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A Review of Power Control Methods for Load Balancing for Microgrids with Uncontrollable Renewable Energy Sources

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Abstract

This paper addresses the growing energy demand by exploring the realm of microgrids (MGs) and their crucial role in modernizing the conventional grid (CG). As energy needs continue to escalate, the CG has integrated advanced communication technologies, including sensors, demand response, energy storage systems, and electric vehicle integration. MGs have emerged as a viable solution to ensure local energy stability and reliability within low or medium voltage distribution systems. They achieve this by efficiently managing power exchanges between the primary grid, locally distributed generators (DGs), and consumers. This article provides an overview of microgrids, explaining their operational principles and examining various energy management methodologies. At the core of microgrid control strategies lies the energy management system (EMS), which orchestrates the interaction between different energy resources (CG, DG, ESS, and EVs) and loads, ultimately enhancing utility profitability. The paper systematically categorizes EMS design methodologies based on their structural attributes, control mechanisms, and underlying techniques.

Keywords: Microgrid, Excess Power, Frequency Control, Average Power.

1. INTRODUCTION

The rapid adoption of renewable energy technologies is transforming the global energy sector [1,2,3]. This trend is evident not only in large-scale utility and commercial applications but also in residential settings [4]. While the importance of incorporating renewable energy sources into commercial-scale operations is well-recognized, this article aims to shift its focus to a specific area—the integration of renewable energy sources within microgrid systems.

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In the context of designing, upgrading, or expanding microgrid systems, a range of challenges emerge. One of the key challenges discussed in this article is the complex interaction of various brand components within microgrid configurations.

When designing a microgrid system that uses components from a single supplier [5], the inherent compatibility of these components typically allows for smooth operation, reducing the likelihood of complications [6,7,8]. However, the situation becomes significantly more complex when components from different brands are integrated into the same system [9,10,11]. The complexities of interoperability arise when these components may not inherently communicate with each other or experience communication issues, leading to a web of complications [12,13]. For example, battery inverters may communicate effectively with an off-grid photovoltaic inverter, but a different brand of grid-tied inverter may remain isolated and fail to establish communication. In this scenario, the microgrid system is controlled by a battery inverter as its master generating unit, which manages voltage, frequency, demand, and supply. The disconnection of the grid-tied inverter, along with its unique characteristics, leads to power balance issues within the system [14, 15, 16].

Addressing the power balance issue requires a strategic approach to utilizing surplus power, as it is crucial for resolving the existing power imbalance [17]. While several well-established solutions exist for managing excess power in microgrid systems—such as dump loads, vehicle-to-grid (V2G) and grid-to-vehicle (G2V) systems, hydrogen storage, batteries, scheduling, and pumped storage—many of these solutions have their limitations [18,19,20]. These limitations can include issues related to timing, complexity of implementation, and effects on stored energy levels. A detailed examination of these approaches for utilizing excess power is provided in Table 1.

Amid the evolving landscape of power utilization strategies, a significant innovation has emerged in the form of the Variable Average Power Load (VAPL) device

Table 1. ***Excess power utilization options.***

Excess Power Utilization Option	**Reference**	**Drawback**
Heat/thermal storage	[2,3,4,5]	Excess power is used in a fixed manner, which leads to the discharge of the microgrid system's batteries.
Pump storage	[6,7,8,9]	It is challenging to implement at both commercial and residential scales.
Scheduling	[10,11,12,13,14,15,16]	Using excess power comes at the expense of consumer comfort.
V2G/G2V; fuel cell	[17,18,19,20,21,22]	Using excess power in a fixed manner only temporarily addresses the issue, as it does not increase the accumulated energy level in the microgrid system.
Dump load	[23,24,25]	Excess power is used in a fixed manner, which leads to the discharge of the microgrid system's batteries.
Inverter/system control via communication	[26,27,28,29,30]	Complex to implement across various system designs, making it impractical to develop a plug-and-play solution.

[21,22,23,24]. This device effectively manages the dynamic use of excess power within microgrid configurations while preserving stored energy and ensuring consumer comfort [25,26,27,28]. Specifically designed for microgrid systems that incorporate non-controllable inverters and primarily rely on renewable energy, the main goal of this study is to examine power control methodologies for the VAPL device [29]. The study also aims to provide researchers with insights to select the most suitable control approach for managing excess power [30]. A unique aspect of this article is its thorough review of optimal average power control methods for the innovative VAPL device—a novel solution that currently lacks comparable alternatives in the existing market. The VAPL device operates based on a distinctive principle, adjusting its load rate in sync with the fluctuations of excess power within the microgrid [24,25].

In the subsequent sections, this article explores average power control methods in Section 2. It then conducts a comparative analysis of power control strategies in Section 3. Finally, Section 4 offers a thorough examination and discussion of the findings, presenting a comprehensive synthesis that encompasses the entire discourse.

2. AVERAGE POWER CONTROL METHODS IN MICROGRID SYSTEMS

Microgrid systems, representative of contemporary energy ecosystems, frequently integrate various energy storage technologies, including hydrogen storage [31,32,33], batteries [34,35,36,37], supercapacitors [38], and electrochemical systems [39,40]. These technologies are designed to maintain power balance. The primary goal of these storage solutions within microgrids is to capture surplus power during periods of excess supply and to utilize it during times of increased demand. Achieving effective energy flow management typically involves the use of bi-directional inverters, which convert alternating current (AC) to direct current (DC) and vice versa, thereby facilitating storage control.

In microgrid configurations where inverters serve as the primary generating units, the system's response to power fluctuations exhibits low inertia [42,43]. This characteristic arises from the role of inverters as the main energy sources, enabling quick and significant adjustments in power output. Excess power is often detected by monitoring the frequency, as surplus power increases the virtual rotational speed of a corresponding motor, resulting in a rise in system frequency. In this context, the Variable Average Power Load (VAPL) device stands out as an innovative solution. The VAPL device's primary function involves monitoring frequency and adjusting average power at a rate that synchronizes with the frequency change. A detailed understanding of the VAPL device, encompassing its structure, operational principles, control algorithms, placement within a microgrid configuration, power electronics, and control loop schemes, is provided in Reference [44]. Although the underlying scheme remains consistent, variations arise in the control of switching devices, leading to the identification of four distinct switching control methodologies for analysis [45].

The adjustment of average power primarily depends on changing the duty cycle, which includes the duration of load activation (on-time) and deactivation (off-time) [46]. Higher duty cycles indicate longer on-time periods compared to off-time. The duty cycle progresses through predetermined incremental steps. For example, with a non-controllable excess power limit of 10 kW and 10 predefined steps, each step represents a 1 kW adjustment in average power. If the non-controllable excess power measures at 1.1 kW, the average power load must shift to 2 kW to alleviate the excess, resulting in a battery discharge rate of 0.9 kW. Increasing the granularity of average power control steps improves the accuracy of excess power management [47].

Choosing the most effective average power control method for microgrid systems that utilize an inverter as the primary generating unit depends on several factors. First and foremost, the VAPL device must demonstrate a cost advantage over an additional inverter to ensure economic feasibility [48,49,50]. Additionally, versatility and ease of implementation are crucial, highlighting the importance of a plug-and-play design that eliminates the need for complex custom programming across different scenarios. A device that can seamlessly adapt and integrate into various system configurations is essential [51]. Moreover, the chosen method must minimize the effects on ancillary devices, including the reduction of current and voltage harmonics as well as voltage fluctuations. Only through careful selection of the most effective average power control method can the VAPL device achieve market acceptance [52].

To this end, four distinct average power control methods have emerged, each deserving of careful examination: burst control, phase delay control, pulse width modulation (PWM) [53] on the AC side, and PWM on the DC side. Each method presents unique features and challenges, requiring a thorough analysis to assess their effectiveness in microgrid systems with inverter-dominated master generating units [54]. The following exploration aims to uncover the complexities of these methodologies and clarify their potential contributions to the evolving field of microgrid energy management and optimization [55].

A key feature of the Burst method is its minimal switching losses [44], which result from its zero-crossing switching mechanism. This characteristic reduces heat generation and, in turn, decreases the cooling requirements within the power electronics loop. The Burst control method is primarily used on the AC side and can be configured for either single-phase or three-phase systems, depending on the nature of the non-controllable excess power source. In the case of three-phase configurations, three separate average power electronic loops are created, all coordinated by a single control unit [59].

In the Phase Delay control method, the duty cycle period corresponds to half of an AC sine wave cycle. This technique primarily utilizes bidirectional three-electrode AC switches (TRIACs) [45]. By intentionally delaying the activation of the AC load, this method results in reduced power consumption. The delayed switching interval lowers the average voltage applied to the load, facilitating effective power management. However, this approach is associated with higher switching losses, which can account for up to 85% of total losses [47], leading to increased heat generation and a greater need for enhanced cooling mechanisms. Although Phase Delay control can generate harmonics [48] and may lead to voltage and current spikes, it also provides a distinct advantage. By allowing the master generating unit—typically an inverter—to quickly respond to rapid changes in power balance, the Phase Delay method can help reduce sudden voltage and current fluctuations during switching. Like the Burst and PWM methods on the AC bus, Phase Delay control requires the development of separate VAPL devices for single-phase and three-phase non-controllable excess power sources [60].

The use of Pulse Width Modulation (PWM) on an AC-side bus as an average power control method builds on its established application in inverters. The duration of a PWM duty cycle typically occupies a very small fraction of time in the kHz range. This configuration helps avoid issues related to harmonic generation and beat phenomena, especially when the number of switches is limited [49]. Changes in the duty cycle, which control the on and off times of the load, directly affect the average power output. Longer on-times compared to off-times result in higher duty cycles, leading to increased average power levels.

However, implementing PWM on an AC-side bus requires careful consideration of power quality. Soft-switching techniques [50] or additional hardware like filters may be necessary to mitigate any adverse effects. Analogous to the previous methodologies, the PWM on AC Bus approach requires tailored VAPL devices for single-phase and three-phase non-controllable excess power sources.

At the end of the range of average power control methods is PWM on the DC side of microgrid systems. This approach utilizes PWM to regulate power dissipation on a DC bus, requiring a PWM-controlled device. While the operational principle is similar to that of PWM on the AC bus, only one PWM power electronics loop is needed for either a single-phase or three-phase configuration. However, higher DC bus voltages may necessitate increased current through the switches.

Like its AC counterpart, PWM on the DC bus adjusts the duty cycle to control average power. By increasing the duty cycle and, consequently, the on-time duration, the dissipation of excess power increases. It is important to note that while PWM on the DC side offers a promising solution, there are potential concerns regarding battery aging that depend on the PWM frequency [51]. To minimize negative impacts on battery health, techniques can be employed for estimating battery aging [52]. can be employed.

Considering these distinct methodologies, the search for an optimal average power control method continues. Each approach presents distinctive characteristics and challenges that require careful evaluation, propelling the advancement of microgrid energy management toward enhanced efficiency and sustainability.

Excess power in a microgrid system is identified by measuring and monitoring frequency. When excess power is present, the virtual rotating motor spins faster, resulting in an increase in frequency. The primary objective of the VAPL device is to track frequency changes and adjust the average power accordingly. A detailed description of the VAPL device's structure, operational function, control algorithm, placement within a microgrid framework, power electronics, and control loop schemes can be found in Reference [53]. Fig. 1 illustrates the main configuration of the VAPL device's power and control loops. While the overall scheme is similar across most average power control methods, the control of the switching devices varies, and the four different switching control methods are reviewed.

3. COMPARING AVERAGE POWER CONTROL METHODS IN MICROGRID SYSTEMS

A thorough evaluation of average power control methods is crucial for determining the suitability of the Variable Average Power Load (VAPL) device for various market demands. This assessment focuses on three key factors: versatility, impact on other devices, and cost-effectiveness. The VAPL device's effectiveness as a market solution depends on its ability to meet these criteria [61].

3.1. Versatility Comparison of Power Control Methods

In the context of this article, versatility refers to the adaptability of the final VAPL device prototype across different system designs. The aim is to develop a plug-and-play solution that reduces the need for complex programming for various applications or system configurations. As a result, power control methods are assessed based on their versatility [61].

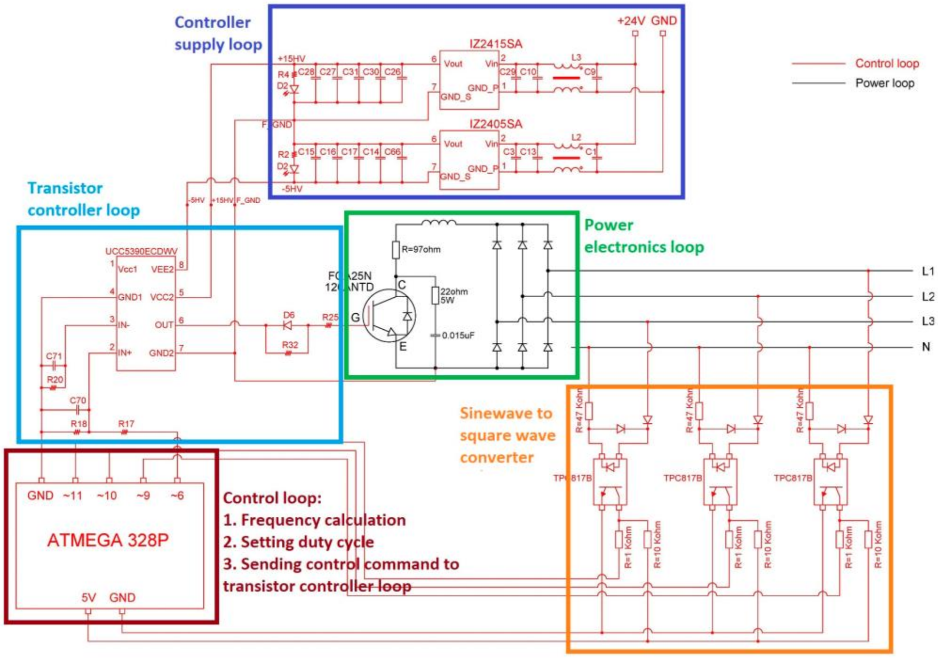

Fig. 1. The scheme of a VAPL device.

A duty cycle control loop is essential across all average power control methods. This loop determines the necessary average power and directs the average power control device accordingly. The evaluation of the required average power is based on frequency measurements within the AC bus, where excess power is detected. Therefore, each average power control method requires a connection to the AC bus to calculate the needed average power, ensuring the efficient use of excess power without jeopardizing the system's energy reserves [61].

Load activation and deactivation take place on the AC bus for the Burst control, Phase Delay, and PWM on AC Bus methods. As a result, the versatility of integrating these methods is largely comparable. Regardless of the selected approach, a VAPL device must be connected to the AC bus. Furthermore, the calculation of the duty cycle is closely tied to this connection. This relationship facilitates streamlined connections within the VAPL device itself, simplifying the integration process. The application of these methods on the AC side makes them versatile solutions suitable for various AC systems, regardless of the brand or type of inverter used [63].

In contrast, the versatility of a VAPL device controlled by the PWM on the DC Bus method is affected by several factors. Firstly, excess power detection relies on frequency measurement, necessitating an AC connection. This adds complexity to installations in various system designs. Secondly, the versatility of the PWM on the DC Bus method is limited by the varying voltage levels of battery systems. To ensure compatibility with battery systems ranging from 12 V DC to 48 V, and up to 400 V DC, separate devices may need to be developed for each voltage range. Thirdly, integration might require additional programming in cases where battery inverters and batteries communicate with each other. Finally, the transient conditions resulting from rapid load switching may affect the aging of DC bus batteries [53], necessitating the use of filters or careful selection of switching frequency. These factors collectively limit the method's versatility across different systems [64].

Given the direct influence of average power control methods on the design of the VAPL device, circuit board layout, and system integration, it is clear that the greatest versatility can be attained through the use of Burst control, Phase Delay, or PWM on AC Bus methods. These methods are inherently aligned with the AC side, offering simplified connections and broad applicability, making them ideal candidates for versatile implementation across various microgrid configurations. The duty cycle affects the on and off times of the load; specifically, longer on time than off time results in a higher duty cycle and, consequently, a greater average

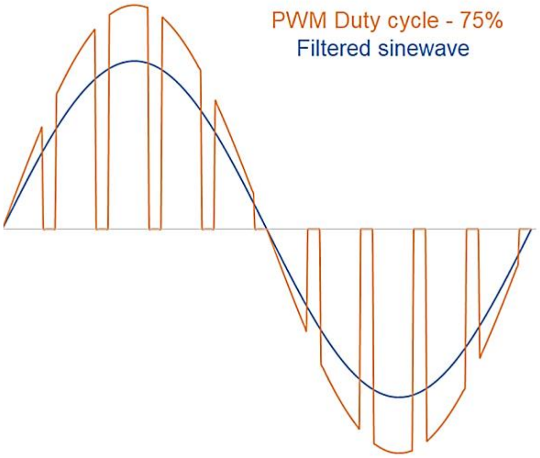

Fig. 2. PWM on AC-side bus control operation mode.

value, as illustrated in Fig. 2. To prevent the VAPL device using the PWM on the AC-side bus control method from affecting power quality, techniques like soft-switching [50] or additional hardware such as filters must be implemented. Similar to the burst and phase angle control methods, the PWM on the AC-side bus approach necessitates separate VAPL devices designed for single-phase and three-phase non-controllable excess power sources.

3.2. Not Harmful to Other Devices in a System

An experimental system was used to examine whether high-voltage switching at the peak of a sine wave leads to transient processes. The study involved assessing voltage spikes in an off-grid system caused by switching during the high-voltage phases of the sine wave.

The complete sine wave period is 20 ms; however, rapid switching at high-voltage points of the sine wave generates transient processes. These transient periods can last up to 1.2 μs and may cause voltage spikes exceeding 200 V, which in turn can lead to current spikes. As a result, methods such as phase delay and PWM on the AC bus could produce undesirable voltage and current spikes that compromise power quality and potentially damage off-grid AC appliances.

A similar, though less severe, effect occurs with direct PWM control on a DC bus, which may affect battery aging due to transient conditions during rapid switching. To address this issue, it becomes essential to implement filters to reduce aging or to select a switching frequency that minimizes harm.

The burst control method is preferred because it generates minimal or negligible transient processes, as switching occurs near 0 V. Similarly, PWM on a DC bus produces minimal transient processes on the AC side due to its operation on the DC side. Consequently, both the burst control and PWM on DC bus methods are considered to have little or no negative impact on other devices in the system.

3.3. Cost Evaluation of Power Control Methods

To keep a VAPL device competitive, its cost must be comparable to that of a new inverter. If the price of the VAPL device is similar to that of an inverter, consumers may prefer to buy a new inverter designed for their system instead of opting for a VAPL device to address excess power issues. In such cases, the attractiveness of the VAPL device could decrease. Therefore, it is crucial to evaluate the costs of power control methods, taking into account any necessary additional components.

The Burst control method offers a significant advantage in terms of its primary cost. Because it operates near 0 V, it incurs minimal switching losses, resulting in lower heat dissipation and reduced cooling system requirements. Furthermore, it does not generate voltage or current harmonics, eliminating the need for filters or additional cooling systems. As a result, the Burst method stands out as an optimal choice for minimizing the overall cost of a VAPL device.

In contrast, the Phase Delay and PWM on AC Bus methods incur higher switching losses, requiring more robust cooling systems. Filters are necessary to mitigate voltage and current spikes. These methods involve additional components, increasing the primary cost of the VAPL device and potentially making it comparable to the price of a new inverter. This factor may limit their market appeal.

Although the even power dissipation of the PWM on the AC Bus method appears advantageous, it generates high current and voltage harmonics that lead to significant filter costs, making it less cost-effective. The Phase Delay method, while producing lower harmonics than PWM on AC Bus, may introduce inrush voltage and current spikes. This approach might require customized filters for different systems to maintain power quality.

Direct PWM control on a DC Bus is a cost-effective solution. It evenly distributes average power, eliminates voltage fluctuations on the AC side, and prevents inrush current or voltage in the sine wave, which benefits other AC devices in the system. Although the potential increase in primary costs due to varying battery system voltage levels presents a challenge, the overall advantages of this method are significant.

In conclusion, the Burst average power control method seems to be the most suitable option, effectively balancing its effects on other appliances while keeping the primary cost low. Additionally, PWM on a DC Bus shows potential, providing controlled average power with minimal impact on overall costs.

The final method for controlling average power is PWM on the DC side of a microgrid system. Excess power can be dissipated using a PWM-controlled device on a DC bus. While the operating principle of PWM is similar to that used for the AC bus, the configuration differs due to the three-phase system compared to the DC bus. In this case, there is only one PWM power electronics loop; however, depending on the DC bus voltage, it may need to handle a higher current through the switches.

Average power control is achieved through the duty cycle, which consists of phases where the system is switched on and off, similar to the PWM method used on the AC side. The greater the excess power that needs to be dissipated, the higher the duty cycle required for the PWM, resulting in a longer on-time compared to off-time, as illustrated in Fig. 6. While PWM on the DC side may initially seem like the preferred control method, it can also contribute to battery aging, depending on the PWM frequency [51]. Battery aging can be monitored by assessing the battery's state of

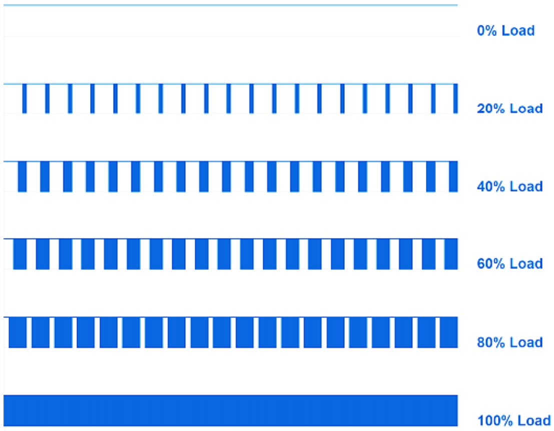

Fig. 3. PWM control on the DC-side bus operation mode. The more excess power that needs to be dissipated, the higher the duty cycle of the PWM is required to be, and the longer the switched-on time is compared to the switched-off time, as in the example given in the figure.

health [52] to mitigate the negative effects of VAPL devices on batteries. Consequently, it is essential to compare all proposed methods.

3.4. Summary of Comparison of Power Control Methods

The evaluation of average power control methods provided valuable insights, which are summarized in Table 2. While the PWM on AC Bus method offers uniform power dissipation, it produces significant current and voltage harmonics, leading to higher filter costs. The Phase Delay method may result in voltage fluctuations and generate current and voltage harmonics, requiring filters tailored to specific systems. In contrast, direct PWM control on a DC Bus stands out as a favorable solution, as it evenly distributes power without adversely affecting other AC devices.

The selection process took into account the versatility, cost-effectiveness, and impact of the VAPL device on other devices. After balancing these criteria, the Burst average power control method emerged as the optimal choice. It offers a versatile and straightforward solution that meets all requirements without the need for additional components.

4. CONCLUSIONS

In microgrid systems, excess power can cause frequency increases. The VAPL device activates when the frequency surpasses a predetermined threshold, using non-controllable excess power at the necessary rate. The VAPL algorithm adapts power utilization to align with fluctuations in excess power, ensuring the maintenance of energy reserves and electricity quality. For optimal performance, the VAPL device adjusts power incrementally, requiring different models for one-phase and three-phase sources, with the exception of PWM on a DC bus.

The comparison results suggest that the burst control method is the most suitable for VAPL. While it may cause voltage fluctuations in systems with a rotating master generator, it is less problematic in inverter-based systems. However, further validation through simulations and real-world testing is necessary.

Microgrid systems with non-controllable generators, particularly unpredictable renewable sources, face excess power issues that affect frequency and stability. The VAPL device, equipped with four control methods (burst, phase-angle, PWM on an AC bus, or PWM on a DC bus), offers a solution to this problem.

Table 2. Comparison of average power control methods.

Power Control Method	Versatile	Cost-Efficient	No Filtering Needed
Burst	Yes	Yes	Yes
Phase delay	Yes	No	No
PWM AC bus	Yes	No	No
PWM DC bus	No	Yes	Yes

Considering the requirements, context, and capabilities of the VAPL device, burst control emerges as the most appropriate method for regulating average power in microgrids with non-controllable excess power sources. It minimizes costs and the impact on the system while effectively utilizing excess power. Further research should involve simulations and real-world prototypes to confirm its effectiveness and viability in practical applications.

Integrating renewable energy sources into microgrid systems poses a complex challenge due to the intricate interactions among various components. The Variable Average Power Load (VAPL) device offers an innovative solution for managing the dynamic use of excess power in microgrid configurations while preserving the integrity of stored energy and ensuring consumer comfort. The primary function of the VAPL device is to monitor frequency and adjust average power in sync with frequency changes. Four distinct average power control methods have emerged, each with its own unique characteristics and challenges: Burst control, Phase Delay control, Pulse Width Modulation (PWM) on the AC side, and PWM on the DC side. A thorough evaluation of these methods is crucial for assessing their suitability for various market demands. This assessment concentrates on three key factors: versatility, impact on other devices, and cost-effectiveness. The Burst, Phase Delay, and PWM on AC Bus methods demonstrate greater versatility because they are compatible with the AC side and feature simplified connections, making them strong candidates for implementation across diverse system designs. In contrast, the PWM on the DC Bus method is limited by fluctuations in battery system voltage levels, necessitating separate devices for each voltage range and additional programming. The versatility and adaptability of the VAPL device are vital for its success in the market. Consequently, choosing the most suitable average power control method requires balancing these attributes with considerations of cost-effectiveness and ease of implementation.

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