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An Optimization Approaches and Control Strategies of Hydrogen Fuel Cell Systems in EDG-Integration Based on DVR Technology

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ABSTRACT

Electrical Distribution Grid (EDG) will be required to further enhance PQ while also providing higher-efficiency electrical technology. The relationship between the elements of EDG and Hydrogen Fuel Cell Systems (HFCS) was thoroughly examined in this study. This investigation, emphasizes the controller techniques of DVR technology and HFCS interface, as well as the connected converter topology such as multi-input single-output dc-dc converters topology, voltage double boost converters topology, and high step-up coupled inductor converter topology, could contribute to decreasing the danger of EDG by limiting the consumption of fossil fuels for power-generation, reducing the emission of hazardous. Moreover, according to what the research discussed HFCS with EDG interfacing is based on DVR technology. The article delivers several novel contributions to the realm of electrical engineering and renewable energy integration. It presents a pioneering integration of hydrogen fuel cells with DVR technology to enhance power delivery reliability and efficiency within electrical distribution grids. This work introduces advanced optimization algorithms aimed at im-proving the operational efficiency, lifespan, and cost-effectiveness of hydrogen fuel cells. Furthermore, it develops robust control strategies for dynamic voltage restoration, crucial for maintaining stable voltage levels under variable loads. The article also includes detailed simulation models to provide empirical support for the proposed strategies and assesses both the environmental impacts and scalability aspects of the system. These innovative elements ensure that the article contributes significantly to the existing body of knowledge, providing practical solutions and theoretical insights that could influence future research and development in the integration of renewable energy technologies within electrical distribution systems.

1. INTRODUCTION

Achieving a net zero emissions energy system necessitates the development of more diverse and extensive infrastructure. Under the Net Zero Emissions Scenario, transmission and distribution grids are projected to expand by approximately 2 million kilometers annually through to 2030. Additionally, the construction of 30,000 to 50,000 kilometers of CO_2 pipelines is essential during the same period. The establishment of new hydrogen infrastructure is also critical. The successful deployment of this required infra-structure partially relies on streamlining and accelerating the planning and permitting processes to meet these ambitious goals. Following this, there is a strong interest among the public in addressing power quality problems and decreasing emissions of greenhouse gases. It is estimated that PQ concerns cost the economies of the European Union approximately 10 billion euros annually. The Electric Power Research Institute in the United States has estimated that the financial cost of power outages each year approaches USD 100 billion. This has led to a focus on studying the combination of hydrogen fuel cell systems (HFCS) with an electrical distribution grid (EDG) employing dynamic voltage restorer (DVR) technology. Recently, HFCS have assumed a pivotal role within diverse operational domains encompassing transmission, distribution grids, power-generation facilities, demand load management, and industrial applications [1, 2]. In such a scenario, options for storage will be critical, and the pro-duction of green hydrogen has been considered an attractive option for both short-term and seasonal storage [3]. However, the electric distribution grid (EDG) is intrinsically configured to effectuate the dissemination of electrical energy to accommodate the requisites of demand loads [4]. To ensure the unimpeded and seamless operation of a power grid, it necessitates augmentation using a steadfast and dependable power source [5]. Among the most auspicious modalities within the purview of renewable systems for fostering the realization of sustainable energy-generation endeavors, one finds HFCS, wind turbines (WTs), and photo-voltaic (PV) installations [6]. In this direction, the HFCS emerges as a technologically innovative energy system that has garnered significant attention as a prospective solution to the impending energy challenges of the future [7], owing to its intrinsic capacity to furnish commensurate energy supplies in consonance with prevailing load demands [8, 9].

It is obvious that PQ is an increasingly important subject concerning EDG, demand load, and the detrimental impact of pollution on the environment [10, 11]. The primary factors that will determine the impact of temporary disturbance occurrences in the network [12, 13]. Furthermore, DNG-related induction motor starting and transformer energizing problems could have been brought on by PQ issues [14-17]. On top of that, the issue of voltage sag is essential to consider in the context of the fact that the demand load affects EDG alongside how voltage sag adversely impacts the output of the network. The department of energy (DOE), which has been pointed out, predicts that the financial cost of electrical power outages per hour for a brokerage firm is approximately USD 6.50 million, which serves as evidence of this. PQ concerns are thought to cost the European Union's economies 10.0 billion euros per year. Moreover, the electric power research institute (EPRI) U.S. has determined that the yearly financial cost of outages is approaching USD 100.00 billion [18, 19]. Due to this motive, EDG considers it challenging to reach the objective of expected improvements in efficiency, which necessitates significant capital investments. From this angle, the HFCS can be utilized by EDG integration based on DVR technology, which is coupled to deliver stable electricity throughout in short-term or long-term.

The HFCS has the potential to achieve its primary objective of efficient and sustainable energy utilization. As a consequence, a few of study have been dedicated to this subject according to converter topology and optimization approaches. In literature [20], a novel adaptive model predictive control (AMPC) technique for operating proton exchange fuel cells (PEMFCs) has enhanced the output power tracking performance in DC Microgrids. The suggested AMPC technique outperforms the traditional MPC and PI controllers in terms of PEMFC control performance. However, a co-simulation platform has additionally been developed to enable the analysis of transmission and distribution (T&D) network interconnections. Utilizing parallel distributed real-time simulations increases simulation performance. This platform offers an ex-ante evaluation of the influence of T&D network control methods. The performance of the developed primary frequency control strategy employing solid oxide FC systems was proved by a set of experimental findings on European T&D network benchmarks [21]. Kilic and Altun [22] attempted to evaluate the impact of renewable energy resources that can reduce annual emissions by 68-78% for battery storage and 84-90% for hydrogen storage when compared to a diesel-only system. Despite their greater costs, systems with hydrogen storage can store energy over a long period resulting in lower CO_2 emissions. According to the findings of the study [23], employing FC operated by hydrogen produced by renewable energy resources can greatly enhance self-consumption and self-sufficiency. The annual results indicated that using 2.5 kW FC is capable of raising renewable fraction application from 0.622 up to 0.918, energy self-consumption is able to exceed 3338.2 kWh/year, a 98.4% increase and energy self-sufficiency can reach 3218.8 kWh/year, 94.41% increases as well. These results indicate that the suggested PV system is a viable choice for running semi-autonomous or completely autonomous applications in a self-sustaining medium at 95% efficiency.

Identifying article gaps in the article highlights several areas for further investigation. These include the long-term durability and reliability of integrated HFCSs, which may lack sufficient data on maintenance challenges and operational efficiency over time. Additionally, the article could benefit from real-world implementation data and case studies to validate theoretical models and reveal practical challenges. Regulatory and policy implications, as well as the full environmental impact of such systems, might also be underexplored. Moreover, studies on the technological compatibility and integration challenges with existing grid infrastructures, alongside the development of advanced control systems utilizing artificial intelligence or machine learning, could significantly enhance the practical deployment and efficiency of these systems. Addressing these gaps would provide a more robust framework for deploying sustainable and resilient power solutions in the energy sector.

The article presents several novel contributions to the field of electrical engineering and renewable energy integration. The key novelties of this article are outlined as follows:

-Innovative Integration of Hydrogen Fuel Cells with DVR Technology: This article introduces a pioneering approach by combining HFCS with dynamic voltage restorer technology within electrical distribution grids. This integration aims to enhance the reliability and efficiency of power delivery, particularly in scenarios where grid stability is compromised due to variable renewable energy sources.

-Advanced Optimization Techniques for Fuel Cell Management: The paper develops and evaluates advanced optimization algorithms that improve the operational efficiency of hydrogen fuel cells. These algorithms are designed to optimize the fuel cell's performance, extend its lifespan, and reduce operational costs, thereby addressing key challenges in fuel cell technology.

-Robust Control Strategies for Dynamic Voltage Restoration: The article proposes novel control strategies that utilize the capabilities of hydrogen fuel cells to provide dynamic voltage restoration. This aspect is crucial for maintaining voltage levels within acceptable boundaries, thereby ensuring the stability and quality of power in distribution grids, especially under fluctuating load conditions.

-Simulation and Analysis of EDG Performance: By incorporating detailed simulation models, the article provides empirical data and comprehensive analysis on how hydrogen fuel cells can effectively support voltage stability in electrical distribution grids. This analysis helps validate the proposed optimization and control strategies, demonstrating their practical applicability and effectiveness.

-Environmental Impact Assessment: The research also explores the environmental implications of integrating hydrogen fuel cells with DVR technology, highlighting how this approach can significantly reduce the carbon footprint of electrical distribution grids. This is particularly important in the context of global efforts to transition towards cleaner energy solutions.

Besides that, this article is organized as follows: Section 2 describes the integration of HFCS to EDG, types and utilization of FCs in EDG, PQ related to the challenge of EDG, and the Converter Topology of DVR technology. Section 3 discusses the optimization approaches of HFCS in EDG. Section 4 deals with the advantages of HFCS in EDG. Section 5 demonstrates a power protection system for an EDG equipped with HFCS. To sum up, the conclusions are presented in Section 6.

2. INTEGRATION OF HFCS TO EDG

The adoption of HFCS has been widespread within the EDG infrastructure, particularly in the context of Distributed Flexible AC Transmission System (D-FACTS) Technology. Nevertheless, the assessment of HFCS performance presents a formidable challenge, largely attributable to the pronounced divergence in evaluation software among different EDG aspects. Figure 1 illustrates the interfacing diagram between HFCS and DVR technology within the EDG framework. The components that can be combined to interact with the EDG infrastructure include DC-DC and DC-AC converters, filtering systems, and step-up transformers.

2.1 Types and utilization of FCs in EDG

The fuel cells (FCs) demonstrate an electrochemical device characterized by the presence of two dis-tinct electrodes, denoted as the anode and cathode, that facilitate the generation of electrical energy via tandem reduction-oxidation (redox) reactions. These redox processes harness the chemical energy resident in hydrogen or other suitable fuels, typically in the presence of an oxidizing agent, conventionally oxygen. The classification of fuel cells is based on many factors such as the kind of electrolyte, temperature range for operation, and the specific fuel used [24-26]. Regarding this matter, the most extensively studied fuel cell varieties include PEMFCs, alkaline fuel cells (AFCs), solid oxide fuel cells (SOFCs), and molten carbonate fuel cells (MCFCs). Table 1 proposes a summary of the primary FC types used in EDG. Figure 2 depicts a graphical representation of the PEMFC power technology, including additional components such as a hydrogen tank operating under elevated pressure, a compressor for air, valves for both cathode and anode inlets, an output manifold, a nozzle, as well as pressure and humidity sensors.

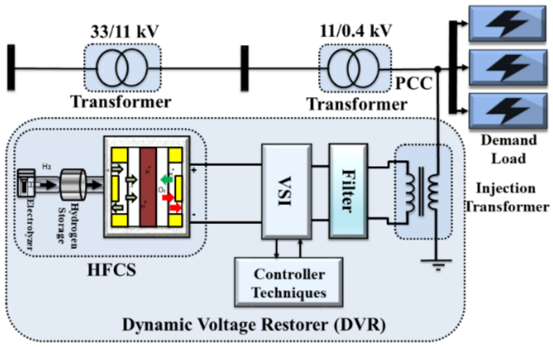

Figure 1. HFCS with EDG interfacing to DVR technology

Table 1. The most prevalent types of FCs employed in EDG [24-30]

FC	Temp. (°C)	Electrolyte	Utilization
PEMFC	Up to 80	Flexible polymer	PEMFC finds diverse applications across various domains, including distribution networks, clean energy power generation, electronic throttle valve control, DC motor systems, servo control mechanisms, and within the field of robotics.
AFC	Up to 600	Solution of potassium hydroxide in water	AFCs are applied in a range of sectors, notably in space exploration, rail transportation, and transit networks.
MCFC	Up to 700	Melton alkali metal carbonates	MCFCs serve multiple applications, including grid power stabilization, distributed generation, power generation, heating production, and cooling production.
SOFC	Up to 850	Solid ceramic oxide	SOFCs can help electrical utility in several applications, encompassing electrical power generation, clean water provision, hydrogen production, integration with diesel-based engines, and incorporation into gas turbines.

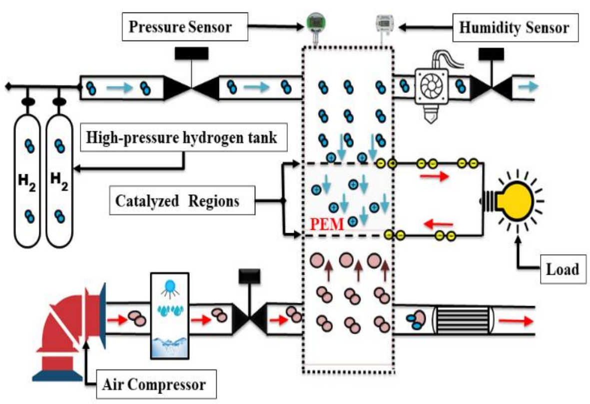

Figure 2. A diagram of PEMFC

In order to enhance the ability of fuel cells to withstand corrosion and operate efficiently, especially with regards to the proton-exchange membrane, novel low-cost bipolar plates have been created. These developments enhance the overall durability of the PEMFC by optimizing operational settings to suit the changing features of the system [27-30]. The hydrogen oxidation reaction (HOR) described here is the essential partial redox process occurring at the anode in a PEMFC.

$$H_2 \rightarrow 2H^+ + 2e^- \quad (1)$$

where, *e* knows an electron.

Simultaneously with another partial redox process occurring at the cathode, hydrogen reacts with oxygen, resulting in the production of water, electricity, and heat, as shown in Eq. (2) and Eq. (3) hereunder.

$$\frac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow H_2O \quad (2)$$

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O + Electricity\ +\ Heat \quad (3)$$

Figure 2 illustrates the functional behavior of a PEMFC, including the levels of electric current and the resulting output voltages. In this scenario, polarization refers to the difference between the maximum voltage that can be achieved theoretically and the actual output voltage. It can be quantified using the Eq. (4) as follows:

$$E = -\frac{\Delta G}{nF} \quad (4)$$

where, $\Delta G\ (J\ mol^{-1})$, refers to the Gibbs free energy; n, knows as to the number of electrons transferred into a $hydrogen$ molecule, and F illustrates to the Faraday's constant, 96,485.0 Coulombs mol^{-1}. Hence, the total energy (the difference in enthalpy, ΔH) can be computed using Eq. (5) as shown. The symbol T (K) denotes the temperature in Kelvin, whereas $\Delta S\ (J\ mol^{-1})$ indicates the entropy difference between the product and reactant for one mole of hydrogen. The highest possible energy efficiency (η_{max}) of FC can be determined using Eq. (6). In its entirety, the PEMFC has unequivocally augmented efficiency performance by over 83% under conditions set at 25°C [31]. Consequently, the voltages exhibited by the PEMFC, denoted as (E_{cell}), may be expressed through the formulation outlined in Eq. (7).

$$\Delta H = \Delta G + T\Delta S \quad (5)$$

$$\eta_{max} = \frac{\Delta G}{\Delta H} \quad (6)$$

$$E_{cell} = E_{OCV} - \eta_{act} - \eta_{ohm} - \eta_{trans} \quad (7)$$

where, E_{OCV} indicates the open-circuit voltage, while η_{act} deals with activation loss. η_{ohm} shows the loss of electrical resistance, and η_{trans} refers to the mass transport loss.

2.2 DVR technology controller techniques

The emergence and advancement of DVR technology have been propelled by its efficacy in optimizing energy utilization, stabilizing voltage levels, exerting control over power demand, rectifying power factor discrepancies, mitigating voltage sags, and alleviating harmonic distortions, as elucidated in references [32, 33]. Consequently, the foundational underpinnings of DVR technology are rooted in the comprehension and application of high-voltage power electronics to regulate both transmission and distribution grids [33-36], Table 2 provides an overview of recent DVR technology controller techniques, serving as a reference point for understanding the variations in this technology's implementations.

Table 2. Recent controller techniques of DVR technology

Ref.	Year	Type of D-FACTS	Controller Techniques	Aims	PQ Issue
[37]	2023	DVR technology	ANFIS	•A Compressed Air Energy Storage (CAES) based on DVR technology has been devised to effect series voltage compensation within EDG linked to highly sensitive loads. •The control and operation of the DVR technology are seamlessly orchestrated by an Adaptive Neuro-Fuzzy Inference System (ANFIS) controller, which affords comprehensive governance over the pulse width modulation inverter. •The system's performance has been rigorously scrutinized across various fault scenarios within the EDG, yielding a comprehensive set of analytical findings.	Voltage sag
[38]	2023	DVR technology	MOPO	•In the pursuit of the article's objective, an enhanced approach is introduced, employing an optimized differential evolution algorithm in conjunction with Multi-Objective Parallel Operation (MOPO). •This particular optimization technique has been chosen due to its demonstrated attributes of rapid convergence and the capacity to assign elevated priority to population members based on the hyper-volume metric defined by the Pareto front.	voltage sags voltage swells
[39]	2022	DVR technology	Lyapunov stability theory Uncertainty and disturbance estimator (UDE)	•In this article, the efficacy of the suggested approach is empirically substantiated through the utilization of MATLAB/Simulink software, wherein a comprehensive range of conditions is meticulously examined without encountering any control constraints. •The novel control system exhibits a multitude of advantages, encompassing robustness, streamlined design, proficient harmonic attenuation, minimal tracking error, swift response characteristics, and the capability for precise tracking of sinusoidal references.	Harmonic
[40]	2022	DVR technology	SMC	•This paper introduces a control system predicated upon the principles of sliding mode control (SMC) specifically tailored for a three-phase three-wire DVR technology, designed with the primary aim of mitigating voltage anomalies characterized by sag and swell phenomena. •The proposed control methodology offers several distinct advantages, including robustness in the face of parameter fluctuations, guaranteed system stability, ease of implementation, and a notably swift dynamic response.	Voltage harmonics
[41]	2022	DVR technology	ZSA	•This study illustrates a notable reduction in the zero sequence attenuation (ZSA) load voltage. Moreover, it was discerned that the conventional topology exhibits diminished efficacy in mitigating unbalanced voltage sags and swells, particularly in cases involving extremely low power loads.	voltage sags voltage swells

To date, several studies have investigated DVR technology which is a widely recognized, low-cost beneficial properties to mitigate severe sag and swell and other PQ issues [42]. A DVR's mitigation capability depends on the highest voltage it can inject and active power involvement. However, Standard DVRs utilization batteries as their DC input are difficult to obtain, costly, and dangerous to dispose of after usage. This study recommends boosting the DVR's VA assessment by 1.5 times by boosting the DC interconnection voltage to 1.5 times with the microgrid regulator's voltage and quality enhancement approaches. In this direction, the primary objective of the present investigation [43] is to improve the transient responses of 3-phase load voltage and DC-link voltage during immediate grid voltage distortion scenarios. For the DC-link voltage regulation of the DVR technology, an outstanding recurrent compensation petri fuzzy neural network (RCPFNN) controller is initially demonstrated as an alternative to the existing proportional-integral (PI) and fuzzy neural network (FNN) controllers. The identified RCPFNN controller's detailed network topology and online learning method are derived. Furthermore, some results from tests are shown to validate the potential and efficacy of the DVR technology employing the suggested RCPFNN controller for enhancing load transient voltage quality.

Moreover, a great deal of previous research into DVR technology has focused on PQ issues in EDG [44]. This article recommended a transformer less Packed U Cell (PUC)-based DVR technology solution with single-phase solar power systems. The explored topology is distinguished by its more affordable price and size due to the absence of the injection transformer. During the voltage line disruptions, a reliable finite control set model predictive control (FCS-MPC) technique was presented to ensure the generation of the appropriate compensatory voltage while managing the filtering current and the PUC capacitor voltage within their references. Besides that, theoretical analysis, simulation, and actual implementation results were provided under normal and disturbed operation situations to illustrate the suggested solution's high dynamic efficacy and efficient operation. To address PQ issues in EDG, the sliding variable is proposed [45] for each converter leg that is a function of the respective filter-capacitor voltage and a fictional voltage that relies on the converter neutral-point voltage (NPV). The suggested approach permits control of both the compensator voltages and the converter NPV. This article additionally demonstrates methods to calculate the optimal sliding coefficient for a four-leg DVR technology in order to achieve the optimum sliding existence region. To conclude, the suggested control scheme's performance is experimentally confirmed within several operating situations employing a laboratory prototype of a four-leg DVR technology.

2.3 PQ related to the challenge of EDG

In order to address PQ-related issues such as voltage sag, current disturbance, harmonics, and unbalancing, PQ needs to bring together technical approaches. To be able to provide an excellent power energy supply, which in its purest form necessitates symmetry, balance, and access to clear, noise-free sinusoidal wave appearance, the electrical system as a whole need to fulfill certain requirements [46, 47]. Whenever frequency and voltage are brought into account, DVR technology is a typical solution that forms stability of EDG in PQ issues. The IEEE and IEC Standards are rapidly developing definitions to describe power quality. The PQ issues were the primary cause of the EDG failure. Table 3 shows the most frequently PQ-related issues in EDG.

Table 3. The most frequently PQ-related issues in EDG [48-51]

Issue	Impact	Description	Solution
Voltage sag	•Heavy motor starts •Errors in the customer's implementation •Insufficient maintenance of the system •EDG system failures	At the moment V_{rms}> < V_{nom} from 10 % to 90 % for 0.50 cycles to 60 seconds.	DVR Technology
Voltage swell	•Unreliable power utility sources •Switching demands •Regulated incorrectly transformers •Unstable power sources	Whenever V_{rms}> V_{nom} from 10% reached to 80% for 0.5 cycles to 60 seconds.	DVR Technology
Variable fluctuation	•The primary cause of frequent switching •The underlying reason for welding plants •Identify the source of arc furnaces	When the fluctuations in V_{rms} from 90% reached up to 110% of V_{nom}.	DVR Technology
Voltage spikes/surges	•Heavy loads must be disconnected	Voltage rate abruptly changes for many seconds to a few milliseconds	DVR Technology
Long interruptions	•Inadequate coordination of protective equipment •Equipment breakdowns and fire	When EDG supply interruptions occur for > 1s or 2s duration of time	DVR Technology
Harmonic	•The main driver of system resonance •Non-linear loads have been employed in the tool to generate non-sinusoidal currents	The essential frequencies of the voltage or current waveforms involve non-sinusoidal waveforms within others.	DVR Technology

2.4 The converter topology of DVR technology

Essentially, EDG is able to obtain power from HFCS employing DVR technology. The DC converters generate demand power by HFCS and then support the required power into EDG based on injection transfer. Concerning this, DVR technology at the utility-scale involves the following elements:

2.4.1 DC-DC converters topology

Due to their significant DC output voltages, DC-DC converter's topology has various industrial uses for generating large step-up voltage gain, such as in DVR technology and energy-efficient systems, as well as other alternative sources of energy [52]. A traditional boost converter, on the other hand, cannot achieve such high-voltage benefits due to its restricted duty cycle [53, 54]. It is possible to achieve boost converters with higher voltage gains by employing an extreme duty-cycle design and utilization. The voltage and power output in high-frequency current source (HFCS) applications exhibit variability and a substantial dependence on the operating parameters. Therefore, DC/DC power converters are frequently utilized to ensure a consistent voltage that aligns with the subsequent power bus. Due to the nonlinearity of HFCS and load pat-terns. In this point, power converters must be designed to be more resilient. The EDG continues to rapidly create such applications [54-56]. Bidirectional power flow is supported by the DC-DC converter topology. Figure 3 depicts a standard boost converter (BC) topology connected to HFCS whereas Figure 4 depicts an interleaved boost converter (IBC) topology coupled to HFCS.

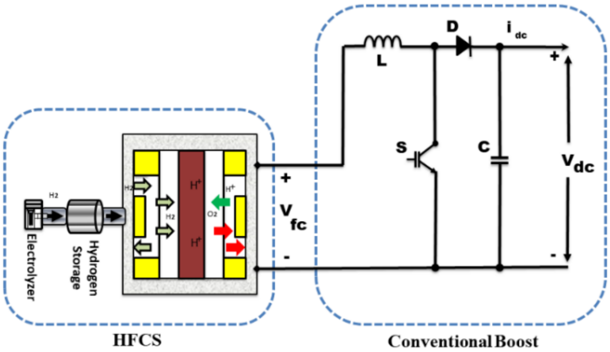

Figure 3. The standard BC topology

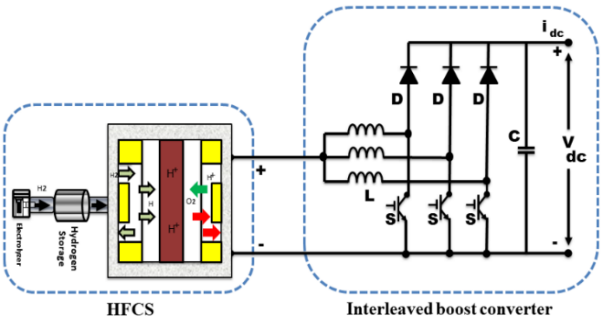

Figure 4. The IBC topology

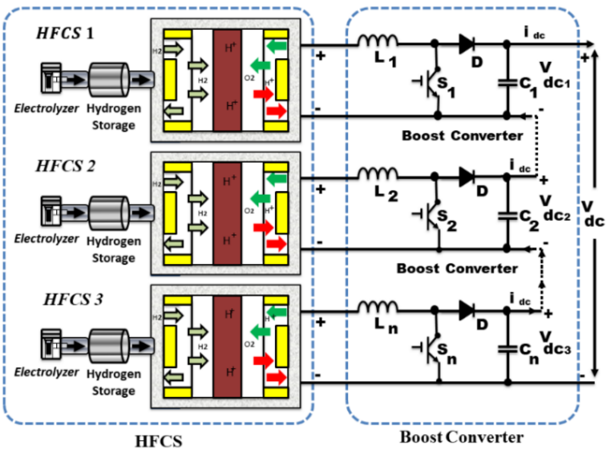

Figure 5. The MISO topology

The isolated boost converter (IBC) configuration is used in conventional design approaches for DC-DC converter topologies, largely to mitigate potential problems related with the operation of high-frequency semiconductor switches. The interleaved DC-DC converter, on the other hand, is used delib-erately to achieve two goals: reducing input current ripples and minimizing switching losses. This novel tech-nique contributes greatly to the overall efficiency of the converter system, distinguishing it from typical converter topologies. However, The IBC topology uses in small electronic components. Meanwhile, some recent studies of DVR technology applied multi-input single-output (MISO) converters topology interfaced with HFCS as shown in Figure 5.

Nevertheless, the impact of passive circuit components, which include inductors and capacitors, on cir-cuit performance is crucial in DC-DC power converter architecture circuits. The voltage that produces ripple is substantially influenced by characteristics such as duty ratio values and the switching frequency of the ac-tive power semiconductor. This ripple, in turn, can exhibit variation contingent upon the prevailing load con-ditions. Furthermore, in the realm of HFCS, voltage doubler boost converters (VDBC) topology is charac-terized by the utilization of four parallel phases as depicted in Figure 6 which have gained widespread adop-tion. Figure 7 illustrates the VDBC topology that incorporates an isolation transformer.

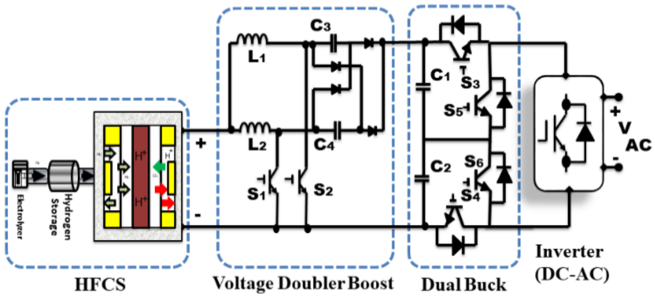

Figure 6. The configuration of a voltage doubler, boost converter, and dual buck converter

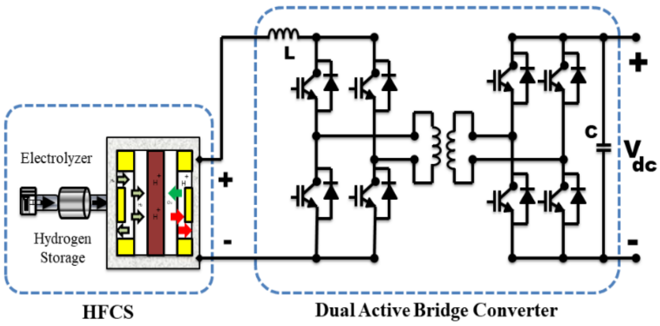

Figure 7. The VDBC topology, which relies on the utilization of an isolation transformer

Bridge converters are frequently employed in the analysis of isolated DC-DC converter topologies to enhance the stability of the output voltage. Figure 8 depicts the configuration of a dual half-bridge converter (DHBC) in a high-frequency current source (HFCS) system utilizing an isolation transformer. While the dual full-bridge converter (DFBC) topology is more intricate and costly, the power regulation in this converter is less complicated than in other DC-DC converters. This article discusses two types of bridge-based DC-DC converters: the current-fed DHBC and the voltage-fed DHBC. Furthermore, the dual active bridge is a type of bridge converter commonly employed in high-frequency communication systems for interconnecting energy delivery grids. Figure 9 depicts the schematic diagram of a dual-active bridge converter (DCBC) topology. Figure 10 depicts the circuit of a forward converter topology (FCT), which utilizes a transformer to achieve galvanic isolation. On the other hand, Figure 11 illustrates the topology of a high step-up coupled inductor converter (HSUCIC). In addition, the high step-up coupled inductor converter and zero-voltage transition are two other topologies that offer significant voltage conversion ratios. Figure 12 depicts the configuration of zero-voltage transition converters (ZVTC) coupled to high-frequency current sources (HFCS).

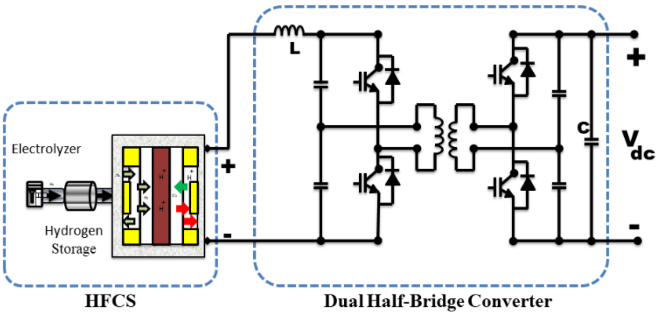

Figure 8. The DHBC topology

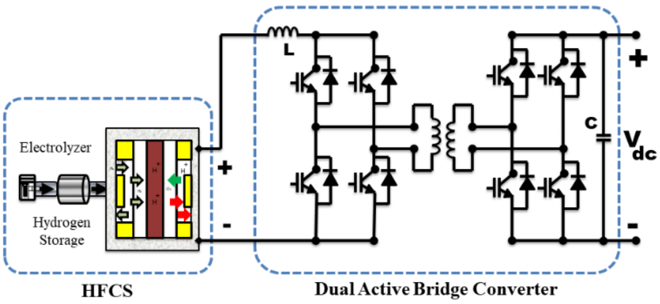

Figure 9. The circuit of DFBC topology

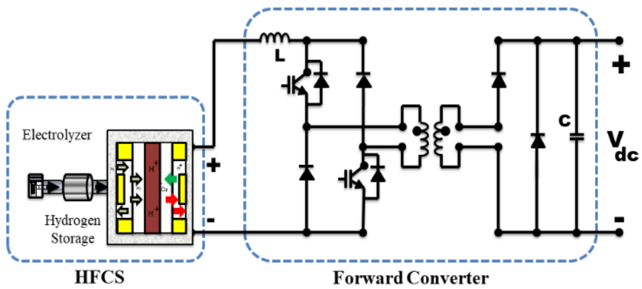

Figure 10. The circuit of FCT

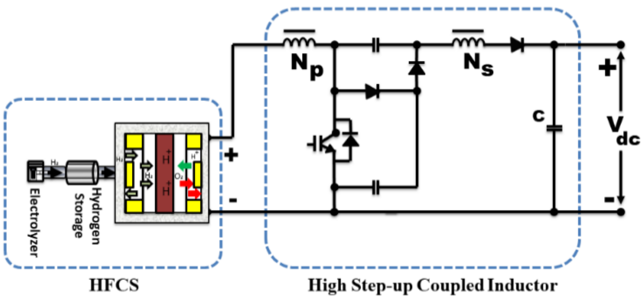

Figure 11. The HSUCIC topology

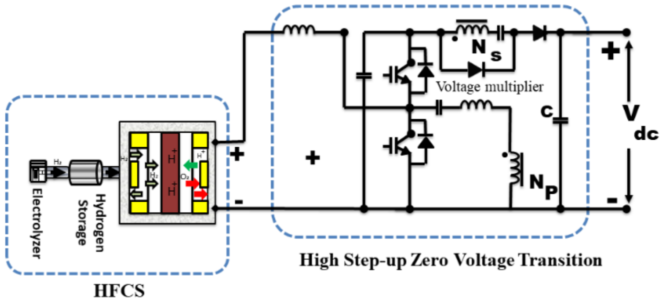

Figure 12. The ZVTC topology

2.4.2 The DC-AC inverter

The voltage-source inverter (VSI) of DVR technology operates as a power interconnection between the HFCS stack and an EDG network. It converts DC electricity to sinusoidal AC [57], and can produce three-phase waveforms employing the DC/AC inverter. The inverter controls energy by modulating it through six semiconductor switches. Each of them has a controllable on-off state determined by the duty ratio of PWM [58]. The network characteristics will undoubtedly alter with the integration of several power inverters, posing additional technical issues such as sophisticated control systems, sophisticated stability analyses, and systematic protection. The primary function of this VSI-DVR technology is to supervise the real and reactive power flowing through the HFCS and EDG interactions.

2.4.3 Filters

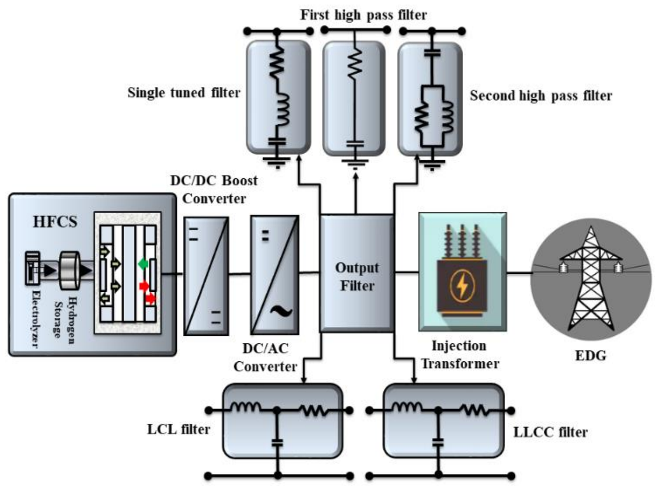

Figure 13. Several types of passive filters at EDG connected with HFCS

DVR technology relies on filters to ensure effective harmonic protection, reap reactive power ad-vantages, achieve load balancing, compensate for neutral current, and reduce flickering. The inclusion of filters in VSI in DVR technology is linked to improved noise performance, leading to a decrease in size, volume, and cost [59, 60]. Passive filters that make employing DVR technology are commonly used in ELG systems to enhance power quality. The inclusion of voltage harmonics reimbursement, current harmonics re-imbursement, three-phase mains voltage balancing, and three-phase mains current balancing renders it a highly attractive and widely adopted an approach even in the present day. Harmonic distortion is particularly problematic due to the line current produced by non-linear loads. Total harmonic distortion (THD) can cause a multitude of issues, including conductor excessive heat, voltage distortion, transformer failure, unneeded protective device trip, and network interference. As to the IEEE Standard 519-2014, if the THD level at the point of common connection (PCC) falls below 8% at low voltage levels, it is necessary to assess the system. Moreover, IEEE Standard 1547 imposes a restriction on the THD of the injected current, setting the maximum allowable value at 5%. Figure 13 depicts various types of passive filters for DVR technology attached to EDG alongside HFCS.

2.4.4 Transformer

Currently, the benefits of improving the energy efficiency of EDG coupled with HFCS are becoming more evident. This includes enhancing the reliability of power utility systems, reducing operational expenses, improving signal PQ, and minimizing negative environmental impacts. Due to these factors, DVR technology transformer stations have become a crucial component in all EDG systems. Furthermore, distribution transformers are strategically placed at the final stations in order to provide electrical feeders, hence enhancing the efficiency of the distribution chain [61]. Attaining targeted and efficient advancements in standards plays a crucial role in shaping the equilibrium of demand and supply, as well as the success of the network process. This, in turn, determines the smooth functioning of the system. An in-depth analysis of the electrical power requirement of the Emergency Diesel Generator (EDG) has been conducted utilizing distribution transformers, which also provides precise forecasts for the EDG. In this regard, transformers are subject to extremely harsh operating conditions and have inflicted significant harm to unwanted high-frequency impulses as a result of direct lightning impulses, electrical circuit breaker functioning, and system malfunctions [62].

The significant benefits of improving the energy efficiency of EDG coupled with HFCS have become more readily apparent in recent years. This increased efficiency not only improves the performance of mod-ern utilities systems, but it also reduces costs related to operation, improves PQ, and reduces negative environmental impacts. As a direct consequence, transformer stations that employ DVR technology have become essential components of all EDG systems. Furthermore, the well-chosen placement of distribution trans-formers at terminal stations entrusted with delivering electrical feeders improves the overall EDG's efficiency [61]. In this situation, achieving precise and effective developments in standards emerges as a critical determinant impacting the demand-supply balance. The success of this network process, in turn, dictates the system's smooth operation. Through the use of distribution transformers, a thorough examination of the EDG's consumption is methodically carried out. This approach not only offers precise estimates for the EDG, but it also emphasizes the vital function of transformers, which collaborate in difficult situations. They have been critical in preventing substantial damage resulting from high-frequency impulses generated by circuit breakers, direct lightning strikes, and failures in systems [62].

3. OPTIMIZATION APPROACHES OF HFCS IN EDG

The present trend is technically interesting and invigorating; specifically, optimization approaches that contributed to a better comprehension of HFCS, the incorporation of a hybrid energy storage system (HESS), and the integration of renewable energy sources (RES) with the EDG. Optimization approaches are typically considered a necessary component of both HESS and DVR technology, and they have been enhanced by intensive content in the EDG as well as technical and academic investigations in research and development centers. Enhancing the EDG's power efficiency is a critical issue in this regard, both economically and environmentally. The following are some of the findings, HFCS, CAES, SMES, SC, PHES, FES, BESS, and wind-turbine (WT), photovoltaic (PV) [63-65]. Electrical utilities are considering HFCS as the most viable power solution for directed-PQ trouble and EDG instabilities. Because of their ability to integrate with other EDG, SMEs are additionally considered HESS. A further significant feature of EDG is the ability to incorporate RES, which is fundamental to the electric utility's long-term future. Other important characteristics are high energy density, high power density, quick reactivity, outstanding efficiency, increased dependability, and the capacity to integrate RES. The technical integration of HFCS could potentially be employed in many different kinds of approaches to achieve the main purpose. Table 4 highlights the optimization approaches applied in HESS and RES, integrating HFCS.

Table 4. The optimization approaches applied in HESS and RES, integrating HFCS

Ref.	Year	HESS	RES	Optimization	Objectives
[66]	2023	HFCS - HESS	PV	COE & NPC	•The analysis of article revolves acoording calculating the most suitable size of the PV/PEMFC system according to two essential criteria: the lowest possible cost of electricity (COE) and the lowest possible present price (NPC). PEMFCs with power ratings of 30 kW, 40 kW, and 50 kW are considered in the study, as the following PV panel possibilities. •The work offers the most affordable values for NPC at USD 703,194 and COE at USD 0.498 per kWh according to these optimal circumstances. •The levelized cost of hydrogen ranges from USD 15.9 to 23.4 per kilogram. Furthermore, replacing the 30 kW Trina PV panel with a 50 kW Tindo PV module saves 32% on costs.
[67]	2023	HFCS - HESS	BESS PEMFC	DLO & Hybrid PSO-GWO	•The purpose of this paper is to concentrate on developing a strategy to address the ESS lifespan which is estimated using a battery deterioration model. •The sizing challenge, and the optimal allocation of power are combined into a minimizing expenses challenge, which is handled using a double-loop optimization (DLO) technique, hybrid particle swarm optimization (PSO), and gray wolf optimization (GWO).

[68]	2023	HFCS-HESS	PVESS		•In this study, a large-scale EDG-interfaced PV-hydrogen-natural gas interfaced energy system is established to explore the effects of the configuration of the interfaced energy system on the economic side and its environmental aspect. •A multi-objective hierarchical optimization allocation theory has been developed and a strategy for optimization with carbon emission greater in terms of overall cost has been established.
[69]	2023	HFCS-HESS	PEMFC & Li-ion battery	FLC, GA, & K-MC	•This article targets strategy optimization based on fuzzy logic controller (FLC) and optimized by genetic algorithm (GA), K-means clustering (K-MC) method with driving cycle recognition to achieve near-optimal fuel economy, stable BESS charge sustenance, minimum equivalent hydrogen consumption of four typical driving cycles. •The full PEMFC framework, which comprises an EDG, dynamic system, and management of energy system, has been determined. •The modeling findings show that the suggested technique reduces equivalent hydrogen consumption by 16.55% and 40.50%, respectively, as compared to GA-optimized fuzzy EMS and standard fuzzy EMS.
[70]	2022	HFCS - HESS	PV, WT, DG, & BESS	NPC & LCOE	•The aim indicates that the net present cost (NPC) and leveled energy cost (LCE) as optimum solutions for RES in Kayseri. •This article objects to implementing the HESS involving hydrogen storage. PV, WT, diesel generator (DG), and BESS using the HOMER Pro software. •This article finds that HESS is the most economical, and the price of energy is 0.376 $/kWh. Moreover, the 68% RES ratio has the least CO_2 emission for meeting the residential load requirements.

Despite its great efficiency, zero emissions, minimal noise, and numerous other benefits, HFCS have been demonstrated to be capable of mitigating PQ issues in EDG. The development and implementation of optimization approaches to energy management have become the focus of recent research to extend the lifespan of HFCS. Musharavati and Khanmohammadi [71] discussed the effect of FC based on the following aspects, output power and voltage, and current density on voltage losses. A parametric analysis is also performed to illustrate the impact of main design parameters on system efficiency. In this direction, energy-economic multi-criteria optimization is applied to figure out optimum parameters to achieve improved efficiency and lower fuel and equipment costs as well. According to computing, the proposed setup can produce 53.46 kg/s of water from desalination, 54.8 MW of power, and 7.43 kg/h of hydrogen energy. The overall exergy efficiency within this scenario is approximately 36.45%, but optimization approach findings demonstrated that that percentage could be increased between 50.8% and 61.17% with the cheapest system price. Meraj et al. [72] pro-posed the PSO algorithm-based energy management system to optimize the approach to managing energy and address the problem of PQ-related degradation in FC hybrid power grid ships. Besides that, using the FC ship as the target power grid ship, the Matlab/Simulink system simulation model is created to validate the recommended energy management method. The optimized hybrid power system's bus voltage curve varies more softly, and the issue of voltage sag is decreased, as a result of simulations and comparisons. When compared to the original ship, the amplitude of the voltage fluctuation during maneuvering situations is reduced by 55%, respectively. To sum up, the HFC-DVR technology integration can significantly enhance the overall stability of EDG by addressing certain stability concerns through appropriate design and optimization approaches [73-75].

4. ADVANTAGES OF HFCS WITHIN EDG

Tripling the capacity of renewable energy sources constitutes the primary mechanism for achieving emission reductions by 2030 within the context of the Net Zero Emissions by 2050 Scenario. Advanced economies and China are anticipated to attain approximately 85% of the requisite renewable capacity by the year 2030 under existing policy frameworks. However, to realize similar advancements in other developing nations, the implementation of more vigorous policy measures and enhanced international support are imperative. This strategic expansion is essential for aligning global energy practices with the ambitious targets set forth in the NZE Scenario, highlighting a pivotal shift towards sustainable energy systems. Following this, reducing methane emissions from the energy sector yields substantial climate advantages. Within the frame-work of the Net Zero Emissions by 2050 Scenario, it is estimated that approximately USD 75 billion in cumulative investment is needed by 2030 to implement all methane abatement strategies in the oil and gas industry. Remarkably, this investment represents merely 2% of the net income that the oil and gas sector recorded in 2022. This juxtaposition underscores the economic feasibility of significant methane reduction measures relative to the industry's financial capabilities, highlighting an efficient pathway towards mitigating one of the most potent greenhouse gases [76-80].

Emerging technologies like hydrogen and carbon capture, utilization, and storage (CCUS) are projected to play a pivotal role in emissions reduction primarily post-2030. In the context of the Net Zero Emissions by 2050 Scenario (NZE Scenario), if all currently announced projects for hydrogen electrolysis capacity come to fruition, they are anticipated to fulfil approximately 70% of the requisite capacity by 2030. Similarly, the CCUS projects that have been announced, predominantly within advanced economies, are expected to meet nearly 40% of the global requirements by the same year. These figures underscore a critical need for enhanced policy measures aimed at fostering demand for low-emission products and fuels, thereby ensuring these technologies achieve their potential in reducing greenhouse gas emissions effectively and sustainably. In this direction, the realization of hydrogen deployment as outlined in the Net Zero Emissions by 2050 Scenario (NZE Scenario) hinges critically on significant investments in the production, transmission, and distribution of low-emissions hydrogen and hydrogen-based fuels. Current annual investments approximate USD 1 billion;

however, this figure must escalate to around USD 150 billion by 2030 to align with NZE tar-gets. Additionally, achieving these goals requires an investment of at least USD 100 billion in dedicated renewable electricity capacity. This substantial increase in funding is essential to establish the infrastructure needed to support a hydrogen economy that contributes effectively to reducing global emissions [81-84].

The advantages associated with the integration of HFCSs within EDGs represent a subject that transcends the confines of the present discourse. HFCSs exhibit the potential to ameliorate power quality (PQ) concerns, notably in addressing voltage sag mitigation. Furthermore, HFCSs have demonstrated their proficiency in load peak shaving through energy storage during off-peak periods and subsequent energy discharge into the distribution grid feeders during peak demand intervals. By employing HFCS-equipped EDGs for this purpose, demand profiles can be rendered more uniform, thereby enhancing PQ. This comprehensive assessment takes into consideration all pertinent capital outlays and economic dividends arising from HFCS adoption, drawing upon the substantiated competencies of this technology. The utilization of HFCSs engenders substantial benefits for the EDG and can be enumerated as follows:

(i) HFCS-equipped EDGs possess the inherent capacity to deliver peaking power without exerting a significant impact on CO2 emissions reduction.

(ii) HFCS-equipped EDGs exert a substantial influence on the enhancement of distribution grid infra-structure, ameliorating the resilience of the network against power quality challenges.

(iii) HFCS-equipped EDGs significantly contribute to the fortification of the EDG system, thereby enhancing its robustness against power quality issues, including voltage sag.

(iv) HFCS-equipped EDGs play a pivotal role in providing support for both reactive and active power, facilitating the maintenance of voltage levels within the EDG.

(v) The HFCS-equipped EDG represents a pivotal technological enabler for the dependable and adaptable integration of various renewable energy sources into diverse applications within the power grid.

(vi) HFCS-equipped EDGs offer an elevated degree of flexibility in the context of static power electronic devices such as DVR, and DSTATCOM.

(vii) The HFCS-equipped EDG is capable of storing substantial quantities of energy, further enhancing its utility and versatility.

5. POWER PROTECTION SYSTEM FOR AN EDG EQUIPPED WITH HFCS

EDG has recently been connected to other types of DG, such as RES and ESS. Along with the positive effects of integrating DG into the EDG, such as eliminating peaks and enhancing EDG reliability, DG sources pose additional and more complicated issues in terms of sensitivity as well as selectivity in the power protection system. Consequently, the effects of DG on EDG must be carefully considered while designing an appropriate protective system. In more general terms, many investigators focused on the power protection challenges posed by the integration of renewable energy sources in the EDG without taking into account the ES. There have been barely a few authors that have explored and researched the implications of connecting ESS to the EDG. In comparison to the EDG without ESS, the ESS generates an elevated level of short circuit current in the EDG dependent on the ESS operation state (charging, storing, discharging). As a result, of this during islanded operations, protection relays struggle to identify the issue using typical overcurrent protection devices and algorithms. Depending on the ESS operation scenario, the ESS might raise the fault cur-rent level, which allows the protection relays to operate.

The article offers a detailed exposition on the design, operation, and performance evaluation of the pro-posed protection scheme as following.

According to Barra et al. [85], the integration of distributed energy resources (DERs) and various operating modes can render traditional protection schemes ineffective. Consequently, novel protection schemes have been developed specifically for microgrids, as well as for distribution systems equipped with distributed generation (DG). This paper provides an extensive survey focused on research pertaining to such innovative protection mechanisms. Particular emphasis is placed on adaptive protection strategies, which some re-searchers consider to be a highly promising approach for ensuring the safety and efficiency of microgrid systems. This survey aims to synthesize the current knowledge base, highlight advancements, and identify the potential of adaptive protection solutions in the context of modern electrical power systems.

Tsimtsios et al. [86] presented a novel pilot-based distance protection scheme is proposed for meshed distribution systems characterized by high penetration of DG. The scheme is designed with distance relays installed at opposite ends of each main line segment. To safeguard the integrity of the main line segment, a forward distance element is activated in each relay, while a reverse distance element is employed to protect adjacent buses and laterals. These relays, responsible for protecting either a main line segment or a bus/lateral, utilize permissive logic communication to balance protection sensitivity with security. The proposed protection scheme ensures comprehensive primary and backup protection against all types of faults, including those with significant fault resistance, and remains effective under weak-infeed conditions. Furthermore, the scheme is adept at functioning in both grid-connected and islanded modes of operation. Additionally, the coordination between the distance protection scheme and lateral protection methods is thoroughly examined to enhance overall system reliability and safety.

Faria et al. [87] proposed a multi-objective optimization approach to effectively manage the allocation, sizing, and coordination of control and protective devices within distribution networks that incorporate various types of distributed generation. The model integrates three objective functions: minimizing investment costs, reducing the system's non-supplied energy, and lowering the average interruption duration index. A probabilistic short-circuit routine is utilized to assess current values, taking into account the uncertainties associated with renewable power generation, system loading, and the randomness of fault parameters. This probabilistic methodology facilitates accurate planning of the protection system. It also permits the acceptance of a certain level of risk regarding non-coordinated operation, with the strategic aim of reducing overall solution costs. This approach provides a comprehensive framework for enhancing the reliability and economic efficiency of distribution networks, particularly in the context of increasing integration of renewable energy sources.

In the study [88], a focus is placed on the critical areas of protection and monitoring within distribution systems, topics of paramount interest to distribution providers who are continually seeking innovative management strategies. The paper proposes several potential applications that leverage smart meters for the protection and monitoring of distribution systems. The underlying expectation articulated in this study is that the utilization of smart meters will facilitate the necessary justifications and validations needed to advance and promote future smart metering projects. The authors argue that smart meters can significantly enhance the efficiency and reliability of distribution systems by providing more precise and real-time data, thus supporting more informed decision-making and potentially leading to cost reductions and improved service quality in the long term.

Rezaei and Haghifam [89] proposed a novel intelligent distance relaying scheme tailored for series-compensated lines that are integrated with wind farm systems. This scheme uniquely employs only current measurements to facilitate its operations. For fault detection, the methodology relies on analyzing the signs of the half-cycle magnitude differences of the line end positive-sequence currents. Additionally, the task of fault classification is accomplished exclusively using local current measurements. These measurements are processed through an advanced analytical technique known as the Fourier–Bessel series expansion combined with a bagging ensemble classifier. This methodological approach enhances the reliability and accuracy of fault detection and classification, crucial for maintaining system stability and efficiency in complex power networks such as those incorporating renewable energy sources.

In conclusion, the integration of HFCS with EDG represents a significant advancement in the quest for sustainable and resilient energy systems. The development of power protection systems tailored for this integration is essential to ensure the stability, reliability, and efficiency of the grid under varying operational conditions. In addition, the deployment of HFCS within EDGs introduces unique challenges, primarily due to the dynamic and variable nature of hydrogen fuel cells as an energy source and the potential for grid instability it poses. A robust power protection system mitigates these risks by managing irregularities and protecting the grid infrastructure from potential damage caused by faults and fluctuations. In this context, key components of an effective protection strategy for HFCS integrated with EDGs include advanced detection mechanisms for rapid identification of faults, sophisticated control algorithms that adapt to the unique characteristics of hydrogen fuel cells, and comprehensive monitoring systems that continually assess the health and performance of the grid. Addition-ally, the system must be capable of distinguishing between normal operational variations and genuine fault conditions, a task that requires precise calibration and a deep understanding of both HFCS and EDG dynamics.

6. CONCLUSIONS

A significant contribution of this article lies in its comprehensive exploration of the integration of HFCS with EDG utilizing DVR technology. This article addresses a pressing global concern, as it is increasingly imperative to mitigate PQ issues and reduce greenhouse gas emissions. The article recognizes the pressing need for enhanced PQ in EDG. By using DVR era in association with HFCS. This innovation is crucial for making sure the reliable functioning of various electrical gadgets and structures connected to the EDG. The article recognizes the want of implementing more powerful energy tech-neologies' with a view to lower the usage of fossil fuels for the motive of generating electricity. This efficiency is better by integrating HFCS with EDG and utilising advanced converter topologies. This technique well-known shows capacity for reducing the release of greenhouse gases and fostering sustainability. The article explores one-of-a-kind converter to-apologies, which includes MISO dc-dc converters, VDBC, and HSUCIC. This thorough analysis gives useful insights into deciding on appropriate converter designs packages, subsequently mitigating the risks related to EDG operation. EDGs outfitted with HFCS were diagnosed for their ability to enhance the robustness and steadiness of the EDG. They offer crucial assistance for managing each reactive and energetic strength, ensuring that voltage levels stay inside permissible thresholds. This feature enhances the reliable and resilient functioning of the electricity grid, specifically while dealing with PQ troubles. In end, this newsletter now not simplest highlights the importance of integrating HFCS with EDG the use of DVR generation but also affords valuable insights into the technical elements, converter topologies, and blessings related to this integration. By addressing critical issues related to PQ, emissions reduction, and grid stability, this research offers a substantial contribution to the field of electrical power systems and sustainable energy technologies.

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