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Energy Management and Controlling of Microgrid Using a Hybrid Proposed Method

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Abstract

The relentless pursuit of sustainable and efficient energy solutions in contemporary power systems has led to the development of novel methodologies to address the complexity of Microgrid (MG) dynamics. This paper illustrates the combination of the ε-variables method, a practical approach which leverages graph theory to simplify the analysis, management, and operation of MG systems and the if/else statement method. The evolution operator guides the system through state transitions, emphasizing the role of energy management in MG control. The integration of if/else statements enhances practicality, enabling dynamic adjustments without extensive re-modifications. This paper explores the theoretical foundations and practical applications of the ε-variables methodology, focusing on the integration of if/else statements and a hybrid approach. By shedding light on the adaptability and simplicity offered by ε-variables, the research contributes to the discourse on innovative strategies for enhancing the efficiency, resilience, and sustainability of contemporary MG systems. Through an in-depth analysis, we demonstrate the versatility and potential impact of the ε-variables method on the evolving landscape of energy systems engineering.

Keywords: Adaptability; ε-variables; Energy management system; if/else statement; Microgrid control; Simplicity

Abbreviations: PV: Photovoltaic; EMSs: Energy Management Systems LD: Load; utility grid (GR; battery (BAT)

Introduction

The ever-growing demand for efficient and sustainable energy solutions has prompted the exploration of innovative methodologies to enhance the analysis, management, and operation of power systems [1,2]. In response to this challenge, the ε-variables method, as introduced by [3] presents a unique and comprehensive approach to the intricate dynamics of Microgrid (MG) systems. Microgrids, characterized by their decentralized and versatile nature, are at the forefront of modern energy infrastructure, providing opportunities for improved resilience and integration of renewable energy sources [4-6]. The ε-variables method draws inspiration from graph theory, conceptualizing each component within a Microgrid as a node and the interconnecting energy or matter flows as edges. This paradigm shift allows for a simplified representation of complex MG systems, categorizing assets into converters, accumulators, and flows. Converters, responsible for energy/matter transformation, include Photovoltaic (PV) arrays, loads, and utility grids, while accumulators, storing energy/matter, are exemplified by batteries. The flows, symbolizing power exchange, form the intricate web that governs the dynamics of the hybrid power system. Key to understanding the dynamical nature of MG systems is the establishment of a state space (S) and an evolution operator (ϕ), as highlighted by [7]. The state of the MG, at any given moment, is intricately defined by the status of its nodes and edges, encompassing variables such as power flows $(F^{j}_{a \to b})$, accumulator states $(SOAcc^{i})$, and converter statuses $(\varepsilon_i(k))$. The evolution operator ϕ guides the system through state transitions, particularly emphasizing the energy management approach as a control mechanism.

Accumulators, crucial components in the MG energy ecosystem, play a pivotal role in the ε-variables method [6]. Introduce an evolution operator for accumulators, dependent on their capacity and the directed flows, further emphasizing their role in the overall energy dynamics. The integration of if/else statements into the ε-variables framework enhances the practicality of managing MG systems, allowing for dynamic adjustments in response to changing conditions without extensive re-modifications. This paper explores the ε-variables methodology in depth, shedding light on its theoretical foundations, practical applications, and contributions to the field of energy systems engineering. Through an analysis of the integration of if/else statements and a hybrid approach, we aim to demonstrate the adaptability and simplicity afforded by ε-variables in managing Microgrid systems. Ultimately, this research contributes to the ongoing discourse on innovative strategies for enhancing the efficiency, resilience, and sustainability of contemporary power systems.

Methodology

The Implementation of ε-variables for the MG

The main idea behind the ε-variable method is that every asset is symbolized by a node, and every flow of matter/energy is symbolized by an edge in the complicated MG system. Using this theory, this power system's analysis, management, and operation can be simplified. This method states that any hybrid power system consists of three key factors: converters, accumulators, and flows. Converters are used to convert the energy/matter to matter/energy, the accumulators accumulate energy/matter, and the flows symbolize the flow of energy/matter. Lastly, the control statements are the evolution operators based on the logical operators, illustrating the different types of energy management systems (EMSs) exploited by the multi-vector system [3]). According to the graph theory, the converters are the PV array, load (LD), and utility grid (GR); the battery (BAT) can be considered as an accumulator, and power can be regarded as flows. The assets of the MG system can be split into two sets as follows:

i. The set of converters: $Rs^{Con} = \{PV, LD, GR\}$

ii. The set of accumulators: $Rs^{Acc} = \{BAT\}$

In addition, the connection between two nodes can be called a flow, such as PV to BAT and BAT to PV as a power flow. Therefore, the set of flow for the complicated hybrid power system can be illustrated as follows Giaouris et al. [6]:

i. The set of flow: $Flow = \{Power\}$

To identify any dynamical system, we require two tasks: (a) the set of its possible states (state space - S) and (b) an evolution operator (ϕ) that determines which specific state the system will be in at any given time. In this regard, the state S of a graph (i.e., of the MG) at a specific instant is given by the states of the nodes and edges specified as follows:

i. A state must specify its presence and the type/amount of flow it includes for the edges. This is symbolized by variable $(F^j_{a\to b})$ with $j \in Flow$ and m,n two adjacent nodes. If there is no edge, $(F^j_{a\to b})$ is zero.

ii. The state of an accumulator is the normalized amount of stored matter or energy, represented by variable $SOAcc^l \in [0,1],\ l \in Rs^{Acc}$.

iii. The state of the converters is their status (whether they are activated or not), which is indicated by variable $\varepsilon_i(k) \in 0,1,$ $i \in Rs^{Con}$.

Hence, the states $s \in S$ of the graph are:

$$s = \{F^j_{a\to b}, SOAcc^l(k), \varepsilon_i(k)\} \qquad l = BAT$$

The next step is constructing the evolution operator ϕ to give a state s in the state space S at an instant t_0. We can calculate the state at the instant t as $s(t) = \phi\left(t, s(t_0)\right)$ where $\phi : S \to S$.

This evolution operator is the energy management approach utilized to control the MG and the accumulator operation principle for our purposes. As in dynamical systems, we require a different evolution operator for each state variable, i.e., an evolution operator for each $s \in S$ in our graph. The evolution operator for an accumulator l with a state variable $SOAcc^l$ is effectively an integrator and is dependent on its capacity C_l and the flows $F^j_{a\to b}(k)$ that are directed towards and away from the accumulator:

$$SOAcc^l(k) = SOAcc^l(k-1) + \frac{\sum_{k_1 \in Rs^{Con}} F^j_{k_1\to l}(k) - \sum_{k_2 \in Rs^{Con}} F^j_{l\to k_2}(k)}{C_l}$$

An edge with the evolution operator $F^j_{a\to b}(k)$ has the following definition:

$$F^j_{a\to b}(k) = \varepsilon_i P_i^j, \quad i \in \{m,n\}, \quad j \in Flow$$

where ε_i is the state of the corresponding converter and P_i^j is the amount of energy or matter that can be converted by the k_{th} unit per unit of time. Variables P_i^j might be either uncontrollable (like the PV energy flow) or controlled by the grid's designer or the energy management strategy (for example, the flow of energy from the BAT).

Depending on the energy management technique, the evolution operator for the converters (i.e., the variables ε_i) can be a complex function. Nonetheless, it depends on three variables that have a binary representation:

i. $\varepsilon_i^{Av}(k)$ which stands for the availability of the material or energy to be transformed.

ii. A conversion's demand for materials or energy is represented by the symbol $\varepsilon_i^{\mathrm{Req}}(k)$.

iii. Other potential desired conditions that are not connected to the are represented by $\varepsilon_i^{Gen}(k)$.

The state of the accumulators determines whether materials or energy are available or required to complete a conversion. A binary variable that is 1 when there is availability or demand and 0 otherwise is used to assess this:

$$\varepsilon_i^{Av}(k) = L^{Av}\left(\rho_i^{SOAcc^l}\right)$$

$$\varepsilon_i^{\mathrm{Req}}(k) = L^{\mathrm{Req}}\left(\rho_i^{SOAcc^l}\right)$$

where the logical operators L^{Av} and L^{Req} are used on the

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variables to quantify the need for and the supply of/from the accumulator l.

The general condition may be dependent on a node or an edge, but it is typically dependent on the state of other converters and can be characterized as follows:

$$\varepsilon_i^{Gen}(k) = L^{Gen}\left(\rho_i^{SOAcc^l}\right)$$

where L^{Gen} is a logical operator.

Using a logical operator L^i the device i's final evolution operator is found:

$$\varepsilon_i(k) = L_i\left(\varepsilon_i^{Av}(k), \varepsilon_i^{Req}(k), \varepsilon_i^{Gen}(k)\right)$$

The implementation of the if/else statement method

As shown in Figure 1, the if/else statement implementation consists of several steps in the MATLAB. Initially, the loop calculates the net values of equal PV power minus load demand. The condition of SOC is then evaluated to determine whether it is greater or less than the minimum/maximum values of SOC. At that time, both negative and positive values are examined. This technique operates based on the four distinct situations formulated within ε-variables, as shown in Figure 1's large rectangular area. These conditions include:

i. if $P_{net}(k) > 0 \rightarrow SOAcc^{BAT}(k) > SOAcc^{\max}$ and $SOAcc^{BAT}(k) < SOAcc^{\max}$

ii.

iii. if $P_{net}(k) < 0 \rightarrow SOAcc^{BAT}(k) > SOAcc^{\min}$ and $SOAcc^{BAT}(k) < SOAcc^{\min}$

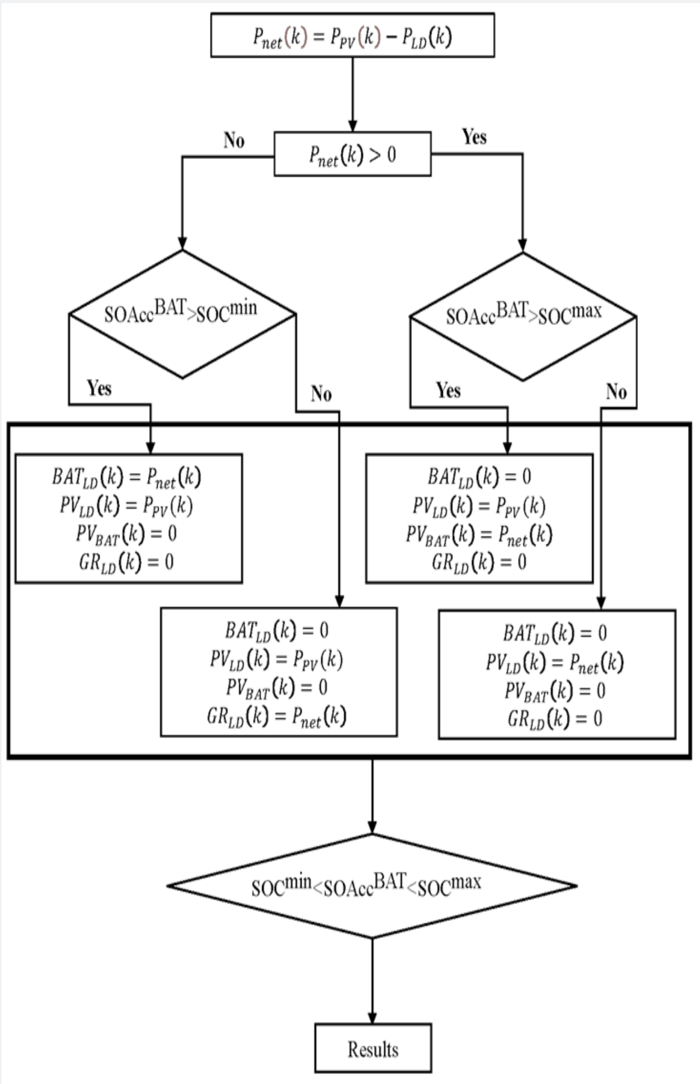

Figure 1: The flow-chart of the if/else statement.

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The results of the if/else statement are evaluated based on these four conditions. Using logical operators, including AND and OR, the results are binary variables (0 or 1). Finally, the power flows are calculated by incorporating the battery's SOC constraint. Concerning the feedback line, the if/else statement's results are compared to those obtained by the if/else statement. As depicted in Figure 1, despite the fact that we get the same results with ε-variables, the if/else statement is neither straightforward nor practical. To make it clear, supposing that we decide to change the value for the initial SOC or remove one of the power flows, the controller is required to be re-modified. Nevertheless, in the ε-variables, we do not need to re-modify too many things in this controller, supposing that we decided to change something in this controller. Therefore, ε-variables are primarily used to make the MG system more practical and simpler to implement, particularly hybrid MG systems.

The Implementation of hybrid if/else statement-ε-variables technique

As depicted in Figure 2, the 'data' utilized as input data by the hybrid if/else statement-ε-variables technique are initially obtained using the if/else statement method. In Figure 2, the 'data' are GR_{LD}, PV_{LD}, PV_{BAT}, and BAT_{LD}. The evolution operators are then computed using the state of the accumulators and converters. To be more specific:

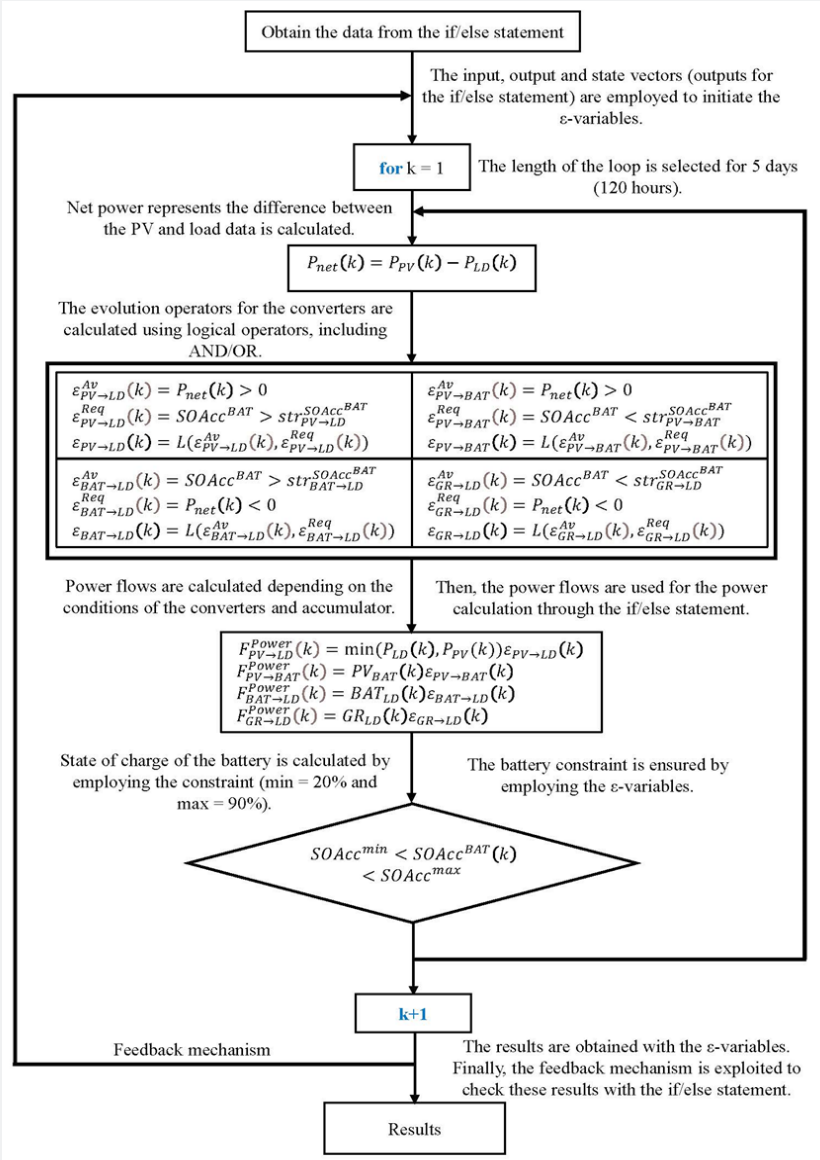

Figure 2: The flow-chart of the hybrid if/else statement-ε-variables technique.

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i. As illustrated in Figure 2, the evolution operator for converters can be defined by three factors represented by binary variables: ε_i^{Av}, $\varepsilon_i^{\text{Req}}$, and ε_i^{Gen} represent the availability of power, the load requirement, and the potentially desired condition, respectively. The energy supply is dependent on the condition of the accumulators. As shown below, the binary variable ρ is either 0 or 1 depending on the accumulators:

$$\varepsilon_i^{Av}(k) = L_{Acc}^{Av}\left(\rho_i^{SOAcc^{BAT}}(K)\right)$$

$$\varepsilon_i^{\text{Req}}(k) = L_{Acc}^{\text{Req}}\left(\rho_i^{SOAcc^{BAT}}(K)\right)$$

$$\varepsilon_i^{Gen}(k) = L_{Acc}^{Gen}\left(\rho_i^{SOAcc^{BAT}}(K)\right)$$

$$\varepsilon_i(k) = \varepsilon_i^{Av}(k) \wedge \varepsilon_i^{\text{Req}}(k) \wedge \varepsilon_i^{Gen}(k)$$

where L^{Av} and L^{Req} are the logical operators 'and' or 'or', and the general condition relies on the general condition of converters. $i(k)$ is also the state of converter i, while $\varepsilon_i^{Av}(k)$ and $\varepsilon_i^{\text{Req}}(k)$ are Boolean variables that determine the availability and requirement of converter i, respectively.

ii. Power flows are computed as follows:

$$F_{GR\to LD}^{Power}(k) = P_1(k)\varepsilon_i(k)$$

$$F_{PV\to LD}^{Power}(k) = P_2(k)\varepsilon_i(k)$$

$$F_{PV\to BAT}^{Power}(k) = P_4(k)\varepsilon_i(k)$$

$$F_{BAT\to LD}^{Power}(k) = P_4(k)\varepsilon_i(k)$$

where P_1, P_2, P_3, and P_4 are power flows GR to LD, PV to LD, PV to BAT, and BAT to LD, respectively.

iii. The final step is to compute the accumulator's evolution operator:

$$SOAcc^{BAT}(k+1) = SOAcc^{BAT}(k) + \frac{F_{PV\to BAT}^{Power}(k) - F_{BAT\to LD}^{Power}(k)}{Battery\ Capacity}$$

Depending on their operational status (active or inactive), the converters are depicted as $\varepsilon_i(k) \in \{0,1\}$ where $i \in Rs^{Con}$.

Results and Discussions

Simulation results of hybrid the if/else statement-ε-variables technique

Figure 3 depicts the PV and load data obtained from a building in the UK during the autumn season. Energy generation starts at the beginning of the morning (different morning times depending on sunlight) during these days. Also, peak energy generation occurs at 1 PM and 2 PM. On the other hand, there is no PV generation during the non-sunlight times. Regarding the load demand, it fluctuates due to several parameters such as the number of occupants, special days, and colder/warmer days, e.g., For instance, the load demand peaks on the first day between 7 PM and 8 PM since the occupants may return from their works or special day along with Christmas or Easter days. When sunlight is insufficient, or there is excessive load-generation mismatch, especially on nights, the battery (as a priority), then the utility grid is utilized. On the other hand, if the PV generates excess energy after covering the load-generation mismatch, the energy is exploited in order to charge the battery. The following figures will effectively demonstrate energy usage using the if/else statement and the if/else statement-ε variables.

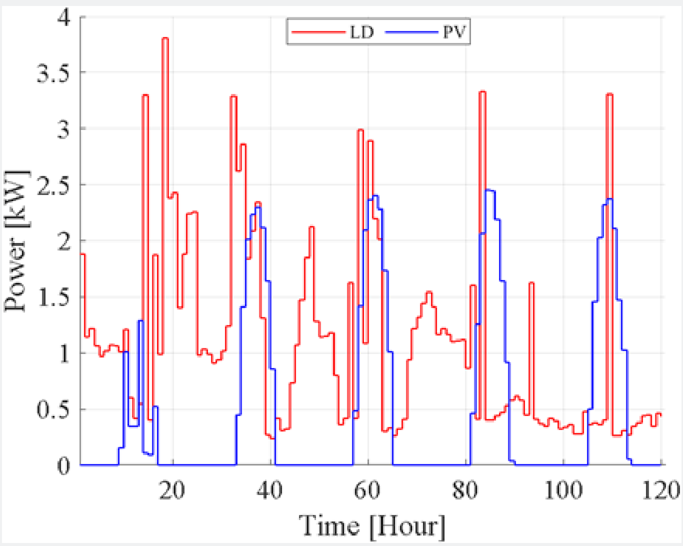

Figure 3: Hourly PV and load demand (120-hours) for the building in the UK during winter.

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Initially, the if/else statement is implemented, and then the ε-variables is merged to compare each strategy's results. According to our results, the standard the if/else statement and the merged the if/else statement-ε-variables have the same results. Moreover, our results indicate that the proposed method does not alter the fundamental goals and behavior of the if/else statement. It is simple to extend the use of ε-variables to more complex systems and control constraints by modifying their logical operators. If the initial value of SOC is chosen as 55%, the energy from the battery to the load $\varepsilon_{BAT\to LD}$ is increasing initially. The SOC of the battery is dramatically decreasing during the first day (see Figure 4b), but it does not pass critical value due to the evolution operator of $\varepsilon_{BAT\to LD}$. After the first day, the binary variables of $\varepsilon_{BAT\to LD}$ are converted from 1 to 0. Therefore, the value starts to decrease as demonstrated in Figure 4. On the contrary, the utility grid works instead of the battery. In this case, the logical operators of the $\varepsilon_{GR\to LD}$ are turned from AND to OR. By doing that, the binary variables of $\varepsilon_{GR\to LD}$ are converted to 1. Hence, energy imported from the utility grid $GR \to LD$ is increased, whereas energy imported from the battery is decreased $BAT \to LD$. In summary, the MG system is re modified when changing the initial value of SOC of the battery because of ε-variables. To meet the load-generation mismatch, the utility grid runs much more than before rather than the usage of the battery.

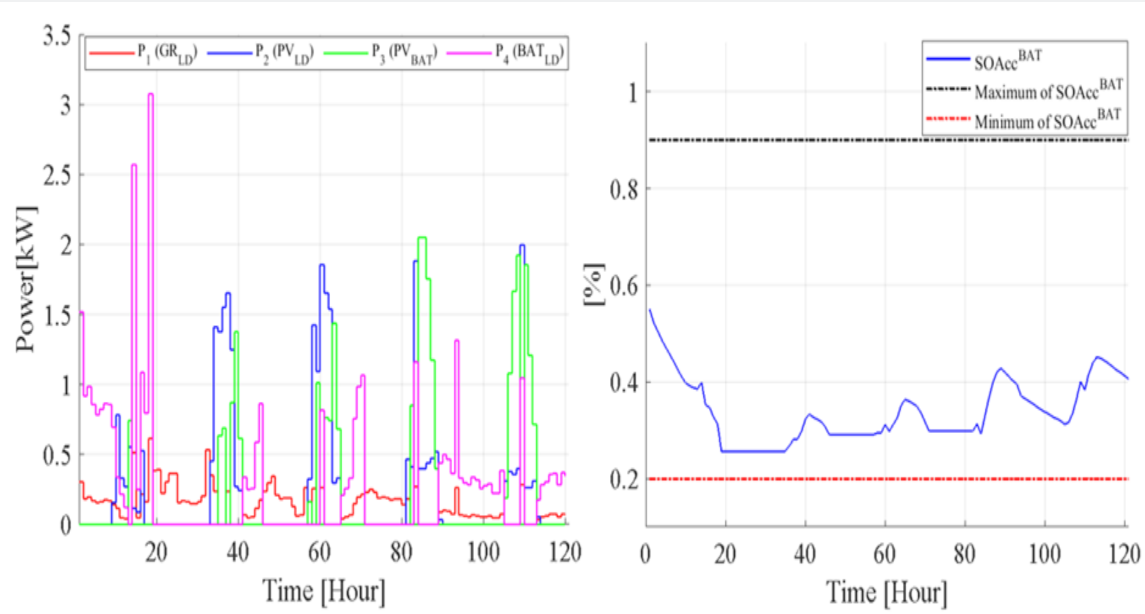

Figure 4: The results of power flows and SOC of the battery using the hybrid method.

Conclusion

In conclusion, the ε-variables method emerges as a promising and comprehensive approach to address the intricate dynamics of MG systems. By leveraging graph theory and categorizing assets into converters, accumulators, and flows, this methodology provides a systematic framework for analyzing, managing, and operating hybrid power systems. The integration of if/else statements enhances the practicality of the approach, allowing for dynamic adjustments without necessitating extensive re-modifications. Through the exploration of the theoretical foundations and practical applications of the ε-variables methodology, this research contributes to the evolving discourse on innovative strategies for enhancing the efficiency, resilience, and sustainability of MG systems. The demonstrated adaptability and simplicity of ε-variables, particularly through the integration of if/else statements and a hybrid approach, underscores its potential impact on the field of energy systems engineering. As we move forward, the ε-variables method stands as a valuable tool for researchers, engineers, and practitioners engaged in the development and optimization of MG systems. The insights gained from this methodology not only advance our understanding of complex energy systems but also pave the way for more adaptive, practical, and sustainable solutions in the ever-changing landscape of contemporary power systems.

Conflict of Interest

There is not any economic interest, or any conflict of interest exists.

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