



**ADDIS ABABA UNIVERSITY**

**COLLEGE OF TECHNOLOGY AND BUILT ENVIRONMENT  
SCHOOL OF ELECTRICAL AND COMPUTE ENGINEERING**

**TITLE: TECHNICAL AND ECONOMIC FEASIBILITY STUDY OF  
FUEL CELL BASED ALTERNATIVE POWER SUPPLY FOR ETHIO  
TELECOM HUBSITES**

**(CASE STUDY MICRO WAVE DATA CENTER)**

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A Thesis Submitted to College of Technology and Built Environment (CTBE),  
School of Electrical and Computer Engineering, in partial fulfillment for the  
Degree of Master of Science in Electrical Engineering (Power Engineering  
Stream)

**November,2025**

**Addis Ababa Ethiopia**



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## Declaration

I, the undersigned, hereby declare that this thesis entitled: “**Technical and Economic Feasibility Study of Fuel Cell Based Alternative Power Supply for Ethio Telecom Hub sites**” is my original work carried out under the guidance of my advisor. This thesis has not been presented for degree in this or any other universities. All source of materials used in this thesis work have been duly acknowledged and referenced in accordance with accepted academic practices.

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## Acknowledgment

First, I would like to express my deepest gratitude to the Almighty God, whose grace, guidance, and blessings have been my strength throughout the journey of my academic pursuits. Without His endless support and encouragement, this thesis would not have been possible.

I am profoundly grateful to my major advisor, *[Dr. Dawit Habtu]*, for His invaluable guidance, unwavering support, and constructive feedback throughout the course of my thesis. Your expertise, patience, and encouragement have been a source of inspiration for me, and I am truly honored to have had the opportunity to work under your supervision.

My sincere appreciation also goes to all the workers of Ethio Telecom who generously shared their time, knowledge, and resources with me during the data collection and thesis phases. Your cooperation and insights have significantly contributed to the completion of this thesis.

I would like to extend heartfelt thanks to my friends, who provided me with moral support, encouragement, and moments of relief during challenging times. Your companionship and understanding have meant so much to me.

A special word of thanks goes to my beloved family. Your unconditional love, prayers, sacrifices, and continuous encouragement have been my foundation. You have stood by me through thick and thin, and I am forever indebted to you for your unwavering support.

Finally, I would like to express my sincere gratitude to all the staff of the College of Technology and Built Environment (CTBE) who, directly or indirectly, contributed to my academic journey. Your dedication, professionalism, and support created a nurturing environment that enabled me to pursue my studies and achieve my goals.

This work is as much yours as it is mine. Thank you all.

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## List of Acronyms

<b>PEMFC</b>	Proton Exchange Membrane
<b>AFC</b>	Alkaline Fuel Cell
<b>SOFC</b>	Solid Oxide Fuel Cell
<b>SAIDI</b>	System Average Interruption Duration Index
<b>SAIFI</b>	System Average Interruption Frequency Index
<b>CAIDI</b>	Customer Average Interruption Duration Index
<b>MTTR</b>	Mean Time to Failure
<b>MTBF</b>	Mean Time between Failures
<b>IEEE</b>	Institute of Electrical and Electronics Engineers
<b>NREL</b>	National Renewable Energy Laboratory
<b>AC</b>	Alternating Current
<b>DC</b>	Direct Current
<b>UPS</b>	Uninterruptable Power Supply
<b>ULSFO</b>	Ultralow Sulphur Fuel oil
<b>HFO</b>	HFO : Heavy fuel oil
<b>ITU</b>	International Telecommunication Union
<b>IEA</b>	IEA : International Energy Agency
<b>TCP</b>	TCP : Technology Collaboration Program
<b>ETAP</b>	Electrical Transient Analyzer Program

## Abstract

For modern data centers, where even short outages can cause major financial losses and service interruptions, it is imperative to ensure dependable and sustainable backup power. With an emphasis on replacing the current 1500 KVA diesel generator, this thesis examines the technical and financial viability of using fuel cell technology as an alternate backup system for Ethio Telecom's data center. A comparative evaluation is conducted using ETAP software for reliability analysis, MATLAB for fuel cell design modeling, and economic metrics (LCC, NPV and ROI) based on CAPEX and OPEX considerations.

The study evaluated the reliability and technical performance of integrating fuel cell technologies into a Telecom data center system. Three distinct fuel cell types Alkaline Fuel Cell, Proton Exchange Membrane Fuel Cell, and Solid Oxide Fuel Cell were modeled under various operating conditions, both with and without boost converters. The analysis focused on comparing their efficiency, voltage stability, and scalability to determine the most suitable option for data center applications. Although each technology demonstrated unique advantages, the SOFC emerged as the most promising solution due to its superior overall technical performance and adaptability. Despite its relatively high initial capital cost, its long-term operational advantages were considered significant for sustainable infrastructure development.

The results and findings revealed that the existing diesel generator-based system produced a SAIDI of 10.422 hours/customer-year and a SAIFI of 1.293 f/customer-year. With the integration of the SOFC backup system, these values decreased to 4.0320 and 0.2670, respectively, indicating a substantial improvement in service reliability and reduction in outage frequency and duration. Economically, the SOFC demonstrated strong feasibility, achieving annual savings of \$158,853.08, a net present value (NPV) of \$30,500, a payback period (PBP) of 5 years, and a return on investment (ROI) of 10%. These findings confirm that implementing SOFC as a backup system for Ethio Telecom's data center is both technically viable and financially advantageous, offering enhanced sustainability, operational efficiency, and system reliability compared to conventional diesel generators.

**Key Words: Generator, Solid Oxide Fuel Cell, Ethio Telecom, Microwave Data center, Green Power**

## CHAPTER ONE

### INTRODUCTION

A fuel cell system operating on compressed hydrogen can provide backup power for significantly longer than batteries, depending on the amount of on-site hydrogen storage, and more reliable backup power than diesel generators [1]. Compressed hydrogen has a higher energy density than do batteries, requires no special housing or space conditioning (locating the storage tank outside is acceptable), and is less likely to be stolen than diesel fuel. Diesel fuel is also subject to degradation after extended storage, whereas compressed hydrogen is not [2].

Additionally, diesel engine backup power may be limited to a small number of total run hours per year by environmental regulations. Therefore, a fuel cell system using outside storage for hydrogen offers operational and potential cost advantages over battery and diesel engine backup power.

Fuel cells, specifically solid oxide fuel cells (SOFCs), present a promising solution for hubsite power. Like all fuel cells, SOFCs convert chemical energy from fuel, e.g., hydrogen or natural gas, directly to electricity through electrochemical reactions. SOFCs are reliable, efficient at almost any scale, modular, and produce ultra-low criteria pollutant emissions. Furthermore, generating electricity onsite and using DC electricity from the fuel cell could eliminate a large portion of the excess power conversion and inversion equipment in hubsites [3].

A fuel cell is an electrochemical device that converts the chemical energy of a fuel directly to usable energy of electricity and heat without combustion. Typically, the process of electricity generation from fuels involves several energy conversion steps:

- (i) Combustion of fuel converts the chemical energy of fuel into heat.
- (ii) This heat is then used to boil water and generate steam.
- (iii) Steam is used to run a turbine in a process that converts thermal energy into mechanical energy.
- (iv) Finally, mechanical energy is used to run a generator that generates electricity.

To implement such a system, it is essential to show that SOFCs can provide the highly reliable electricity that hubsites need to maintain sufficient server availability without the support of the traditional backup topology. It is the goal of this thesis to determine if a sufficiently reliable SOFC system could be designed to hubsite requirements. This is accomplished through the reliability analysis of a simplified SOFC system. A preliminary analysis is accomplished to address two basic questions: is the desired three-9 (0.999) availability for an SOFC system attainable? And, under what conditions is this availability attainable? The goal of this thesis is not only to develop a SOFC system which can reliably power Ethio Telecom hubsite, but also to facilitate a more sustainable design paradigm for Ethio Telecom hubsites [4], [5].

### **1.1 Background of the study**

Traditional Ethio Telecom hubsites backup power solutions include batteries for short duration and diesel generators for longer duration backup. Batteries are relatively inexpensive for 1 to 2 hours of backup power. Batteries are not ideal for longer-duration backup power applications because they can be expensive to maintain, unreliable after aging, temperature-sensitive, and hazardous to the environment after disposal.

Generators are suitable for longer-duration backup power. Nevertheless, generators require high maintenance, emitting high pollution levels and greenhouse gases into the atmosphere. To overcome the above challenges technical and economic feasibility of fuel cell-based alternative power supply for Ethio Telecom hubsites are more reliable, zero-emission power and quiet, with fewer moving parts than a generator, and, a wide operating temperature range,  $-40^{\circ}\text{C}$  to  $50^{\circ}\text{C}$  than a battery [6].

When fueled with pure hydrogen, the only by-products are heat and water, making fuel cell products a zero-emission, sustainable power source. In addition, fuel cell-based alternative power supply for Ethio Telecom hub sites are expected to have a lower lifetime cost than a generator. Compared to batteries and diesel generators, fuel cells save money. They eliminate the need to change, charge, and manage batteries, subsequently reducing labor, time, space, and peak power demands. The lower cost for fuel cell-based alternative power supply for Ethio Telecom hubsites are the result of low maintenance and higher system efficiency when compared with generators.

Fuel cell-based alternative power supply for Ethio Telecom hubsites provide backup power to critical communication network infrastructures in wireless networks, digital economy (tele cloud, tele birr), fixed and broadband Ethio Telecom applications. A fuel cell is an electrochemical cell that converts the chemical energy of a fuel (often hydrogen) and an oxidizing agent (often oxygen) into electricity through a pair of redox reactions.

In principle, a fuel cell-based alternative power supply for Ethio Telecom hub sites is seen as an alternative to the conventional batteries, both convert chemical energy into electricity but there are key differences between them. Batteries need to be recharged, while fuel cells do not need to be charged. The fuel cell uses hydrogen – oxygen which is good for the environment, with available hydrogen-oxygen they can continue producing electricity, the reaction of hydrogen and oxygen forms water, and the hydrogen and oxygen are separated by electrolytes. The purpose of a fuel cell-based alternative power supply for the Ethio Telecom hub site is to produce an electrical current that can be directed outside the cell to do work, such as powering an electric motor and illuminating a light bulb. Because of the way electricity behaves, this current returns, to the fuel cell completing an electric circuit. The chemical reactions that produce this current are the key to how a fuel cell works.

## **1.2 Statement of the problem**

Ethio Telecom, previously known as the Ethiopian Telecommunications Corporation (ETC), is an Ethiopian Telecommunication company serving as the major internet, Telebirr, Tele cloud and telephone service provider. As of July, 2023 Ethio Telecom has above 83.5 million customers [7].

The future of Telecom in Ethiopia must simultaneously provide affordable, universal service and universal access to all citizens and provide services to those businesses, institutions, and individuals who need them. It is well known that power is the backbone for the Ethio Telecom hub site network to give sufficient and reliable service to its customers on time properly.

Ethio Telecom hubsite is the site that unites all Ethio Telecom stations from various locations. Once the Ethio Telecom hubsite is down, all sites that belong to that hub site are down leading to unavailability of any communication channels within that region.

During grid outages, two 1500 kVA diesel generator sets that provide 750 kW of essential load are part of the backup power infrastructure currently in place at Ethio Telecom's data center. Despite their operational sufficiency, these generators have a number of technical, financial, and environmental issues that risk the data center power system's overall reliability and efficiency. References [87], [88], [89] states technically, the diesel generators have low conversion efficiency, high maintenance frequency, and frequent mechanical failures, particularly when operating below rated capacity. Additionally, the generators generate a sound level of about 85 dBA at a distance of 7 meters, which is higher than the safe noise threshold that is advised for continuous operation next to important ICT infrastructure and employee offices. As a result, the data center compound presents environmental and occupational challenges.

Economically speaking, the system's life-cycle cost (LCC) is very high because of growing diesel fuel prices, maintenance costs, and the cost of oil and spare parts. Furthermore, the current configuration raises carbon emissions, which runs counter to the institution's sustainability objectives and Ethiopia's low-carbon development strategy. When taken as a whole, these issues raise the total cost of ownership throughout the course of operation and lower overall system reliability.

Therefore, the design, modeling, and analysis of an alternative backup power system based on Solid Oxide Fuel Cells (SOFC) and integrated with the grid and battery storage is urgently needed. Enhancing power reliability, increasing energy efficiency, lowering operating costs, minimizing noise and emissions, and coordinating Ethio Telecom's backup power infrastructure with sustainable energy transition objectives are the objectives of the SOFC system.

### **1.3 Objective of the study**

#### **1.3.1 General objective**

The main objective of this thesis work is to make technical and economic feasibility of fuel cell-based alternative supply for Ethio Telecom hub sites to prevent power outages.

#### **1.3.2 Specific objectives**

The specific objectives of this thesis are as follows:

- ❖ To understand the overall components, design, requirements, and failure of a typical modern Hubsites and Ethio Telecom hubsites.
- ❖ To conduct performance evaluation by making reliability analysis of the current and SOFC systems.
- ❖ To demonstrate efficiency improvement of Solid Oxide fuel cell systems.
- ❖ To perform economic analysis and achieve cost reduction for Ethio Telecom hubsites.

## 1.4 Methodology

This thesis will explore the challenges of designing a sufficiently reliable solid oxide fuel cell system for powering the Ethio Telecom data center in a distributed fashion.

**Task 1:** Conduct a continuous literature search on hubsite power, solid oxide fuel cell reliability, efficiency, and economic analysis.

**Task 2:** Understand the components, design, requirements, and failures of the existing and SOFC system.

**Task 3:** Make a comparison of the existing power system with the SOFC system.

**Task 4:** Create a number of integrated fuel cell-with Matlab software.

**Task 5:** Examine the reliability with ETAP software,

**Task 6:** Examine economic analysis of the existed and SOFC system.

## 1.5 Literature Review

### 1.5.1 Diesel Generator Systems in Data Centers

Diesel generators have long served as the backbone of backup power in Telecom data centers due to their availability and quick startup. Nonetheless, research points out important drawbacks, such as high fuel consumption, frequent maintenance, low energy efficiency, and considerable CO<sub>2</sub> and particle emissions [5], [18], [22]. In addition to raising operating costs and exposing data centers to fuel price variations, Ethiopia's reliance on imported diesel runs counter to the country's energy sustainability objectives [22], [73]. Diesel-based backup is becoming less practical for contemporary, high-demand data centers, as these limitations show.

### 1.5.2 Fuel Cell Technologies for Backup Applications

Because of their efficiency, environmental advantages, and adaptability, fuel cells are becoming more and more acknowledged as good backups. Due to their small size and quick

startup, proton exchange membrane fuel cells, or PEMFCs, have been extensively researched for Telecom and small-scale applications [10], [26], [36]. However, obstacles like membrane deterioration, short lifespan, and fuel impurity sensitivity limit their widespread use [21], [73]. On the other hand, Solid Oxide Fuel Cells (SOFCs) are better suited for continuous, large-scale data center operations, offer fuel flexibility (hydrogen, natural gas, and biogas), and run at greater efficiency (45–60%) [5], [21], [87].

### **1.5.3 Techno-Economic and Reliability Considerations**

Numerous techno-economic analyses show that, while having greater initial capital expenditures, SOFCs have lower lifespan costs because they use less fuel, require less maintenance, and have a longer service life [24], [32], [39], and [67]. The economic potential of SOFCs for critical infrastructures is confirmed by international efforts like the IEA Advanced Fuel Cells TCP [85] and Horizon 2020 initiatives [13]. In comparison to diesel generators, SOFCs provide more steady power quality, smoother transitions, and a longer mean time between failures, according to reliability studies [34], [47], and [70]. The need for continuous electricity in Telecom systems is further highlighted by standards like the IEEE Gold Book [83] and ITU technical publications [84], where outages directly lead to lost income and eroded client confidence.

### **1.5.4 Research Gap**

The technological and financial advantages of SOFCs are promisingly demonstrated by international studies, but little is known about how they are implemented in Telecom data centers in Africa. Despite their high cost and operational risks, diesel generators continue to be the sole source of backup power in Ethiopia [14], [34], and [41]. As a result, localized research on SOFCs as a backup power option for Ethio Telecom operations is conspicuously lacking. This thesis fills that gap by examining the environmental advantages, economic viability, and technical performance of switching from diesel generators to SOFCs for Ethio Telecom data center.

## CHAPTER TWO

### OVERVIEW AND THEORETICAL BACKGROUND OF SOLID OXIDE FUEL CELL

According to a recent study by the Uptime Institute, hubsites' average power consumption increased by more than 50% in just six years, from 1.5 Megawatts to 2.5 Megawatts. Furthermore, within the same time period, CO<sub>2</sub> emissions increased by 10%. At a rate of 10% per year, hubsite electricity usage is increasing [8].

Traditional hubsites also contribute to criterion pollutant emissions because they rely on diesel generators for backup power and acquire their electricity from power plants. Air pollutants that are restricted in response to public health and welfare concerns are known as criteria pollutant emissions [9]. The hubsite should be powered by a technology that emits low levels of CO<sub>2</sub> and low levels of criteria pollutants.

The construction, operation, and maintenance costs of traditional hubsite power systems are high. In locations where the utility grid network functions efficiently, the electrical grid offers 99.9% energy uptime; in most other locations worldwide, this is less than this. Hubsite wants uptime of 99.999%. When using grid electricity, the backup systems become complicated in order to ensure the needed uptime. [10]

The overall loss of electricity could be decreased by a hubsite that uses decentralized generation instead of the other way around traditional structures that depend on the power grid. Due to the inefficiency of the power systems. The server is powered by the power plant's energy input, and less than 1% of the energy is used for productive tasks on the server [11].

A hubsite can reduce its greenhouse gas and criterion pollutant emissions by using renewable power generating sources like photovoltaics, wind, or fuel cells. The resources are situated at a central topology, parallel to the utility grid network. They have been built and studied [90]. Nevertheless, the removal of the complex systems of redundant equipment that contribute to hubsite inefficiencies has not been taken into account in these investigations. In addition to the energy storage needed to handle interruptions from wind and solar, hubsites that rely on

intermittent renewable energy sources like these still require a significant number of redundant devices.

This gap is immediately addressed by the NREL study (Kurtz et al., 2015), which offers field data on hydrogen fuel cells utilized in Telecom locations in the United States. It demonstrates that compared to diesel generators, fuel cells offer greater reliability, environmental advantages, and lifespan cost savings. However, the U.S.-centric framework presumes developed regulatory backing and hydrogen infrastructure, which may not exist in Ethiopia. This emphasizes the necessity of conducting local feasibility studies in areas with varying economic and infrastructure circumstances [12].

One of the most recent extensive European projects to show the technical and financial potential of fuel cells in replacing diesel generators in mission-critical ICT infrastructure is the Horizon 2020 (H2020) project on Fuel Cells for Prime Power in Data Centers (European Commission, 2024). Proton exchange membranes (PEMFC) and solid oxide fuel cells (SOFC) are being evaluated for continuous power supply, not only backup, in European data centers as part of this initiative. It demonstrates that fuel cells may provide high efficiency, lower emissions, and modular scalability, which makes them ideal for contemporary data centers with quickly increasing power demands.

The H2020 project demonstrates how fuel cells can lower total cost of ownership across extended lifecycles from an economic perspective, particularly when combined with hydrogen generated from renewable energy. It highlights operational benefits via fewer maintenance cycles, less cooling requirements, and decreased emissions-related compliance expenses. This supports my thesis by demonstrating that fuel cells are becoming more and more popular in developed markets for prime power applications in data centers as well as backup.

However, the Horizon 2020 initiative mainly focuses on European conditions, where hydrogen infrastructure and renewable integration are already well developed. In contrast, Ethiopia is still at an early stage in terms of hydrogen logistics, financing, and renewable deployment.

Additionally, the study does not consider hybrid systems such as grid+SOFC+battery configurations, which are more practical for telecom applications in Ethiopia. It also does not

include key reliability indices like SAIDI and SAIFI, which are commonly used in Ethio Telecom power system studies in Ethiopia. Therefore, its direct application to the Ethiopian context is limited, highlighting the need for localized analysis as carried out in this study [13]. By minimizing or removing the massive backup and operating power infrastructure that will enable electricity to be delivered with sufficient quality and reliability, hubsite design and construction costs can be decreased along with electricity consumption. This might be accomplished by dismantling redundant equipment, all AC/DC and AC/AC power conversion equipment, and distributing on-site power generation [14].

## 2.1 Fuel cells

A distributed configuration of SOFCs is feasible. Distributed systems reduce the domain of failure. This would remove the requirement for considerable redundancy by allowing only a small portion of the hubsite to go down for service at any given time. By using DC current in combined with the distributed SOFC architecture, it may be possible to minimize power losses and simplify hubsite power distribution, doing away with the need for large, energy-intensive backup systems. Although there are many different kinds of fuel cells, high-temperature fuel cells are typically used for big fuel cells in stationary applications. In order to minimize losses and the requirement for extra equipment, high-temperature fuel cells can either reform fuel inside the cell or process the fuel using the high-quality heat generated by the electrochemical reactions. Because of this, they may be used in the majority of places where natural gas is easily accessible worldwide. Installing SOFCs on the property would lower pollutants, reduce reliance on the grid, boost efficiency, and increase the reliability of the electrical supply while utilizing the current natural gas infrastructure. Stationary fuel cells can supply power with minimal to negligible criterion pollutant emissions [15].

Others have already proposed fuel cell power generation for hubsites. The National Fuel Cell Research Center at the University of California, Irvine, in partnership with Microsoft, has investigated the use of proton exchange membrane fuel cells (PEMFCs) in hubsites [8], while others have investigated phosphoric acid fuel cells (PAFCs) [6], [13], [14]. However, there are a number of disadvantages to using PEMFCs and PAFCs in the modern world. First of all, they are not the most effective fuel cell choice when used with readily available hydrocarbon fuels like natural gas. When using a hydrocarbon fuel, SOFCs are 10–20% more efficient than

PEMFCs and PAFCs. SOFCs are an excellent option for hubsites, which are frequently situated in remote areas, due to their capacity to operate on natural gas. Second, a costly platinum catalyst is used in both PEMFCs and PAFCs. The cost of a platinum catalyst is avoided by the ceramic and non-precious metal composition of SOFCs. Natural gas can power SOFCs with internal fuel processing or with relatively minimal external fuel reformation. This would remove a significant amount of the unnecessary, redundant equipment in hubsites by enabling on-site electricity generation and the use of DC electricity straight from the fuel cell [15].

## **2.2 SOFC power plant**

The SOFCs produce power, and the fuel cells are supported by a number of components. Additionally, there are many different system options for a SOFC power plant. To get understanding of the potential for an Ethiopian Telecom data center SOFC power plant, this section examines the key features and advancements in the major SOFC system components. Discussions are held regarding SOFC stacks, combined cycles, and the other plant components.

## **2.3 SOFC Stack**

The electrolyte of a solid-state full-array capacitor (SOFC) is made of ion-conducting ceramic oxide. SOFCs' high working temperatures (600–1000°C) offer a number of advantages. First, it is possible to create the catalyst without using precious metals. These usually raise the price of low-temperature fuel cells and make them less resistant to fuel contaminants. (16). Second, high-temperature exhaust gas can be utilized in combined cycles for heating or cooling in order to increase efficiency [17]. Thirdly, some fuels, such as methane and ammonia, can internally reform [18]. Although the high operating temperature of the SOFC has potential, there are also major design challenges. In addition to being stable physically and chemically, every component of the stack needs to be compatible with thermal expansion across a broad temperature range [19].

The difference between planar (PSOFC) and tubular (TSOFC) SOFC stack designs is depicted in Figure 2; the former is the focus of the majority of research [20] and is mostly used in commercial products. PSOFC provides a higher power density and is easier to manufacture. Its issues are the expensive gas-tight interconnects and the mechanical stability of the cells. TSOFC does not require gas-tight interconnects because the fuel cell itself is stronger

mechanically and seals the air from the fuel. However, the power density decreases and the cost of production increases [21]. System and thermal efficiency improved when tubular SOFC stacks were used rather than planar stacks.

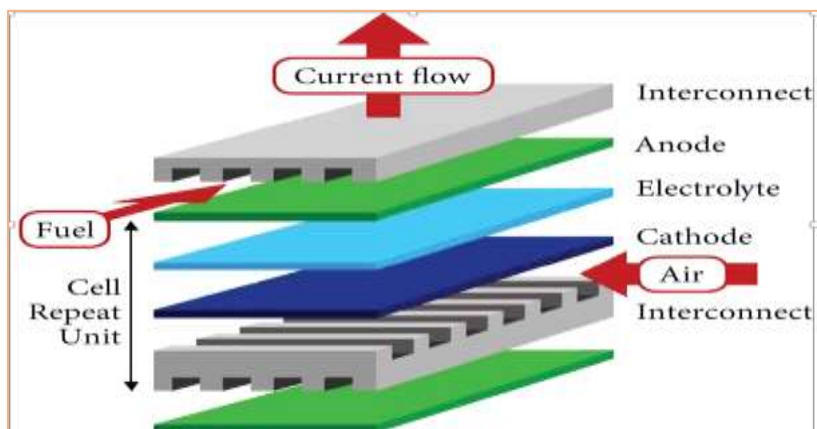


Figure 2.1 Planar SOFC design [20]

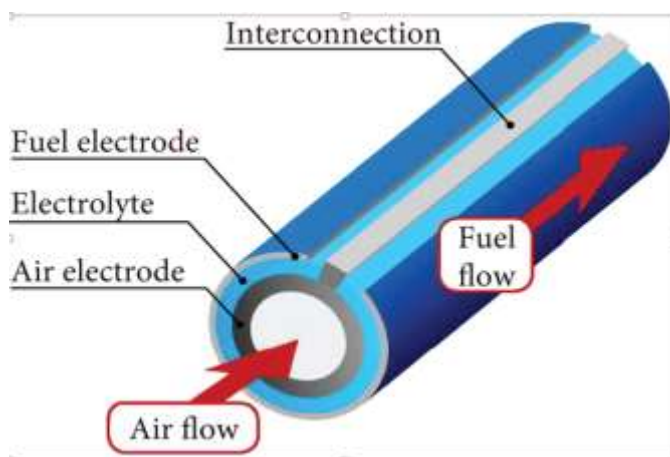


Figure 2.2 Tubular SOFC design [20]

### 2.3 Balance of Plant Components

The parts that help fuel cells generate electricity are known as balance of plant (BoP) components. This includes equipment for fuel processing, airflow control, temperature control, water management, and power conditioning [22]. The components of these systems, which comprise a significant amount of the system as a whole, include reformers, burners, blowers, evaporators, heat exchangers, generators, sensors, and valves. System efficiency, transient capability, power density, and cost are all significantly affected by the components.

Liquid fuels are transferred from their liquid phase into their gaseous phase using evaporators. In order to prepare fuel and air before they enter the SOFC, recuperators also referred to as counter flow heat exchangers often employ the thermal energy in the SOFC outputs. Consequently, there are less temperature fluctuations and carbon emissions in the SOFC. The fuel and outside air are compressed to the operating pressure of the fuel cell before they enter the stack. Nonreacted fuel and residual air are often combined and burned in a combustor to increase the thermal energy in the exhaust stream.

Diffusion or catalytic burners are often utilized because of they are diluted fuel [23]. When anode recirculation is used, fuel is recycled before to burning. The gas flows inside the fuel cell system are controlled by blowers, valves, and pressure regulators.

### **2.3.1 Desulphurization**

To stop the fuel cells from degrading too quickly when the SOFC system is powered by natural gas, the sulfur compounds that are present as odorants must be eliminated using activated carbon filters [24]. The optimal desulfurization method depends on the kind of fuel and the sulfur tolerance of the fuel cell. Sulfur concentration must be below 1 to 10 ppm for SOFCs, which are significantly more tolerant of it than LT-PEMFC, according to suppliers and researchers. Hydrodesulphurization (HDS) is a process used in refineries to reduce the concentration of sulfur. However, this approach is not the best for Telecom data center applications due to its size and cost [24].

Moreover, HDS is troublesome for internally reformed SOFC since it necessitates the input of a hydrogen-rich stream. Another strategy is to use sorbents to remove sulfur particles in a targeted manner. After comparing several available sorbents with tests, Van Rheinberg et al. [21] proposed nickel-based selective adsorbents for fuel cell applications to obtain the necessary <1 ppm sulfur concentration.

If the SOFC system is operated on natural gas, the sulfur compounds present as odorants need to be removed through activated carbon filters to prevent rapid degradation of the fuel cells [24]. The kind of fuel and the fuel cell's sulfur tolerance determine the best desulfurization technique. Researchers and suppliers claim that SOFCs are far more tolerant of sulfur content than LT-PEMFC, requiring it to be below 1 to 10 ppm. Refineries use hydrodesulphurization

(HDS) to lower the Sulphur concentration. However, because of its size and expense, this method is not ideal for Telecom data center applications [24].

Furthermore, because the HDS reactor requires the feeding of a hydrogen-rich stream, HDS is inconvenient for internally reformed SOFC. Utilizing sorbents to remove sulfur particles selectively is an additional approach. Van Rheinberg et al. [24] suggested nickel-based selective adsorbents for fuel cell applications in order to achieve the required <1 ppm sulfur concentration after comparing a number of commercial sorbents with tests.

However, they would not have enough capacity and would take a long time to adsorb the material, they questioned adsorbents for high sulfur fuels. Additionally, adsorbents must be replaced.

### **2.3.2 Reforming Strategy**

With a fuel cell, the chemical energy of hydrogen can be converted into electrical energy. Fuel cells are powered by hydrogen or hydrogen-containing fuel. The most efficient method for SOFC among the different methods for converting hydrogen carriers into a hydrogen-rich mixture is steam reforming [25]. The endothermic process known as steam reforming requires a continuous supply of heat and steam. It may be converted by a reformer outside the system. The heat and steam produced by the electrochemical process in the SOFC can also be used to internally reform the fuel. System complexity and capital costs are significantly reduced by internal reforming, which eliminates the need for an external reformer [26]. Internal reforming can be classified as either direct or indirect. Only the heat released by the fuel cells is used in indirect internal reforming, or IIR. Feeding the fuel straight to the anode, where the reforming occurs, is known as direct internal reforming, or DIR. DIR simplifies the process and lowers capital expenses [17].

Wider temperature differences in the stacks and an increased risk of carbon deposition on the anode are disadvantages of direct internal reformation that may cause the ceramic cell material to deteriorate [23]. A pre-reformer is used in some studies to boost power output and accelerate the electrochemical processes of the fuel cell [27].

### **2.3.3 Anode off –Gas Circulation**

Steam is often needed for the reforming process. The requirement for steam can be used by a heat recovery steam generator (HRSG) that uses demineralized water and exhaust heat [28, 29]. Nevertheless, a SOFC's anode off-gas already contains steam because water is produced at the anode during the electrochemical reaction.

The anode off-gas (AOG) can be recirculated back into the fuel cell by mixing it with new fuel using blowers or ejectors. Consequently, the capital cost is reduced because a smaller steam generator is required [30]. By encouraging a more consistent temperature and particle concentration distribution across the stack [31], recycling the fuel not only lowers local fuel consumption [32], but it also increases cell lifetime [33]. Additionally, a fuel cell's anode does not use all of the fuel that is delivered to it. Fuel recycling makes it possible to use unreacted fuel, which somewhat boosts system performance [34–36].

The method of anode recirculation offers many advantages. First, there is less fuel to preheat. Second, gasoline enters the fuel cell already partially reformed, reducing the strain on the catalyst during reformation [37]. According to studies by Jia et al. [28] and Peters et al. [38], an externally reformed SOFC system without anode off-gas recirculation has a system efficiency that is 16–20% lower than a SOFC system with internal reforming and AOG recirculation.

In contrast, carbon deposition may need less accurate control of the steam-to-carbon ratio [39]. The high operating temperature also presents extra challenges for the recirculation system's blower or injector design. To use commercial blowers that can run at temperatures as high as 300°C, Peters et al. [40] and Hollmann et al. proposed lowering the temperature of the recirculation loop.

### **2.3.4 Power Conditioning**

Fuel cells generate direct current, and their voltage is influenced by age and current, among other factors. Moreover, reverse and ripple currents are difficult for fuel cells to control [40]. For a sufficient and dependable power supply, power conditioning equipment is also necessary. Power converters are used to increase and regulate voltage. Converters are commonly incorporated into these converters to protect the fuel cells from abrupt voltage fluctuations.

DC/AC inverters, which are three-phase inverters used for non-residential applications, are then used when AC power is required. Diodes can be used to prevent reverse current from reaching the fuel cell, despite the fact that they result in additional losses [41]. Capacitors increase the system's bulk and cost, even if they can be used to reduce current ripple [42].

### **2.3.5 Start Up and Cool Down**

During startup, the SOFC needs to reach its operating temperature. There are two common methods for heating the SOFC. First, the heating components of the bipolar plate can be connected to an electrical power source. Second, an electric burner can be used to preheat the cathode air before it is fed through the stack because the flow resistance in the stack increases with temperature. The input pressure needs to be changed during this procedure.

The heating energy requirements for both methods are almost equal, and the heating rates must be maintained within the allowed thermal stress of the SOFC stack [43]. The stacks must be cooled gradually after a shutdown. It is possible to cool the cathode of the SOFC stack using air. Because the heated components have less thermal mass, the start-up and cool-down times are shortened [44]. During startup or shutdown, no air may reach the anode in order to prevent oxidation. Using advanced flow control or a nitrogen delivery system that flushes the anode will ensure this. However, a nitrogen supply adds more piping and mixing elements to the system [45].

## **2.4 Combined Cycles**

### **2.4.1 SOFC –Gas Turbine**

The combination of SOFC and gas turbines can increase power output. This is good since the streams that exit a SOFC's stack and afterburner are at the same temperature as the turbine's inlet. SOFC-gas turbine (GT) is the most researched combined cycle plant. This system uses a gas turbine to expand and burn the anode-off gas to generate additional power, and the SOFC generates energy with excellent efficiency. The bulk of the SOFC-GT plants under examination operate under pressure, which connects the roles of the SOFC and GT. This has the disadvantage that the transient behavior of the slowest component is influenced by the dynamics of the entire system.

A combined cycle analysis found that the electrical efficiency of SOFC-GT systems varies from 58% to 76% [18]. Kawabata et al. released their testing evaluation of the first commercially available SOFC-GT system [46]. They tested the SOFC's load-following behavior, vibrations, noise, emissions, and degradation. The safety of emergency shutdown events, such as earthquakes, power outages, and internal issues, was also evaluated. Safe outdoor operation was demonstrated at 53.6% electrical efficiency (LHV), and a practical durability of 10 years was established.

#### **2.4.2 SOFC –Steam Turbine**

The burned anode-off gas can also be used to power steam turbines (SOFC-ST). Similar to the SOFC-GT system, the steam turbine can be used to increase the SOFC system's efficiency [47]. For SOFCs operating at high stack temperatures, moderate cell voltages, and relatively low fuel use, gas turbine integration makes greater financial sense, according to van Biert et al. [18]. A steam turbine is the better choice when the stack temperatures are relatively low and the voltage is high. Additionally, they concluded that the average stack power densities for pressurized SOFC-GT and SOFC-ST are 75% and 25% higher, respectively, than a standalone system with a comparable electrical efficiency.

The relationship between this and the system's overall power density is unknown, though. For relatively modest power plants, steam turbines (and gas turbines to a lesser extent) are inefficient, according to Arsalis [48]. A 1.5 MW and a 5 MW application were found to differ significantly in terms of efficiency.

#### **2.4.3 SOFC –Reciprocating Engine**

Additionally, it is possible to integrate a SOFC stack with a reciprocating engine (RE). These frequently provide better part-load, cost, and durability features than gas turbines [44]. Additionally, the engine's operation can be decoupled by supplying fuel directly into it. Rapid load transients cause the fuel cells to degrade, which shortens the SOFC lifetime. Engines can respond quickly to changes in load, but SOFCs and turbines react more slowly. As a result, by increasing the system's dynamic capabilities, integrating SOFC with RE prolongs the SOFCs' lifespan. Overall, the combined cycle produced by SOFC-RE is more cost-effective than that of GT [48].

According to van Biert et al.'s research [18], SOFC-RE is less efficient than SOFC-GT and SOFT-ST for a comparable system running at nominal. They do, however, note that the advantages of transient capacity and the simplicity of the control method may outweigh this.

The optimal power split for a SOFC-RE system (RE fueled with AOG) was examined by Sapra [48] for Telecom data center applications. Even while the system's efficiency grew as the power split toward the SOFC increased, the systems overall weight and volume also increased. The optimal value was found to be 28% SOFC load share, which results in a combined system efficiency of 52%. As a result, the system was twice as big, about the same weight, 9% to 11% more efficient, and had a 36% to 43% lower NO<sub>2</sub> than a standard system. The power split was further validated by Sapra et al. [30] through engine testing.

The dynamic behavior of an integrated SOFC-engine system was analyzed by Wu et al. [49], who found that the slow dynamics of the SOFC regulate the system's overall dynamics even though they did not use a fuel bypass. Their recommendation to incorporate a metal hydride reactor for H<sub>2</sub> addition improved the dynamics of the system as a whole.

The majority of real-world demonstrators have failed to meet the high system efficiencies that theoretical studies expected for SOFC-combined cycle facilities [19, 34–35].

Moreover, plants with mixed cycles are more complicated and have more control problems. Independent SOFC systems, on the other hand, have been showing higher efficiency than expected [48]. Consequently, recent studies have revisited SOFC systems without coupled cycles.

## **2.5 Fuel Possibilities for SOFC**

Although a range of fuel types can be used with SOFCs, some fuels need to go through several reforming and purification process. This section discusses the fuels that have been studied for SOFCs in Telecom data centers. When selecting fuels for Telecom data center applications, consideration must be given to fuel pricing and emissions during the fuel manufacturing and distribution operations.

### **2.5.1 Diesel**

These days, diesel fuels are the most common fuel used in Telecom data centers. They are more energy-dense and relatively cheap than other fuels. HFO's maximum sulfur concentration was 3.0%, but gas oil and Ultralow Sulphur Fuel Oil (ULSFO) now have a 0.1% restriction [50]. Because diesel has a high energy density, is widely available, and is used in Telecom data centers, it has been thoroughly studied for SOFC systems. Low-sulfur fuels are less taxing on the desulfurizer, making them easier to employ in SOFC systems.

Without desulphurization, SOFCs might even be able to operate consistently on ULSFO with a minor performance reduction from sulfur poisoning [51]. However, low-sulfur fuels are more costly due to the necessity for additional catalysts and chemical additives during the refining process [52]. Furthermore, biodiesel has successfully undergone internal and external reformation in SOFCs [50]. The production of biodiesel is expected to be less accessible since it competes with the production of food [54].

Diesel fuels have a well-known production and delivery infrastructure and are governed by established legislation. Due to these advantages, diesel-type fuels were often considered for SOFCs in Telecom data center applications [55, 56]. Diesel, on the other hand, presents challenges for SOFCs since it requires a large and complex fuel processing infrastructure [57], which lowers the power density and efficiency of the SOFC system.

### **2.5.2 Hydrogen**

Governments and companies have recently launched a number of efforts that show an increasing interest in hydrogen for Telecom data center applications. The two most common ways to store hydrogen are through cryogenic storage or compressed air. Therefore, cryogenic storage (henceforth referred to as LH2 in this study) is currently the most energy-dense solution [57], which makes it ideal for Telecom data center applications [58]. Insulation and cylindrical containers are required for cryogenic storage in order to control pressure gradients and keep the fuel in the liquid phase at a low temperature. Both expand the data center's capacity required for fuel storage; LH2 storage has the lowest volumetric energy density among alternative fuels. Additionally, cooling hydrogen to a cryogenic stage requires a significant amount of energy [58].

The choice to use hydrogen in SOFCs is not easy, even though it can be done with respectable efficiency [59]. The principal advantages of SOFC over LT-PEMFC are its ability to internally reform and its remarkable resistance to carbon monoxide (CO) and carbon dioxide (CO<sub>2</sub>), which are ineffective in the presence of hydrogen. In order to increase efficiency even more, SOFCs also use CO as fuel. Additionally, the SOFC stack is cooled by internal reforming since heat is needed for the reaction. When employing hydrogen, more airflow is required to cool the stack, increasing the parasitic blower power. Despite their apparent contradiction, SOFCs that run on hydrogen often have lower system efficiencies than those that run on hydrocarbons [60,61].

### **2.5.3 Natural Gas**

The most common way that liquid natural gas, or LNG, is kept for usage in Telecom data centers is in cylindrical tanks at -162 degrees Celsius. Stored LNG has a volumetric and gravimetric energy density that is significantly lower than diesel but higher than hydrogen. As the use of natural gas in Telecom data centers increases, so does its production capacity and fuel infrastructure [62, 63].

The bulk of SOFC research and commercially manufactured SOFC systems utilize natural gas as their main fuel, and studies have demonstrated its high efficiency [24,64]. Although natural gas can be used directly in a SOFC after desulfurization, the inclusion of a pre reformer is often recommended to reduce the strain on the fuel cell catalyst by promoting steam methane reforming. Compared to an engine powered by LNG, methane slip is minimal [65]. Biogas-fueled SOFCs have shown equivalent performance to hydrogen in terms of power generation [66].

### **2.5.4 Methanol**

Methanol in liquid form does not need insulation or cylindrical tanks to be stored at room temperature. Consequently, methanol has a higher energy density for storage than gaseous fuels. Liquid storage is much more beneficial for Telecom data center applications. Additionally, methanol can be used with diesel infrastructure with a few small adjustments [67]. Few studies have examined the performance of SOFCs powered by methanol [68].

External reforming of the fuel is convenient since methanol has a lower reforming temperature than natural gas [68]. Rechberger et al. [69] added methanol prior to the anode output in order to allow for internal reforming of methane in the stacks. This is due to the fact that internal reformation usually enhances the cells' efficiency and thermal balance. Methanol has been investigated for use in SOFCs [70], demonstrating good performance without appreciable cell deterioration [71]. At the same time, research on direct methanol SOFC systems is still in progress [72].

### **2.5.5 Dimethyl Ether**

Over the past five years, dimethyl ether (DME) has gained increased attention as a fuel for the Telecom data center industry since its deployment will reduce NOX, SOX, and PM emissions [73, 74]. Over 700 C, DME rapidly transforms into methane, carbon monoxide, and hydrogen, making it a convenient fuel for high-temperature fuel cells [75].

Murray et al. [76] established a high-power density for SOFC devices that were directly fueled with DME. One practical problem of giving DME directly to SOFC is coke formation. In order to suppress this, fuel can be injected at high temperatures, although this adds complexity to the system [75]. Sato et al. did a study on the potential of steam-reformed DME for SOFC [77]. DME was found to be readily reformed with a commercial catalyst; theoretical power level and electrical efficiency were achieved, and no coke was produced.

### **2.5.6 Ammonia (NH<sub>3</sub>)**

Ammonia (NH<sub>3</sub>) is a chemical commodity that is manufactured in large quantities and has recently gained more interest from the Telecom data center industry because of its possible uses in fuel cells and modified engines [78]. Ammonia in liquid form can be stored at 10 bar of pressure or -33 C [79, 80]. The storage of ammonia has a moderate volumetric energy density in comparison to the other fuels discussed. Since ammonia contains no carbon, it can be used in SOFC without increasing the risk of coke formation or carbon monoxide poisoning. By delivering ammonia directly to the anode, where it is internally cracked, the heat efficiency of the SOFC system can be increased [81]. Carbon dioxide and methane are not released as the fuel contains no carbon. In contrast to an ammonia-fueled SOFC system, which predominantly produces N<sub>2</sub>, which contains nitrogen and prevents the majority of NOX formation, an engine powered by ammonia produces NOX during combustion [82].

Several studies have shown that a SOFC that only uses ammonia has efficiency levels that are comparable or even higher than those of hydrogen. Frandsen et al. demonstrated that heat exchanger reformation is negligible, internal cracking happens reasonably quickly under normal operating conditions, and anode recirculation appears feasible using a Multiphysics 3D stack model and cell data. For a SOFC that runs on ammonia, a desulfurization phase is not necessarily required because ammonia contains no sulfur.

## **2.6 Possible Fuel Cell-Server Designs**

The industry standard for evaluating power continuity and reliability in commercial and industrial systems is founded on the IEEE Gold Book (IEEE Std 493-2007). Its techniques for calculating indices, like SAIFI and SAIDI, offer a quantitative basis for assessing backup power options. This standard is especially helpful for comparing the reliability improvements that occur when new technologies like fuel cells are used in place of diesel generators in Ethio Telecom's data centers. Despite having a solid methodology, it doesn't offer industry-specific insights on fuel cell or Telecom systems. [83].

By examining sustainable backup power options for Telecom data center networks globally, the ITU report (2012) has direct significance to the Telecom industry. It highlights hybrid power systems, renewable integration, and the financial strains on operators in emerging nations. Crucially, the ITU emphasizes that backup power decisions need to strike a balance between sustainability, cost, and reliability. The ITU offers guidelines, but it omits specific performance modeling for fuel cells in data centers. This enforced me to offer unique insights using economic analysis and ETAP simulation [84].

An international perspective on the price, functionality, and state of deployment of solid oxide fuel cell (SOFC) devices is given by the IEA Advanced Fuel Cells TCP (2024). In some applications, fuel cells are becoming competitive with traditional diesel generator systems, as evidenced by the report's estimate that the cost of SOFC technology in 2024 will vary from \$1,695 to \$2,825 per kilowatt. According to the paper, SOFCs' high efficiency, modular scalability, and extended operating life make them appropriate for prime power applications in critical infrastructure, including data centers, in addition to stationary backup [85].

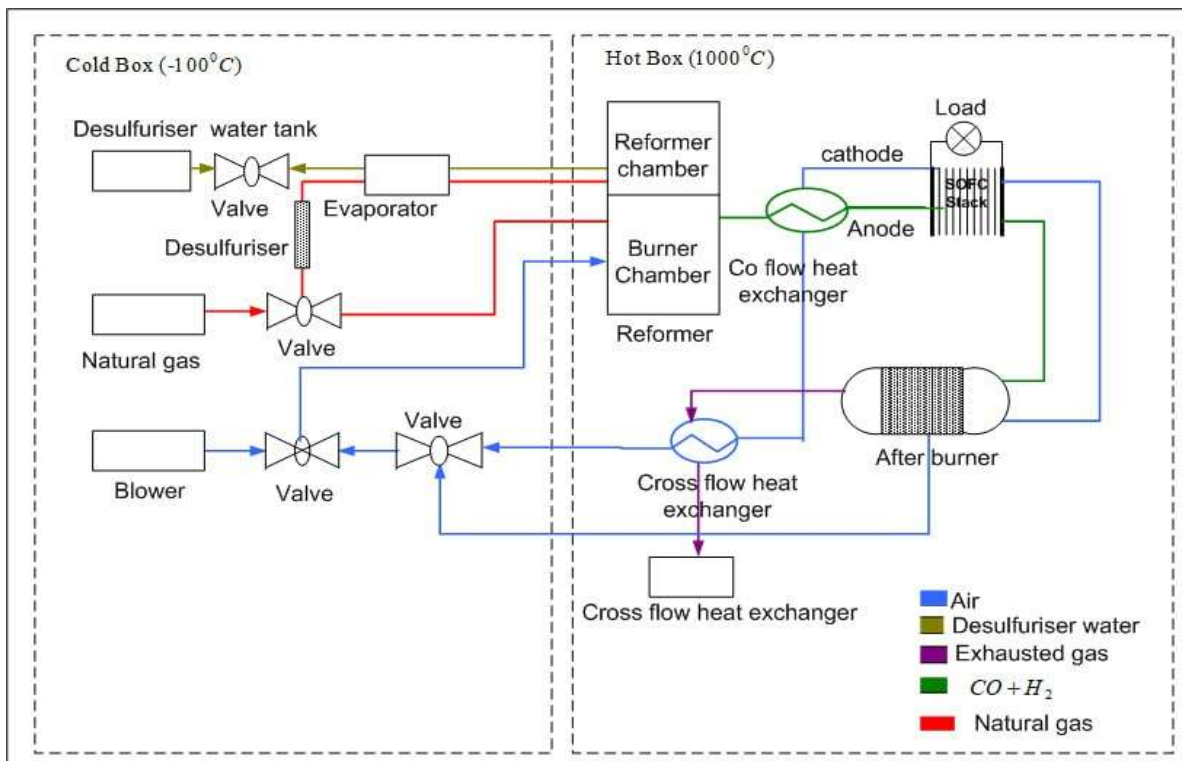


Figure 2.3 A Typical Solid Oxide Fuel Cell system [86].

The operating temperature of SOFCs is 600–1000 °C, which is a comparatively high temperature. Internal reforming and preheating of incoming gases are two examples of how the heat generated by the electrochemical reactions in the fuel cell is used in other parts of the system. For self-sustaining operation, the heat exchanger is a crucial part of the thermal management subsystem [87].

The fuel and air are moved throughout the system by a number of valves, blowers, and plumbing. There will be one or more heat exchangers, depending on the kind of fuel cell and the temperature at which it runs.

**2.6.1 Reformer:** Hydrocarbon fuels are transformed into hydrogen and carbon monoxide by a reformer, which is a part that powers the SOFC system. Reformers, which can be either indirect internal or steam reformers, are essential to the SOFC system's overall performance and efficiency. For the majority of fuel cells, converting natural gas into a mixture rich in hydrogen requires some kind of fuel processing. This fuel processing is carried out in a reformer subsystem, which is typically made up of a steam reformer that partially reforms natural gas into hydrogen and a desulfurizer that removes sulfur from the gas. Subsystems for

fuel processing may include extra parts to remove carbon monoxide (CO) or reform more natural gas.

However, since they can reformat inside the fuel cell and use CO as a fuel, allowing for less intensive fuel processing, they are typically absent from high temperature fuel cell systems. There are two types of reformer chamber used in our process: Reformer chamber and Burner chamber.

**Reformer chamber:** is used to generate hydrogen from the reforming process, while the burner chamber is responsible for combustion. The reformer chamber focuses on producing hydrogen, a crucial fuel for the SOFC system.

**Burner chamber** is involved in the combustion of fuel to generate heat and power. Since Telecom hubs usually get natural gas, the reformer is essential for fuel preparation.

**2.6.2 Fuel:** The fuel is the energy source for the SOFC, which can be natural gas, biogas, pure hydrogen or other specified fuels, enters the system to provide the necessary energy for the fuel. The main importance of the fuel is that, choice of fuel affects efficiency, cost, and reliability. Natural gas is common in data centers due to stable supply.

**2.6.3 Valve:** Valves are used to regulate the flow of gases within the SOFC system. They can help maintain the desired operating conditions and prevent excessive pressure or gas leakage. It prevents overfeeding, maintains safety, and ensures optimal stoichiometry for the stable SOFC operation

Inside the SOFC system, valves control the flow of gases. They can help in preserving the ideal operating conditions and avert gas leaks or high pressure.

**2.6.4 Air:** The main function of the air is to supply oxygen to the cathode for the electrochemical reaction. Air is supplied to the system to facilitate the chemical reactions within the fuel cell. Oxygen ions migrate through the electrolyte and react with fuel at the anode. Continuous airflow is critical for SOFC efficiency.

**2.6.5 Blower:** A blower is used to circulate air or fuel gas within the SOFC system. In some cases, the blower can change the flow rate according to an input signal, allowing for a better control and efficiency.

The SOFC system's blower is used to move fuel gas or air around. In certain instances, the blower has the ability to alter the flow rate in response to an input signal, improving efficiency and control. It maintains correct flow dynamics inside SOFC and ensures uniform temperature distribution.

**2.6.6 Fuel cell (SOFC Stack):** The SOFC unit is the heart of the system where the electrochemical reactions (the fuel hydrogen at anode and the oxygen at the cathode) take place to produce electricity. The importance of SOFC stack is to produce DC electricity, heat, and water. Determines the system's efficiency and reliability.

**2.6.7 Evaporator:** The evaporator receives heat from the SOFC exhaust gases to heat the refrigerant-absorbent solution, facilitating the cooling process. Also it converts liquid water into steam for steam reforming of methane and for humidification.

It prevents carbon deposition in reformer and maintains steam to carbon ratio that play a vital role for long stack life.

**2.6.8 Burner Chamber:** Enhances heat transfer efficiency by channeling high-temperature exhaust, contributing to improved thermal management in the system which aids in recovering waste heat. It provides additional heat for reforming, evaporation, or preheating incoming air/fuel. The process is crucial for optimizing the overall efficiency of the system.

**2.6.9 Afterburner Chamber:** Afterburner chamber is a component designed to enhance system efficiency by burning excess and unspent fuel. This process allows for the recovery of waste heat and optimization of the overall efficiency of the SOFC system. It ensures clean exhaust and recovers extra heat for heat exchangers.

**2.6.10 Heat Exchanger:** Heat exchangers transfer heat between hot exhaust gases and incoming air or fuel. It plays crucial role in managing heat generated by the SOFCs. These heat exchangers are essential for efficient heat recovery and temperature control within the

system. It improves system efficiency by recycling waste heat, reducing external heating needs.

**2.6.11 Cross Flow Heat Exchanger:** Utilized for various heat transfer requirements, particularly in applications with smaller fluid temperature differences to enhance heat transfer performance.

**2.6.12 Co Flow Heat Exchanger:** Required in the plate heat exchanger desorber to enable boiling of the refrigerant –absorbent solution within the flow, crucial for efficient operation of the system. It ensures smoother temperature gradients, reduces thermal stress on components. Inverters, power regulation, monitoring and control, and power supply management make up the Power Electronics subsystem. Usually, this subsystem connects to an alternating current (AC) electrical system by converting and inverting the DC power from the fuel cell stack.

Nonetheless, it has been demonstrated that hubsites powered by direct-DC experience increases in efficiency [13]. Thus, conversion from AC to DC power will not be taken into consideration because the goal of this thesis is to use DC power directly from the fuel cell.

## **2.7 Fuel cell integration**

Fuel cells can be integrated into existing Ethio Telecom data center systems by connecting SOFC modules to main systems through an inverter to convert DC to AC power output to supply Ethio Telecom equipment. Cohen pointed out that many fuel cell modules can be created by combining inverter modules [88]. In addition to lowering the system's cost and size, this also lowers redundancy. To effectively distribute the power of the energy storage devices, fuel cells, and any other power sources among the electrical users, a power management system is needed. Smart management in the start-up, cool-down, and power modulation of the numerous installed modules provides the ability to run at optimal efficiency at varying energy needs because SOFCs have higher efficiency and longevity at part load.

The majority of studies on Ethio Telecom data center SOFCs assume a normal electrical loss and pay little attention to the Power Electronics and power and energy management system design. Nevertheless, a DC power supply, modularity, and excellent part-load efficiency provide further chances to lower electric losses and raise system efficiency overall.

## CHAPTER THREE

### DATA COLLECTION AND ANALYSIS

#### 3.1 Elements in a power system

**AC Switch board:** is the central node of electrical power distribution in the data center. It collects incoming AC power (from the utility grid and diesel generator), protects it, and distributes it to critical loads. The AC input to the power system is taken from the switch board. It ensures selective protection, continuity of service, and safety.

**Diesel Generator:** Ethio Telecom microwave data center uses **two 1500KVA** diesel generator at microwave data center. The diesel generator is a small power plant that generate AC current. The Generator is used as a standby power that will be connected when mains fail. The generator can be connected automatically.

**AC Input protection:** Circuit breakers for protection of individual protection. It prevent damage by cutting off power when the current becomes too high or fault occurs. Ensure continuity of service by coordinating with upstream (Utility, generator) and downstream devices. Isolate faulty sections without affecting the entire data center.

**Surge protection:** Protection against surge and spikes on the AC supply. It diverts lightning/switching surges to earth, protecting sensitive AC/DC and Telecom electronics.

**DC rectifier:** The rectifier system converts the current from AC to DC. The system consists of rectifiers and control and monitoring unit. The rectifiers convert from AC to DC while control and monitoring unit monitors all the essential parameters in the system (voltage, current and alarms). Parameters can also be changed from the unit.

**Fuses:** Fuses of circuit breakers is used for the distribution of DC power to the Ethio Telecom data center equipment. It is fast fault clearing with high breaking capacity, selective protection down to device level. Also, it is used for the protection of individual battery banks against short circuit.

**Batteries:** The batteries store the energy for use when the AC mains fail. Provide uninterrupted power backup during grid or generator outage. Allow smooth transfer to diesel generator. It improves power quality by stabilizing voltage and reducing transients.

**LVBD:** low voltage battery disconnects (LVBD) is used for disconnecting the batteries before they are damaged due to deep discharge.

- **LVBD (Battery protect):** opens battery path to prevent over discharge that damages Li-ion. Implemented via contactor with shunt –trip electronic breaker, controlled by the rectifier controller.



*Figure 3.1 Backup battery for Ethio Telecom Microwave Data Center*

**Uninterrupted Power Supply (UPS):** Converts power from AC to DC and back to AC again. The UPS usually have a small battery bank on the DC side.

**Inverter:** It is used to convert from DC to AC power. Also, it is used for AC load that require long battery backup. Telecom equipment (routers, BTS, switches, transmission gear) use

48VDC directly. It equipment (servers, storage, network switches, lightning) require 230/400 VAC. Inverter is the bridge between DC plant and AC loads.

The overall power system building blocks of the existing power system building blocks for the Ethio Telecom data center are as follows:

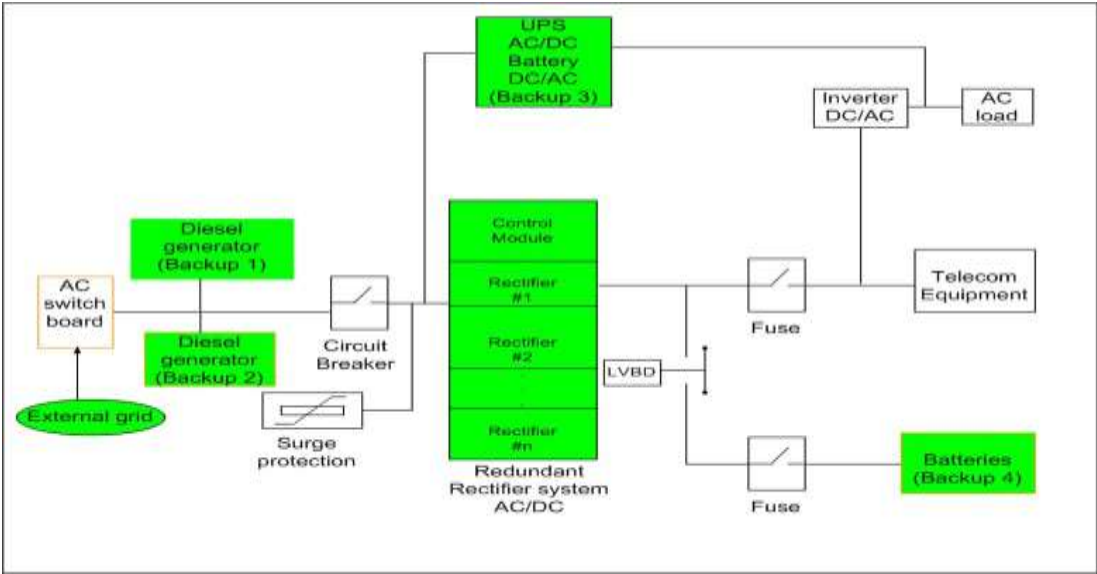


Figure 3.2 Power system building blocks of Ethio Telecom data center

**3.2 Generator specifications**

The specifications of generators collected from the Ethio Telecom data center can be classified into four categories. Those are generator specifications, alternator specifications, engine specifications, and controller specifications. And are shown in the below tables.



Figure 3.3 Backup Generator for Ethio Telecom Microwave Data Center

*Table 3- 1 Generator Specification*

Generator Serial No.	NC8J8804607
Manufactured in	China/3Tech
Dim (L x W x H)	12192 x 2438 x 2896mm
Weight	20,000kg
Controller Type	PCC2.2 DSE7320
Standby KVA	1650KVA
Prime KVA	1500KVA
Rate Voltage	400V/3P
Engine speed	1500 rpm
Power factor	0.8
Standby KW	1,320KW
Prime KW	1200KW
Rated current Prime)	2165A
Rated Frequency	50HZ
Sound level	85 dBA@7M

*Table 3- 2 Engine Specifications*

Engine Serial No.	33218542
Engine Manu	Cummins/UK
No. of Cylinder	16
Injection	Cummins MCRS
Governor	Electronic
Aspiration	Turbo charged
Air Filter	Dry type
Cooling type	Water cooled
Coolant (Eng. +Rad) Liter	535
Lub oil in liter	535
DC Voltage	24V
Start Battery	200Ah
No. of battery	8
No. of battery banks	2x2
Sound level	85 dBA@7M

*Table 3- 3 Alternator Specifications*

<b>Alternator Serial No.</b>	<b>P1734E1</b>
Alternator Manu	Stamford
Insulation class	H
AVR	MX321
Standby KVA	1791KVA
Prime KVA	1672KVA
Rate voltage	400V/3P
Rated Freq	50HZ
Standby KW	1433KW
Prime KW	1338KW
Rated current (prime)	2413A
Alternator speed	1500 rpm

*Table 3- 4 Controller Specifications*

<b>Controller Serial No.</b>	<b>N41J88010494</b>
Controller type (Main)	Power command 2.2
Controller type (standby)	Deep sea 7320
DC voltage	24V
AC voltage	230V
Battery charger	CM360

Overall information about the generators in the microwave data center are as follows:

- Two 1500 KVA diesel generators.
- Fuel consumption: 300 liters per hour.
- Backup time, 1 hour.
- One fuel tank with 12,500 liters.
- 156–260 hours of operation per month.
- Three times full maintenance within a year.
- Fuel consumption for the last ten years.
- Maximum fuel recorded =2000 liters
- Minimum fuel recorded =400 liters
- Life time: 20 years.

### 3.3 Main cause of Generator failure

Insufficient monitoring and maintenance of generator in data center can lead to various consequences, including:

**Power outages:** without proper maintenance, the generator is at risk of experiencing failures, leading to power outages and disruptions to data center operations.

**Expensive repairs:** lack of monitoring and maintenance can result in minor issues escalating into major problems, leading to costly repairs and potential permanent damaged to the generator.

**Loss of efficiency:** the generator lose its efficiency and overall energy capacity, impacting its ability to provide reliable power during outages.

Fuel issues: some potential causes include:

**Lack of Fuel:** The generator crank and will not start due to lack of fuel reaching the engine.

**Contaminated Fuel:** can log filters and cause equipment malfunction, leading to downtime and data loss.

**Bad fuel mix:** A bad fuel mix, such as too much or too little fuel, impurities in the fuel, can prevent proper combustion within the engine.

**Old Fuel:** Not replacing old fuel can lead to issues, as fuel that has been standing in a tank for long periods of time may contain impurities or water.

#### **Battery problems:**

Failure or inadequate maintenance and testing of the batteries, which are integral to the proper functioning of the generator set.

**Low coolant levels:** low levels of coolant in the generator system cause overheating, leading to battery failure.

**Aging and chemical degradation:** over time, the chemical reactions within the battery degrade its capacity.

**Human error:** related issues such as oversight of necessary maintenance tasks.

**Operational mistakes:** human error occurred during the operation of generator, such as improper handling of generator controls or overlooking warning signs of potential issues.

### 3.4 Generator efficiency

From Generator data recorded above:

The efficiency of 1500KVA generator with the serial number NC8J8804607 is typically between 93 -95%.

This means that for generator of this size the type, the ratio of electrical power output to mechanical power input is 95%.

### 3.5 Battery

Overall information about the Battery in the Ethio Telecom data center for microwave are as follows:

- Lead Acid battery
- There are 6 Battery banks in Ethio Telecom data center.
- 1 Battery bank =24 individual battery
- 1 battery bank have =48V
- There are 144 batteries.
- 1 battery =2v
- Recommended average charge time :24h
- Charging current 0.05%
- $0.05 \times 3000 = 150\text{Ah}$  for battery bank.
- It have capacity of 3000Ah for each bank.
- Back up time 30 minute.
- Redundant mode 2+1
- Temperature compensation range : 10-40°C
- Life time: 3 years.

Although they are less efficient than other battery types, lead-acid batteries are well-known for their dependability in Ethio Telecom data centers. Lead acid batteries have a lower charging and discharging efficiency, usually around 80%, as compared to lithium-ion batteries. Lead-

acid batteries are also less effective overall for usage in Ethio Telecom data centers due to their lower energy density, shorter lifespan, and increased maintenance requirements.



*Figure 3.4 Backup battery for Ethio Telecom data center*

## **CHAPTER FOUR**

### **SYSTEM MODELLING OF A SOLID OXIDE FUEL CELL AND SIMULATION RESULTS**

#### **4.1 Modeling and design details of the Existing System**

The Ethio Telecom data center's current backup power design consists of two 1500 KVA diesel generators set up in parallel standby. During grid outages, the standby generators automatically start and take over the load, ensuring continuous power supply to critical microwave data center equipment without interruption. Despite the arrangement's many years of reliable service, its efficiency, environmental performance, and operating costs are severely limited. The schematic layout of the existing configuration is illustrated in Figure 4.1.

##### **4.1.1 System Description**

Normally, the data center receives power from the external grid via the AC switchboard and surge-protection network. Power is sent to the redundant rectifier system (AC/DC), which uses the Power Distribution Frame (PDF) to charge the battery bank while converting incoming AC to DC for the Ethio Telecom data center DC equipment load. The Uninterruptible Power Supply (UPS) keeps the batteries completely charged by operating in float-charge mode and ensuring a constant AC supply to sensitive loads.

The Automatic Transfer Switch (ATS) detects the outage and signals one of the diesel generators to start up in the case of a grid failure. Through the circuit breaker (CB), the ATS moves the load from the grid to the generator output once the generator reaches its rated voltage and frequency. For crucial operations, the second generator stays in standby mode to offer N + 1 redundancy. The PDF ensures the safe distribution and control of DC power to the Ethio Telecom data center equipment, while the Low-Voltage Battery Disconnect (LVBD) isolates the battery in the event of abnormal current flow.

##### **4.1.2 Operational Behavior**

There are four main steps in the current system's functioning sequence:

### **1. Normal Mode (Grid-Connected)**

The Ethio Telecom data center is powered by the grid via the AC switchboard. Rectifiers charge batteries and convert AC to DC for Ethio Telecom data center loads. The UPS is still in float mode and prepared to provide immediate support.

### **2. Transition Mode (Grid Outage)**

The ATS starts the generator when grid voltage or frequency drops below the set threshold. During the gap between generator starts, the UPS and battery supply continuous power.

### **3. Generator Supply Mode**

The ATS uses the CB to send the load to the diesel generator after the generator output has stabilized. The UPS continues to supply vital AC loads while the rectifier resumes AC/DC conversion. Although it is synchronized for automatic takeover in the event of a fault, the standby generator stays offline.

### **4. Grid Restoration Mode**

The ATS returns the load to the utility source once stable grid conditions are restored. After a few minutes of no-load cooling, the generator automatically shuts down. After recharging the battery, the UPS and rectifier resume standby operations.

#### **4.1.3 Limitations and Challenges**

Aspect Limitation:

- Energy Efficiency: Significant mechanical and thermal losses.
- Reliability Sensitive to engine wear, lubrication, and fuel contamination.
- High Cost OPEX from fuel and spare-parts maintenance.
- Environmental Impact High CO<sub>2</sub> and NO<sub>x</sub> emissions with noise > 85 dBA.
- Scalability Limited flexibility for modular load expansion.

#### **4.1.4 Performance Overview of the SOFC Based System**

There are a number of operational and environmental benefits to the suggested SOFC system described in Section 4.8 as compared to the existed system.

When compared to diesel systems, the SOFC system achieves electrical efficiency above 55% and produces very little noise (less than 50 dBA). Furthermore, it lowers life-cycle cost (LCC) and OPEX while increasing reliability.

Ethio Telecom's data-center power infrastructure is therefore much more reliable, energy-efficient, and sustainable when switching from a diesel based system to a SOFC based system.

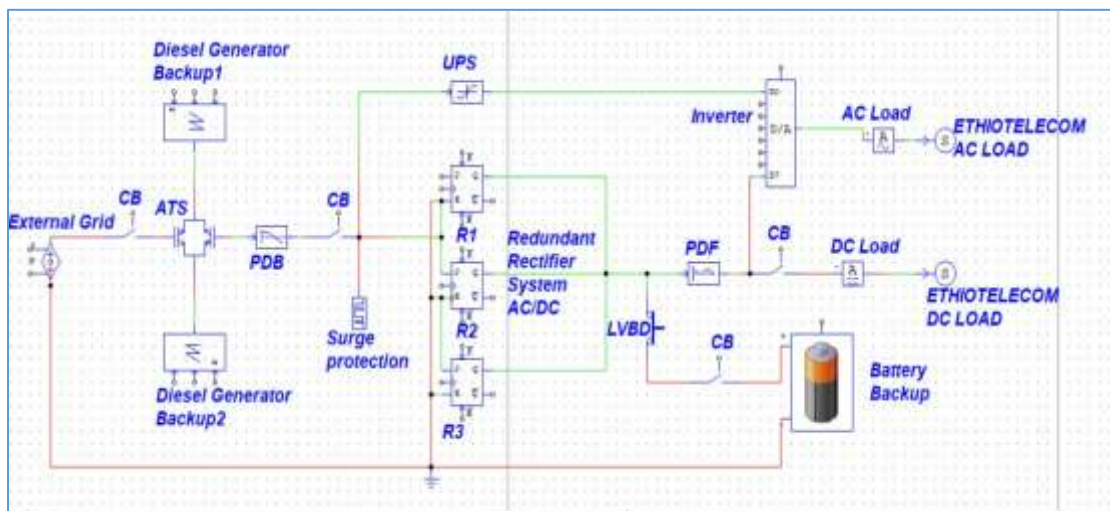


Figure 4.1 Design details of the existing system

## 4.2 Design Without Generators and Backup Batteries

### Reliability Analysis

The process of quantitatively assessing a system's or its components' capacity to carry out their intended function without failure under specified conditions for a period of time is known as reliability analysis in power systems. In relation to a Telecom data center's power supply. It computes how reliably important loads can be powered continuously by the system (generators, SOFC, batteries, grid, etc.). Because ETAP integrates economic effect analysis, simulations, realistic system modeling, and integrated reliability indices into a single platform, it is superior for reliability analysis. Compared to simulation tools like Matlab, this makes it particularly appropriate for assessing the technical and feasibility assessment of SOFC-based alternative power supply systems in Ethio Telecom data centers.

In ETAP, reliability analysis is performed by using:

- Failure rate ( $\lambda$ ): expected number of failure per unit time.
- Mean Time to Repair (MTTR): average time required to restore service.
- Availability (A):  $\frac{MTBF}{MTBF+MTTR}$
- SAIDI (System Average Interruption Duration Index): average outage duration per customer.
- SAIFI (System Average Interruption Frequency Index): average number of interruptions per customer.

SAIFI and SAIDI are used in reliability analysis to evaluate the performance of existing power system and compare it with the proposed system.

### **Importance of SOFC in Ethio Telecom data center**

Solid Oxide Fuel Cells (SOFCs) are very important in Telecom data centers because they provide a reliable and efficient source of power. Unlike traditional diesel generators, SOFCs produce electricity in a cleaner way, with higher efficiency and much lower pollution, making them more environmentally friendly. In terms of operation, SOFCs help ensure that critical telecom equipment continues running without interruption, even when there is a grid outage. When combined with batteries and the grid, they provide a smooth and stable power supply, which improves the overall reliability of the system.

Another advantage is that SOFCs can reuse the heat they produce for other purposes, which increases the total system efficiency. Although the initial cost can be high, they save money in the long run by reducing fuel consumption and maintenance needs. Ethio Telecom data center manage vital communication services. Even brief disruptions have the potential to impact millions of customers, cause financial loss, and interfere with connection. Comparing the suggested FC-based alternative to diesel generators, reliability analysis verifies if FC can satisfy the strict availability requirements.

**2, Comparison of Backup options (diesel vs SOFC):** Through the simulation of reliability indices (SAIDI and SAIFI) in ETAP, the study is able to compare the proposed SOFC with the current 1500KVA diesel generators.

The generator in ETAP is modeled with a rated power of 1.275 MW and a voltage of 15 kV, operating at 0.85 power factor and 95% efficiency. Based on these values, the full-load current is about 57.74 A. This simply means the generator will draw around this current when it is operating at its maximum rated load under normal conditions. The generator's apparent power capacity at this rating is 1.5 MVA. The needed 50 Hz system frequency is met by the machine's 1800 RPM synchronous speed. The generator's electrical characteristics are described by these factors taken together, which ensure that it can consistently provide active and reactive power within the designated range. In addition to highlighting the generator's mechanical input requirements, the inclusion of its continuous and peak prime mover ratings (1.275 MW / 1709.8 HP) demonstrates that the unit can sustain consistent performance under operation.

Furthermore, the generator can be simulated under different operating modes in ETAP, including normal, standby, shutdown, and emergency. The model also incorporates reactive power limits for voltage control, with a maximum reactive power output set to 0.79 Mvar based on the generator's defined operating limits.

In stability and load flow studies, these factors are crucial because they determine how the generator communicates with the grid both normally and during disruptions. In the context of the suggested power supply system for the Ethio Telecom data center, this ETAP configuration is appropriate for technical, financial, and reliability analysis since it offers a thorough depiction of the synchronous generator.

**Power grid:** The external source of electricity is the power grid, which is usually supplied by the national utility. It provides Telecom data centers with 132KV of high voltage power.

**Bus 1:** A bus is a node that connects essential components, such as loads, transformers, or lines. The high voltage level at which power enters the facility from the grid is represented by a 132KV bus.

**Bus 2 (15KV):** After stepping down from 132KV using transformers 1 and 2, the medium voltage bus decreased the voltage to 15KV.

**Transformer 3:** is known as a distribution transformer, and it can be used to step down from 15 KV to 400 volts or 220 volts in order to accommodate Ethio Telecom data center and building loads.

**Circuit breakers:** protect the system by isolating faulty sections during faulty or overloads.

**Two generators:** provide backup power in case of grid failure. It is synchronized with the grid.

**DC converter 1 and 2:** Rectifiers or DC – DC converters convert AC to regulated DC to charge the batteries or to supply DC loads.

**Inverter 1 and 2:** It convert DC power from the batteries or fuel cell back to AC during power failure.

**Battery backup 1 and 2:** Stores energy in DC form to supply loads during power outages. Often sized for minutes to hours of backup.

**Ethio Telecom equipment load:** The actual critical load of the data center.

The below tables represent the input reliability parameters of Bus, branch, circuit breakers and load in the existed and proposed system.

**Failure Rates:** Shows the active failure ( $\lambda_A$ ) the probability that the devices actively fails while in service and passive failure ( $\lambda_p$ ) is the device fails to operate with explanation respectively. Low values indicate that high reliability.

**Momentary Rate:** indicates that the percentage of failures that are momentary (temporary) issues. It shows that most failures are short lived rather than permanent.

**Repair and Switching times:** Mean time to repair (MTTR) is the average time required to repair the devices after failure. Low MTTR means faster restoration.

*Table 4- 1 Source input data*

Bus	Momentary				Replacement
	$\lambda_A$ (f/yr)	Rate ( $\lambda_A\%$ )	MTTR (Hr)	Hour (Hr)	Time (Hr)
Power Grid	0.6430	80.00	2.00	2.00	10.00
Inverter	1.2540	80.00	5.00	2.00	10.00

TECHNICAL AND ECONOMIC FEASIBILITIES OF FUEL CELL BASED ALTERNATIVE POWER SUPPLY  
FOR ETHIO TELECOM HUBSITES

Table 4- 2 Bus input data

Bus	Momentary				Replacement
ID	$\lambda A$ (f/yr)	Rate ( $\lambda A\%$ )	MTTR (Hr)	Hour (Hr)	Time (Hr)
Bus 1	0.0010	80.00	2.00	2.00	10.00
Bus 2	0.0010	80.00	2.00	2.00	10.00
Bus 3	0.0010	80.00	2.00	2.00	10.00

Table 4- 3 Branch Input data

Switching Device	Momentary			Switching time	Replacement
ID	$\lambda A$ (f/yr)	Rate ( $\lambda A\%$ )	MTTR (Hr)	Hour (Hr)	Time (Hr)
T1	0.0150	80.00	200.00	200.00	10.00
T2	0.0150	80.00	200.00	200.00	10.00
T3	0.0150	80.00	200.00	200.00	10.00

Table 4- 4 Switching device input data

Switching Device	Momentary				Switching time	Replacement
ID	$\lambda A$ (f/yr)	$\lambda p$ (F/yr)	Rate ( $\lambda A\%$ )	MTTR (Hr)	Hour (Hr)	Time (Hr)
CB1	0.0030	0.0045	80.00	50.00	50.00	10.00
CB3	0.0030	0.0045	80.00	50.00	50.00	10.00
CB5	0.0030	0.0045	80.00	50.00	50.00	10.00
CB4	0.0030	0.0045	80.00	50.00	50.00	10.00
CB6	0.0030	0.0045	80.00	50.00	50.00	10.00
CB10	0.0030	0.0045	80.00	50.00	50.00	10.00

Table 4- 5 Load input data

Switching Device	Momentary			Replacement
ID	$\lambda A$ (f/yr)	Rate ( $\lambda A\%$ )	MTTR (Hr)	Time (Hr)
Fuel cell 1	0.0200	80.00	50.00	10.00
Fuel cell 2	0.0200	80.00	50.00	10.00
Telecom equipment load	0.0200	80.00	50.00	10.00

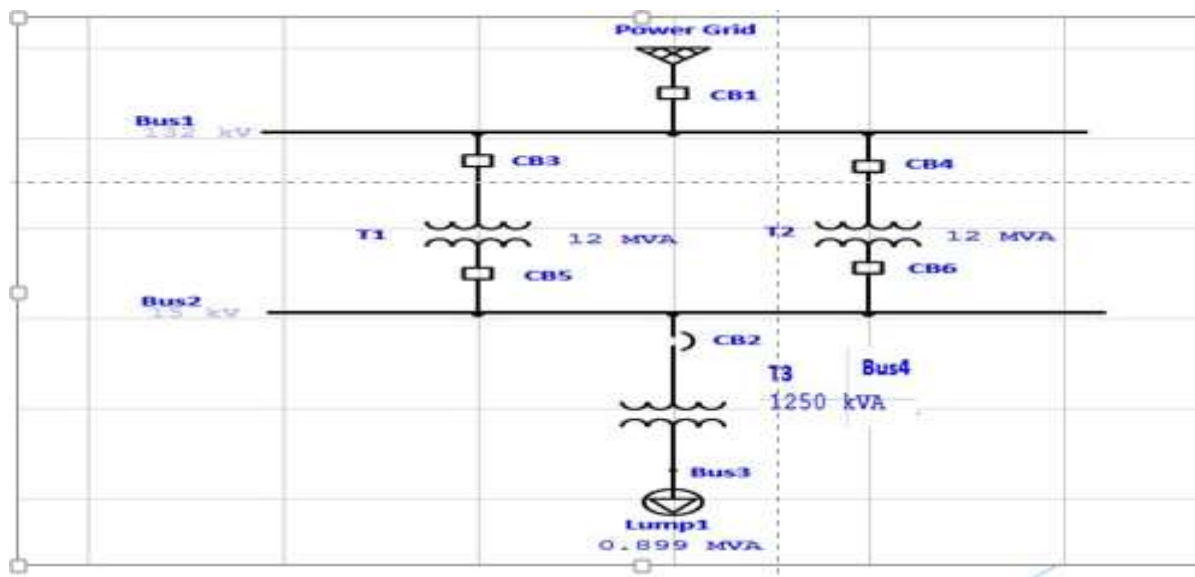


Figure 4.2 Single line diagram of the existing system without backup

From a single line diagram layout above, Ethio Telecom data center's electrical supply comes from the 132 kV transmission grid from Mexico Substation, which is connected to Bus1, the main high-voltage bus. A number of circuit breakers (CBs) are installed to provide protection, switching, and fault isolation within the entire power system. Power is distributed downstream to two parallel channels by the main feeder circuit breaker, CB1, which acts as the main entry point from Bus1. Transformer T1's primary winding receives one path via CB3, and CB2 secures a second, redundant 132 kV feeder. After that, the power is converted. T1 lowers the high voltage down to a medium-voltage level of 15 kV, which is then fed onto the crucial 15 kV switchgear at Bus2 via its corresponding secondary-side circuit breaker, CB4.

The data center loads receive additional power distribution at the 15 kV Bus2. The medium-voltage power is directed by a main distribution circuit breaker, CB5, to a downstream transformer, T2, which completes a final voltage transition to a utilization level, such as 400V. The various important loads are supplied by T2's output, which is shielded by its own low-voltage circuit breaker. Lump1, a server bank or cooling unit with a 0.899 MVA demand, is one such load that gets its power from Bus3, the last load bus. From CB1 to the load, the complete chain creates a single, continuous electrical route.

The resilient design of the system is characterized by its non-redundant architecture, where the loss of any one component, like a circuit breaker or transformer, would result in a complete loss of power to the data center load.

#### **4.3 General Model and Design of Existing System**

The system has a dual-fed, medium-voltage architecture and is powered by a 15 KV utility grid via a main bus (Bus1). The design includes redundancy at the primary distribution level with two parallel 12 MVA transformers (T1 and T2) to ensure outstanding reliability for Ethio Telecom data center infrastructure. Dedicated circuit breakers (CB2, CB5, CB3, and CB6) protect these transformers, enabling the isolation of either transformer for maintenance without affecting vital data center operations.

The system has a multi-layered backup power architecture for the crucial server and switching loads. There is a second power line from the utility that act as a backup, so if the main line fails, the system can still receive power. A reliable Uninterruptible Power Supply (UPS) system with specialized battery banks, inverters (Inv1, Inv2), and DC converters (dcConv1, dcConv2) manages the core power continuity for the delicate Telecom Equipment Load (0.899 MVA). By ensuring zero power interruption during a grid outage. Additionally, two on-site diesel generators (Gen I and Gen II, each 1.275 MW) are integrated to provide sustained backup power for extended grid outages, which is a basic requirement for maintaining Ethio Telecom data center services.

Therefore, the main topic of this thesis inquiry is how the overall design of the Ethio Telecom data center facility maintains high availability through a layered protection and power supply plan. To build a fault-tolerant design, the system makes use of generators, UPS systems, a secondary utility source, and the primary utility feed. In order to ensure that a problem in any section is cleared by the nearest upstream breaker without producing a cascade failure, the strategic placement of circuit breakers, such as CB12 and CB13, is examined for selective coordination.

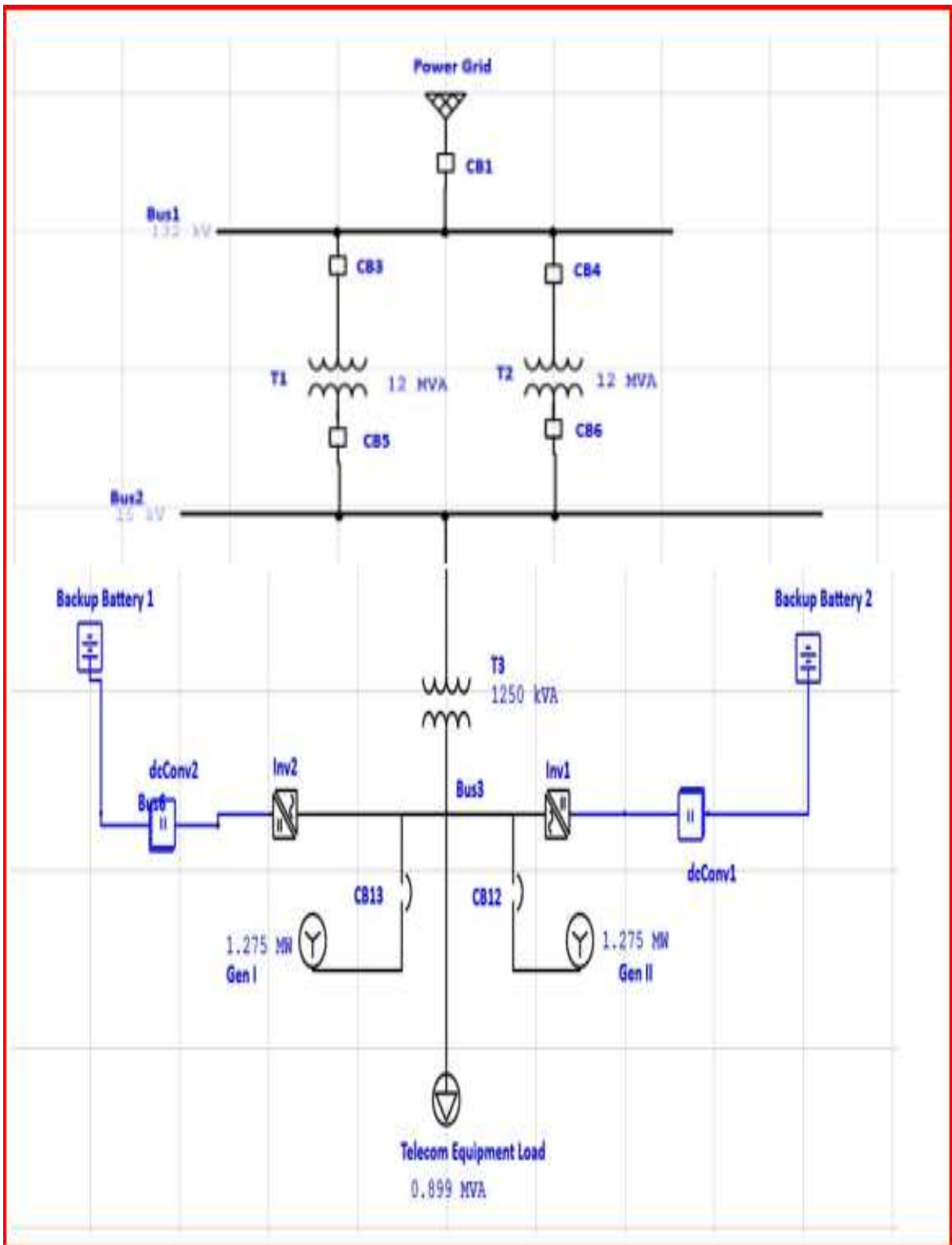


Figure 4.3 Mode and design of the existing system with ETAP

#### 4.4 Simulation Result of Existing system

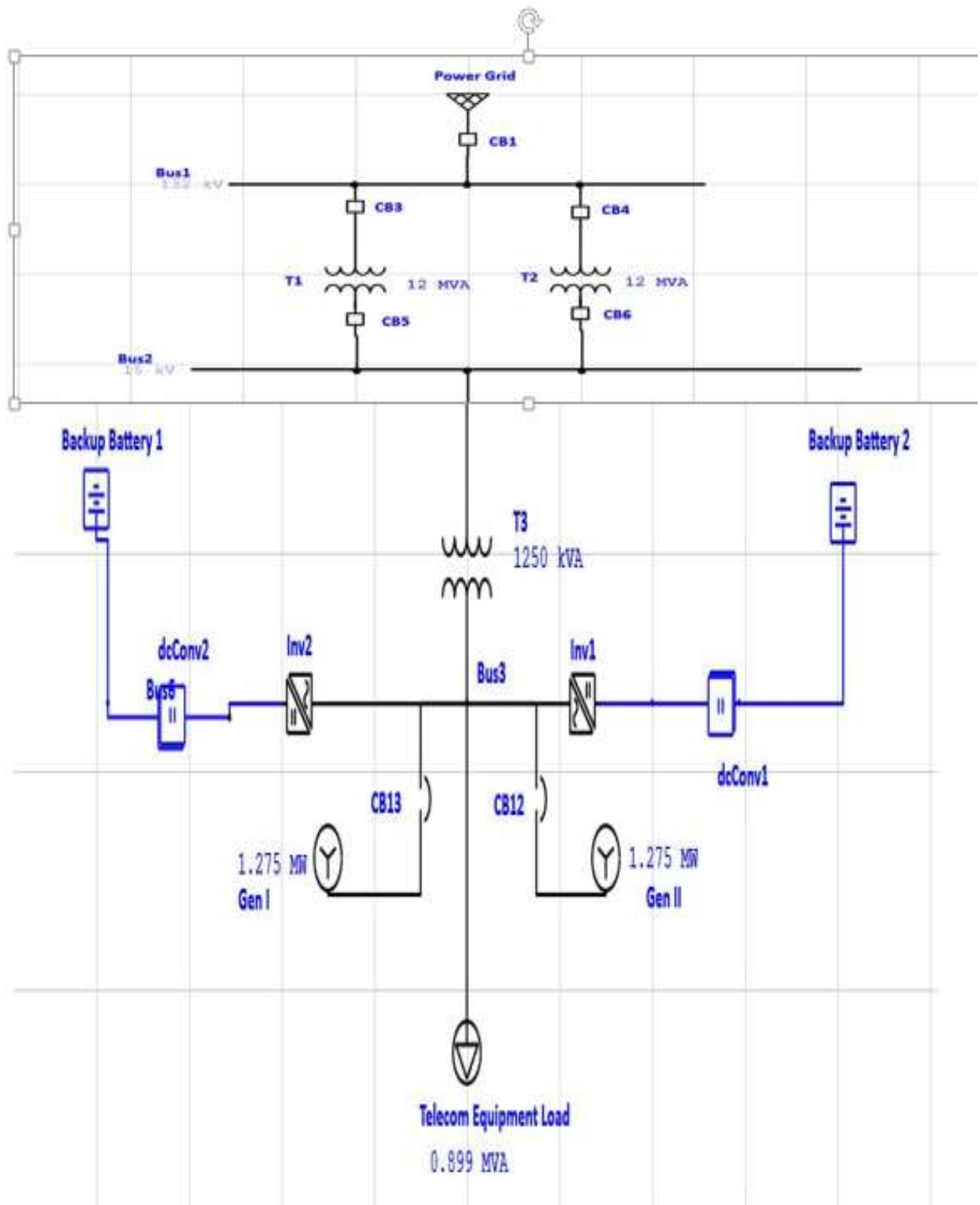


Figure 4.4 Simulation result of the existing system with ETAP

Project: FUEL CELL BASED POWER SUPPLY	ETAP	Page: 1
Location: ADDIS ADBABA UNIVERSITY	19.0.1C	Date: 02-07-2025
Contract: 0911592842/0910250616		SN:
Engineer: NEMOMSA ABEBE NEGESSA	Study Case: RA	Revision: Base
Filename: Namomsa Abebe AAU		Config: Normal

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SUMMARY

System Indexes

ASAI	0.9988 pu
ASUI	0.00119 pu
CAIDI	8.060 hr / customer interruption
CTAIDI	10.422 hr / customer.yr
SAIDI	10.4220 hr / customer.yr
SAIFI	1.2930 f / customer.yr

ASAI	Average service Availability Index
ASUI	Average Service Unavailability Index
CAIDI	Customer Average Interruption Duration Index
CTAIDI	System Customer Total Average Interruption Duration Index
SAIDI	System Average Interruption Duration Index
SAIFI	System Average Interruption Frequency Index

### 4.5 Design of Fuel cell under three scenarios

In order to model fuel cell,

- Ideal gas law and
- electrochemical relations used in fuel cell modelling, especially when calculating the required air input or stack voltage.

#### Step 1: Electro chemical reaction in FC



#### Step 2: Faraday's Law – Relating current to Moles

Moles of O<sub>2</sub> =  $\frac{I \cdot t}{Z \cdot F}$ , if you are calculating per second, then t = 1 and:

$n_{O_2} = \frac{I}{Z.F}$  where, I =current, Z= electrons per oxygen moles =2, and F= Faradays constant 96485C/mol

### Step 3: Convert moles to volume using Ideal Gas Law

From ideal gas law;

$PV = nRT$    $V = \frac{nRT}{P}$ , So volume of oxygen required per second is :

where:

P = pressure (Pa)

V = volume (m<sup>3</sup>)

n = number of moles (mol)

R = universal gas constant (8.314 J/mol·K)

T = absolute temperature (K)

### Mole to Volume Relationship

To find the volume of a gas, the equation is rearranged as:

$$V = \frac{nRT}{P}$$

This means the volume of a gas depends on:

- how many moles of gas are present,
- the temperature,
- and the pressure.

Thus, more moles or higher temperature increases volume, while higher pressure reduces it.

### Step 4: Adjust for air composition

Air contains only 21% oxygen by volume, so it get airflow rate divided by 0.21:

$$V_{air} = \frac{I.R.T}{Z.F.P.021}$$

#### Step 4: Unit conversion

$$V_{imp(air)nom} = \frac{60000.R.Tnom.Inom.N}{2.Z.F.Pnom.0.5.0.21}$$

#### 4.5.1 Detailed explanation and flow of SOFC each part can be discussed as follows.

**1, Hydrogen input (Fuel source):** provides the fuel cell stack with hydrogen gas. Through a flow regulator, stored hydrogen is transferred to the fuel cell stack.

**2, Air (oxygen input):** Through a compressor (blower), it typically delivers oxygen from the surrounding air to the fuel cell stack.

**3, Fuel cell stack:** use an electrochemical reaction to convert hydrogen and oxygen into electrical energy. DC power, heat, and water are produced from inputs (oxygen and hydrogen).

**4, DC voltage measurements:** It keeps an eye on the fuel cell's output in real time. It is connected across the stack's output terminals. Output signal for voltage regulation to the Boost Converter and control unit.

**5, Boost Converter:** enhances the fuel cell's low voltage DC to a steady, high voltage appropriate for Ethio Telecom data center loads.

**6, Series RLC branch (initial stage):** Prior to conversion, it simulates the internal impedance or load characteristics at the fuel cell output.

- Resistance (R) represent power loss due to heating or ohmic loss.
- Inductance (L) models the electrical inertia of the stack and how fast the current changes.
- Capacitance (C) provides smoothing or filtering stabilizing the output voltage.

The purpose of series RLC branch is to simulate realistic fuel cell behavior and conditions before voltage regulation.

**7, MOSFET and Pulse generator:** It is the Boost Converter's switching mechanism. Metal Oxide Semiconductor Field Effect Transistor is referred to as MOSFET. It functions as an electronic switch that is controlled by a pulse generator and turns on and off quickly. The duty cycle (on/off) period of the MOSFET is controlled by a Pulse Width Modulated (PWM) signal

produced by the pulse generator. The duty cycle controls the output boost voltage. By increasing the voltage, MOSFETs and pulse generators control fuel cell output to match 48VDC Ethio Telecom data center loads. Because MOSFETs are voltage regulated rather than current controlled, less power is needed to operate them. Additionally, it increases overall system efficiency and conserves energy.

**8, Diode:** It ensures unidirectional current flow and is positioned after MOSFET. It stops the reverse current that can harm the converter or fuel cell. Enabling safe power flow and preserving DC output integrity during switching are the diode's primary functions.

**9, series RLC branch 1:** Placed immediately after the MOSFET and diode, and serves as a filter to even out the converters pulsed current. It protects against ripple noise on sensitive Ethio Telecom data center equipment. Before the current reaches the power distribution function, series RLC branch 1 aims to enhance its quality.

**10, series RLC branch 2:** is the last step of filtration before power is delivered. It monitors output voltage stability using a final scope and voltage measurement. The goal is to ensure that the Ethio Telecom data center receives clean, controlled voltage.

### Why all the above components are necessary?

Power quality and reliability are crucial in Ethio Telecom data centers. These elements:

- Condition the fuel cell output.
- Boost and stabilize voltage.
- Filter noise or ripple.
- Protect equipment and ensure regulation compliance.

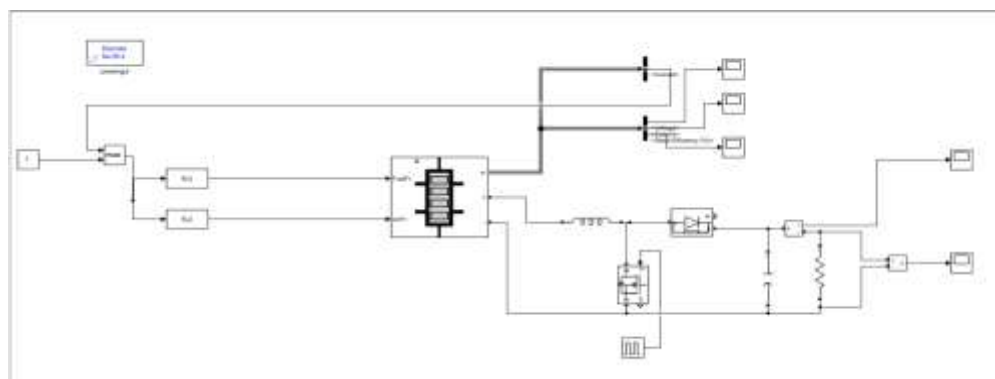


Figure 4.5 Overall design of Fuel cell with Matlab

#### 4.6 Phase I: Simulation result from the Design of the system with Proton Exchange Membrane Fuel Cell

PEMFC by itself generated a 46V voltage, which increase to 68V when combined with a Boost Converter, proving the efficiency of Power Electronics-based voltage regulation. Let's examine each MATLAB Simulink simulation result individually, as indicated below:

- a) Output voltage from the PEMFC alone without a Boost Converter.
- b) Simulation results of current from PEMFC alone without a Boost Converter.
- c) Stack efficiency.
- d) PEMFC voltage output with a Boost Converter.

##### a) Output voltage from the PEMFC alone without a Boost Converter.

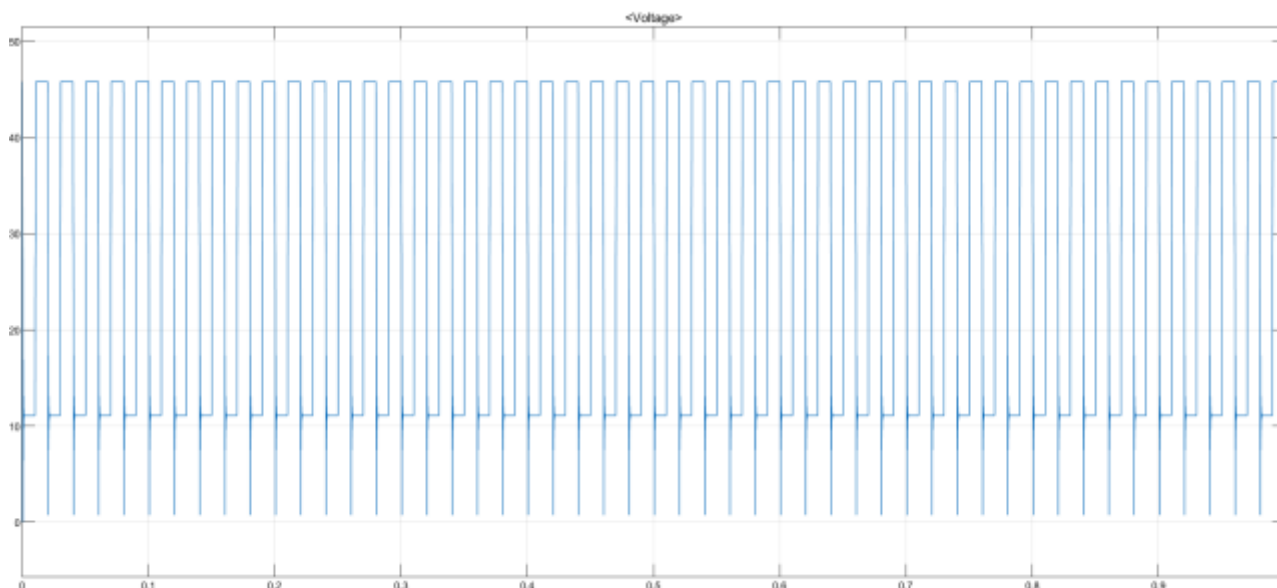


Figure 4.6 Output voltage from the PEMFC alone without a Boost Converter

##### From the above result:

- Under load, a single PEM fuel cell generates a low DC voltage, usually 0.6 to 0.8 V per cell.
- The overall voltage increases proportionally as cells are stacked. However, the practical voltage is usually lower than the theoretical voltage because of ohmic, activation, and concentration losses.

- The output of the PEMFC stack is typically not enough to directly power the loads of Ethio Telecom data centers, which require higher and more stable DC/AC voltages. Consequently, power conditioning (Boost Converters) is required.

This demonstrates why integrating PEMFC into actual systems, such as Ethio Telecom data centers, requires a power electronic interface, which is not an optional feature.

## b) Current

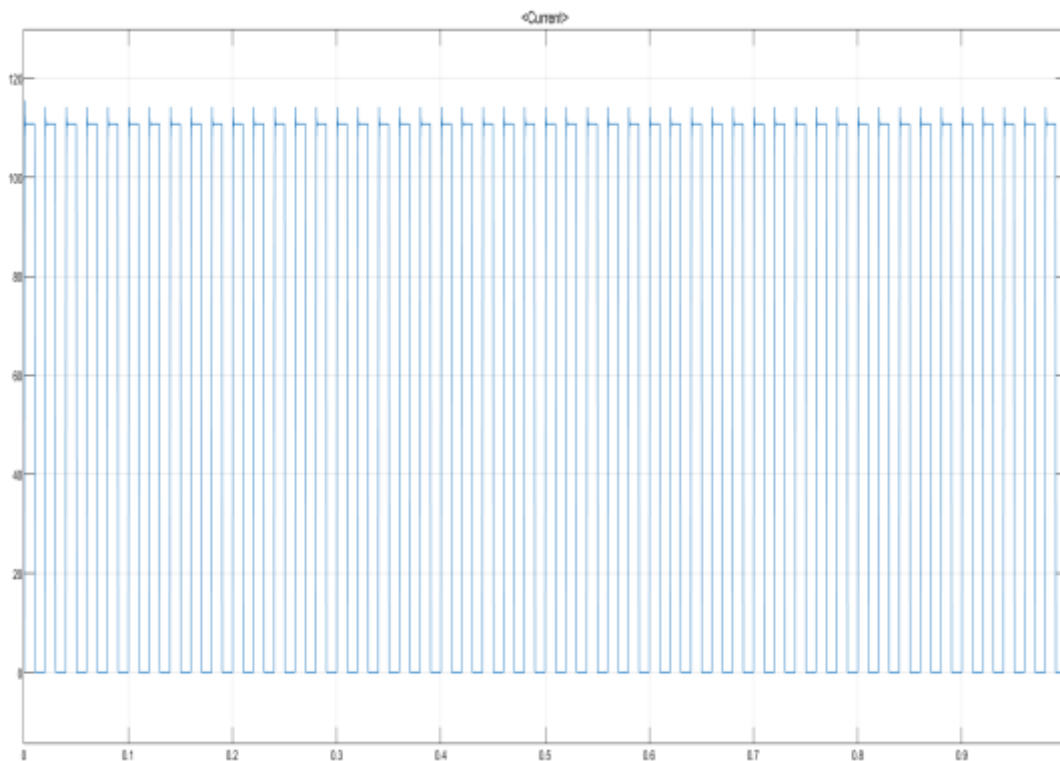


Figure 4.7 Current output without Boost Converter

### From the above result:

- The rate of hydrogen consumption and the electrochemical reaction are directly related with the current.
- Current increases with load, this causes voltage drop due to internal resistance.
- Because overcurrent causes electrodes and membranes degradation more quickly, the stack current needs to be appropriately controlled.

The technological limitations of PEMFC in continuous, high-demand applications, like as data centers, are demonstrated by the current-voltage tradeoff.

c) Stack efficiency

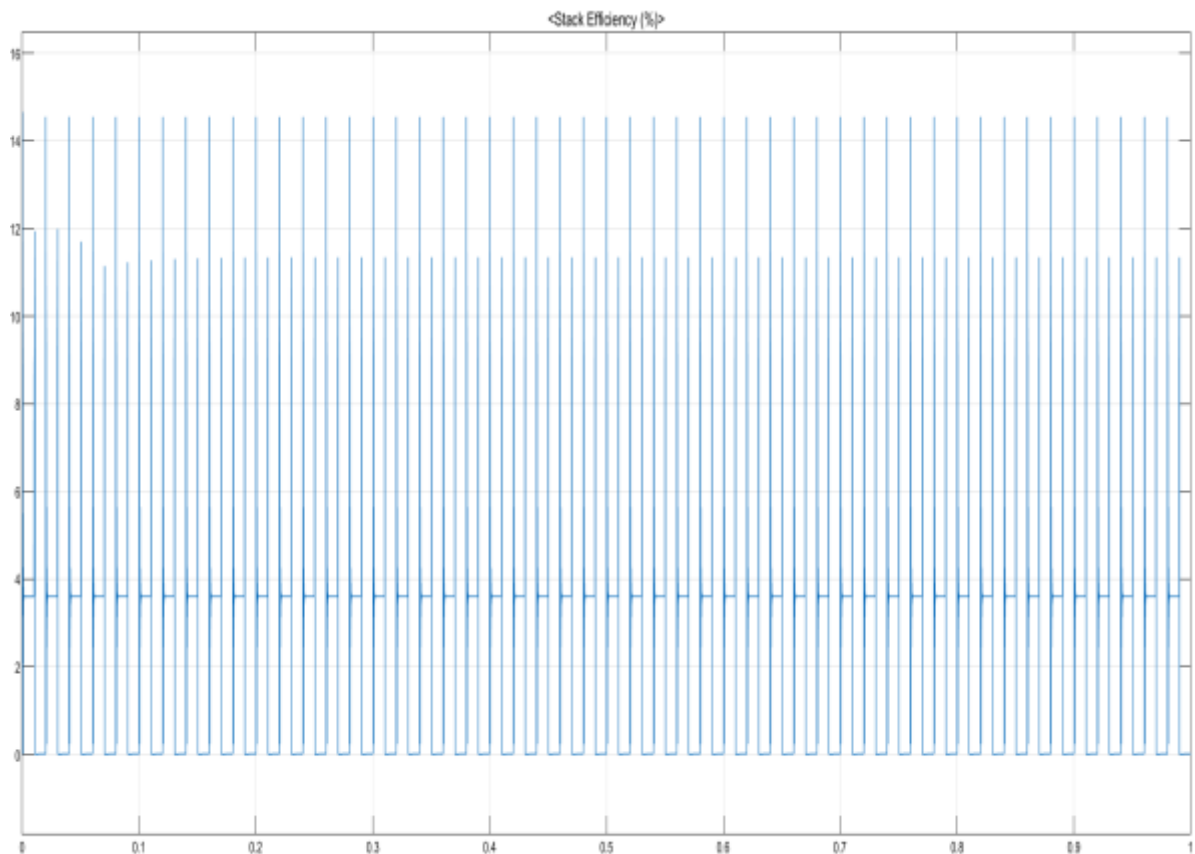


Figure 4.7 Stack efficiency

**From the above result:**

- The efficiency of a typical PEMFC stack varies from 40 to 60% according on temperature, operating pressure, and load current.
- Efficiency is highest at low current density (less losses, but less power output) and decreases at high current density due to resistive and mass transport losses.

**Note:** Efficiency curves play a crucial role in the choice to switch from diesel generators to fuel cells since increased efficiency lowers operational costs and fuel usage.

d) PEMFC voltage output with a Boost Converter.

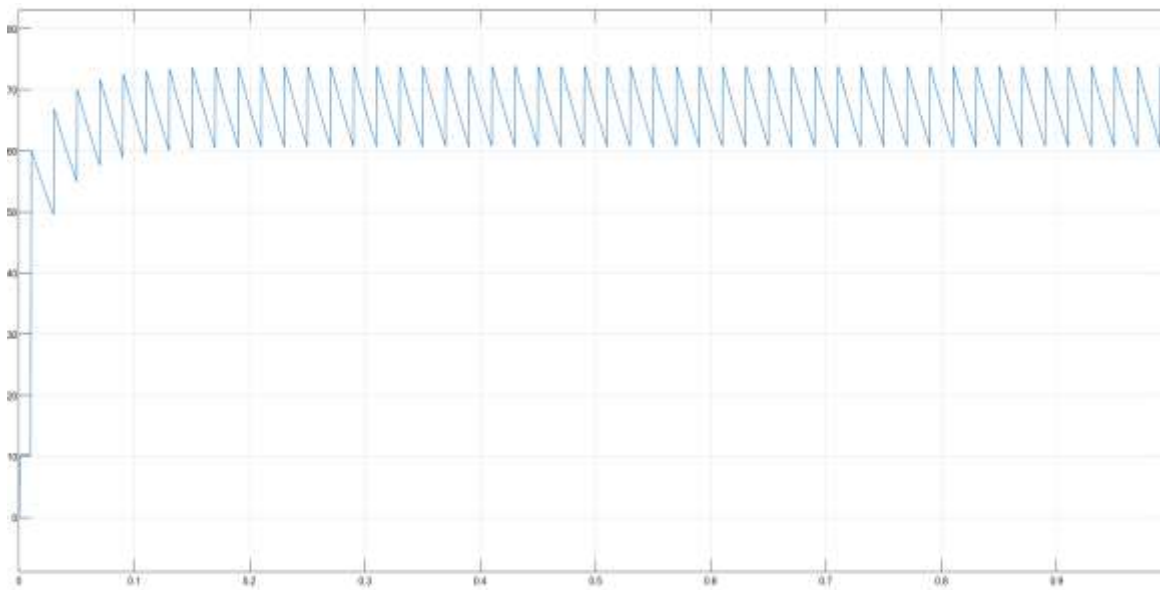


Figure 4.8 PEMFC voltage output with a Boost Converter

**From the above result:**

- The low and fluctuating PEMFC voltage is increased using a boost DC–DC converter to a regulated DC bus voltage in accordance with Ethio Telecom data center standards.
- The converter modifies the duty cycle to stabilize the output.
- This makes the PEMFC practically useable as a backup by enabling grid integration and load compatibility.

**Note:** The key that turns PEMFC from laboratory technology into a commercially feasible power source is the Power Electronics interface.

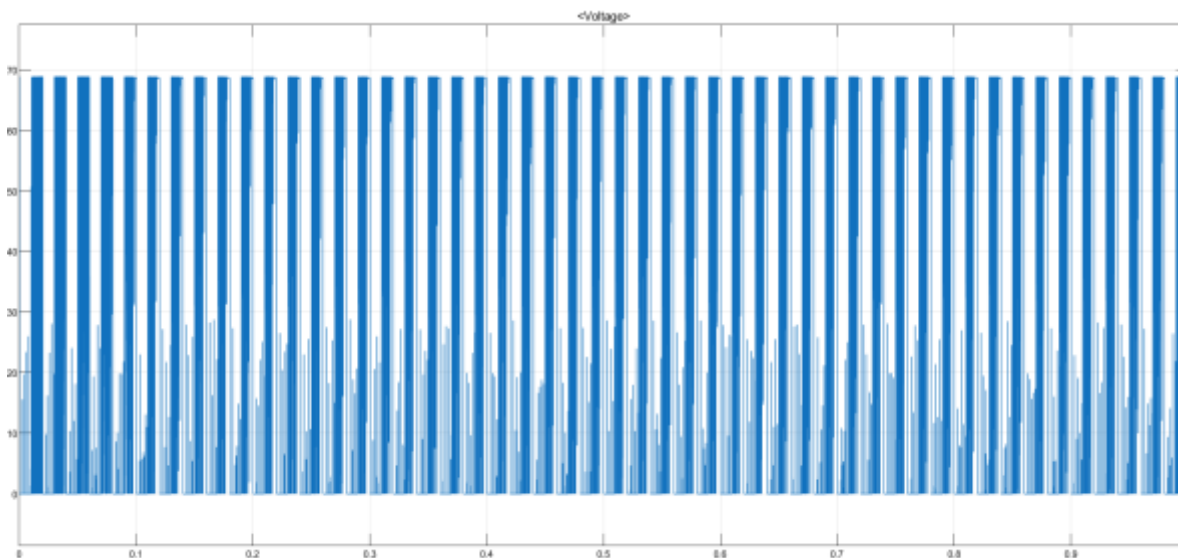
**4.6.1 Phase II: Simulation result from the Design of the system with Alkaline Fuel cell (AFC)**

AFC systems function at a naturally higher voltage than PEMFC systems, but still benefit from boosting. This is demonstrated by the fact that AFC alone achieved 68V natively and that the voltage significantly increased to 72V with a Boost Converter.

a) Output voltage from AFC alone without a Boost Converter,

b) Alkaline Fuel cell voltage output with a Boost Converter.

**a) Output voltage from AFC alone without a Boost Converter**



*Figure 4.9 Output voltage from AFC alone without a Boost Converter*

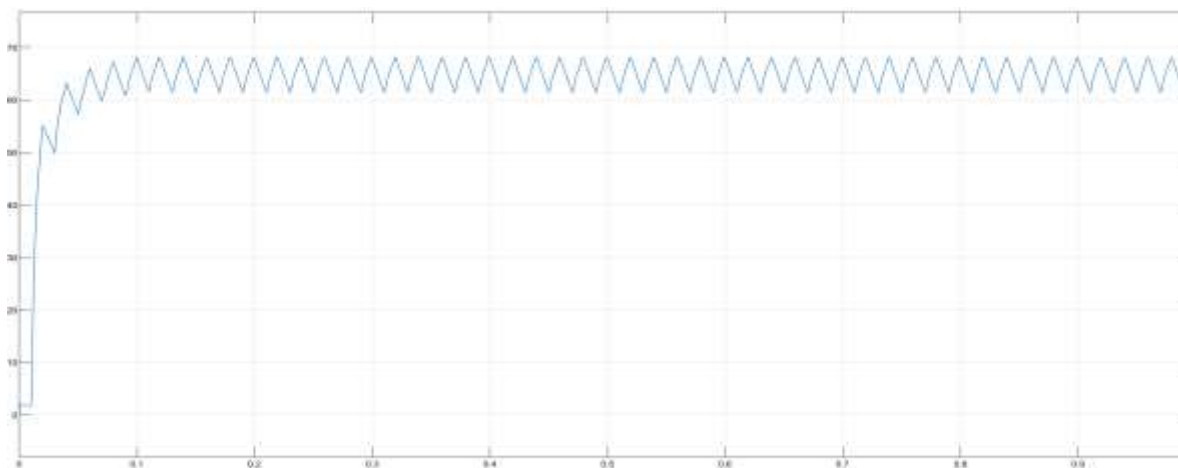
**From the above result:**

It is unsuitable for direct integration into sensitive electrical loads due to its unstable and uncontrolled character. There are two disadvantages to unregulated DC voltage:

**Load Sensitivity:** Ohmic loss causes voltage to decrease as current increases.

**Incompatibility:** For Ethio Telecom data center applications, 68V is not a common DC bus level.

**b) Alkaline Fuel cell voltage output with a Boost Converter**



*Figure 4.10 Alkaline Fuel cell voltage output with a Boost Converter*

**From the above result:**

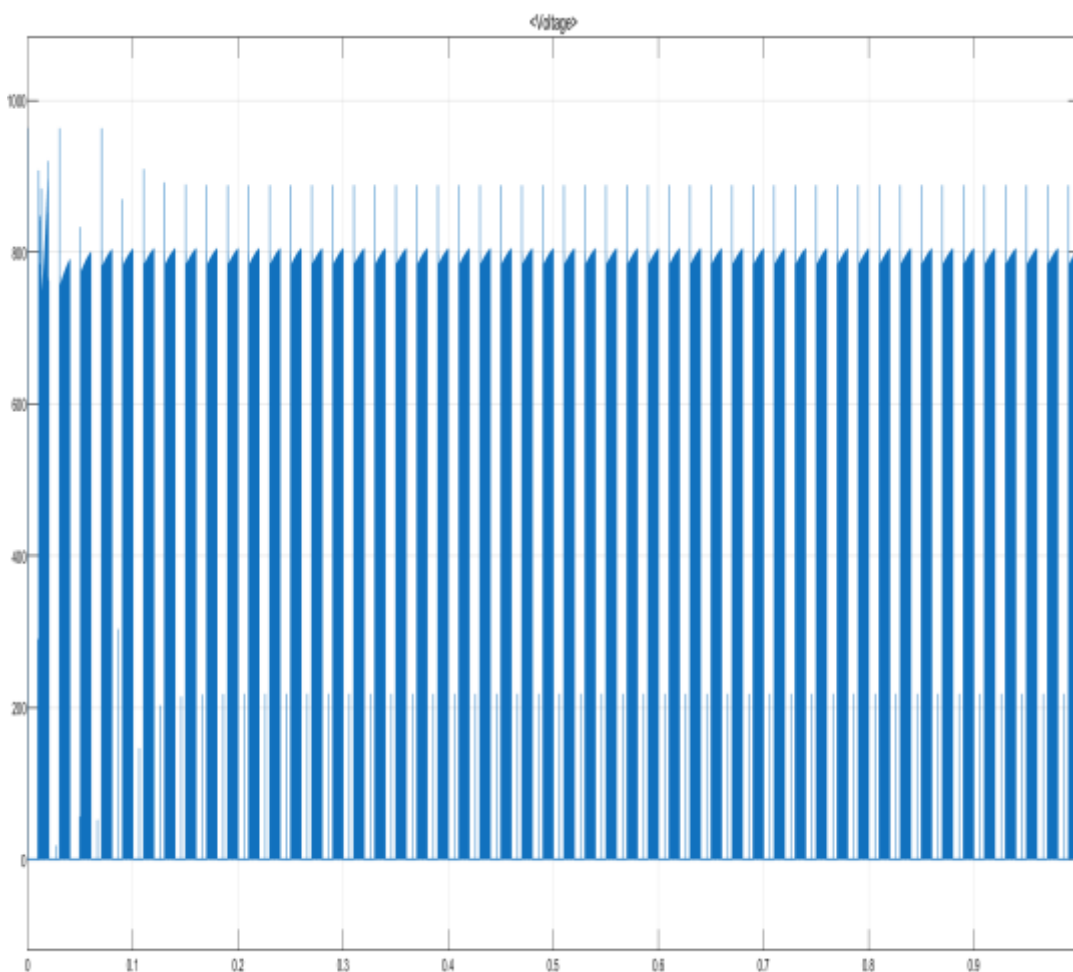
- A small rise in output from 68V to 72V occurs when the stack is connected to a DC-DC Boost Converter.
- Despite its slightness, this increase is noteworthy for three reasons:
  1. **Voltage regulation:** In order to ensure that down stream devices receive a constant voltage even in the face of load variations, the Boost Converter stabilizes the output at a slightly higher level.
  2. **Power conditioning:** Any current surge causes a significant reduction in voltage in the absence of conditioning. Reliability is increased by the Boost Converter, which keeps the stack voltage at 72V.
  3. **Efficiency and System integration:** A slight voltage increase ensures a better match with the DC bus. Because less current is needed to get the same power at 72V as compared to 68V, copper losses in converters and cabling are decreased.

**Note:** *The small rise from 68V to 72V highlights how important Power Electronics are to fuel cell systems since they ensure stability, effectiveness, and compatibility even when the raw voltage change appears minimal.*

#### **4.6.2 Phase III: Simulation result from the Design of the system with Solid Oxide Fuel Cell (SOFC)**

Because of its distinct electrochemical properties and high-temperature functioning, SOFC alone generated a very high voltage output of 1250V without the need for any additional boost, indicating its naturally high operating voltage.

- a) Output voltage from SOFC alone without a Boost Converter,
- b) Solid Oxide Fuel cell voltage output using a Boost Converter.
- a) Output voltage from SOFC alone without a Boost Converter



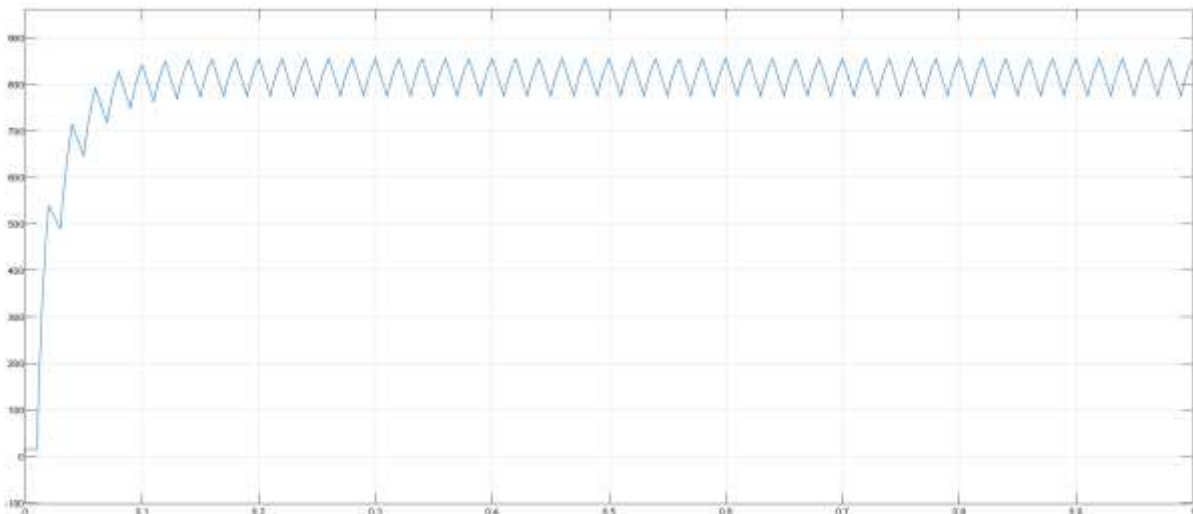
*Figure 4.11 Output voltage from SOFC alone without a Boost Converter*

**From the above result:**

- 780 V is the raw SOFC voltage.
- Which is uncontrolled and unstable
- Varies with load, indicating that it is not directly appropriate for an Ethio Telecom data center.
- It displays the stack's maximum capacity prior to conditioning.

**Note:** Without a Boost Converter Although SOFC voltage is a theoretical electrochemical capability, it is not a workable power source for sensitive loads.

**b) SOFC voltage output using a Boost Converter.**



*Figure 4.12 SOFC voltage output using a Boost Converter*

**From the above result:**

- According to my simulation, the SOFC voltage is increased from 780 to 880 V when it is connected to a DC-DC Boost Converter.
- Stability, reliability, and compatibility with Ethio Telecom data center DC buses are ensured by the Boost Converter-connected SOFC output (880 V).

**4.7 Brief description based on simulation outputs:**

When connected with a Boost Converter, the voltage generated by the PEMFC alone rose to 68V, proving the importance of Power Electronics-based voltage regulation. AFC systems function at a naturally higher voltage than PEMFC systems, but still benefit from boosting. This is demonstrated by the fact that AFC alone achieved 68V natively and that the voltage significantly increased to 72V with a Boost Converter. Because of its distinct electrochemical properties and high-temperature functioning, SOFC by itself generated a very high voltage output of 1250V without the need for any additional boost, indicating its naturally high operating voltage.

In comparison, SOFC provides the highest voltage output by far, suitable for high-power applications, while PEMFC and AFC systems require voltage boosting for applications need higher voltage levels.

#### **4.8 System Configuration and Integration of the Proposed Solid Oxide Fuel System**

A continuous, clean, and efficient power supply for the Ethio Telecom data center is ensured by the proposed hybrid power system, which combines Solid Oxide Fuel Cells (SOFCs), battery energy storage, UPS, and grid connectivity. All subsystems communicate with each other through the Automatic Transfer Switch (ATS), Reclosure, Redundant Rectifier System, and Power Distribution Function (PDF) of the control and protection system, which is depicted in Figure 4.14 below. In order to ensure continuous Ethio Telecom data center operation, this integrated arrangement replaces the traditional diesel generator setup with a reliable, smart, cleaner, and self-regulated power source that ensures continuous, efficient, and environmentally friendly backup and swap sources automatically.

The SOFC system network consists of:

**External Grid Power:** the primary source during normal operation.

**Two SOFC backup units (Fuel Cell Backup 1 and 2):** secondary power sources for redundancy.

**Battery Bank:** energy storage for voltage stability and temporary backup.

**UPS System:** to maintain uninterrupted supply during switching delays.

**Redundant Rectifier System (AC/DC):** to convert AC to DC for Ethio Telecom data center loads.

**Inverters (1 and 2):** for DC/AC conversion of SOFC output.

**ATS and Reclosure:** for intelligent power routing and fault recovery.

**PDF (Power Distribution Function):** for distribution control, load prioritization, and power quality management.

##### **4.8.1 Power Flow and Mode of Operation**

Under typical grid conditions, power is delivered from the external grid to the redundant rectifier system via the ATS, where it is converted to DC. Both the batteries and Ethio Telecom data center equipment load are powered by this DC power (via LVBD and circuit breaker).

During any disruption, the battery stays in float charge mode, keeping it ready for an immediate discharge.

When the grid experiences a fault or voltage disturbance, the ATS transfers the load to the SOFC system after confirming the abnormal condition through its sensing and control mechanism. This transfer occurs within a short switching time to ensure continuity of supply. If the disturbance is temporary, the reclosure attempts to restore the grid to normal operation after a brief delay. The reclosure continuously monitors the grid status and isolates the affected section if the fault persists.

During this process, the SOFC inverters (Inverter 1 and Inverter 2) take over and supply power to the Ethio Telecom data center loads, including the UPS and rectifier systems. At the same time, the UPS provides short-term backup power to critical loads during the transition period, ensuring that there is no interruption until the SOFC output becomes fully stable.

#### **4.8.2 Automatic Transfer Switch (ATS) Function**

ATS is an essential automation component, and it detects voltage loss or frequency deviation from the grid and immediately provides power to the SOFC inverters without the need for human intervention.

Functions of ATS include:

**Automatic Source Selection:** When voltage or frequency deviates, it switches from the grid to SOFC.

**Load Priority Management:** ensuring that the most important Ethio Telecom data center loads are served first.

**Manual Override:** Provides operational safety and maintenance switching.

**Status Feedback:** Notifies the PDF of the switching state so that the system can be monitored. By using ATS, the system ensures uninterrupted operation during power outages and removes source transfer delays.

#### **4.8.3 Reclosure Control Behavior**

In order to reduce unnecessary SOFC startup, the Auto Reclosure immediately closes the grid connection following transient faults, which is a complement to the ATS.

Operational sequence:

1. **Fault Detection:** Monitors unusual grid voltage or current.
2. **Temporary Opening:** Allows the circuit to open for a predetermined dead period
3. **Reclosing Attempt:** Grid power is restored if the problem is resolved.
4. **Lockout:** The Reclosure isolates the grid and instructs the ATS to switch to the SOFC if the problem continues

This feature enhances that the Ethio Telecom data center network has the shortest possible outage duration and improves grid reliability.

#### **4.8.4 Inverters and Rectifier System**

The two SOFC backup units' DC is converted to a synchronized AC supply by Inverters 1 and 2. Critical Telecom loads are ensured a steady and isolated DC output by the Redundant Rectifier System (AC/DC). Rectifiers and inverters minimize harmonics and voltage sags by maintaining phase synchronization during load transfer. Bidirectional control between the grid and SOFC is made possible by this dual conversion technology (AC/DC–DC/AC), which also improves voltage stability.

#### **4.8.5 Surge Protection and Power Quality**

The rectifier input is preceded by a Surge Protection Device (SPD) to absorb transient overvoltage's brought on by switching surges or lightning strikes. In addition to the PDF, the SPD ensures: keeping harmonics, keeping components from failing due to surges, and keeping semiconductor devices used in inverters safe.

#### **4.8.6 Battery and LVBD Protection**

The battery subsystem acts as a harmonic buffer and short-term energy storage. When there is an under voltage or deep discharge, the battery is automatically isolated using LVBD (Low Voltage Battery Disconnect). High short-circuit currents are avoided by circuit breaker protection.

#### **4.8.7 UPS and PDF Role**

The UPS reduces voltage dips and ensures continuous AC power during ATS or Reclosure switching delays. Centralized coordination is carried out by the Power Distribution Function (PDF), which includes:

- Power distribution among Telecom loads, rectifiers, and UPSs.
- Voltage, and load balance monitoring.
- Providing Ethio Telecom data center load prioritization and redundancy in distribution.
- Serving as a simplified solution for local energy management.

In order to maintain system stability and balance, the PDF efficiently monitors and regulates crucial electrical parameters in real-time.

#### 4.8.8 System Reliability and Efficiency Performance

Coordination between ATS, Reclosure, and PDF ensures that power outages are managed automatically with little assistance from humans. When compared to the previous 1500 KVA diesel generator system, the SOFC–Battery–UPS system offers greater reliability, lower emissions, and increased efficiency.

The Telecom data center accomplishes the following through redundancy in SOFC systems, rectifiers, inverters, and Reclosure operations:

- No outages in service.
- Increased system accessibility.
- Lower operating and maintenance costs.
- A stable voltage profile and a notable decrease in THD.

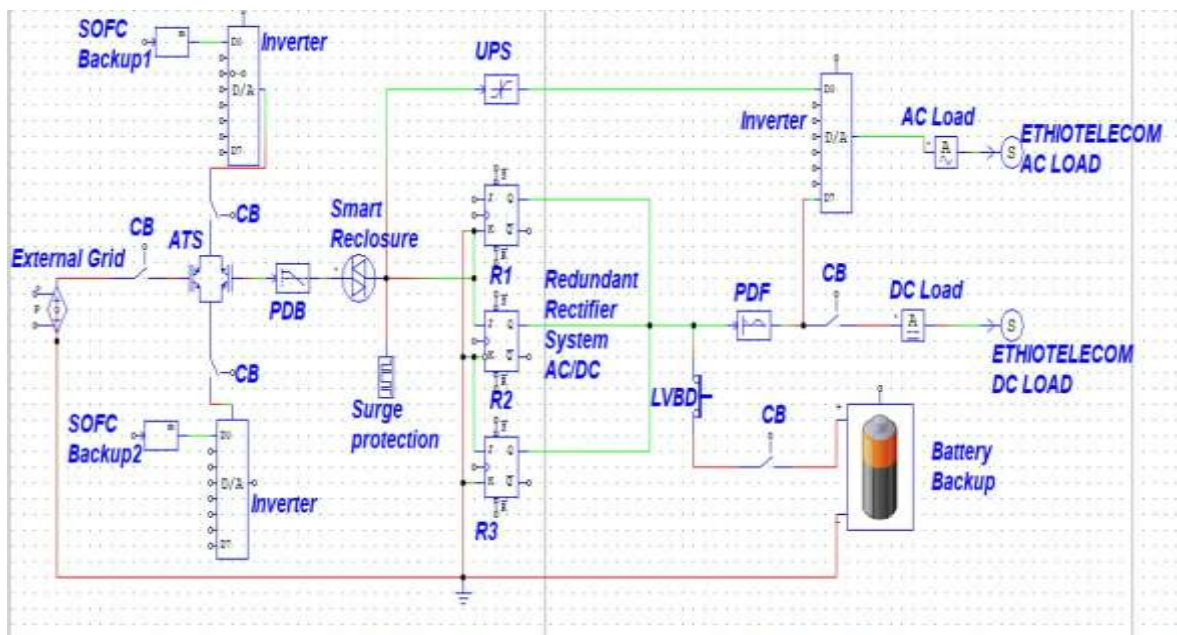


Figure 4.13 General Design overview of fuel cell-based system

## **4.9 Simulation Result Analysis with SOFC**

### **4.9.1 CB14: Main Grid Incomer Protection**

As the main incomer circuit breaker with extensive protection features, CB14 acts as the principal interface between the utility grid and the data center power system. In order to ensure selective coordination during grid-side faults, this crucial device integrates time-overcurrent protection with inverse-time characteristics to coordinate with utility upstream protection. The breaker has ground-fault protection for equipment safety and short-circuit protection with high-set instantaneous elements for quick clearance of serious faults. The breaker has advanced metering capabilities for energy measurement and power quality monitoring, which provide crucial information for system performance analysis and utility billing verification.

### **4.9.2 CB12 & CB13: SOFC Backup System Protection**

Differential protection is the main protective method used by CB12 and CB13, which offer specialized protection for the SOFC backup systems. By continuously comparing the input and output currents of the SOFC systems, these breakers provide current differential protection, which allows for the extremely quick identification of internal faults within the protected zone that includes the SOFC and its related inverter. The protection method incorporates voltage-controlled overcurrent devices for backup protection and harmonic restraint to prevent nonfunctional during transformer energization and other transient circumstances. In addition to having frequency-based load shedding capabilities to preserve system stability during islanded operation, both breakers have synchronization check relays to ensure correct phase matching prior to paralleling with the grid. The settings of the breakers are synchronized to enable smooth transmission between SOFC units while avoiding simultaneous operation that can result in circulating currents.

### **4.9.3 CB15: UPS Input Protection**

The Uninterruptible Power Supply system's input circuit is protected by CB15, which offers coordinated protection that strikes a balance between system reliability and equipment security. In order to provide trouble-free operation during typical start-up conditions, the breaker uses time-delayed overcurrent protection that is set above the UPS input inrush current but below cable thermal limitations. It has under voltage protection that starts switching to

battery operation during prolonged voltage dips, as well as ground-fault protection with sufficient time delay to synchronize with downstream devices. Personnel safety during maintenance operations is greatly improved by CB15's advanced arc-flash detection, which uses light and current sensors for quick fault clearance.

#### **4.9.4 CB16: UPS Output Protection**

CB16 uses a thorough protection scheme intended for crucial power quality management to safeguard the UPS system's output side. The breaker ensures quick clearance of downstream faults by implementing short-circuit protection with instantaneous elements set above the UPS maximum output current but below the cable withstand rating. It incorporates overload protection with thermal memory functions that account for past loading circumstances, reducing wasteful tripping during real overload events while protecting equipment from thermal damage. In order to prevent excessive current distortion, CB16 has harmonic overload protection. This is especially crucial for contemporary switched-mode power supplies that are commonly found in Ethio Telecom data center equipment. In order to maintain UPS availability for other essential loads, the breaker coordination makes sure that CB17 operates first in the event of an AC load circuit fault.

#### **4.9.5 CB17: Inverter Output Protection**

By applying thermal overload protection based on  $I^2t$  characteristics that precisely simulate cable and equipment heating, CB17 offers the last line of protection for the AC load circuit. The breaker provides phase unbalance protection to identify single-phasing situations that could harm three-phase equipment. In order to differentiate between transient fluctuations and persistent under frequency circumstances, it incorporates under frequency protection for load shedding during generator operation, which is adjusted with the proper time delays.

Core-balance current transformers are used in CB17's ground-fault prevention for highly sensitive earth leak detection, which is crucial for worker safety in Ethio Telecom data center. In coordinating with upstream UPS protection, the breakers are designed to protect particular AC loads.

#### **4.9.6 CB18: Rectifier Input Protection**

By using symmetrical coordination to ensure equitable load sharing and fault current distribution, CB18 protect the redundant rectifier systems' input circuits. These breakers provide overload protection for rectifier input components by using time-overcurrent protection with long-time delays set above rectifier inrush currents but below component thermal limits. They have voltage-dependent overcurrent features that improve coordination during voltage dips by adjusting protective settings according to system voltage conditions. The breakers incorporate temperature adjustment to take into account variations in the power room's ambient temperature, as well as di/dt-based protection for quick detection of emerging faults inside rectifier circuits. Their configurations ensure that, in the event of a rectifier fault, just the impacted unit is isolated while the system continues to function on the rectifier that is in good condition.

#### **4.9.7 CB19: Rectifier Output Protection**

By using directional overcurrent protection to stop reverse power flow from the battery to a faulty rectifier, CB19 protect the DC output circuits of the rectifiers. In order to provide improved sensitivity under battery discharge situations, these breakers use voltage-restrained overcurrent protection, which modifies pickup settings in response to DC bus voltage. They have incremental current detection, which enables predictive maintenance before total failure by providing early warning of rectifier component deterioration. The breakers have protective settings that are coordinated to ensure smooth transfer between rectifiers during maintenance or fault conditions, and they have harmonic content monitoring to identify abnormal operation in switching power supplies. To avoid competing operations, their operation is integrated with the battery protection system.

#### **4.9.9 CB20: PDF Output Feeder Protection**

As the primary selective coordination device in the DC distribution network, CB20 protects the major output feeder from the Power Distribution Frame to the load distribution system. In order to distinguish between overload situations and downstream failures, the breaker uses precisely graded time-current characteristics. This ensures that, in the event of a distribution system failures, the nearest downstream breaker will operate first. In order to enable instantaneous clearance for faults inside its zone while maintaining coordination for faults

outside its zone, it integrates current-based zone selective interlocking that communicates with downstream devices. Proactive maintenance is made possible by CB20's load profiling capabilities, which monitor typical load patterns and issue alerts for unusual loading circumstances. The breaker's settings are designed to safeguard distribution cables while permitting acceptable overload scenarios during system startup and transient events.

#### **4.9.10 CB21 & CB22: General DC Load Protection**

Thermal-magnetic protection appropriate for common power distribution applications is implemented by CB21 and CB22, which offer separate protection for non-critical DC loads. In order to prevent insulation damage during prolonged overloads, these breakers use bi-metallic thermal elements that match cable thermal limitations. For short-circuit protection, they use magnetic instantaneous components, and their settings are designed to work with devices upstream while offering quick clearance for serious problems. In order to maintain constant protection qualities despite changes in the Ethio Telecom data center's environment, the breakers have ambient temperature compensation. Individual load circuits can be separated without compromising other vital system settings, which ensure sufficient protection for associated loads while preserving selectivity with the main distribution protection.

#### **4.9.11 CB22: Critical Telecom Load Protection**

Through the implementation of a comprehensive, multi-function protection mechanism, CB22 offers the highest level of protection for the critical Ethio Telecom data center's DC load. The breaker ensures safety against prolonged overloads that could harm delicate Ethio Telecom equipment by combining thermal overload protection with electronic trip units that offer exact time-current characteristics.

In order to minimize stress on linked equipment, it integrates comprehensive short-circuit protection with current-limiting capabilities to lower let-through energy during breakdowns. In addition to arc-flash detection for increased worker safety, CB22 has high-sensitivity ground-fault prevention to identify low-level ground faults that can interfere with delicate electronic circuits.

The breaker provides useful information for troubleshooting power-related problems in Ethio Telecom equipment by implementing power quality monitoring.

Its settings are tailored for optimal dependability with suitable margins to prevent nuisance tripping while assuring speedy clearance of actual problems, and it links with the building management system for remote monitoring and control of the critical load.

This comprehensive circuit breaker protection system ensures complete coordination from source to load, providing layered protection that maintains system reliability while enabling rapid fault clearance and equipment protection throughout the Ethio Telecom data center.

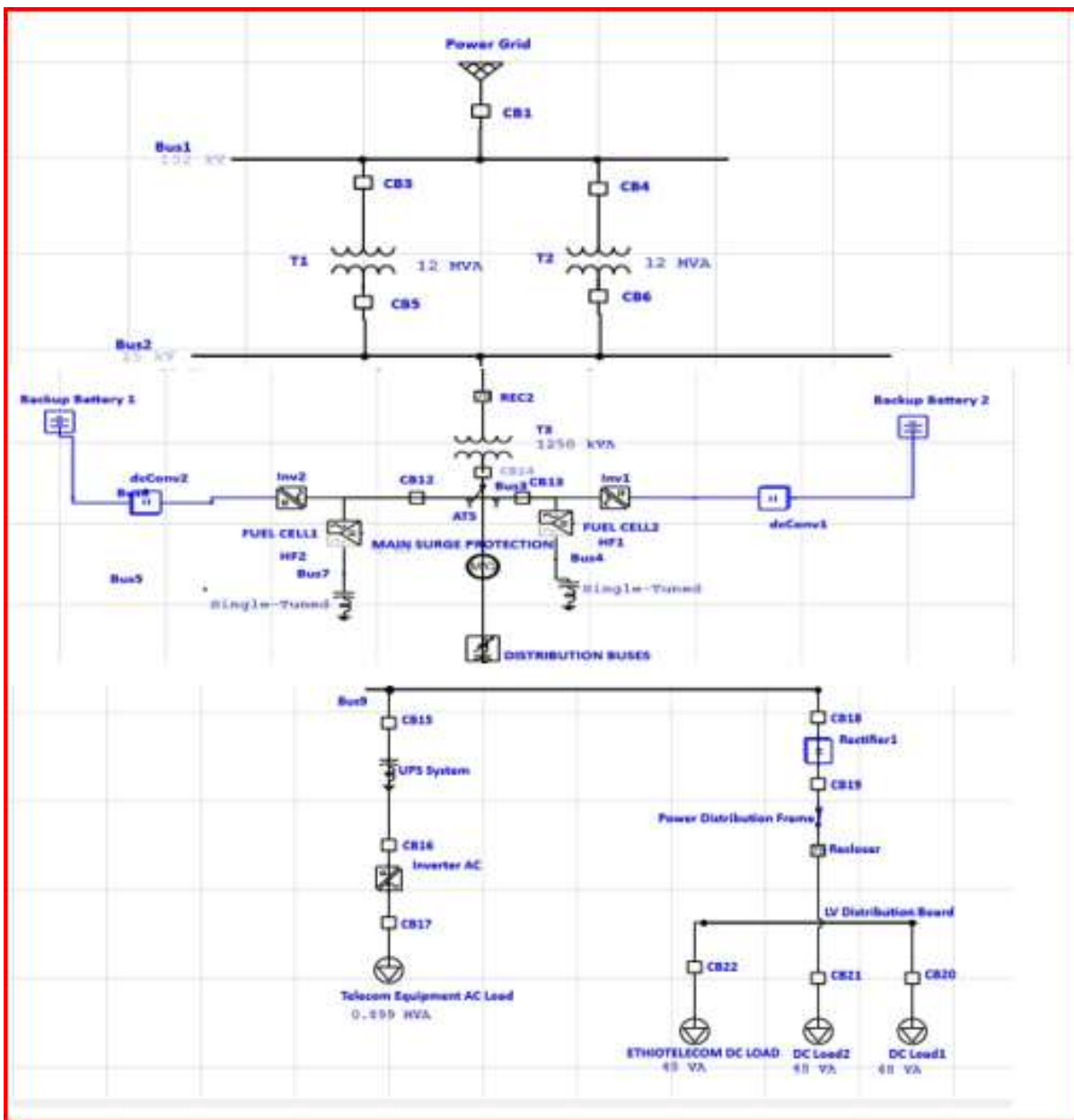


Figure 4.14 Simulation result of the SOFC system with ETAP

Project: FUEL CELL BASED POWER SUPPLY	<b>ETAP</b>	Page: 1
Location: ADDIS ADBABA UNIVERSITY/CTBE	19.0.1C	Date: 11-26-2025
Contract: 0911592842/0910250616		SN:
Engineer: NEMOMSA ABEBE NEGESSA	Study Case: RA	Revision: Base
Filename: Namomsa Abebe.AAU/CTBE		Config.: Normal

SUMMARY  
System Indexes

ASAI	0.9992 pu
ASUI	0.00078 pu
CAIDI	6.3210 hr / customer interruption
CTAIDI	5.0451 hr / customer.yr
SAIDI	4.0320 hr / customer.yr
SAIFI	0.2670 f / customer.yr
ASAI	Average service Availability Index
ASUI	Average Service Unavailability Index
CAIDI	Customer Average Interruption Duration Index
CTAIDI	System Customer Total Average Interruption Duration Index
SAIDI	System Average Interruption Duration Index
SAIFI	System Average Interruption Frequency Index

#### 4.10 Comparison of Fuel Cell Alternative Power supply and Diesel Generator Power supply

##### 4.10.1 Regarding with simulation Analysis

Let's calculate the **percent improvement** for both **SAIDI** and **SAIFI**:

##### 1. SAIDI Improvement

Formula:

SAIDI improvement (%) =

$$\frac{\text{Existed system SAIDI} - \text{SOFC system SAIDI}}{\text{Existed system SAIDI}} \times 100 = \frac{10.4220 - 4.0320}{10.4220} \times 100$$

$$= 61.313\%$$

From the calculation, SAIDI is improved by 61.313%.

##### 2. SAIFI Improvement

Same formula, now for SAIFI:

SAIFI improvement (%) =

$$\frac{\text{Existed system SAIFI} - \text{SOFC system SAIFI}}{\text{Existed system SAIFI}} \times 100 = \frac{1.2930 - 0.2670}{1.2930} \times 100 = 79.35\%$$

**SAIFI is improved by 79.35%.**

### 3. CAIDI Improvement

Same formula, now for CAIDI:

CAIDI improvement (%) =

$$\frac{\text{Existed system CAIDI} - \text{SOFC system CAIDI}}{\text{Existed system CAIDI}} \times 100 = \frac{8.060 - 6.3210}{8.060} \times 100 = 21.58\%$$

**CAIDI is improved by 21.58%.**

### 4. CTAIDI Improvement

Same formula, now for CTAIDI:

CTAIDI improvement (%) =

$$\frac{\text{Existed system CTAIDI} - \text{SOFC system CTAIDI}}{\text{Existed system CTAIDI}} \times 100 = \frac{10.422 - 5.0451}{10.422} \times 100 = 51.59\%$$

**CTAIDI is improved by 51.59%.**

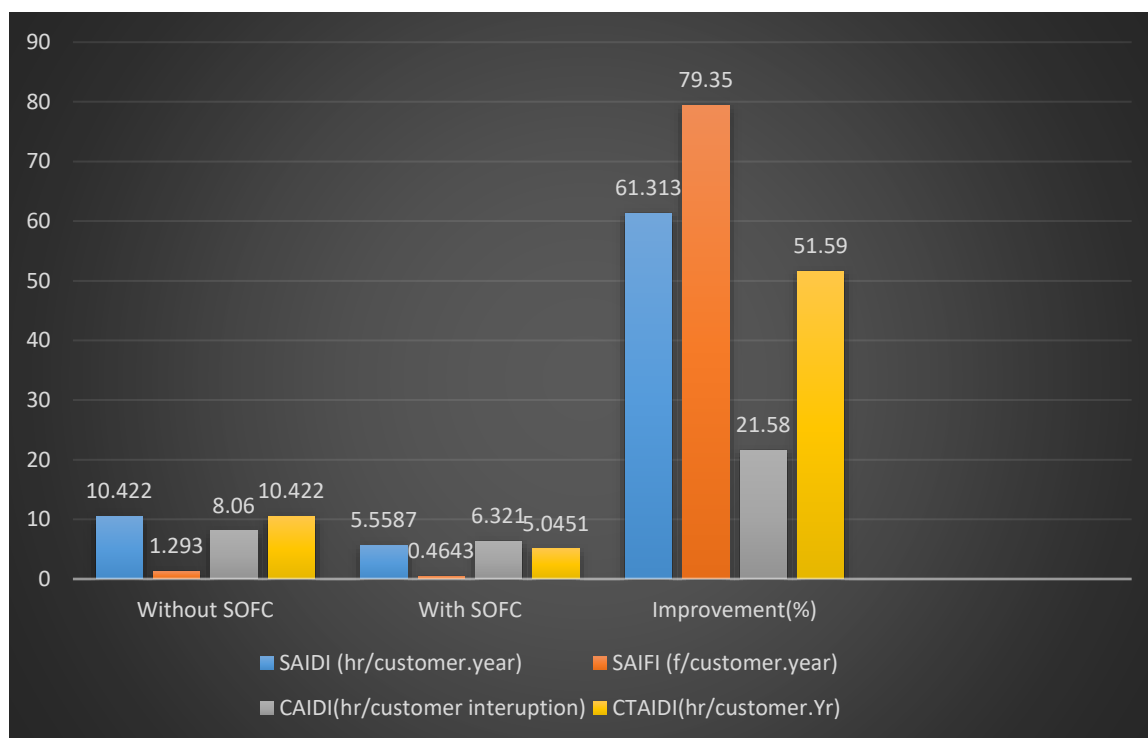


Chart 4.1 Comparison of SAIFI, SAIDI, CAIDI, and CTAIDI of existed system with SOFC system

### SAIDI (System Average Interruption Duration Index)

The Ethio Telecom data center's average outage duration (in hours per customer annually) is illustrated in the SAIDI chart. While a lower SAIDI value indicates better service continuity, a greater value indicates longer interruptions for customers.

When compared to the current diesel generator system, the implementation of a fuel cell-based backup system dramatically decreased SAIDI in the ETAP reliability analysis, suggesting that the suggested solution ensures quicker restoration and improved service availability.

### **SAIFI (System Average Interruption Frequency Index)**

The average number of interruptions per customer annually is displayed in the SAIFI graph. It draws attention to how frequently customer experience power outages of any duration. According to the ETAP data, using a fuel cell backup significantly decreased SAIFI when compared to the generator-based system, indicating higher reliability and fewer outages. This demonstrates that adding fuel cells to the data center's power supply reduces the frequency and impacts of outages.

### **CAIDI (Customer Average Interruption Duration Index)**

The Customer Average Interruption Duration Index (CAIDI), which is calculated by dividing the total customer interruption duration by the number of customer interruptions, is a core reliability indicator that calculates the average time needed to restore service to customers following a power outage. Because it measures the responsiveness and restoration effectiveness of the backup power, CAIDI is especially significant in Ethio Telecom data center.

It has a direct impact on equipment safety, service continuity, and overall system resilience. The ETAP simulation results show that the suggested SOFC-based backup system greatly enhances restoration performance in the context of Ethio Telecom's data center, lowering CAIDI to 21.58% is a noteworthy improvement over the current diesel generator design. In the end, this enhancement contributes to a more reliable and efficient power supply for critical Ethio Telecom data center operations by highlighting the SOFC system's quicker stabilization time, smoother transition characteristics.

### **CTAIDI (System Customer Total Average Interruption Duration Index)**

The Customer Total Average Interruption Duration Index (CTAIDI) is a reliability statistic that provides a comprehensive assessment of how seriously disruptions affect the system as a whole by measuring the average outage length experienced by all impacted customers over a specified period. CTAIDI is essential for evaluating the efficiency of power continuity techniques in

large infrastructures like Ethio Telecom data centers since it assesses the overall interruption load, in contrast to CAIDI, which concentrates on restoration time per interruption. According to ETAP simulation results, Ethio Telecom's suggested SOFC-based backup system significantly outperforms the current diesel generator system, lowering CTAIDI by 51.59%. In the end, this significant improvement strengthens the data center's reliability performance and lowers the risks of service disruption by demonstrating the SOFC's capacity to reduce cumulative outage time through faster reaction, more reliability, and superior operational stability.

#### 4.10.2 Regarding Economic Analysis

##### 4.10.2.1 Define Cost Parameters

##### **Step 1, Capital Expenditure**

Capital cost can be defined as initial investment required for procuring and installing the power system.

The estimated cost to implement in microwave Data Center without labor cost is shown in the below table. This can be categorized.

*Table 4- 6 Capital Expenditure*

No.	Cost Component	Diesel Generator System (USD \$)	Fuel Cell system in (USD \$)
1	Initial Equipment Cost	1,725,253.44 (2x1500KVA)	2,107,450
2	Fuel tank, Installation (Generator & Fuel tank) and commissioning including transportation as shown on appendix	100,000	417,275
3	Power Electronics (Inverters)	50,000	100,000
4	Grid Connection Modifications	30,000	74,600
	<b>Total CAPEX</b>	<b>1,905,253.44 USD</b>	<b>2,699,325 USD</b>

## Step 2, Operational Expenditure

Operational expenditure can be defined as the recurring expenses during the system’s life such as fuel, maintenance, stack replacement for fuel cell and diesel fuel, oil changes, filters, and frequent maintenance for generators respectively.

*Table 4- 7 Operational Expenditure*

No.	Cost Component	Diesel Generator System (USD \$/Year)	FC System (USD \$/Year)
1	Fuel Cost	105,000 (Diesel)	29,481.92 (Natural Gas)
2	Maintenance Cost	50,000	19,396
3	Environmental Compliance (Carbon Tax, Emission)	21,731	5,000
4	Grid Connection Modifications	50,000	13,000
	<b>Total OPEX</b>	<b>226,731 USD</b>	<b>67,877.92 USD</b>

The Environmental Compliance (Carbon Tax, Emission) is calculated from collected data of fuel consumption from Ethio Telecom data center based on global carbon pricing ranges from \$1 to \$100 per ton of CO<sub>2</sub> [92]

For diesel generator a widely accepted emission factor is:

1 Liter of diesel =2.68 Kg CO<sub>2</sub>.

From annual fuel use:

Fuel consumption of 2023 year is 81,084 Liters/year.

CO<sub>2</sub> emission: 81,084 x2.68 = 217,310 Kg CO<sub>2</sub> = 217.31 tons CO<sub>2</sub>/year

## Step 3, Perform Life Cycle Cost (LCC) Analysis

Life cycle cost can be defined as the total cost of ownership over the systems expected life.

Life cycle cost analysis can be calculated by using the below formula:

$$LCC = CAPEX + \sum_{t=1}^n \frac{OPEX_t}{(1+r)^t}$$

n= System life time (10 years)

r = Discount rate (15%)

The discount rate is the rate of return used to convert future cash flows into present value. It reflects the time value of money –money today is worth more than the same amount in the future because of inflation, opportunity cost and risk. It allows to compare costs and benefits occurring at different times on the same present value basis.

As of June 30, 2025, the National Bank of Ethiopia (NBE) has maintained its policy interest rate at **15%**.

After calculation LCC results become

- Diesel generator system LCC (for 10 years): **\$3,043,518**
- SOFC system LCC (for 10 years): **\$3,043,518**

SOFC saves **\$30,500** over years compared to diesel generators.

#### **Step 4, Net Present Value (NPV) Calculation**

Net present value is the value of cash flows over the project’s life, accounting for time value of money. It can be calculated by using the below formula:

- Annual savings = (Diesel OPEX –SOFC OPEX) =\$158,853.08/Year
- Initial Investment difference =(SOFC CAPEX –Diesel CAPEX) = \$794,071.56
- Let’s calculate NPV:
- NPV = Saving x discount factor (10 years, 15%) - Initial investment difference

$$\$158,853.08 \times 5.019 - 794,071.56 = \mathbf{+3,171 \text{ USD}}$$

- Positive NPV indicates that investing in SOFC is financially beneficial over 10 years.

### Step 5, Payback period (PBP) calculation

Payback period is time it takes to recover the initial investment from net savings. It can be calculated by using the below Formula:

- Payback Period =  $\frac{\text{Initial Investment Difference}}{\text{Annual Savings}} = \frac{794,071.56}{158,853.08} = 5 \text{ years.}$
- Payback period result
- Payback period for SOFC investment: 5 years
- After 5 years, SOFC provides net savings compared to diesel generators.

#### 4.10.2.5 Financial Internal Rate of Return (FISR)

The financial Internal rate of Return (FISR) represents the discount rate at which the project's net present value becomes zero. It is a key indicator used to evaluate the investment attractiveness. To maintain simplicity and consistency, the straight-line depreciation method is applied over a project lifetime of 10 years, with a salvage value assumed to be 10% of the initial capital investment.

Formula:

$$D = \frac{C-S}{N}$$

Where:

C represents the initial capital cost,

S is the salvage value, and

N is the system lifetime.

#### **Diesel Generator system**

Capital cost = **1,905,253.44 USD**

Salvage value = **190,525.34 USD**

The result in an annual depreciation of **171,472.81 USD**

**For SOFC System:**

Capital cost = **2,699,,325 USD**

Salvage value = **269,932.5 USD**

**Depreciation Tax Benefit**

One of the key advantages of higher depreciation is the resulting tax shield, which directly improves cash flow. a corporate tax rate of Ethio Telecom is of 30%, the annual tax savings are:

Diesel system: **51,441.84 USD**

SOFC system: **72,881.78 USD**

This leads to an additional benefit of:

**21,439.94 USD** per year in favor of the SOFC system

This difference is important because it strengthens the financial performance of the SOFC option over time.

**Adjusted Cash Flow** = 158,853.08 + 21,439.94 = 180,293.02 USD

FISR is calculated as follows:

$$\text{FISR} = -794,071.56 + \sum_{t=1}^n \frac{180,293}{(1+r)^t}$$

FISR = **18.5%**

- From FISR result greater than Ethiopian discount rate (15%)
- Economically attractive.

**4.10.3.5 Return on Investment (ROI) Calculation**

Return on investment is the efficiency of investment. It can be calculated by using the below formula:

- $$\text{ROI} = \left( \frac{\text{Total Savings over 10 Years} - \text{Initial Investment Difference}}{\text{Initial Investment Difference}} \right) \times 100$$

- $ROI = \left( \frac{158,853.08 \times 10 - 794,071.56}{794,071.56} \right) \times 100 = 100\%$

**From the aobove calculation:**

- ✓ SOFC reduces total Ethio Telecom data center cost over 10 years by 30,500 USD.
- ✓ The investment pay back in 5 years, making it financially viable.
- ✓ SOFC provides a 100% ROI, making it superior long – term choice.
- ✓ Lower fuel costs,
- ✓ Minimum maintenance and reduced emissions make SOFC ideal for Ethio Telecom data center power backup.

**4.10.3 Regarding with world warm Contribution and Green Energy**

Detailed comparison between Fuel Cells and Engine Generators (like diesel or gas generators) specifically focusing on world warming contribution and their role in green energy systems:

Table 4- 8 World warm Contribution and Green Energy

Aspect	Fuel Cell	Engine Generator
Basic Operation	Electrochemical conversion of fuel (e.g., hydrogen) into electricity, no combustion.	Internal combustion of fuel (diesel, gasoline, or natural gas) to generate mechanical energy, then converted to electricity.
Main Emissions	Water vapor (H <sub>2</sub> fuel), some CO <sub>2</sub> if using hydrocarbon fuels; very low NO <sub>x</sub> , SO <sub>x</sub> , and particulate emissions.	High CO <sub>2</sub> emissions; also emits NO <sub>x</sub> , SO <sub>x</sub> , unburned hydrocarbons, and particulates, contributing to air pollution.
Greenhouse Gas (GHG) Contribution	Very low if using green hydrogen or pure H <sub>2</sub> ; moderate if using reformed hydrocarbons. Overall, much lower GHG impact than engines.	High GHG emissions, especially CO <sub>2</sub> , due to fuel combustion. Diesel generators are particularly significant contributors to climate change.
Efficiency	40–65% electrical efficiency; can exceed 80% in combined heat and power (CHP) systems.	25–40% electrical efficiency; large energy loss as heat, lower than fuel cells.
Energy Source	Can use renewable hydrogen, biofuels, or even methane from waste systems.	Typically relies on fossil fuels (diesel, gasoline, natural gas); renewable fuels are possible but less common.
Role in Green Energy Systems	Critical for green hydrogen ecosystems, zero-emission mobility, backup power without carbon footprint, and integration with renewables (like solar + hydrogen storage).	Less compatible with green energy goals unless using renewable biofuels (still emits CO <sub>2</sub> ); mainly used in remote/off-grid backup where quick startup is vital.
Impact on Air Quality	Excellent — minimal to no harmful emissions.	Poor — contributes heavily to urban air pollution (smog, respiratory diseases).
Sustainability	Highly sustainable if paired with renewable fuel production.	Not sustainable in the long term due to fossil fuel dependence.
Noise Pollution	Very quiet operation.	Noisy — vibration and engine noise are significant issues.

Fuel Cells are much greener than Engine Generators. They offer low to zero carbon emissions, higher efficiency, cleaner air, and less noise. All important for combating global warming and building a sustainable energy system.

Engine Generators, while reliable and well-established, heavily contribute to climate change through CO<sub>2</sub> and other harmful emissions and are generally not aligned with green energy goals, unless significantly modified to use low-carbon fuels (which is still rare today).

#### **4.11 Safety and Protection Considerations**

To guarantee dependable operation, worker safety, and adherence to international standards, the proposed 746 kW Solid Oxide Fuel Cell (SOFC) system which is intended to replace the diesel generator in Ethio Telecom's data center needs strong safety and protection measures. Since SOFC systems use flammable fuels and run at high temperatures, unlike diesel generators, integrated protection techniques are essential for their successful deployment.

##### **4.11.1 Electrical Protection**

An inverter and a step-up transformer are used to integrate the SOFC into the medium-voltage distribution system. The inverter converts the SOFC DC output into AC power, while the step-up transformer raises the inverter output voltage to the medium-voltage level required by the Ethio Telecom Microwave data center distribution network. The following precautions are taken to protect the Ethio Telecom data center loads and electrical infrastructure:

- Circuit breakers and fuses, sized for the 746 kW load at 0.8 power factor (~930 kVA), are used for overcurrent and short-circuit protection.
- The transformer and inverter have differential protection to identify internal equipment problems.
- To avoid worker dangers, ground fault protection is implemented using earth leakage relays and residual current devices.
- Safe disconnection during grid failures is ensured by synchronization and anti-landing protection in compliance with IEEE 1547 and IEC 61727 standards.
- Surge and Voltage Protection to reduce lightning or switching transients, metal-oxide varistors and surge protection devices (SPDs) are used.

#### **4.11.2 Fuel and Thermal Safety**

Natural gas or hydrogen reforming is necessary for SOFC functioning, which presents some risks:

- Methane and hydrogen sensors connected to automatic shut-off valves are used to detect gas leaks.
- Fuel processing rooms should include ventilation systems to prevent the buildup of flammable gasses.
- NFPA 853-compliant fire-rated enclosures with thermal insulation surrounding the stack.
- Programmable logic controllers (PLCs) regulate automatic shutdown protocols to stop uncontrolled overheating.

#### **4.11.3 Cooling and Pressure Protection**

- Temperature monitoring sensors and backup pumps are features of redundant cooling systems.
- Relief of Pressure pipework and reformer valves to avoid over pressurization.
- During shutdown events, emergency venting systems (catalytic combustors or flare stacks) provide for the safe release of unburned fuel.

#### **4.11.4 Fire and Explosion Protection**

- Clean-agent extinguishers (FM-200/Novec 1230) are used by fire detection and suppression systems to protect critical Ethio Telecom data center infrastructure.
- IECEx/ATEX-compliant explosion-proof equipment is required in fuel handling locations.
- Plans for emergency preparedness that include employee education and compliance with NFPA 70 and Ethiopian fire safety regulations.

#### **4.11.5 Control and Cybersecurity Protection**

Considering the reliance on advanced digital controllers and Power Electronics:

- Fuel flow, temperature, and stack voltage may all be tracked in real time with SCADA integration.
- Cybersecurity measures to protect against cyberattacks or illegal access.

- Redundant communication channels for continuous security and monitoring.

#### **4.11.6 Compliance with Standards**

The design for safety and protection adheres to global best practices, which include:

- Interconnection of Distributed Resources (IEEE 1547).
- Functional Safety of Electrical/Electronic Systems, IEC 61508.
- IEC 62282: Fuel Cell System Safety.
- NFPA 853: Fuel Cell Installation.

## CHAPTER FIVE

### CONCLUSIONS AND RECOMMENDATIONS

#### 5.1 Conclusions

This thesis evaluated the technical and economic feasibility of using a Solid Oxide Fuel Cell (SOFC)-based backup power system for the Ethio Telecom data center as an alternative to the existing 1500 KVA diesel generator system. The study used ETAP reliability analysis, MATLAB/Simulink modeling, and economic assessment to compare both systems. The results showed that the proposed SOFC system provides improved reliability, better efficiency, and long-term operational benefits, making it a sustainable alternative backup power solution for Ethio Telecom data centers.

From the standpoint of reliability, the current diesel generator-based system have a SAIDI of 10.422 hours/customer-year and a SAIFI of 1.293 f/customer-year, according to the reliability evaluation. These numbers dramatically decreased to 4.0320 and 0.2670, respectively, after the SOFC-based backup system was included. Reliability indicators significantly increased as a result of the fuel cell integration: SAIFI improved by roughly 79.35%, SAIDI improved by about 61.313%, CAIDI is improved by about 21.58%, and CTAIDI is improved by 51.59%.

The superior features of SOFC were demonstrated by MATLAB-based modeling of AFC, PEMFC, and SOFC under three operational situations. Although the voltage and current outputs of the AFC and PEMFC were encouraging, the SOFC continuously offered superior stability, scalability, and stack efficiency. Additionally, the addition of a Boost Converter enhanced output voltage control even more, ensuring compliance with Ethio Telecom data center. In line with the energy requirements and operating standards of mission-critical Ethio Telecom data center systems, this confirms the SOFC's potential as a more reliable and effective backup source.

From an economic standpoint, the comparison of the diesel generator and SOFC demonstrated that, despite the fuel cell technologies comparatively higher initial capital expenditure (CAPEX), long-term savings are achieved through its reduced operating expenditure (OPEX) and increased efficiency. The diesel generator system was predicted to have a life cycle cost

(LCC) of \$3,043,518, while the SOFC system achieved a slightly lower LCC of \$3,040,017, resulting in a \$30,500 lifetime savings.

Furthermore, under the presumptive conditions (10-year lifetime, 15% discount rate), the annual savings of \$158,853.08, the Net present value (NPV) of \$30,500, the payback period (PBP) of 5 years, and the ROI of 100% all support the economic feasibility of implementing SOFC technology. With a corporate tax rate of 30%, the Financial Internal Rate of Return (FISR) is estimated to be about 18.5%. This increase is largely driven by the benefit of depreciation, which helps improve the overall cash flow of the SOFC system. Since this value is higher than the 15% discount rate, it clearly indicates that the investment is financially sound and worthwhile over the long term. Overall, despite the higher initial cost, the SOFC system proves to be a more cost-effective, environmentally friendly, and sustainable alternative compared to conventional diesel generators.

Ethio Telecom can reduce its reliance on diesel generators and increase efficiency, minimize operating costs, improve reliability indices, and reduce its environmental impact by incorporating SOFC technology.

## 5.2 Recommendations

The organization should implement a modern SOFC system that utilizes Ethiopia's emerging LNG and natural-gas infrastructure as its primary fuel source. As the country begins expanding natural gas extraction, processing, and LNG import facilities, SOFC technology becomes a strategically aligned solution because it converts natural gas to electricity at significantly higher efficiency than diesel generators, with minimal emissions and no combustion-related losses. The Ethio Telecom data center obtains cleaner, more reliable power without the noise, frequency variations, and harmonic problems associated with diesel generator outputs because the SOFC's steady, low-ripple DC output is intrinsically more compatible with Ethio telecom rectifiers and UPS systems. Generator downtime are eliminated when diesel generators are replaced with SOFCs, which directly reinforces the SAIFI and SAIDI gains seen in the ETAP simulation. By eliminating the long repair and restart periods associated with diesel systems, the organization can significantly increase CAIDI with modular redundancy (N+1 SOFC architecture) and battery-supported fast transfer.

The company should put in place a long-term transition strategy that gradually replaces diesel generators with SOFC modules powered by natural gas and backed by an enhanced battery-UPS subsystem. Due to decreased fuel price volatility, less maintenance requirements, and the removal of diesel-related logistics such fuel transportation, on-site storage, security hazards, and routine overhauls, SOFC systems employing LNG/natural gas offer lower lifetime costs (LCOE) from an economic standpoint. Reliability increases because SOFCs run continuously with fewer moving parts, leading to significantly reduced failure rates and quicker repair times. ETAP reliability simulations verify that SOFC systems can lower energy-not-served, enhance CAIDI, and reduce outage-related financial losses for the Ethio Telecom data center, particularly when battery bridging and quick ATS are in place. As natural gas infrastructure develops, the company should scale system capacity after conducting a controlled pilot deployment to verify power quality and redundancy behavior. This strategic shift positions Ethio Telecom to benefit from cleaner energy, lower operational cost, superior reliability, and national alignment with Ethiopia's LNG/natural-gas development goals.

**Further Research and Pilot Testing:** By implementing these recommendations, Ethio Telecom can ensure a smooth, secure, and cost-effective transition to fuel cell-based backup systems, strengthening the reliability and sustainability of its national telecom infrastructure.

### **Future Work**

There are numerous opportunities to expand this study, particularly as Ethiopia advances in utilizing its LNG and natural gas resources. A logical subsequent step involves investigating the performance of SOFC systems when they are directly powered by locally sourced natural gas. This entails assessing the efficiency of on-site fuel reforming, determining if the quality of the gas influences performance, and comparing the long-term operational costs with the existing diesel-based system.

Another avenue for future research involves investigating how SOFC can be integrated with renewable sources other than the battery, rectifier, and UPS discussed in this thesis. Potential complementary sources include solar PV, small wind turbines, biogas reformers, and low-level geothermal support. For instance, solar PV could reduce the SOFC's operational hours during daylight, while wind or biogas solutions might be more suitable for rural or windy areas. Gaining insight into how these sources can be combined would aid in developing a more adaptable energy system tailored to various site conditions.

In the future, this thesis could be expanded to benefit other sectors. Government bodies, schools, hospitals, banks, and many non-governmental organizations heavily depend on stable electricity and face similar challenges during extended power outages. Exploring the effectiveness of SOFC–renewable hybrid systems in these environments would help these organizations choose cleaner and more reliable alternatives to diesel generators.

The progressive addition of hydrogen to natural gas supply is another fascinating topic. Even a tiny blend can cut emissions, but its impacts on SOFC life and efficiency require additional exploration. This would be helpful in Ethiopia's future efforts to develop green hydrogen.

Lastly, lifecycle planning and long-term maintenance should be included in future research. This entails monitoring SOFC deterioration over time, determining reasonable replacement intervals, and contrasting the environmental effects with those of current diesel systems. Future large-scale rollouts will be simpler for Ethio Telecom and other organizations.

## References

1. Larminie, J., & Dicks, A. (2003). *Fuel Cell Systems Explained* (2nd ed.). John Wiley & Sons.
2. Barbir, F. (2013). *PEM Fuel Cells: Theory and Practice* (2nd ed.). Academic Press.
3. O'Hayre, R., Cha, S.-W., Colella, W., & Prinz, F. B. (2016). *Fuel Cell Fundamentals* (3rd ed.). Wiley.
4. EG&G Technical Services. (2004). *Fuel Cell Handbook* (7th ed.). U.S. Department of Energy.
5. Singhal, S. C., & Kendall, K. (2003). *High-Temperature Solid Oxide Fuel Cells: Fundamentals, Design and Applications*. Elsevier.
6. Larminie, J., & Dicks, A. (2003). *Fuel cell systems explained* (2nd ed.). John Wiley & Sons.
7. *Ethio Telecom annual performance report 2022/2023*. Addis Ababa, Ethiopia.
8. Bose, B. K. (2007). *Power Electronics and Motor Drives: Advances and Trends*. Academic Press.
9. Kaldellis, J. K. (2010). *Stand-Alone and Hybrid Wind Energy Systems: Technology, Energy Storage and Applications*. Woodhead Publishing.
10. U.S. Department of Energy, "Case Study: Fuel Cells Increase Reliability at First National Bank of Omaha Technology Center," 2014.
11. Chandan, A., Hattenberger, M., El-Kharouf, A., et al. (2013). High temperature polymer electrolyte membrane fuel cells: A review. *Journal of Power Sources*, 231, 264–278.
12. J. Kurtz, G. Saur, and S. Sprik, Hydrogen Fuel Cell Performance as Telecommunications Backup Power in the United States, National Renewable Energy Laboratory (NREL), Golden, CO, Tech. Rep. DOE/GO-102015-4566, 2015.
13. European Commission, Fuel Cells for Prime Power in Data Centres (Horizon 2020 Project), Horizon 2020 Programme, Brussels, 2024.
14. Mekonnen, A., & Bekele, G. (2015). Feasibility Study of Renewable Energy Resources for Rural Electrification in Ethiopia. *Journal of Energy Technologies and Policy*, 5(1), 93–103.
15. Hodge, B. K. (2017). *Alternative Energy Systems and Applications* (2nd ed.). Wiley.

16. McLarty, D., Brouwer, J., & Samuelsen, S. (2014). Fuel cell–gas turbine hybrid system design. *Journal of Power Sources*, 256, 274–285.
17. Larminie, J. (2014). *Introduction to Fuel Cells*. Wiley.
18. IEEE Standards Coordinating Committee. (2017). *IEEE Recommended Practice for Emergency and Standby Power Systems for Industrial and Commercial Applications*.
19. IRENA. (2020). *Hydrogen: A Renewable Energy Perspective*.
20. T. Tronstad and L. Langfeldt, *Study on the use of fuel cells in shipping. Technical Report*, EMSA European Maritime Safety, 2017.
21. Ghouse, J. H., et al. (2017). Solid oxide fuel cells: Materials and applications. *Energy Technology*, 5(7), 929–952.
22. International Energy Agency (IEA), *The Future of Hydrogen: Seizing Today's Opportunities*, Paris, France, 2019.
23. US Department of Energy. (2019). *Fuel Cells Fact Sheet*.
24. Demirbas, A. (2008). *Biohydrogen: For Future Engine Fuel Demands*. Springer.
25. Zamel, N., & Li, X. (2013). Life cycle analysis of vehicles powered by a fuel cell and by internal combustion engine for Canadian conditions. *International Journal of Hydrogen Energy*, 38(22), 9604–9615.
26. Wang, Y., Chen, K. S., Mishler, J., Cho, S. C., & Adroher, X. C. (2011). A review of polymer electrolyte membrane fuel cells: Technology, applications, and needs on fundamental research. *Applied Energy*, 88(4), 981–1007.
27. Renewable Energy Solutions for Africa Foundation. (2022). *Ethiopia Energy Market Overview*.
28. Birol, F. (2020). *World Energy Outlook*. International Energy Agency.
29. Rowe, A., & Li, X. (2001). Mathematical modeling of proton exchange membrane fuel cells. *Journal of Power Sources*, 102(1-2), 82–96.
30. Hannan, M. A., et al. (2017). Review of energy storage systems for electric vehicle applications: Issues and challenges. *Renewable and Sustainable Energy Reviews*, 69, 771–789.
31. Jacobson, M. Z. (2009). Review of solutions to global warming, air pollution, and energy security. *Energy & Environmental Science*, 2, 148–173.
32. Rostrup-Nielsen, J. R. (2005). Hydrogen and synthesis gas by steam- and CO<sub>2</sub> reforming. *Advances in Catalysis*, 47, 65–139.

33. Fuel Cell & Hydrogen Energy Association. (2021). *Hydrogen and Fuel Cells: Opportunities for Clean Energy*.
34. Tesfaye, A., & Teshome, W. (2020). Challenges and Prospects of Renewable Energy Development in Ethiopia. *Renewable Energy Journal*, 5(2), 65–74.
35. Zhu, H., Kee, R. J., & Janardhanan, V. M. (2009). Modeling solid oxide fuel cells: An overview. *Wiley Interdisciplinary Reviews: Energy and Environment*, 1(3), 326–345.
36. Zhao, J., & Zhang, J. (2017). *Dynamic modeling and simulation of PEM fuel cells*. Springer.
37. United Nations Development Programme (UNDP). (2021). *Renewable Energy for Sustainable Development in Africa*.
38. IEA Hydrogen TCP. (2020). *Hydrogen Production and Storage: R&D Priorities and Gaps*.
39. National Renewable Energy Laboratory. (2020). *Fuel Cell Technical Manual*.
40. Bessarabov, D., et al. (2018). *PEM Electrolysis for Hydrogen Production: Principles and Applications*. CRC Press.
41. Aliyu, A. S., et al. (2018). Current status and future prospects of renewable energy in Nigeria: A review. *Renewable and Sustainable Energy Reviews*, 81, 2541–2550.
42. Jansen, J. (2010). Fuel Cell Technology Status. *Electrochemical Society Interface*, 19(2), 37–40.
43. Hirschenhofer, J. H., et al. (1998). *Fuel Cells: A Handbook* (4th edition). U.S. Department of Energy.
44. Chauhan, A., & Saini, R. P. (2014). A review on integrated renewable energy system based power generation for stand-alone applications. *Renewable and Sustainable Energy Reviews*, 38, 99–120.
45. Bossel, U. (2006). Does a Hydrogen Economy Make Sense? *Proceedings of the IEEE*, 94(10), 1826–1837.
46. International Electrotechnical Commission (IEC). (2015). *IEC 62282 - Fuel Cell Technologies Standards*.
47. Kazim, A., & Forges, F. (2002). Comparative study of fuel cells for telecommunications applications. *IEEE Communications Magazine*.
48. DOE Hydrogen and Fuel Cells Program. (2020). *Annual Merit Review and Peer Evaluation Report*.

49. Masson, S., et al. (2018). PEMFC and battery hybridization strategies for distributed generation. *Applied Energy*, 229, 572–584.
50. Khaligh, A., & Onar, O. C. (2010). *Energy Harvesting: Solar, Wind, and Ocean Energy Conversion Systems*. CRC Press.
51. Kothari, D. P., & Nagrath, I. J. (2018). *Electric Machines*. McGraw-Hill Education.
52. Spakovsky, M. R. V. (2001). Fuel Cell Systems: Design, Analysis, and Optimization. *Journal of Energy Resources Technology*, 123(1), 1–8.
53. Denholm, P., et al. (2010). *The Role of Energy Storage with Renewable Electricity Generation*. NREL Report.
54. Lasseter, R. H. (2002). MicroGrids. *IEEE Power Engineering Society Winter Meeting*.
55. Akikur, R. K., et al. (2013). Comparative study of stand-alone and hybrid renewable energy systems for rural electrification. *Renewable and Sustainable Energy Reviews*, 27, 738–752.
56. Panwar, N. L., Kaushik, S. C., & Kothari, S. (2011). Role of renewable energy sources in environmental protection: A review. *Renewable and Sustainable Energy Reviews*, 15(3), 1513–1524.
57. Ethiopian Ministry of Water, Irrigation and Energy. (2018). *National Electrification Program (NEP 2.0)*.
58. Mohamed, F. A., & Koivo, H. N. (2007). System modelling and online optimal management of microgrid using mesh adaptive direct search. *International Journal of Electrical Power & Energy Systems*, 29(5), 397–407.
59. Kong, L., et al. (2021). Solid oxide fuel cell (SOFC) system modeling and control: A review. *Renewable and Sustainable Energy Reviews*, 145, 111078.
60. EPRI. (2019). *Opportunities for Renewable Hydrogen in the Electric Sector*.
61. Blomen, L. J. M. J., & Mugerwa, M. N. (1993). *Fuel Cell Systems*. Springer.
62. Logan, B. E. (2008). *Microbial Fuel Cells*. Wiley.
63. Shaffer, B., et al. (2020). Economic analysis of fuel cell systems for off-grid telecom power. *Energy Reports*, 6, 489–498.
64. Abbaszadeh, M., et al. (2019). Optimal energy management in microgrids with renewable energy and hydrogen storage: A review. *International Journal of Hydrogen Energy*, 44(15), 7575–7590.

65. Rehman, S., et al. (2012). Feasibility study of a wind-pumped hydro storage system for off-grid renewable energy supply. *Energy Conversion and Management*, 58, 79–85.
66. Hwang, J. J., et al. (2017). Sustainable hydrogen production strategies: Challenges and opportunities. *Renewable and Sustainable Energy Reviews*, 79, 743–761.
67. International Renewable Energy Agency (IRENA). (2021). *Green Hydrogen: A Guide to Policy Making*.
68. U.S. Energy Information Administration (EIA). (2021). *International Energy Outlook*.
69. Bhatt, A., Sharma, M. P., & Saini, R. P. (2016). Feasibility and sensitivity analysis of an off-grid micro hydro–photovoltaic–biomass and biogas–diesel–battery hybrid energy system. *Renewable Energy*, 90, 30–41.
70. Zubi, G., et al. (2018). The transition towards a 100% renewable energy system: The role of storage. *Energy Procedia*, 155, 25–34.
71. Shih, Y. Y., & Jang, Y. W. (2012). Feasibility Study of Solid Oxide Fuel Cell in Telecom Backup Applications. *IEEE Transactions on Industry Applications*.
72. Romm, J. (2004). *The Hype About Hydrogen*. Island Press.
73. Yuan, X. Z., et al. (2007). *PEM Fuel Cell Failure Modes and Mitigation Strategies*. CRC Press.
74. Walker, G., et al. (2008). *Fuel Cell Systems*. McGraw-Hill.
75. Energy Commission of Ethiopia. (2020). *Ethiopia Energy Balance Report*.
76. Khatiwada, D., et al. (2021). Role of Renewable Hydrogen in Decarbonization Strategies: A Review. *Energy Policy*, 150, 112147.
77. Green, M. A. (2012). *Third Generation Photovoltaics: Advanced Solar Energy Conversion*. Springer.
78. Patel, M. R. (2005). *Wind and Solar Power Systems: Design, Analysis, and Operation*. CRC Press.
79. Wood, D. L., Li, J., & Daniel, C. (2015). Prospects for reducing the processing cost of lithium ion batteries. *Journal of Power Sources*, 275, 234–242.
80. Jacobson, M. Z., & Delucchi, M. A. (2011). Providing all global energy with wind, water, and solar power. *Energy Policy*, 39(3), 1154–1169.
81. Global Hydrogen Council. (2021). *Hydrogen Insights Report*.
82. World Bank Group. (2020). *Ethiopia Electrification Program Review*.

83. IEEE, IEEE Recommended Practice for the Design of Reliable Industrial and Commercial Power Systems (IEEE Gold Book, Std 493), IEEE Std 493™-2007 (Revision of IEEE Std 493-1997), 2007.
84. International Telecommunication Union (ITU), Green Power for Mobile: Charging Choices, ITU-T Technical Report, Geneva, 2012.
85. International Energy Agency (IEA), Advanced Fuel Cells Technology Collaboration Programme (TCP): Status and Outlook for Solid Oxide Fuel Cell Systems, IEA, Paris, 2024.
86. S. C. Singhal and K. Kendall, High-Temperature Solid Oxide Fuel Cells: Fundamentals, Design and Applications, Elsevier, 2003.
87. A Comprehensive Review of Thermal Management in Solid Oxide Fuel Cells: Focus on Burners, Heat Exchangers, and Strategies — Energies, 2024.
88. Sammes, N. M., et al. (2000). *Fuel Cell Technology Handbook*. CRC Press.

## Appendices

### A. Initial Capital Cost of Existing System collected from Ethio Telecom Microwave Data Center

Items	Cost
Initial Equipment Cost	47,064,913.84
Installation and commissioning with transportation	2285615.92
Fuel tank	324,484.64
Fuel tank installation	117899.44
Power Electronics (Inverters)	1,364,100
Grid Connection Modifications	818,460
<b>Total</b>	<b>51,975,473.84</b>

*For the initial investment, all costs covering equipment, installation, commissioning, transportation, fuel tank supply and installation, power electronics, and grid connection modifications were collected and converted from Ethiopian Birr to US Dollars using the August 2018 exchange rate of 1 USD = 27.28 ETB, providing a consistent and clear basis for cost comparison.*

### B. Fuel Consumption of Generators

Generator 1			
Asset number	Asset Group	Description	Scheduled date
G-111051(1)	GENR.00001	2600Liter	8/4/2023 9:10
G-111051(1)	GENR.00001	2800Liter	8/8/2023 8:37
G-111051(1)	GENR.00001	2200Liter	8/29/2023 10:16
G-111051(1)	GENR.00001	2600Liter	8/31/2023 9:14
G-111051(1)	GENR.00001	2200Liter	9/19/2023 9:14
G-111051(1)	GENR.00001	2300Liter	10/9/2023 9:11
G-111051(1)	GENR.00001	2400Liter	10/19/2023 9:09
G-111051(1)	GENR.00001	2800Liter	11/2/2023 13:46
G-111051(1)	GENR.00001	2380Liter	11/6/2023 9:22
G-111051(1)	GENR.00001	2500Liter	11/8/2023 13:17
G-111051(1)	GENR.00001	2800Liter	11/28/2023 9:57
G-111051(1)	GENR.00001	2379Liter	12/4/2023 10:39

TECHNICAL AND ECONOMIC FEASIBILITIES OF FUEL CELL BASED ALTERNATIVE POWER SUPPLY  
FOR ETHIO TELECOM HUBSITES

<b>Fuel consumption of Generator 1, in 2023</b>		<b>29954 Liters</b>	
<b>Generetor 2</b>			
<b>Asset number</b>	<b>Asset Group</b>	<b>Description</b>	<b>Scheduled date</b>
G-111051(2)	GENR.00001	2200Liter	3/7/2023 9:31
G-111051(2)	GENR.00001	2400Liter	3/9/2023 7:33
G-111051(2)	GENR.00001	2400Liter	3/13/2023 10:39
G-111051(2)	GENR.00001	2570Liter	4/4/2023 9:09
G-111051(2)	GENR.00001	2400Liter	4/17/2023 10:41
G-111051(2)	GENR.00001	2200Liter	5/16/2023 9:43
G-111051(2)	GENR.00001	2400Liter	5/30/2023 11:11
G-111051(2)	GENR.00001	2600Liter	6/29/2023 10:21
G-111051(2)	GENR.00001	2400liter	7/21/2023 11:27
G-111051(2)	G-111051(2)	2400liter	8/1/2023 9:32
G-111051(2)	G-111051(2)	2400Liter	8/8/2023 8:42
G-111051(2)	G-111051(2)	2600Liter	8/29/2023 10:19
G-111051(2)	G-111051(2)	2400Liter	8/31/2023 9:21
G-111051(2)	G-111051(2)	2600Liter	9/19/2023 9:18
G-111051(2)	G-111051(2)	2600Liter	10/9/2023 9:15
G-111051(2)	G-111051(2)	2600Liter	10/19/2023 9:12
G-111051(2)	G-111051(2)	2300Liter	11/2/2023 13:48
G-111051(2)	G-111051(2)	2200Liter	11/6/2023 9:31
G-111051(2)	G-111051(2)	2400Liter	11/8/2023 13:19
G-111051(2)	G-111051(2)	2600Liter	11/28/2023 10:04
G-111051(2)	G-111051(2)	2400liter	12/4/2023 10:42
<b>Fuel consumption of Generator 2, in 2023</b>		<b>51070</b>	

*In 2023, data collected from the Ethio Telecom microwave data center shows that the two 1500 kVA diesel generators used a total of 81,084 liters of fuel. With a unit price of 69.96 ETB per liter, the total fuel cost reached 5,670,059.52 ETB (about 105,000 USD), reflecting the high cost of running diesel generators over a year.*

### C. Maintenance cost of Generator

Type of maintenance	Items	Items price	maintenance cost for Gen in one year.	maintenance cost for two Gen in one year.
SAE -40	200 x3	957*	574,000*	1,148,000*
Feltro	12 x3	17,500*	630,000*	1,260,000*
Air cleaner	1 x1	55,000*	55,000*	110,000*
Starter Motor	1 x 1	115,000*	115,000*	230,000*
Total =				2,748,000*

*Based on record data from Microwave data center, in 2023, the total maintenance cost for the two 1500 kVA diesel generators at the microwave data center was 2,748,000 ETB (about 50,000 USD).*

\*All figures are in ETB.