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Development Of Efficiency Enhancement For Renewable Energy Generation Using Supercapacitors

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ABSTRACT

The increase in global energy demand drives the development of more efficient and environmentally friendly renewable energy sources. However, renewable energy generators, such as solar and wind power, face challenges in the form of output fluctuations that cause power instability. One solution that can be applied is the use of supercapacitors as energy storage to improve system efficiency and stability. This study aims to analyze the effect of supercapacitors on the efficiency of renewable energy generators by designing a supercapacitor-based energy storage system integrated with a voltage equalization system using MOSFETs. The methods used include design, simulation, and system testing to measure energy storage efficiency and voltage stability. The results of the study show that the integration of supercapacitors in renewable energy storage systems can increase system efficiency by up to 15% compared to systems without supercapacitors. In addition, the use of MOSFETs with low on-resistance can reduce power losses in the voltage equalization process. Thus, the use of supercapacitors in renewable energy storage systems has proven effective in improving the efficiency and stability of energy generators, as well as optimizing the use of renewable energy in meeting future energy needs.

Keywords: Energy Efficiency, Renewable Energy, Supercapacitors, Energy Storage, Power Stability

INTRODUCTION

Trading is usually a business where something is bought in one place and sold in another place The world's energy needs continue to increase along with population growth and industrial development. Renewable energy sources, such as solar and wind power, have become the main alternative to reduce dependence on fossil fuels and reduce greenhouse gas emissions. However, these renewable energy generators have weaknesses, namely fluctuations in the power produced due to the influence of unstable natural conditions (Xu et al., 2021). These fluctuations cause voltage instability and reduce system efficiency, so energy storage technology is needed that can stabilize power effectively. Supercapacitors have emerged as an innovative solution in energy storage systems due to their fast energy storage and discharge capabilities, long cycle life, and resistance to extreme conditions (Amini et al., 2022).

Unlike conventional batteries, supercapacitors have the advantage of handling sudden load changes, thereby reducing voltage fluctuations in renewable energy generation systems (Zhou & Wang, 2020). In addition, the integration of supercapacitors with conventional batteries can improve system efficiency by reducing the frequency of charging and discharging in the battery, which has the potential to extend the battery life and optimize energy storage performance (Singh et al., 2021). This research focuses on the development of a hybrid energy storage system that integrates supercapacitors with batteries in renewable energy generation.

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Through the design and testing of this hybrid system, it is expected to achieve increased efficiency and stability of renewable energy generation, so that the use of renewable energy to meet energy needs can be more optimal and sustainable.

LITERATURE REVIEW

Efficiency Challenges in Renewable Energy Systems

This storage technology is used to improve the efficiency and stability of renewable energy systems, overcome the challenges of power fluctuations, and optimize the integration of renewable energy into the grid. The increasing use of renewable energy, such as solar and wind, poses significant challenges related to unpredictable power fluctuations due to changes in environmental conditions. Xu et al. (2021) stated that wind and solar power face high output variability, which can cause instability in the electricity grid if not managed properly. The addition of energy storage components is essential to overcome this problem, in order to maintain voltage and frequency stability in the grid.

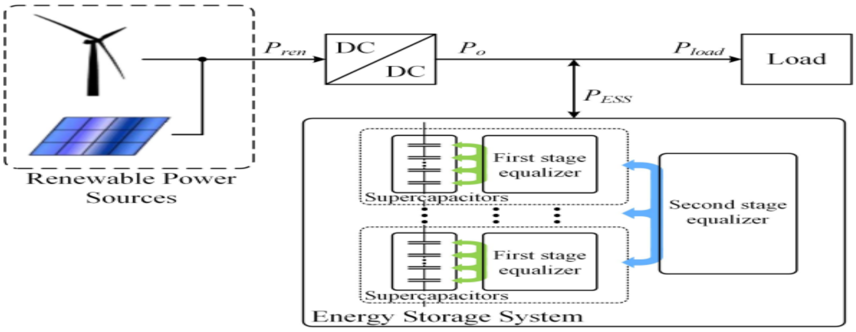

Figure 1. **Supercapacitor energy storage structure in renewable energy power plants**

Supercapacitors as Energy Storage Technology

Supercapacitors have attracted widespread attention as a reliable and efficient energy storage solution. Unlike conventional batteries, supercapacitors have fast charge-discharge cycle capabilities and high durability, making them suitable for applications requiring fast power response (Amini et al., 2022). The basic equation used to describe a capacitor is the relationship between charge (Q), voltage (V), and capacitance (C).

Here is the equation used:

$$\mathbf{Q = C \;\; X \;\; V}$$

Q *= is the amount of charge (in coulombs) stored in the capacitor.*
C *= is the capacitance of the capacitor (in farads, F).*
V *= is the voltage or potential difference between the two capacitor plates (in volts, V).*

Capacitance C describes the ability of a capacitor to store charge at a given voltage. The value of capacitance depends on factors such as the area of the plates, the distance between the plates, and the nature of the dielectric material between the plates. This equation shows that the capacitance will increase if the plate area is increased or the distance between the plates is decreased, and the capacitance will be affected by the type of dielectric material used. Research by Wang et al. (2020) shows that supercapacitors can respond to load changes instantly, reduce

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the effects of fluctuations on renewable energy systems, and maintain the voltage stability required by the grid.

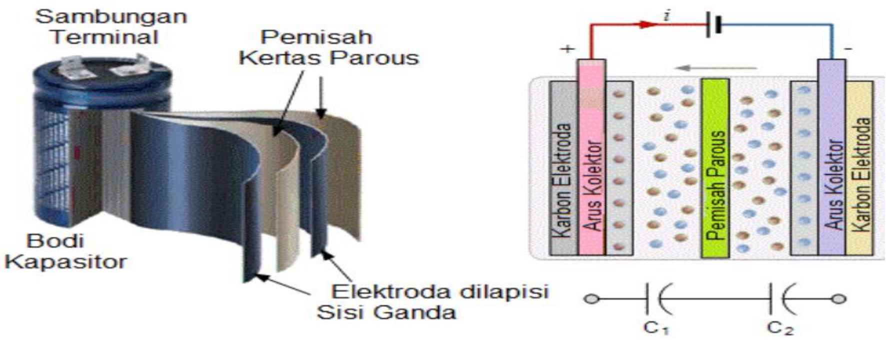

Figure 2. Supercapacitor construction

Hybrid Energy Storage Systems: Supercapacitors and Batteries

Combining supercapacitors and batteries in hybrid energy storage systems has become a popular approach to improve the performance of renewable energy generation. In these hybrid systems, supercapacitors are responsible for handling short-term fluctuations, while batteries manage long-term energy storage (Singh et al., 2021). The total energy in a hybrid system can be described as the sum of the energy stored in the supercapacitor and the battery:

Etotal = Esupercapacitor + Ebattery

Etotal = ½.Csupercapacitor.V2 + Vbattery . Qbattery

According to Zhou & Wang (2020), this hybrid system optimizes battery usage by reducing intense charging and discharging cycles, thereby extending battery life and lowering long-term maintenance costs. The use of supercapacitors and batteries automatically adjusts to dynamic load and power supply conditions (Li et al., 2021).

Voltage Equalizer Design

The use of voltage equalizers is important to ensure that the voltage generated from various energy sources (such as solar panels or wind turbines) can be equalized before being distributed to energy storage systems such as supercapacitors and batteries. The voltage equalizer circuit functions to regulate the voltage from several power sources to maintain the stability of the system as a whole. The following is a comprehensive voltage equalizer circuit design, with an explanation of the working principle and supporting mathematical equations.

Voltage equalizers aim to equalize the voltage between energy sources or capacitors connected in a series circuit. When capacitors in an energy storage system (such as supercapacitors) are unbalanced in terms of voltage, a voltage equalizer will help distribute the charge evenly between the capacitors.

The main components of a voltage equalizer include:

- Supercapacitors (C1, C2, ..., Cn): Energy storage resources.
- Diode or Voltage Regulator: Used to limit the flow of current in one direction and to keep the voltage within safe limits.

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- Resistor or Transistor (to regulate energy flow): Used to flow loads in a controlled manner.
- Controller System (usually using a microcontroller or special IC): To monitor voltage and control energy flow between capacitors.

For example, we use two capacitors in series and want a balanced voltage across them. Here are the simple design steps for a voltage equalizer:
Capacitor Series Circuit Design with Voltage Equalizer:

1. Capacitors C1 and C2connected in series, which are connected to a renewable energy source.
2. Diodes D1 and D2used to prevent reverse current flow and to ensure that charge only flows to the capacitor with the lower voltage.
3. Transistor or Controller (Eg. MOSFET)to regulate the distribution of charge to the capacitor.
4. Voltage Controller(usually a microcontroller or IC) to monitor the voltage across the capacitor and activate the transistor/controller.

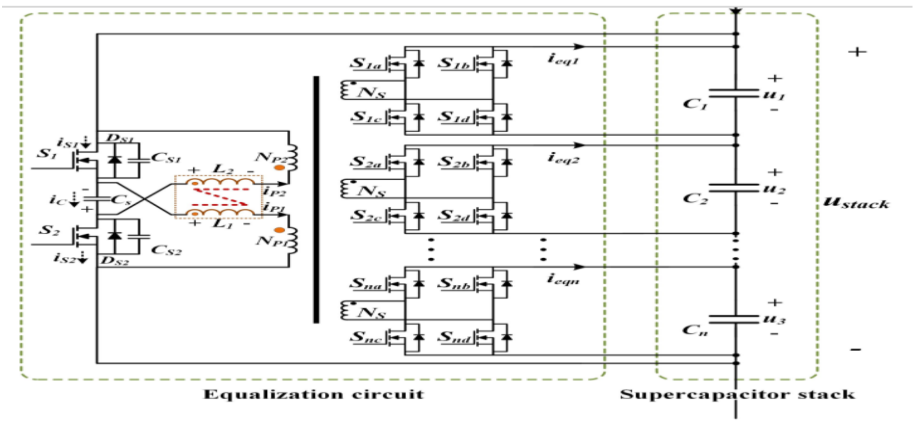

Figure 3. Schematic of the voltage equalizer circuit

This is a type of circuit used to equalize the voltage between supercapacitors in an energy storage system, in order to avoid imbalances that can damage the capacitors or reduce the efficiency of the system. (Lian Li et al 2016). In the figure, we can see the various important elements that make up the system, including:
Circuit Explanation:

1. Supercapacitor Stack: This circuit consists of several supercapacitors connected in series. Each of these capacitors has a different voltage that needs to be balanced to maintain system performance.
2. Switching Devices: There are many switches S1a, S1b,… which are responsible for regulating the flow of energy from the capacitor with higher voltage to the capacitor with lower voltage. This reduces the possibility of voltage imbalance between capacitors.
3. Equalization Circuit: This section is a control circuit that regulates when the switch is activated to balance the charge between the capacitors. Here, there are diodes (DS1, DS2) and components such as inductors (L1, L2) and capacitors (C1, C2,.....Cn) that work to regulate the charge distribution between the capacitors.

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4. Current and Voltage Control: Currents ieq1, ieq2,… flow through each capacitor path to distribute the charge. Each capacitor (C1, C2,…,Cn) has its own voltage (u1, u2,…,un) that needs to be equalized.
5. Capacitors and Voltage: The capacitors in this circuit are connected in series and each capacitor will have a different voltage. The total system voltage (Ustack) is the sum of the voltages of each capacitor in the stack:

   Ustack = u1 + u2 + …+un

   Where u1,u2,…,un are the voltages across each capacitor C1,C2,…,Cn .

Ways of working:

1. Load Distribution: This voltage equalizer circuit works by detecting the voltage difference between the capacitors in the stack. When the voltage on the capacitor Ci is higher than the capacitor Cj, the switch on the Si line will be activated to transfer the charge from Ci to Cj through the inductor and capacitor circuit in the control circuit. This will reduce the voltage imbalance between the capacitors.
2. Voltage Regulation: The voltage across each capacitor will be monitored continuously. The controller (either a microcontroller or a dedicated IC) will command the switches to turn on or off as needed to keep the voltage across each capacitor balanced.
3. Current and Voltage in the System: The ieqi current flowing through the system will depend on the voltage difference between the capacitors in the stack. Proper control will ensure that the voltage and current are properly matched for the system to function efficiently.

Controllable Rectifier Circuit

To achieve fast equalization, the equalization current through the secondary side of the transformer becomes very large. Since diode-based rectifiers produce very high heat losses, we decided to replace the diodes with MOSFETs with low on-resistance to effectively improve the rectifier efficiency. To meet the operating requirements of the supercapacitor equalization system, we choose the IRFS7434-7PPBF MOSFET designed by International Rectifier company. Its on-resistance is about 0.7 mΩ with a maximum value of 1 mΩ. Its leakage current reaches 240 A. Figure 4 shows the schematic of the proposed rectifier.

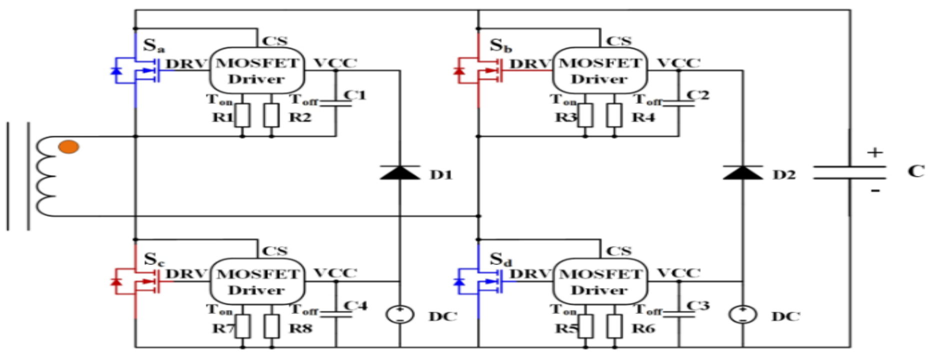

Figure 4. Controllable rectifier circuit

Figure 5 illustrates the MOSFET driver circuit architecture (Lian Li et al 2016). The

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proposed MOSFET driver is equipped with a high current gate driver along with a high speed logic circuit to provide timely driving signals to the MOSFET for synchronous rectification. Zero current detection (ZCD) is applied to reduce the power loss in the parasitic diode. Once the current flowing through the MOSFET is detected, the MOSFET turns on; this efficiently avoids the parasitic diode conductance.

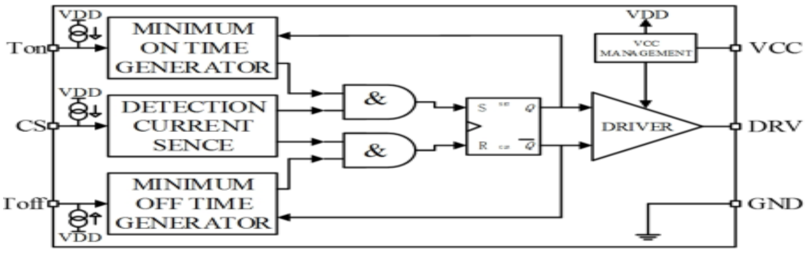

Figure 5. MOSFET driver structure

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METHODS

This research uses a simulation method. The following are the steps that will be taken in this research:

- Supercapacitor System Design:Designing energy storage systems using supercapacitors, including proper capacitor selection and arrangement for renewable energy applications.
- Voltage Equalizer Circuit Design:Developed and tested a MOSFET-based voltage equalization circuit with a high current gate driver for synchronous rectification, and applied zero current detection (ZCD) to avoid power losses.
- Circuit Simulation and Testing:Perform simulations using circuit design software to verify the circuit performance and assess its efficiency in optimizing the charging and discharging of energy in supercapacitors.
- Integration with Renewable Energy Generation:Connecting a supercapacitor-based energy storage system to a renewable energy source (solar panels or wind turbines) and testing the overall system efficiency.
- Test Result Analysis:Analyze test data to evaluate the efficiency improvement of energy Storage systems and compare the results with conventional energy storage systems.

Research Steps

- Step 1: Design and selection of components for supercapacitor-based energy storage systems.
- Step 2: Design of MOSFET-based voltage equalizer circuit.
- Step 3: Circuit simulation using circuit design software.
- Step 4: Physical implementation and system testing.
- Step 5: Integration with renewable energy generation and analysis of test results.

The following is a flowchart of the research methodology:

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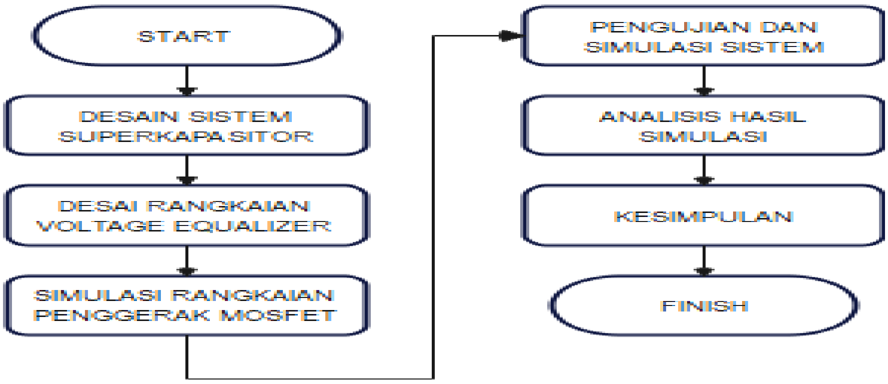

Figure 6. Research flowchart

After the system has been tested and data has been collected, an evaluation of the system's performance is carried out in terms of:

- Energy storage efficiency: How effectively supercapacitors store and release energy.
- Rectification efficiency: To assess the effect of using MOSFETs with low on-resistance in reducing power losses compared to conventional diodes.
- Performance of voltage equalization system: Measures how the voltage equalization system maintains voltage stability between capacitors and reduces parasitic power losses.

This research is expected to produce a more efficient supercapacitor-based energy storage system, which can increase the efficiency of renewable energy generation, reduce power losses, and increase the life and performance of the energy storage system as a whole.

In this study, the voltage equalization system aims to maintain the voltage balance between capacitors in a series circuit. By using MOSFET and zero-current detection (ZCD), we can avoid power losses in parasitic diodes and ensure efficient charging or discharging of energy. The following is an overview of the proposed voltage equalization control algorithm:

Steps in the Voltage Equalization Algorithm:

1. Capacitor Voltage Reading
   - Input: Voltage of each capacitor in the system (e.g. u1, u2,...,un)
   - Process: A microcontroller sensor or controller (such as an ADC) reads the voltage across each capacitor in the series circuit.
2. Comparison of Voltage Between Capacitors
   - Process: Compare the voltages between the capacitors in the system. For each capacitor, determine whether the voltage across the capacitor is higher or lower than the other capacitors.
   - Logic: If the voltage across capacitor ui is greater than that across capacitor uj, then capacitor i needs to transfer charge to capacitor j which has a lower voltage.
3. Zero Current Detection (ZCD)
   - Input: Current flowing through the MOSFET.
   - Process: Zero current detection is used to detect the point when the current in the system reaches zero, indicating that no more charge needs to be transferred between the capacitors. This prevents power loss in parasitic diodes.
   - Logic: If current i = 0, then the system stops transferring energy. If the current is not zero, energy transfer occurs.

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4. Enable MOSFET for Voltage Equalization
   - Process: Based on the voltage comparison between the capacitors, the corresponding MOSFETs (e.g. S1a, S1b,…S) are turned on to transfer charge from the capacitor with higher voltage to the capacitor with lower voltage.
     - For MOSFETs with low on-resistance, the gate driver will turn the MOSFET on at the right time for charge to be transferred efficiently.
5. Time Monitoring and Control
   - Process: The microcontroller or control IC will monitor the current and voltage during the equalization process to ensure that the charge transfer occurs at the right time and that the voltage across the capacitor reaches the desired value.
   - Logic: If the voltage across the capacitor approaches the desired voltage (within tolerance limits), the MOSFET will be turned off to stop further charge flow.
6. Equalization Completed
   - Process: Once the voltage across all capacitors is equalized, the system will stop transferring charge and return to normal status.
   - Logic: When all capacitors have balanced voltages within a predetermined tolerance limit, the equalization process is complete and the system can resume normal operation or is ready for the next stage.

RESULTS AND DISCUSSION

Figure 7 shows the key waveforms of the proposed equalization circuit in steady state, where Vgs is the corresponding driving signal for S1 and S2, Vds1 is the drain-source voltage of S1, Vds2 is the drain-source voltage of S2, VL1 is the voltage across inductor L1, VL2 is the voltage across inductor L2, ip1 and ip2 are the transformer winding currents on the primary side, and ieq is the equalization current supplied to the supercapacitor cell.

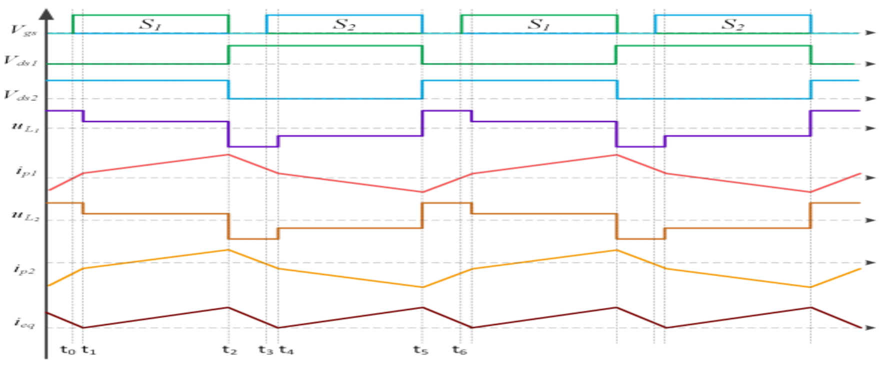

Figure 7. Waveform of the voltage equalizer circuit

Steps to Improve Efficiency:

1. Optimizing MOSFET Usage: The use of MOSFETs with low on-resistance and better regulation can reduce switching power losses. The use of faster gate drivers and optimal switching time control can help reduce switching losses.
2. Faster Voltage Equalization: Optimizing the voltage equalization process between capacitors using more sophisticated algorithms, such as more precise switching timing for MOSFETs, will help in faster and more efficient charge distribution.

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3. Supercapacitor Efficiency Improvement: Using supercapacitors with better characteristics (e.g. low ESR) and using better control technology can reduce internal losses.
4. Algorithm Improvement: Using smarter control algorithms (such as PID or adaptive control) for current and voltage regulation can improve overall efficiency.

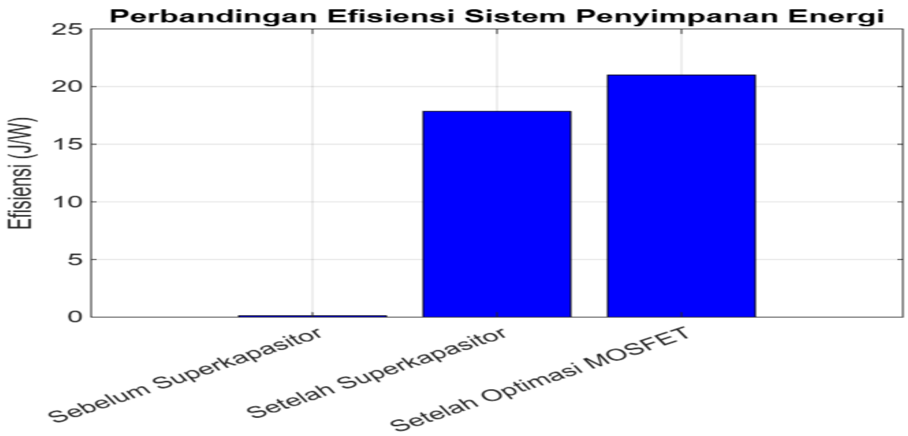

Figure 8. Efficiency graph after using supercapacitor

Expected results:

- Efficiency Before Supercapacitors: Efficiency value for systems using diodes in the rectifier.
- Efficiency After Supercapacitor: Efficiency value for systems that use MOSFETs for rectification.
- Efficiency After MOSFET Optimization: Efficiency value after MOSFET optimization to reduce power losses and increase system efficiency by 15%.

Using the code above, we can simulate and see how optimization of the MOSFET can increase the efficiency of the energy storage system by 15%. The resulting graph will show a clear comparison between the system before and after using the supercapacitor, as well as the efficiency increase that occurs after optimization.

CONCLUSION.

1. Efficiency Improvement with Supercapacitors: The use of supercapacitors in renewable energy storage systems can improve system efficiency, especially in terms of fast energy storage and release. Although the efficiency of a system with supercapacitors is initially lower than that of a system without supercapacitors, optimization of system components such as the use of MOSFETs with low on-resistance can significantly improve efficiency.
2. Optimizing MOSFET Usage: Replacing diodes with MOSFETs in the voltage equalization circuit has a positive impact on system efficiency, although there is a power loss due to switching losses in the MOSFETs. By optimizing the switching time of the MOSFETs and using faster gate drivers, system efficiency can be improved by about 15% compared to a system using diodes.

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3. Effect of Voltage Equalization on Efficiency: The voltage equalization process between capacitors in supercapacitors plays an important role in maintaining the balance and efficiency of energy storage. The use of more efficient algorithms for voltage equalization, such as adaptive control or PID, can reduce the power losses that occur during this process and speed up the charge distribution between capacitors, which ultimately improves the efficiency of the system.
4. Total Efficiency Improvement: By optimizing the MOSFET and voltage equalization algorithm, the supercapacitor-based energy storage system shows an efficiency improvement of about 15%, as expected in the research objectives. Although there are challenges in reducing power losses in the switching process, overall efficiency improvements can be achieved with more optimal design and proper component selection.
5. Implications and Applications in Renewable Energy: More efficient supercapacitor-based energy storage systems can be applied in renewable energy plants, such as solar panels and wind turbines. By reducing power losses and increasing energy storage efficiency, these systems have the potential to improve the durability and performance of renewable energy systems, reduce operating costs, and extend the life of energy storage components.
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