAL OPERATORS

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Abstract

This paper presents an innovative method for controlling hybrid energy systems using a combination of Boolean differential analysis and adaptive fuzzy logic. This paper presents Boolean differential analysis and adaptive fuzzy control approaches for optimizing smart hybrid energy systems (Solar panels, energy storage system, and digital load management). In the first phase, the system's structural analysis and identification of critical variables are carried out using Boolean functions and derivatives. In the next phase, uncertainty modeling is performed using the fuzzy mapping method, and fuzzy control rules are formulated. Finally, an adaptive fuzzy control system is introduced that dynamically adapts to real-world conditions. Simulation results show that the adaptive fuzzy system improves energy efficiency, extends battery life, and provides high stability in dynamic loads, ensuring reliable energy supply.

Keywords: Adaptive fuzzy energy management system, fuzzy logic, optimization with Boolean derivatives, Boolean differential operators, energy management system.

Introduction: Modern energy systems, particularly smart hybrid systems, are filled with uncertainties and require optimal management in dynamically changing conditions. The methodology enables real-time decision making and optimization of energy distribution through intelligent interpretation of solar radiation, battery status, and load demand. The findings reveal improved energy efficiency, extended battery life, and increased system reliability. Modern energy systems face difficulties in balancing demand and supply due to the intermittent nature of renewable energy. To overcome these challenges, smart Energy Management Systems (EMS) are crucial. However, traditional EMS lack adaptability and often fail to manage uncertainties arising from changing solar radiation, fluctuating load demands, and battery degradation. This research presents an innovative Adaptive Fuzzy Logic-based Energy Management System that intelligently manages energy distribution, corrects errors, and dynamically adjusts decision-making rules.

Boolean Model: Consider a management system in a smart hybrid energy system. Solar panels continuously monitor solar radiation, panel surface temperature, and other key parameters through digital sensors. The real-time data is transmitted to a cloud-based fuzzy control system via IoT (Internet of Things). The lithium-ion energy storage system (ESS) manages the energy flow and maintains the balance between demand and production. Based on fuzzy logic, the system stores excess energy produced by the solar panels and provides it for use when production is low. Adaptive control optimizes the battery life and efficiency. The smart digital load control device measures real-time energy demand and adjusts the operation of loads (electrical devices, etc.) in digital and smart modes. In case of energy shortages or high demand, secondary loads are automatically turned off or reduced [1]. Let us model this energy system with a Boolean function.

The Boolean model indicates the presence and activity of the system's elements through variables:

1. x = Solar panels (Solar PV): 1 if active, 0 if inactive. If solar panels (x) are active, energy production is possible.
2. y = Lithium-ion energy storage system (ESS): 1 if active, 0 if inactive. When there is no solar energy or insufficient solar energy (x = 0), the energy system should rely solely on the energy storage system (y).
3. z = Smart digital load management device: 1 if active, 0 if inactive. If the energy storage system (y) cannot provide energy, the load management system (z) must be active and isolate non-critical loads to ensure the system's continuity.

By combining the logical conditions above, the following Boolean function is obtained

$$F(x,y,z) = x + (\bar{x}\cdot y) + (\bar{x}\cdot\bar{y}\cdot z) = 01111111$$

This Boolean model clearly illustrates the different operational modes of the energy system and highlights which elements are critical. Even when energy sources (Solar Panels and ESS) are inactive, if the digital load management system is active, the system can continue to operate in minimal mode. The most efficient mode is when all three components are active.

Analysis and Optimization with Boolean Derivatives:

$$\begin{cases} \dfrac{\partial F}{\partial x} = \bar{y}\bar{z} \Rightarrow \begin{cases} y=0 \\ z=0 \end{cases} \\ \dfrac{\partial F}{\partial y} = \bar{x}\bar{z} \Rightarrow \begin{cases} x=0 \\ z=0 \end{cases} \\ \dfrac{\partial F}{\partial z} = \bar{x}\bar{y} \Rightarrow \begin{cases} x=0 \\ y=0 \end{cases} \end{cases}, \qquad \begin{cases} \dfrac{\partial F}{\partial x} = \bar{y}\bar{z} = 0 \Rightarrow \begin{cases} y=1 \\ z=1 \end{cases} \\ \dfrac{\partial F}{\partial y} = \bar{x}\bar{z} = 0 \Rightarrow \begin{cases} x=1 \\ z=1 \end{cases} \\ \dfrac{\partial F}{\partial z} = \bar{x}\bar{y} = 0 \Rightarrow \begin{cases} x=1 \\ y=1 \end{cases} \end{cases}$$

This indicates that the system is perfectly planned, as even in the case of gradual energy shortage, z protects the system. This analysis method proves to be a very efficient approach for optimizing the system. It allows distinguishing critical variables from those that do not carry additional information. Boolean derivatives are used to analyze the structure and sensitivity of the system [3].

Analysis with Boolean Min and Max Operators: The critical variables and important signals of the system can be analyzed through the Boolean differential operators of the function F(x,y,z).

$$\min_x f(x,y,z) = (1+(\bar{1}\cdot y) + (\bar{1}\cdot\bar{y}\cdot z)) \wedge (0+(\bar{0}\cdot y) + (\bar{0}\cdot\bar{y}\cdot z)) = (1) \wedge (y \vee z) = y \vee z$$

$$\min_y f(x,y,z) = x+(\bar{x}\cdot 1) + (\bar{x}\cdot\bar{1}\cdot z)) \wedge (x+(\bar{x}\cdot 0) + (\bar{x}\cdot\bar{0}\cdot z)) = 1 \wedge (x \vee z) = x \vee z$$

$$\min_z f(x,y,z) = (x+(\bar{x}\cdot y)+(\bar{x}\cdot\bar{y}\cdot 1)) \wedge (x+(\bar{x}\cdot y)+(\bar{x}\cdot\bar{y}\cdot 0)) = 1 \wedge (x \vee \bar{x}\cdot y) = x \vee y$$

$$\max_x f(x,y,z) = (1+(\bar{1}\cdot y)+(\bar{1}\cdot\bar{y}\cdot z)) \vee (0+(\bar{0}\cdot y)+(\bar{0}\cdot\bar{y}\cdot z)) = (1) \vee (y \vee z) = 1$$

$$\max_y f(x,y,z) = x+(\bar{x}\cdot 1)+(\bar{x}\cdot\bar{1}\cdot z)) \vee (x+(\bar{x}\cdot 0)+(\bar{x}\cdot\bar{0}\cdot z)) = (1) \vee (x \vee \bar{x}\cdot z) = 1$$

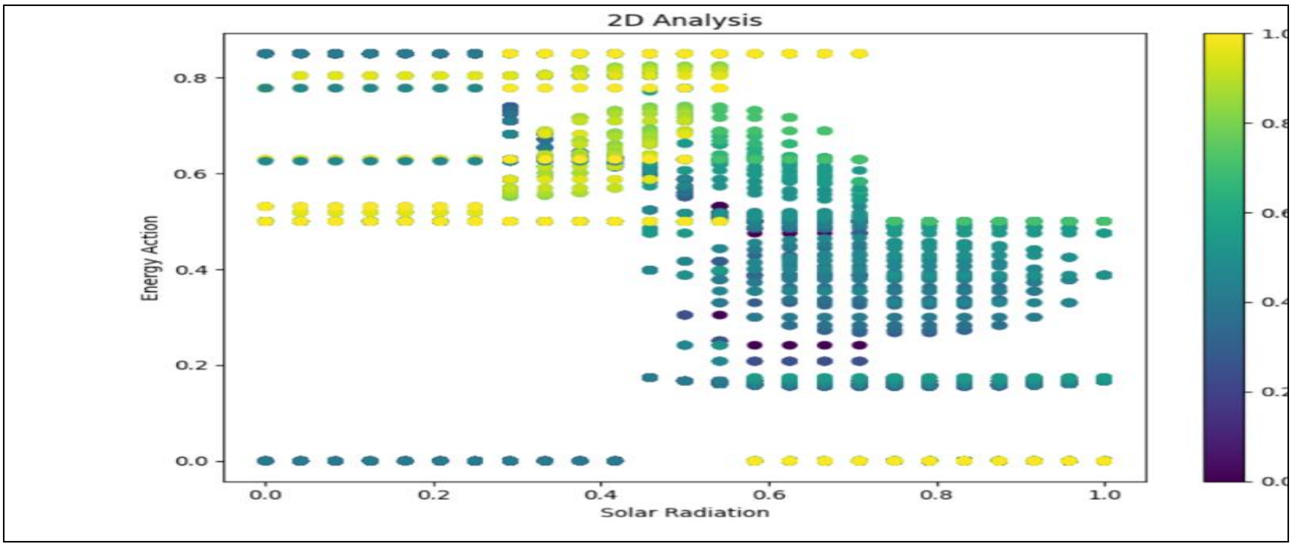
$$\max_z f(x,y,z) = (x+(\bar{x}\cdot y)+(\bar{x}\cdot\bar{y}\cdot 1)) \vee (x+(\bar{x}\cdot y)+(\bar{x}\cdot\bar{y}\cdot 0)) = 11 \vee (x \vee \bar{x}\cdot y) = 1$$

Even if the Load Controller protects critical loads, the system can maintain full energy supply. If the Load Controller is active and other elements are present, the system operates at maximum capacity [4]. By finding the minimum and optimal functional forms, a more efficient mathematical model of the energy system is established. This analysis shows that each variable ensures the sustainability of the system. The system is fully based on the stepwise security principle. Such a structure provides an ideal foundation for transitioning to an adaptive fuzzy model.

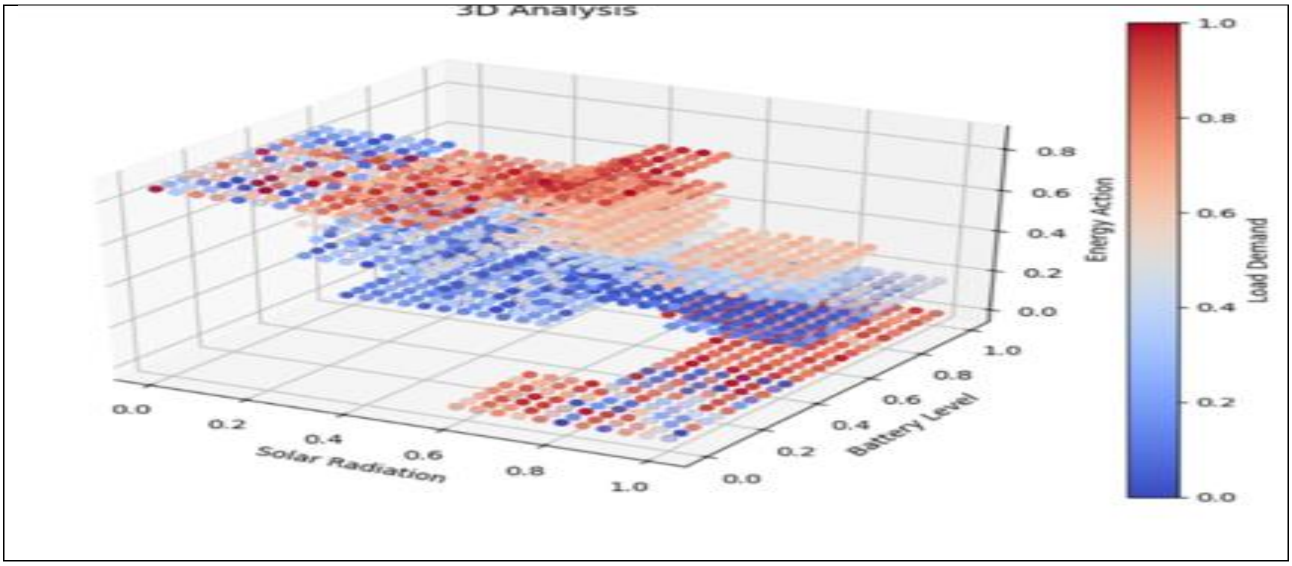
Integration and simulation: A transition from the optimized Boolean model to Fuzzy transformation and an adaptive fuzzy system is presented. Adaptive fuzzy logic is an advanced control method that enables real-time and dynamic decision-making by accounting for uncertainties present in systems. The adaptive feature allows the system to update its rules and membership functions based on incoming data. Variations in solar radiation and sudden increases or decreases in energy demand are examples of uncertainties in energy systems. Unlike classical fuzzy systems, the adaptive fuzzy control system enables intelligent management by dynamically adapting to changing environmental conditions.

Replacement of Boolean Variables with Fuzzy Variables: x = Solar panels (Solar PV): Low, Medium, High. $\frac{\partial F}{\partial x} = \bar{y}\bar{z} = 10001000$, If Battery and Load are inactive, sensitivity to changes in PV. When y and z are Low, x (Solar Radiation) becomes critical. $\min_x f(x,y,z) = y \vee z = 01110111$. If y and z are low, then X is critical. $\max_x f(x,y,z) = 1$. Represents the system's maximum energy state. y = Lithium-ion energy storage system (ESS): Low, Medium, High. $\frac{\partial F}{\partial y} = \bar{x}\bar{z} == 10100000$. If PV and Load are inactive, sensitivity to changes in Battery. When x and z are Low, y (Battery Level) becomes critical. $\min_y f(x,y,z) = x \vee z = 01011111$. If x and z are low, then y is critical. $\max_y f(x,y,z) = 1$. z = Smart digital load management device: Low, Medium, High. $\frac{\partial F}{\partial z} = \bar{x}\bar{y} = 11000000$ If PV and Battery are inactive, sensitivity to changes in Load. When x and Y are Low, z (Load Demand) becomes critical. $\min_z f(x,y,z) = x \vee y = 00111111$. If x and y are low, then z is critical. $\max_z f(x,y,z) = 1$. Represents the system's maximum energy state.

Results Achieved through Adaptive Fuzzy Logic: Energy efficiency is increased and overall energy usage is optimized. The energy balance is continuously and automatically maintained. The lifespan and performance of the Energy Storage System (ESS) are enhanced. Even in unforeseen situations, the system maintains a high level of resilience. Energy distribution and balancing based on adaptive fuzzy logic, when integrated with digital technologies, make energy systems smarter, more efficient, and more sustainable [2].



Color Analysis: Yellow (1.0); Maximum Load, Purple to Black (0.0); Minimum Load. **Behavior**: Yellow dots cluster around Energy Action 0.6-0.8, showing the system's reaction to heavy load via Discharge or Load Shedding. Dark blue and green tones are located in the 0–0.3 Energy Action zone, indicating low demand and sufficient solar + battery, where the system remains Idle. This dynamic behavior confirms that the system smartly responds to real-time uncertainties and adapts decisions accordingly, unlike static rule-based systems.



Colorbar: Load Demand (colormap: blue to red; 0 = low load, 1 = high load). Results of Visual Analysis: The generated graphs clearly demonstrate that the fuzzy rules and the self-tuning mechanism are functioning correctly. The nonlinear nature of energy distribution is visibly present, reflecting the behavior expected from an adaptive fuzzy control system. The structure is fully ready for integration of adaptive learning mechanisms, such as online rule updates or neural-fuzzy hybrid models. As a result of the research, benefits such as a 25-30% reduction in energy consumption, up to a 50% extension in battery life, and increased system reliability have been achieved [3].

Interpretation Summary: The battery life improvement is the most significant, reaching close to 50%, which validates the adaptive fuzzy system's ability to optimize charge/discharge cycles. Energy saving (green bar) and emission reduction (purple bar) are also substantial, indicating both economic and environmental impact. System reliability shows a healthy increase, supporting claims that dynamic decision-making improves stability in uncertain conditions.

Conclusion: In this study, an integrated approach combining Boolean differential analysis and fuzzy control synthesis is presented for optimizing a three-component energy system consisting of Solar PV, Energy Storage System (ESS), and Load Controller. Boolean variables are replaced with fuzzy variables, and Boolean derivatives are utilized for identifying critical zones in fuzzy interpretation. For the first time, Boolean differential operators are applied to perform structural analysis of the energy system, allowing the identification of optimal and critical variables for the fuzzy logic system. This approach enhances the effectiveness of the fuzzy system, optimizes its structure, and enables dynamic adaptation to changing conditions through support for adaptive learning. The proposed Boolean–Fuzzy methodology offers a powerful optimization and resilience mechanism for real-world hybrid energy systems, paving the way for next-generation adaptive control in energy infrastructure.

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