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PV Power System Design of DC Microgrids using Supercapacitors and Batteries

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Abstract- The characteristics of batteries and supercapacitors are very different, so it is very difficult to implement a storage system as part of a transmission network (grid) that is directly connected to a power demand (load demand). Microgrids are mainly used in situations where the energy sources come from Photovoltaics and the storage systems exist from a combination of Batteries and Supercapacitors as the energy source. Supercapacitors and batteries are used in combination to reduce the excessive performance of batteries by combining the two technologies. In this system, the Power Management Strategy is used to determine the amount of power that is needed based on the power demand graph, and Fuzzy Logic Control is used as the main control to determine the input reference for the supercapacitor. Simulations, it has shown that the Supercapacitor is capable of providing energy to batteries in less time despite energy shortages in batteries.

Keywords: Photovoltaic, DC microgrid, Supercapacitors, Power Management Strategy, Fuzzy

1. Introduction

In the realm of energy storage systems, the distinct characteristics of batteries and supercapacitors present a formidable challenge when integrating them into transmission networks or grids that directly handle load demand [1]. One primary issue arises from the disparity in voltage output, leading to difficulties during periods of surging power demand. Consequently, a Power Management Strategy is imperative to serve as a voltage output controller within the storage system, enabling a harmonious amalgamation of batteries and supercapacitors to meet power demand efficiently [2]. One potential solution to address these challenges is the implementation of a Direct Current Microgrid (DC Microgrid) transmission network. This innovative approach draws its energy from renewable sources, particularly Photovoltaic (PV) systems [3]. To ensure the optimal and desired functioning of a Microgrid system, it is crucial to consider the unique characteristics of PV as an energy source. In the current era, electric networks have become easier to control, while also exhibiting enhanced efficiency and cost-effectiveness in terms of installation and energy utilization. This transition can be attributed to the diminishing reliance on fossil fuels, which have traditionally served as the primary source of electricity generation worldwide [4]. As the world shifts towards greater utilization of renewable resources, the use of fossil fuels is gradually declining. Within the context of energy systems, a DC Microgrid transmission network presents itself as a viable solution. This sophisticated system comprises interconnected renewable energy sources and energy storage units, effectively catering to load power demands at any given time [5]. By leveraging the capabilities of batteries and supercapacitors, combined with the inherent advantages of PV systems, a DC Microgrid offers an unprecedented opportunity to optimize energy generation, storage, and distribution. The integration of batteries and supercapacitors within the DC Microgrid is facilitated through a carefully devised Power Management Strategy [6]. This strategy assumes a critical role as a voltage output controller, synchronizing the different characteristics of these energy storage technologies to meet the ever-changing power demands of the grid. By seamlessly orchestrating the interplay between batteries and supercapacitors, the Power Management Strategy ensures a stable and reliable power supply, even during periods of heightened demand [7]. The utilization of PV systems as the primary energy source in a DC Microgrid capitalizes on their unique attributes. Photovoltaic technology harnesses solar energy to generate electricity, offering clean and renewable power. However, it is essential to recognize the distinctive characteristics of PV systems, such as intermittent generation due to variations in solar irradiation and weather conditions [8]. Consequently, the Power Management Strategy must account for these fluctuations and optimize the utilization of both batteries and supercapacitors to ensure a consistent power supply. The advent of a DC Microgrid transmission network provides a paradigm shift in the field of energy distribution. By tapping into renewable resources and leveraging the distinct capabilities of batteries and supercapacitors, this innovative system exemplifies the potential for efficient and sustainable power generation. As the world gradually moves away from fossil fuels, embracing the advantages of renewable energy sources, the implementation of DC Microgrids becomes an increasingly attractive option for ensuring a reliable, cost-effective, and environmentally friendly electricity supply [9]. In summary, the characteristics of batteries and supercapacitors pose significant challenges when integrating storage systems into transmission networks. However, a well-designed Power Management Strategy, functioning as a voltage output controller, enables the successful combination of these energy storage technologies [10]. Furthermore, a DC Microgrid transmission network, powered by renewable energy sources such as PV systems, offers a viable solution to meet the evolving power demand requirements. Embracing these innovative approaches allows for enhanced control, efficiency, and economic viability in energy installation and utilization, ultimately contributing to a sustainable and resilient electricity grid [11]. DC transmission networks offer high efficiency due to their power factor of 1, resulting in reduced power losses and minimized voltage drop during the transmission of electrical energy. This characteristic enables the system to distribute power over long distances while maintaining economical and efficient isolation. Unlike AC systems, DC networks do not encounter stability issues, making them ideal for avoiding grid voltage fluctuations and potential blackouts [12]. The grid's primary objective is to balance power generation and consumption while allowing for a margin of error. By incorporating DC Microgrid networks, this balance can be achieved more effectively. DC Microgrid networks play a crucial role in regulating their own network, ensuring that any disturbances in the system can be swiftly addressed. This capability allows them to continue generating and distributing power to meet the required load, effectively serving as a backup to the main electricity network. By doing so, these networks mitigate the risk of power shortages or disruptions. The primary power source in DC Microgrid networks is photovoltaic (PV) energy. PV systems, commonly referred to as solar cells, offer numerous environmental benefits and operate silently with high efficiency [13]. To maximize energy production in PV systems, the implementation of the Maximum Power Point Tracking (MPPT) method is essential. The MPPT technique optimizes the PV system's performance by continuously adjusting the operating point to maintain peak energy output. By harnessing the potential of photovoltaic technology, DC Microgrid networks not only contribute to a more sustainable and environmentally friendly energy landscape but also offer several advantages. The inherent high efficiency of DC transmission networks, combined with the use of PV as the primary energy source, results in reduced power losses and enhanced overall system performance. Moreover, the simplicity and economic viability of DC Microgrid networks make them an attractive option for meeting power demands. The utilization of photovoltaic energy in DC Microgrid networks provides a renewable and clean source of electricity generation. Solar cells convert sunlight directly into electrical energy, reducing reliance on fossil fuels and minimizing greenhouse gas emissions [14]. Furthermore, the absence of noise in PV systems ensures a quiet and peaceful operation, making them suitable for various environments. To ensure optimal energy production from PV systems, the MPPT method plays a crucial role. This technique continuously monitors and adjusts the operating point of the PV system, allowing it to operate at its maximum power output. By dynamically adapting to changing environmental conditions, such as variations in sunlight intensity, the MPPT method maximizes energy harvesting efficiency, further enhancing the overall performance of DC Microgrid networks [15]. In conclusion, DC transmission networks offer high efficiency, reduced power losses, and minimized voltage drop, making them ideal for long-distance power transmission. DC Microgrid networks provide an effective solution to avoid grid voltage fluctuations and blackouts by regulating their own network. These networks utilize photovoltaic energy, which is environmentally friendly, noise-free, and highly efficient. The incorporation of the MPPT method ensures that PV systems operate at their maximum power output, optimizing energy production. By embracing DC Microgrid networks powered by photovoltaic technology, the world can move towards a more sustainable, resilient, and efficient energy infrastructure. Supercapacitors (SC) serve as an excellent solution for short-term power needs and backup energy storage in renewable energy systems. When combined with batteries, supercapacitors can enhance system performance and prolong battery life [16]. In the context of a DC Microgrid network powered by photovoltaic energy, the integration of supercapacitors and batteries as a storage system creates a self-sufficient transmission network. Energy management and distribution challenges between batteries and supercapacitors are addressed using fuzzy logic-based algorithms. Unlike classical control systems, fuzzy logic does not necessitate complex mathematical models [17]. The primary function of the Fuzzy Logic Controller is to act as a backup system when there is insufficient energy power, based on the State of Charge (SoC) of the battery. Each component connected to the DC bus network in the DC Microgrid possesses its own converter. Due to the distinctive characteristics of each element, such as batteries and supercapacitors, the Power Management System is designed to accommodate these differences [18]. The system employs separate block sections for setting input and output power for each element. This division allows for the determination of the energy generated by each element through the Energy Management System, also known as the Power Management System [19]. The utilization of supercapacitors alongside batteries in the DC Microgrid network provides several advantages. Supercapacitors offer rapid charging and discharging capabilities, making them ideal for meeting short-term power demands and buffering energy fluctuations. Batteries, on the other hand, excel in storing and releasing larger amounts of energy over extended periods. By combining these two energy storage technologies, the system can leverage the strengths of both to optimize overall performance. The integration of fuzzy logic-based algorithms in the energy management and distribution process allows for efficient power utilization. Fuzzy logic controllers are capable of making decisions based on imprecise or incomplete information, providing a flexible and adaptable approach to energy management [20]. By considering the SoC of the battery, the fuzzy logic controller can intelligently allocate power from the supercapacitors or activate the backup system if required. This dynamic control mechanism ensures the stability and reliability of the DC Microgrid network. Each component connected to the DC Microgrid network possesses unique characteristics and requires tailored control strategies [21]. The Power Management System takes into account these differences and designates separate block sections for input and output power settings. This modular approach facilitates effective energy management and enables a comprehensive understanding of the energy flow within the system. Through the Energy Management System, the DC Microgrid network can accurately measure and monitor the energy generated by each component, enabling precise control and optimization of the overall system. In conclusion, the combination of batteries and supercapacitors in a DC Microgrid network powered by photovoltaic energy presents an efficient and reliable solution. By employing fuzzy logic-based algorithms, energy management, and distribution challenges can be effectively addressed [22]. The modular Power Management System accounts for the distinct characteristics of batteries and supercapacitors, ensuring optimized performance. The integration of supercapacitors and batteries enhances the system's capabilities by providing fast response times and extended energy storage capacities. Through the implementation of the Energy Management System, the DC Microgrid network can accurately track and regulate the energy generated by each component. Ultimately, these advancements contribute to the stability, efficiency, and resilience of the DC Microgrid transmission network.

2. Methodology

There are several components in a DC Microgrid system, which are shown in Figure 1, including solar panels, boost converters, buck converters, batteries, and supercapacitors as well as the power management system and load.

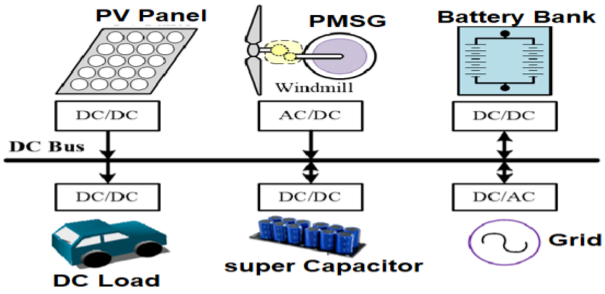

Fig 1. Network configuration for DC microgrids

2.1 Boost Converter

Boost converters, also known as voltage boosters, are essential components in DC systems for amplifying DC voltage. Within electronic circuits, these converters play a crucial role in voltage amplification by acting as power supplies. They effectively boost the voltage when the circuit's voltage falls below the supply voltage [23]. In this manner, boost converters ensure that the voltage value in the circuit is elevated to match or exceed the supply voltage, guaranteeing the proper functioning of the circuit. Overall, boost converters fulfill the role of voltage boosters by supplying increased voltage to circuits where the existing voltage is insufficient. The boost converter circuit is shown in Figure 2.

$$D_{Boost} = 1 - \frac{V_s}{V_o} \text{ ----------- } (1)$$

Calculation of inductor value,

$$L_{min} = \frac{(1-D)^2 X\, D\, X\, R}{2f} \text{ ---------- } (2)$$

Calculation of capacitor by using Equation 3,

$$C_{Min} = \frac{D\ X\ V_{out}}{V_r\ X\ R\ X\ f} \text{ ----------- } (3)$$

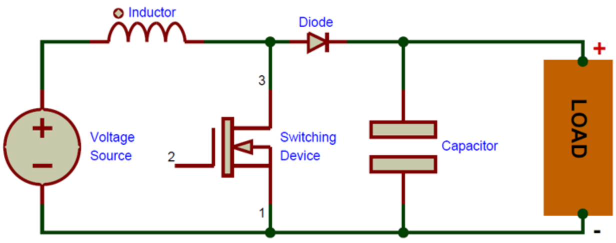

Fig 2. Circuit of a booster converter

2.2 Buck-boost Converter

The Buck-Boost converter is a circuit designed to adjust voltage levels by either decreasing or increasing the voltage as shown in Figure 3. In the buck section, it decreases the voltage when it exceeds a predetermined limit, while in the boost section, it increases the voltage when it falls below the desired level [24]. The duty cycle in this mode can be calculated using Equation 4, which provides the necessary formula for determining the duration of the on-state in relation to the total switching period. This calculation is crucial for ensuring the proper operation and control of the Buck-Boost converter in regulating voltage levels.

$$D = \frac{V_O}{V_O - V_i} \text{ --------- } (4)$$

According to equations 5 and 6, the minimum L and minimum C components are calculated.

$$L_{min} = \frac{(1-D)^2}{2 \,X\, f} \,X\, R \text{ ---------- } (5)$$

$$C = \frac{V_O \,X\, D}{R \,X\, \Delta V_O \,X\, f} \text{ ---------- } (6)$$

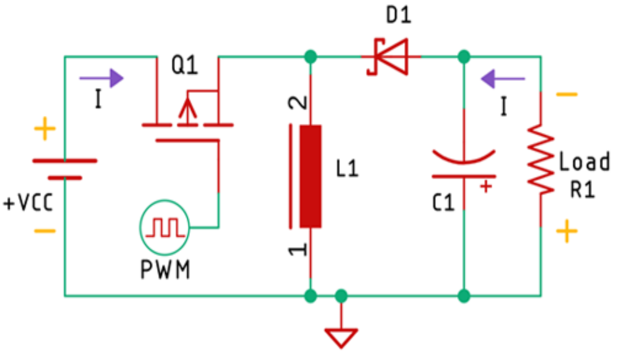

Fig 3. Circuit for Buck-Boost Converters

2.3 Fuzzy Control

This fuzzy logic controller is aimed at monitoring how much capacity the supercapacitor still has left and to determine how much energy will be stored in the supercapacitor according to its output [18]. There are two inputs in fuzzy control: SC SoC and load demand (Pdem), together with one output: SC load (Psc). In fuzzy control input, there are 3 membership functions on the SoC SC, each of which has a different value limit. Specifically, the low function has a value limit between 0 and 60, the medium function has a value limit between 50 and 100, and the high function has a value limit between 95 and 100. There are limits to the performance of the supercapacitor, which represents the value of its capacity. It is used as a reference value to determine the output value based on the Pdem (Load Demand) function. It is important to note that there are five membership functions in Pdem. There are limits for Vlow from 0-3000, low from 2000-5000, medium from 4000-7000, high from 6000-9000, and Vhigh from 8000-1000. The value associated with these limits is the level of power demand that is desired [11]. A fuzzy output is sent to the supercapacitor (Psc) which is a membership parameter at the output of the fuzzy control, in the form of a power request on the supercapacitor. In the fuzzy logic output (Psc), there are three membership functions that serve as a limitation on the fuzzy logic output value that will be entered into the supercapacitor converter. The three membership functions are low, which has a limit of 0-5000, medium, which has a limit of 2500-7500, and high, which has a limit of 5000-10000.Table 1. Shows the Fuzzy rules.

Table 1. Fuzzy Rules

PSC		Pdem				
		VLow	Low	Med	High	VHigh
SoCsc	Low	Low	Low	Low	Med	High
	Med	Low	Low	Med	High	High
	High	Low	Low	Med	High	High

2.4 Strategic Power Management

The Power Management Strategy is used to meet the energy needs of the organization. Power management is based on the fact that batteries and supercapacitors have different characteristics and are designed for varying applications [12]. It is possible to feel the disturbance (power disturbance) simultaneously on the battery and supercapacitor when they are in a parallel position since the supercapacitor and battery are in a parallel position. It has the advantage of protecting the battery from short circuits and power fluctuations as the supercapacitor power fluctuations are caused by excess and lack of power inputs to the supercapacitor, thus preventing short circuits or power fluctuations. In Figure 4, the Power Management block receives the supercapacitor's SoC SC and the demand power Pdem. When the Power Management block is used as a converter input, a reference power signal PSC is generated by reducing the reference current by a supercapacitor sensor's input current [21]. To determine whether the converter will operate on buck or buck-boost, the resultant feedback signal can be converted into a PWM signal that can be used as a switch on the converter.

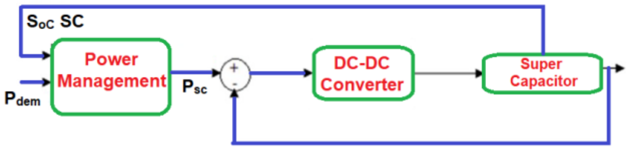

Fig 4. Block diagram of a power management strategy

2.5 Model of Demand Power

This energy demand power is used as a measure of how much energy will be required to satisfy the demand as shown in Figure 5. Figure 5. illustrates how the power used by the device varies according to the condition [22]. The arranged power supply power will only be active at certain times (seconds). When the load is active between seconds 0 and 1.2, it will be between 2500 and 7000 Watts, seconds 1.2 to 2 will be from 7500 to 9400 Watts, seconds 2.2 to 2 will be from 7500 to 9400 Watts, seconds 2.2 to 8000 Watts, seconds 2.6 to 5000 Watts, seconds 2.8 to 9500 Watts, seconds 3 to 4000 Watts, seconds 3.2 to 8300 Watts, seconds 3.4 to 3.5 by 9200 Watts, and secs 3.8 to 5 from 8600 to 4000 Watts.

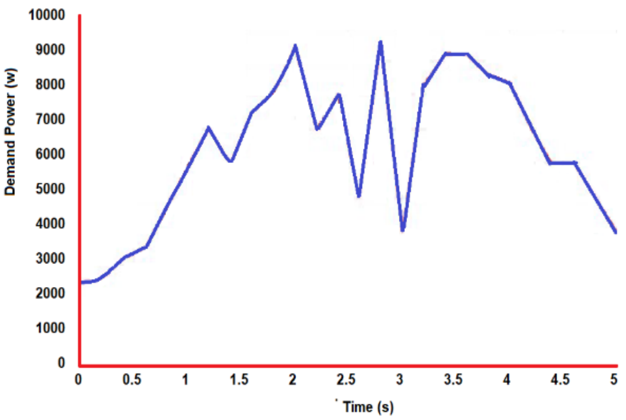

Fig 5. An analysis of demand power

3. Results and Discussion

3.1 PV Testing

Photovoltaic testing assesses the performance of solar panels by examining their characteristics, including voltage and current under varying levels of irradiance (Ir) and temperature (T). This evaluation involves conducting tests with different T input values while keeping the Ir input value constant [23]. The findings, illustrated in Figure 6, demonstrate the outcomes obtained when testing various temperature values while maintaining a consistent radiation value. The results indicate that as the temperature decreases, the voltage value rises correspondingly with the radiation level. Through photovoltaic testing, researchers aim to gain insights into the behavior of solar panels under different environmental conditions. By analyzing the relationship between temperature, irradiance, voltage, and current, they can optimize solar panel designs and maximize their efficiency. These evaluations help in understanding how solar panels perform in real-world scenarios, enabling the development of improved photovoltaic systems for renewable energy generation [8].

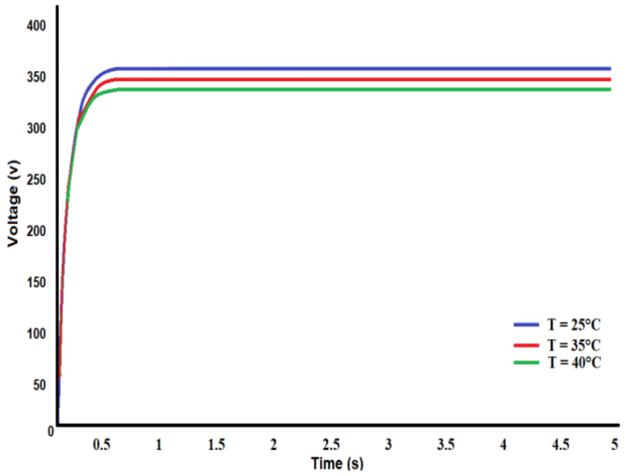

Fig 6. Voltage PV when T (different) Ir (same)

3.2 Batteries and supercapacitors tested for power management

Figure 7. shows the simulation results for batteries and supercapacitors under load demand. Based on the figure, it can be seen that the battery and supercapacitor have the ability to deliver the power that is needed for the load demand, which means that the power output of the battery and supercapacitor is able to meet the needs of the load. At seconds <1.5s, it can be seen that the slow response can't fulfill each power demand of 1000, but at the next second, the battery and supercapacitor can fulfill each one [9]. The battery and the supercapacitor are able to provide the power needed for the given application. The difference in output results can be seen in the figure, where the difference in power generated by the battery and supercapacitor at second 2.85 is 9324W while the demand power is 8130W, which means with a power difference of 1194W, the battery, and supercapacitor are able to meet the demand power. Figure 7. shows the power output of the batteries and supercapacitors against the demand for power. The demand power used is an indication of the amount of energy required. The power arranged will be active at certain times (seconds). The load will be active at seconds 0 to 1.2 which is 2500 to 7000W, second 1.2 by 6000W, seconds 1.6 to 2 by 7500 to 9400 W, sec 2.2 by 7000W, sec 2.4 by 8000W, sec 2.6 by 5000W, sec 2.8 by 9500W, sec 3 by 4000W, sec 3.2 by 8300W, sec 3.4 - 3.5 by 9200W, sec 3.8 to 5 by 8600 to 4000W.

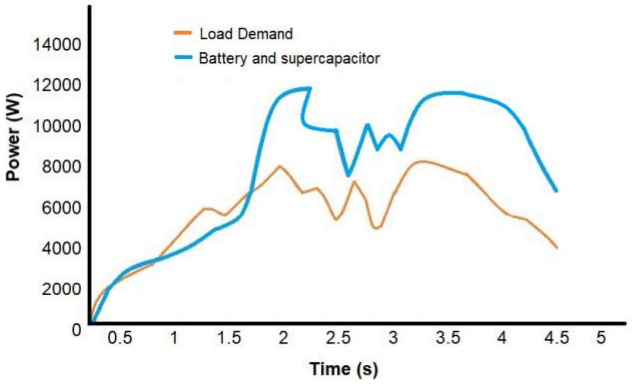

Fig 7. Power output of batteries and supercapacitors

3.3 Battery and Supercapacitor Simulations

Figure 8 presents a clear depiction of the supercapacitor's response to a sudden spike in power demand, occurring precisely at 2.93 seconds when the battery becomes overloaded. This graph showcases a scenario where an unexpected power surge transpires. In this critical moment, the supercapacitor steps in as a reliable energy source, effectively supplying power to the computer system. During the 2.93-second mark, a surge in power demand puts excessive stress on the battery. This surge could be the result of a sudden increase in energy-hungry processes or components within the computer system. The overload on the battery at this juncture could potentially lead to issues like voltage instability or even system failure. However, the supercapacitor proves to be a valuable asset in such situations. It quickly responds to the escalating power demand by releasing stored energy, ensuring that the computer system continues to receive a stable power supply. This dynamic response is crucial in preventing any disruptions or downtime that may occur when a power source, in this case, the battery, is unable to cope with sudden spikes in power requirements. Figure 8 serves as a visual testament to the supercapacitor's ability to act as a rapid and effective power buffer. It underscores the supercapacitor's capacity to bridge the gap during periods of intense power demand, safeguarding the computer system from potential instability and ensuring uninterrupted operation. This capability highlights the significance of supercapacitors in enhancing the reliability and resilience of power systems, particularly in scenarios where immediate power support is essential to prevent critical system failures.

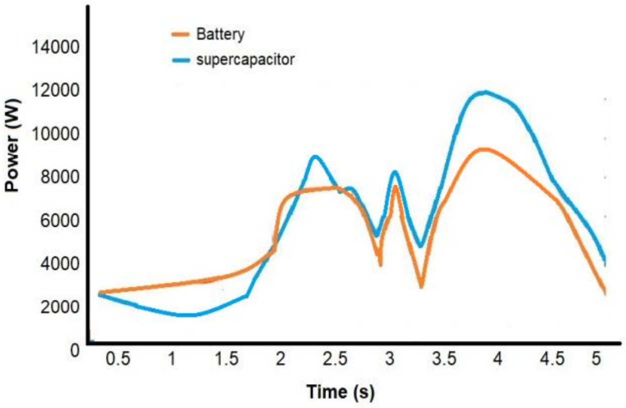

Fig 8. Battery and supercapacitor simulation results

3.4 Buck-Boost Converter Simulation

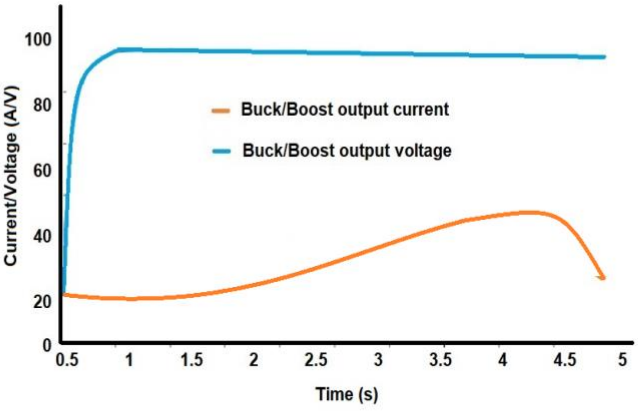

Fig 9. Buck-Boost Converter Current/Voltage Response

A supercapacitor circuit contains a set of current and voltage magnitudes related to the results of the converter output response captured by a supercapacitor circuit. The fuzzy output is used to generate the power input for the converter, which can then be converted into current and voltage by the converter [17]. A Buck-Boost converter responds to a power demand pattern in which the resulting voltage value tends to stabilize, whereas the frequency response of the converter is affected by a power demand pattern in which the current value changes. The buck-boost converter current/voltage response as shown in Figure 9. The supercapacitor circuit records current and voltage data associated with the converter's output response. A fuzzy output based on this data is utilized to determine the converter's power input. This power input is subsequently converted into current and voltage by the converter. The Buck-Boost converter responds to power demand patterns, focusing on voltage stabilization, while the converter's frequency response is influenced by changes in current values.

3.5 Boost converter response simulation

Figure 10 illustrates the output response of a boost converter in relation to its boost level. It provides compelling evidence that the battery system adeptly adheres to the desired power pattern depicted on the power demand graph. This adherence is apparent in two key aspects: voltage variation and battery current output. Firstly, the voltage variation closely mimics the fluctuations in the power demand graph. This synchronization highlights the battery's ability to maintain the ideal voltage levels required to meet varying power needs. The voltage's alignment with the power demand pattern underscores the boost converter's proficiency in consistently delivering the required voltage, ensuring that the system operates smoothly and reliably. Secondly, the battery current output mirrors the desired power pattern, demonstrating the battery's agility in adapting to shifting power demands. This synchronization indicates that the boost converter efficiently adjusts the current output to meet fluctuations in power requirements, striking a harmonious balance between supply and demand. This adaptability is vital for effective power management, preventing overload or underutilization of the battery's capacity. Figure 10 is a visual testament to the boost converter's effectiveness and the battery's ability to meet power demands precisely. The voltage closely tracks the power demand, and the battery current output aligns with the desired power pattern, showcasing their adaptability and responsiveness. This synchronization ensures efficient power management, reduces energy waste, and prolongs the battery system's operational lifespan. As the demand for dependable and eco-friendly power solutions continues to rise, Figure 10's insights hold promise for a wide range of applications, contributing to more efficient and sustainable power systems.

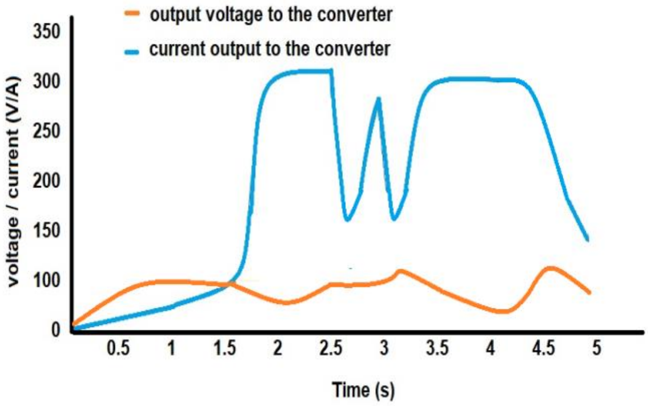

Fig10. Buck-Boost Converter Current/Voltage Response

4. Conclusion

A photovoltaic test conducted at the University of California at Davis showed that if the radiation value was held at 1000 and the temperature value changed from 25, 33 or 40, then the voltage would decrease following the temperature change. This is due to the fact that as the value of temperature increases, the PV efficiency value will decrease with it. A PV's voltage output value will be affected by the temperature value that is fixed, and the irradiance value that is changed from 1000 to 800 to 500, so the higher the irradiance value, the higher the voltage value at the PV's output. As a result, when the irradiance value is higher, then the voltage output value will be greater, which means that when the temperature value is higher, then the PV efficiency will be decreased as a result of the increased voltage output value. Battery and Supercapacitors are able to supply electricity when there is a surge in power demand at second to 2.93 seconds in the case of a surge in power demand. At that second, the supercapacitor is able to deliver energy when a surge in power occurs. It is estimated that 1158 watts of power are generated at that moment in time. It can be seen that the Power Management system manages to control the output of batteries and supercapacitors in order to meet the required power demand, but the slow response is then the reason due to the calculation process of the fuzzy logic algorithm that the demand power isn't met.

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