Chapter 1

Introduction

1.1 Motivation

In recent decades, the depletion of fossil fuels (coal, oil, and gas) are growing environmental pollution concerns have significantly increased the importance of renewable energy sources (RESs) [4]. Renewable energy has become crucial in recent times because it diversifies the energy supply and reduces dependency on imported fuels [5]. RESs harness energy from natural sources like sunlight, wind, tides, and biomass, which are abundantly available in nature. Among these sources, wind power generation is widely used and considered an efficient energy source [6, 7]. However, wind power plants require more maintenance than other RESs and tend to produce a significant amount of noise [7]. Additionally, wind power plants are not suitable for residential installations, such as rooftop installations on residential or commercial buildings, to meet localized demands. Solar photovoltaic (PV) and fuel cell systems are more suitable for residential and commercial distribution systems compared to wind power plants due to their lack of mechanical moving parts, lower maintenance costs, and compactness. Furthermore, PV sources do not emit harmful greenhouse gases, unlike biomass energy sources, and can be deployed close to load centers for use in applications ranging from large solar plants to small household installations [8]. Among all RESs, solar PV is considered one of the most cost-effective renewable energy sources [9–11]. Research in the area of solar PV and fuel cell power generation and its applications is growing steadily, particularly through the use of various power electronic converters (PECs).

1.2 Research background

Global electricity consumption is increasing at an unprecedented rate, driven by growing prosperity and urbanization in emerging economies. Currently, the majority of energy demand is met by conventional fossil fuels, primarily coal and oil. The extensive use of these fossil fuels has led to record high greenhouse gas emissions and other toxic pollutants, resulting in significant climate change and elevated air pollution levels [12, 13]. The EIA report [14] indicates that since 2000, the transportation and industrial sectors have been the largest energy consumers in the United States and other developed nations, with petroleum being the predominant fuel source, as shown in Fig. 1.1. Data reveals that the adoption of renewable energy in the transportation sector is still minimal. Furthermore, countries such as China, the United States, and India are the primary contributors to global energy consumption and greenhouse gas emissions, as highlighted in Fig. 1.2 [15]. Recently, there has been a slower increase in global energy consumption (1.3%) and carbon emissions compared to the peak in 2018 (2.8%), as illustrated in Fig. 1.3 [13].

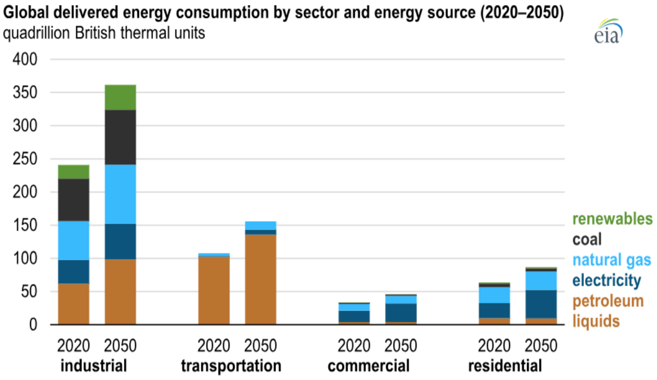
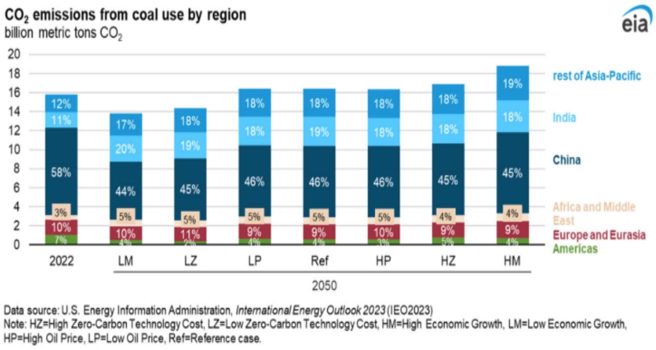


Figure 1.1: Energy Consumption in the U.S. by End-Use Sector (Source: EIA Report).

Nevertheless, climate change remains a significant issue due to the continuous rise in global C_{O2} emissions and the depletion of fossil fuels. This underscores the urgent need to reduce global emissions and address the energy crisis. Consequently, today's energy strategies are increasingly shifting from heavily relying on coal and petroleum to non-polluting renewable sources such as solar, wind, geothermal, and biofuel. These renewable sources are viewed as clean, inexhaustible, and increasingly competitive for sustainable energy solutions. The progress in the renewable sector is transforming energy systems worldwide. Although the share of renewables has increased from 9.3% to 10.4%, integrating renewables more broadly into global electricity generation remains challenging due to technological limitations, intermittency, lower efficiency, and lenient policy measures [16, 17].


CO_2 emissions from coal use by region
billion metric tons CO_2

Data source: U.S. Energy Information Administration, *International Energy Outlook 2023* (IEO2023)
Note: HZ=High Zero-Carbon Technology Cost, LZ=Low Zero-Carbon Technology Cost, HM=High Economic Growth, LM=Low Economic Growth, HP=High Oil Price, LP=Low Oil Price, Ref=Reference case.

Figure 1.2: Share of Global Energy Consumption (Source: BP Statistical Review of World Energy).

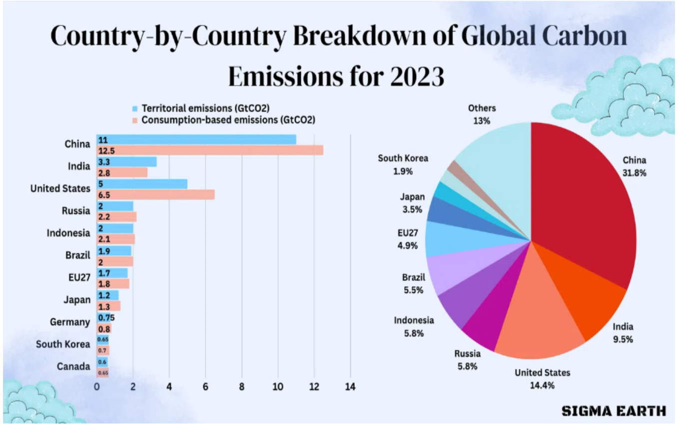

Country-by-Country Breakdown of Global Carbon Emissions for 2023

Figure 1.3: Worldwide Carbon Emissions from Energy (Source: International Energy Agency, 2023 Report).

This situation necessitates a collaborative effort that integrates cutting-edge renewable energy technologies with a greater willingness to transition to low-carbon energy solutions. This includes encouraging adoption through incentives, implementing effective energy policies, and aligning with societal preferences. The transformation of the global energy landscape to reduce carbon emissions can be achieved through the following approaches. Transitioning to low-carbon electricity production entails decreasing carbon emissions per unit of energy and replacing coal and oil with alternative non-conventional energy sources.

- Move towards sustainable transportation by substituting petroleum with electricity.
- Quickly implement affordable low-carbon energy solutions and battery technologies to provide accessible energy in low-income nations.
- A range of fuel sources, competitive pricing, localized generation, all with an upward trend in installations.

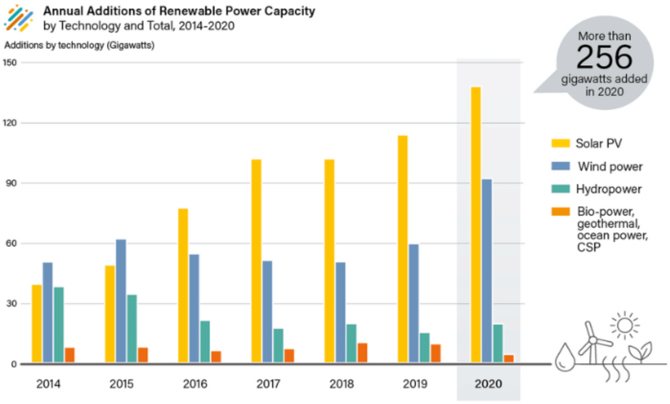


Figure 1.4: Annual growth in renewable energy capacity (Source: IRENA International Renewable Energy Agency).

With these strategies implemented, it is forecasted that by 2050, over 40% of the world's electricity needs will be met by the renewable energy sources illustrated in Fig. 1.4. Similarly, akin to 2019, there has been a notable surge in global renewable power capacity, surpassing 760 GW annually, showcasing a growth rate three times that of fossil fuels, as evidenced in Fig. 1.5. Solar photovoltaic (PV) stands out as the leading renewable energy source, commanding a market share of over 50% (around 115 GW), followed by wind energy at 30% and hydropower contributing approximately 8%. As of 2020, the global solar PV capacity reached 760 GW, contributing to a total installed capacity of 2,588 GW worldwide. This rapid growth in the renewable power sector is propelled by various factors, including a significant reduction in cost per kilowatt, escalating electricity demand, increasing awareness, and supportive government policies and regulatory frameworks.

Fig. 1.6 shows the projected growth of the fuel cell market from 2023 to 2033, increasing from USD 8.4 billion in 2023 to USD 42.6 billion in 2033. Key fuel cell types include Proton Exchange Membrane (PEM) Fuel Cells, which dominate the market, along with

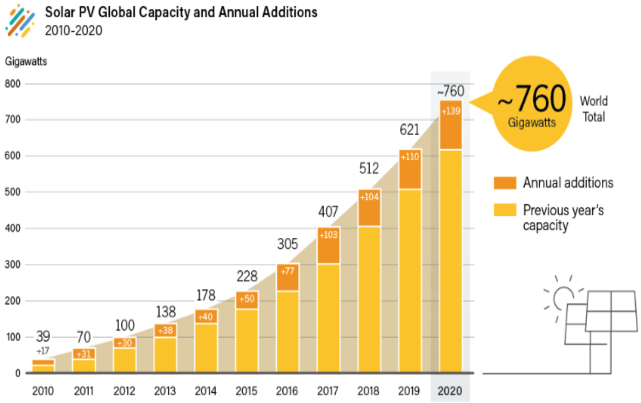


Figure 1.5: Worldwide annual Installed Capacity of Solar Photovoltaic (PV) Systems [1].

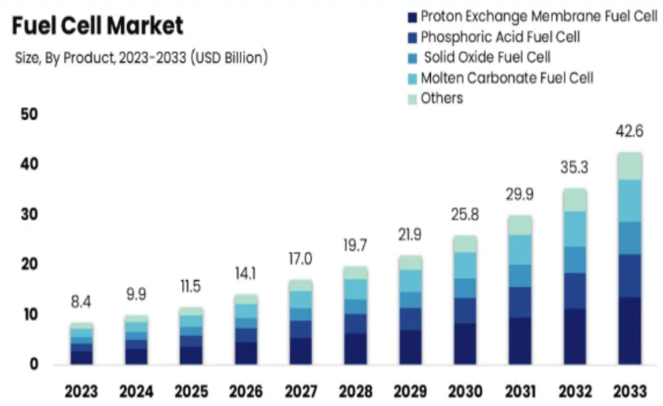


Figure 1.6: Worldwide Installed Capacity of Fuel Cell (FC) Systems [2].

Phosphoric Acid, Solid Oxide, and Molten Carbonate Fuel Cells. The steady year-on-year growth highlights the rising demand for clean energy technologies driven by decarbonization efforts and advancements in fuel cell applications for transportation, industrial power, and energy grids.

1.3 Micro Grid Architecture

With a strong emphasis on decarbonizing power generation and minimizing transmission costs, small-scale distributed energy systems are gaining popularity. This trend is propelled by the rapid incorporation of renewable energy sources, battery storage, and contemporary DC loads like electric vehicles (EVs) and data centers [18, 19]. Moreover, investments in clean energy technologies and localized installations are steadily increasing to combat global climate change and enhance energy access in rural regions. Distributed generation, whether through microgrids or conventional grid-connected setups, provides a multitude of advantages that accelerate the global shift toward cleaner and more sustainable energy sources [20–23].

A typical microgrid architecture is illustrated in Fig. 1.7. Microgrids can be uniquely controlled, either operating independently in standalone mode or in conjunction with the main grid [24, 25]. In the current energy landscape, solar PV-enabled microgrid systems are among the most competitive options for low-to-medium power applications in residential, commercial, and industrial sectors [26]. Power from low-voltage renewable energy sources can be harnessed to supply a high-voltage DC microgrid (380V), which powers common DC loads such as modern data centers and EV charging stations [27–29]. Additionally, microgrids can support utility-scale solar inverters, uninterruptible power supplies (UPS), and motor drive applications through an additional inversion stage at the 380V intermediate DC link. The integration of energy storage is crucial for ensuring seamless power transfer from sources with inherently intermittent characteristics. Furthermore, energy storage systems are beneficial even in grid-connected setups, as they help prevent grid instability. Small-scale decentralized generation with auxiliary energy storage systems enhances reliability and grid flexibility by providing backup power during grid interruptions and blackouts. Transitioning to clean energy systems stimulates local economies, benefits populations worldwide, and reduces reliance on conventional energy sources [30–32].

However, due to the intermittent and unique characteristics of low-voltage renewable sources, their effective utilization is often constrained by conversion technologies and interfacing systems [33–35]. To establish a safe and efficient interconnection, extensive research is necessary, focusing on innovative DC-DC interfaces that can adapt to the inherent characteristics and seasonal variability of renewable energy sources like solar PV and wind [36–42]. Additionally, to align the voltage profiles of the sources and loads within a microgrid system, a high voltage conversion ratio is required, which non-isolated boost converters cannot achieve. Consequently, high conversion ratio non-isolated DC-DC converters become essential for interfacing low-voltage sources with a high-voltage DC microgrid, ensuring the desired voltage gain and providing safety isolation between the converter and the utility line [43,44]. Moreover, PV and fuel cell systems operating in the 30V-48V range are preferred for delivering domestic power levels due to their reduced cost and scalability. Thus, this voltage range is chosen for investigating PV and fuel cell interfacing [45, 46].

Additionally, the cost of electricity from solar PV and other clean energy sources has dropped dramatically over the past decade, significantly boosting the distributed generation market and providing promising solutions for microgrid applications. As the demand to revolutionize distributed energy systems with eco-friendly sources grows, it is also crucial for the technology interface to be highly efficient and cost-effective in terms of both performance and expenditure.

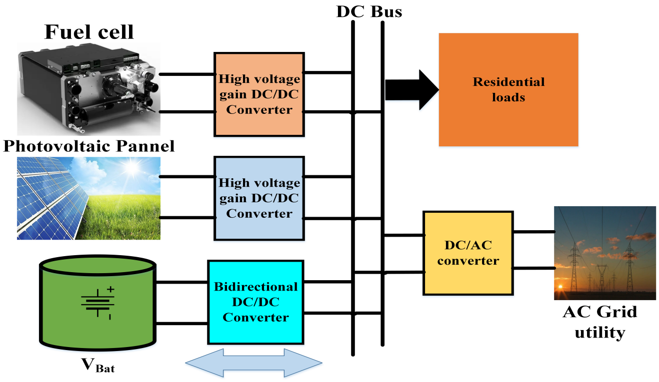


Figure 1.7: Configuration of a typical microgrid system.

1.4 Solar Power Generation

The typical circuit diagram of a p-n junction diode is shown in Fig. 1.8, which varies with change in temperature. It can be observed that the forward breakdown voltage of the diode is close to 0.7 V in the case of silicon at room temperature. The PV cell is also a p-n junction diode which is designed to let the light penetrate the junction area in order to develop electron-hole pairs. These generated free charges cause a current to flow across a closed circuit across the diode. This current is called the light current(I_L), which shifts the V-I characteristic of the diode in the fourth quadrant. After taking a mirror image of this shifted V-I characteristic across the voltage axis, the V-I characteristic of a PV cell is generated as shown in Fig. 1.9.

The expression for the V-I characteristic of solar cells is given by [47]:

$$I = I_o[e^{\frac{qV}{\eta KT}} - 1] - I_L \tag{1.1}$$

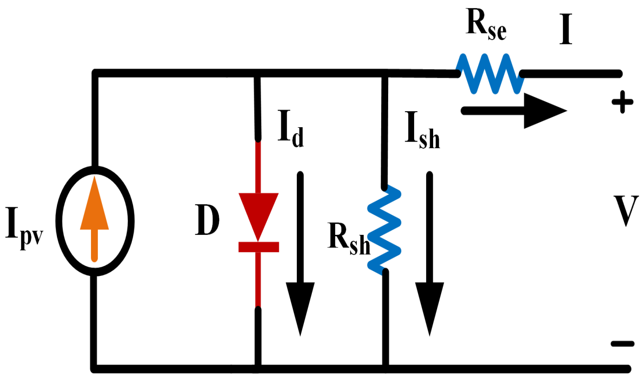


Figure 1.8: Equivalent circuit diagram of a PV panel.

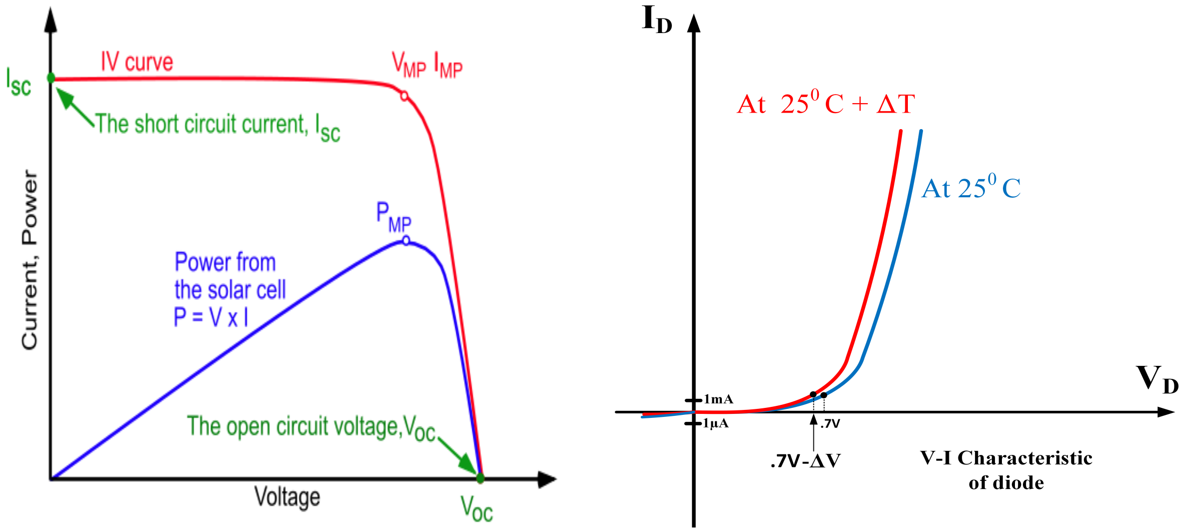


Figure 1.9: (a) I-V curve of PV (b) Characteristic curve of PV panel.

The PV cell is inherently a low voltage and high current source, but this problem can be easily solved by using a long string of solar cells in order to get high voltage levels. But developing high voltage systems using PV cells leads to many problems, such as:

(a) Predominant shading effect, as PV cells with low levels of irradiance, start acting as loads, which leads to heating of PV panels and subsequent efficiency degradation.

(b) A small amount of leakage current starts owing on the surface of the PV panels when PV panels experience a higher level of operating voltages. This small current is responsible for the ionization of the panel glass surface as well as the degradation of the p-n junction, and this leads to a reduced operational lifetime of the PV panels. This is called Potential induced degradation(PID).

(c) Another problem associated with the operation of the PV generation system is the oscillation of the maximum power point (MPP). If there is a presence of current ripple in the output of the PV panel, the operating point of the solar panel starts oscillating, which leads to oscillation of the MPP and thus efficiency degradation. It is observed that the presence of only a 2.5 % ripple in output current leads to an approximately 7 % fall in PV generation. The oscillation of the MPP is depicted in Fig. 1.9.

(d) The PV generation systems have low output voltage. Increasing the output voltage by using long strings leads to potential induced degradation (PID) and predominant shading effect losses.

(e) Current ripple from the solar panels causes the operating point to fluctuate around the maximum power point (MPP), resulting in reduced efficiency and increased panel heating.

The possible solutions entail the following:

(a) A high-gain converter is used to integrate low-voltage PV panels with a high-voltage DC microgrid, helping to mitigate issues related to predominant shading effects and Potential Induced Degradation (PID).

(b) Low-cost DC-DC converter for a highly distributed structure.

(c) Developing a DC-DC converter with low input current ripple to reduce the oscillation of MPP.

1.5 Fuel Cell Energy Conversion System

Fuel cells are a type of energy conversion technology that takes the chemical energy contained within a fuel and transforms it into electricity along with certain by-products (depending on the fuel used) [48]. It's important to note that fuel cells are not heat engines, so they can have incredibly high efficiencies. However, when a heat engine is used to power a fuel cell, the heat engine still has a limiting thermal efficiency. Fuel cells can be seen as an energy storage device, as energy can be input to create hydrogen and oxygen, which can remain in the cell until its use is needed at a later time. In this sense, they work much like a battery. There are multiple types of fuel cells, but two common types are the solid oxide fuel cell (SOFC) and the polymer electrolyte membrane fuel cell (PEMFC). To produce electricity in a solid oxide fuel cell, oxygen in the air combines with free electrons to form oxide ions. The oxide ions travel through a ceramic electrolyte and react with molecular hydrogen to form water. The reaction that makes water also releases electrons which travel through an external electrical circuit, producing electricity [48]. This process can be seen in Fig. 1.10.

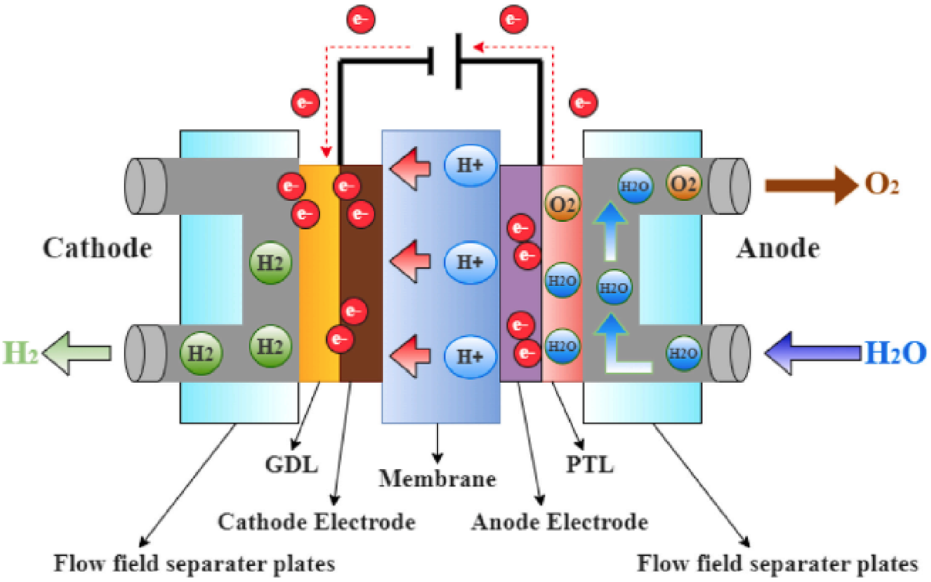


Figure 1.10: Schematic view of PEM water electrolysis working principle [3].

1.5.1 Fuel Cell Model Development

Hydrogen production from sustainable energy sources makes its use as an energy carrier a promising option for changing energy trends. Because it is 70% efficient, the Solid Oxide Fuel Cell (SOFC) is one of the most effective fuel cells available. First, because SOFC cells typically run at high temperatures, they can directly handle fuel inside of them, like natural gas. Second, these cells are dependable for fuel-efficient stationary power generation because they can quickly increase their electric efficiencies. Therefore, compared to low-temperature power plants that require hydrogen synthesis with an additional process unit, such properties lower the system's complexity equivalent circuit diagram, and their characteristics are shown in Fig. 1.11(a) and Fig. 1.11(b). As fuel cells having high temperatures cannot be turned off easily, therefore, they are acceptable in the stationary sector only. Because they have a longer working life, SOFC cells are mostly used in commercial systems. Additionally, extra water can be moved through the steam turbines once again to produce more electricity and improve the system's efficiency.

1.5.2 Working Principle of fuel cell

FC transforms chemical energy into electrical energy by means of an oxidation reduction reaction. Hydrogen oxidized on anode electrochemically produces proton H^+ and e^-. Proton move through membrane to cathode and electron are compulsively move to circulate in the external closed loop circuit, generating electric current i_o. At the cathode, electrons are carried through the external circuit, and the protons move through the membrane combined with O_2 molecule, producing heat and water. Oxidation and reduction reactions are given below

$$Anode : 2H_2 \rightarrow 4H^+ + 4e^- \tag{1.2}$$

$$Cathode : O_2 + 4e^- + 4H^+ \rightarrow 2H_2O \tag{1.3}$$

Terminal Voltage of fuel cell

The terminal voltage of FC is obtained after various drops of FC like concentration drop, ohmic drop, and activation drop from Nernst voltage.

$$V_{FC} = E_{Nearst} - V_{act} - V_{ohmic} - V_{con} \tag{1.4}$$

$$V_S = nV_{FC} \tag{1.5}$$

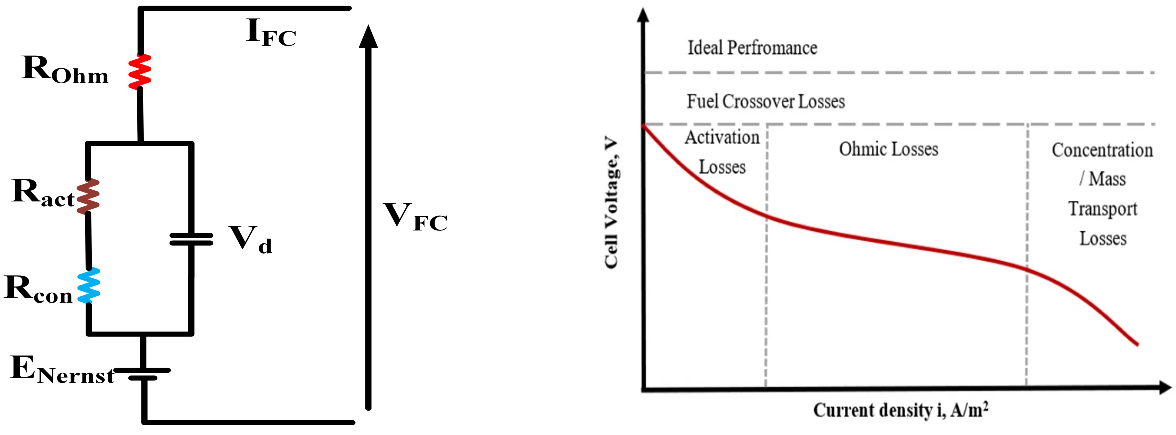


Figure 1.11: (a) Equivalent circuit of a fuel cell (b) Characteristic curve of the fuel cell.

Nernst Voltage

The Nernst voltage of the fuel cell depends on the partial pressure of individual species, which is calculated by using mass flow conservation. The electrochemical equation is represented by the parallel RC circuit. The voltage that appears across the capacitor of the parallel RC circuit is equal to the partial pressure P_i of the gases.

$$E_{Nearst} = -\frac{\Delta H^o}{2F} + \frac{\Delta S^o}{2F}(T_{f_c} - T_{f_{c_o}}) + \frac{RT_{f_c}}{2F}[ln(P_{H2}) + .5 * ln(P_{o2})] \tag{1.6}$$

where E_{Nearst} is thermodynamic potential of each cell, R=8.314KJ/Kmol, T(Kelvin) is temperature of fuel cell during operation, F=96486 C/mol is faradays constant, P_{H2}, P_{O2} is hydrogen and oxygen partial pressure.

Activation Voltage Drop

Activation losses are related to electrochemical reaction kinetics in FC. These losses occur due to charge transfer, causing slowness of the reaction taking place on the surface of the electrode. At certain temperatures due to low current density and catalyst effectiveness cause polarisation losses. Activation potential is given by the Butler Volmer equation. This potential change in temperature and current density can be expressed as:

$$V_{act} = -[\zeta_1 + \zeta_2 * T * \zeta_3 * ln(C_{o2}) + \zeta_4 * T * ln(I_{fc})] \tag{1.7}$$

Ohmic Losses

This drop is the same as the resistance drop, which occurs in charge flow from one electrode to another electrode; resistance suffered by the charge between these electrodes causes ohmic losses. The electrolyte works as the resistance between the electrodes. Reduction in voltage at the terminal of the fuel cell is due to ohmic losses, and this ohmic loss is expressed as electronic resistance (R_{elec}) and ionic resistance (R_{ionic}) of the FC. This can be written as

$$V_{ohmic} = i_{FC} * (R_{ionic} + R_{elec}) \tag{1.8}$$

R_{ionic} is electrolyte resistence of solution in fuel cell, and R_{elec} denote electrical resistance of bipolar plates.

Concentration Loss

Concentration loss occurs due to changes in the concentration of a reactant at the surface of the electrodes as fuel cells are used. This concentration loss affects the voltage of FC.

$$V_{con} = -\frac{RT}{nF} * ln(1 - \frac{I_{fc}}{I_L}) \tag{1.9}$$

where I_L is the limiting current density of the cell. where E_{Nearst} is thermodynamic potential of each cell, R=8.314KJ/Kmol, T=25°C is temperature of FC during operation, F=96486 C/mol is faradays constant, P_{H2}, P_{O2} is hydrogen and oxygen partial pressure. All values are put together to get a final equation of Nernst voltage.

A bridgeless sepic converter-based fuel cell emulator is designed to address several challenges associated with using actual fuel cells in research and testing. These challenges include the high initial cost of setting up a fuel cell, handling and safety concerns with hydrogen gas, the expensive manufacturing process due to the high cost of catalysts (like platinum), the lack of infrastructure for hydrogen distribution, and the fact that hydrogen is expensive to produce and not widely available. Additionally, many fuel cell technologies are still in the prototype stage and have not yet been validated. To mimic the behavior of a real fuel cell, allowing researchers to conduct experiments and validate power conditioning systems without the need for an actual fuel cell stack. This approach helps in overcoming the limitations related to cost, safety, and availability while still providing accurate emulation of fuel cell characteristics [49].

1.6 High Voltage Gain DC-DC Converter Requirements

Despite their numerous advantages, the integration of solar PV and fuel cells into microgrid applications faces several operational challenges. These challenges include low DC output voltage, an intermittent source profile with wide voltage oscillations, complex control mechanisms, seasonal variability, low reliability, and high per-unit costs. Additionally, fuel cells, known for their ease of accessibility, high energy density, and superior storage and transport capabilities, are also competitive clean energy sources. To effectively integrate these low-voltage renewable energy sources, DC/DC converters serve as crucial interfacing units, designed with specific features to address these challenges [50,51]. These high-gain converters should have the following criteria.

1.6.1 High Voltage Gain Capability

Solar PV panels and fuel cell panels typically produce DC voltages in the range of 30 to 48V, which is too low to directly meet the high DC voltage, around 380V, needed by microgrids or distributed energy systems. To address this, a high voltage gain, usually greater than 10, is required to step up the low voltage to the necessary level for the DC bus.

1.6.2 Variability in Source Voltage

The unregulated and discontinuous DC output voltage from a typical solar PV array depends on factors such as available solar irradiance, ambient temperature, and other environmental conditions. Similarly, the voltage of a fuel-cell stack is affected by variable fuel inflow. Therefore, the DC-DC interface must ensure reliable and efficient operation despite wide variations in source voltage.

1.6.3 High Density and High Efficiency

To enhance power density, higher switching frequencies are preferred, as they enable the use of smaller magnetic components and filters, resulting in more compact, cost-effective, and lightweight converters. However, operating at higher switching frequencies is constrained by increased switching losses in semiconductor devices, necessitating the implementation of soft-switching techniques.

1.6.4 Control Flexibility and Modularity

DC-DC converters with fewer switching devices offer greater control flexibility due to simplified control logic and reduced gate drive requirements. Additionally, modular structures are favored for their ability to meet high power demands and ease of implementation.

1.7 Literature Review

1.7.1 Review of High Gain DC/DC Converter

With the advancements in power electronics and semiconductor devices, the interfacing of DC-DC converters with innovative modulation and control techniques has been effectively leveraged to maximize power extraction from low-voltage renewable sources in hybrid microgrid systems. This section reviews the literature on DC-DC converter topologies. Based on their source functionality and characteristics, they can be broadly categorized into two primary types: isolated and non-isolated high-gain converters. In the context of isolated converters, the gain is magnified using the transformer turns ratio. These converters offer benefits for high-power scenarios owing to their galvanic isolation capabilities. The effectiveness of these structures suffers from significant limitations like cost and size [52]. Additional limitations include losses due to leakage inductance and saturation in the transformer core.

Another category falls within the classification of non-isolated high gain boost converters. In [53], a cascaded boost converter configuration is proposed, where multiple individual units of traditional converters are connected in series. This design achieves high gain through a high duty ratio, leading to diminished efficiency due to considerable conduction losses. The configurations proposed in [54] and [55] employ coupled inductors (CIs) to achieve high gain. Within this approach, the switch is subjected to constrained voltage and current stress. However, a significant limitation arises from the loss of leakage inductance within the coupled inductor winding. To recover this leakage energy, an additional clamping circuit becomes necessary, introducing complexities in the converter control and contributing to increased losses [11, 56]. The topology outlined in [57] adopts an interleaved structure incorporating two coupled inductors and four switches, leading to increased circuit and control complexity. The literature [58, 59] discusses a voltage lift technique that enhances the converter's gain. However, this method places substantial voltage and current stresses on the intermediate capacitor. The DC-DC converter [60] is cascaded with a clamped circuit to achieve high voltage, but it draws more current through input diodes. Voltage multiplier cells [61–63], achieve significant voltage gain, but this comes at the cost of reduced efficiency due to the high number of components, especially when employing multiple voltage multiplier cells. Moreover, managing the converter operation becomes challenging with an increasing number of stages.

References [64] and [65] introduced configurations based on the switched capacitors (SC). These converters involve parallel charging of capacitors followed by series discharging. However, this approach leads to inadequate voltage regulation and necessitates integration with other techniques to ensure proper output voltage control, resulting in high current spikes. Active passive inductor cell based topology is reported in [66, 67] with a gain of (1+3D)/(1-D) (D is duty cycle), this configuration utilises switched inductor arrangement to produce this voltage gain. However, in this converter, switches are under high current stress, causing large conduction losses. Similarly, [68] requires more components to achieve high gain. Another switch inductor based converters are presented in [69, 70], these converters have lower gain with high voltage stress across the switch. In [71], hybridization of boost and Cuk is reported to achieve voltage gain by a factor (1+D)/(1-D). However, this converter suffers from higher voltage stress across switches and the absence of common ground. In [72] suggested a converter with a single switch, this converter lacks of common grounding, low gain, and more voltage stress across devices. Buck-boost integrated with zeta converter presented in [73] has a discontinuous input current. Converters presented in [74, 75] are designed to get high gain by using more components. A switch inductor based converter is presented in [76] this converter has lower gain and high-frequency pulse width modulation (HF PWM) voltage, which increases the radiated EMI and requires additional periodic maintenance. The converter in [77] presents a buck-boost based topology that achieved a gain of 3D/(1-D) with a drawback of discontinuous input current with high voltage and current stress through the devices. The converter [78] achieves a gain of (3+D)/2(1-D) but high current stress through the switch, which causes a reduction in the overall efficiency of the converter. [72] proposes a converter with a single switch with low gain and more voltage stress across devices. Buck-boost integrated with zeta converter is presented in [73] and has a discontinuous input current. The converters [79,80] both have the same gain in comparison with the proposed converter, but one has a higher component count, and the other one has a pulsating input current. The configuration in [81] and [82] are based on the switched capacitors (SC). These converters involve parallel charging of capacitors followed by series discharging. However, this approach leads to inadequate voltage regulation and necessitates in integration with other techniques to ensure proper output voltage control, resulting in high current spikes. Active passive inductor cell based topology is reported in [83] with a gain of (1+3D)/(1-D), this configuration utilizes switched inductor arrangement to achieve this voltage gain. However, converter switches are under a high current stress, and high-frequency pulse width modulation (HF PWM) voltage, which increases the radiated EMI and requires additional periodic maintenance.

1.8 Organization of the Thesis

This thesis deals with alleviating the limitations of PV and fuel cells. The major challenge in PV generation is to keep the string voltage at lower levels and eliminate the elimination of current ripple from the output of the solar panels to remove the MPP oscillation. One of the major challenges in fuel cells in practical applications is to step up the fuel cell voltage and minimize the input current ripple. These are addressed by developing high-gain converters for PV and Fuel cells. Furthermore, other aspects of a converter, like the component reduction and reduction of voltage stress on the switches, are explored as well. The integration of PV and fuel cells is also explored in this thesis.

The thesis is organized as follows:

- Chapter 2 presents the analysis and design of a high gain converter with reduced voltage stress for renewable applications. Merging of two converter boost and Luo converter to obtain high voltage gain. The operational behavior of the converter is evaluated for both continuous and discontinuous conduction modes of operation, and its design parameters are presented. Efficiency, design equations, and current stress of used devices are computed and compared.

- Chapter 3 deals with a high gain bipolar converter with reduced input current ripple for fuel cell integrated DC microgrid. The interleaved converter topology is controlled to effectively eliminate the current ripple under all operational duties. The proposed topology has low voltage stress across the switches and diodes. Its only drawback is the lack of a common grounding feature from the load ground to the source ground.

- Chapter 4 presents a coupled inductor based boost-Cuk converter with a single switch derived high gain and reduced voltage stress for PV application. In this chapter developed converter is tested by using a PV simulator. The steady-state analysis and all mode operation are covered in detail.

- Chapter 5 shows isolated DC microgrid operation with hybridization of PV, FC, and battery. The proposed work covers the modeling, control, energy management, and operation of a hybrid system comprising a fuel cell, photovoltaic (PV) system, and battery energy storage system (BESS).
- Chapter 6 contains the conclusion of the thesis. Possibilities for improving the topologies are outlined as future work.

After concluding the brief introduction to fuel cells, photovoltaics, and hybrid energy conversion, and presenting the literature review on the topic, the next chapter introduces the high-gain converter with reduced voltage stress for renewable energy applications.