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Review

A Comprehensive Review of Event-Triggered Consensus Schemes in DC Microgrids

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Abstract

This paper provides a comprehensive review of recent studies on event-triggered control schemes for DC microgrids. Several event-triggered mechanisms (ETMs) are thoroughly discussed, including static, dynamic, self-triggered, and edge-based algorithms. Considering the strengths and weaknesses of these algorithms, it is found that although such ETMs can decrease communication burden in the system, they are also susceptible to communication delays, Zeno behaviour, sensitivity to control parameter changes in triggering conditions, and inability to adapt to the fluctuating nature of renewable energy sources (RESs). Furthermore, this article examines implementation challenges, including data packet loss, quantisation effects, actuator faults, and a lack of cybersecurity measures, to provide readers with a clear vision of future trends in this field. Based on the main findings of the investigation, this review paper proposes possible areas for future research, highlighting the need for event-triggered control schemes that operate in discrete time, handle delays, and adapt to varying operating conditions. Other concepts, including adaptive control parameters for triggering conditions based on machine learning, the adoption of advanced cybersecurity measures, and data-aware transmission approaches that consider both communication frequency and total data volume, are also discussed. To conduct a comprehensive review of all the above-mentioned ETMs, several databases, including IEEE Xplore, Elsevier, and MDPI, were searched using the main keywords in this field, such as event-triggered, self-triggered, and edge-based ETMs, in conjunction with DC microgrids. This facilitated an in-depth analysis of such control schemes, including their strengths and weaknesses, providing readers with a strong basis for selecting a proper control scheme suited to their future research.

Keywords: DC microgrids; data transmission domains; ETM; ETM issues

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1. Introduction

Electric power networks are a crucial requirement in today's digital age, with estimates indicating that power unavailability is expected to become a notable issue in many countries, especially on islanded-grid sites [1]. The chief reason for the lack of electrification in remote regions is their isolation from the centralised power network and the financial impracticality of extending grid infrastructure to those locations [2]. Moreover, energy consumption in such regions is substantially lower than in urban areas [3]. In this respect, off-grid microgrids (MGs) can be a feasible option for inaccessible locations with no grid availability [4]. Different control methods have been proposed in the literature to coordinate DC microgrids, such as centralised, decentralised, distributed, and hierarchical control schemes [5]. The primary objectives of such control schemes are to ensure accurate power distribution and maintain acceptable voltage levels in both individual and clustered microgrids. It has been found that the previous three control approaches have been inadequate for meeting the complex and uncertain requirements of modern power networks, particularly when power systems require complex decision-making [6,7]. From this perspective, a hierarchical control scheme, characterised by high reliability and smooth operation of microgrids (MGs), is considered a practical option in the field of Microgrids [8]. This control scheme is divided into three interconnected control levels, incorporating primary, secondary, and tertiary [9], as clearly explained in [7]. At the third control layer, time-triggered consensus-based protocols are employed to facilitate coordination between the microgrids [10–12]. These protocols can achieve convergence within different time intervals, including infinite-time, finite-time, and fixed-time intervals [5]. However, they are time-triggered control approaches that depend on periodic sampling and data packet transmission, which require frequent state data collection for each agent at equidistant sampling periods, regardless of the network state or resource utilisation [13]. In real-world applications, the requirement for continuous communication to transmit data and updates from controllers within the system is essentially unrealistic, as it may consume extensive computational power and communication resources [14].

Accordingly, it is crucial to design new control strategies that ensure the proper performance of DC microgrids while substantially reducing data exchange and computing resource consumption among generation units within microgrids. To tackle these challenges, event-triggered mechanisms (ETMs), which require interaction and control updates only when necessary, have been proven to be an effective solution, as stated in [15–19]. These control schemes can lower communication costs and improve efficiency [20]. In this respect, different ETMs have been employed to manage data exchange among microgrids. Static ETMs are challenged by high triggering frequencies under perturbation-based disruptions (PBDs), leading to ineffective operation of communication networks in DC microgrids [21], and are one type of ETM. These control mechanisms are hindered by critical weaknesses, including Zeno behaviour, non-dynamic adjustability of threshold parameters, and susceptibility to cyber-attacks [21]. To tackle some of these issues, dynamic ETMs have been proposed in the literature to dynamically adjust threshold parameters and thereby avoid Zeno behaviour, by virtue of their discrete-time implementation [22]. However, it is observed that traditional dynamic ETM schemes are not robust against Denial-of-Service (DoS) attacks, in which communication disruptions lead to incorrect controller updates and significantly degrade the stability and performance of DC microgrids.

New attack-resilient dynamic event-triggering control mechanisms are introduced in [23] to address these constraints and enhance recovery and communication efficiency. Although such improvements have been introduced, ETM control mechanisms still rely on continuous-time signals, making their practical implementation difficult [24]. Additionally, using continuous-time controllers for discrete-time microgrids may introduce uncertainties that compromise system stability. Consequently, designing discrete-time event-triggered controllers explicitly derived from discrete-time models is needed to enhance robustness in control design [25]. Furthermore, self-triggered control schemes (STMs) effectively alleviate communication and computation loads; however, they require greater communication rates than event-triggered mechanisms. They are flawed by computational complexity and robustness issues in highly uncertain systems [26,27]. Recent studies have focused on incorporating quantisation in ETMs to further improve communication efficiency, as neither control scheme can independently decrease communication bandwidth requirements [28].

Therefore, real-world applications of DC microgrids often use quantisation to reduce communication bandwidth requirements. Quantisation, however, introduces unavoidable errors that may compromise control accuracy [29]. Therefore, it is necessary to focus extensively on this concept.

Additionally, ideal voltage supplies for DC microgrids have been adopted in previous studies, which may not be compatible with practical operating conditions, where parasitic factors and disturbances introduce significant performance degradation [30]. To address this gap, a new study proposes a practical control scheme that can cope with non-ideal conditions, specifically relevant to power fluctuations experienced by PV systems [30]. Integrating modified secondary control schemes, such as model predictive control (MPC) and data-driven approaches, has been an area of interest for addressing communication limitations and uncertainties in DC microgrids. Such advanced control schemes can outperform traditional PI-based controllers used in previous studies by improving optimisation, adaptive parameter selection, and dynamic response [31,32]. Furthermore, event-triggered control schemes have been further improved by adopting finite- and fixed-time algorithms in the secondary control layer, which can affect system stability, computational burden, and communication rate [33]. It is evident that event-triggered consensus algorithms play a crucial role in efficiently coordinating microgrids with reduced dependency on communication networks; therefore, it is essential to thoroughly investigate them to provide readers with a clear understanding of both current and future directions. Based on the investigation conducted in this paper, it is found that there is a lack of review studies on event-triggered control schemes in DC microgrids. Although several review papers have investigated various aspects of DC microgrids, to the best of our knowledge, this comprehensive review is the first to explore event-triggered mechanisms for DC microgrids. This comprehensive review study distinguishes itself from prior review articles [6,7,34–36]. An early overview of various control schemes, including centralised, decentralised, and distributed secondary control schemes for DC microgrids, without focusing on event-triggered mechanisms (ETMs), is presented in [34]. Furthermore, the authors in [6] conduct an extensive review of control schemes for both DC microgrids and DC clusters, primary and secondary controls of DC microgrids within a hierarchical control framework and briefly mention an event-triggered control scheme under the distributed secondary control layer. A comprehensive review paper [7] discusses different control schemes for DC microgrid clusters, including centralised, decentralised, distributed, and hierarchical control strategies, but does not consider event-triggered mechanisms. Furthermore, a comprehensive review of different microgrid applications, market segments and adopted control schemes, including centralised, distributed, decentralised and hierarchical control strategies, is conducted in [35]. In [36], several consensus algorithms, including dynamic, leader-follower, finite-time, PI, and event-triggered, are considered, treating event-triggered consensus as one category among others. Unlike the above-mentioned review articles, this comprehensive review paper presents a mechanism-level analysis of event-triggered control mechanisms for DC microgrids. It also provides a new unified categorisation framework to organise the investigated control schemes into four groups, including static, dynamic, self-triggered, and edge-based event-triggered mechanisms. An evaluation framework for these schemes is introduced based on several criteria, including communication efficiency, robustness to communication delays, cyber-resilience, sensitivity to control parameter tuning, avoidance of the Zeno phenomenon, and adaptability to the intermittency of renewable energy sources in networks. This review paper also identifies several important open research problems related to the application of ETM schemes in DC microgrids for future research. The main contributions of this review paper can be summarised as follows:

1. A comprehensive review of the main event-triggered consensus algorithms, such as static, dynamic, self-triggered, and edge-based consensus algorithms, that have been adopted in the literature to coordinate DC microgrids.
2. Comparative discussions about their strengths and weaknesses to facilitate choosing a proper control scheme based on microgrid requirements.
3. A summary of open research issues and potential future directions in this field is presented.
4. Control scheme evaluation factors are proposed in this paper to assist readers in this field in assessing the robustness of the control schemes in the literature.

2. DC Microgrids Structure

Microgrids (MGs) are small-scale electrical grids composed of multiple interconnected distributed generation units (DGUs) [37]. This concept has been proposed as a practical solution for integrating different renewable energy sources (RESs) into modern power systems [38]. In this article, attention is focused on DC microgrids, which have attracted growing interest owing to their high efficiency, simple control structure and compatibility with DC-based renewable sources and energy storage units. A cluster of DC MGs is an assembly of multiple DCMGs that provides power to a specific region, as illustrated in Figure 1. Within a cluster, individual DCMGs incorporate various distributed energy resources (DERs), such as photovoltaic (PV) systems, wind turbines (WTs), and energy storage systems (ESSs) [39]. These resources are typically interfaced to a common DC bus via power electronic converters that regulate the power flow between them and the bus [40]. While each MG can operate independently, the participant MGs are connected via communication networks. Such a combination enables the sharing of information and the collaborative operation of the cluster [15]. From a control perspective, a DC microgrid can be considered a cyber-physical network with two network topologies, including a physical and a cyber control layer [41]. The physical topology describes the electrical connections between MGs and DGUs, and S manages the power flow among them. In this regard, graph theory provides a mathematical representation of this layer as an undirected weighted graph $gp(Vp, \mathcal{E}p)$, where the vertex set $\mathcal{V}p = \{1, 2, ..., N\}$ represents the N DGUs/MGs, while the edge $Ep \in \mathcal{V}p \times \mathcal{V}p$ represents the power line among them [15,17]. The adjacency matrix of the graph gp $\mathcal{A}p = [G_{ij}] \in R^{N\times N}$ comprises non-negative elements with $G_{ij} = 1$ if the power line exists between MG_i and MG_j otherwise G_{ij} = 0. The Laplacian matrix is defined as $\mathcal{L}p = [D_p - A_p]$, where $\mathcal{D} = diag\{G_{11}, G_{22}, ..., G_N\}$. Conversely, the cyber layer represents the communication links among local controllers in DC microgrids, enabling them to exchange data and coordinate effectively within the system [42]. This layer can also be modelled as a weighted undirected graph $Gc(\mathcal{V}c, \mathcal{E}c, wc)$, where the vertices $\mathcal{V}c = \{1, 2, ..., N\}$ denote the N controllers, while the edge set $\mathcal{E}c \in \mathcal{V}c \times \mathcal{V}c$ represents the communication line among them. For example, an edge (i, j) indicates that the controller i can receive data from its neighbouring controller j. The adjacency matrix $\mathcal{A}c$ of the graph Gc is defined analogously to $\mathcal{A}p$ with $a_{ij} = 1$ if the communication line exists between the controllers i and j otherwise $a_{ij} = 0$ [43,44]. The Laplacian matrix is similarly given by $\mathcal{L}c = [D_c - A_c]$ [45].

The above-described graph-theoretical framework provides the basis for the event-triggered mechanisms (ETMs) discussed in the subsequent sections. In the Laplacian matrix concept, each local controller transmits data only when the control scheme's triggering condition is satisfied, thereby significantly reducing the communication burden while maintaining the other control objectives, including accurate power sharing and optimal voltage regulation.

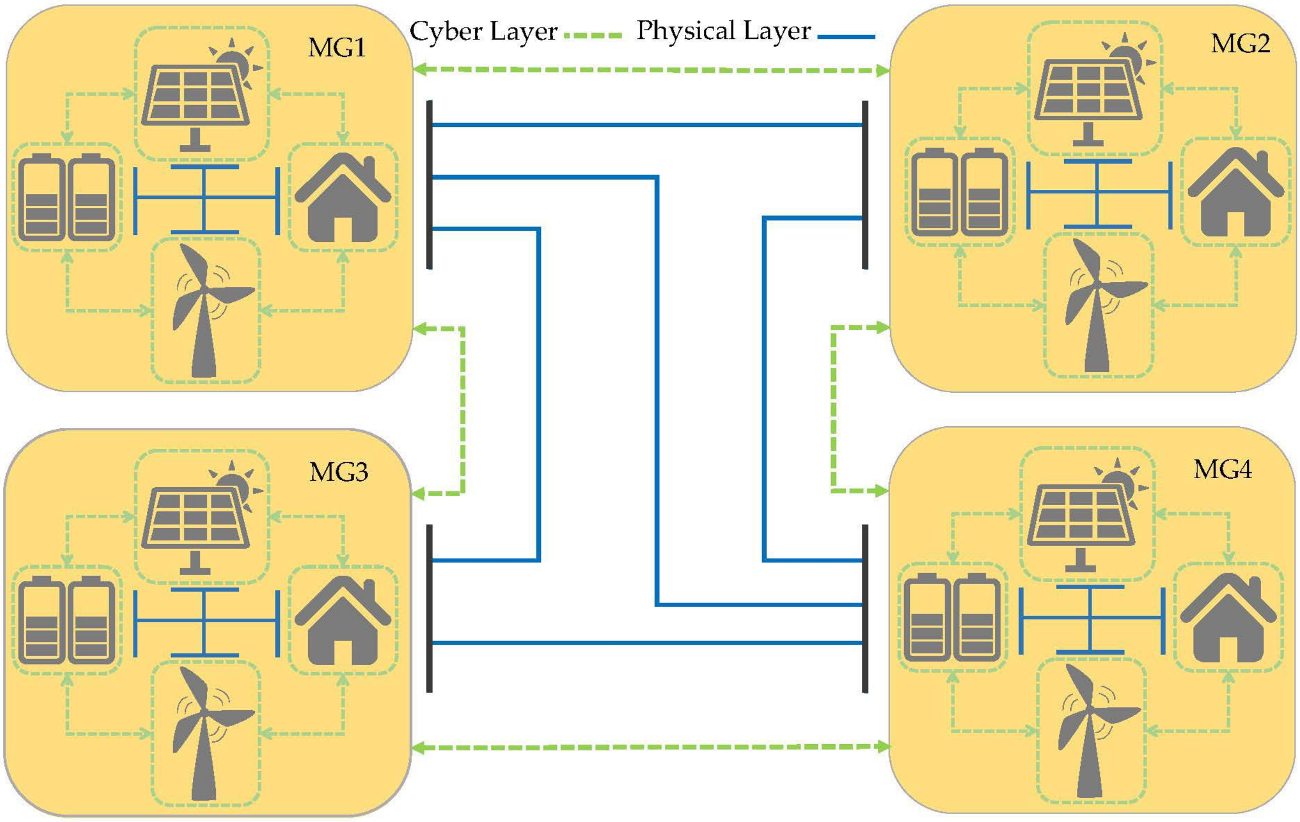

Figure 1. The configuration of the MG Cluster.

3. Data Exchange Mechanisms in DC Microgrids

Data exchange among generation units or microgrids in DC microgrids and clusters is essential for designing an optimal control mechanism that can achieve the primary control objectives of DC microgrids, including accurate current sharing, optimal voltage regulation, and reduced communication burden. The data exchange mechanisms discussed in this article can be organised into two categories: time-triggered mechanisms (TTMs), which rely on periodic sampling and transmission regardless of the network state, and event-triggered mechanisms (ETMs), which transmit data only when the predefined triggering condition is met, potentially enhancing communication efficiency. Time-triggered mechanisms (TTMs) can also be classified into three categories: infinite-time, finite-time, and fixed-time consensus algorithms. Furthermore, Event-triggered mechanisms (ETMs) can be further classified into subcategories, including static event-triggered mechanisms (SETMs) with constant predefined thresholds; dynamic event-triggered mechanisms (DETMs) with dynamic thresholds based on the network's dynamics; self-triggered mechanisms (STMs), where the next triggering instance is predicted based on the current state of the network; and edge-based event-triggered mechanisms (EETMs), where the trigger occurs on each communication edge instead of on nodes. The hierarchy of classifications, communication aspects, and typical applications of these mechanisms is provided in the table.

3.1. Time-Triggered Consensus Algorithms

Consensus-based control approaches are employed to achieve coordination among diverse units, such as Distributed Generation (DG) units in DC microgrids, in a distributed manner, without the need for a central controller [40]. Data exchange occurs between each DG unit and its adjacent units to reach consensus on the MG's significant parameters, including voltage and current, especially in standalone DC networks [9]. These algorithms can converge within three distinct time boundaries: infinite-time [9], finite-time [46], and fixed-time [47], as illustrated in Figure 2. They have been adopted in many studies in the literature to ensure a consensus among either generation units or microgrids in systems such as those in [5,9,11,37,46,48–57]. However, it is noted that existing time-consensus schemes adopted in DC microgrids rely heavily on time-scheduled periodic sampling, in which network measurements are gathered at fixed intervals to update microgrid controllers synchronously, leading to overutilization of communication networks [15,18,58]. It is evident that the need for controller updates and continuous interaction among microgrids might be infeasible for practical applications, as such requirements may require a massive amount of unnecessary computing and communication resources [14,59,60]. This extensive data exchange can strain the network's resources, thereby degrading network performance [31]. Additionally, time-scheduled periodic sampling limits networks' responsiveness to dynamic operating changes in the system, resulting in a slow response to faults or disturbances [18]. Although these control schemes are easy to implement in DC microgrids, they have notable drawbacks that hinder efficiency and scalability, particularly in industrial environments, due to limited communication bandwidth [57]. Therefore, it is necessary to reduce communication traffic in microgrids to enhance scalability and maintain reliable operation of such grids under constrained network resources [24]. This reduction in the frequency of updating the networks' controllers may prolong the lifespan of actuators in microgrids by preventing redundant control actions [39,61,62].

As compared with the previous challenges, network congestion, time-varying communication delays, and data packet loss caused by frequent periodic communication among microgrids seem to be the most critical issues that need to be tackled, as they can reduce system reliability [15,63,64]. Furthermore, Control schemes that depend on permanent communication networks to coordinate data exchange among microgrids are highly impacted by cyber delays, potentially leading to higher settling time and disrupting the performance of the control systems [65]. It is found that as the number of DGUs increases, communication needs grow significantly, leading to possible congestion and data packet losses, making such control schemes ineffective for large-scale networks [32,66–68]. It is noted that real-time control systems may exacerbate this issue, as they require high-bandwidth networks, which may be unachievable in such environments. Additionally, their constant communication intervals may create predictable communication patterns, making them more vulnerable to cyberattacks. The fragility of such control schemes, due to the need for continuous communication networks and high computational demands, underscores the need to develop more efficient control schemes that can meet the requirements of complex power grids.

3.2. Event-Triggered Control Schemes for DC Microgrids

Event-triggered control schemes have recently attracted significant interest in DC microgrids, as they can avoid redundant control updates [69] and maintain network performance [70]. In such control schemes, each agent in the network is equipped with an event detector to gather local data and update its control inputs in coordination with adjacent agents. The agent, which implies DG or MG in the field of DC microgrids, transmits the required data to its neighbours once the triggering condition is met [71]. As opposed to the time-triggered control mechanisms, initiating control actions once specific conditions are fulfilled [44] successfully reduces the communication burden in a system [72,73], and this, in turn, sustains bandwidth and decreases needless data exchange among units in the network [45,74]. The features of these control schemes have been exploited to improve the performance of AC Microgrids (ACMGs), including frequency and voltage control [75–77], demand response [78], economic dispatch [79], and reactive power control [80]. Furthermore, the virtues of ETM approaches, particularly in terms of communication costs and computational savings, have inspired many researchers to adopt them in DCMGs. In the following subsections, various event-triggered mechanisms (ETMs), detailed in Figure 3, are discussed, including their merits and demerits.

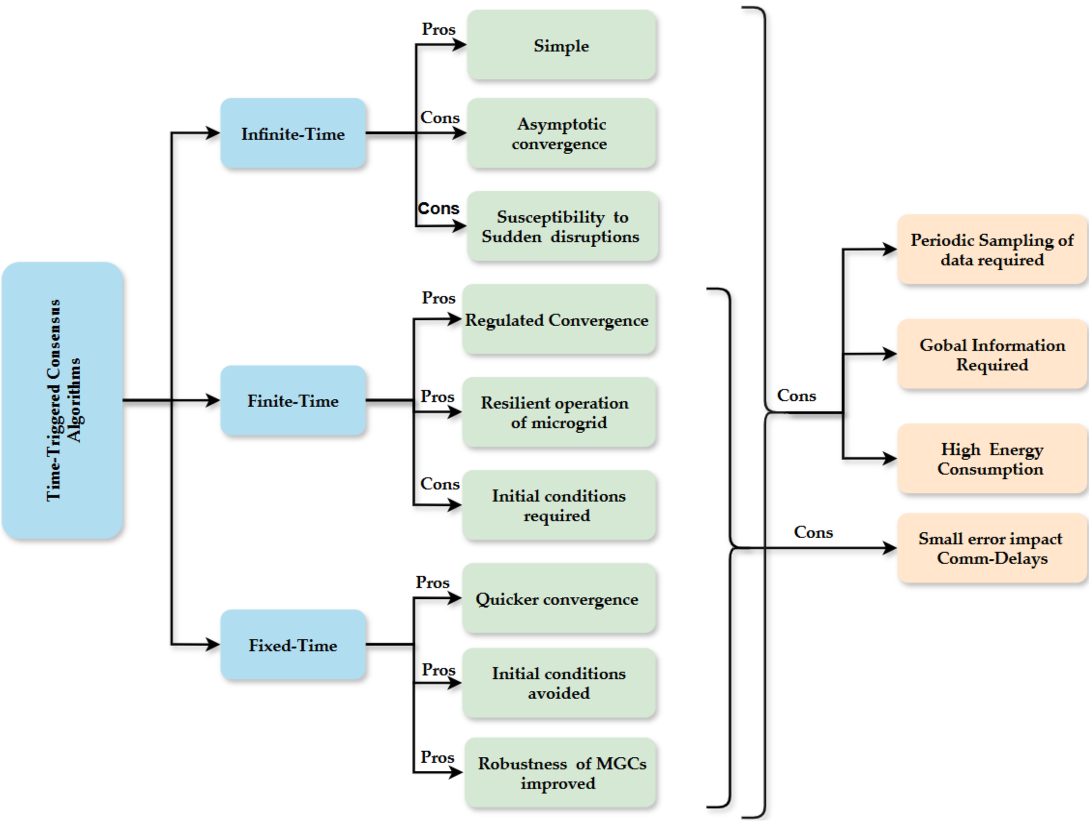

Figure 2. Time-Triggered Consensus Algorithm [81].

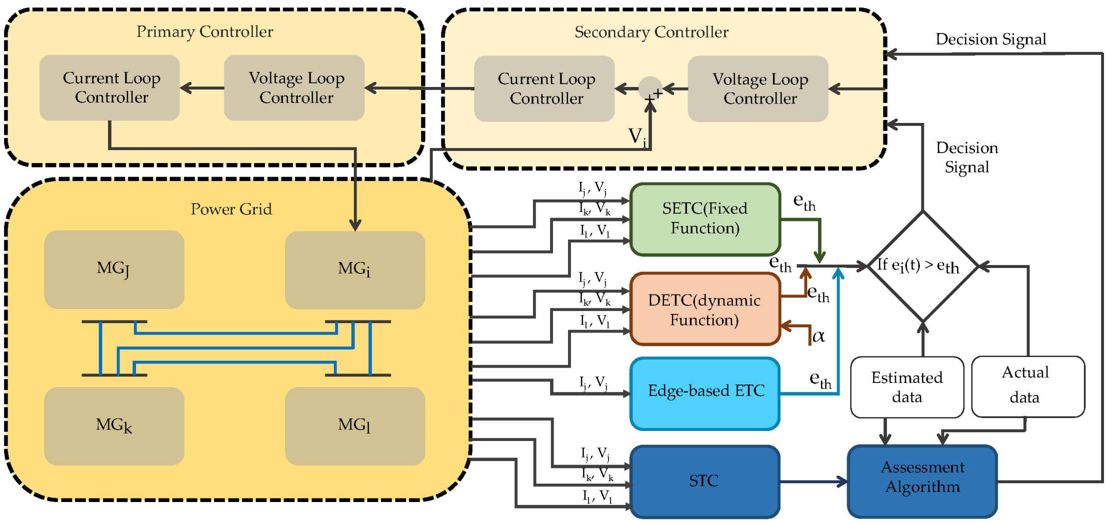

Figure 3. Event-Triggering Control Schemes in DC Microgrids.

3.2.1. Static Event-Triggered Control Mechanisms (SETMs)

SETMs have been adopted in the literature to enhance communication and computation for control schemes in DC microgrids. In contrast to periodic sampling schemes, which update at a constant interval regardless of network needs, SETMs update only when specific conditions are met, thereby avoiding redundant computation and communication overhead in networks [82]. These control schemes employ simplified, static event-triggering rules, such as state-dependent triggers that occur when a state (voltage or current) deviates, and time-dependent triggers that occur when a specified time has elapsed since the previous update [83]. SETMs have been adopted in the literature to exploit their benefits in reducing data exchange among microgrids, thereby decreasing the communication burden, particularly in large-scale microgrids. In this respect, a novel adaptive event-triggered communication (AETC) is introduced in [84] to enhance the secondary control layer in DC microgrids. It alleviates communication stress by reducing excessive data communication without compromising proportional current sharing and average voltage regulation in the network. However, this article notes that centralised average-voltage regulation detectors are required, which may pose challenges in multi-agent networks. To address this issue, a distributed event-triggered control scheme is proposed in [15] to achieve accurate proportional load current sharing, improve average voltage regulation, and reduce communication congestion. This control scheme reduces network communication requirements through event-triggered control and a distributed voltage observer, eliminating the need for the centralised control scheme employed in [84]. Nevertheless, the proposed scheme in [15] has not been examined with the uncertainty of the renewable energy sources (RESs); thus, the system's resilience to load changes and solar radiation fluctuations is not proven, which may cause complexities in communication channels, leading to the transmission of unnecessary data among microgrids. Furthermore, the performance of the adopted microgrid in [15] appears to be influenced by communication delays, potentially degrading its stability. It is also found that both current and voltage data need to be exchanged in the studies mentioned above, which further complicates the implementation of the proposed control schemes. This issue is partially addressed in [15,17]. Additionally, high communication delays are not accounted for, thereby making the DC microgrid more susceptible to the challenges of practical networks. It is noted that the SETMs adopted in [15,18,84] exhibit less adaptability to dynamic operating conditions, thereby compromising flexibility and efficiency. Additionally, continuous monitoring of their event-triggered control conditions may impose an additional computational burden, thereby increasing resource consumption. Furthermore, the Distributed Periodic Event-Triggering (PET) strategy is proposed in [64] to achieve improved voltage regulation and accurate load current sharing in DC microgrids, with a low communication burden and without the Zeno phenomenon. However, it is challenged by a trade-off between convergence speed and communication frequency: smaller control gains can improve convergence, but the system's communication requirements increase. Consequently, accurately tuning control parameters is crucial, as imprecise settings can significantly degrade control performance. The commutativity assumption for both electrical and communication network Laplacian matrices is another challenge, as in [15], reducing adaptability to different network topologies. The robustness of this control scheme to high communication delays remains unaddressed, potentially leading to performance uncertainties in real-world network conditions. Moreover, a novel event-triggered signal-based secondary control scheme is proposed in [85] to enhance current sharing and DC bus voltage regulation while reducing communication overload among converters in a DC microgrid. In this study, a local decision-making strategy is adopted to facilitate transmissions to converters in the microgrid, which is deemed a viable solution to the problem [84]. However, the system's performance is sensitive to the event-triggering threshold; thus, an inappropriate selection of these parameters can degrade voltage stability, current sharing accuracy, and communication frequency in the microgrid. Also, the proposed control scheme is less effective under high communication delays, which can destabilise the system. It has been found that the importance of the amount of data packets in event-triggered consensus schemes has not been considered in previous studies. This issue has been addressed in [59] by adopting quantised signal exchange, thereby ensuring accurate current sharing and reduced voltage restoration, while also significantly decreasing communication overhead without compromising the stability and performance of DC microgrids. It is observed that an unsuitable selection of quantisation levels and control parameters for the event-triggered condition may lead to current-sharing failure under dynamic loads, thereby impacting communication and system stability. Moreover, an increase in communication delay progressively lessens current sharing accuracy and voltage restoration. It is noted that constant monitoring of the event-triggering conditions in [15,24,85] results in significant implementation complexity and a substantial computational burden for event detection and evaluation. This issue has been addressed in [86], which proposes an event-triggered distributed control approach to achieve appropriate power sharing and reduced voltage restoration in DC microgrids, with low communication overhead, using discrete sampled voltage values. In this study, continuous-time signalling is replaced by aperiodic voltage feedback, thereby reducing the communication burden. Nonetheless, it is susceptible to communication delays, resulting in oscillation and slower voltage recovery. Furthermore, adjusting the control parameters is complicated, as triggering levels must be optimally selected to prevent instability. Although prior studies have improved the performance of ETM schemes, they assume flawless communication conditions with no data packet losses, which may not be realistic in real-world scenarios. Due to data packet losses, which degrade performance and cause system instability, studies in [87,88] explore alternative control schemes to mitigate their impact on the microgrid's stability. However, studies [87,88] have ignored the communication burden effect and random packet losses, which have been successfully addressed in [89]. Another observation from prior studies is that PI controllers have been adopted, making the network highly sensitive to disturbances. Additionally, each microgrid is assumed to have ideal sources. Consequently, studies in [30,90,91] partially address some of these issues. The main objectives of the control scheme in [90] are to stabilise the microgrid's voltage, suppress uncertainties, and boost the rejection of disturbances while maintaining a lower communication frequency. However, the influence of communication delay is not considered in this study. It is also noted in [90] that the triggering condition is less adaptable to system changes, limiting communication when needed under extreme conditions and causing over-communication in a steady state, thereby reducing its effectiveness [92]. Furthermore, ref. [91] presents an event-triggered distributed control strategy for DC microgrids to enhance reliability and communication efficiency via fuzzy-logic-based power-flow optimisation. It effectively reduces communication overload and ensures efficient power sharing and voltage regulation. However, it is vulnerable to changes in the event-triggered threshold control parameters, which could reduce communication efficiency and, in turn, lead to grid instability. Additionally, it is not examined for data packet loss or cyber-attacks, which are possible causes of system instability. To enhance the realism of DC microgrids, an event-triggered distributed sliding mode control (SMC) approach is proposed in [30] for DC microgrids powered by imperfect voltage sources. The primary objectives of this study are to achieve voltage regulation and power sharing, and to reduce communication frequency with imperfect voltage sources. However, the proposed control scheme in [30] does not consider cyber threats in the microgrid. It is evident that SETCs still have technical issues that can reduce their effectiveness in DC microgrids, so further investigation may be required to address them.

3.2.2. Dynamic Event-Triggered Control Mechanism (DETM)

DETMs have been shown to tackle several of the identified issues in SETM schemes. These control schemes employ adaptive dynamic thresholds that adjust according to the system's state error [20]. Therefore, they are expected to conserve more communication resources by dynamically adjusting their threshold parameters to limit excessive

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triggering, minimise communication and computational burdens, and preserve the microgrid's stability [93]. Moreover, they can guarantee a positive minimum interevent time and decrease the likelihood of Zeno behaviour in the network under proper design conditions [17,94]. DETMs can achieve lower triggering frequencies and enhanced resource utilisation and have been shown to be more effective alternatives to the static event-triggered control schemes adopted in DC microgrids [22], as shown in Figure 4 and Table 1. This control approach has been adopted in DC microgrids to tackle operational issues, including current sharing, voltage regulation, fault tolerance, and communication efficiency, as stated in [17,20–23,25,88,94–100]. The current developments in distributed energy management have reawakened interest in adopting DETM in DCMGs, given its merits in reducing communication overhead without compromising robust operation. For example, a distributed, dynamic event-triggered consensus algorithm for power buffer control in DC microgrids is introduced in [94] to reduce computation and communication burdens without compromising cluster stability and eliminating Zeno behaviour. In this study, local information is utilised to reduce dependence on global cluster information, in contrast to the control scheme in [84]. However, with higher communication delays, convergence is slower and less effective, potentially affecting network responsiveness in real-world applications. Moreover, the event-triggered scheme adopted in this study requires precise adjustment of the triggering condition's control parameters, making network design more challenging. In comparison to SETMs in [19,59,64,84–86], DETMs in [17,93,94] have been designed to adopt both the system information and dynamic internal variables, consequently allowing triggering control mechanisms to adjust dynamically, which contributes to enhancing the communication efficiency. Although this additional dynamism improves flexibility while decreasing unnecessary communication, it introduces greater complexity in both design and implementation. Also, Internal variables and adjustable control thresholds in DETM schemes normally require appropriate parameter selection to ensure stability and proper system performance. This may make implementing the control scheme more challenging, potentially rendering the network less suitable for environments with uncertain operating conditions.

It is evident that the prior research does not consider cyberattacks; thus, a dynamic event-triggered fuzzy control scheme is proposed in [22] to investigate false data injection (FDI) attacks, imperfect premise matching, and network delays in DC microgrids. The control parameters for the event-triggered condition are adjusted to preserve communication resources while maintaining system stability under operating conditions. Similarly, the control scheme in [20] addresses issues such as false data injection attacks and network delays, thereby enhancing the performance of the DC microgrid. In this study, communication bandwidth is optimised using adaptive event-triggering conditions while ensuring stability under uncertainties. Although the proposed control scheme in [20] enhances the utilisation of the network's resources and resilience, higher computational complexity has been added due to reliance on internal control variables.

The above-mentioned studies do not account for input and output saturation, which could be influential in practical deployments. Consequently, the authors in [25] introduce a distributed event-triggered consensus algorithm that accounts for input saturation and time-delay constraints, aiming to achieve fast voltage restoration and appropriate current sharing in DC microgrids while minimising communication load. Nonetheless, the control scheme also reveals a trade-off between convergence speed and communication frequency. While the control scheme can decrease data exchange among microgrids, it may also lower the microgrid's responsiveness. Additionally, fault-tolerant functions have not been adopted to address potential failures in communication links or cyberattacks, which may pose significant risks in DC microgrids. This issue has been addressed in [101]. Additionally,

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this study assumes ideal communication networks, overlooking realistic conditions such as data packet losses and cyberattacks that may compromise network performance.

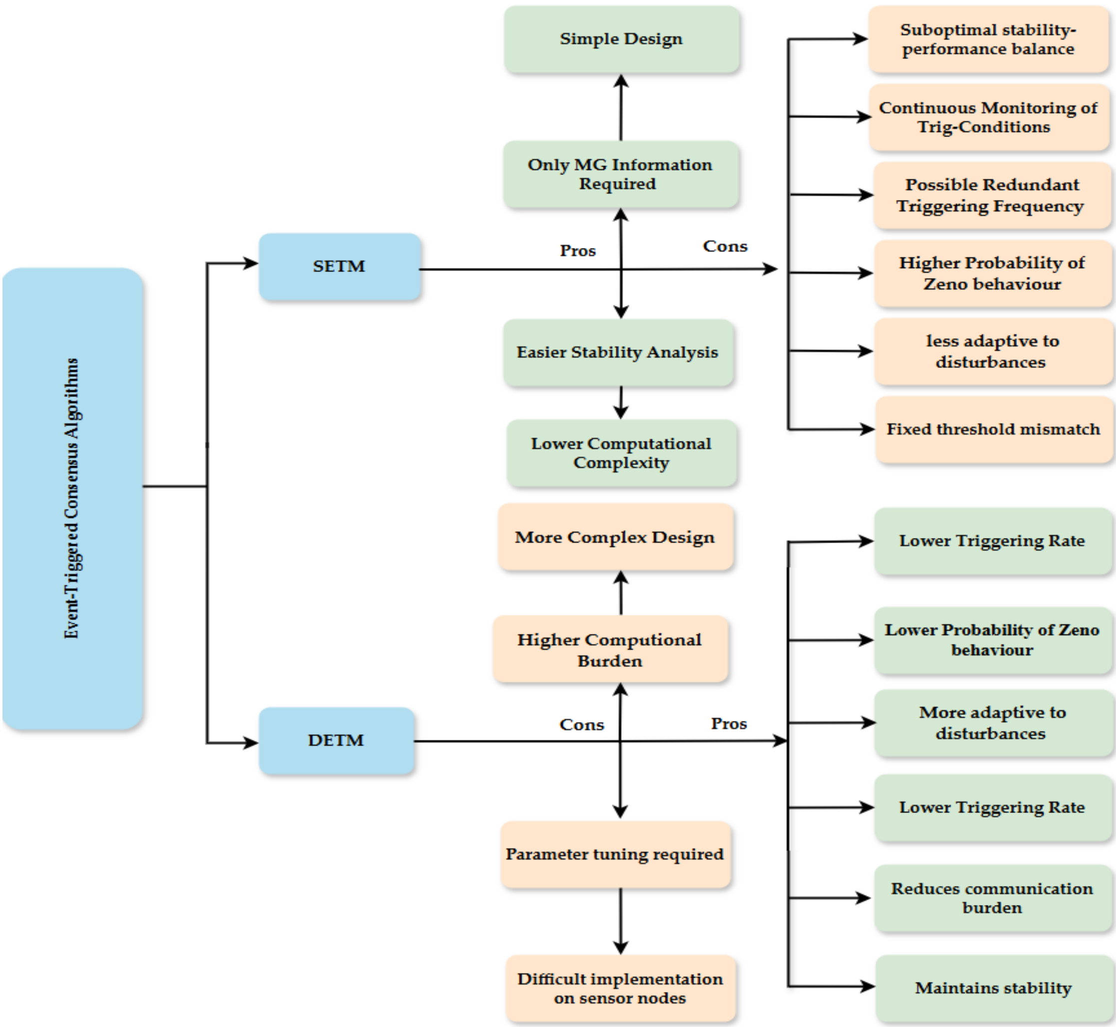

Figure 4. Comparison of SETMs and DETMs Schemes.

It is obvious that the control schemes in studies [17,20,22,95,96,102] largely exclude data packet loss, which could result in instability and degraded network performance [87]. Consequently, an event-triggered Mechanism is introduced in [88] to address data packet losses and transmission delays, thereby stabilising the microgrid. It can guarantee a designable positive minimum inter-event time (MIET), restricting unnecessary data exchange and the Zeno behaviour. However, a loss of functionality can occur at communication delays exceeding the MIET, potentially compromising the microgrid's stability. This study primarily focuses on communication issues under ideal conditions, excluding random network malfunctions. Therefore, the study in [89] considers random packet loss in the data exchange network. Based on analysing previous studies, it is observed that although the proposed control approaches hold significant potential to improve DC microgrid communication efficiency, they struggle to balance restricting unnecessary data exchange among microgrids with maintaining dynamic control responsiveness. They also need proper tuning of control parameters, specifically the event-triggering threshold, as an unsuitable selection could lead to excessive triggering or delay, thereby affecting the system's efficiency. Furthermore, most of those studies overlook the effective maintenance of communication, delays, data packet loss, and security problems, which are deemed important for improving the robustness of DC microgrids under real-time operating conditions. Additional efforts may be needed to design delay-tolerant, cyber-secure, and resource-efficient DETMs. Also, properly tuned parameters for machine learning algorithms, as first introduced in [42], might be required. Additionally, it is important to incorporate the nonlinear dynamics of renewable-based microgrids into future studies.

3.2.3. Self-Triggered Control Mechanism (STM)

This control scheme is also a distributed approach adopted in DC networks to achieve coordinated operations, such as voltage regulation and current sharing, without requiring constant communication. It is worth noting that the self-triggered control mechanism (STM) can address issues in optimal control [103]. In this scheme, the next triggering time is calculated using the network state and the current time [85]. In this regard, controllers and sensors in the system can sample data and then update when the network reaches the next triggering time [103,104]. Therefore, STM can mitigate the high communication and computational burden associated with the constant sampling of network sensors and continuous monitoring of triggering conditions in ETM schemes [26,105]. In ETM schemes, a dedicated device is required for continuous detection, which may limit their applicability in some realistic scenarios; hence, STM is introduced to address this issue [106]. However, the STM schemes are technically complex and are vulnerable to robustness issues in some uncertain systems, such as microgrids [27,107]. This control scheme has been adopted in numerous studies, including [87,103,106,108]. For example, a dynamic STM mechanism is proposed in [108] to improve voltage regulation and load current sharing, and to reduce communication and computation burdens in DC microgrids. Contrasting the ETM schemes adopted in [15,18,19,31,85], which regularly monitor network states, the proposed control scheme in [108] can estimate the next triggering time from the available network information, thus decreasing unnecessary data exchange and enhancing efficiency. Nevertheless, it is vulnerable to control parameter tuning under event-triggered conditions, as inappropriate adjustments to these parameters can lead to unnecessary triggering. It is also challenged by a marginally increased implementation complexity due to the trigger-time correction mechanism, which enhances the network's responsiveness but incurs a greater computational burden. Furthermore, no cybersecurity measures are implemented in [108], leaving the network susceptible to data packet losses and cyberattacks, which are common in real-world scenarios. Moreover, a dynamic, self-triggered adaptive control scheme is proposed in [106] to enhance voltage regulation while reducing communication and computation burdens. However, the control scheme is designed as a nonzero-sum game and an adaptive dynamic programming approach with critic neural networks to estimate optimal control approaches, which may increase its complexity. In addition, renewable energy sources are not addressed, which may leave the robustness of the control scheme under such intermittent power variations unproven. Additionally, this study does not consider time-varying delays, which can impact its applicability in real-world scenarios, as delays and network data loss can compromise its stability [100]. To address these challenges, a new discrete-time self-triggered distributed control strategy is introduced in [87] to overcome difficulties associated with data dropouts, time-varying delays in DC microgrids, and reduced communication traffic through proactive update scheduling. However, it also faces some issues and constraints that would be encountered in its implementation. The calculation of self-triggering time, which determines the maximum number of control updates, requires complex computations influenced by network behaviour and previous measurements [109] and consequently increases the complexity of the control process. It is sensitive to minor errors, which can initiate Zeno behaviour in the system; however, this issue has been addressed in [103]. The proposed control approach can maintain network stability and mitigate Zeno behaviour, resulting in an optimally adjustable minimum triggering time. STM and ETM suffer from efficiency limitations: the ETM scheme requires constant monitoring, while the ST scheme necessitates excessive conservatism, leading to unnecessary data exchange in the network [26], as illustrated in Figure 5. To tackle such issues, a hybrid STM-ETM control scheme is proposed in [26] to integrate ETM's communication capabilities with STM's sampling and computation capabilities, aiming for a low triggering frequency, fast voltage recovery, and proportional current sharing. However, this control scheme may not handle voltage and current ripples, leading to unnecessary data exchange in DC microgrids. Moreover, unexpected delays could result in reduced network functionality, leading to high oscillations [15,17]. The risk of instability from aggressive parameter tuning is another challenge that can destabilise the system; therefore, proper selection of these control parameters is important for maintaining the system's stability.

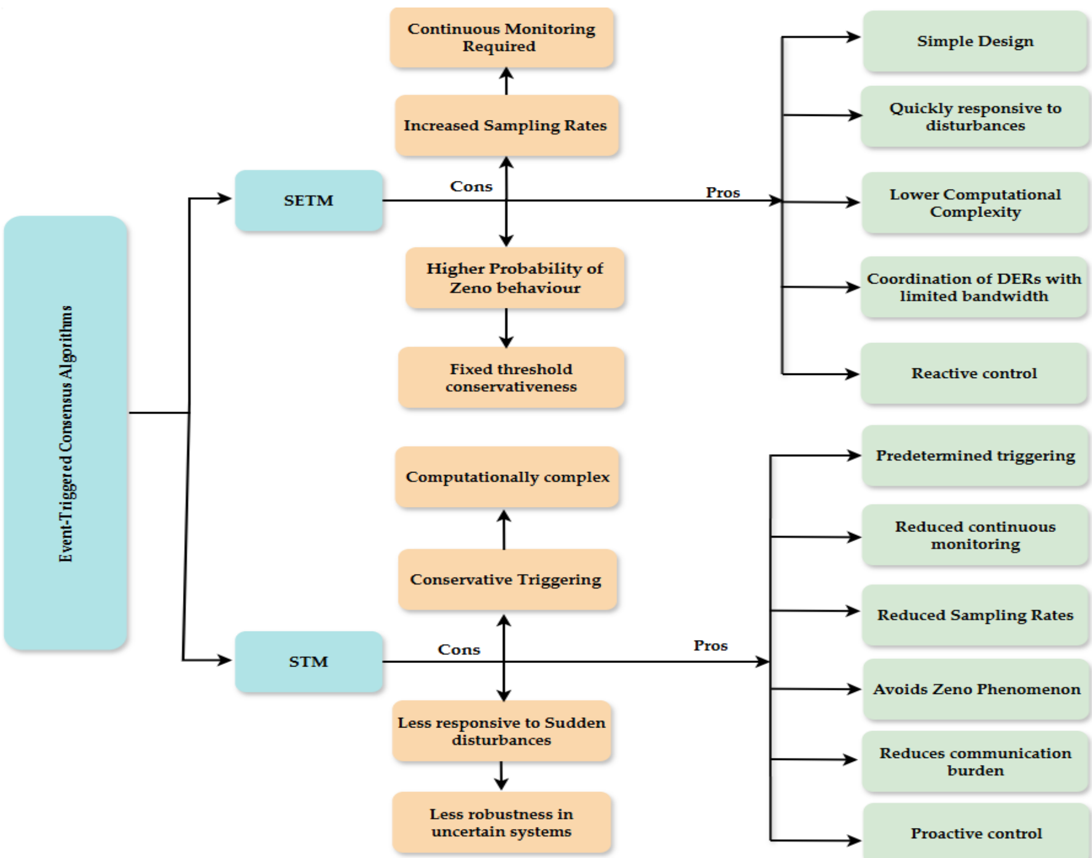

Figure 5. Comparison of STM and ETM Control Schemes.

3.2.4. Edge-Based Event-Triggered Control Mechanism (EETM)

This control scheme has been adopted in a wide range of multi-agent system (MAS) applications, as shown in [95,110–112], including coordinated tracking and heterogeneous agent regulation. It is found that ETM schemes adopted in prior studies are categorised as node-based strategies, as they depend on event triggering using absolute state measurements from each agent in the system. Therefore, the network's agents must continuously monitor and transmit their terminal states to all neighbouring agents whenever an event is activated, which may impose an additional computational burden. Conversely, EETM schemes, which are classified as point-to-point triggering control strategies [95,113] because they use relative differences in neighbour agents' states, which are linked via communication networks [114], are proposed in the literature to address the issues of node-based ETM schemes. In that case, events are triggered directly on communicative edges without involving the state data of all neighbours, as shown in Table 1. In other words, they maintain communication between only two interconnected agents when their shared edge condition is satisfied [111], thus substantially reducing the data exchange rate. Such a control mechanism is characterised by avoiding global transmission requirements and reducing communicable overhead [95]. Consequently, it is instrumental in applications where absolute measurements of agents are not accessible [115]. As communicable needs decrease, it can be perfectly adapted to systems with bandwidth constraints [116]. The inherent asynchrony of edge-based ETM further enhances adaptability in dynamic environments, making it suitable for scalable, distributed control schemes. Thus, considering their characteristics, EETMs have become a viable option for applications rather than conventional multi-agent systems (MASs). Thus, this control scheme has recently been adopted in DC microgrids, marking a new direction in this field. In this regard, a fully distributed edge-event-triggered control approach is adopted in [95] for multi-bus DC microgrids. It enhances current-sharing accuracy while reducing the need for communication and reliance on centralised network data. Nevertheless, significant computational complexity arises from the use of internal dynamic variables in the event-triggered control condition. Although data exchange among microgrids is alleviated by adopting an EETM scheme, the processing demand on microgrid controllers increases. Additionally, the proposed control scheme in [95] does not sufficiently mitigate the adverse effects of communication delay, which may negatively affect the system's accuracy and stability in practical applications. Moreover, a distributed edge-based control scheme is proposed in [117] to mitigate denial-of-service (DoS) attacks on DC microgrids, ensuring lower voltage deviation and accurate load sharing while reducing communication overhead. However, the performance of this control scheme appears to degrade with high communication delays. Although the likelihood of Zeno behaviour can be reduced by properly selecting the time constant, adopting a static threshold may compromise the system's adaptability to variable network conditions. Furthermore, an edge-event-based distributed model-free adaptive control (MFAC) scheme is proposed in [118] to tackle multi-pattern deception attacks in a DC microgrid. This control scheme realises proper voltage regulation and proportional current sharing by mitigating the effects of malicious signals via a data-driven predictive algorithm. However, the use of pseudo-partial-derivative dynamics, along with a predictive compensation strategy, may make the entire system complex to design and tune. Although an adjustable edge-triggered threshold in the proposed control scheme can significantly reduce communication in a DC microgrid, adopting a model-free estimation approach may complicate parameter tuning in practical deployments, as MFAC is sensitive to network initial conditions and the selection of control parameters [119]. Also, the control scheme focuses solely on deception attacks and does not address communication delays, which can adversely impact the network's responsiveness and stability in real-world applications. Although this edge-based event-triggered mechanism (EETM) offers promising features, its adoption in DC microgrids remains at an early exploratory stage, with only a small number of studies conducted, as shown in [95,117,118]. Therefore, by focusing on the key features of this control scheme and addressing its primary challenges, the performance of DC microgrids can be enhanced in future studies.

To facilitate a structured comparison of ETM schemes discussed in the previous subsections, Table 1 summarises their main features, while Table 2 summarises their mathematical triggering conditions. These tables may facilitate researchers in this field in quickly identifying the appropriate mechanism for DC microgrid applications, exposing the underlying design trade-offs across control schemes, revealing the main gaps in the existing literature, and providing the mathematical modelling required to develop robust ETMs in future research.

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Table 1. Presents the summary of the features of control mechanisms of DC MGs.

Feature	SETM	DETM	ST	EETM
Triggering Rule	■ State-time-dependent rule with a constant threshold.	■ A state-error-dependent rule with an adaptive threshold	■ Predictive scheduling of the next triggering instant from the current state and time	■ Edge-decoupled triggering on relative neighbour state differences
Threshold	■ Static	■ Dynamic	■ Prediction-based	■ Dynamic/Static
Communication Topology	■ Node-based	■ Node-based	■ Node-based	■ Edge-based
Computational complexity	✓ Lower computational complexity due to fixed control parameters	× Higher computational complexity due to internal dynamic variables	× Increased implementation complexity due to trigger time correction	× Increased computational complexity due to extra trigger variables in the triggering conditions.
Zeno Behaviour probability	× Higher due to fixed thresholds	✓ Lower probability due to positive MIET	× Susceptible to minor error induced Zeno; mitigated in discrete ST schemes	✓ Reduced by properly selected time constants in fixed threshold schemes.
Communication efficiency	✓ Lower triggering frequency than TTC; ✓ Trade-off with convergence speed	✓ Lower triggering frequency ✓ Improved resource utilisation relative to SETM	× Inter-event conservatism yields unnecessary data transmissions versus ETM	✓ Substantially reduced data exchange frequency
Key strengths	✓ Simple design ✓ High responsiveness to network disturbances ✓ tractable Lyapunov-based stability analysis.	✓ Adaptive responsiveness to disturbances ✓ Supports stable operation. ✓ Reduces communication burden ✓ Enhances network resilience	✓ No continuous monitoring of the triggering conditions ✓ Predictive scheduling with reduced sampling rates. ✓ Proactive control scheme	✓ Point-to-point data transmission. ✓ Does not require global network information ✓ Adaptable to bandwidth-constrained networks ✓ Naturally asynchronous and scalable control scheme.

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Table 1. *Cont.*

Feature	SETM	DETM	ST	EETM
Main limitations	× Limited adaptability to dynamic operating conditions × Continuous monitoring of the triggering conditions × Possible redundant triggering frequency	× Implementation challenges on resource-constrained sensor nodes. × Parameter-tuning complexity, especially in uncertain operating conditions.	× Algorithmic complexity × Limited robustness in uncertain networks × Less responsive to abrupt disturbances	× High computational burden × Limited adoption in DC microgrids

Table 2. Presents the summary of the mathematical triggering condition for each Mechanism.

Mechanism	Triggering Condition	Local Error Term	Desing Parameters	Triggering Instants
SETM [15]	$e(t)^2 \geq \sigma K_I\left(\frac{\lambda_{Qmin}-\varepsilon_1 L_e(i,i)}{(\frac{K_I}{\varepsilon_1}+\frac{K_V}{\varepsilon_2})L_e(i,i)}\right)\hat{u}_i^2+\sigma K_V\left(\frac{\lambda_{Qmin}-\varepsilon_2 L_e(i,i)}{(\frac{K_I}{\varepsilon_1}+\frac{K_V}{\varepsilon_2})L_e(i,i)}\right)\hat{u}_V^2$	$ei(t)=(\frac{I_i(t_{k+1})}{I_{ci}}-\frac{\hat{I}_i(t_k)}{I_{ci}})$	$(0<\sigma<1)$; $0<\varepsilon_1, \varepsilon_2 < \frac{1}{L_e(i,i)}$; $\lambda_{Qmin} \rightarrow$ Minimum eigenvalue of matrix); $L_e \rightarrow$ Laplacian matrix of electrical networks	$t \in \left(t_k^i, t_{k+1}^i\right)$
STM [87]	$m_l = min\left\{ m_l^i = \left[\sqrt{\frac{\lambda_{Qmin}-2\varepsilon L_e(i,i)}{8c^2\sum_{i=1}^n L_e(i,i)^3/I_{ci}^2} - \frac{L_e(i,i)}{2c^2\sum_{i=1}^n L_e(i,i)^3/I_{ci}^2}\, x\, \frac{e_{Ii}^2}{\hat{u}_i^2[k]}}\right]\right\}$	$ei(t)=(\frac{I_i(t_{k+1})}{I_{ci}}-\frac{\hat{I}_i(t_k)}{I_{ci}})$	$(0<c<c_{max})$; $0<\varepsilon<\frac{\lambda_{Qmin}}{2L_e(i,i)}$	$t \in \left(t_k^i, t_{k+1}^i\right)$
DETM [17]	$n_i(t) = \begin{cases} \dot{n}_i(t)\begin{cases} min\{\overline{\omega}_i(t),0\}-\sigma_i & , \ if\ e_i \neq 0 \\ -\sigma_i & , \ if\ e_i \neq 0 \end{cases} \\ \quad n_i(t^+) = \beta_i\ for\ t = t_k^i \end{cases}$ $t_{k+1}^i = inf\left\{t > t_k^i + \tau_i \middle\| n_i(t) \leq 0\right\}$ By assuming $\overline{\omega}_i(t) \leq 0$ $e_i(t)^2 \geq \frac{k\sigma_i K_I(\lambda_{Qmin}-3kd_i)}{2(K_I+K_V)d_i(1+\eta_i^2(t))} x \left[\sum_{j\in n_i^c} a_{ij}((\frac{\hat{I}_i(t_k)}{I_{ci}}-\frac{\hat{I}_j(t_k)}{I_{cj}})\right]^2 + \frac{k\,\sigma_i K_V\left(\frac{K_V\,\lambda_{Qmin}-2kd_i}{K-K_I}\right)}{(K_I+K_V)d_i(1+\eta_i^2(t))} x(\overline{V}_i-V_n)^2$	$ei(t)=(\frac{I_i(t_{k+1})}{I_{ci}}-\frac{\hat{I}_i(t_k)}{I_{ci}})$	$\alpha i>0,\ \beta i>0,$ $0<\sigma i<1,\ and\ 0<\kappa<k_{max};$	$t \in \left(t_k^i, t_{k+1}^i\right)$
EETM [95]	$t_{k+1}^{ij} = inf\left\{t > t_k^{ij} \| \left(1+\varsigma_{ij}\sigma_{ij}\right)\|Ke_{ij}\|^2 - \frac{1}{4}\|K\left(\hat{\zeta}_{ij}-\hat{\zeta}_{ji}\|\right.^2 - \alpha_{ij}e^{-\beta_{ij}t} - \rho_{ij}\gamma_{ij} \geq 0\right\}$ $\dot{\gamma}_{ij} = \mu_{ij}(\frac{1}{4}\|K\left(\hat{\zeta}_{ij}-\hat{\zeta}_{ji}\right)\|^2 + \alpha_{ij}e^{-\beta_{ij}t} - \left(1+\varsigma_{ij}\sigma_{ij}\right)\|Ke_{ij}\|^2) - v_{ij}\gamma_{ij}$	$e_{ij} = \hat{\zeta}_{ij} - \zeta_i$	$\varsigma_{ij}, \sigma_{ij}, \beta_{ij}, \gamma_{ij}, \mu_{ij}, K\ and\ \alpha_{ij}$	$t \in \left(t_k^{ij}, t_{k+1}^{ij}\right)$

4. Data Transmission Domains in DC Microgrids

Control schemes for DC microgrids have advanced significantly for data transmission in discrete-time (DT) and continuous-time (CT) environments. They, however, still have some differences between these domains, which may affect their performance and practical implementation. Based on the extensive analysis in this regard, it is found that most of the existing studies, such as [15,18,24,25,58,84,85,120], have focused mainly on the continuous-time environment, which may cause considerable implementation issues due to the adopted continuous-time algorithms needing transformation to operate in discrete-time systems effectively, adding more complexity and uncertainty to control schemes [25,87]. It is also found that event-triggered control schemes (ETMs) implemented in continuous-time environments are more susceptible to Zeno behaviour [20,121]. Furthermore, they continually require monitoring of the trigger conditions [32]; accordingly, they place high demands on computation and increase implementation complexity [20,22]. To address these issues, discrete-time control techniques, which feature simple implementation with a fixed sampling rate and prespecified iteration principles, have been proposed in the literature to alleviate the need for continuous event monitoring [122] and increase their applicability in DC microgrids [87]. As opposed to continuous-time ETC schemes, discrete-time ETM schemes inherently prevent Zeno behaviour due to fixed sampling intervals and thus guarantee a positive minimum inter-event time (MIET) [69,87], thereby reducing computation and enabling easier integration with existing digital control systems [123]. Also, such schemes not only significantly reduce computational requirements but also increase system stability, as discussed in [64,71,87]. Furthermore, Discrete-time ETC schemes can be implemented through software adjustments between controllers and sensors. In contrast, continuous-time control schemes can generally be retrofitted only within previously stated networks, with greater complexity and higher execution cost [25,124]. It is clear that the discrete-time ETM schemes have noteworthy advantages, including improved stability through preventing discretisation-induced instabilities, preventing Zeno phenomena, and lessening communication overhead [125]. On the other hand, the main issues in addressing the CT domain of controlling DT systems are the infeasibility of direct digital implementation, instability caused by sampling intervals, and the high computational demands of addressing Zeno behaviour [64,87]. These problems reduce the applicability of CT event-triggered control in real-world digital systems. Therefore, recent studies have adopted a discrete domain to transmit data packets among microgrids, as shown in [20,22,39,62,64,69,71,72,83,86,87,122,125–130]. All of that research confirms the practical superiority of the discrete-time ETC schemes in DC microgrids.

5. Main Challenges in Communication-Based Algorithms

The performance of DC microgrids relies on the effectiveness of converter control [7], which combines power electronic converters with information and communication technologies. In this regard, hierarchical control schemes are normally utilised to coordinate microgrid converters [131]. Such control strategies face challenges related to the communication network, which may impact the stability and reliability of the DC microgrid. Cyber-attacks, including False Data Injection Attacks and Denial-of-Service attacks, are considered one of the chief challenges that might destabilise microgrids or misinform controllers [128,132]. False Data Injection Attacks (FDIAs), which are classified as the most common network attack [133] they attempt to inject false data into the system to destabilise or shut it down. It is noted that permanent or intermittent injection may desynchronize DG frequencies, leading to instability [134]. Another major cyber-attack is Denial-of-Service (DoS), which can cause data congestion in communication networks by sending vast quantities of false data packets through them [135] and, accordingly, disrupt the system [136]. It is found that ETM schemes are vulnerable to failure under DoS conditions because blocked data in communication channels prevent timely controller updates, leading to system instability and impairing their performance [109]. Therefore, cybersecurity strategies are a significant factor to consider when designing ETM schemes for DC microgrids.

Zeno behaviour is the irregular occurrence of an infinite number of events within a limited time interval [25]. This issue arises in many ETM schemes [15,17,18,45,58] due to adjustments in the system's structure or parameters. It is found that Continuous-time ETC schemes are more susceptible to Zeno behaviour [137], as they often fail to guarantee a positive minimum inter-event time [20], which needs continuous real-time monitoring [20,138] and thus compromises practicality and reliability [20,138]. Moreover, controllers can inadvertently create an infinite rate of event occurrences through parameter adjustments, so most existing ETM schemes do not systematically handle Zeno behaviour [18,24]. DETM schemes have been introduced in the literature to address this challenge by utilising internal dynamic variables to ensure a positive minimum inter-event time, thereby reducing triggering frequency and enhancing resource efficiency [20]. The possibility of Zeno behaviour is also tackled by discrete-time strategies. Discrete-time ETM schemes demonstrate robustness against Zeno behaviour, since triggering events are constrained by the sampling time [64,71,87]. It is also obvious that self-triggered control [87] and the PET algorithms in [125] can prevent Zeno behaviour at the cost of increased communication frequency or slower convergence rates. It is obvious that the Coordination of Microgrids within a cluster may also be vulnerable to data packet losses, since secure communication networks are critical for data exchange between DGUs [139]. It is important to note that data Packet losses due to network congestion, signal interference, data transmission errors, or hardware limitations [140] can compromise the accuracy of shared data, leading to control mismatches and performance degradation [141]. Another change is that Actuator faults in DC microgrids can arise from hardware or software damage to sensors and actuators [142]. As actuators execute control actions based on sensor information, faults in energy storage devices [143], device ageing, cyberattacks, and environmental variations can occur [142,144]. These faults can impact voltage stability and power regulation, thereby degrading system performance [145]. In this regard, event-triggered control schemes can support fault compensation by executing the control action only when deviations exceed a threshold, thereby reducing communication load while maintaining voltage regulation and power sharing [145]. It is evident that there is limited research on addressing actuator faults in DC microgrids, with few studies, such as [125,145,146], focusing on this issue. This underscores the need for robust control designs and evaluation criteria that explicitly account for actuator-fault conditions.

To provide readers with a clear understanding of the main issues in the adopted control schemes in the literature, a summary of relevant articles is included in Table 3. This table discusses the advantages and disadvantages, which may enable researchers in this field to more intensively address these issues and design holistic control approaches for DC microgrids in future studies.

Based on previous discussions of event-triggering mechanisms, several technical issues that may affect their effectiveness in DC microgrids have been identified. To facilitate researchers' analysis of the effectiveness of existing control schemes in addressing such technical problems, an evaluation framework based on ten factors is illustrated in Figure 6. These factors take into consideration communication reliability issues, including links, packet loss, and latency; triggering scheme issues, such as controller parameters and Zeno behaviour; practicality aspects, including voltage sources and renewable energy sources; and resilience issues, including actuator faults, cyber-attacks, and fault tolerance.

Table 3. Presents the summary of the relevant articles with respect to ETMs of DC MGs.

Ref.	Control Approach	Merits	Demerits
[100]	Distributed cooperative control scheme	1. It boosts voltage regulation and current sharing. 2. It suppresses demands for communication.	1. It greatly relies on selecting the control parameters in event-triggering thresholds. 2. It does not have a delay compensation mechanism, making the system susceptible to high-delay networks. 3. Its cybersecurity robustness is untested. 4. Zeno's behaviour is not studied in this study.
[96]	Distributed Dynamic Event-Triggered Consensus Control Scheme	1. Accurate current sharing is achieved. 2. Communication overhead is reduced.	1. Its effectiveness hinges on accurate tuning of control parameters in the event-triggering control condition. 2. It does not consider communication delays.
[88]	Distributed Event-Triggered Consensus Control Scheme	1. Communication overhead is lowered. 2. Data packet loss and transmission delays are addressed.	1. It is vulnerable to high delays. 2. It focuses on communication issues under assumed conditions. 3. Event-triggering control parameters need to be optimally tuned. 4. Random packet losses are not considered. 5. Stochastic communication failures are not tackled.
[95]	Fully distributed edge-event-triggered control scheme	1. Current sharing accuracy is enhanced. 2. Communication requirements are reduced. 3. Global system structures are not required, enhancing network scalability.	1. It requires high computational complexity. 2. Processing loads on the microgrid controllers are increased. 3. Communication delays are not evaluated.
[18]	Event-triggered communication-based distributed control	1. It enhances current-sharing and average voltage regulation. 2. It decreases the communication overload.	1. Parameter design and selection of event-triggered control conditions are complex. 2. Both current and voltage data need to be exchanged, which adds further implementation complexity. 3. The static ETM scheme exhibits limited adaptability to varying operating conditions.
[147]	Distributed Event-triggered Average Consensus Algorithm	1. Voltage stabilisation and energy balancing are improved. 2. Network traffic is managed, and the communication load is decreased. 3. Accurate load sharing and system stability are ensured.	1. Continuous monitoring of the event-triggering condition is required to manage triggering events. 2. Zeno's behaviour is not addressed, which may lead to excessive triggering instances. 3. Identification of link failures and fault detection might be hindered by the adopted sparse communication.

Table 3. *Cont.*

Ref.	Control Approach	Merits	Demerits
[120]	An event-triggering function based on a Kalman filter	1. Voltage stabilisation and energy storage balancing are improved. 2. Network traffic and energy consumption are decreased.	1. It is sensitive to communication delays. 2. Event-triggering control parameters must be optimally adjusted, as poor selection could lead to excessive data exchange or slow responsiveness.
[68]	Distributed Event-triggered Secondary Control Scheme	1. Average bus voltage is well regulated. 2. Proportional current sharing is ensured. 3. Flexibility and scalability of the system are achieved.	1. Communication delays are not addressed, which might weaken the network's stability in real-life applications. 2. Proper adjustment of the event-triggering threshold is required.
[83]	Distributed Event-triggered control scheme	1. Current sharing and voltage regulation are enhanced. 2. The communication burden is decreased. 3. Zeno behaviour is addressed.	1. Proper adjustment of the event-triggering threshold is required, which may increase design complication. 2. It is vulnerable to high communication delays. 3. Continuous monitoring of the network's states may increase communication and computation burdens, restricting its scalability.
[64]	Distributed Periodic Event-Triggered Algorithm	1. Proportional Current sharing and voltage regulation are achieved. 2. Communication requirements are decreased. 3. Zeno behaviour is avoided.	1. A static state-dependent threshold may restrict the network's adaptability to varying operating conditions. 2. Precise adjustment of the event-triggering threshold is required. 3. It has not been tested with communication uncertainties such as random delay and data dropout. 4. It is challenged by a trade-off between convergence speed and communication frequency.
[69]	Distributed Periodic Event-Triggered Algorithm	1. Communication overload is reduced. 2. Zeno behaviour is evaded. 3. Average bus voltage is successfully regulated.	1. It is sensitive to communication delays. 2. A trade-off between convergence speed and accuracy due to the tuning requirements of the control parameters. 3. It depends on the accurate knowledge of network parameters.
[71]	Optimal consensus-based event-triggered control strategy	1. Proportional current sharing and average bus voltage restoration are achieved. 2. Communication overhead is reduced. 3. It addresses Zeno behaviour.	1. It highly depends on the accurate adjustment of event-triggered control parameters, 2. A trade-off between shorter system response time and less communication could require efficient optimisation.

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Table 3. *Cont.*

Ref.	Control Approach	Merits	Demerits
[72]	Distributed Event-Triggered Consensus-Based Control Scheme	1. Voltage regulation and current sharing are achieved proportionally among DGUs. 2. It lowers the overhead of communication by transmitting data only when needed. 3. It boosts cybersecurity resilience against cyberattacks.	1. Communications delay is not addressed. 2. It is constrained by a specific microgrid topology under coordinated communication and physical configuration, limiting generalizability. 3. Its performance depends greatly on the tuning of the control parameter.
[60]	Hierarchical Event-Triggered Consensus Algorithm	1. Lower communication costs. 2. It ensures adequate current sharing. 3. It enhances voltage regulation.	1. Both Zeno behaviour and communication delays are not tackled. 2. Global information is required. 3. It depends on the accurate adjustment of event-triggered control parameters.
[84]	adaptive event-triggered communication algorithm	1. It enhances the secondary control layer in DC microgrids. 2. It alleviates communication stress by reducing excessive data communication. 3. Proportional current sharing and average voltage regulation in the network are achieved.	1. Zeno behaviours are not tackled, causing potential instability. 2. Global information is required, limiting its flexibility. 3. Continuous-time monitoring of the triggering conditions. 4. High communication delays are not taken into account.
[93]	Dynamic Event-Triggered Control scheme	1. It boosts voltage restoration and current distribution in DC microgrids. 2. It decreases the communication burden. 3. Event-triggering threshold is dynamically adjusted, boosting flexibility and decreasing unnecessary data exchange.	1. It is vulnerable to large communication delays, causing the network to become unstable. 2. Precise adjustment of the threshold and internal variable may increase implementation complexity and restrict applicability in uncertain operation conditions.
[133]	A distributed event-triggered dynamic average consensus scheme	1. Voltage restoration and current sharing are ensured. 2. Redundant communication is decreased due to the adaptive time-varying threshold. 3. Stable operation is maintained. 4. Zeno behaviour is avoided.	1. Precise adjustment of multiple control parameters is required. 2. A strongly connected graph is assumed, so practical implementation might be restricted. 3. Communication delays are not addressed, which might impact consensus tracking.

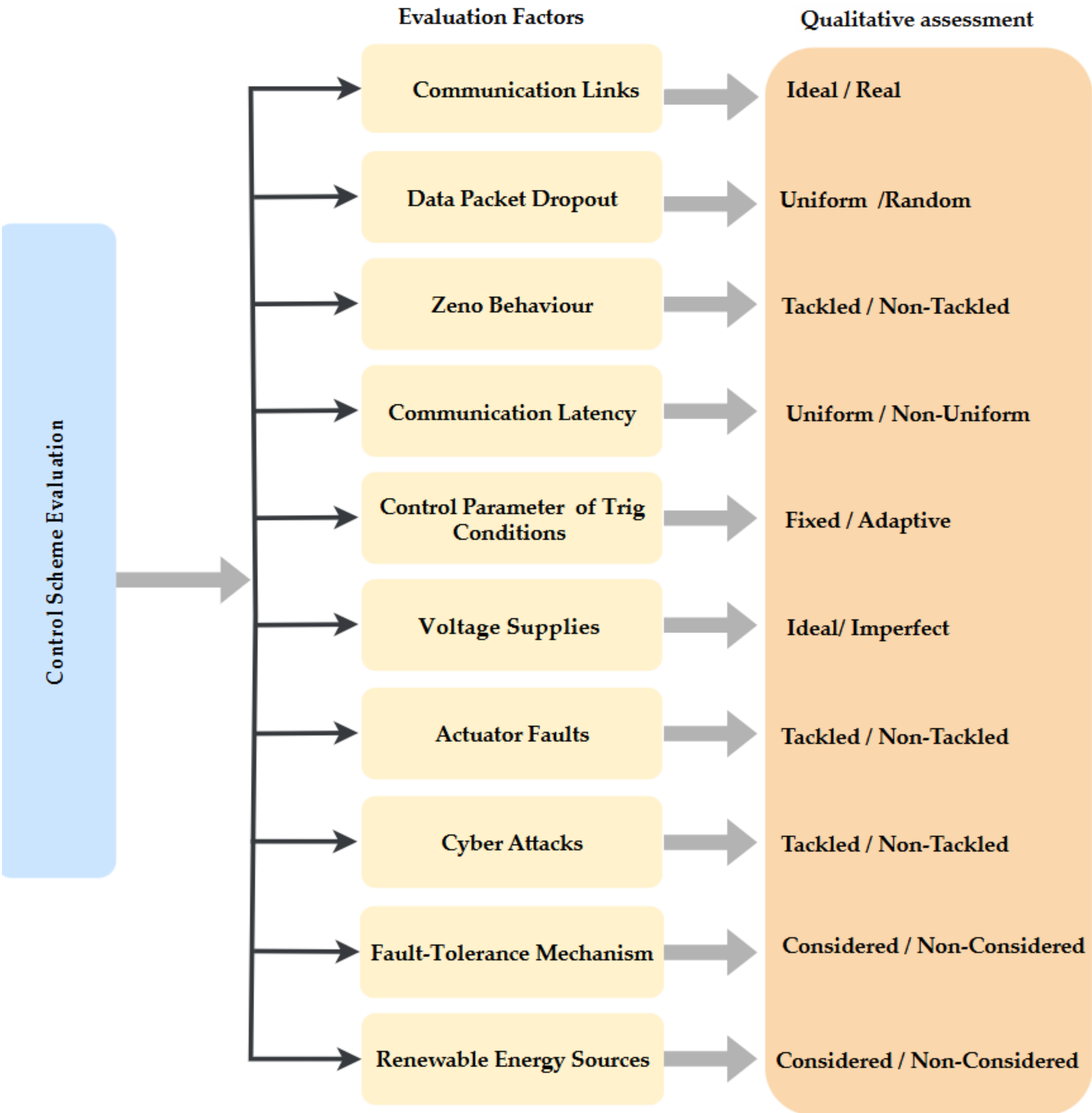

Figure 6. Taxonomy of qualitative evaluation dimensions of ETM schemes in DC Microgrids.

To ensure reproducibility of the proposed evaluation framework in Figure 6, each criterion has been assessed on a discrete three-point scale with anchor points {0.2, 0.5, 0.8}. Each point on this scale corresponds to a verifiable property of the source article, so that applying the same rubric to the same set of papers yields the same results. These three anchor points can be defined as follows: a score of 0.2 indicates that the criteria are not addressed or are considered via an idealising assumption, which may impede further examination, such as an assumption of an ideal communication channel in the context of robustness to communication delays in networks. Also, a score of 0.5 implies the criteria are partially considered, either through qualitative discussions, through a limited theoretical approach, or through simulation-based analysis, while a score of 0.8 indicates that the criteria are appropriately analysed and supported by theoretical derivation, simulation, or other forms of experimental evidence.

Applying the proposed rubric to the six papers chosen from the existing literature yields the results shown in Table 4. Each number in the table is supported by a specified, verifiable feature of the relevant paper, whether a theorem statement, a simulation scenario, or an explicit modelling assumption. It is important to note that, even though the scale of evaluations is discrete, the use of equidistant anchors per paper is interpreted as an interval-scale index.

Table 4. Coverage index comparison of ETMs across the key performance criteria in Figure 6.

Criterion	[18]	[96]	[95]	[88]	[100]	[147]
Communication Links	0.5	0.2	0.5	0.8	0.8	0.5
Data Packet Dropout	0.5	0.2	0.2	0.8	0.2	0.2
Zeno Behaviour	0.5	0.8	0.8	0.8	0.5	0.5
Communication Latency	0.2	0.2	0.2	0.8	0.5	0.5
Control Parameter of Trig. Condition	0.5	0.8	0.8	0.8	0.8	0.2
Voltage Supplies	0.2	0.8	0.5	0.5	0.5	0.5
Fault Tolerance	0.8	0.5	0.5	0.5	0.8	0.2
Renewable Energy Incorporation	0.5	0.8	0.8	0.2	0.8	0.8
Mean (coverage index)	0.46	0.54	0.54	0.65	0.61	0.43

This evaluation framework may offer several advantages when applied to the existing literature. It enables researchers to identify the major shortcomings of each control scheme and perform systematic comparisons across the available alternatives along all eight dimensions, as shown in Figure 7. As a result, the proposed framework can reveal dimensions that have been overlooked or ignored in prior studies, thereby providing a clearer view of potential gaps in the literature. Additionally, the presented coverage index helps researchers focus on dimensions that have received comparatively limited investigation.

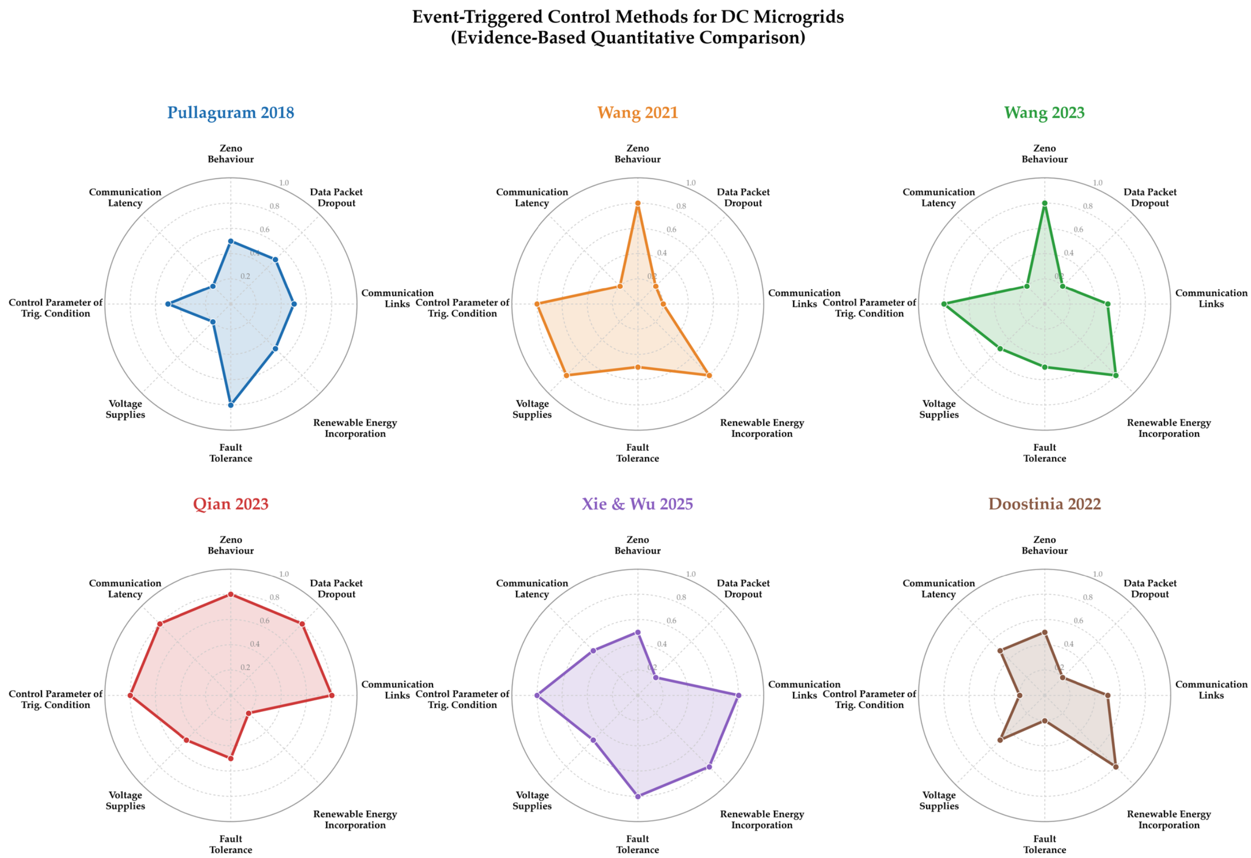

Figure 7. Evidence-based quantitative comparison of event-triggered control methods for DC microgrids [18,88,95,96,98,147].

6. Main Challenges and Open Issues in ETM Schemes

This section outlines issues with ETM schemes identified in the literature that may inform future research directions, as illustrated in Figure 8.

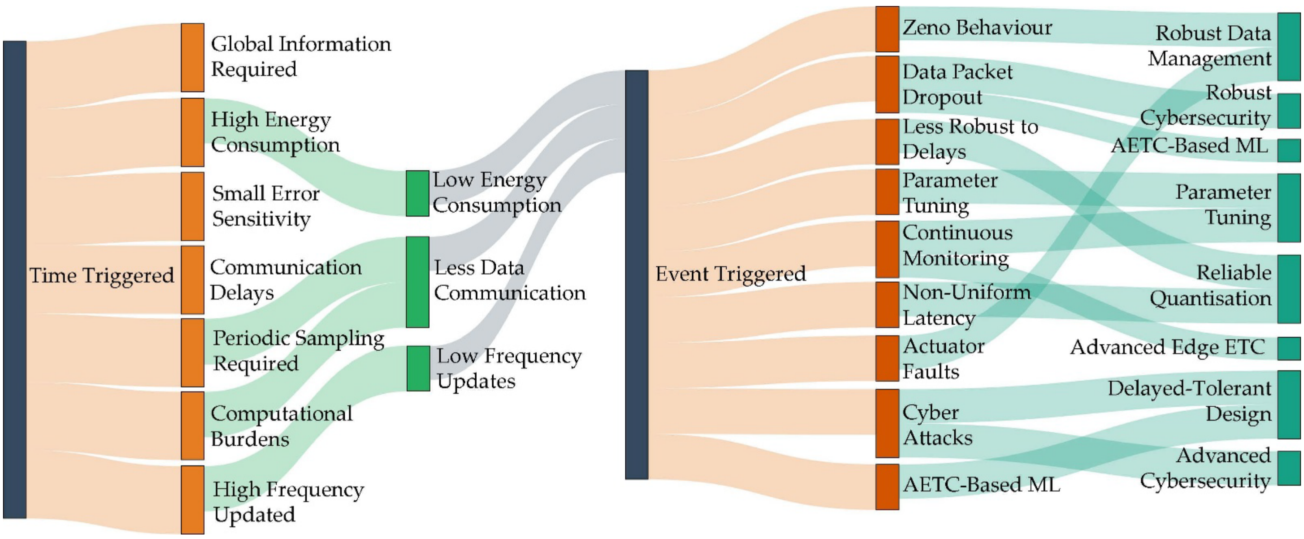

Figure 8. Comparison of time-triggered and event-triggered mechanisms, highlighting their key changes and potential solutions.

(A) Limited Adaptation of Event-Triggered Control Schemes in Renewable Energy-Based DC Microgrids

ETM schemes have recently gained significant interest for DC microgrids, but have not been widely implemented in renewable energy-based DC microgrids. Based on the investigation conducted in this paper, it is found that although many studies have shown that ETM schemes are preferred in DC microgrids due to their reduced communication frequency, they are still partially untested under real-life conditions with unpredictable renewable inputs and fluctuating demands, raising uncertainties about their robustness and the increased communication overheads. Some studies [30,33,90,91,125,135,147–154]. It is worth noting that most current studies lack robustness to real-life network conditions, such as communication delays, cyberattacks, and variable renewable energy inputs. Therefore, Future research can address such issues by developing delay-tolerant systems, proposing advanced cyberattack protection techniques, and adopting machine learning to adjust the control parameters of triggering control conditions. These new control schemes should be examined under conditions based on real-world sporadically renewable sources.

(B) Limited Adoption of Edge-Based Event-Triggered Algorithms in DC Microgrids

The use of an edge-based ETM scheme in DC microgrids has not been extensively investigated, since it has been employed in one study, as illustrated in [117]. Although these new control schemes are employed in multi-agent systems [95,110–112] that incorporate coordinated tracking control and heterogeneous-agent regulation, their use in DC microgrids remains limited.

(C) Limited Consideration of Communication Delays and Non-Uniform Latency in DC Microgrid Control Approaches

Non-uniform communication delays cause serious issues in the distributed control systems of DC microgrids [139]. It is noticed that packet losses and high delays negatively affect stability and performance, leading to transient oscillations and restraining reliable operation in low-latency systems [17,136,155]. While some networks tolerate moderate communication delays within certain limits, they do not have effective control strategies to manage higher latencies and remain susceptible to instability [100]. The study in [107] addresses this challenge by modifying the communication topology and controller parameters and adopting the ETM scheme to share communication loads while maintaining efficient voltage control and power allocation. The network can realise input-to-state stability by defining the most acceptable delay. However, investigation of this aspect remains limited in the field of DC microgrids. Hence, there is a strong need to explore robust control schemes that can handle realistic scenarios with communication delays.

(D) Limited Adoption of Hybrid ETM-STM Schemes in DC Microgrids

An extensive investigation is conducted in this paper to evaluate the feasibility of these schemes in coordinating data exchange among microgrids. It is found that although ETM schemes effectively decrease communication frequency, they require constant sampling and monitoring, which in turn impose additional computational and sampling burdens on the system, potentially increasing computational demands. In contrast, STM schemes help lower communication, sampling and computational loads. Nevertheless, STM approaches are commonly conservative and require more frequent communication compared to their ETM counterparts [26]. Hybridisation of these control schemes effectively addresses these problems by enabling microgrids to adopt ETMs for inter-unit communication and local STM schemes for sampling and assessing trigger conditions. This hybridisation aims to balance communication effectiveness and reduce sampling and processing loads. However, it is found that research on hybrid ETM-STM control approaches in DC microgrids is limited, so further studies may need to be performed to develop this new scheme.

(E) Limited Consideration of Data Packet Dropouts in DC Microgrids

Successful communication links among distributed generation units (DGUs) are crucial for exchanging data. However, data packet losses in these systems can substantially affect the stability and accuracy of control performance in power grids. Considerable contributions have been made in the literature to address such challenges in communication networks, as seen in studies such as [87,140,141]. However, these studies make deterministic assumptions and fail to adequately reflect the inherent randomness of realistic scenarios. Therefore, studies in [89] were conducted to enhance robustness and communication effectiveness in the presence of random packet dropouts. Investigation of data packet losses in DC microgrids is comparatively limited, despite their potential to affect control performance. Future studies can consider data transmission volumes, packet loss rates, and cybersecurity threats to develop a reliable control scheme that addresses these challenges in a DC microgrid.

(F) The challenges of Control parameter tuning in Event-Triggered Control Conditions

Traditional ETC schemes face considerable challenges in responding to the dynamic operating conditions of DC microgrids. While such control schemes can achieve an effective coordination of distributed energy resources within bandwidth constraints [15,18,24,84], they do not respond dynamically to variable operating conditions in DC microgrids. One serious concern is that adjusting multiple event-triggering control parameters increases the complexity and computational requirements of power networks [68]. Such an ETM scheme faces a control–performance trade-off with a communication trade-off, as increased responsiveness requires higher data exchange frequency, thereby increasing communication burdens [17]. These problems can be exacerbated in large-scale networks, where parameter tuning complexity increases, and system sensitivity compromises overall performance [25,28]. Due to the ETM schemes' performance largely relying on accurate control parameters, such tuning inaccuracies can result in deficient performance or excessive triggering, thereby restricting their implementation in a practical, dynamic, real-world microgrid [148,150]. Therefore, Machine learning techniques can be adopted in future studies to address such issues in DC microgrids.

(G) Limited Adoption of Quantised State in Event-Triggered Control Approaches

Quantisation is the conversion of a continuous value or signal to a set of discrete levels. Compressing control system data before transmitting it over a communication system has been discussed in [156]. It reduces the amount of data communicated, thereby relieving the communication burden. This approach is implemented significantly on digital communication interfaces to tackle the channel bandwidth limitations [130]. However, it can introduce minor errors, known as quantisation errors, because the nearest discrete level approximates the actual value. Because of its unique features, it has been recently adopted in DC microgrids, as stated in [59], to enhance control improvement by sending fewer bits during transmission and converter interactions, thereby further decreasing the communication burden compared to other ETM schemes. As cyber-physical networks continue to evolve, the practical communication requirements increase; thus, meeting these growing requirements requires more than just the application of a single ETM or quantisation. To address such emerging technical issues, researchers have therefore been attempting to integrate ETM schemes and quantised control strategies to further reduce the communication burden. Future studies may focus on this aspect to remedy this gap.

(H) Limited Consideration of Data Amount in ETM Schemes

Several studies have recently examined various data exchange strategies in DC microgrids. For example, studies in [87–89] have proposed dynamical and distributed event-triggered control (ETM) strategies to alleviate the effects of data losses. However, most of these studies have primarily focused on the rate of data exchanged rather than the data size, which may need to be considered, particularly in large-scale microgrid networks, to optimally exploit the communication channels. To address this issue, the study in [146] introduces a novel pre-averaged event-triggered control mechanism to handle the large amount of data. It uses average values within sampling periods rather than relying on discrete samples, thereby substantially reducing unnecessary data exchange. Accordingly, this control approach enhances efficiency and robustness by significantly reducing the data volume transmitted across communication links among DC microgrids. Hence, effective data management in DC microgrids requires careful consideration of three significant factors: the volume of data exchanged, the likelihood and implications of data dropouts, and the selection of a sampling paradigm, either averaging or fixed. It is evident that such factors should be thoroughly considered in future studies to ensure robust control schemes in DC microgrids operating in real-world network environments.

(I) Continuous Monitoring Challenge in ETC Schemes

ETM schemes are communication-efficient strategies that activate a control action once a predefined condition is met [15]. However, these schemes are hindered by the continuous monitoring of network states to assess the trigger conditions [39,71,157], which may be computationally costly and require persistent access to real-time data, leading to substantial communication overhead and implementation complications [20,69,111]. This continuous assessment of triggering conditions exploits vast network bandwidth, specifically for monitoring voltages in long-cable resistance power schemes [32,108]. To tackle such issues, especially in [18,71,84], an alternative control strategy is proposed in [86] to detect the triggering conditions based on sampling instants, thus decreasing monitoring load and lessening the frequency of data exchange among microgrids to prevent Zeno behaviour [26,71,86,105]. It has been noticed that these control strategies increase controller design complexity and make them more suitable for industrial applications [87,103].

Future studies can focus on addressing the constant monitoring requirements for ETM conditions in DC microgrids by extensively adopting sampling-data-based and self-triggered control schemes.

7. Future Directions of ETM Schemes

Future studies on ETM schemes for DC microgrids can focus on developing robust hybrid adaptive ETM frameworks that can sustain network stability against practical limitations, such as communication delays, non-uniform latencies, cyber-attacks, and data packet losses. Many existing ETMs rely on continuous-time signals and static thresholds, limiting their adaptability and deployment in dynamic environments. Adaptive ETM based on machine learning algorithms may support the adjustment of control parameters, optimisation, reduction in information transmission overhead, and mitigation of Zeno behaviour. Furthermore, the limited adoption of ETM in renewable-based DC microgrids underscores the critical need for control schemes that can effectively manage intermittent energy sources and unpredictable demand. Although edge-based triggering control schemes offer a promising approach for asynchronous operation and reduced communication, they have been rarely adopted in existing DC microgrid studies; further research is therefore required to develop them. Also, Hybrid ETM schemes that combine event-triggered and self-triggered mechanisms can effectively balance communication efficiency with reduced sampling frequency. This hybridisation can be further refined to prevent the conservatism and excesses associated with individual control mechanisms. Moreover, the role of quantisation control approaches in reducing bandwidth consumption needs to be further developed, taking into account quantisation errors and the design of hybrid quantizers. Additionally, a control scheme that considers the influence of data volume alongside transmission frequency, by incorporating pre-averaged sampling and data-triggering control mechanisms, may also require further development.

Another significant consideration is the adoption of event-triggered mechanisms (ETMs) to address cybersecurity challenges common in DC microgrids, given the continuous data transmission pattern of a time-triggered census algorithm, which makes them highly susceptible to denial-of-service (DoS), false-data injection (FDI), and deception attacks. Although ETMs can play a vital role in tackling such attacks, their reliance on node-to-node data exchange within DC microgrids makes them vulnerable to cyberattacks. In this regard, Attack-resilient triggering conditions, such as edge-based ETM schemes, can be adopted to localise the effects of cyberattacks to a single communication link, ensuring consensus despite intermittent communication interruptions. In this regard, edge-based triggering remains the most promising backbone for unified cyber-resilient ETM designs, as its architecture can prevent the propagation of attacks that could disable the entire network. Although several studies have addressed these issues by adopting edge-based detectors to detect DoS attacks [117] and a model-free adaptive framework to withstand multipattern deception attacks [118], each study addresses a specific threat, so a cyber-resilient ETM scheme should be designed as a multi-layered defence. The emerging triggered mechanism could be further developed by including additional unexplored observers from the literature, thereby strengthening the control schemes for DC microgrids. A holistic architecture incorporating delay-tolerant design, cyber resilience, data management, and dynamic thresholding can play an essential role in achieving the scalability, applicability, and robustness of ETM schemes in DC microgrids.

8. Conclusions

This article presents a comprehensive review of event-triggered consensus control schemes in the literature, which aim to coordinate data exchange among DC microgrids.

These control schemes are classified into four groups, including SETM, DETM, STM, and EETM, based on the triggering conditions used in each. Their strengths and weaknesses are thoroughly analysed in terms of implementation simplicity, communication efficiency, fault tolerance, and resilience to communication delays. Furthermore, this article discusses the approaches' difficulties with Zeno behaviour, vulnerability to cyber-attacks in networks, sensitivity to adjustments in control parameters under triggering control conditions, and limited adaptability to dynamic operating conditions. This paper also explores the optimal integration of quantisation techniques to improve the transmission of data packets in DC microgrids, as well as the impact of renewable energy resource variability on control performance. The primary objective of this comprehensive review is to provide researchers with a clear roadmap for designing a robust ETM scheme that can be effectively implemented in real-world scenarios. This objective can be achieved by developing delay-tolerant, cyber-attack-resilient, and adaptive ETM-based machine learning algorithms in future studies to effectively address communication constraints, variability in renewable resources, and unpredictable real-time operating conditions.

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