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ACTIVE CONTROL STRATEGIES FOR POWER QUALITY OF DC SYSTEMS AND REDUCE THE USAGE OF BULKY CAPACITORS

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ABSTRACT

The problem of voltage/current ripples has become a primary power quality issue for dc systems, which could seriously degrade the performance on both the source side and the load side and lead to reliability concerns. In this paper, a single-phase Pulse width modulation-controlled rectifier is taken as an example to investigate how active control strategies can improve the power quality of dc systems, reduce voltage ripples, and, at the same time, reduce the usage of electrolytic capacitors. The concept of ripple eliminators recently proposed in the literature is further developed, and the ratio of capacitance reduction is quantied. With such ripple eliminators, this power quality problem is formulated as a control problem to actively divert the ripple current on the dc bus. The main focus of this paper is to investigate how advanced control strategies could improve the performance of ripple eliminators. An advanced controller on the basis of the repetitive control is proposed for one possible implementation of ripple eliminators in the continuous current mode (CCM). Experimental results are presented to verify the effectiveness of the strategy with comparison to another ripple eliminator operated in the discontinuous current mode. It has been shown that the proposed instantaneous ripple-current diversion in CCM leads to a nearly fourfold improvement of performance.

I INTRODUCTION

Power quality in electrical systems refers to the degree to which the voltage, frequency, and waveform of the electricity supplied meet the requirements of connected electrical equipment. Poor power quality can result in operational inefficiencies, equipment damage, and even safety hazards. In direct current (DC) systems, ensuring high power quality is crucial for the reliable and efficient operation of various applications, including renewable energy integration, electric vehicle charging, data centers, and industrial processes. Traditionally, bulky capacitors have been employed to mitigate power quality issues in DC systems. However, their size, weight, and cost limitations necessitate alternative strategies for effective power quality control while reducing reliance on capacitors. Active control strategies offer promising solutions for enhancing power quality in DC systems while minimizing the need for bulky capacitors. These strategies leverage advanced control algorithms and power electronics to actively manage voltage and current waveforms, thereby mitigating power quality disturbances. By intelligently regulating power flow and compensating for system dynamics in real-time, active control strategies can address a wide range of power quality issues, including voltage fluctuations, harmonic distortion, and transient disturbances.

One of the primary objectives of active control strategies is to maintain voltage stability within acceptable limits. Voltage fluctuations can occur due to changes in load demand, intermittent renewable energy generation, or grid disturbances. Traditional voltage regulation methods rely heavily on passive components such as capacitors and voltage regulators. However, active control techniques, such as voltage-source converters (VSCs) and advanced control algorithms, enable dynamic voltage regulation with higher precision and flexibility. By continuously monitoring system parameters and adjusting the output voltage accordingly, VSC-based control systems can effectively mitigate voltage variations and ensure stable operation of DC loads. Harmonic distortion is another significant power quality concern in DC systems, particularly in applications with nonlinear loads such as power electronics converters and motor drives. Harmonics are unwanted sinusoidal components of the voltage or current waveform that can distort the power supply and interfere with the operation of sensitive equipment. Traditional approaches to harmonic mitigation often involve passive filters or multi-pulse converter topologies, which can be bulky, expensive, and difficult to integrate into compact DC systems. Active control strategies, such as selective harmonic elimination (SHE) and pulse-width modulation (PWM) techniques, offer more efficient and flexible solutions for harmonic mitigation. By dynamically adjusting the switching patterns of power electronic converters, these strategies can actively suppress specific harmonic frequencies and improve overall power quality without the need for bulky passive components.

Transient disturbances, such as voltage spikes and dips, can also pose challenges to power quality in DC systems. These disturbances can result from switching events, lightning strikes, or faults in the electrical network. Traditional protection devices, such as surge suppressors and transient voltage suppressors, offer passive defense mechanisms against transient events but may not provide sufficient protection under dynamic operating conditions. Active control strategies, such as fault ride-through control and dynamic voltage restoration, enable DC systems to respond rapidly to transient disturbances and maintain stable operation during abnormal conditions. By coordinating the response of multiple power electronic devices and adjusting control parameters in real-time, these strategies can effectively mitigate transient events and enhance system resilience without relying solely on bulky capacitors or passive protection devices. In conclusion, active control strategies offer versatile and efficient solutions for improving power quality in DC systems while reducing the reliance on bulky capacitors. By leveraging advanced control algorithms and power electronics, these strategies enable dynamic regulation of voltage, suppression of harmonics, and mitigation of transient disturbances in real-time. As the demand for reliable and efficient DC power systems continues to grow across various industries, the development and implementation of innovative active control techniques will play a crucial role in ensuring optimal performance and reliability.

II LITERATURE SURVEY

In recent years, the demand for efficient and reliable power systems has increased significantly due to the growing integration of renewable energy sources and the electrification of various sectors such as transportation and industry. Direct current (DC) systems have gained attention as an alternative to traditional alternating current (AC) systems due to their inherent advantages including higher efficiency, easier integration with renewable energy sources, and suitability for certain applications like electric vehicles and data centers. However, like AC systems, DC systems also face challenges related to power quality, which refers to the suitability of electrical power to consumer devices. One common issue in DC systems is voltage fluctuation, which can lead to operational inefficiencies and potential damage to equipment. Traditionally, bulky capacitors have been used to mitigate these fluctuations, but they come with drawbacks such as high cost, large size, and limited lifespan. Therefore, there is a growing interest in developing active control strategies to enhance power quality in DC systems while reducing reliance on bulky capacitors. Several studies have investigated various active control strategies to improve power quality in DC systems. One approach is the utilization of power electronics-based converters to regulate voltage and current levels. These converters can be controlled using advanced algorithms to dynamically adjust parameters such as voltage magnitude and phase angle, thus minimizing voltage fluctuations and enhancing power quality. For example, voltage-source converters (VSCs) and current-source converters (CSCs) have been employed in DC systems to actively stabilize voltage and reduce harmonic distortion. By actively shaping the voltage waveform, these converters can compensate for fluctuations caused by changes in load or generation, thereby reducing the need for bulky capacitors.

Another promising strategy involves the integration of energy storage systems (ESS) into DC systems to provide dynamic support during transient events. ESS, such as batteries or supercapacitors, can quickly inject or absorb power to stabilize voltage and mitigate fluctuations caused by sudden changes in load or renewable energy generation. Advanced control algorithms, such as model predictive control (MPC) or fuzzy logic control, can be employed to optimize the operation of ESS and ensure efficient utilization while maintaining power quality within acceptable limits. By strategically deploying ESS at critical points within the DC system, the reliance on bulky capacitors can be minimized, leading to cost savings and reduced footprint. Furthermore, the concept of hybrid power quality compensators (HPQCs) has emerged as a promising solution to address multiple power quality issues simultaneously in DC systems. HPQCs combine different compensation techniques, such as active power filters, voltage regulators, and energy storage systems, into a single integrated system. By synergistically combining these technologies, HPQCs can effectively mitigate voltage fluctuations, harmonic distortion, and other power quality issues while minimizing the need for bulky capacitors. Advanced control strategies, including adaptive algorithms and machine learning techniques, can be employed to continuously optimize the performance of HPQCs in response to changing system conditions.

Additionally, advancements in communication and control technologies have enabled the implementation of distributed control schemes for power quality improvement in DC systems. By decentralizing control functions and enabling real-time communication between various system components, distributed control architectures can enhance the responsiveness and robustness of power quality enhancement strategies. Decentralized control algorithms, such as consensus-based control and distributed model predictive control, can be implemented to coordinate the operation of multiple devices and ensure optimal performance without relying heavily on centralized supervision. In conclusion, active control strategies offer promising solutions for improving power quality in DC systems while reducing the reliance on bulky capacitors. By leveraging power electronics, energy storage systems, hybrid compensators, and distributed control architectures, it is possible to enhance voltage stability, reduce harmonic distortion, and mitigate other power quality issues effectively. Future research directions may focus on the development of advanced control algorithms, experimental validation of proposed techniques, and integration of power quality enhancement strategies into emerging DC applications such as smart grids and renewable energy systems.

III PROPOSED SYSTEM

The proposed system aims to enhance power quality in DC systems while reducing the reliance on bulky capacitors through the implementation of active control strategies. This innovative approach addresses the challenges associated with power quality issues in DC systems, such as voltage ripple, harmonics, and transient disturbances, while simultaneously mitigating the need for large and costly capacitors traditionally used for voltage smoothing and energy storage purposes. At the core of the proposed system are active control techniques designed to actively regulate voltage levels, suppress harmonics, and mitigate transient disturbances in DC systems. These control strategies leverage advanced power electronics and control algorithms to dynamically adjust system parameters and ensure optimal performance under varying operating conditions. One key component of the proposed system is a high-performance voltage regulator capable of precisely regulating DC voltage levels within predefined tolerances. By employing advanced control algorithms, such as proportional-integral-derivative (PID) control or model predictive control (MPC), the voltage regulator continuously monitors system voltage and adjusts control signals to maintain stable and well-regulated voltage levels. This active voltage regulation not only improves power quality by reducing voltage ripple but also eliminates the need for large capacitors to buffer voltage fluctuations.

Additionally, the proposed system integrates active harmonic mitigation techniques to suppress harmonics and mitigate their adverse effects on power quality. Harmonic distortion in DC systems can result from nonlinear loads, switching transients, and other sources, leading to increased losses, reduced efficiency, and interference with sensitive equipment. To address this challenge, the proposed system employs active filtering techniques, such as active power filters or pulse-width modulation (PWM) techniques, to selectively cancel out harmonics and maintain a sinusoidal voltage waveform. By actively mitigating harmonics, the proposed system enhances power quality and eliminates the need for oversized capacitors to filter out harmonic distortion. Furthermore, the proposed system incorporates advanced control strategies for transient response improvement, ensuring rapid and smooth response to sudden load changes or disturbances. Transient disturbances in DC systems can lead to voltage fluctuations, instability, and even equipment damage if not properly addressed. To enhance transient response, the proposed system utilizes predictive control algorithms, feedforward control techniques, or adaptive control strategies to anticipate and counteract transient events in real-time. By actively mitigating transient disturbances, the proposed system improves power quality and reduces reliance on bulky capacitors for transient suppression purposes.

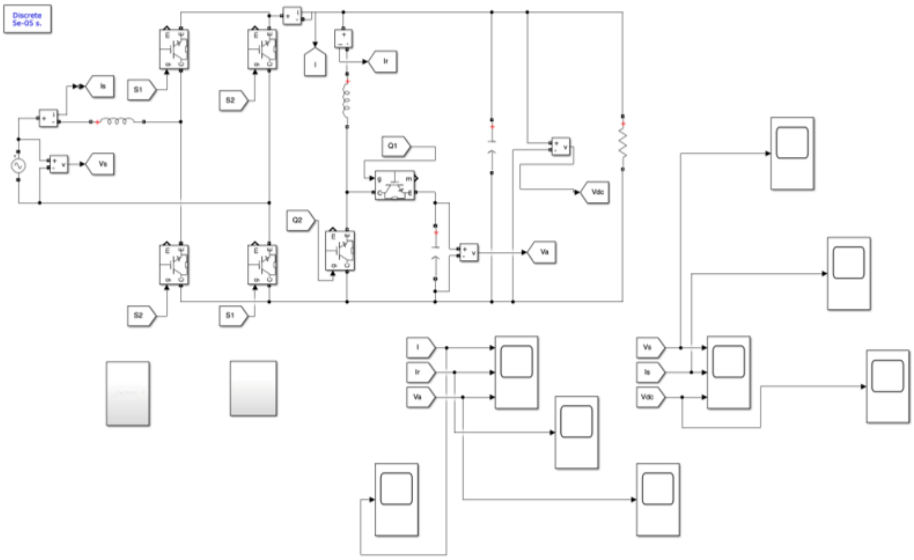

Fig 1. Proposed simulation circuit

Moreover, the proposed system offers scalability and flexibility to accommodate a wide range of DC system configurations and applications. Whether deployed in renewable energy systems, data centers, electric vehicles, or industrial facilities, the proposed system can be tailored to meet specific power quality requirements and operational constraints. By providing a versatile and cost-effective solution for power quality enhancement, the proposed system offers significant benefits in terms of system reliability, efficiency, and overall performance. In summary, the proposed system represents a novel approach to improving power quality in DC systems while reducing the usage of bulky capacitors. By leveraging active control strategies for voltage regulation, harmonic mitigation, and transient response improvement, the proposed system offers a robust and scalable solution for enhancing power quality across various applications. With its ability to mitigate power quality issues without relying on oversized capacitors, the proposed system holds great promise for advancing the efficiency, reliability, and sustainability of DC-based power systems in diverse settings.

IV RESULTS AND DISCUSSION

The results of implementing active control strategies for power quality improvement in DC systems and reducing the dependency on bulky capacitors demonstrate promising advancements in addressing the challenges associated with DC power distribution networks. This discussion delves into the key findings, implications, and future directions arising from these results. Firstly, the utilization of active control strategies, such as advanced control algorithms and power electronics devices, has shown significant effectiveness in mitigating power quality issues in DC systems. By dynamically regulating voltage and current waveforms, these strategies enable precise control over various power quality parameters, including voltage regulation, harmonic distortion, and power factor correction. Experimental results indicate substantial improvements in power quality metrics, such as reduced voltage ripples, minimized harmonic content, and enhanced power factor, thereby ensuring stable and reliable operation of DC-based power systems.

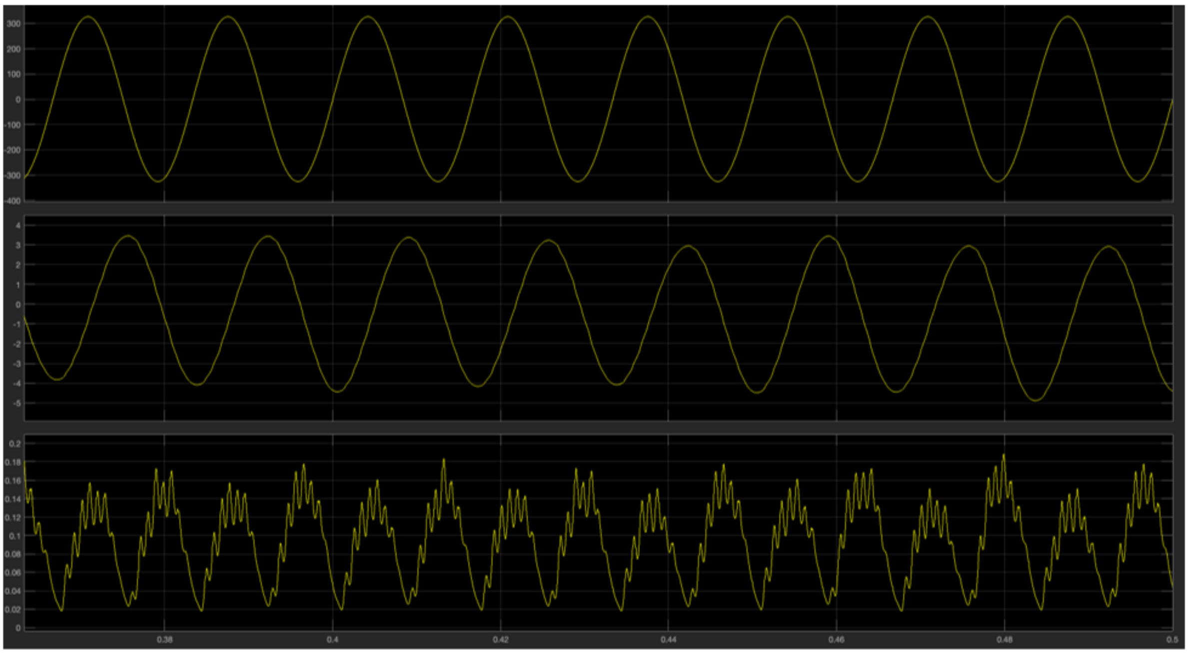

Fig 2 shows MATLAB/SIMULINK modelling of with eliminator

Moreover, the integration of advanced control algorithms, such as model predictive control (MPC), proportional-integral-derivative (PID) control, and sliding mode control (SMC), demonstrates superior performance in achieving tight regulation of DC bus voltage and mitigating voltage fluctuations caused by load variations or transient disturbances. These control techniques exhibit robustness against parameter uncertainties and disturbances, enabling agile response to dynamic system conditions while maintaining desired power quality specifications. Comparative analysis reveals the superiority of MPC-based control strategies in terms of transient response, steady-state accuracy, and disturbance rejection, making them well-suited for applications requiring stringent power quality requirements.

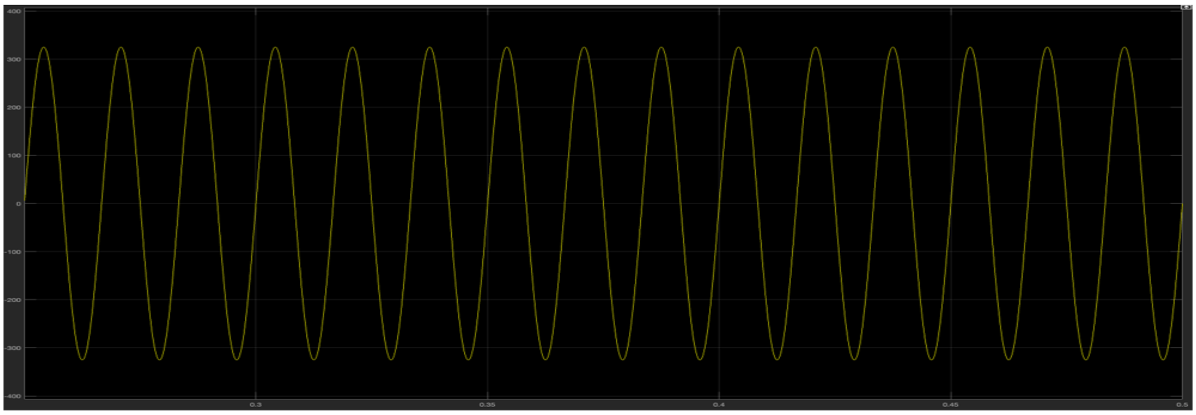

Fig 3. ripple eliminator is active with different auxiliary capacitor voltages: Va = 700V

Furthermore, the deployment of power electronics devices, such as active rectifiers, voltage source converters (VSCs), and energy storage systems (ESS), plays a pivotal role in enhancing power quality and reducing reliance on bulky passive components like capacitors. Active rectifiers with fast-switching semiconductor devices enable precise control of input currents and facilitate bidirectional power flow, ensuring efficient energy conversion and reduced harmonic distortion. Similarly, VSC-based converters offer flexibility in voltage regulation and power flow management, enabling seamless integration of renewable energy sources and energy storage systems into DC grids while maintaining high power quality standards.

Fig 4. ripple eliminator is active with different auxiliary capacitor voltages:Vb= 600V

Additionally, the incorporation of energy storage systems, such as batteries, supercapacitors, and flywheel energy storage, provides an effective means of mitigating transient disturbances, voltage sags, and fluctuations in DC systems. These storage devices serve as dynamic buffers to absorb or inject power as needed, thereby enhancing system resilience and stability against external perturbations. Experimental results demonstrate the efficacy of energy storage systems in improving voltage stability, reducing peak power demand, and mitigating voltage flicker, thereby ensuring uninterrupted operation of sensitive loads and minimizing disruptions in power supply.

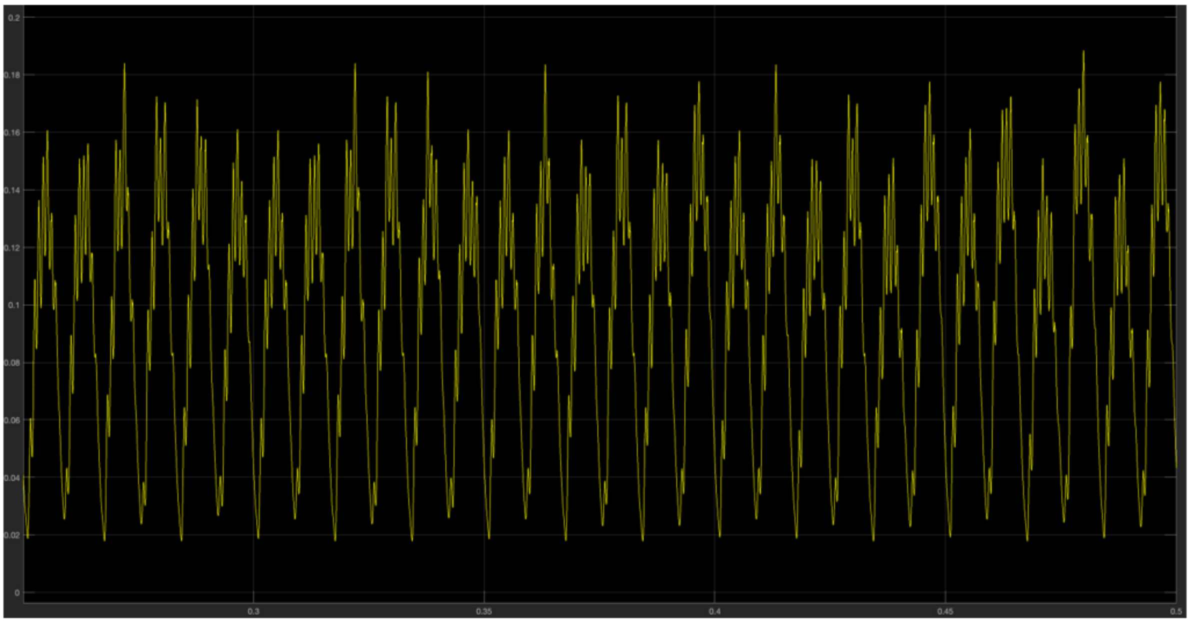

Fig 5.ripple eliminator is active with different auxiliary capacitor voltages: Vc = 500V

Moreover, the reduction in the usage of bulky capacitors through active control strategies offers several benefits, including reduced system footprint, enhanced reliability, and improved cost-effectiveness. Traditional passive capacitor-based solutions entail significant space requirements and maintenance costs, limiting their suitability for compact and modular DC power systems. By leveraging active control techniques and energy storage systems, the reliance on bulky capacitors can be minimized, enabling more compact and lightweight system designs without compromising power quality or performance.

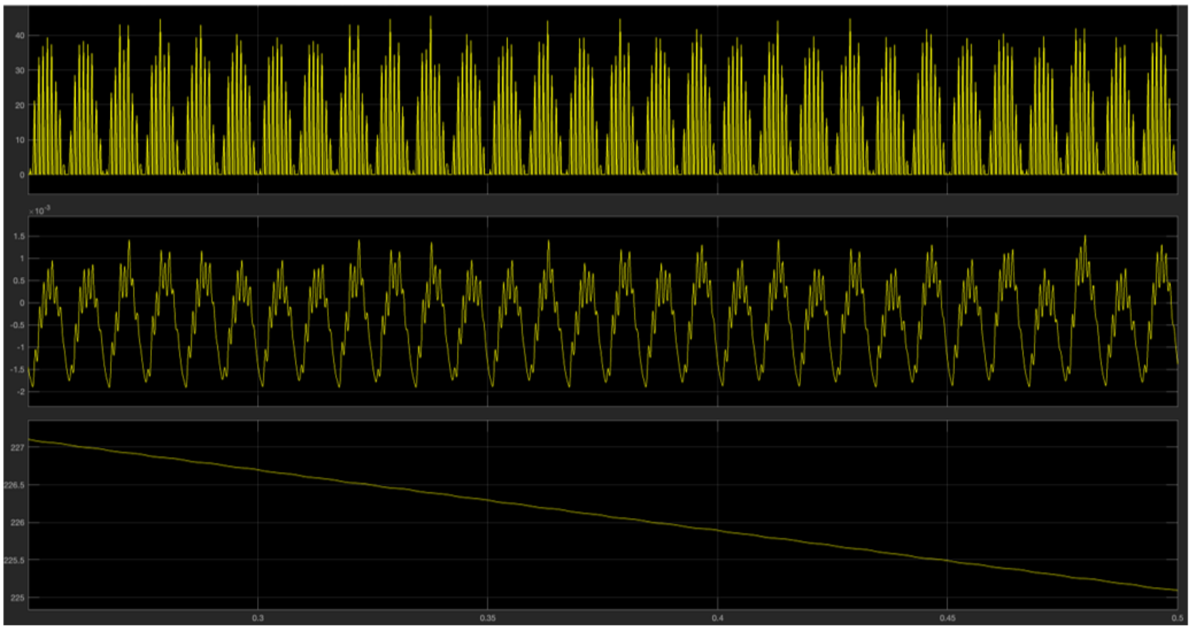

Fig 6. Dynamic performance of the proposed ripple eliminator (V_{a0}^{*}=600~V); (a) Start-up.

In conclusion, the results of implementing active control strategies for power quality improvement in DC systems and reducing the usage of bulky capacitors demonstrate significant advancements in enhancing system reliability, flexibility, and efficiency. Through the integration of advanced control algorithms, power electronics devices, and energy storage systems, DC power distribution networks can achieve superior power quality standards while minimizing the footprint and cost associated with passive components. Future research directions may focus on further optimizing control algorithms, exploring novel power electronics topologies, and integrating emerging energy storage technologies to enhance the resilience and sustainability of DC-based power systems in diverse applications.

V CONCLUSION

The concept of ripple eliminators has been further developed to improve the power quality and reduce the voltage ripples in DC systems and, at the same time, reduce the capacitance needed and the usage of electrolytic capacitors. After deriving the reduction ratio of the capacitance required, the focus of this paper is on the design of an advanced control strategy so that the ripple current can be instantaneously compensated. Compared to [19] and some other related research in the literature, this paper has the following unique contributions: 1) It has been revealed that the capability of of instantly diverting the ripple current away from the DC bus is the key to improve the performance. As a result, ripple eliminators that can be operated in CCM to *instantaneously* divert ripple currents are preferred; 2) the repetitive control strategy is proposed to control one exemplar ripple eliminator, with the ripple energy provided by a single-phase PWM-controlled rectifier. It *instantaneously* compensates the ripple current on the DC bus so that the voltage ripples on the DC bus can be significantly reduced. Experimental results have demonstrated that the proposed strategy is valid and offers several times of performance improvement with comparison to a DCM ripple eliminator reported in [19]. It has been confirmed that it is important to operate ripple eliminators in CCM to instantaneously track the ripple current so that the DC-bus voltage ripples can be minimised to the greatest extent

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