Jurnal
Teknologi

Full Paper

INVESTIGATING THE IMPLICATIONS OF DC DISTRIBUTION NETWORKS ON RENEWABLE ENERGY INTEGRATION AND FLEXIBLE ENERGY STORAGE EFFICIENCY

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Article history
Received
10 July 2024
Received in revised form
21 January 2025
Accepted
4 March 2025
Published Online
24 October 2025

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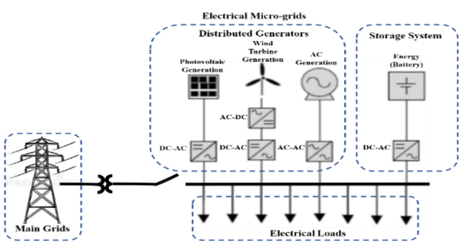
Graphical abstract



Abstract

This research examines the impact of DC distribution networks on integrating renewable energy sources and the effectiveness of flexible energy storage systems in enhancing network efficiency. The study evaluates the performance, stability, and potential of DC distribution networks as key enablers for achieving a sustainable and reliable energy system. The analysis focuses on the potential benefits and challenges associated with integrating renewable energy sources into DC distribution networks. It investigates how these networks efficiently manage and utilize renewable energy, addressing issues such as voltage regulation, power quality, and system stability. Additionally, the research explores the role of flexible energy storage technologies in mitigating the intermittency of renewable energy sources. It evaluates the effectiveness of energy storage systems, including batteries, pumped hydro storage, and compressed air energy storage, optimizing network stability, improving energy dispatch ability, and maximizing renewable energy utilization. An economic analysis assesses the viability and cost-effectiveness of implementing DC distribution networks with renewable energy integration and flexible energy storage. This analysis considers investment costs, operational expenses, and potential revenue streams, providing insights for decision-makers and energy planners. They inform policymakers, system operators, and energy industry stakeholders, facilitating informed decision-making and the development of strategies to optimize energy system efficiency, reliability, and sustainability. In conclusion, this research provides a comprehensive assessment of the implications of DC distribution networks on renewable energy integration and flexible energy storage efficiency. The insights gained significantly impact achieving a more sustainable and resilient energy future.

Keywords: Direct Current, Distribution Network, Energy Storage System, Micro-Grid, Stability

Abstrak

Mengkaji kesan rangkaian pengedaran arus terus (DC) terhadap sumber tenaga boleh diperbaharui dan keberkesanan sistem penyimpanan tenaga fleksibel dalam meningkatkan kecekapan rangkaian. Kajian ini menilai prestasi, kestabilan dan kebolehlaksanaan terhadap ekonomi sebagai pemboleh ubah utama untuk mencapai sistem tenaga yang mampan dan boleh dipercayai. Analisis memfokuskan pada potensi manfaat dan cabaran berkaitan dengan penyepaduan sumber tenaga ke dalam rangkaian pengedaran DC. Menyiasat cara rangkaian diuruskan dan menggunakan tenaga yang boleh diperbaharui dengan cekap dalam menangani isu seperti peraturan voltan, kualiti kuasa dan kestabilan sistem. Selain itu, penyelidikan meneroka peranan teknologi penyimpanan tenaga yang fleksible dalam mengurangkan sumber tenaga yang terputus-putus. Ia menilai keberkesanan penyimpanan sistem simpanan tenaga termasuk bateri, penyimpanan hidro yang dipam dan penyimpanan tenaga udara termampat dalam mengoptimumkan kestabilan rangkaian, meningkatkan kebolehantaran tenaga dalam analisis ekonomi dan dapat menilai daya maju dan keberkesanan kos melaksanakan rangkaian DC. Ia juga dapat mempertimbangkan kos pelaburan, perbelanjaan operasi dan aliran hasil yang berpotensi dalam memberikan cerapan untuk keputusan secara fleksible. Mereka memaklumkan pengubal dasar, pengendali sistem dan pihak berkepentingan industri tenaga. Kesimpulan, penyelidikan ini memberikan penilaian menyeluruh tentang implikasi terhadap penyepaduan tenaga boleh diperbaharui serta cerapan yang diperolehi mempunyai implikasi yang ketara dalam mencapai masa depan tenaga yang lebih mampan dan berdaya tahan.

Kata kunci: Arus terus, rangkaian pengagihan, sistem simpanan tenaga, grid-mikro, kestabilan

1.0 INTRODUCTION

In 1880 – 1900s, the battle of the currents between Thomas Edison (DC) and Nikola Tesla (AC) marked the early development of electrical power systems. Edison promoted DC for simplicity and lower initial costs, while Tesla and Westinghouse advocated AC due to its efficiency over long distances. At that time, ACs dominated the systems due to the ease of voltage transformers, enabling efficient long-distance transmission [1]. This led to the widespread adoption of AC for electrical distribution networks globally but by the mid-20th century electronics predominantly operated on DC distribution. In traditional systems, this DC power is converted to AC for distribution and then back to DC for storage or certain types of consumption. These include computer networks, communications devices, and various industrial applications. New technological advancements rely on DC and are under semiconductor technology on power electronics with the efficiency of DC-AC and AC-DC conversion[2]. Renewable energy integration is from solar photovoltaic (PV) to produce DC power storage for batteries, pumped hydro, and compressed air energy. These multiple energy conversions lead to energy losses. Directly integrating renewable energy into a DC distribution network, energy conversion steps are reduced, which improves overall system efficiency [3].

The method used in this paper is to evaluate the reliability of DC distribution compared to AC distribution, which often refers to a holistic analysis involving several key aspects such as network efficiency, renewable energy utilization, energy storage integration, economic considerations, and stakeholder involvement. This comprehensive approach helps decision-makers and stakeholders develop strategies to optimize energy distribution systems, particularly in the context of the growing shift toward renewable energy.

1.1 Impact of DC Distribution Network

The transition to renewable energy sources like solar and wind has brought about significant changes in the electrical systems that are designed and operated. One of the key challenges in integrating renewable energy is the variability and intermittency of power generation. To overcome these challenges, DC distribution networks emerged as a promising solution for improving renewable energy integration and enhancing the efficiency of flexible energy storage systems [4]. These DC networks offer advantages such as improved compatibility, reduced losses due to fewer power conversions, and enhanced control and stability. These DC energy storage systems, particularly batteries pumped hydro, and compressed air energy, are crucial for managing the intermittent nature of renewables. Storing excess energy during periods of high generation and releasing it during demand peaks is key to balancing supply and demand [5]. DC network is flexible energy storage that is more efficient on connection which improves round trip on charging and discharging with faster response time due to easy to control and can enhance flexibility to support load leveling, particularly in decentralized or islanded systems. This has directed a growing interest in DC transmission systems for applications, offering advantages such as reduced losses and improved control capabilities [6].

Several studies based on the reliability and efficiency of the DC distribution are being approached by using mathematical model-based, stating that it is better with 2.28% of independent converter for the load and 1.57% driven by a single converter with efficiency advantages compared with AC distribution [7]. Indeed the concept of DC distribution systems has gained attention as a potentially superior method for electrical power delivery, especially with the rise of small distributed generation units like solar panels and wind turbines [8]. There are numerous advantages associated with DC distribution systems such as they often exhibit higher efficiency compared to AC systems, particularly when considering losses associated with AC-to-DC conversion. The DC systems typically do not have a reactive power component which can simplify power management and reduce the need for reactive power consumption equipment. Furthermore, many modern appliances, such as LED lighting and electronic devices operate using DC voltage internally to become the new distribution system that is more compatible with loads[9]. Researchers worldwide are actively investigating the feasibility and potential benefits of using DC distribution systems instead of traditional AC systems. Their studies have led to numerous publications covering various aspects of the subject, including system design, control strategies, and economics analysis. This ongoing research aims to address technical challenges and identify opportunities for the widespread adoption of DC distribution systems in future electrical grids.

2.0 APPLICATION OF DC DISTRIBUTION

The rise in energy consumption and the increasing scarcity of fossil resources encouraged the proliferation of renewable energy sources and their integration with conventional power systems. A transition to renewable-based energy systems is looking progressively likely as the costs of solar power systems have dropped significantly in the past 30 years [10]. The price of oil and gas continues to fluctuate in the international market with the fossil fuel and renewable energy values, while social and environmental costs are heading in opposite directions. Additionally, the economic and policy mechanisms needed to support the extensive distribution and sustainable markets for renewable energy systems have also speedily grown [11]. It is becoming clear that future growth in the energy sector is mainly in new renewable sources such as DC distribution while it is not conventional on oil and coal sources.

A DC system has various applications across multiple industries due to its unique characteristics. The powering communication systems that are reliable power supply often on 48V DC to ensure uninterrupted communication that comes with battery backup during outages. In industrial applications also DC motors are being utilized especially where variable speed and precise control are required in conveyor belts and cranes. Others are on DC micro-grids that are becoming popular for off-grid applications due to their efficient integration with renewable energy sources like solar and wind. Overall, DC systems are favoured in situations where energy efficiency, reliability, and integration with renewable energy or backup power are crucial [9].

2.1 Energy Solar Photovoltaic (PV)

Solar energy, specifically solar photovoltaic as one of the DC distribution networks, offers significant benefits in terms of environmental sustainability, climate resilience, financial viability, and general welfare. Its potential necessitates enhanced gearbox capacity and dependable, sustainable systems. The primary means by which solar photovoltaic cells transform sunlight into electrical energy is via boost converters [12]. Solar agriculture makes use of exposed areas to maximize the absorption of sunlight. Power electronics in solar photovoltaic generation facilities facilitate the management of grid connections, thereby providing active grid stability. Microgrids, comprised of various renewable energy sources, reduce transmission losses and increase reliability [13]. Notwithstanding the advantages such as enhanced dependability and decreasing emissions, microgrids also present obstacles. The structure of a typical micro-grid is illustrated in Figure 1 from the main grid to the storage system.

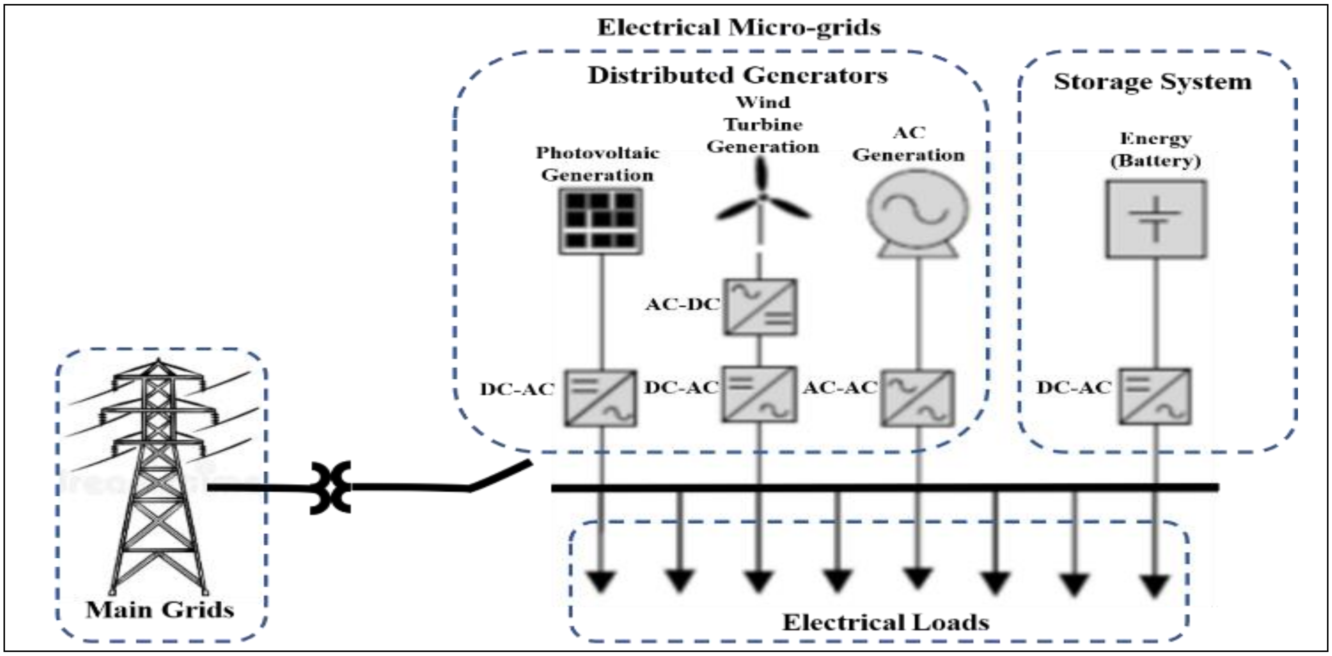


Figure 1 The general structure of microgrid

Harnessing the power received from the sun through Micro-Grid Distribution Generation (DG) technology has proven to be an effective way to tap into renewable energy resources. However, when integrating various units of DG technology in a multi-machine power system, can lead to uncertainty in the AC load due to sudden changes such as load fluctuations, power oscillations, and frequency deviations [14]. Furthermore, the fast-paced fluctuations in demand or generation arrays, as well as trading operations, can cause challenges such as power mismatch, higher current in the load, and excessive temperature in the system for the current microgrid power system [15]. To overcome this issue, an advanced algorithm for grid inverters can be implemented to constantly adjust the impedance seen by the solar array, ensuring optimal performance of the photovoltaic (PV) system [16]. A breakthrough solution is to introduce a non-linear controller that utilizes fuzzy logic. Testing the proposed non-linear controller is crucial to ensure its superiority over the traditional control of PV microgrid systems. It is vital to design a superior control system to enhance power stability and tackle swift changes and disturbances in the PV system. Simulation research is crucial for solar photovoltaic systems to operate more stably and boost performance since they require a conversion from DC to AC, which results in energy loss. Therefore, the dangers posed by system instability must be addressed through stability prediction and the need to boost system performance. It is predicted that the proposed non-linear controller will outshine the conventional controller in terms of stability and response system during outages or system disturbances [17-18].

2.2 Wind Turbine Power

Wind energy generates electricity, as traditionally output by AC. Still, it is possible to use converters to directly output DC power that can integrated more efficiently with the DC distribution grid. The advantages of DC distribution can reduce conversion losses and make the system more energy efficient. Wind energy in a DC distribution system provides an efficient, scalable, and reliable approach to sustainable energy. Its ability to integrate with other renewable sources and energy storage solutions enhances system resilience, efficiency, and long-term sustainability [19].

Integrating wind turbines with DC distribution systems has several benefits, especially in off-grid applications or micro-grids which are efficient long-distance transmission and energy storage. There are several advantages of DC distribution for wind power it can reduce losses over distances, simplify integration with renewable energy, with efficient storage, and have more flexibility in micro-grids [20].

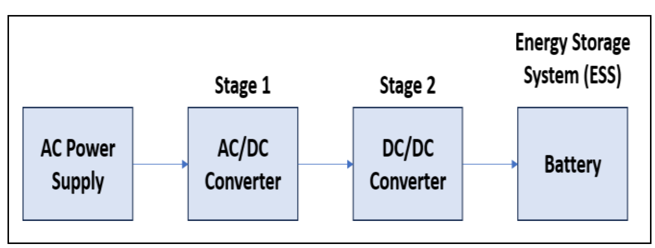


Figure 2 Two-stages Power Conversion Structure

Figure 2 shows a two-stage power conversion structure widely used in charging equipment. The process involves the following steps; the input from the AC power supply is converted into DC power as the first stage of AC/DC conversion. To improve system efficiency and ensure compliance with utility standards, this stage typically incorporates power factor correction (PFC). These PFCs reduce harmonic distortion and reactive power, mitigating the poor power factor caused by the rectification and filtering process. The second stage of DC/DC conversion performs high-frequency isolation to separate the utility power from the battery system. Additionally, it regulates the current and adjusts the DC voltage to meet the specific requirement of the battery, effectively providing energy for charging. This structure is widely adopted because it offers flexibility, and ensures safe and efficient energy delivery to the battery, which acts as the energy storage system (ESS) for various applications [21-22].

3.0 POTENTIAL BENEFITS OF DC DISTRIBUTION

The adoption of the DC distribution network continues with the environmental benefits of reduced conversion losses by eliminating the need for multiple AC-DC and DC-AC conversion also it lowers transmission losses that are more efficient over long distances with lower resistive losses especially when using HVDC systems [23]. The integration of renewable energy uses solar power generates DC electricity that allows direct utilization of this energy without conversion losses, enhancing the overall PV systems. DC distribution also a better compatibility with battery storage and discharge that integrates into the DC network. As for the reduction in greenhouse gas emissions, it already increased efficiency by improving power distribution and reducing losses that lead to lower overall energy consumption. This translates to reduced demand on power plants also enhanced use of renewable energy for easier integration of renewable energy sources into the grid reducing reliance on fossil fuels [24]. This section focuses on the centralization power generation, micro-grid operational modes, energy management, off-grid systems and challenges that appeared during the DC distribution system was used.

3.1 Centralization Power Generation

In DC distribution systems are an evolving concept, particularly relevant as energy infrastructure adapts to the growing adoption of renewable energy and more efficient power delivery methods. Large-scale renewable integration on centralized solar or wind farms that generate DC power can be directly integrated into DC networks without the need for AC/DC conversions and can reduce energy losses. While for data centers, the large consumers of DC power, and centralized DC systems can efficiently supply these loads. As future trends it is essential for large-scale projects, micro-grids with a mix of centralized and distributed generation might emerge, combining the benefits of both models [9].

As smart grid technology advances, integrating centralized DC generation into a network of distributed, intelligent nodes will enable more efficient management of electricity flow, demand response, and storage. This system has distinct advantages, especially when it is combined with renewable energy sources and efficient transmission methods. However, it also faces challenges, particularly in retrofitting or competing with existing AC infrastructure [25].

3.2 Micro-grids (MG) Operational Modes

DC distributed resources are added to a centralized power system, and the system's complexity is likely to rise rather than decrease in terms of reliability. On the other hand, in the event of higher-level disruptions, distributed energy supplies allow for the independent operation of some grid segments [26]. Thus, it would be advantageous if the future distribution grid was made up of linked micro-grids. In this scenario, even if a portion of the grid fails, it can continue on the function. Given that the weather may limit supply in these isolated systems, demand response is probably going to be crucial. It is possible to put storage and a traditional backup supply strategically. Nevertheless, distributed energy resources allow for the independent functioning of grid sections during higher-level outages. Therefore, it would be advantageous for the future distribution grid to comprise interconnected microgrids. This way, the grid can continue operating even if certain sections fail. In this DC-isolated system, demand response is anticipated to have a significant impact, especially on supply whether weather conditions constrain it or not [27]. There are two modes of MG operation that will be discussed in this section:

3.2.1 Isolated Mode MG

This mode can detach and be characteristic autonomously in this mode of operation, especially at some stage in grid disturbance interval (fault on the most important grid) or when perturbance in electricity first class occurs. MG keeps high electricity fine and reliable with continuous energy furnished to customers except for interruptions via working in this mode of operation. Disturbance activities such as frequency drops and voltage sags may appear on the fundamental electrical energy grid. Therefore, this unique feature of MG to detach from the power grid is famously regarded as islanding [28-29].

In Malaysia, the development of such microgrids is encouraged to support sustainable development goals and reduce reliance on fossil fuels. Government initiatives and partnerships with private sectors are key to advancing these projects, focusing on enhancing resilience to climate change and promoting energy independence [30].

3.2.2 Grid-Connected Mode

This working mode of MG depends on the accumulative power demand and supply. MG can export or import energy to the primary electrical energy grid. During this mode of operation, the bi-directional glide of electricity on import or export is also maintained through MG and this will continue on their operation towards this mode until electricity perturbance or fault occurrence. Furthermore, in this mode, the MG can also feed its complete load. Figure 3 shows the MG operation modes for grid grid-connected operation state and island operation state [31]. There are two types of operation in MG on energy management under maximization and minimization management covering operation power, cost lifetime storage systems and environmental. Furthermore, the classical side comes with different types of methods shown in Figure 4

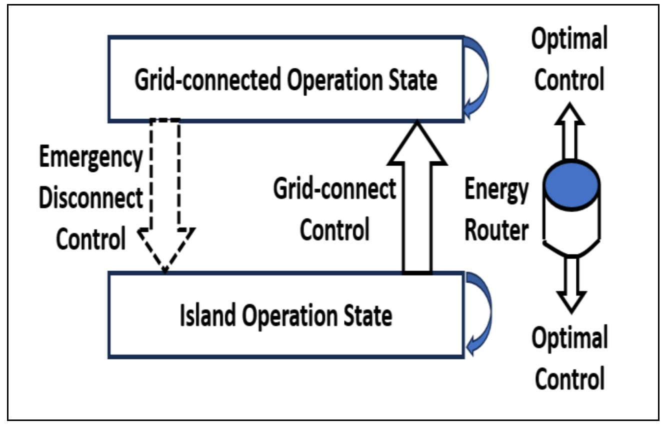


Figure 3 The MG Operational Modes [31]

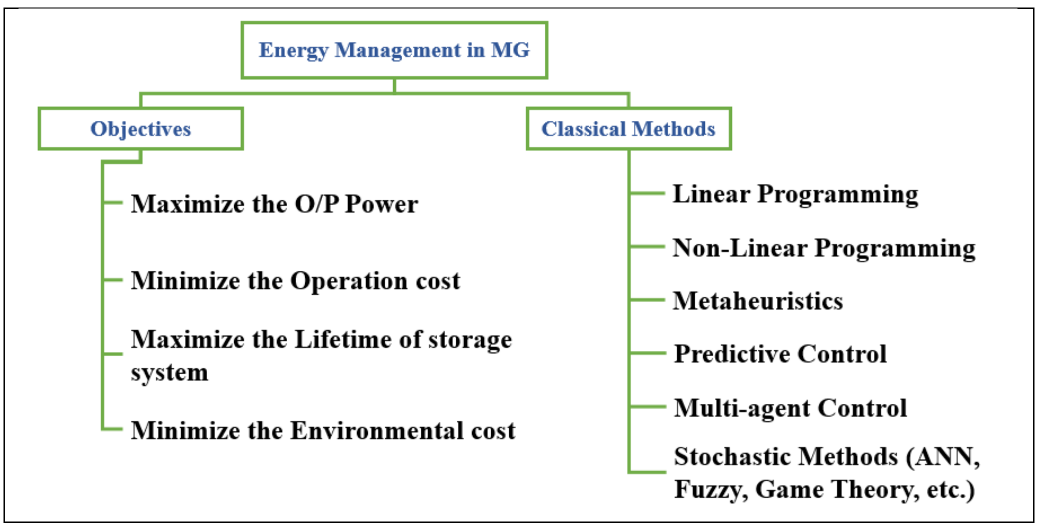


Figure 4 Objectives and Classical Methods in the MG

3.3 Energy Management in Micro-grid (MG)

Energy management in a DC microgrid involves optimizing the types of generations, distribution, and consumption of energy within a localized grid that operates on DC power. This is particularly relevant for integrating renewable energy sources, improving efficiency, and ensuring reliability. Many authors proposed different techniques for MG energy management [32]. Table 1 shows the summary of the effectiveness of the energy storage system with the objectives, constraints and limitations for different techniques under the programming system that is being used.

Table 1 Effectiveness of Energy Storage System (ESS)

Technique	Objective	Constraint	Limitations
Mixed Integral Linear Programming (MILP) [33]	Minimization of total operating cost (1) Day ahead (2) Annual cost including a battery storage system.	Battery Generation	Degradation cost is not included.
Mixed Integral Nonlinear Programming	Minimization of operating costs for various Distributed Generation Units	AC/DC Converter's power Generation Unites power	The emission cost associated with biomass-based DERs is not considered. Similarly, no

Technique	Objective	Constraint	Limitations
(MINLP) [34]			storage system is included in this study.
Particle Swarm Optimization (PSO) [35]	Minimization of total operating cost and carbon footprints (Economic vs environmental analysis)	Generation Units power. Exchange with the host grid Storage units charging /discharging Balance of supply and demand	The emission cost associated with generation units is not included.
Artificial Bee Colony (ABC) [36]	Minimization of total operating cost for Islanded MG	DERs (dispatchable / non-dispatchable) Storage System Power Balance	Mathematical formulation complexity and emission cost associated with microturbines are not included.
Fuzzy Logic [37]	Minimization of total operating cost, Maximization of renewable energy resources, maintaining voltage and frequency with MG	Load (Battery) Power Balance Generation Units power.	Battery degradation cost is not included.
Artificial Fish Swarm Optimization (AFSO) [38]	Minimization of total operating cost, while meeting the demand and storage constraints.	Host grid power exchange Power Balance Storage System Generation Power.	Degradation cost is not included.
Bacterial Foraging Algorithm (BFA) [39]	Minimization of total operating cost for MG	Storage Units Generation unites cost DERs Power Balance	Fast convergence but without considering the power loss of the system.
Dynamic Rule (DYRU) [40]	Minimization of total operating cost	Battery Storage Power Balance	Battery system cost and degradation rate are not included.
Multi-Agent System (MAS) [41]	Improving the efficiency and reliability of MG	Battery system charging /discharging	Several layers of coordinated control, thus a highly complex approach.
Game Theory (GT) [42]	Minimization of total operating cost	DG Unites Power Balance Conventional Generation Unites power MG to host grid power exchange.	Minimizing fuel cost but emission cost is not included.
Markov Decision Process (MDP) [43]	Minimization of total operating cost over a specified time horizon	Gas Turbine emission and capacity	Linear model but with a limited number of combinations

3.4 Off-Grid System

As dispersed energy options become more prevalent, we should consider whether the grid is truly necessary. Independent distribution networks are frequently perceived as unavoidable ends. In remote areas where the cost of connection surpasses the cost of extra energy generation and/or storage, off-grid technologies may be more cost-effective.
However, because of the high usage factor and cheap cost of connecting, the benefits of resource sharing in more populous areas outweigh the additional expense. Furthermore, it is improbable that multiple people will consume significant power loads simultaneously because the load peaks are unlikely to coincide with the peaks in weather, it can be costly to meet 100% of the demand with local renewable energy and storage [44].

Setting up an off-grid system in Malaysia can be a great way to harness renewable energy, given the country's abundant sunlight and natural resources with energy sources such as solar power, wind power, and hydropower with reliable battery storage system using lithium-ion batteries that are an efficient and longer lifespan [45].

3.5 Challenges

In sectors like industrial facilities, commercial buildings, and data centres, several challenges and opportunities arise in terms of operational expenses, potential revenue streams, decision-making, and energy planning for the DC distribution system. Under operational expenses, this system may reduce overall operational costs. The potential revenue streams also open up new cost-saving opportunities such as energy efficiency gains, micro-grids, and energy trading with demand response programs that involve asset utilization [46].

Energy planning for DC distribution requires careful analysis of several factors and that is energy demand forecasting, storage optimization, and resiliency strategies with environmental impact. Decision-makers must balance the operational expenses and potential revenue streams against the initial costs and technological integration challenges. Long-term energy planning will be critical in determining the success of DC distribution, especially with growing renewable energy integration [47].

Several challenges appear during DC distribution networks used with standardization; the lack of universally accepted systems poses a significant barrier to widespread adoption. Regarding safety concerns, these DC systems present unique safety challenges such as arc flash hazards that require specialized protection and safety protocol, with the higher initial costs set for DC distribution networks, including power conversion and protection equipment that can be a deterrent [48]. DC distribution networks, once overshadowed by AC systems are experiencing a renaissance driven by modern technological advancement, the rise of renewable energy, and the increasing demand for efficient energy solutions. With ongoing research and development DC networks are poised to play a pivotal role in the future of power distribution, particularly in applications where efficiency, reliability, and integration with renewable energy sources are paramount [9].

4.0 ADVANCED NETWORK EFFICIENCY

There are categories based on different strategies that have been classified under control systems in the structure of the DC distribution network. Malaysia can enhance the efficiency of its DC distribution network, benefiting both consumers and the overall energy ecosystem [49]. These strategies can manage all the intelligent actions introduced across the entire system to facilitate and exchange data and information by improving network efficiency in renewable energy systems 3 critical factors that interact are voltage regulation, power quality, and system stability.

4.1 Voltage Regulation

Maintaining stable voltage levels in a DC network is crucial for efficiency and to ensure the proper functioning of connected devices. Related to voltage regulation maintaining stable voltage levels in a DC network is crucial efficiency to guarantee the functioning of connected devices. The challenges appear on intermittency such as solar and wind power that are inherently variable causing voltage fluctuation while for harmonic distortion, these DC systems generally avoid issues that plague AC systems leading to potentially better power quality or else in the decentralization that often distributed makes more complex compared to the centralized system [50]. The solution by use smart inverters that dynamically can adjust voltage levels by improving regulation for the energy storage system (ESS) the batteries and other forms of storage will help smooth fluctuation by storing excess energy when generation is high and supplying it when generation is low.

4.2 Power Quality

On power quality, the issues with harmonics, flickers, frequency variations, and reactive power need continuous management and for lifespan the matures technology with predictable operational expenses. The lower transmission losses as DC eliminates inductive and capacitive losses at the same time with potentially lower maintenance due to simpler and more efficient components that are used. The power quality of DC is better for integrating renewable energy sources and battery storage systems with lifespan than emerging technology but initially together with data suggests potentially lower operational cost. The challenges under harmonic distortion when the DC systems generally inverters or avoid issues with harmonics into the grid by distorting the waveform. While for flicker and frequency variation, the variable deviation will affect sensitive equipment [51]. On power quality, the issues with harmonics for AC distribution and reactive power need continuous management and for lifespan the matures technology with predictable operational expenses. The DC eliminates inductive and capacitive losses at the same time with potentially lower maintenance due to simpler and more efficient components that are used. The power quality of DC is better for integrating renewable energy sources and battery storage systems with lifespan than emerging technology but initially together with data suggests potentially lower operational cost [52]. All of this information on the power quality can give a solution either using active harmonic filters (AHF) to mitigate harmonic distortion, or synchronous condensed which helps stabilize frequency and power factor correction (PFC) by enhancing the efficiency and voltage stability.

4.3 System Stability

Under reliability and stability, DC systems face challenges in fault management detection and then being isolated as DC arcs that are more persistent with efficient protection mechanisms. It incorporates redundancy and backup systems to improve reliability with affect efficiency and an optimal balance that is necessary. The stability of future distribution grids in DC is more intricate when compared to AC grids. Additionally, constant power loads pose a significant challenge to stability due to their negative incremental independence [11].

There are two main methods commonly used to maintain stability in DC-distributed systems. The first method is passive stabilization, which involves the use of passive elements to mitigate disturbances within the system. The second method is active stabilization, which employs advanced control techniques. However, it is more cost-effective to ensure inherent stability in the DC distribution system whenever possible [32].

This system stability for DC distribution refers to the ability of the power system to return to a steady state after a disturbance such as a sudden loss of generation of a short circuit. The solution by using batteries or pumped hydro can provide fast-responsive energy compensate for generation shortfalls and maintain stability. All of these solutions not only improve network efficiency but also enable a more resilient sustainable power grid.

5.0 FLEXIBLE ENERGY STORAGE

Energy storage technologies play a crucial role in DC distribution systems with different characteristics and applications. This DC distribution is more efficient for data centres and electric vehicles due to fewer conversion losses. These renewable integration storage technologies especially for batteries are well suited for integration like solar photovoltaics due to compatibility with DC output. Commonly used in telecom and data centers known as micro-grids, they utilize energy storage to ensure a reliable power supply and manage fluctuations in demand. To guarantee the reliable functioning of a flexible DC distribution network to enhance the multi-energy complementary synergy of the power from batteries, energy storage from pumped hydro and compressed air being measured [53]. The voltage regulations assist by maintaining stable voltage levels within the system and the rapid charging in electric vehicle applications for the fast-charging stations that are used to provide high-power charging, by reducing charging time significantly. These DCs come with fast response making them suitable for applications that require rapid power delivery or absorption such as in electric vehicle charging stations [54].

5.1 Mitigating the Intermittency

It is mitigating intermittency challenges that are unpredictable with the nature of renewable energy generation, which can lead to mismatches. The solution is deploying flexible energy that can quickly charge and discharge to balance supply and demand and develop a smart DC energy management system to forecast renewable energy production and optimize storage usage accordingly [13].

There are several effective energy storage systems (ESS) in a DC distribution network that involve examining the effect on network stability, energy dispatch ability, and renewable energy utilization, including batteries, pumped hydro storage, and compressed air energy storage shown in Table 2 below.

Table 2 Effectiveness of Energy Storage System (ESS)

Energy Storage Systems	Network Stability	Energy Dispatchability	Renewable Energy Utilization
Batteries	Fast response on time for maintaining network and quickly react to fluctuation in supply demand for voltage and frequency [55].	Precise control over energy dispatch is beneficial for managing load and generation in real-time. The peak shaving discharges energy during peak demand periods [56].	Higher penetration on sources by storing excess generation during periods of low demand and releasing will help mitigate the intermittency by providing a reliable backup during periods of low generation [57].
Pumped Hydro	Provide large scale that significantly contributes to overall grid stability and is more applicable to AC systems [28].	Bulk energy management provides substantial energy reserves over long periods for long-term balancing over longer timescales by storing energy during low demand and releasing it during high demands [12].	Suitable for seasonal storage during high-generation periods and its effectiveness is limited by geographical constraints that require terrain and significant capital investment [58].
Compressed Air (CAES)	Moderate response time suitable for secondary frequency regulations and providing stability over medium timescales. It contributes to frequency support and voltage stabilization [59].	Provides intermediate-term storage solutions ideal for load levelling and managing daily demand fluctuations that are scalable and dan deployed in locations where geological formations allow for underground storage [60].	Effective for wind energy integration, storing excess wind power, and the efficiency considerations are round trip is lower than batteries which impacts overall effectiveness in maximizing renewable energy [51].

In a DC distribution network, batteries are the most effective ESS for optimizing network stability and improving energy dispatchability due to their fast response and precise control. While pumped hydro storage is highly effective for large-scale and long-term energy management but is limited by geographical constraints [61]. Compressed air energy storage provides a good balance for medium-term storage needs and is particularly suitable for integrating wind energy, despite its lower efficiency. Each ESS has unique advantages and limitations, and a combination of these technologies can offer a comprehensive solution to optimize network stability, improve dispatch ability, and maximize renewable energy utilization in DC distribution networks [62].

6.0 ECONOMIC AND OPTIMIZATION

This detailed economic analysis considers several actions to optimize energy system efficiency based on the DC distribution networks. Providing insights for decision-makers and energy planners will help to evaluate whether DC distribution networks could be a viable option for future energy systems [37]. Reduced infrastructure and operational costs on DC distribution can lead to significant cost savings in both infrastructure and operation from an economic point of view under operational cost. The simpler architecture of DC systems requires fewer components, which can lower installation and maintenance costs. Additionally, the improved efficiency reduces operational expenses, contributing to a more cost-effective energy system in the long run [63].

6.1 Investment Cost

Based on the AC distribution network, the infrastructure requires a transformer in various stages such as generation, transmission, and distribution with components like circuit breakers, relays, and other protection devices that are [53] designed. It comes with the installation of that well-established focusing and substation that needs to multiply to stem down/up for voltage levels. Compared to DC distribution, it requires fewer transformations between voltage levels, and the DC-DC converter components come with fewer transformers and different protection devices. Newer technology installation might have a higher initial cost but the potential cost reduction as technology matures and the substations are needed due to the nature of DC voltage conversion [64].

There are several advantages in conclusion for the investment cost of the DC distribution system:

i. Lower transmission losses can be more efficient over long distances for high-voltage transmission in reducing energy losses [65].
ii. Certain applications in simpler infrastructure for DC distribution under renewable energy such as solar and wind naturally generate DC power for battery storage [66].
iii. The cables for DC distribution are less expensive for underground or subsea transmission. It may be cheaper since it requires fewer conductors and simpler insulation compared to AC systems [67].

The investment cost of DC distribution is cheaper in specific cases only such as for high-voltage, long-distance transmission for example HVDC systems, and for data centers and renewable energy systems. This system is more expensive under general distribution because, in residential and standard industrial settings, the cost of switching to DC would generally be higher due to the need for extensive conversion equipment. In summary, DC distribution can offer cost savings in certain specialized applications but is more generally more expensive than AC distribution in typical cases due to new infrastructure and conversion costs [64].

6.2 Potential Revenue Streams

There are 3 categories in potential revenue streams differentiated under energy sales, AC continuing in traditional metering and the billing systems are still in place compared to the DC which means that more efficient energy delivery could reduce losses and improve margins. The grid ancillary services for AC with frequency regulation and voltage support with peaking shaving established demand response programs to reduce peak demand. Grid services for DC are superior for direct integration and the new services have the potential for fast charging, direct-to-renewable integration, and advanced demand response [68].

6.3 Policymakers

To sum up, policymakers related to DC distribution would be the individuals or bodies, and this paper is under the Energy Commission of Malaysia that are involved in crafting the regulatory framework for the adoption, safety standards, and integration of DC systems within national or local energy grids that oversees electricity supply distribution at Malaysia [69]. They are focusing on developing supportive policies and regulations that create a financial incentive, such as tax credits and grants to encourage the adoption of DC distribution systems and integration of renewable energy sources. Thus, policies will develop and promote standards for these systems to ensure compatibility and safety, facilitating easier and broader adoption [19]. For long-term energy planning, the grid modernization initiatives promote the existing grid infrastructure to support the transition to these networks, including upgrading substations and transmission lines [70].

6.4 System Operators

System operator refers to the entity or utility provider that is responsible for overseeing and managing the operation of an electrical grid. This includes ensuring the balance between supply and demand, maintaining system reliability, and coordinating maintenance activities. In Malaysia, the operator of the national grid is Tenaga Nasional Berhad (TNB). They manage the transmission and distribution of electricity across the country, including any developments related to direct current (DC) distribution systems [64-65].

6.5 Energy Industry Stakeholder

Nowadays, with the investment that is highlighted in the development and deployment of innovative DC technologies that come in high-efficiency power converters, advanced energy storage solutions, and smart grid components, the infrastructure is being upgraded including installing new lines, substations, and metering systems designed for DC. In the energy industry stakeholders of DC, the public-private partnership is very important to leverage combined resources and expertise for large-scale projects [73]. Forter collaboration within the industry to share best practices, technology advancement, and lessons learned from DC distribution implementations [74]. These network systems are directed on economic viability that conducts comprehensive cost-benefit analyses to evaluate the economic feasibility of DC projects by taking into account long-term savings and efficiency gains.

Gathering all the business model that capitalizes on the benefits of the DC distribution in such performance by contracting and energy-as-a-service offerings. Optimizing energy for DC distribution systems requires a coordinated effort from policymakers, system operators, and energy industrial stakeholders. By developing supportive policies, improving grid management, investing in innovative technologies, and fostering collaboration, these stakeholders can enhance the performance and economic viability of DC distribution networks, paving the way for a more efficient and sustainable energy future [75].

7.0 CONCLUSION

The investigation into the implications of DC distribution networks on renewable energy integration and flexible energy storage efficiency has yielded several critical insights that highlight the potential benefits and challenges associated with the adoption of DC systems.

Enhanced renewable energy integration in these networks offers a more efficient platform for integrating renewable energy sources. Unlike traditional AC systems, DC networks can handle variable power inputs from solar, and wind energy storage more effectively, reducing conversion losses and improving overall energy efficiency. This seamless integration is crucial for maximizing the utilization of renewable energy and supporting the transition to a more sustainable energy grid. It is also an improved energy storage efficiency and is more flexible as energy storage systems, such as batteries, pumped hydro, and compressed air operate. Increased system reliability on DC networks is inherently more resilient to certain types of failures and can improve the reliability of power supply. The modular nature of DC systems allows for easier integration of backup and auxiliary power sources, enhancing the overall resilience of the grid. This is particularly important in the context of increasing energy demand and the need for robust energy systems.

The implementation of DC distribution networks in Malaysia holds significant potential for enhancing the efficiency of renewable energy utilization, especially as the country seeks to meet its renewable energy targets and improve grid resilience. Areas such as advanced power electronics, efficient DC-DC conversion technologies, and robust grid management systems are key focus areas. Collaboration between academia, industry, and government will be essential to drive innovation and support the deployment of DC systems at scale. In conclusion, DC distribution networks present a promising avenue for enhancing the integration of renewable energy sources and improving the efficiency of flexible energy storage systems. While there are challenges to be addressed, the potential benefits in terms of efficiency, cost savings, reliability, and sustainability make DC networks a compelling option for the future energy landscape. Continued investment in research, technological development, and regulatory adaptation will be crucial to unlocking the full potential of DC distribution networks.

In conclusion, DC distribution in Malaysia presents a promising avenue for enhancing energy efficiency, particularly in the context of renewable energy integration and energy storage. By leveraging technologies like batteries, pumped hydro storage, and CAES, Malaysia can optimize its energy network and create economic benefits through reduced costs and increased investment opportunities. However, careful planning and supportive policies will be crucial to realize these benefits fully.

Acknowledgement

This research is fully supported by The Dato' Low Tuck Kwong (DLTK) International Research grant, 2023823DLTK, Innovation & Research Management Centre (IrMC), and UNITEN Finance Department for the approved fund which makes this important research viable and effective.

Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper.

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