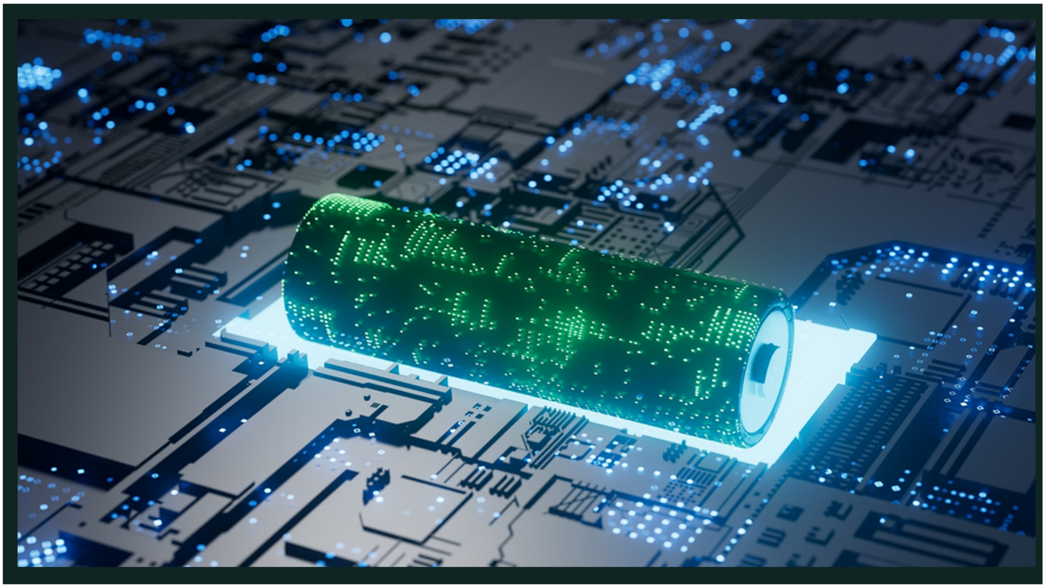

Advancements and Emerging Topics in Electrical and Electronics Engineering

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Advancements and Emerging Topics in Electrical and Electronics Engineering
Editor*: *Assoc. Prof. Dr. Mehmet BÜYÜK

Editor in chief: Berkan Balpetek
Cover and Page Design: Duvar Design
Printing : December -2024
Publisher Certificate No: 49837
ISBN:978-625-5551-19-1

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CHAPTER 1

A Review of Prominent Powertrain Structures and Converter Topologies in Fuel-cell Electric Vehicles

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Introduction

The progressively diminishing availability of fossil fuels, coupled with significant environmental concerns such as gas emissions, global warming, noise pollution and public health impacts, has prompted the need to explore alternative energy sources that are both environmentally friendly and clean. Electric vehicles (EVs) are generally classified into four types and have been established in the industry as battery electric vehicles (BEVs), hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), and fuel cell electric vehicles (FCEVs). The features of these EVs on the market can be listed as Table 1. Due to the adverse impacts of fossil fuels use, battery and hydrogen based fuel cells (FCs) technologies have recently become significant research area for both academicians and industrialists (Aboumadi et al., 2023; Celebi et al., 2021; Erel et al., 2023; Simsek et al., 2021). Li-ion battery technology has been predominantly utilized in the electric vehicle (EV) industry in recent years. However, the cost of the battery system can account for up to 30% of the total vehicle cost (Gu & Liu, 2021). Compared to existing clean energy sources, FCs have garnered significant interest, with notable industrial developments in recent years. The high operational efficiency and adaptable power outputs of fuel cells (FCs) make them suitable for a wide range of transportation applications (Waseem et al., 2023). Additionally, FCs provide sustainable and reliable energy source, characterized by zero emissions and high energy density. The power ratings of FCs vary significantly, ranging from 500 W to 1 MW, depending on the specific area of use (İnci & Türksoy, 2019). FC vehicles usually combines with energy storage devices such as battery and/or ultracapacitor in the industry. The conventional FCEV powertrain scheme can be represented as in Figure 1. Here, the system comprises a FC stack, hydrogen tank, a unidirectional DC-DC converter (UDC) with FC stack, a bidirectional DC-DC converter (BDC) with auxiliary side (optional), an AC or a DC drive system and an electric motor (İNCİ, 2019).

Tablo 1: Features of EVs on the market

Features	BEVs	HEVs	PHEVs	FCEVs
Power	Battery	ICE + EM	ICE + Battery	FC + EM
Refueling	Electric outlets	. Gas stations + Regen braking	. Electric outlets or gasoline	Hydrogen stations
Energy Source	Battery	. Gasoline + battery	. Gasoline + battery	FCs
Emission	Zero Emissions	Less Emissions	Less Emissions	Zero Emissions
Cost	.High cost due to upfront	. HEVs < BEVs due to smaller battery size and power train	. PHEVs > HEVs due to larger battery, . PHEVs < BEVs due to smaller battery and powertrain	. High cost due to FCs
Key Merits	.High efficiency .Regenerative .Noise reduction	. Low fuel cost . Regenerative . No range anxiety	. Long range . Cost effective .Regenerative breaking	. Long range .Energy density .High incentives
Key Demerits	.Limited range .Long Charging times .Cold weather	.High costs .Fossil fuels based .Lack of incentives	.Upfront costs .Partially dependence on fossil fuels .Vehicle weight and complexity	.Lack of refueling stations .High costs .Bulky design

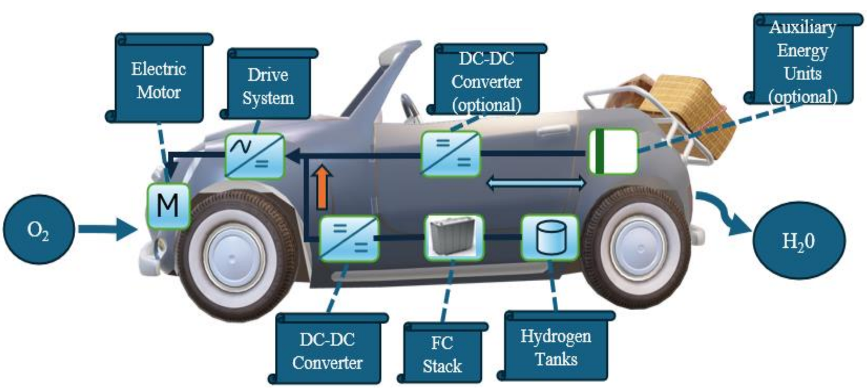

Figure 1: Conventional FCEV powertrain with optional parts

1. Prominent topologies of fuel-cell powertrains

The powertrain mechanism is a critical component in the operation of FCEVs. Along with the full FCEV topology, the hybrid powertrain topologies are also used in this concept. Batteries, ultracapacitors (UCs), photovoltaic panels, flywheels are mostly employed to hybridize the FCEVs as depicted in Figure 2. FCs exhibit significantly higher energy density and efficiency compared to other energy sources. Moreover, their modular structure enhances their adaptability to transportation applications (Trimm & Önsan, 2001).

Batteries are widely used as a power source, serving as a portable and rechargeable energy storage solution for FCEV hybridization. However, their limited lifespan and restricted usability present significant challenges (Saib et al., 2017). Also, FC has a slow dynamic response in the system. The UCs are utilized as energy storage elements to enhance the system's dynamic response. The UCs can maintain performance for approximately one million charge-discharge cycles (Valdez-Resendiz et al., 2020).

The integration of PV systems in FCEVs offers several benefits such as increased driving range, reduced FC loading, potential of off-grid, and increased system performance.

A flywheel technology has rapid response with high power capability and long lasting cycle life (Eltaweel & Herfatmanesh, 2024). But, it possesses a substantial weight and long charging times. Full FCEV powertrain scheme is represented in Figure 3. FCEV with battery hybridization is depicted in Figure 4. FCEV with UC hybridization is shown in Figure 5. FCEV with flywheel hybridization is depicted in Figure 6. Battery and UC hybridization topology for FCEV is presented in Figure 7. The powertrain structure for FCEV with battery and PV is represented in Figure 8. The powertrain structure for FCEV with UC and PV is depicted in Figure 9. In this section, the prominent powertrain topologies are considered in detail.

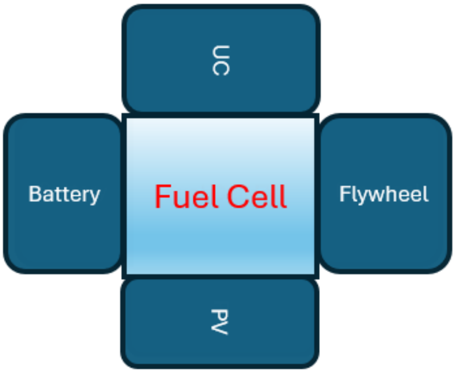

Figure 2: Hybrid energy sources with Fuel cell technology

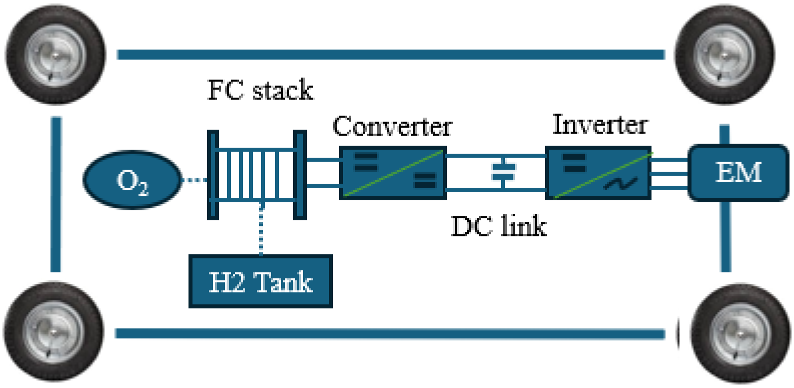

Figure 3: The powertrain structure of FCEVs

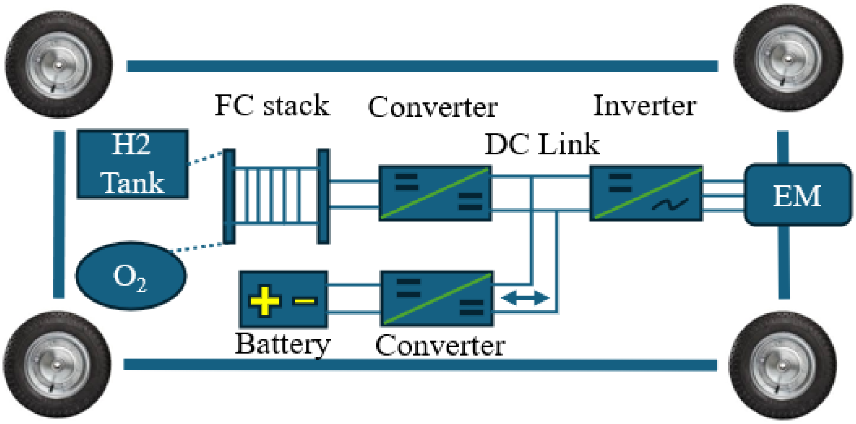

Figure 4: The powertrain structure of FCEVs with battery

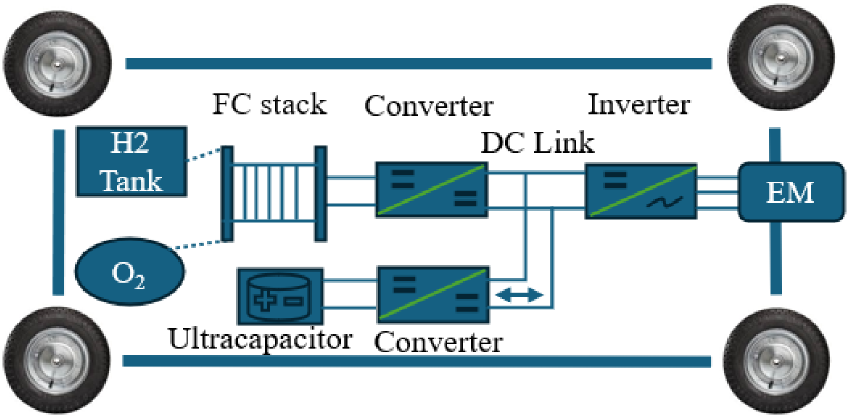

Figure 5: The powertrain structure of FCEVs with ultracapacitor

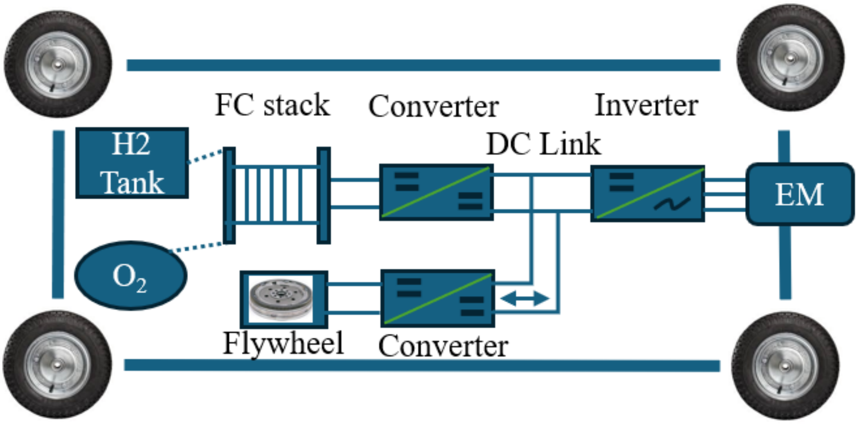

Figure 6: The powertrain structure of FCEVs with flywheel

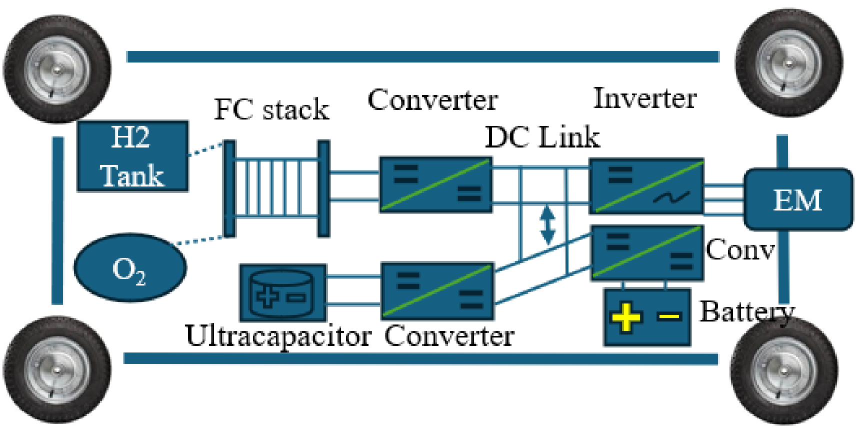

Figure 7: The powertrain structure of FCEVs with battery and ultracapacitor

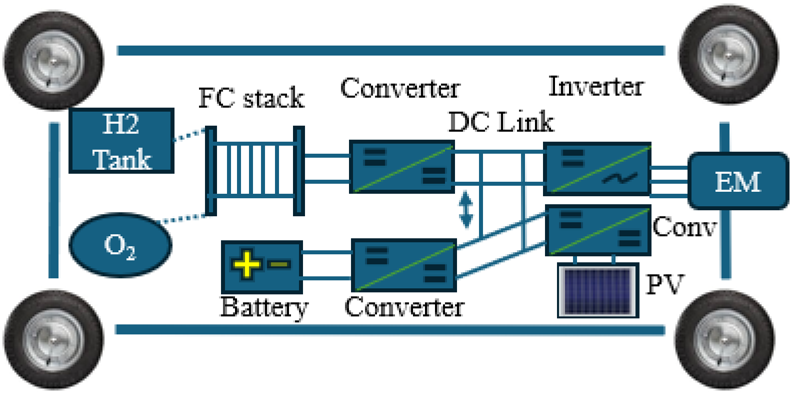

Figure 8: The powertrain structure of FCEVs with battery and PV

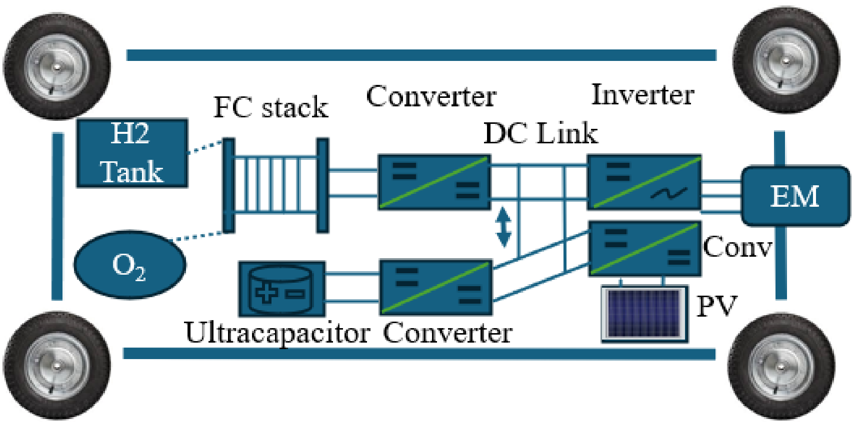

Figure 9: The powertrain structure of FCEVs with ultracapacitor and PV

FC hybridization with single auxiliary energy source is listed as in Table 2. Moreover, FC hybridization with two auxiliary energy sources is represented as in Table 3. Within the concept, the advantages and disadvantages are considered in detail.

Tablo 2: FC with single auxiliary energy source hybridization

Energy source	Specifications
Full Fuel cell (İnci et al., 2021; Pramuanjaroenkij & Kakaç, 2023)	☺ Simply structure ☺ Fast charging time ☺ High efficiency ☺ Cold start capability ☺ Silent operation ☺ Low carbon emissions ☹ High initial cost ☹ Harsh weather conditions ☹ Safety concerns
Fuel cell with battery operation (Peng et al., 2007; Xu et al., 2009)	☺ Energy recovery capability due to battery ☺ Higher flexibility ☺ Enhanced load management ☺ Longer driving range ☹ Complex thermal management ☹ Limited battery lifespan
Fuel cell with UC (Bi et al., 2019)	☺ High power density ☺ Improved system efficiency ☺ Enhanced FC lifecycle ☺ Fast response ☹ Low energy storage ability ☹ Weight and space limitations
Fuel cell with flywheel (Huang & Chen, 2017)	☺ High power rating ☺ Wide temperature operating range ☺ High energy storage ability ☹ Weight and size ☹ Limited application areas

Tablo 3: FC with two auxiliary energy source hybridization

Energy source	Specifications
Fuel cell with battery and UC (Garcia et al., 2013; García et al., 2013)	☺ Bidirectional converter ability ☺ Improved dynamic response ☺ Enhanced scalability ☹ High cost ☹ Limited application areas
Fuel cell with battery and PV	☺ Enhanced scalability ☺ Continuous operation ☺ Eco friendly user option ☹ Weight and size ☹ Limited application areas ☹ Slow charging
Fuel cell with UC and PV (Krishan & Suhag, 2020)	☺ Better active power balance compared to PV-FC-BESS ☺ More economical compared to PV-FC-BESS ☹ High cost ☹ Maintenance complexity

2. Prominent converter topologies in FCEVs

Converter topologies play an important role in FCEVs. Within this concept, two types of converters are considered prominent: DC-DC and DC-AC. Non-isolated and isolated DC-DC converters are taken into consideration. The DC-DC converter type can be selected due to the power flow ability of the energy source. For instance, FC and PV have energy generation capabilities, while UC, battery and flywheel present both energy storage and energy generation capabilities. Thus, a UDC is suitable for FC and PV applications, while BDC type can be utilized for auxiliary energy sources such as UC, battery and flywheel.

Inverter structures are used for motor drive systems. Prominent inverter topologies in the literature are reviewed as follows.

2.1 Prominent non-isolated DC-DC converter types

DC-DC converters are utilized to regulate dc voltage and ensure optimal power transfer. According to the power flow direction, UDC and BDC topologies are used in the FCEVs. UDC is typically used for both FC and PV hybridization applications, on the other side, BDC is employed with energy storage ability sources. Conventional boost converter topology stands out due to its simply structure and cost effective feature as shown in Figure 10 (Jarin et al., 2022). But, this causes high voltage ripple and requires high capacitance value of capacitor in the circuit. Additionally, it adversely affects the lifetime of the FC. Thus, interleaved boost converter structures is proposed in FCEVs to reduce the aforementioned problems as depicted in Figure 11. To obtain high voltage gain, modified boost converter structure is utilized in FCEVs as shown in Figure 12. To reduce the current stress on the switching components along with high power transfer, multiphase interleaved boost converter is used in the literature as shown in Figure 13 (Thounthong & Davat, 2010).

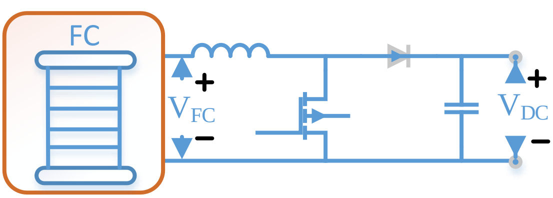

Figure 10: Conventional boost converter

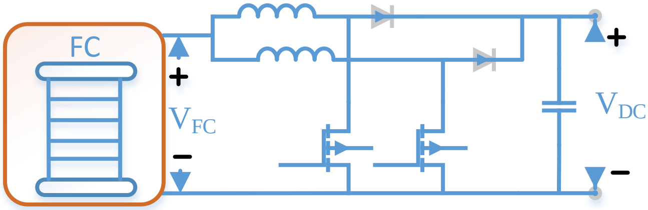

Figure 11: The two-leg interleaved boost converter

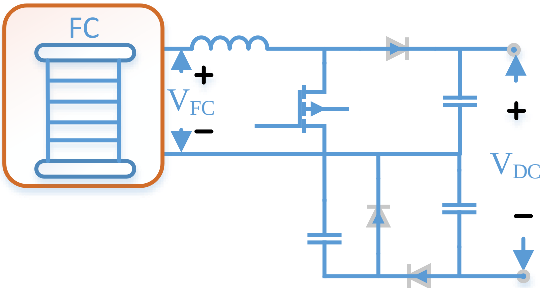

Figure 12: Modified boost converter

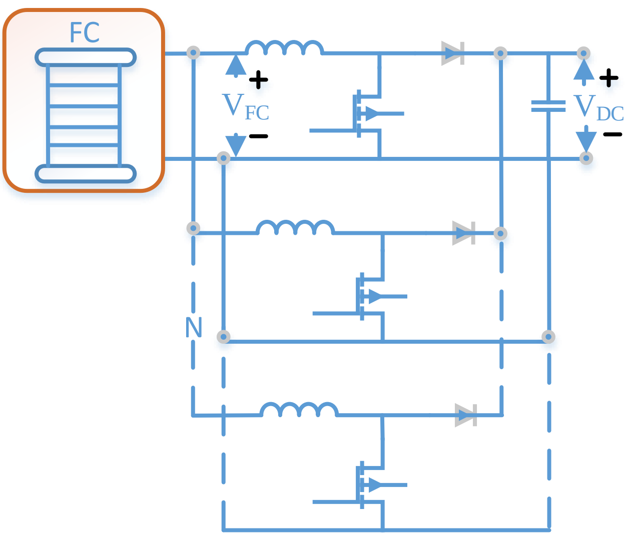

Figure 13: Multiphase interleaved boost converter

2.2 Prominent Isolated DC-DC converter types

DC-DC converters are typically listed as two main parts, isolated and non-isolated converter types. While the isolated converters have a common ground point between input and output, non-isolated converters have an electrical isolation between the input and output parts (Bhaskar & Member, 2020). Among the isolated converters in FCEVs, transformer based DC-DC converters are more used due to its high power transfer ability. But, its bulky structure and more component count can be the drawback side of this method. Here, isolated full-bridge converter structure is utilized for unidirectional FCEV applications as shown in Figure 14. This topology provides flexible output voltage transformation and high efficiency. BDC facilitate power flow in both directions, allowing for both supplying and absorbing power as depicted in Figure 15 (Kumar et al., 2024). However, the control complexity and cost adversely affect the system in FCEVs.

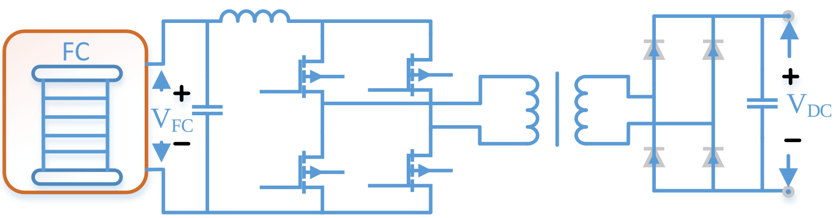

Figure 14: Isolated full-bridge converter

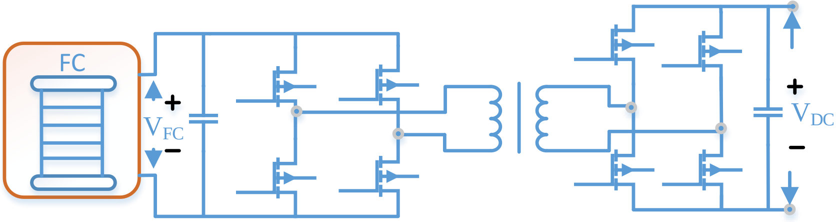

Figure 15: bidirectional isolated full-bridge converter

2.3 Prominent inverter topologies in FCEVs

The inverter functions as a motor drive, enabling effective control and operation in FCEVs. The most commonly used inverter method is three phase voltage source inverter as depicted in Figure 16. Here, an FCEV system is simply composed of a DC-link bus and a three-phase inverter structure. VSI enables precise control of motor speed and torque as well as high efficiency operation (Shen et al., 2007). Another prominent inverter topology is three phase current source in FCEVs as shown in Figure 17. Due to the series inductor in CSIs, they minimizes the high frequency harmonics as well as reducing the EMI effects. Additionally, CSI has naturally limit the current due to its series inductor usage and enables protection against short circuits in FCEVs. To balance cost-effectiveness, efficiency, and performance of the system, switched boost inverter topology particularly suitable for recent FCEVs striving for improved energy utilization and system simplicity as shown in Figure 18. Compared to conventional inverter topologies, z-source inverter topology has voltage boosting and inversion capability eliminating the need separate conversion stages due to its impedance feature as depicted in Figure 19.

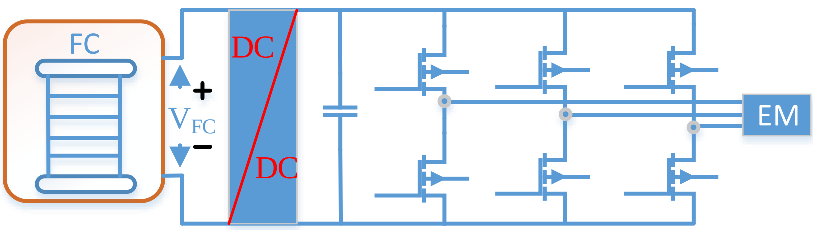

Figure 16: Three phase VSI

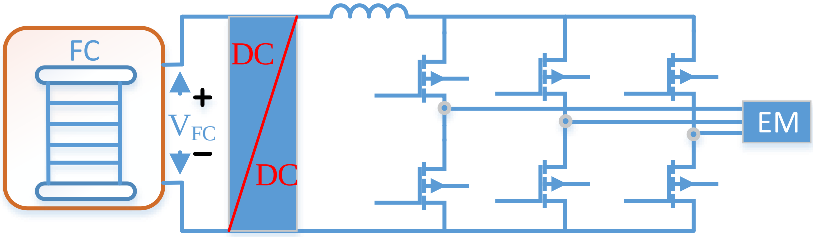

Figure 17: Three phase CSI

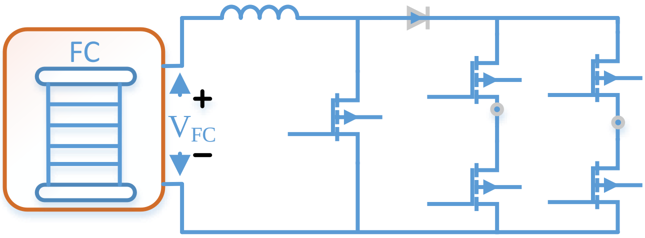

Figure 18: Switched boost inverter

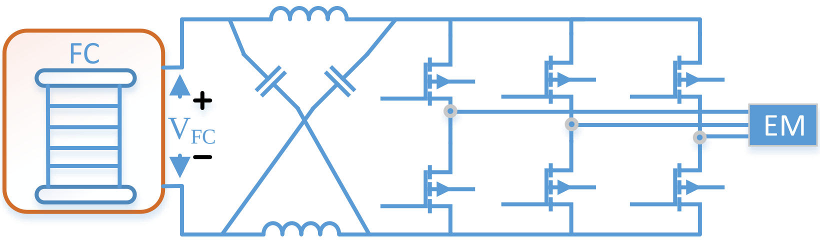

Figure 19: Z source inverter

3. Conclusions and Discussions

Powertrain topologies and power electronics converters play a critical role in the efficient operation of FCEVs. The integration of DC-DC and DC-AC converters provides seamless energy management between the fuel cell, auxiliary components, and drive system, ensuring optimal performance and energy utilization. While unidirectional DC-DC converters provide stable voltage regulation and power flow for the fuel cell's output, bidirectional converters enhance system operation by supporting regenerative braking and dynamic energy storage. Prominent inverter topologies such as Z-source, switched boost inverter, and VSIs offer benefits like high efficiency, compact design, and reduced system complexity.

The adoption of wide-bandgap semiconductors like SiC and GaN could further revolutionize powertrain performance by enabling higher switching frequencies and compact converter designs. The synergy between advanced powertrain topologies and innovative power electronics converters will enable the continued evolution of FCEVs and remain a cornerstone for achieving sustainable and high-performance mobility solutions.

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CHAPTER 2

Simultaneous Wireless Information and Power Transfer (SWIPT): An Overview and Contemporary Progress

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Introduction

The development of mobile communications has progressed through distinct generations, each introducing unique features and technological advancements along the way. These generations have consistently responded to the ever-increasing demands for higher data rates, improved connectivity, and enhanced service capabilities. Each new generation builds upon the achievements of its predecessor, striving to enhance connectivity, boost data transmission speeds, and support a wider range of applications, therefore driving the continuous advancement of communication technologies.

The first generation (1G) of mobile communication, introduced in the 1980s, mainly supported analog voice communication. It utilized frequency division multiple access (FDMA) technology, which enabled multiple users to share a common frequency band by allocating separate frequency channels to each user. However, 1G systems had notable drawbacks, including limited capacity, inadequate security, and lower service quality, as they were just restricted to voice calls and lacked support for data transmission [1].

Launched in the 1990s, the second generation (2G) marked a shift from analog to digital communication. It initiated technologies such as global system for mobile communications (GSM) and code division multiple access (CDMA). In addition to voice calls, 2G also supported basic data services like short message service (SMS) and low-speed data transmission. Security was enhanced through digital encryption, and the capacity to handle more simultaneous users significantly increased compared to 1G. The intermediary 2.5G systems, often referred to as general packet radio service (GPRS), bridged the gap between 2G and 3G by offering higher data speeds and enabling packet-switched data services [2].

The third generation (3G), standardized as IMT-2000, presented technologies such as wideband code division multiple access (WCDMA) and CDMA2000. These advancements enabled mobile multimedia services, video calls, and higher-speed internet access. 3G networks significantly enhanced data transmission speeds, paving the way for more sophisticated applications and services [3].

The fourth generation (4G) networks, especially Long-Term Evolution (LTE) and LTE-Advanced, were developed to deliver ultra-broadband internet access. They enable high-definition video streaming, online gaming, and other data-heavy applications. Utilizing orthogonal frequency division multiple access (OFDMA) for efficient spectrum usage, 4G systems can achieve data speeds of up to 1 Gbps. This generation prioritizes low latency and improved capacity to accommodate the growing number of connected devices and mobile applications [4].

The fifth generation (5G) of mobile communication is currently being deployed and is set to revolutionize mobile connectivity in all aspects. It focuses on delivering ultra-reliable low-latency communication (URLLC), massive machine-type communications (mMTC), and enhanced mobile broadband (eMBB). By utilizing higher frequency bands, such as millimeter waves, 5G achieves dramatically faster data rates (up to 10 Gbps) and lower latency (as low as 1 ms). It is specifically designed to support a vast number of connected devices, paving the way for internet of things (IoT) and smart city applications [5].

Simultaneous wireless information and power transfer (SWIPT) is gaining prominence as a key technology in 5G communications, largely because it addresses the energy limitations of numerous devices within the IoT ecosystem. SWIPT allows devices to harvest energy from radio frequency (RF) signals while concurrently receiving data. This dual functionality is especially critical in 5G networks, where the growing number of IoT devices requires effective energy management to extend battery life and improve the network's overall sustainability [6-8]. In this study, a comprehensive summary of the fundamentals of SWIPT is presented. In addition, some of the emerging technologies for 5G communication systems that integrate SWIPT are also provided. The rest of the study is structured as follows: Section 2 offers an overview of energy harvesting (EH) technology. Section 3 provides a review of wireless power transfer (WPT). Section 4 discusses SWIPT technology and summarizes distinct receiver architectures employed in SWIPT schemes. In section 5 a survey about emerging SWIPT scenarios is introduced. Finally, section 6 provides a summary of the study.

1. Energy harvesting

EH is an important concept in 5G telecommunications, catering to the increasing demand for energy-efficient solutions in modern wireless networks. With the ongoing expansion of 5G, the technology is designed to support a wide array of applications, such as mMTC, eMBB, and URLLC. The integration of EH is essential for addressing the energy needs of these applications, especially for IoT devices and other low-power systems.

EH refers to the process of collecting and converting ambient energy from the environment into usable electrical energy. This enables devices to function without relying on traditional power sources like batteries, thus improving sustainability and reducing maintenance costs. EH can utilize various energy sources, including electromagnetic, solar, mechanical, thermal, wind or hydro energy. Among these, electromagnetic EH is especially notable, as it captures energy from ambient electromagnetic waves, such as RF signals. RF energy harvesting is increasingly favored for powering low-power wireless devices [9,10].

EH is essential for creating self-sustaining devices that eliminate the requirement for frequent battery replacements. This is particularly valuable in applications like wireless sensor networks (WSN), where devices can continuously track environmental conditions without relying on external power sources. Wearable electronics also benefit from EH, as it helps extend battery life and improves user convenience. Furthermore, EH has significant applications in smart cities and infrastructure, providing power for sensors and devices used to monitor traffic, environmental conditions, and energy usage [11-13].

One of the primary motivations for incorporating EH in 5G networks is the need for sustainable energy solutions. With the expected surge in data traffic and connected devices, traditional energy sources may not be sufficient. EH methods, such as RF EH, enable devices to draw energy from ambient signals, reducing dependency on conventional power sources [14-16]. This is particularly beneficial for low-power IoT devices, which often operate in remote or inaccessible areas where traditional power may be unfeasible. Additionally, EH can significantly enhance the efficiency of 5G networks. Techniques like SWIPT allow devices to receive both data and energy simultaneously, maximizing resource efficiency. This not only improves the network's energy efficiency but also prolongs device lifespans, which is highly important for applications requiring uninterrupted connectivity [17-19].

2. Wireless power transfer (WPT)

WPT is an EH method that captures energy from ambient electromagnetic signals, particularly RF signals, to power devices wirelessly. This technology supports the development of energy-efficient and sustainable wireless networks, enabling devices to operate without relying on conventional power sources. WPT transfers electrical energy from a power source to a device without the need for physical connectors or wires, using electromagnetic fields. This makes it especially useful for applications where traditional wired connections are impractical or undesirable. In recent years, WPT has garnered significant attention due to the growing demand for convenient and efficient charging solutions for a variety of devices, from portable electronics to electric vehicles [20,21].

The most widely used method of WPT is inductive coupling, which relies on the principle of electromagnetic induction. In this process, a transmitter coil produces a time-varying magnetic field, that induces an electric current in a nearby receiver coil, thus transferring energy wirelessly. This method is commonly applied in scenarios like smartphone and electric vehicle charging systems, where efficient power transfer is critical. Inductive WPT (IWPT) systems are favored for their high efficiency and short operational range, typically working within a meter [22,23].

Another noteworthy method is capacitive WPT (CWPT), which relies on electric fields instead of magnetic fields for transfer energy. CWPT systems employ coupled capacitors to generate an electric field between a transmitter and a receiver, allowing for energy transmission over short distances. Although CWPT offers advantages like potentially more compact designs, it is generally less efficient than inductive methods and remains an area of ongoing research for wider applications [24,25].

WPT systems can also be classified by their range of operation: near-field and far-field systems. Near-field systems, including inductive and capacitive transfer, are suited for short-range applications, typically under one meter. In contrast, far-field systems, which use technologies like microwaves or lasers, can transmit power over longer distances although often with reduced efficiency. The resonant inductive coupling technique has improved the performance of near-field WPT by enabling greater distances and improved power transfer rates [26].

The range of applications of WPT is extensive and continues to expand. Beyond consumer electronics, WPT is being explored for medical devices, military uses, and even for powering sensors in remote locations. Its convenience and safety make it an appealing option across various industries, particularly as the demand for wireless charging solutions continues to grow [27,28].

3. Simultaneous wireless information and power transfer (SWIPT)

Simultaneous Wireless Information and Power Transfer (SWIPT) is a cutting-edge technology enabling the simultaneous transmission of data and energy over wireless channels. This approach is particularly valuable for energy-limited devices, such as those in WSNs and IoT applications, where a reliable power supply is critical for prolonged operation. SWIPT uses RF signals to deliver both information and energy, meeting the dual demands of data communication and energy replenishment within a single transmission [29,30].

The core concept of SWIPT lies in splitting the received RF signals into two components: one for information decoding and the other for EH. An example communication scheme with SWIPT is given in Figure 1. Here, the purple straight lines represent the information flow and orange lines represent the power flow, where the arrow heads show the direction of the flow. Passive users just perform EH either from the static or mobile base stations. On the other hand, active users perform information transmission with the static and mobile base stations, in addition to EH.

In a SWIPT system, it is impractical to perform both EH and ID on the same received signal because performing EH on the RF signal will destroy the information content of the signal. Furthermore, a single antenna receiver may not be enough to aid a reliable energy supply, because of the limited total of energy. To address these challenges, the received signal can be split into two, or dedicated antennas can be used for EH and ID. Additionally, to provide enough power for reliable devices, a centralized or distributed antenna array configuration such as MIMO, relaying, etc. is needed. Various techniques are available to divide the received signals into multiple components in SWIPT schemes [7].

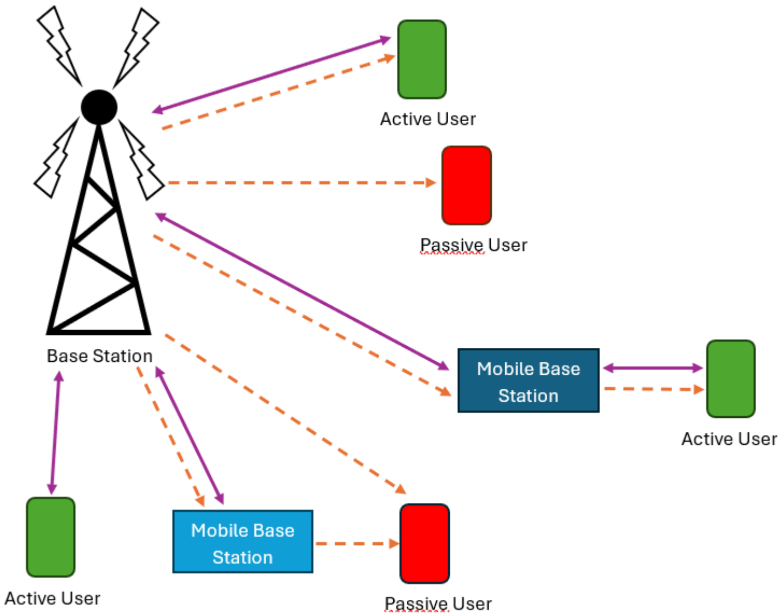

Figure 1: A SWIPT communication scheme example

3.1 Seperate receiver

This method involves utilizing distinct circuits in distinct receivers for EH and ID. The separate receiver architecture is given in Figure 2. This design is crucial for optimizing the performance of SWIPT systems, as it allows dedicated resources to be assigned to each function, therefore enhancing overall efficiency and reliability. The benefits of this approach are particularly significant in scenarios where power efficiency is a priority. For instance, the dedicated units for EH and ID can be individually optimized, resulting in higher energy conversion rates and better data throughput. Furthermore, this architecture supports the incorporation of advanced signal processing techniques tailored to each function, further enhancing the system's performance. Additionally, the separate receiver setup enables the integration of multiple antennas, which greatly enhances the robustness and reliability of the communication link. By employing methods such as multiple-input multiple-output (MIMO) configurations, the system can effectively balance the trade-offs between EH and information transmission [31].

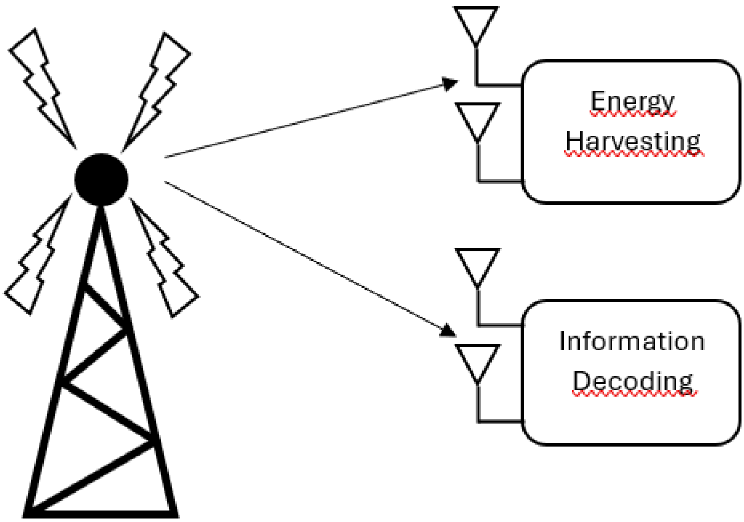

Figure 2: Separate receiver architecture in SWIPT

3.2 Time switching receiver

In the TS scheme, the receiver alternates between EH and ID at regular intervals. The TS receiver architecture is given in Figure 3. During the EH phase, the receiver exclusively focuses on harvesting energy from the incoming RF signals, typically for a predetermined period, to accumulate sufficient energy for its operations. In the subsequent ID phase, the receiver processes the received signals to extract information. This time-division strategy enables the receiver to optimize its performance for each function without mutual interference [32].

The TS method stands out for its simplicity and effectiveness in managing the trade-offs between EH and data throughput. By dedicating specific time slots to each function, it achieves a high level of energy efficiency while maintaining a reasonable data rate. This is particularly beneficial for applications where energy constraints are significant, such as in WSNs and IoT devices [33]. Additionally, the TS method is adaptable to various communication protocols and network setups, making it a versatile option for implementing SWIPT in diverse scenarios. For instance, in multi-user environments, the TS approach can be combined with resource allocation strategies to improve system performance by optimizing the time slots assigned for EH and ID across users [34]. However, the TS method does have its own limitations. The need for time division restricts simultaneous operation, potentially lowering data transmission rates. As a result, careful planning of the time allocation for each phase is essential to ensure that the system meets the required quality of service (QoS) standards [35].

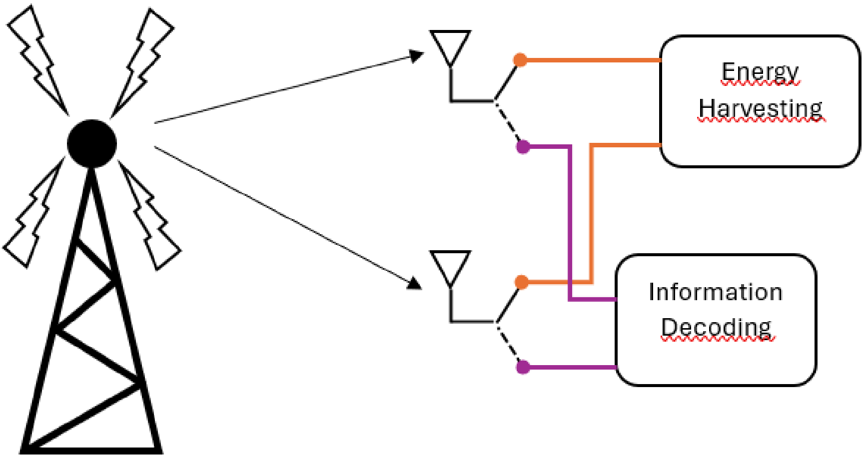

Figure 3: Time switching receiver architecture in SWIPT

3.3 Power splitting receiver

This approach allows a receiver to divide an incoming RF signal into two distinct streams: one for EH and the other for ID. The PS receiver architecture is given in Figure 4. In the PS architecture, the received signal is split according to a predetermined power splitting ratio, which dictates the portion of the signal's power allocated to each function. This ratio is critical, as it directly affects the performance of both EH and ID processes. The harvested energy can power the receiver or charge batteries, while the decoded information can be sent to other devices or systems [36,37].

A key advantage of the PS method is its ability to operate continuously, allowing the receiver to harvest energy and decode information simultaneously, albeit with varying power levels. This contrasts with the TS technique, which alternates between EH and ID phases, potentially causing inefficiencies in energy utilization and data transmission [38]. The PS method is particularly well-suited for environments requiring a consistent power supply, such as in WSNs and IoT applications [39]. However, the PS technique also comes with challenges, particularly in determining the optimal power splitting ratio. An imbalanced ratio may lead to suboptimal performance, where either insufficient energy is harvested or the information decoding suffers from poor signal quality [40]. Recent studies have aimed to optimize the power splitting ratio in various scenarios, including multi-antenna systems and cognitive radio networks, to improve SWIPT system efficiency [41]. Techniques like dynamic power splitting have also been proposed to adaptively adjust the splitting ratio based on the current operating conditions, further enhancing system performance [42].

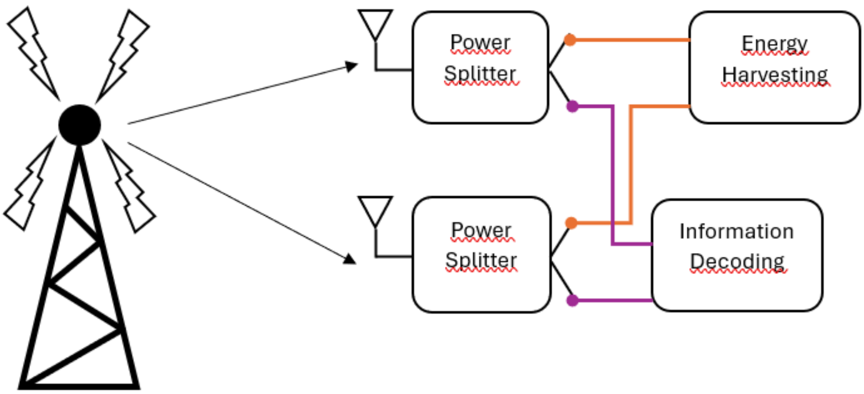

Figure 4: Power splitting receiver architecture in SWIPT

3.4 Antenna switching receiver

This approach focuses on strategically selecting antennas to optimize the performance of both EH and ID functions. The receiver dynamically switches between antennas based on their signal quality and EH capabilities. The AS receiver architecture is given in Figure 5. In the AS architecture, the receiver incorporates multiple antennas but activates only a subset at any given time. Antenna selection is guided by the antennas' ability to deliver optimal signal quality for ID while simultaneously harvesting energy from the received RF signals. This targeted strategy minimizes interference and maximizes the effective use of available resources [43,44].

The AS method is particularly advantageous in environments with fluctuating channel conditions, enabling the receiver to adaptively choose the most suitable antennas for optimal performance [45]. A key benefit of the AS technique is its lower complexity compared to other SWIPT techniques such as PS and TS. While PS requires more complex circuitry to divide the incoming signal into separate streams for EH and ID, and TS demands precise timing to alternate between the two functions, AS simplifies the receiver design by relying solely on antenna selection without the need for intricate signal processing [46]. This simplicity translates to lower implementation costs and improved reliability in real-world applications [47]. Furthermore, the AS technique integrates effectively with MIMO systems, leveraging spatial diversity to enhance both the EH efficiency and the data transmission rates. Incorporating AS in MIMO setups can significantly boost performance, particularly in environments with high levels of interference or variable channel conditions. However, the AS method does have drawbacks, particularly in terms of the need for rapid antenna switching and potential latency during the selection process. Additionally, its effectiveness heavily depends on accurately estimating the channel state information (CSI) to ensure optimal antenna selection [48].

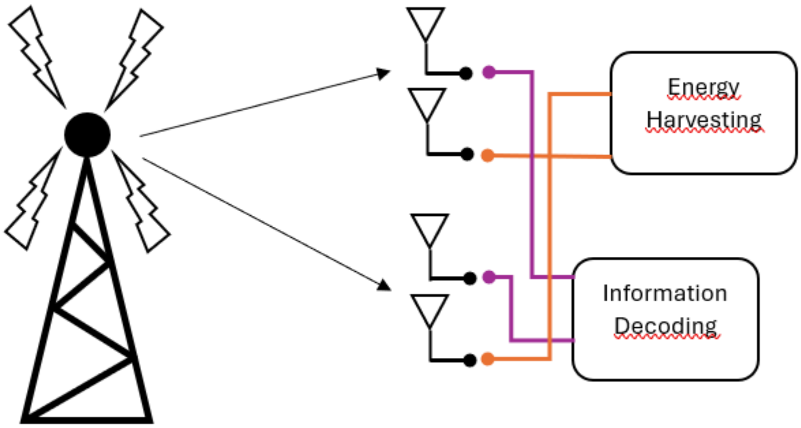

Figure 5: Antenna switching receiver architecture in SWIPT

4. Emerging SWIPT scenarios

SWIPT is a cutting-edge technology that has attracted significant interest in recent years due to its potential to improve the energy efficiency of wireless communication systems. Research highlights various emerging scenarios where SWIPT can be effectively implemented, particularly regarding 5G and beyond networks. This section explores some of the key emerging technologies powered by SWIPT in distinct application areas.

4.1 NOMA systems

A notable application of SWIPT is non-orthogonal multiple access (NOMA) systems, which enable multiple users to share a common frequency band, thereby improving spectral efficiency. The core concept of NOMA is to serve multiple users at distinct power levels within a shared time-frequency resource.

In [49], the spectral and energy efficiency of NOMA-SWIPT IoT relay systems under Rayleigh fading channels is analyzed, focusing on the network's outage probability and showcasing the potential of this integration to improve capacity in next-generation IoT networks. [50] examines the outage performance of SWIPT-NOMA systems considering imperfect successive interference cancellation and channel state information (CSI), highlighting practical challenges and opportunities in integrating SWIPT with NOMA. A performance evaluation of PS relaying protocols in SWIPT-based cooperative NOMA systems is presented in [51], emphasizing the advantages of using relays in forwarding information while harvesting energy. [52] explores the integration of SWIPT with NOMA through a cooperative protocol where nearby NOMA users assist in EH for more distant users. Their findings underscore the importance of optimizing network parameters to improve overall performance. In [53], the joint power allocation and TS control for energy efficiency optimization in a TS-based SWIPT NOMA system is considered with the goal of optimizing the energy efficiency of the system whilst satisfying the constraints on maximum transmit power budget, minimum data rate, and minimum harvested energy per terminal.

4.2 Device to device communications

Device-to-Device (D2D) communication allows mobile devices in close proximity to connect directly, bypassing the conventional cellular infrastructure. This method has garnered significant attention for its potential to improve the efficiency of wireless networks, particularly in the realms of the IoT and 5G mobile networks.

[54] explores how devices can harvest energy from ambient RF environments, enabling continuous operation without frequent recharging – an essential feature for energy-constrained D2D scenarios. While combining SWIPT and D2D communication offers numerous advantages, it also introduces challenges, such as interference management and the need for robust communication protocols. In [55], various techniques are proposed to tackle these challenges, focusing on minimizing interference and enhancing the reliability of EH and data transmission. [56] investigates new schemes for transmit power adaptation to maximize the average data rate and to minimize the outage probability of D2D communications over fast and slow-fading channels, where the D2D network and a SWIPT-based IoT cellular network operating with the TS protocol coexist. Furthermore, [57] examines resource allocation strategies for D2D communications using SWIPT, emphasizing efficient power and bandwidth management to maximize the benefits of both technologies. Their findings suggest that effective resource management significantly improves network performance and user experience.

4.3 Cooperative relaying systems

The use of SWIPT in cooperative relaying systems has become a significant area of research. Cooperative relaying involves multiple nodes collaborating to transmit information, which can be enhanced through the integration of SWIPT technologies. By exploiting the broadcast nature of wireless channels, nodes can serve as relays for one another, as a result improving reliability and extending coverage.

One of the main frameworks for integrating SWIPT with cooperative relaying include the amplify-and-forward (AF) and decode-and-forward (DF) protocols. In AF relaying, the relay amplifies the received signal while uses harvested energy for its operation. For instance, [58] introduces a TS and PS based relaying protocol that effectively utilizes SWIPT in AF systems. Similarly, DF relaying has been extensively studied with SWIPT integration. A greedy switching approach between data decoding and EH in cooperative networks is discussed in [59], which optimizes the use of harvested energy for relaying tasks. A notable scenario described in [60] involves users with strong channel conditions acting as EH relays to assist users with poorer conditions, enhancing reception reliability. This cooperative approach not only improves the network's spectral efficiency but also incentivizes user cooperation through energy sharing. [61] evaluates the performance of AF cooperative relaying networks with SWIPT, demonstrating that such networks can outperform those without it under favorable EH conditions. In [62], a best-near best-far user selection scheme is proposed, in which the outage performance of cooperative relaying transmissions in NOMA systems, where SWIPT is employed at the near users to power their relaying operations is explored.

4.4 Industrial internet of things

The Industrial Internet of Things (IIoT) marks a significant development in industrial operations by integrating advanced IoT technologies into manufacturing and industrial environments. Research shows that SWIPT can address the energy challenges faced by many IIoT devices.

A joint optimization of transmission rate and EH in SWIPT NOMA-enabled IIoT devices is given in [63]. The study in [64] underscores the importance of SWIPT in prolonging the lifespan of wireless nodes, which is vital for sustaining energy-limited networks. This is especially important in IIoT contexts where numerous devices are deployed and require a reliable power source for long-term operation. One major advantage of combining SWIPT with IIoT is its ability to support the continuous operation of WSNs that monitor key industrial metrics such as temperature, pressure, and machine performance. As noted in [65], SWIPT is being utilized in various industrial applications, enabling smart sensors to track critical parameters in real-time, thereby improving operational efficiency and minimizing downtime. This integration is particularly valuable in environments where traditional power sources are impractical. Additionally, SWIPT's integration into IIoT systems has significant implications for security and resilience in industrial applications. According to [66], SWIPT has the potential to enhance secure communication within IoT networks, a critical factor in industrial settings where data integrity and confidentiality are essential. By allowing devices to simultaneously harvest energy and communicate, SWIPT enhances the robustness of IIoT systems against potential cyber threats.

4.5 Intelligent reflecting surfaces

The integration of intelligent reflecting surfaces (IRS) with SWIPT systems has garnered significant attention in recent literature. IRS is an innovative technology in wireless communications, capable of manipulating electromagnetic waves to improve signal quality and network capacity. Comprising a large array of passive reflecting elements, IRS can adjust the phase and amplitude of incoming signals, thereby allowing intelligent control of wireless channels.

An IRS assisted SWIPT system, where multiple IRSs are deployed on unmanned aerial vehicles (UAVs) and ground building, is considered in [67] for enhancing transmission of information and energy concurrently. The study in [68] highlights that IRS can reconfigure the wireless channel between the transmitter and receiver, improving performance in UAV-assisted SWIPT networks. This functionality is vital for maintaining reliable communication in dynamic scenarios, such as those involving UAVs used for surveillance or delivery. IRS also facilitates advanced communication techniques, such as orbital angular momentum (OAM). According to [69], IRS can reflect OAM waves blocked by obstacles, thereby constructing a direct path for OAM-based SWIPT. This not only improves EH efficiency but also broadens the potential applications of SWIPT in complex scenarios. A key advantage of incorporating IRS in SWIPT systems is its ability to address challenges posed by path loss and interference in wireless channels. As depicted in [70], IRS dynamically tunes the phase shifts of reflected signals, optimizing WPT and wireless information transfer. This creates favorable transmission conditions, enhancing overall SWIPT performance, particularly in environments where direct line-of-sight communication is obstructed. By redirecting signals, IRS ensures to improve reception at the intended receiver. Channel conditions significantly influence the effectiveness of IRS-assisted SWIPT systems. For instance, [71] discusses how IRS can mitigate issues like shadowing and obstruction, which are common challenges in wireless communications. By fine-tuning phase shifts, IRS maintains robust system performance even in less-than-ideal conditions.

4.6 Wireless sensor networks

In WSNs, SWIPT offers an effective approach to overcoming the energy limits of sensor nodes. WSNs consist of autonomous, spatially distributed sensor nodes that collaborate to monitor physical or environmental conditions across various locations. These networks are self-organizing, forming distributed systems without centralized control, which is essential for applications in areas such as military surveillance, environmental monitoring, healthcare, and smart grids.

Cooperative clustered WSNs can utilize SWIPT to enable energy-limited relay nodes to harvest ambient RF signals and use the harvested energy to forward packets from source nodes to their destinations, as highlighted in [72]. Additionally, PS techniques within SWIPT allow for the simultaneous decoding of information and harvesting of energy, which is especially advantageous in multi-hop sensor networks, where nodes relay information across several hops to reach a central base station, as shown in [73]. Research also emphasizes the development of energy-efficient routing protocols that have been developed to optimize the performance of WSNs employing SWIPT. These protocols often incorporate strategies for power allocation, relay selection, and EH management to enhance overall network energy efficiency, as indicated in [74]. For example, [75] proposes energy-efficient routing mechanisms that consider nodes' dual roles as information transmitters and energy harvesters, thereby improving the sustainability of WSNs. Furthermore, the performance of SWIPT in WSNs under Nakagami-m fading channels is explored and optimized in [76].

4.7 Beamforming

The combination of SWIPT with beamforming techniques has been widely explored, showcasing its potential to enhance the efficiency and performance of wireless communication systems. Beamforming, a signal processing method, uses an array of sensors or antennas to direct and shape signal transmission or reception in a specific direction. By enhancing the signal strength from a desired source while suppressing interference from other directions, beamforming proves invaluable in applications like telecommunications, radar, sonar, and medical imaging.

In multiple-input single-output (MISO) systems, beamforming is utilized to maximize EH by receivers while ensuring effective data transmission. For instance, [77] examined MISO SWIPT systems with multiple EH sensors, demonstrating that random unitary beamforming significantly enhances system performance by enabling flexible resource allocation, which improves both energy efficiency and data rates. Similarly, [78] investigated secure beamforming designs for SWIPT in multiuser MISO broadcast channels, highlighting the need to optimize beamforming strategies to balance energy transfer and information delivery without compromising transmission quality. The integration of artificial noise with beamforming has also been studied to enhance the security of SWIPT systems. In [79], a robust beamforming scheme was proposed, using artificial noise to confuse potential eavesdroppers while simultaneously increasing harvested energy. This dual approach enhances both system security and maximizes energy efficiency. Furthermore, hybrid beamforming techniques have been suggested to improve SWIPT performance. As shown in [80], transitioning from fully digital to hybrid analog-digital beamforming in MIMO SWIPT systems enables more efficient energy and information transfer, combining the strengths of digital and analog beamforming to boost energy efficiency and data throughput. [81] studied a joint design of transmit power allocation, beamforming, and receive PS for SWIPT under wideband millimeter wave channel.

4.8 Metamaterials

The use of metamaterials in SWIPT systems represents a novel and promising approach that has emerged in the literature. Metamaterials are artificially engineered materials that exhibit properties not found in naturally occurring substances, with their unique electromagnetic characteristics stemming from their structural design rather than their composition.

An experimental study discussed in [82] investigated WPT systems that integrate highly sub-wavelength metamaterials. The results demonstrated that utilizing negative refractive index metamaterials can enhance power transfer efficiency, a critical factor for optimizing SWIPT performance. These metamaterials offer dual functionality by supporting both EH and information transmission, showcasing their potential for advanced wireless communication technologies. Furthermore, metamaterials have been explored in beamforming applications for SWIPT. [83] examined how smart antenna technologies, including metamaterials, can focus RF energy on energy-constrained sensor networks, thereby boosting the overall efficiency of SWIPT systems. This capability to direct energy to specific nodes while transmitting information simultaneously is a key advantage of integrating metamaterials with SWIPT. As noted in [84], incorporating metamaterial slabs significantly enhances the coupling efficiency of evanescent waves, which is essential for SWIPT systems aiming to maximize energy transfer while maintaining information transmission. Furthermore, [85] proposed the design of tunable metasurfaces for field-localized WPT. This work highlighted how the distinctive properties of metamaterials, such as field focusing and strong electromagnetic resonance, can be used to enhance EH in SWIPT. By manipulating electromagnetic fields, these metamaterials can focus energy to specific receivers, significantly improving energy transfer efficiency. The review in [86] investigates the advances in metamaterials for SWIPT technology.

5. Conclusion

In this study, a comprehensive summary of the fundamentals of SWIPT along with some of the emerging technologies for 5G communication systems that integrate SWIPT are provided. Firstly, an inclusive review of EH technology is given. Subsequently, an overview of WPT is provided. Then a comprehensive description of SWIPT technology and the receiver architectures employed in SWIPT schemes is presented. Finally, a survey about emerging SWIPT scenarios such as NOMA systems, D2D communications, cooperative relaying systems, industrial IoT, IRS, WSNs, beamforming and metamaterials is provided.

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CHAPTER 3

Hybrid Energy Storage System: Topology, Applications

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1. Introduction

Over the past decade, there has been a substantial increase in energy consumption, driven by significant economic growth and escalating industrialization (Emrani and Berrada 2024). Historically, the production of electricity has predominantly depended on fossil fuels, owing to their reliability and efficiency (Elalfy et al., 2024). However, the utilization of fossil fuels exacerbates air pollution and leads to increased CO2 emissions (Simsek et al. 2021). In contrast, renewable energy plays a pivotal role in the sustainable generation of energy, as it mitigates the waste products associated with fossil and fissile materials. The renewable energy sources (RESs) that have been most extensively investigated are solar, wind, thermal, hydroelectric, biomass, and ocean wave energy (Cabrane et al. 2021). The intermittent nature of RESs can lead to power oscillation, voltage, and frequency stability. The energy storage systems (ESSs) are promising solutions to mitigate these problems addressed by RESs (Lin and Zamora 2022). ESSs can be categorized as shown in Figure 1 (Argyrou, Christodoulides, and Kalogirou 2018) .

In the ESSs, two critical metrics are considered: energy density (ED) and power density (PD). ED refers to the amount of energy accumulated per unit volume or mass, whereas PD denotes the rate at which energy is transferred per unit volume or mass. ED and PD of ESS is demonstrated in Table 1 (Hajiaghasi, Salemnia, and Hamzeh 2019; Lee et al. 2023) .

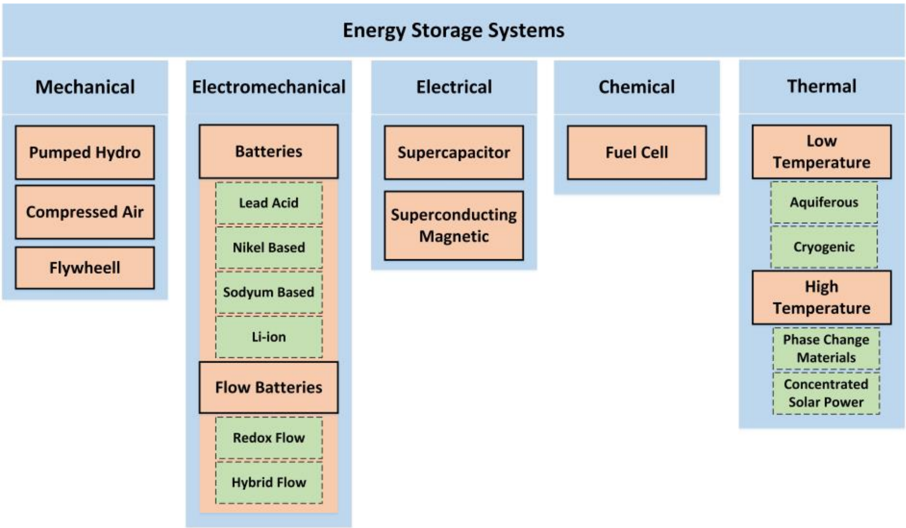

Figure 1. Classification of ESS

ESSs with high ED present significant power control challenges attributable to their slow dynamic response. ESSs that have high PD provide high power demand, but it causes degradation of a lifetime of ESS (Etxeberria et al. 2010). However, none of the existing energy storage technologies can achieve high power and energy densities simultaneously. Therefore, enhancing the operational efficacy of ESS, particularly hybrid energy storage systems (HESS) is a key area of focus. HESS integrates multiple energy storage technologies into a single system to optimize the overall performance and efficiency of energy storage (Hemmati and Saboori 2016; Sutikno et al. 2022; Zimmermann et al. 2016)

Table 1. ED and PD of ESS.

		ESS Technology	**PD W/L**	**ED Wh/L**
Energy storage system	**High Power Storage**	Flywheel	1000–2000	20-80
		Supercapacitor	500–5000	2.5-15
		Superconducting Magnetic	1000–4000	0.2-2.5
	High Energy Storage	Li- ion Battery	1300–10,000	200–400
		Fuel Cell	0-15	600-2500

2. Topology of HESS

The charging and discharging characteristics of energy storage devices exhibit substantial variability, contingent upon the specific energy storage technology utilized. When a HESS is interfaced with the RES, load, or power grid, it operates through various power electronic converter (PEC) topologies. The topology of HESS can be categorized as a passive, semi-active, and active structure (Hajiaghasi et al. 2019).

2.1 Passive HESS topology

The most elementary form of hybridization is achieved by directly connecting two or more distinct ESS technologies in parallel. The coupling of these ESS technologies occurs passively, without the utilization of intermediary PEC. The structure of passive HESS topology is described in Figure 2. As shown in Figure 2, the voltage of each ESS is the same and not regulated. For this reason, the power distribution between ESS units is predominantly assigned by the internal resistances and the voltage-current characteristics. Consequently, the ESS that has the capability of high PD provides limited energy, functioning effectively as a low-pass filter for the HESS. On the other hand, the passive HESS topology is an efficient, simple, and cost-effective solution (Hajiaghasi et al. 2019; Zimmermann et al. 2016). The limitations of passive HESS topology are that the control capabilities are poor, and the HESS voltage is required to be strictly consistent with bus voltage (Vazquez et al. 2010).

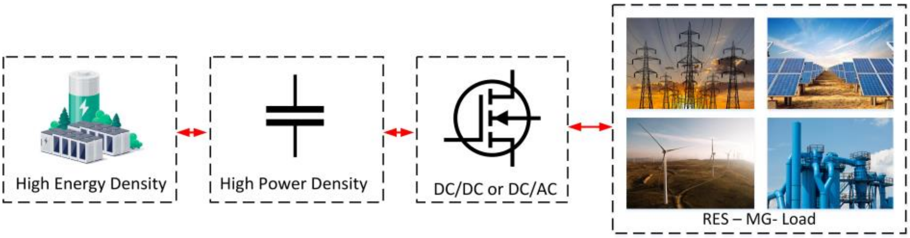

Figure 2. The general overview of passive HESS topology

2.2 Semi-active HESS topology

A general overview of semi-active HESS topology is shown in Figure 3. In semi-active HESS topology, the PEC is connected to one of the ESSs, while the other is directly linked to the DC bus. Although the PEC increases the cost and dimensions of topology, the controllability is better than passive topology (Song et al. 2015). However, the semi-active HESS topology still has limitations such as partial control and strictly consistent with bus voltages for ESS without PEC (Song et al. 2015).

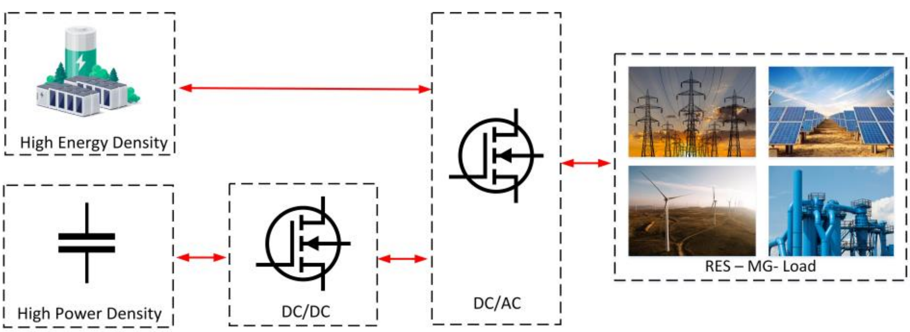

Figure 3. The general overview of semi-active HESS topology

2.3 Active HESS topology

In the active HESS topology, two or more ESSs are connected to the system through PECs. Hence, the power of ESSs can be actively controlled. Although these PECs increase the cost complexity and losses, they improve the controllability, efficiency, and performance of HESS (Lin and Zamora 2022; Ostadi, Kazerani, and Chen 2013). The active HESS can be categorized as a cascaded, parallel, and modular multilevel HESS (Zimmermann et al. 2016).

2.3.1 Cascaded Active HESS topology

A general overview of the cascaded active HESS topology is demonstrated in Figure 4. It is also known as serial active HESS. The topology incorporates multiple distinct energy storage devices arranged in series. These devices are decoupled from one another and from the load by a PEC (Zimmermann et al. 2016).

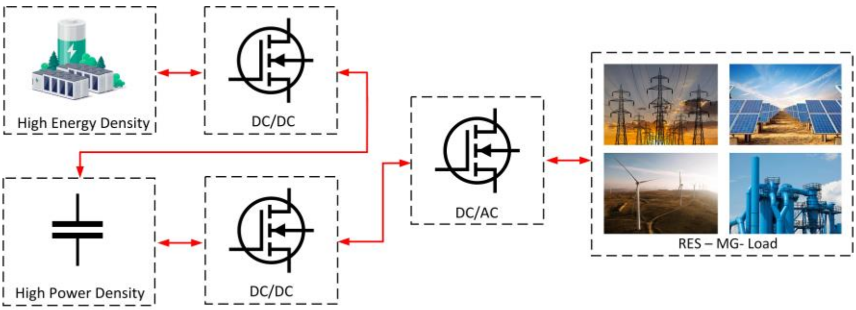

Figure 4. The general overview of cascaded active HESS topology

2.3.2 Parallel Active HESS topology

A general overview of parallel active HESS topology is given in Figure 5. The parallel active HESS topology consists of two or more ESS that are connected in parallel. The ESS and load are decoupled from each other. In this topology, the ESS can be controlled independently depending on the voltage characteristics of the ESS (Camara, Dakyo, and Gualous 2012; Shanmugapriya et al. 2024).

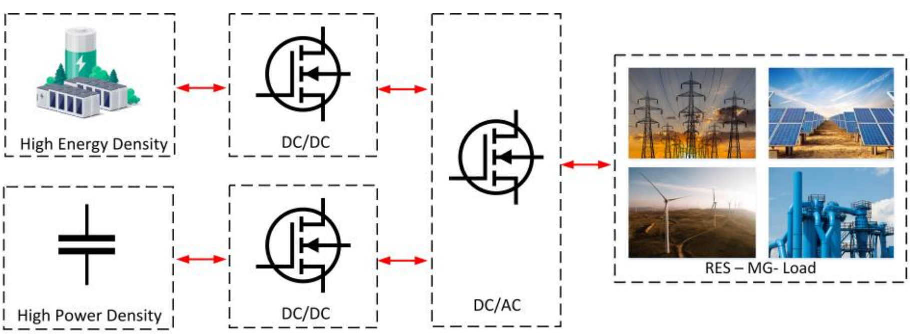

Figure 5. The general overview of parallel active HESS topology

2.3.3 Modular multilevel active HESS topology

A general overview of modular multilevel active HESS topology is depicted in Figure 6. In this topology, multiple ESS are connected in series. Each module consists of ESS which may have different capacities, cell technology, internal resistance, state of health, and PEC. PEC provides that each ESS can be operated at optimum profile. Each PEC should be designed for maximum current of load due to series connection. The complexity and cost of this topology is higher than passive and semi-active topology. Moreover, the topology is sensitive to PEC failures because of the serial connection. One of PEC failure causes system failure (Ju et al. 2014; Zheng et al. 2014).

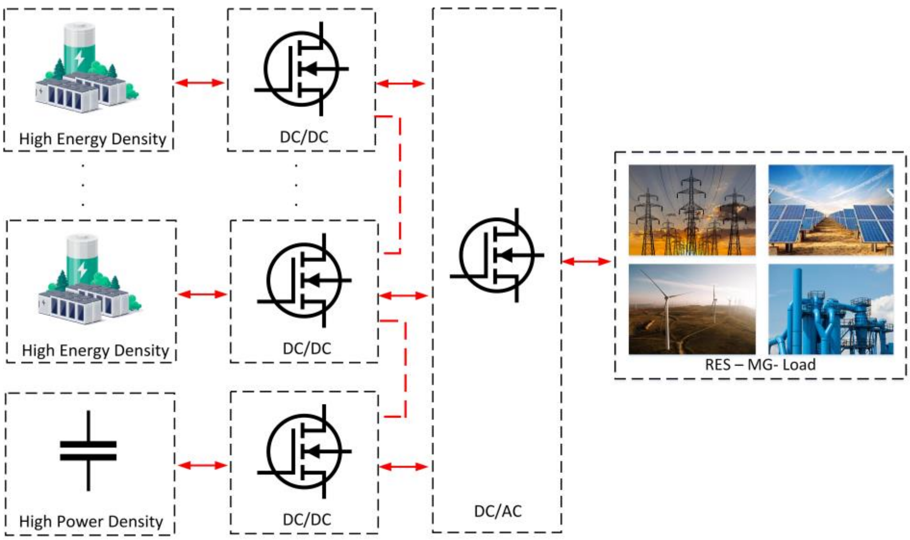

Figure 6. The general overview of multilevel active HESS topology

2.4 Comparison of HESS topology

The energy management system (EMS) is determined according to topology. In passive topology, the output power and voltage of ESS cannot be directly controlled. For this reason, the flexibility of passive topology is low compared to other topologies. However, the passive topology has low cost and complexity. For semi-active HESS topology, the one of ESS output power can be adjusted by PEC. This improves the flexibility and controllability. On the other hand, it increases the cost and complexity. In active HESS topology, the output power of ESSs can be adjusted by control strategy. This topology offers high controllability and flexibility. At the same time, the cost and complexity are high. The PEC converter decreases the efficiency of HESS. So, passive topology has the highest efficiency while active topology has the lowest efficiency (Hajiaghasi et al. 2019; Sutikno et al. 2022).

3. HESS application

Owing to the diverse characteristics of various energy storage technologies, a comprehensive spectrum of hybrid energy storage systems can be developed as represented in Table 2. The selection of appropriate HESS combinations is contingent upon multiple factors, including the objectives of storage hybridization, cost considerations, geographical location, and the availability of storage space (Hajiaghasi et al. 2019). The application of HESS can be categorized as a microgrid, electric vehicle (EV), and renewable energy integration.

Table 2. Various methods of storage combination (Hajiaghasi et al. 2019).

Hybrid Energy Storage Systems	
Near Term	**Long Term**
Battery - SC	SC - Compressed Air
Battery - Flywheel	FC - Flywheel
Battery - Superconducting Magnetic	FC - SCC
Battery - SC - FC	
Battery - FC	
Battery - Compressed Air	

3.1 Renewable energy integration

Due to the intermittent nature of renewable energy plants, power systems faced problems including voltage and frequency stability . In order to solve these problems, ESS is a suitable solution. Since wind/solar power plants cause different frequency components in a generation, HESS can be a more feasible solution as it has low and high-speed response capacity (Sutikno et al. 2022). In (Cabrane et al. 2021), HESS composed of supercapacitors (SC) and batteries is developed for solar power plants (SPPs). The EMS is proposed to distribute energy between the battery and SC. Moreover, the novel control method for DC bus stabilization is introduced. In (Guentri et al., 2021), the robust design method based on particle swarm optimization (PSO), genetic algorithm (GA), pole placement, and linear matrix inequalities is proposed for PEC control in HESS. The performance power management strategy for SPP with HESS is improved. In (Díaz-González et al. 2022), the HESS based on SC and the battery is developed for integration of utility-scale SPP. The principal contribution of the study lies in the formulation and validation of an innovative control methodology for utilizing HESS to concurrently deliver two services to SPP, while simultaneously mitigating the degradation of the embedded storage devices. The 2-level power plant controller is designed to eliminate challenges caused by providing two services at the same time.

In (Wu et al., 2024), the HESS consisting of hydrogen production and Li battery system is designed to address the limitation of a Li-ion battery ESS, which is inadequate for effectively mitigating the fluctuations in solar power generation. The limitation of the battery energy storage system in China is that PV plants are generally installed with 10% li-ion battery ESS. In (Alonso et al., 2024,) the techno-economic assessment of HESS based on hydrogen and batteries is represented for current and future scenarios. Sensitivity analysis is performed for different time zones (2019, 2022, 2030) for on-grid and off-grid conditions. In (Zhou, Ma, and Mu 2025), a new capacity optimization method is presented considering grid-connected constraints and the dynamic economic balance of energy storage systems for HESS. The variational mode decomposition and Savitzky-Golay filtering method are used to decompose and rebuild the photovoltaic signal to minimize the utilization of ESS. In (Sutikno et al. 2022), a comprehensive review of HESS is introduced for SPP. Also, the advances for HESS in SPP are investigated by considering capacity sizing, PEC topology, and EMS. In (Kagichu, Moses, and Kiruki 2022), HESS composed of lead acid battery and SC is proposed for PV systems. The comparison analysis is made for SC and battery over a single battery or SC only. In (Faria et al. 2019), the novel power management system of HESS is developed for standalone SPP utilizing an artificial neural network (ANN). The results demonstrate lifetime of the battery is improved thanks to reduced dynamic stress and peak current. Moreover, the utilization level of SC has increased thanks to the proposed method. In (Rakhshani et al. 2024), the role of HESS is examined with a grid-forming converter (GFM) in low-inertia systems. The primary objective of this paper is to explore the operational advantages of employing a HESS with GFM in contrast to a Battery Energy Storage System (BESS), specifically considering factors such as frequency regulation and grid resynchronization stability.

In (Wicke and Bocklisch 2024), the two-level EMS is developed for HESS considering PV capacity, spot market trading, and peak shaving. The upper-level EMS optimizes the power of the grid taking into account electricity price and the marginal cost of battery operation while the lower-level EMS allocates power in real-time to fulfill the power of grid and ramp-rate requirements, effectively addressing model and forecast inaccuracies. In (Zheng et al., 2014), review of HESS is presented for renewable energy system (RES) technologies and applications. In (Rao, Ranganathan, and Tomomewo 2024), advantages and developmental requirements of HESS are introduced in contrast to standalone Energy Storage Systems (ESS). Additionally, the study offers a comprehensive evaluation of HESS models implemented in practical applications, assessing their performance metrics in real-world contexts. In (Moloelang et al. 2023), HESS including battery and SC is modeled and analyzed for RES considering voltage, current, power, and SOC. (Kumar et al. n.d.) examines the optimal (economically efficient) sizing of a hybrid battery and supercapacitor storage system for a 1 MW SPP, considering a one-hour dispatch period over the course of an entire day. The optimization process is based on the time constant of a low-pass filter (LPF), which is employed to allocate power between the battery and SC. In comprehensive review of HESS is introduced and investigated for potential topologies to increase battery life for standalone SPP. Different HESS topology is tested and compared in Matlab Simulink (Jing et al. 2018).

3.2 Electrical Vehicle

EVs integrated with batteries are increasingly recognized as a crucial power system, owing to their lower air pollution and enhanced efficiency (Khalid et al. 2024). These vehicles are gaining widespread acceptance as a viable solution to the challenges posed by excessive fossil fuel consumption and substantial ecological degradation. Advancements in battery technology have yielded enhanced battery performance. Nonetheless, sustained and uncontrolled charging or discharging cycles will precipitate degradation in the battery's life cycle, consequently diminishing overall system efficacy (Arandhakar et al. 2022). To improve the lifetime of the battery, HESS is proposed combining high PD storage and high ED for EVs (Shanmugapriya et al. 2024).

In (Shanmugapriya et al. 2024) IoT-based EMS is developed for HESS in EV. The self-attention generative adversarial networks (SAGAN) and coati optimization algorithm (COA) are utilized for EMS. While SAGAN estimates the power demand, COA is used to optimize the weight parameter of a neural network to increase the performance of SAGAN. In (C and C 2024), the novel hybrid model is used for EMS of HESS, including battery, fuel cell (FC), and SC, in EV to optimize power allocation and control strategy. The hybrid model consists of sand cat swarm optimization (SCSO) and recalling enhanced recurrent neural networks (RERNN). The main objective of the proposed method is to regulate DC bus voltage and follow SC and battery references. (Raut et al. 2024) presents a SPP integrated battery and SC HESS architecture designed for application in EVs. The system's behaviour has been investigated through modeling and numerical simulation within the MATLAB Simulink. The SC component is incorporated to manage transient peak power demands and mitigate the effects of high-magnitude charging and discharging current fluctuations. This strategic integration serves to enhance the durability and extend the operational lifespan of the battery. In (Pang et al. 2024), a novel method for optimizing HESS design, EMS, and thermal management strategies is proposed in EV. This integrated approach aims to not only modulate battery utilization profiles to extend operational lifespan but also to enhance overall battery performance and mitigate the deleterious effects of low-temperature operation on battery lifetime. (Ahsan et al. 2024) introduce optimization methods for optimal sizing and cost of HESS for EV using metaheuristic particle swarm optimization (PSO) and firefly algorithms. This research establishes a comprehensive framework for the modeling of EVs leveraging simulated EV data to augment the fidelity and predictive accuracy of the resultant models. (Podder et al. 2021) presents a comprehensive review of control strategies of different HESS and optimization for EV. The different HESS configuration is composed of FC-battery, battery-SC, FC-SC, and battery-FC-SC.

3.2 Microgrid

The utilization of RES presents a viable pathway to satisfying the expanding global energy demand. The incorporation of RES modalities, such as solar, wind, geothermal, and biomass, into existing electricity network infrastructures contributes to enhanced energy security, a reduction in CO2 emissions, and increased stability in fuel pricing. (R. and Kowsalya 2024) . The incorporation of RESs into power system infrastructures may engender operational challenges such as voltage instability, reduced inertial response, degradation of power quality, and diminished system reliability (Ippolito et al. 2014). Nonetheless, the deployment of microgrids (MGs) offers a promising strategy for mitigating these adverse effects (Aboumadi et al. 2023; Etxeberria et al. 2012). The MGs can be operated as off-grid or on-grid with RES ESS and loads. The common ESSs used in MGs are batteries, supercapacitors, flywheels, and thermal storage systems. Hybridization of ESSs in microgrids improves the performance of MG (Hajiaghasi et al. 2019).

(Hajiaghasi et al. 2019) present a comprehensive review and classification of critical considerations pertaining to the implementation of hybrid energy storage systems (HESS) within microgrid (MG) architectures. The scope of this review encompasses capacity sizing methodologies, power converter topologies employed for HESS integration, architectural configurations, control algorithms, and energy management strategies. Furthermore, an economic analysis coupled with a design methodology is incorporated to elucidate the implications of HESS implementation from the viewpoints of both investment stakeholders and distribution system engineers. In (R. and Kowsalya 2024), the comprehensive review of control strategies, configuration, PEC topology, and EMS of HESS for microgrids are presented. Moreover, the artificial intelligence techniques for different control methods, fuzzy logic, neural networks, and reinforcement learning, for microgrids are introduced. In (Ramu et al. 2024), the novel EMS based on ANN is proposed for controlling DC microgrid utilizing HESS composed of SC and battery. The proposed EMS provides smooth energy exchange between the battery and SC. (Yang et al. 2024) presents hierarchical EMS for HESS including SC, FC, and battery utilizing fractional order sliding mode control to address nonlinear characteristics of DC MG. In (Singh & Lather, 2021), novel EMS is presented to facilitate effective power sharing between battery and SC energy storage systems. This EMS is implemented to mitigate imbalances between power demand and generation, as well as to ensure robust DC bus voltage regulation. The proposed compensatory mechanism for PI controller-managed HESS achieves enhanced DC bus regulation while simultaneously minimizing stress on the battery components. (Duan et al. 2019) presents the development of a novel reinforcement-learning-based online optimal control methodology designed to facilitate smooth and efficient charge and discharge control of HESS for hybrid AC and DC MG. (Lin and Zamora 2022) present a critical analysis and comparative evaluation of HESS control methodologies within MG architectures, with a further aim of identifying and elucidating the shortcomings inherent in existing control strategies. Moreover, the time delay caused by the communication system on controllers of HESS in MG is examined.

4. Conclusion

The integration of RESs into the power system can cause voltage and frequency problems. To solve this problem, ESS technology is the key solution. However, there is no ESS technology that has high PD and high ED to mitigate low and high-frequency components. So, the HESSs are introduced to improve the performance of ESSs. This study presents a comprehensive overview of HESS topologies and their applications in microgrids, renewable energy integration, and electric vehicles. Moreover, the comparison of HESS topology is introduced in terms of controllability, complexity flexibility, and cost.

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