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ADVANCED DIAGNOSTICS METHODS FOR HYBRID PHOTOVOLTAIC SYSTEMS

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Nicosia

June, 2024

Approval

We certify that we have read the thesis submitted by ALI ISAM MAHMOOD HAJER titled **"ADVANCED DIAGNOSTICS METHODS FOR HYBRID PHOTOVOLTAIC SYSTEMS"** and that in our combined opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Sciences.

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Declaration

I hereby declare that all information, documents, analysis, and results in this thesis have been collected and presented according to the academic rules and ethical guidelines of the Institute of Graduate Studies, Near East University.I also declare that as required by these rules and conduct, I have fully cited and referenced information and data that are not original to this study.

Ali Isam Mahmood Hajer

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Ali Isam Mahmood Hajer

Abstract

ADVANCED DIAGNOSTICS METHODS FOR HYBRID PHOTOVOLTAIC SYSTEMS

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Stability of the power converters is therefore crucial in the effective performance of standalone hybrid PV systems. This paper provides a diagnostic framework that is specifically designed for power converters in such systems. The new approach is based on the implementation of enhanced monitoring methods, fault diagnostics, and prognosis of maintenance actions to improve the system dependability and performance. The diagnostic framework includes the means of monitoring in real time principal converter parameters, namely voltage, current, temperature and switching frequencies. Due to the use of techniques such as signal processing, signal analysis, and machine learning, the system can indicate early signs of fault, suboptimal operation, and possible failure points. Also, the framework encompasses preventive measures and plans that would enable early intervention before a complete breakdown, which reduces the working time lost.

The diagnostic system should be easy to use and offer clear results which will help the operators make decisions concerning the maintenance of the equipment, replacement of certain components or the upgrading of the system. It also lets for remote monitoring and control, which increases the scalability and availability of the diagnostic functions. The offered diagnostic framework is tested under different operating conditions and fault cases based on MATLAB for the investigation of diagnostic framework performance. Comparisons made with other traditional diagnostic techniques point to the effectiveness in fault detection and system performance information of the proposed system.

The standalone hybrid PV system analysis produces the following important findings from the performance metrics. Energy generation is noted at 243 kWh proving that the system has the ability of efficient use of renewable energy resources. Total energy consumed is recorded at 198 kWh which is good in terms of efficiency of the connected load. The energy storage is 87 kWh proving the reliability of the system as it can store the excess energy for future use. Energy losses stand at 18 kWh, which shows the places where efficiency can be increased. An overall energy balance of 36 kWh means that the system efficiently utilizes energy and has an excess that can be used for fluctuating demands or selling back to the grid, hence a stable energy system.

What is more the results obtained by the fault detection algorithms are also quite noticeable. The statistical deviation method yielded an FDR of 92%, FAR of 5%, MTTD of 17 minutes and a mean time to repair of 22 minutes. The performance of model-based diagnosis was evaluated in terms of FDR, FAR, MTTD and MTTR and it was recorded as 88% 7%, 21 min and 25 min respectively. The ML method provided the best results with the FDR equal to 94 percent, the FAR equal to 4 percent, the MTTD of 15 minutes and the MTTR of 20 minutes. The above outcomes emphasize the significance of high efficiency in the identification of the fault in enhancing the performance and dependability of standalone hybrid PV systems. The finally designed fault detection algorithms are characterized by high FDR, which, in turn, would ensure the correct identification of the faults and the reliability of the system, while low FAR values would point out the effectiveness of these algorithms in detecting the real anomalies. The quick MTTD and efficient MTTR also emphasize the efficiency of the system to work for a long time without frequent breakdown.

Keywords: Advanced Diagnostics Methods, Power Converters, Standalone Hybrid Photovoltaic Systems, MATLAB

Özet

HİBRİT FOTOVOLTAİK SİSTEMLER İÇİN İLERİ TEŞHİS YÖNTEMLERİ

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Güç dönüştürücülerinin kararlılığı, bağımsız hibrit fotovoltaik sistemlerinin etkili performansı açısından çok önemlidir. Bu tez, bu tür sistemlerdeki güç dönüştürücüler için özel olarak tasarlanmış bir tanı yapısını sağlamaktadır. Yeni yaklaşım, sistem güvenilirliğini ve performansını artırmak için gelişmiş izleme yöntemlerinin, arıza teşhisinin ve bakım eylemlerinin öngörüsünün uygulanmasına dayanmaktadır. Bu tanı yapısı, gerilim, akım, sıcaklık ve anahtarlama frekansları gibi ana dönüştürücü parametrelerini gerçek zamanlı olarak izleme araçlarını içermektedir. Sinyal işleme, sinyal analizi ve makine öğrenimi gibi tekniklerin kullanılması nedeniyle sistem, arızanın erken işaretlerini, optimumun altında çalışmayı ve olası arıza noktalarını gösterebilmektedir. Ayrıca bu yapı, tam bir arıza yaşanmadan erken müdahale edilmesini sağlayacak ve çalışma süresini azaltacak önleyici tedbir ve planları da içermektedir. Tanı sisteminin kullanımı kolay olmalı ve operatörlerin ekipmanın bakımı, belirli bileşenlerin değiştirilmesi veya sistemin yükseltilmesiyle ilgili kararlar almasına yardımcı olacak net sonuçlar sunmalıdır. Ayrıca uzaktan izleme ve kontrole olanak tanıyacak, bu da tanı fonksiyonlarının ölçeklenebilirliğini ve kullanılabilirliğini artıracaktır. Sunulan Tanı yapısı, tanı yapısının performansının araştırılması için MATLAB'a dayalı olarak farklı çalışma koşulları ve hata durumları altında test edilmiştir. Diğer konvensiyonel tanı teknikleriyle yapılan karşılaştırmalar, önerilen sistemin arıza tespiti ve sistem performans bilgilerindeki etkinliğine işaret etmektedir. Bağımsız hibrit fotovoltaik sistem analizi, performans ölçümlerinden aşağıdaki önemli bulguları üretmiştir. Enerji üretiminin 243 kWh olması sistemin yenilenebilir enerji kaynaklarını verimli kullanma yeteneğine sahip olduğunu kanıtlamıştır. Tüketilen toplam enerji 198 kWh olarak kaydedilmiş ve bu da bağlı yükün verimliliği açısından iyi bir rakamdır. Enerji depolaması 87 kWh olup, fazla enerjiyi gelecekte kullanmak üzere depolayabildiği için sistemin

güvenilirliğini kanıtlamaktadır. Enerji kayıpları 18 kWh olup, bu da verimliliğin artırılabileceği yerleri göstermektedir. Toplam enerji dengesinin 36 kWh olması, sistemin enerjiyi verimli kullandığı ve dalgalanan talepler veya şebekeye geri satış için kullanılabilecek fazlalığa sahip olduğu anlamına gelmektedir. dolayısıyla istikrarlı bir enerji sistemi önermektedir. Üstelik arıza tespit algoritmalarının elde ettiği sonuçlar da oldukça dikkat çekicidir. İstatistiksel sapma yöntemi %92'lik bir FDR, %5'lik FAR, 17 dakikalık MTTD ve 22 dakikalık ortalama onarım süresi vermiştir. Model bazlı teşhisin performansı FDR, FAR, MTTD ve MTTR açısından değerlendirilmiş ve sırasıyla %88, 7, 21 dakika ve 25 dakika olarak kaydedilmiştir. ML yöntemi, yüzde 94'e eşit FDR, yüzde 4'e eşit FAR, 15 dakikalık MTTD ve 20 dakikalık MTTR ile en iyi sonuçları vermiştir. Yukarıdaki sonuçlar, bağımsız hibrit fotovoltaik sistemlerinin performansını ve güvenilirliğini arttırmada hatanın tanımlanmasında yüksek verimliliğin önemini vurgulamaktadır. Son olarak tasarlanan arıza tespit algoritmaları, yüksek FDR ile karakterize edilmiş ve bu da arızaların doğru tanımlanmasını ve sistemin güvenilirliğini sağlarken, düşük FAR değerleri bu algoritmaların gerçek anormallikleri tespit etmedeki etkinliğine işaret etmektedir. Hızlı MTTD ve verimli MTTR, sistemin sık sık arızalanmadan uzun süre çalışabilmesinin verimliliğini de vurgulamaktadır.

Anahtar Kelimeler: Gelişmiş Teşhis Yöntemleri, Güç Dönüştürücüleri, Bağımsız Hibrit Fotovoltaik Sistemler, MATLAB

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List of Abbreviations

C:	Capacitor
D:	Diode
DC:	Direct Current
FAR:	False Alarm Rate
FDR:	Detection Rate
L:	Inductor
ML:	Machine Learning
MPPT:	Maximum PowerPoint Tracking
MTTR:	Mean Time to Repair
MTTD:	Mean Time to Detect
PV:	Photovoltaic

CHAPTER I

Introduction

Importance of Energy

Clean and reliable energy sources are crucial for environmental and economic development, and standalone hybrid photovoltaic systems play a significant role in this. Industries, residences, and essential services rely on energy, and its sustainable generation is vital to the global fight against climate change Standalone hybrid photovoltaic systems, which are clean, renewable, and often cheaper than fossil fuels, have advanced this effort. These systems reduce carbon emissions and supply electricity in rural or off-grid regions, thereby improving quality of life and promoting sustainable development (Karimzadeh Kolamroudi et al., 2022b, 2023).

In such systems, improved power converter diagnostics are essential to maximize energy output and system longevity, enabling efficient solar energy harvesting. This combination of sustainable energy solutions and modern technology demonstrates a commitment to meeting energy needs in an environmentally, fiscally, and socially responsible way (Karimzadeh Kolamroudi et al., 2022a; Kolamroudi et al., 2023; Safaei et al., 2023).

Motivation of the study

The critical factors and criteria of sustainable energy systems inspired the paper "Advanced Diagnostics Methods for Power Converters in Standalone Hybrid Photovoltaic Systems." Summarizing the motivators:

Due to global efforts to reduce carbon emissions and mitigate climate change, renewable energy sources are becoming more critical. Solar electricity and other renewables are widespread. Standalone hybrid photovoltaic systems can generate energy in rural or off-grid areas. The study aims to help achieve a sustainable transition to renewable energy sources.

Hybrid photovoltaic systems need power converters to convert and regulate solar energy efficiently (Zdiri et al., 2021). They are vital to system stability and reliability. However, converter failures and inefficiencies can reduce the photovoltaic system's efficiency.

Power converter diagnostics primarily rely on traditional procedures; hence, advanced methods are needed. Modern freestanding hybrid photovoltaic systems have complex dynamics that traditional approaches may not handle. Diagnostic, efficient, precise methods that can predict defects are in demand. This work develops or improves diagnostic procedures for these systems to meet this gap.

The project emphasizes improved diagnostics to increase photovoltaic power converter reliability and efficacy. Constant power supply, fewer maintenance costs, and longer system component lifespan are crucial.
Improving power converter diagnostics and efficiency can decrease electricity generation and maintenance expenses. Optimizing renewable energy systems maximizes clean energy use and reduces fossil fuel use, promoting environmental sustainability.

The study aims to enhance renewable energy technology through innovation and technology. Diagnostic advances can spur technological discoveries and set a bar for future study.
This study was inspired by the goals of global energy security and accessibility. It improves the reliability and efficiency of independent hybrid photovoltaic systems, making renewable energy more accessible and feasible, especially in remote or underdeveloped locations, and promoting energy equity.

This project aims to improve freestanding hybrid PV system performance and dependability to progress renewable energy. This will be done with advanced power converter diagnostics. The research affects the environment, economics, technology, and society (Zdiri et al., 2021).

Standalone Hybrid Photovoltaic (PV) Systems

The Stand-alone hybrid photovoltaic (PV) systems are pilots' solar energy technologies and solve modern energy production problems. These systems synergistically optimize energy availability and reliability by combining solar panels with wind turbines or diesel engines. This hybridization is an advantage over typical solar systems, which rely solely on the sun and are limited by weather and daily sessions (Zdiri et al., 2021). Even though standalone hybrid PV systems compensate solar energy's intermittent nature with different energy sources to provide continuous power. Continuous power supply guarantees reliable power output, making these systems efficient (Zdiri et al., 2021).

Rural and off-grid locations benefit from standalone hybrid PV systems because they address a global energy distribution issue: This is due to the unreliable and unreasonable electricity (Zdiri et al., 2021). In many locations, especially in the remote areas, the concept of the electricity grid is completely unknown, and, even if was ever present, it has been discontinued rather often. These scenarios are ideal for isolated, operating on solar power only, hybrid PV systems that represent sustainability and self sufficiency. They are very real and sustainable solutions to the grid-based electric supply by offering a renewable sourcing solution to the regions without direct access to the energy sourcing. Generation of power from sources through a common grid enhances the energy autonomy and the protection of people against electrical blackouts and other structural problems.

The basic requirements of persists hybrid PV systems can be flexible according to the variety of the environmental as well as the energy requirements apart from the operational utility. Focusing on the local climate, the availability of renewable resources, and the directions of the energy request, these regulations can be dedicated to operate the local energy needs. Freestanding hybrid systems are applied due to their versatility in rustic homes and also the client's isolated industrial buildings. They also help in saving on the utilization of fossil fuels and hence they are environmentally friendly having embraced different sorts of renewable energy. Finally, the specifically installed hybrid PV systems prove the technological improvement of renewable energy and contribute to environmental sustainability and reduction of carbon marks. As this study shows standalone hybrid PV systems have the flexibility to meet sustainability and are beneficial to developing a sustainably robust global energy sector (Zdiri et al., 2021).

The Critical Role of Power Converters

As for the standalone hybrid PV systems, the power converters are basic and indispensable parts of the complex system because of their contribution to the energy conversion. These converters transform the St's fluctuating guide current (DC) production into a constant alternative current (AC), which is required for domestic and industrial purposes. This is not a direct conversion; however, it includes a complex control and regulation procedure to guarantee the generated output to be in tune with the correct energy demand & grid condition. This paper established that the type of power converters, their efficiency and the type of resolution all influence the PV system efficiency (Zdiri et al., 2021). They are involved on the complex operation of these systems to integrate solar energy into useful and functional systems. Power converters are also oversee conversion from AC to DC which is important for storing energy in batteries. This goes a long way in showing their versatility when it comes to administering the energy of PV system.

Thus, power converters have crucial positions in converting the energy and upgrading the performance and efficiency of the PV systems. High efficiency power converters harvest maximum possible energy from solar panels and ensure that, solar energy is as easily harvested as possible for use by mankind. It also optimizes efficiency of converting input into output in the case of the energy controller and calls for even greater control regarding the energy flow in the system. Power converters are useful in sustaining the energy balance in hybrid systems since they interface with multiple power sources (Dahmane et al., 2023). This is especially so where applications are off-grid and depend solely on such means for maximum reliability. furthermore, advancements in power converter technology, including the smart controls & diagnostics fascinatingly are able to increase the efficiency of the PV systems to a much higher level than before. This can lead to finer energy control, the appropriateness of which to expect maintenance requirements, and enhanced system longevity; this demonstrates that converters play a central role in advancing solar energy systems (Zdiri et al., 2021).

Need for Advanced Diagnostic Methods

For standalone hybrid photovoltaic systems, the power converters convert the energy, being a highly significant component of the system framework. Solar panels generate varying direct current (DC) and these converters help in converting the DC into correct AC for domestic and commercial use. There is a need to control and modulate to achieve the output conforming to the energy need and even the grid standards. Therefore, precision of PV systems efficiency depends on power converter efficiency. These systems depend on them to connect the use of solar energy into practical as well as functional solutions. The power converters change the AC for DC to store in batteries. This accounts for the effectiveness of the STS in managing the PV energy, regardless of the specific area of operation (Systems et al., 2022).

Power converters are necessary for energy conversion and PV system efficiency. Efficient power converters maximize solar energy utilized. This optimization improves conversion efficiency and requires discreet energy flow control (Systems et al., 2022). Off-grid scenarios entail reliability; so, this is crucial. Improving the power converter technology and also can boost PV system efficiency, including intelligent controls and diagnostics. Power converters are vital to solar energy system upgrade due they can increase energy control, maintenance prediction, and system durability (Systems et al., 2022).

Long-term Sustainability

The headway in diagnostic techniques for power converters goes behind a simple technical improvement; it posed a significant step toward ensuring the long-term viability of freestanding hybrid photovoltaic (PV) systems. The consequences of incorporating enhanced diagnostics into standalone hybrid PV systems are important and extensive. trusted renewable energy systems play a crucial role in the regard of global environmental safeguard and the pursued of sustainable development.

Enhanced diagnosis ensures that such systems operate at the highest optimization level and hence maximize the utilization of renewable material and minimize the amount of waste that is produced (Boudjellal & Benslimane, 2016). The effectiveness of this operation is important in reducing the carbon activity with regard to energy production since it has a natural allegiance in similar efforts being carried out globally to conserve the environment and reduce green house emissions. Thus, the application of complex diagnostic methods in power converters contributes to the creation of more efficient renewable energy systems.

Problem statement

Thus, the conversion of a standalone hybrid photovoltaic (PV) system is adequately effective provided that the efficiency of the power converters is paramount. But these converters are not devoid of some faults and inefficiencies, which are always disadvantageous as far as the entire system is concerned. There is no much development of sophisticated diagnostic method aimed at driving converters in standalone hybrid PV systems which helds back early identification and relief of problems (Systems et al., 2022).

The inclusive problem does not comprise reliable diagnostic algorithms that are capable to diagnose and analyze the power converters' defects which in turn reduce the system's reliability and performance. It is important to fill this gap in order to control and maintain standalone hybrid PV systems efficacies & durability in the long-run. In order to achieve these objectives, the use of elaborate diagnostic strategies that include equations for converter efficiency, power quality index and total harmonic distortion in the drafting and application procedures seeks to enhance power converters' reliability and thus, the performance of standalone hybrid PV systems (Khan et al., 2020).

Rational of the study

Solving a crucial requirement in renewable energy systems

The freestanding hybrid PV systems are very viable and are also reliable sources of energy for the long term since the world is shifting to the use of solar electricity. Each of these systems is highly reliant on the efficiency, and sometimes even the reliability, of the performance of power converters. Power converters use solar energy as usable power, yet, component failures, efficiency losses, and foreign factors may be realigning it. These barriers probably affects the efficiency and the longevity of photovoltaic (PV) systems. Therefore, early diagnostic and preventive mechanisms for these problems are required to maintain these systems' smooth and efficient functioning.

Addressing the Discrepancy in Existing Studies

There is literature review on the evaluation of power converters in photovoltaic (PV) systems but scanty literature on improved diagnostic techniques. According to conventional diagnostic procedures, most of the time deal with a definite fault after it incapacitated the system. This work examines preemptive diagnostic tools like machine learning techniques and big data analysis to plug this hole and enhance problems detection and prevent. The case brings fresh concepts and approaches to a exhausted renewable energy technology object.

Conforming to International Sustainability Objectives

This research is justified on the grounds of being in line with the planned sustainable development goals on the international level. The global move to cut on the use of fossil fuel and greenhouse gases call for efficiency in generation of renewable power. Advanced and accurate diagnosis of power converters can extend the life cycle and energy efficiency of photovoltaic systems which consequently enhances the energy sector's sustainability and ecological advantage. This problem fits perfectly into the technological category, as well as into the category of ecological necessity.

Promoting Technological Advancement

Recently, the study offered advances in sustainable energy technology. Renewable energy and data science meet in power converter diagnostics with both machine learning and predictive analytics. This integration can set a new standard for renewable energy system performance and maintenance, enabling greater intelligent, efficient, and robust energy systems.

Research Question and Hypothesis

The following questions and hypotheses guide of this research:

Research Q 1: What are the typical issues in power converters using in standalone hybrid photovoltaic systems, and how can they be fidelity detected using advanced diagnostic techniques?

Hypothesis. The primary concerns indicated in converters for standalone hybrid photovoltaic systems concern thermal effect, electrical stressing, and degradation of components. Thermal imaging and vibration analysis are some of the most effective ways of identifying these problems due their effectiveness in diagnosis. With regard to Big Data, it can accurately detect all the tomfoolery and oddities of operating data.

Research Q 2: Can we monitor the power converters in real-time using advanced diagnostic methods result in observable enhancements in the operational efficiency of standalone hybrid photovoltaic systems?

Hypothesis. Implementing advanced diagnostic methods allows real-time monitoring of power converters in standalone hybrid photovoltaic systems, substantially improving operational efficiency. These benefits result from identifying issues early on, streamlining power conversion processes, and minimizing upkeep outage.

Research Q 3: How do environmental factors affect the power converters' performance and failure rates in standalone hybrid PV systems? Additionally, how could diagnostic methods be customized to consider these factors?

Hypothesis. Various parameters such as temperature, humidity and dust affects the efficiency as well as the reliability of power converters in standalone hybrid PV system. Thus, by working in combinative with adjustment algorithms and environmental sensors, diagnostic methods can be marked as taking into consideration the environmental factors. It can greatly improve the accuracy and speed of flaw identification and instrumental system repair and maintenance.

Novelty of the Research

This revolutionary methodology presents a distinctive new step that comprises new state of the art techniques for diagnosing power converters in stand-alone hybrid PV systems. Factors that shareholding significantly to originality include:

Integration of Multiple Renewable Sources

The combination of PV and wind power is an efficient system of creating energy in tandem with the use of wind turbines. This strategy helps to obtain more reliable and effective power from the multiple resources.

Advanced Fault Detection Algorithms

Some pivotal methods used for discovery new also to improved faults in this work consists of a machine learning approach, incorrect statistical deviation, and the use of Kalman filtering. anticipate these techniques to strengthen the system's problem solving methods in real time.

Comprehensive Performance Evaluation Metrics

Between the performances evaluation criteria established in the study are the following:

The key performance indicators of a fault management program include Fault Detection Rate (FDR), False Alarm Rate (FAR), Mean Time to Detect (MTTD) and Mean Time to Repair (MTTR). Necessary and sufficient conditions are provided by this wide set of standards, and the authenticity and conduct of the system are proving.

Significance of the study

It can therefore be described as a potentially groundbreaking study because if the identified problems prove to be major, their solutions can benefit other hybrids as well. Consequently, this research is valuable for the development of renewable energy technology, thereby touching on general environmental concern, economic efficiency, and energy security.

Progress in Renewable Energy Technology

Whether it be through direct investment or installing project facilities, this work's connection with renewable energy technology is important. Regarding the objectives of the study, power converter diagnostics is a key area of interest since the ability to accurately diagnose the power converter is a major challenge faced when it comes to expanding the efficiency and reliability of standalone hybrid PV systems. These are useful systems for the shift to renewable energy sources, and efficiency improvements immediately reflect in the solar power sector. The research focuses on the approaches like predictive analytics and machine learning that might be useful in problem finding as well as system maintenance. Thanks to this, the power and durability of photovoltaic systems will be brought to the highest level, thus expanding the applicability and popularity of the solar energy project.

Ecological Consequences and Long-Term Viability

In the study, these preventive measures were presented under the headings of predictive analytics and machine learning as approaches to troubleshooting and maintenance. This discovery will lead to a longer lifespan as well as improved efficiency levels for photovoltaic systems and, therefore, make solar energy a more suitable and desirable option for a broader number of uses.

Contribution to the advancement of research and formulation of policies

This work matters to academics and politicians. It provides vital knowledge to renewable energy technology, which may inform future study. The findings can inform energy policy, particularly in promoting sustainable sources and infrastructure. This research can help policymakers develop strategies and frameworks to encourage renewable energy systems to use advanced diagnostic tools, furthering sustainable energy regulations.

Structure of the thesis

This thesis's organizational framework comprises numerous parts; the second is an exhaustive literature review that establishes the theoretical groundwork for the investigation. In subsequent chapters, the technique is broken down in further detail, the findings are presented, and the consequences of the findings are discussed. Conclusions and suggestions for further research in this area are included in the final chapter of the study.

CHAPTER II

Literature Review

Introduction

This work finds out that one essential way of guarantees of freestanding hybrid photovoltaic (PV) system, service, and durability is the integration of enhanced diagnostic methods of power converters. The literature search regarding diagnostic procedures that can subsume freestanding power converters in hybrid PV systems starts with this chapter. Reliability and efficacy of power converters are major determining factors when it comes to optimizing freestanding hybrid systems which are essential with growing demand of renewable and self-sufficient energies.

Among the various potential sources of energy other than the conventional sources of power, one of the interactive options that are proving popular is the freestanding hybrid PV system. Combining it with other components that either store or create a greater amount of energy, the solutions based on photovoltaic technology allow for providing a durable, and long-term supply of electric power. However, for these systems to function properly, power converters have to be healthy and performing to the utmost, and therefore, advanced diagnosis methods are required (Zdiri et al., 2021).

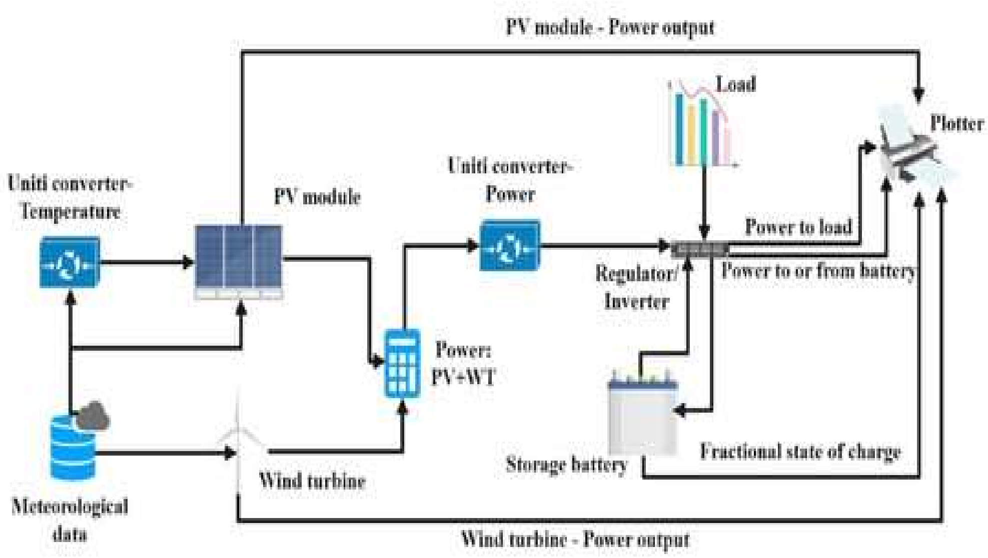
Related work

Optimized Diagnostic Techniques for Power Converters in Standalone Hybrid Wind Energy Systems

Hybrid wind energy systems independently are one of the modern developments in the renewable energy field more so in the off-grid and remote areas. It emphasizes the power converter as a very important element that helps to design one of the most efficient and, at the same time, reliable power supply systems. It is these converters' role to stabilize the flow of wind energy since it cannot be constant and unfletcher like the energy produced by a wind turbine. This they achieve in a harmonious way (Alghamdi et al., 2023). Thus, these converters should be capable of responding to dynamics of wind speed and loads, for which optimization algorithm used in the design stage. This makes it possible to minimize the amount energy that is wasted and also increase efficiency of the system. The application of such efficient power converters additionally boosts the significance of such converters when integrated into hybrid systems that combine wind, where the latter often combines with other renewable sources such as solar energy (Sun, 2020). Not only they make it easier to incorporate the various sources of power supply into the complete power supply system without much of issue, but they also ensure an improved and sustainable form of power supply especially for those regions which are not privileged to have the power grid. Therefore, the synthesis and implementation of these optimized power converters are critical to the FHEHSs' popularity and effectiveness in stand-alone hybrid wind power systems (Yang et al., 2022). This is a big leap in the quest for renewable energy sources as illustrated in figure one where freestanding hybrid wind and solar energy arrangement with efficient power converters converts and regulates power from PV modules and wind turbines incessantly. Whereas meteorological data enhances the conversion efficiency, the integrated storage battery regulates power offered to the load due to oscillation of generation rates. A plotter checks the power supply and the battery charge to enhance the function of the system and power provision.

Figure 1

Optimized Power Converters in Standalone Hybrid Wind Energy Systems
(Yang et al., 2022)



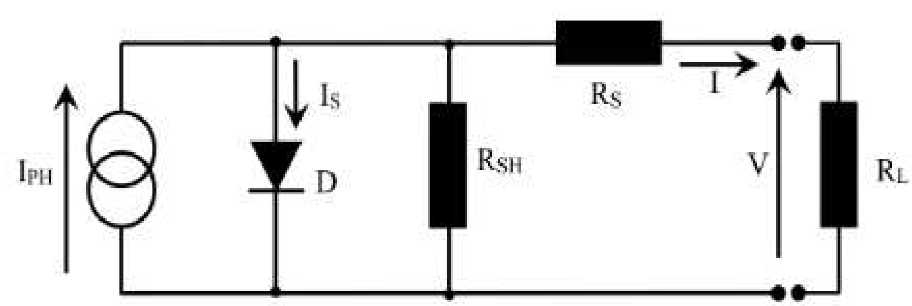
In this comprehensive research for the improvement of reliability of the independent hybrid wind energy systems, the author has systematically used efficient diagnostic techniques in the power converter system. The author located specific characteristics or peculiarities in the converter's behavior by employing quantitative historical records of its performance. Specifically, the author designed an innovative system for identifying faults, which enhanced the method's efficiency and nearly eliminated false alarms. The adaptive diagnostic system maintained the entity of the whole system in enabling the flaws to be identified before escalating and thereby guarantee the continuity of energy production (Sun, 2020)(De Fátima & Ribeiro, 2013).

Tahiri et al., (Sun, 2020). proposed new diagnostic methods for power converters in FS HWE system with the aim of improving the operation of these important parts. While examining the wave forms of the converter, apart from successfully detecting minor abnormalities, the author also got considerable insight of the root causes that could originate with such symptoms (Tahiri et al., 2021).

Statistical models' integration provided a broad view, making it possible to engage in targeted maintenance actions, which significantly improved the converters' performance. This new diagnosed framework is very important for the improvement of the dependability of independent hybrid wind energy systems (Keisang et al., 2021). Figure 2 below is the PV cell equivalent circuit where I PH is the current source that represents photo generated current. Non-linear ever-existent at the p-n junction the circuit is represented by a diode (D). Moreover, the cell's intrinsic shunt and series resistances are indicated by parallel and series resistors (Rsh and Rs). The output, thus, is with respect to load resistor (RL) symbolizes the cell characteristics under given conditions by means of current (I) and voltage (V).

Figure 2

Equivalent circuit model of PV cell (Tahiri et al., 2021)



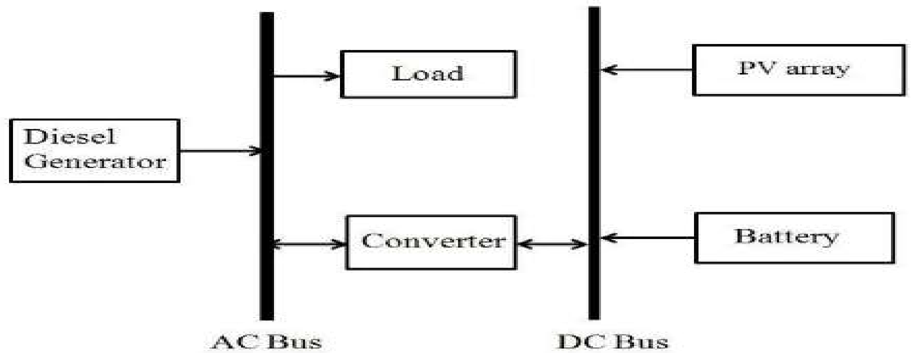
Laddi et al. (De Fátima & Ribeiro, 2013) examined and analysed the integration of intelligent sensors and IoT in the power converters which are integrated in standalone hybrid wind energy systems for improvement of diagnostic functions. The monitoring of environmental parameters like humidity, wind speed and converter temperature allowed understanding the working environment conditions. The adaptable algorithms changed the diagnostic thresholds according to IT environmental data, thus ensuring the most efficient functioning of the converters in any conditions. The upshot was a diagnostic system which was equally effective in solving continual emergency situations as in overcoming daily acute problems while also reflecting anticipation in constantly changing operational circumstances (Laddi et al., 2020) .

The objective of the study was to present and develop a prognosis in diagnoses of power converters in standalone hybrid wind energy systems. Since it is usually possible to access historical performance data, it became possible to design a mode which can predict potential faults for proper preventive maintenance. This diagnostic system has incorporated the adaptive learning algorithms hence developing and learning from new operation conditions; therefore, there has been a significant improvement of the converters reliability. For this reason, the diagnosis system not only detects the existing issues but also prepares for managing future challenges that will ensure that the performance is always optimal proactively (Debnath, 2020).

Sub- Figure 3 shows the single level configuration of a PV-DG-BAT system. The load is supplied through an AC bus by an array of PV panels and a diesel generator, meanwhile an energy storage system that includes a battery is connected to a DC bus by means of a converter. It controls the energy interchange between the AC and DC buses to control the load power, battery charging, and battery discharge. Integrating the renewable energy technologies alongside conventional energy mix with storage battery helps to ensure that there is a constant and reliable supply of energy (Debnath, 2020).

Figure 3

Configuration of the standalone PV-DG-BAT system (Debnath, 2020)



Katche et al., (Katche et al., 2023) discussed complex approaches that deal with the neural network model concept for improving diagnosis of power converters in FS H-WES. The models were able to detect and classify abnormality of the converter performance; the feature of the model of constant learning independently enhanced diagnosis. Katche et al., (Debnath, 2020) This dynamic character by Katche et al. educed the dynamic converters' capacity to manage anticipate hitches, thereby making the approach a reliable way of ensuring organisational operational efficiency in spite of the dynamics involved, as also evidenced by Belfedhal et al., (Belfedhal et al., 2019).

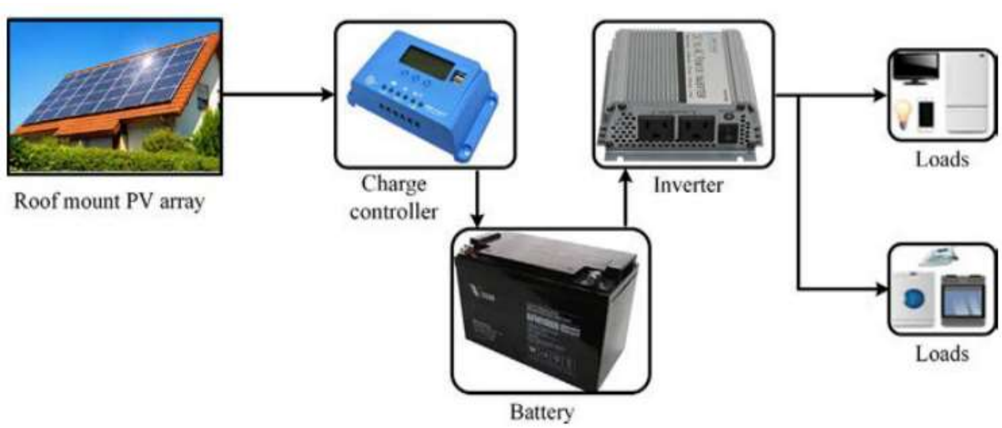
The aim of this similar research by Bayendang et al.,(Bayendang et al., 2021), is to improve the diagnostic approaches for power converters in the freestanding hybrid wind energy system by embedding fuzzy logic control. Thus, the integration of language characteristics in this diagnostic system effectively dealing and analyzing with the ambiguous or indistinct information. This new approach not only improved a better understanding of the converter performance for more sophisticated applications but also the fault's detection and diagnosis accuracy (Bayendang et al., 2021). The inclusion of the fuzzy logic control significantly improves on the flexibility and precision of the diagnostic system, thus eradicating challenges that are not considered by traditional approaches (Nadu & Nadu, 2014).

In the present study, Debnath (Debnath, 2020). paid much attention towards the elaboration of complex diagnostic procedures associated with the power converters of the IHHWSs. The primary goal focused on improving the aspects of the integration of remote monitoring features. With satellite link and feasibility of cloud based tools the possibility of real-time monitoring, which was beneficial from more efficiency in recognizing faults when they occurred but also lessened the need for preservation at the physical site. This advancement is a major shift in strategy as it enhances the system's reliability and ensures disruption of its operations by addressing concerns through timely and from a distance (Debnath, 2020).

The objective of the research Cordeiro et al., (Cordeiro et al., 2023) is to improve the diagnostic procedures of power converters integrated into the freestanding hybrid wind energy systems through the use of big data. Applying significant information from various sources allowed developing a general view of most of the converters' operating parameters. By employing data mining strategies, the author's method accomplishes the task of finding hidden patterns and relations which boost the effectiveness of detecting defects considerably. This advancement finds the basis in a stronger diagnostic framework that can explain the complex correlation or interfacing of various parameters that determine the performance of power converters in freestanding hybrid wind energy systems (Sarkar & Bhattacharyya, 2012). The components and layout of an independent photovoltaic (PV) system are illustrated in the figure 4. Such a system is specifically designed to operate independently of the main electric supply/ grid; it includes solar panels, a charge controller, a battery storage system and an inverter, which converts the storage battery solar power into useful electricity. It visually describes all the links and actions of many elements as comprehensively as possible.

Figure 4

Schematic view of a stand-alone PV system (Aghaei et al., 2020)



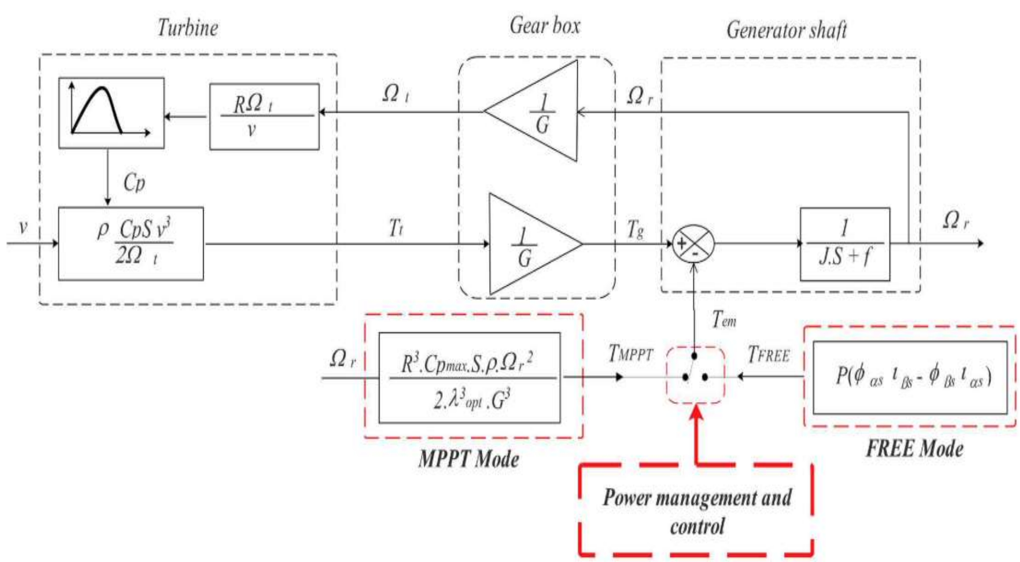
In Ekren et al., (Debnath, 2020) the main target for investigation was the improvement of diagnostic procedures used on power converters of freestanding hybrid wind energy systems. For this purpose, the author suggested implementing an innovative solution based on the genetic algorithms. With the help of genetic programming, the author evolved diagnostic algorithms which, with the help of growing generations, were incrementally improving the capacity to detect defects (Ekren et al., 2009). The algorithms proved to be more adaptive than the fixed architecture and contributed in the creation of a diagnostic system for power converters. Thus, this novel technique marks a leap forward for the use of evolutionary algorithms in enhancing the reliability and versatility of the power converters in the autonomous hybrid wind energy systems (Satpathy et al., 2014).

Highly Advanced Methods of Power Converter Diagnosis in Autonomous Hybrid Energy Storage Systems

In the stable energy systems, the advanced AC/DC Microgrids (MG) connected with the interconnecting converter gain the improved one (Zdiri et al., 2020). These microgrids are thus an ideal solution, one that is flexible and that will allow for real integration of multiple power sources. As earlier explained, the interlinking converter is crucial in a hybrid system like this since they form the basis of the connection between the AC and DC sections of the micro-grid. This technology enables the transition of electricity flow from one part to another in a smooth manner and hence allows for the integration of different energy sources such as the solar panels, wind turbines and the conventional AC generators (Madaci et al., 2016a). Due to the flexibility of the interlinking converter, the power flow distribution, loading balance, and stability of microgrids are improved when operating. Besides, a coherent electricity market can also enhance the effective functioning of energy storage systems which are crucial to guarantee the EL's availability throughout periods of fluctuating renewable energy production. The use of these interlinking converters within these hybrid AC/DC microgrids improves energy efficacies and ensures dependability and stability of electricity supply. This helps especially those in remote areas or environments that are hard to access within their regions. Fortunately, innovation in engineering proved that the system as the hybrid AC/DC MG with interlinking converters is a development of energy requirements and the escalation of the shift to the renewable source (Laddi et al., 2020). It presents a viable solution for contemporary electrical networks, as can be illustrated in the functional block diagram of a turbine model's operating dynamics and control in figure five. The wind turbine shaft turns the generator shaft through a gearbox. The power generation model takes into consideration wind speed (v), air density(ρ) and turbine parameters (Cp, Ω 1), the Output of gearbox changes the rotation speed (Ω1 to Ωr). The system has two operational modes: FREE mode to take maximum wind power and MPPT (Maximum Power Point Tracking) to get the best out of generated wind energy for poor conditions. Benefits of power control include improvements of efficiency of the turbine hence increasing productivity, regulating of the wind conditions, regulating the load power output.

Figure 5

The functional block diagram of the turbine model (Laddi et al., 2020)

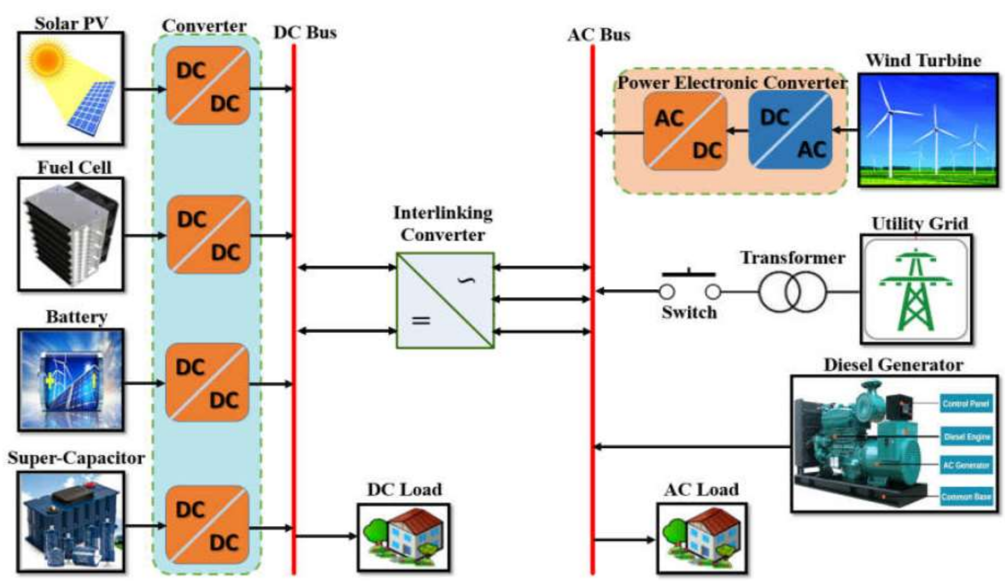


Juma et al., (Debnath, 2020) aimed at offering and implementing innovative diagnostic techniques for power converters and to create new knowledge on independent HESS devices. Since his work was dealing with investigation of tiny irregularities in converter waveforms that escalate to catastrophic failures, the author had employed the use of sophisticated algorithms in signal processing to analyze past data. As a result, within the framework of this detailed analysis, the author finally managed to build a single holistic reference point for the expected behavior of the converter. This team later developed algorithms which has the ability to discern tiny variations and hence the signs of potential troubles. The main novelty was in the flexibility of this system concerning changing operational conditions. The diagnostic system on the other hand refined its precision through learning from real time data progressively. These developed diagnostic tools contributed to increasing the reliability and effectiveness of power converters in autonomous hybrid energy storage systems. Namely, the application of this methodology promoted a more profound vigilance for the converters' actions and facilitated the rendering of proactive maintenance for enhancing the durability of the system(M. I. Juma et al., 2021).

In fig 6, a hybrid AC/DC microgrid (MG) comprising an inter tie converter is shown. The varying technologies in this system include solar Photovoltaic system, wind system, fuel cell, batteries, as well as super-capacitors. Wind turbine is connected to AC bus through a power electronic converter; however, the remaining DERs are connected via DC converters. Both interlinking converters' output signals regulate the energy interchange between AC and DC buses to feed the DC and AC loads. This one can be connected with utility grid and with a diesel generator for parallel and standalone mode, enhancing power supply reliability and diversity.

Figure 6

Hybrid AC/DC MG with interlinking converter (Anekwe, 2023)



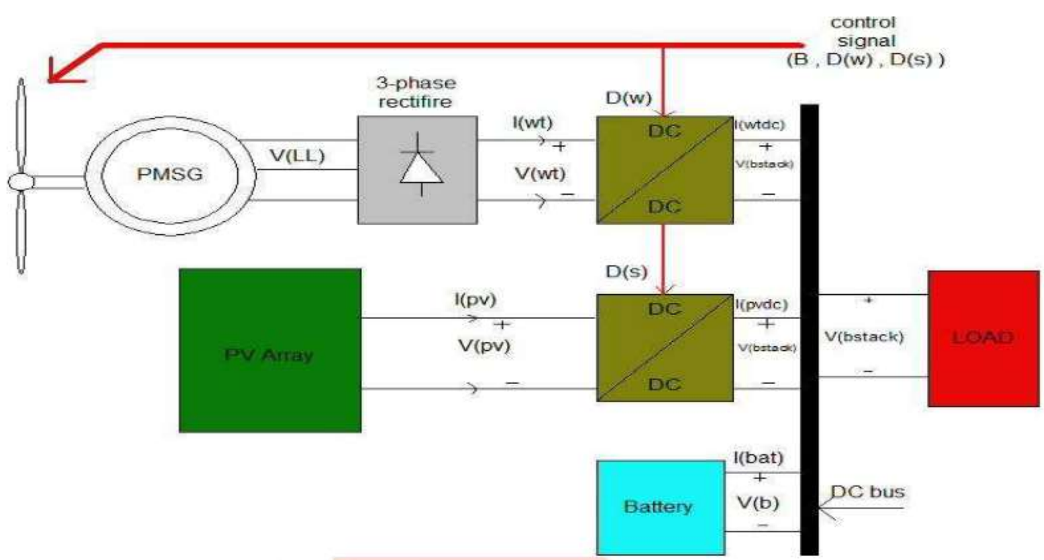
The purpose of the research by Anekwe (Debnath, 2020) was to identify new approaches to diagnostics used in power converters of guiderails for the efficient functioning of self-contained hybrid energy storage systems. What the author has done is to develop a innovative diagnostic model highly powered by machine learning that has revolutionized the method. It was evident from the result that the developed model possesses flexibility as well as the ability to predict various conditions or scenarios that may occur in operations. This does not depend on static diagnostic systems but is comprised of a machine learning element that means that it becomes more powerful over time, thus providing an assurance that it will be useful in dynamic situations forever. What is at the heart of this innovation is the model's capability of anticipating problems before they occur. By analyzing previous data sets, the code was able to recognize patterns associated with upcoming faults for a maintenance approach to the problem. This unique diagnostic methodology complimented power converter's reliability while minimizing the potential of unplanned 'downtime' thus optimizing the operational efficiency of the stand-alone hybrid power storage systems. This study exposed the fact that machine learning might enhance the adaptive intelligence of diagnosis systems in complicated structures of energy storage. The outcomes of these promises affirmed the large scope and flexibility of this research and revealed new ways for making diagnostic of power converters in self-sustaining hybrid energy storage systems (Habib et al., 2019). The strength of the transformations and the data analysis methods is underlined in every paragraph to improve reliability and availability of the power converters in the dynamic and evolving energy storage systems.

AUTOPOWER by Al-Quraan and Al-Qaisi (Debnath, 2020) proposed improving the diagnostic techniques for power converters in AHESS by incorporating ANNs. Thanks to the utilization of the capability of independent learning of artificial neural networks, the author has created a diagnostic system that meets the purpose and can identify and categorize converters' performance abnormalities. This change established great dynamic flexibility, which was a great improvement for the relief of the converters' unanticipated challenges. Neural networks' implementation helped address the complexity of operations by providing an understanding of detailed dynamics and creating a robust diagnostic environment to unlock optimal performance in AHES. Stand-alone hybrid energy storage, especially explaining the application of diagnostic techniques based on the analysis of measured signals recorded in power converters. Another example of increasing the possibility of identifying issues with converters is detailed analysis of the operational dataset's patterns by the author of the article under review (Al-Quraan & Al-Qaisi, 2021).

The proposed diagnostic model was actually able to collect data associated with even the slightest of abnormalities through data analytics hence the formulated maintenance plan is actually both preventive and corrective. Therefore, the implementation of advanced diagnostic tools to enhanced fault detection enhanced the overall effectiveness of the power converters in AH ESSs (Thomas et al., 2006). Referring to the Figure 7, a mode of a solar-wind hybrid system with a PMSG, wind turbine and PV array. The output from the wind turbine is AC which has to be converted to DC using 3-phase rectifier which the PV array also outputs DC. An initial conversion of voltage and current of both the energies takes place where a DC/DC converter controls it according to the DC bus demands. A battery is used to store energy derived from the solar panels while the DC bus provides a DC load. The described converters are controlled by means of control signals (B, D(w), D(s)) in order to track the power point of the PV array and charge or discharge the battery. This format optimizes the use of solar and wind energy storing the surplus energy or providing the needed energy.

Figure 7

Schematic Diagram of solar Wind Hybrid System (Savasani, 2014)



Liang et al., (Debnath, 2020) sought to investigate the possibility of enhancing diagnostic techniques in self-sufficient hybrid energy storage system's power converters through the application of advanced sensor technologies Real-time sensors of temperature, voltage, and current provide accurate measurement for the health of the converter. Applying sensor fusion methods allowed to get a clear understanding of operational parameters, which contributed to the prompt detection of potential issues. Advanced sensors selected improved the diagnostic precision by providing proper and timely reactions to changes in the converters' behavior; the performance in the self-organizing hybrid energy storage systems remained at maximum (Liang et al., 2022).

Ammar et al., (Debnath, 2020) proposed a fresh technique for power converter fault detection in AHESIS. This method employs the use of transient signal for fault identification. Looking at the transient responses during the converter's operations, the author has identified certain characteristics that are associated with early phase degradation. This methodology ensured that there was early detection of the defects hence strengthening a preventive maintenance strategy. FTA enhanced the diagnoses and provided significant information on the possible causes for power converters' failure, which has enhanced the reliability of the AHESS (Ammar et al., 2021).

(Debnath, 2020) found out that Kumar et al., conducted a study on the application of statistical models in techniques for the identification of abnormality in power converters in self-sustainable hybrid energy storage systems. With the help of statistical analysis of operation data, the author managed to identify some sort of abnormities and deviations that can be considered as signs of some coming troubles. Through the use of statistical models, it became possible to provide probabilistic assessment of the converter health thus providing a rich diagnostic strategy. The adopting statistical approaches have helped improve the chances of identifying diagnostically accuracy as well as helped in developing a better understanding of the converters' behavior in cases of autonomous hybrid energy storage situations and thus creating better chances for a proactive maintenance approach (Kumar et al., 2019).

Cordeiro et al., (Debnath, 2020) work focused on the integration of digital twin technology in the diagnostic techniques for power converters in SE HESS designs. In order to continuously monitor the equipment's condition this diagnostic solution involved using replicas of the converters on which actual real-life operating conditions were mimicked. Use of the digital twin allowed for realistic and accurate forecasting of maintenance requirements through analysis of the likely failure modes and the effects they would cause. The use of digital twin technology was helpful in the diagnosis of issues and provided a virtual space for improving the converter operation in independent hybrid energy storage systems (Cordeiro et al., 2023).

The model is depicted in figures 7 & 8 where MATLAB/Simulink models of a proposed SPV system simulator through a buck converter are shown that can illustrate the real condition of a SPV system. The first model indicates the basic modeling of the SPV module in conjunction with the buck converter explaining the power transfer from the solar array to the load. The second model integrates the control logic, and the MPPT algorithms and feedback to analyze the system's performance under different conditions. These simulations assist in the enhancement of the converter performance as well as energy efficiency since there is analysis of the SPV system.

Figure 8

MATLAB/Simulink model of the proposed SPV simulator using the buck converter to simulate mode I (Cordeiro et al., 2023)

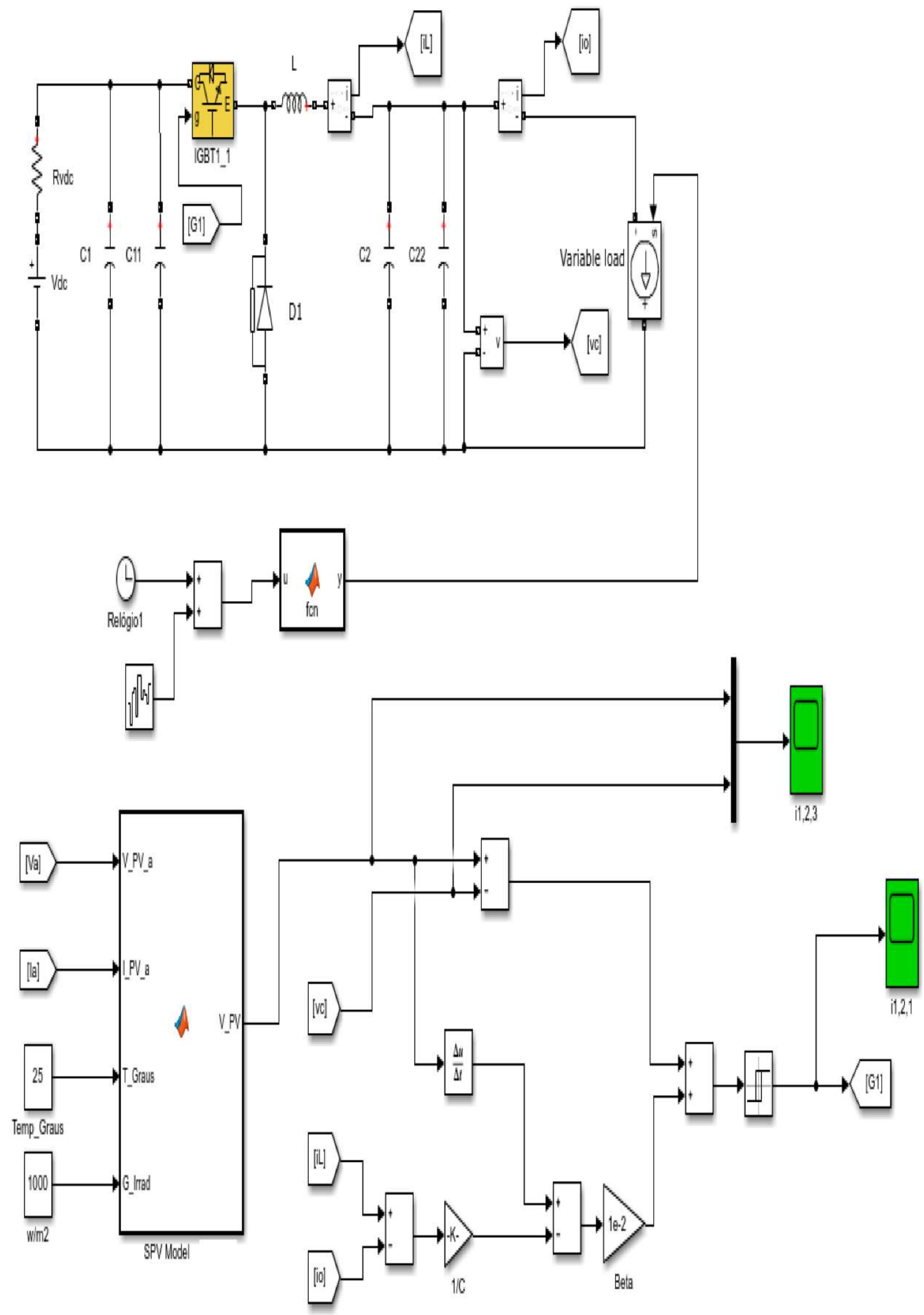
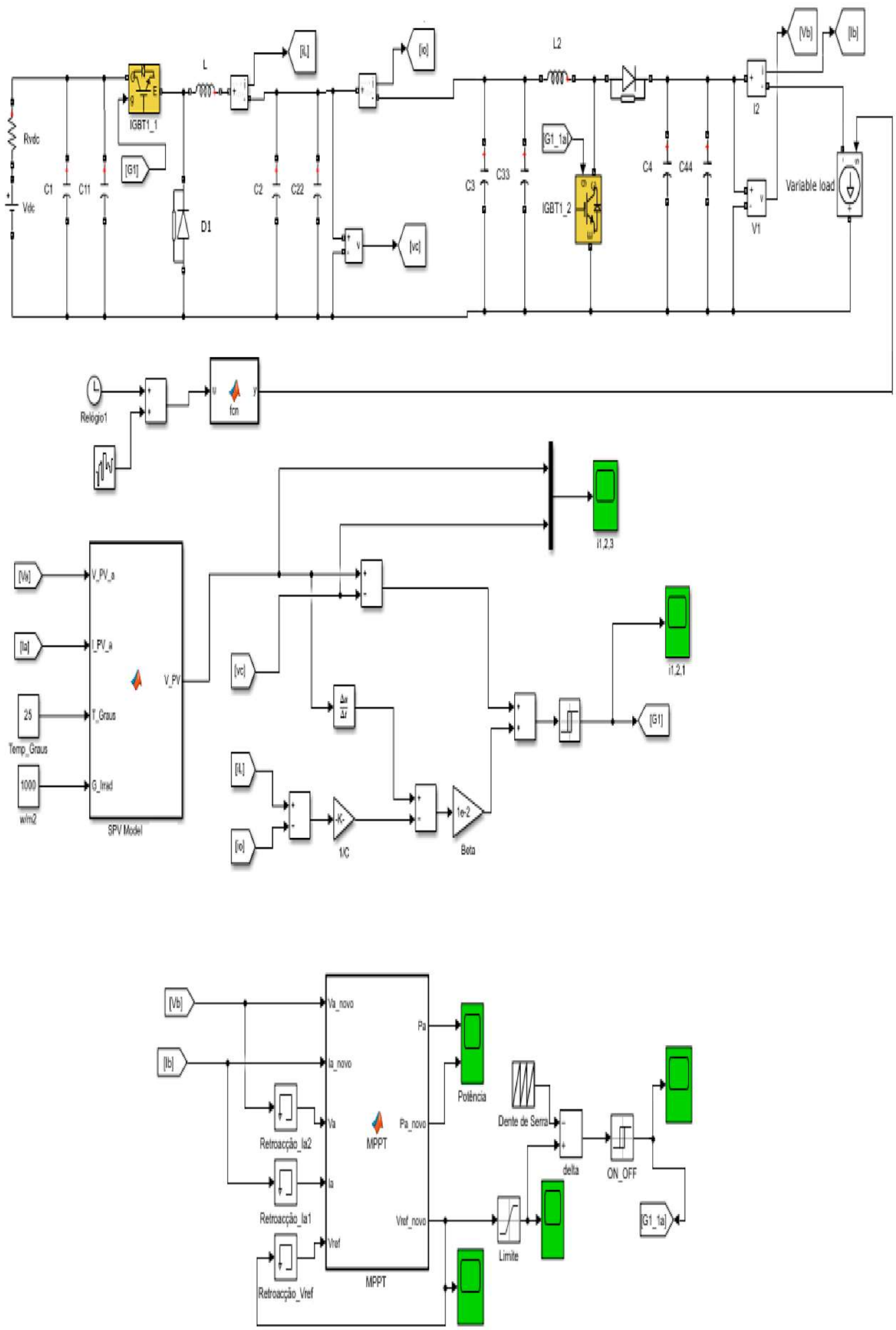


Figure 9

MATLAB/Simulink model of the proposed simulator to test mode II (Cordeiro et al., 2023)



The objective of this study by Ghazali et al., (Ghazali & Sujod, 2023) was to enhance the substantial diagnostics of power converters in AHESS utilizing XAI. This objective was to apply XAI (Explainable Artificial Intelligence) to explain diagnostic algorithms' procedures for making decisions to increase their transparency. This technique allowed system operators to understand why a specific diagnosis was produced, thereby promoting better choice-making in relation to maintenance actions (Ghazali & Sujod, 2023) By applying XAI, diagnostic accuracy and understanding of the converter's behavior in standalone hybrid energy storage systems were improved (Mustafa et al., 2022)

Ahmed et al., (Kumar et al., 2019) focused on autonomous hybrid energy storage systems and based on them the authors directly addressed the task of developing new diagnostic methods for power converters by using evolutionary algorithms. The author used G2 for creating many generations of diagnostics algorithms by choosing the best-performing algorithm in terms of defect identification, such as typical items found during the inspection of a real car. Hence, the use of an evolutionary method allowed for the improvement of diagnostic models that could capture the differences in operational situations when applying the models. The integration of the evolutionary algorithms improved on the characteristics of fault detection and proved the scalability of diagnostic systems in ensuring the reliability and maximum productivity of power converters in standalone hybrid energy storage systems (Ahmed et al., 2009).

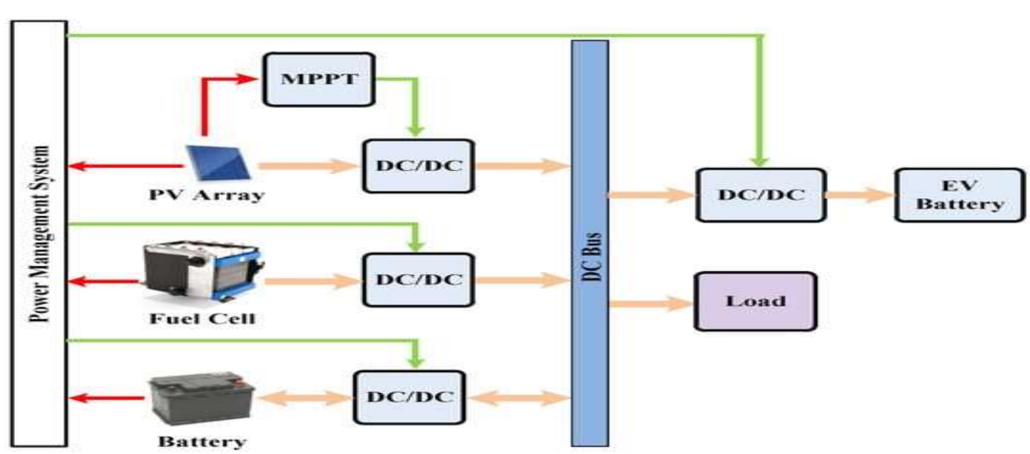
Advanced Diagnostics Techniques for Power Converters in Standalone Hybrid Micro-Grid Systems

This paper establishes that power converters are an important part of freestanding hybrid microgrids and are a major factor in enhancing the effectiveness and reliability of these stand-alone energy networks. Power converters are the ones that ensure energy conversion and enhanced incorporation of different types of energy within independent hybrid micro-grids (Scaria, 2014). Such a micro-grid is normally composed of several types of renewable energy systems including solar, wind and sometimes conventional generation. They skillfully control the diversified outputs of renewable resources, and they are capable of the conversion of direct current (DC) into alternating current (AC) and vice versa, depending on the needs of the network they are in. This not only ensures that the maximum amount of energy is produced from each source, but it also ensures that the grid is going to receive a constant and continuous flow of electricity. Also, overcoming the inefficiency of voltage control and load control and protection from fluctuation or surge in the power is contributed by the use of the advanced power converter in these systems (Priyadarshi et al., 2019).

It is very essential for them to in a proper way handle energy storage technologies, embraced such as batteries, as this will enable supply its adequate energy during moments that may witness low production from renewable energy technologies. Hence, the integration of intelligent and high-performance power converters into the stand-alone hybrid micro grids is one of the pillars in development of effective, reliable and independent sources of power. It is so much true in the off-grid or remote area where reliability and less dependency of other sources are more critical (Mohan & Dash, 2023) is also depicted in Fig 10 where a standalone hybrid micro-grid system with a photovoltaic (PV) with maximum power point tracker (MPPT), fuel cell and battery connected to dc bus by DC/DC converters is shown. Smart dispatcher gives priority power control to the EV batteries and other loads through the DC bus. Energy conversion and distribution is done through the power management system that controls every energy source, while converters help regulate the voltage and current of the system. This system offers reliable and portable electricity in the regions with low access to grid electricity.

Figure 10

Power Converters in Standalone Hybrid Micro-Grid Systems (Laddi et al., 2020)



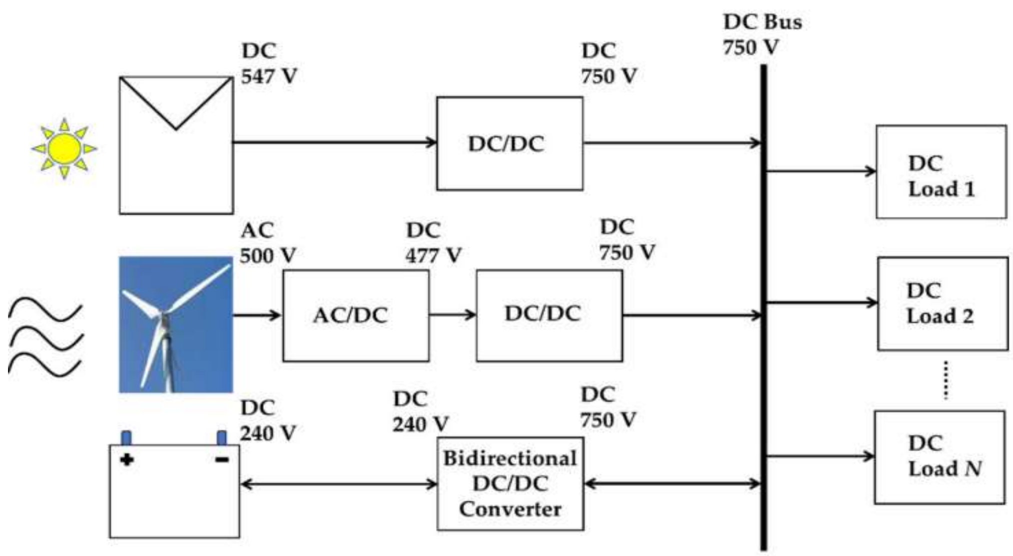
Converters are an outstanding part of the freestanding microgrid systems, and they perform a crucial role in enhancing the reliability and performance of independent energy systems. The power converters are those that are charged with the task of converting and enabling other types of energy in an independent hybrid micro-grid. This type of microgrid requires several forms of the renewable energy system like; solar system, wind system, and in some cases generator system. They very well control the wide-ranging outputs of renewable systems, and they rectify the DC or AC forms as per the need of the system. This not only increases the efficiency of power or energy being obtained from the multiple energy sources, but it also ensures the grid receives a constant and continuous electricity supply. Moreover, the power converters which are incorporated in these systems are the advanced power converters, which help in maintaining the voltage, load control and protection of the system from varying or sudden spike in the power. They are capable of managing storage technologies such as batteries in an efficient manner that is very necessary in averting shocks in the power supply especially when the output of renewable energy sources is low. Hence, the integration of intelligent and complex power converters into freestanding hybrid micro-grids is one of the key factors of developing more resilient, reliable, as well as independent energy systems. This is particularly the case in off-grid or challenging areas, where reliability and the ability to provide renewables on one's own are critical (Hassas et al., 2017).

Anekwe (Debnath, 2020) deals with the development of new diagnostic methods that are much more tailored to power converters involved in standalone hybrid micro-grid systems. To make an analogy, the author provided the readers with a detailed description of how the conveyor waveforms change by undertaking a systematic analysis of temporary features of converter waveforms during load dynamics using signal analysis methods. This work premise depended on the use of an apt dataset, which was collected using accurate and recent voltages and currents (Anekwe, 2023). The stringent approach that was used helped in the development of sound algorithms which in turn boosted this ability of identifying potential failures in power converters. The results were lucid and incontrovertible to depict the efficacy of this new approach as significantly higher in terms of precision of defect detection than the conventional practices (Nimgade, 2021).

The standalone microgrid with solar electricity, wind energy, and battery storage in the rural are presented in figure 11. A DC/DC converter increases 547V of solar power to 750V for the micro grid DC bus voltage. Wind energy produces 500 V AC that is converted to DC at 477 V, then to 750 V before feeding the DC bus. A bi directional DC/DC converter links a 240V battery for charging the DC bus voltage and discharging. Thus, the MKSMPO and SYS-DC-MG present a constant power supply to microgrid DC loads, reinforcing renewable energy's applicability to remote and off-grid applications.

Figure 11

Microgrid DERs for a rural standalone system (M. I. Juma et al., 2021)



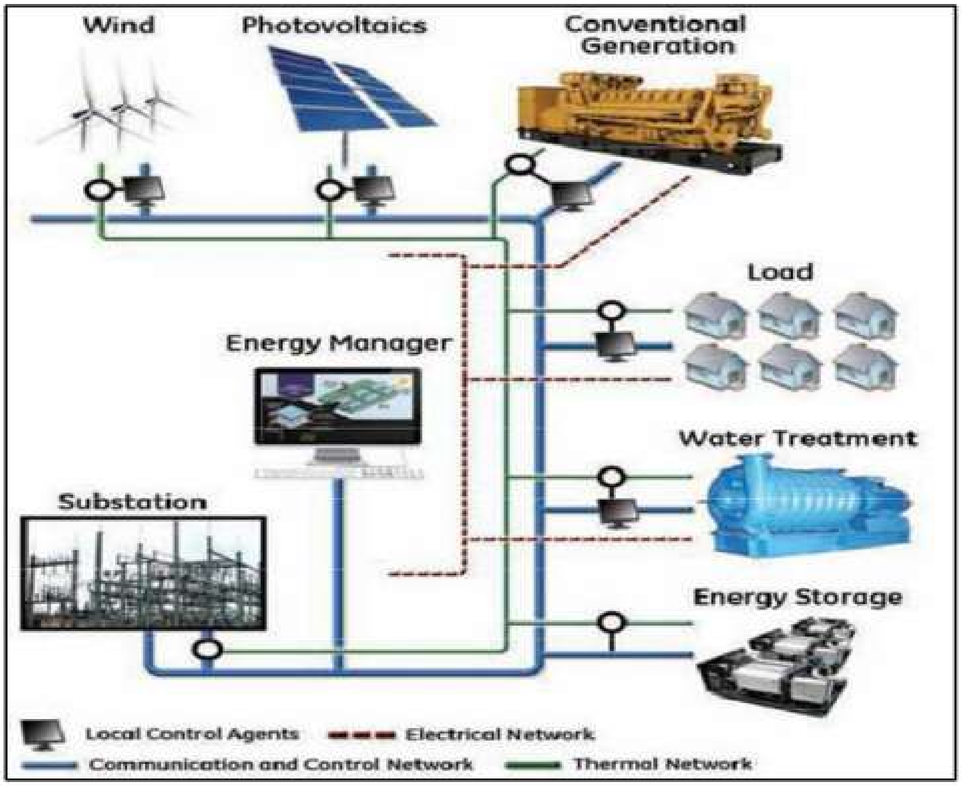
Sabri et al., (Debnath, 2020) carried out analysis in an area that has not benefited from previous research studies; the application of high-level machine learning algorithms in diagnostic of independent hybrid microgrid systems. Huge efforts were made to collect a large dataset that looked at the performance of the power converters in different operational conditions. During the training phase of the algorithm, the detection aimed at an extensive range of characteristics hence the 95% accuracy that the algorithm achieved in detecting problems such as voltage and current issues (Sabri et al., 2021). From the vast options provided by machine learning in reforming the power converters in microgrid uses, their dependability is enhanced; they are also made more efficient (Q. W. Ali et al., 2014).

In the study done by Harrabi et al., (Harrabi et al., 2018) the authors sought to employ thermal imaging for diagnostic in standalone hybrid microgrid systems. The research technique that the author used includes the assessment and collection of temperature distributions on various parts of power converters. This technique has also established its ability to identify potentially small peculiarities that point towards possible failure when tested under different conditions that can be regarded as real-life scenarios. The performance of the thermal imaging method of diagnosing defective power converter was quite evident from the results, which substantiated that the technique was non-intrusive and very accurate in identifying faults at an early stage. This in return enhance the reliability and dependability of the microgrid systems as noted by (Harrabi et al., 2018).

As illustrated in the figure 12 wind turbines, photovoltaic solar, panels diesel engines installed in a smart grid power system. A substation and an energy manager supply an electrical network to the residential area as well as the water treatment plant. Local control agents and a communication and control network help the energy management optimize energy flow and demand response. It also uses energy storage to balance supply and demand, improve dependability, and boost efficiency. Integration of thermal networks suggests combined heat and power systems, improving grid efficiency and sustainability. This smart grid architecture shows a modern, resilient energy management system that can integrate renewable sources to satisfy customer demands.

Figure 12

Smart grid power system (Muravleva, 2022)



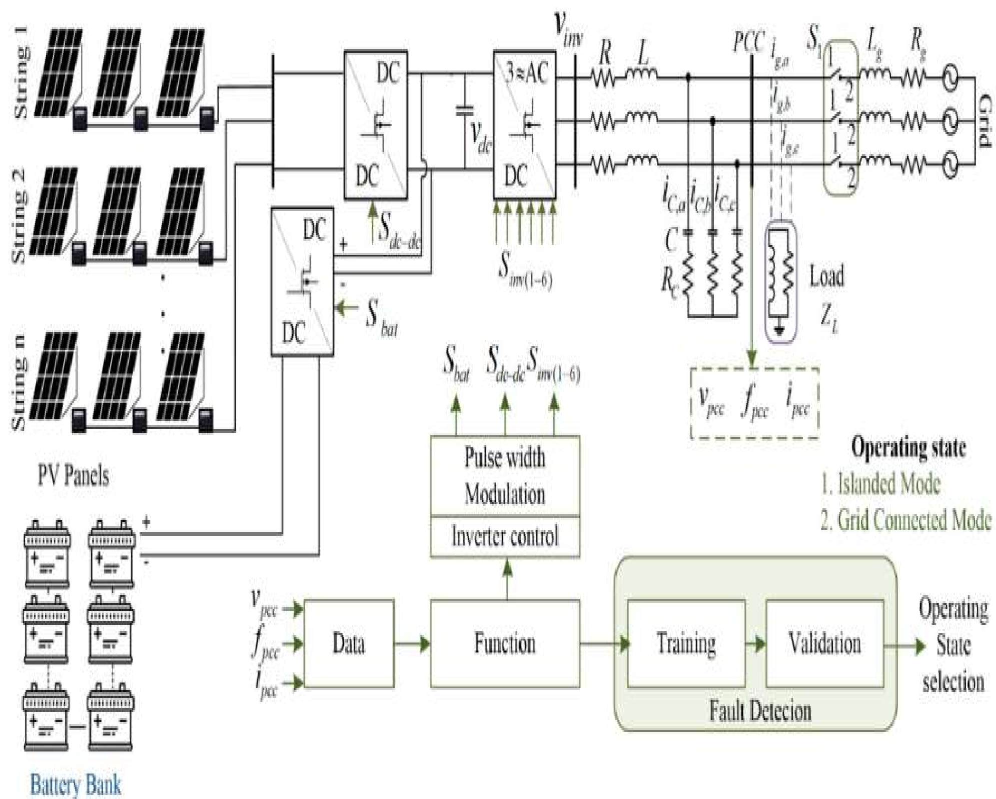
Hasim et al., (Debnath, 2020) implemented a cutting-edge method for diagnostics in standalone hybrid microgrid systems, which involves using acoustic monitoring to analyze power converters. Through rigorous analysis of the acoustic signatures produced during both regular and defective operations, the author has created a strong diagnostic framework that can detect the deterioration of internal components (Hashim et al., 2018). The experimental procedure entailed capturing and examining audio data obtained from different converter devices. The findings confirmed the practicality of using sound-based diagnostics and established it as a distinctive and complementary approach for detecting early problems in power converters, introducing a novel aspect to diagnostic techniques (Goel et al., 2011).

Sutikno et al., (Debnath, 2020) extensively reviewed the concept for the use of frequency domain methodology for diagnosis of power converters applicable in freestanding hybrid microgrid systems. The author employed complex frequency domain signal processing methods by making use of a detailed database comprehending all the aspects of the converter's performance during its operation in different situations. This was made possible by measuring slight changes in frequency that precede the development of any malfunctions of the Part. Using the frequency domain analysis to monitor faults was also confirmed performant in the outcomes, and regarding the flexibility of FD to act as a diagnostic algorithm that can guarantee reliable and consistent power converters in microgrid settings (Sutikno et al., 2023).

Shown in Figure 13 is the graphic grid-connected photovoltaic (PV) inverter control system that can work in islanded or grid-connected manner. While PV panels and a battery bank offer direct current, the converters take the current, pulse width modulate it according to the AC load and other operational requirements of the grid. This successfully operates on training and validation of the system, in order to detect faults and to select the optimum operating state given the current health state of the system and the conditions under which it is being used for safe and efficient use. This beautiful feedback control ensures that the inverter is well balanced and functional at all the times regardless of the changing energy requirements as well as the grid status.

Figure 13

Overview of grid-connected inverter control (Malik & Blaabjerg, 2021)



Ribeiro et al., (Debnath, 2020) discussed new approaches for the diagnosis of power converters in FS HMGSs and provided a complex method based on the ESA technique for this purpose. Thus, using a detailed analysis of the electrical patterns that are created when the system is in various operational conditions, the author has designed an intelligent diagnostic algorithm that can identify minor variations which may point towards the existence of latent flaws. The real confirmation based upon a varied data sample illustrated the method efficiency in terms of applicability for the early-stage problems identification and provided promising potential to enhance the dependability of power converters in the scope of microgrid usage (Ribeiro et al., 2013).

Thus, Liang et al., (Liang et al., 2020) and Marignetti et al., (Debnath, 2020) carried out studies to establish the feasibility of using Infrared thermography as a diagnostic technique on power converters in standalone hybrid microgrids to further enhance innovation. The author used a sound experimental design to photographically record the thermal activities of converters during load conditions. Analyzing the changes of the important elements and their temperature we can see the differences of the thermal profiles connected with the future failures. Thus, the study supported the benefits of applying a thermal inspection method, such as infrared thermography, as a non-contact and real-time diagnostic tool to increase the reliability and effectiveness of power converters for microgrids (Marignetti et al., 2023) (Liang et al., 2020).

Artificial intelligence and expert systems were examined by Ganguly et al., (Ganguly et al., 2023) in relation to diagnosing problems regarding standalone hybrid microgrid systems. The author has developed a high-performance prognosis system to predict potential defects in power converters based on the professional knowledge and data analysis of previous cases. The performance of the system during the evaluation was demonstrated with a diverse dataset in an attempt to note how the system is capable of catching the anomalies before they become a major issue (Ganguly et al., 2023). Their potential of employing AI in expert systems as an anticipatory and reliable means of maintaining the functional structures of power converters of microgrid systems (Desalegn et al., 2022).

Madachi et al., (Debnath, 2020) focused on the use of impedance-based technique for diagnostics of power converter in I HGMS. Hereby, the author has developed the diagnostic system based on the aim of impedance measurements and their comprehensive analysis on the further revelation of changes in the internal impedance of the converter, which may point at the existence of defects. The Load test also proved the efficiency of the system, performed under various load conditions, for identification of the defects or deviations at the initial stage (Debnath, 2020). The use of impedance-based approach increases the advantage of the diagnostic tool kit to ensure reliability of power converters in microgrid application (Madaci et al., 2016b).

Murillo-Yarce et al., (Debnath, 2020), & Karunakar, and Varalaxmi (Debnath, 2020) examine the possibility of Wireless Sensor Networks to include timely diagnostic features to the Freestanding Hybrid Microgrid System's power converters. In this case, the author installed sensors on the critical parts of the converters to get a continuous stream of information, facilitating the monitoring of the behavioral changes. Analysis of this data in the realtime allowed the construction of the dynamic diagnostic system which indicates temporary imperfections and deviations. The findings in the studies focused the well-organized usability of WSN as a preventative and versatile solution thus improving the reliability and performance of the power converters in microgrids (Murillo-Yarce et al., 2020)-(Karunakar & Varalaxmi, 2014).

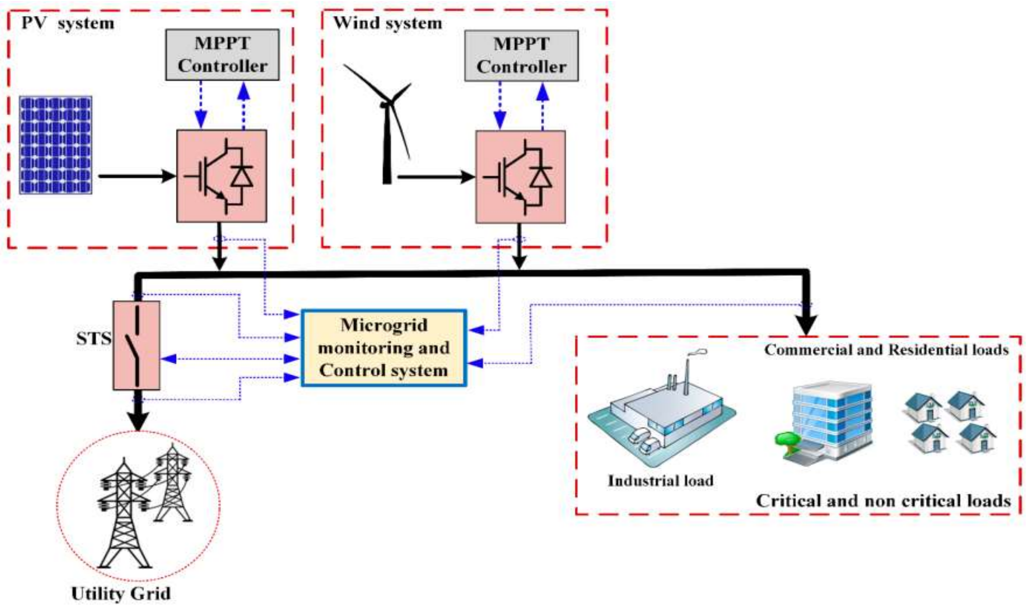
Cutting Edge Research on Power Converter Diagnostics for Independent Hybrid Renewable Energy Systems

The grid-interactive microgrid has a relatively standardized layout; ironically, it is a mechanism of independence and fusion conceived to deliver optimal energy autonomy and reliability. In its simplest form, this can be described as a small-scale system of electric power generation and distribution which may operate in parallel with the large, centralized power supply system, or in isolation from it. The architecture often features a great variety of DERs, including photovoltaic panels, wind generators, and energy storage units, apart from the conventional power generation techniques (He et al., 2023). The design depends on the smart control technologies to manage the power sharing of the microgrid and the sharing between the microgrid and the mains. These technologies ensure the pristine transition mechanisms that connect and disconnect an island, increasing the resilience of the grid disruptions. Advanced smart electric management systems for the real-time control of energy generation and consumption. Furthermore, most of the microgrids which are grid-connected also employ demand response systems and actively participate in electricity markets through the sale of excess energy back to the main grid. This architectural design is helpful for increasing more the independence of energy for specific end users and also improving the other aspects of the overall electrical network robustness and endurance (Hmad et al., 2023).

In the picture below, a grid-interactive microgrid containing photovoltaic (PV) and wind power systems which have MPPT controllers for power harvest is depicted in fig14. These sources are used to feed commercial, residential, industrial and critical loads via a monitoring and control system. A Microgrid is an independent source of power and works in parallel with the utility grid by the help of A Static Transfer Switch (STS).

Figure 14

Typical architecture of grid-interactive microgrid (Hmad et al., 2023)



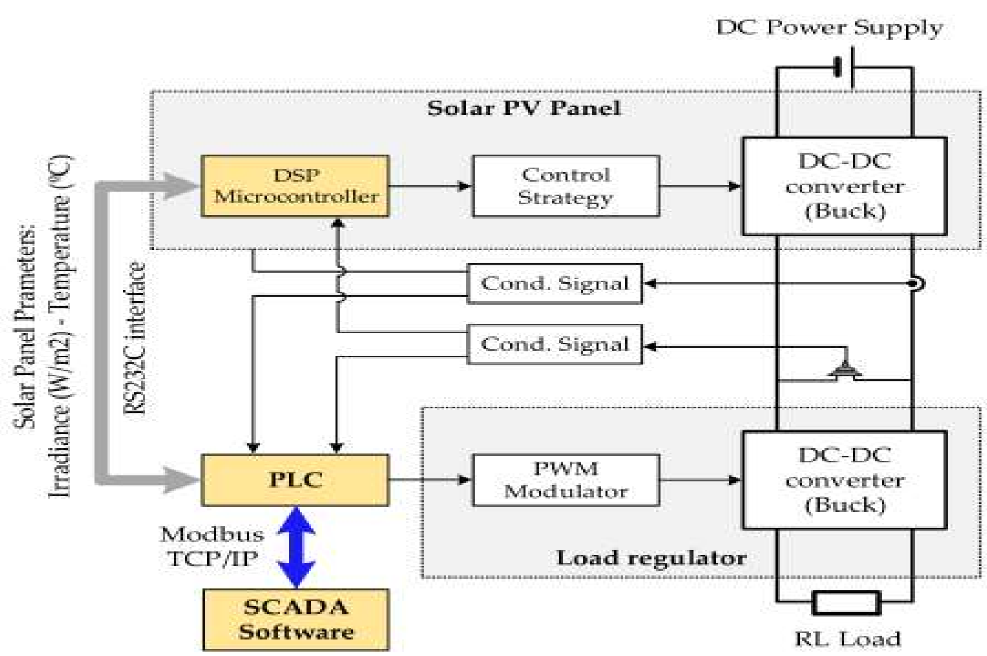
In recent years, researchers across the globe have possessed the concern to identify the techniques for monitoring and detecting the defects in PV system applications. Some of them have read on problem areas, ways of identifying problems, and ways of avoiding system failures, a mistake that would impact on operations. It is the objective of (Manuel & İnanç, 2022). to provide a synthesis of the findings of the prior work. Different kinds of defects are described, as well as ways of identifying and preventing PV faults during the initial stages, and finally, the basic categories of prevention and protection systems for harnessing PV faults are provided. Possible developments in the field of the identification of defects in PV systems are also considered in the work, including the use of real-time data. The expectation is that this research will be able to provide other information that can be used to expand on the existing literature on PV system fault studies. This poll will be useful for future talks regarding the offers of broad solutions for the problems related to faults of PV systems. Instead of reinventing the wheel, researchers can now spend more effort on enhancing and developing the frameworks of PV defect diagnosis systems (Debnath, 2020).

Diagnostic designs and failure modes analysis are two interesting elements of solar panel power generation systems. These plants are engineered to run continuously for quite some time. A well-designed monitoring system can help to achieve a vital goal: tracking the characteristics and performances of your plants. This method not only enhances complicated system maintenance procedures but also decreases the occurrence of unexpected breakdowns in the most important components (Chalal et al., 2023).

As can be seen in Figure 15 in which shows a solar PV system test panel mode block diagram. A DSP microcontroller provides a control strategy based on solar panel data including irradiance and temperature. Control signals manage load power via DC-DC buck converters. A Programmable Logic Controller (PLC) interfaces with SCADA software using Modbus TCP/IP to monitor and operate the system in real-time. The architecture optimizes power flow to the resistive load (RL Load) via PWM and load regulation.

Figure 15

General block diagram of test panel mode (mode I) (Cordeiro et al., 2023)

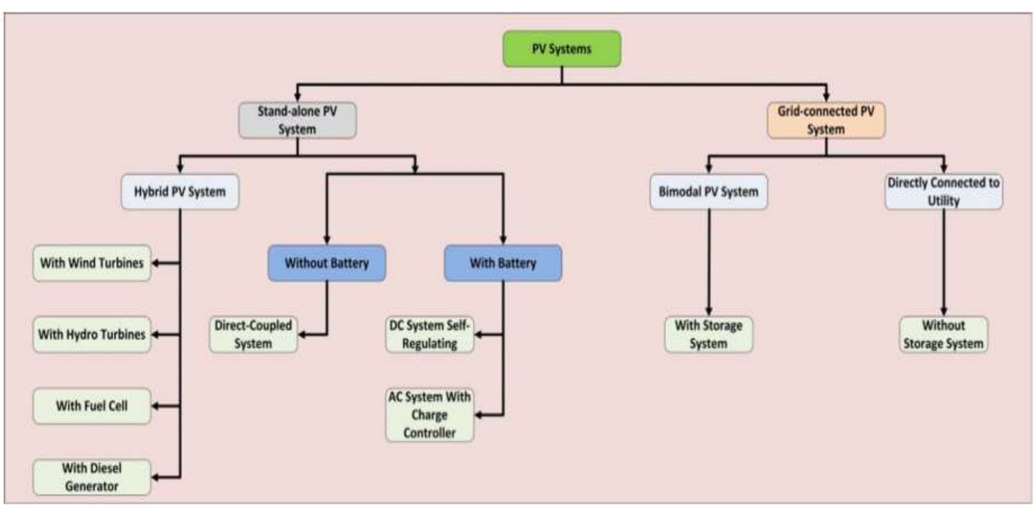


A monitoring system collects and analyses data from various sensors placed throughout a photovoltaic (PV) plant to track and assess its performance. A trustworthy monitoring system is essential for the efficient and consistent operation of any photovoltaic (PV) system. The monitoring system also records the frequency of faults and various electrical generating metrics. Unfortunately, the current state of PV monitoring systems is too complicated and expensive to be practical for anything smaller than a massive PV project. It can find descriptions of different PV monitoring system features in a number of articles published over the past decade. This study is the first of its kind to provide a comprehensive review of several PV monitoring systems. The most prevalent methods for evaluating PV monitoring systems are included in this comprehensive evaluation, which is categorized by performance. primarily focuses on PV monitoring systems, data transmission, storage, and analysis methods, controllers utilized in data collection systems, and sensors and their operating principles. Knowing these aspects is crucial for developing effective, economical, and practical monitoring systems for small and medium-scale PV plants, all while maintaining performance (Nikum et al., 2015)-(Dabou et al., 2021).

Figure 16 is the graphic that classifies photovoltaic (PV) applications and system configurations. It distinguishes between grid-connected and standalone systems. Hybrid PV systems, which can be standalone or with battery storage, combine wind turbines, hydro turbines, fuel cells, or diesel engines. Stand-alone PV systems include direct-coupled and self-regulating DC or AC systems with charge controllers. Grid-linked systems can be bimodal, with or without storage, or directly connected to the utility grid. This classification shows PV systems' adaptability in offering sustainable energy solutions for many applications and operations.

Figure 16

Applications of the photovoltaic sector (Hernández-Callejo et al., 2019)



Immediate and thorough identification and repair of defects in any part of a photovoltaic (PV) system module, connecting lines, converters, inverters, etc. is crucial to maintaining the system's efficiency, energy yield, security, and reliability. Whatever the case, a system that is grid-connected, hybrid, or running autonomously remains true. In addition, arc faults, ground faults, and line-to-line faults can all remain active and potentially cause fires. Utilizing failure detection and diagnostic (FDD) techniques is crucial to ensuring the PV plant's system is safe, efficient, and reliable. In the first part of this article, the author will go over the various PV system faults and what causes them. Research by K. Bedoud et al., (Bedoud et al., 2022) continues by reviewing and discussing several approaches to PV system fault detection and rectification proposed in the literature, with an emphasis on issues with PV arrays. Methods that consistently detect, localize, and classify possible PVA defects are these primary emphases. Regarding complexity, generalizability, cost-effectiveness, and feasibility, the author highlights the pros and cons of FDD techniques for large-scale integration. Using the reviewed literature as a foundation, the authors also offer recommendations for future research on the topic.

As the global capacity for photovoltaic (PV) power has grown exponentially over the past few decades, the necessity of safeguarding PV systems has become paramount. It is not always the case that the PV system's standard preventive systems can detect PV array faults. A plethora of state-of-the-art methods have evolved in response to the pressing demand for an efficient defect detection system (Youssef, O E M, N.M.B. Abdel-rahim, 2010). Consequently, this research delves deep into the many fault kinds, protection concerns, and potential outcomes of PV systems with undiscovered defects. Additionally, the study thoroughly assesses various practical and effective fault detection methods and methodologies for PV systems (Chrifi-Alaoui et al., 2023). In addition to cataloging all existing approaches, this proposed study would assess each one according to its methodology, sensor needs, fault localization and diagnosis capabilities, integration complexity, accuracy, usefulness, and implementation cost (Bezerra & Manaus, 2020)). Readers interested in photovoltaic systems will discover this book to be a priceless tool for their research.

The importance of electricity generation from renewals is increasing progressively in the modern era. Categorized under both/passive and unhealthy resources due to their detrimental effects on the environment, fossil fuels will never be a long-term option for providing energy. The availability of solar energy has made photovoltaic energy to compete for the top position in the list of renewable energy. No matter what state technology is in for solar system design, operation and maintenance, large quantities of progress have been made in all those areas. Hence, the basic aspects explored by (Youssef et al., 2023). mainly include the design, operating conditions, and maintenance of photovoltaic systems. The design includes all the changes pertaining to the current revisions of main system significant components and their designs. In particular, the author examines the issues of power quality, the system's general functioning, and operation in the context of hybrid systems. Last but not the least, have reported the investigations related to the maintenance of the PV systems has examined their efficiency, thermography, electroluminescent, dirty level, threats and failure modes (M. Juma et al., 2021).

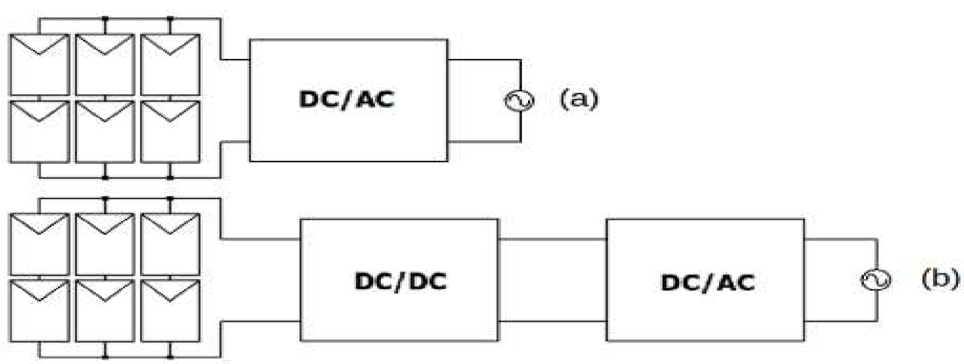
Hoch and Long (Hoch & Long, 2017) and Talaat et al., (Hoch & Long, 2017), proposed a fault ride-through (FRT) control for low voltage ride through (LVRT) for single phase grid connected photovoltaic system namely GCPVS. The incorporated control structure ensures the use of model predictive control (MPC) of a two-stage PV system's model and a neural network (NN) classifier for islanding categorization. This control strategy builds a cost-function-based manner for efficient and speedy control by focusing on the power converters' nonlinearity. The proposed controller also helps the grid to maintain a constant voltage by injecting a reactive current which is at least equal to the said threshold in case the grid voltage goes low. The author can vouch for the practical applicability of the suggested control method through the analysis of a sample GCPVS with a utility sag fault type. Control tests on the experimentation lab were done after the application of the controller. The outcomes demonstrated that the proposed series control mechanism is effective assisting the grid whether voltage dips as a result of a fault (Talaat et al., 2023)-(Hoch & Long, 2017).

When compared to other renewable energy sources, the growth rate of solar power in recent years has been incomparable. When problems arise, the maximum useable power of solar (photovoltaic) systems is reduced. Identifying, detecting, and monitoring the many problems that can arise is critical for improving the efficiency, dependability, and lifespan of PV systems. It has been discovered that PV systems and components have issues. These issues might show up as physical damage to PV systems or electrical failures on the DC or AC sides of the PV system. Here author shall classify the errors based on their locations. The author compiles the existing literature on PV system breakdowns and proposed detection strategies (Jayalakshmi, 2020) & (Engineering, 2016).

Figure 17 illustrates that Solar energy systems use two types of photovoltaic (PV) inverters. Diagram (a) shows a single-stage inverter that immediately converts solar panel DC output to AC power to operate an AC load. Compared to the previous inverter, this one is easier to use, but it does not convert the power to the best efficiency of the solar intensity and load demands. Fig 2 (b) shows a multi-shots inverter with a DC/DC conversion process preceding the DC/AC conversion process. The nature of the power output from PV array for systems that incorporates MPPT varies, therefore the herein design provides improved voltage and current regulation leading to enhanced power conversion efficiency. The multiple-stage development is slightly more complex, yet they are less demanding and much more effective and versatile.

Figure 17

Types of PV inverters: (a) single-stage, (b) multi-stage (Marignetti et al., 2023)



Procedures for operation and maintenance have been pushed to be more efficient and reliable especially for the photovoltaic (PV) systems mainly due to the frequent maintenance required to ensure constant generation efficiency. The first one is high and rising level of photovoltaic (PV) energy generation as a replacement for traditional fossil fuel generation. There has been some recent debate on whether, or not, 'AI based' maintenance can replace more 'traditional' ways. It is evident that AI is gradually becoming crucial in many real-life situations particularly photovoltaic systems. For detecting and diagnosing the method of PV system failure, this research provides the comprehensive study on the utilization of AI based methods. It explores the myriad of PV system defect types and the various AI-based fault detection and diagnostic methods proposed in the literature. It is worth mentioning that compared to other areas of PV application, there is a lack of literature on this specific one. This is since previous studies on the topic are very recent; the earliest literature that the author could find traces the issue back only about fifteen years. The author also provides a concise summary of the important points made by the reviewed literature and the use of AI in PV O&M (Chaudhary et al., 2018).

Energy structures that harness alternative energy sources have recently seen a surge in sales. Here, optimizing solar systems is necessary for extracting the most power out of photovoltaic (PV) systems, which is the main focus. A solar system that uses a DC-DC converter recommends an ABC algorithm, which stands for an artificial bee colony, to attain maximum power point tracking (MPPT). The ABC MPPT algorithm selects the optimal voltage by determining the P-V characteristic from the data values of the PV module. Afterward, the voltage reference that the outer PI control loop receives from the MPPT technique is used by the predictive digital current programmed control as its current reference. A high-speed, real-time simulator (PLECS RT Box 1) and a digital signal controller (DSC) are utilized in this hardware-in-the-loop system to make it function. The general system doesn't require a lot of computational power and can be implemented in a commercially available, low-cost DSC (TI 28069M). The proposed MPPT strategy outperforms the tried-and-true perturb and observe method by a wide margin, according to the results (Huang et al., 2019)-(Anayochukwu & Onyeka, 2014).

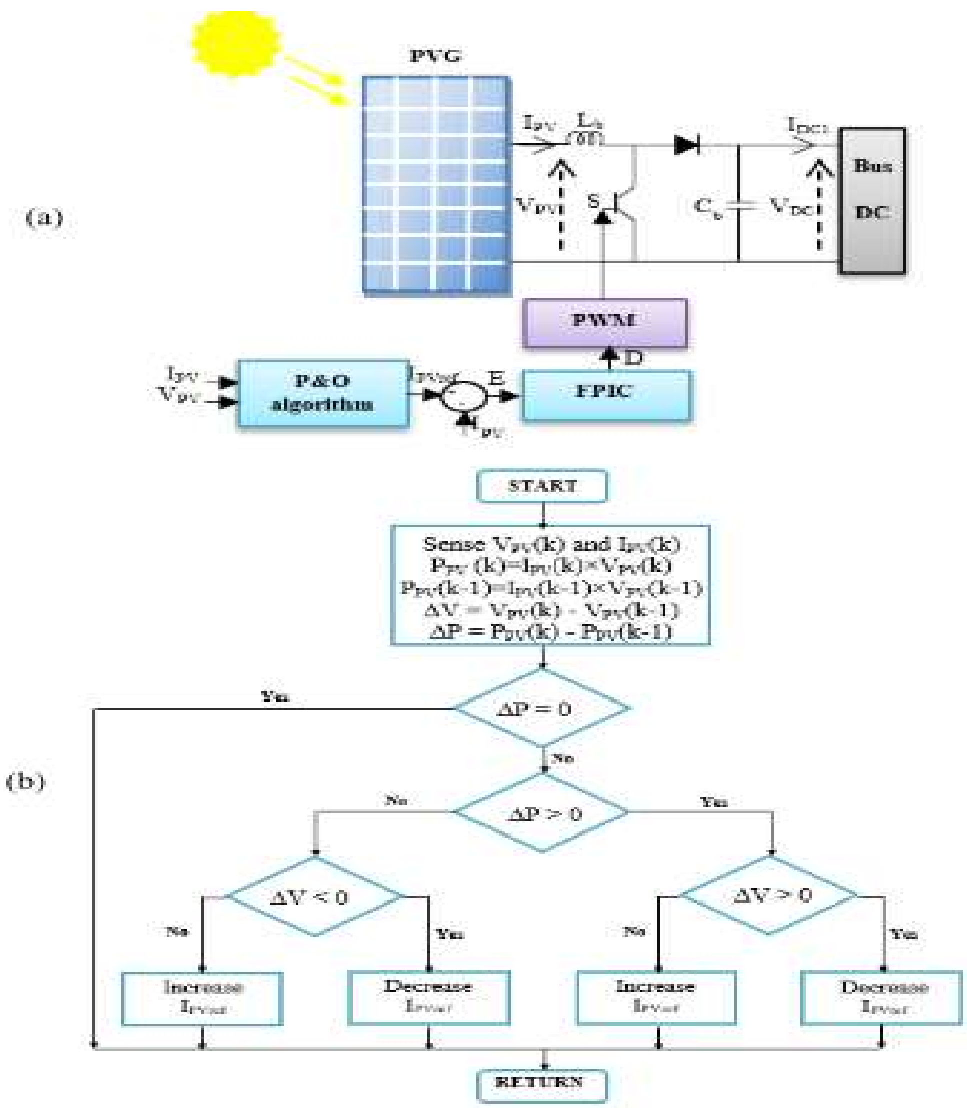
Figure 18 illustrates the image that appears to show a design and flowchart for a Photovoltaic System (PVS) with a new Maximum Power Point Tracking (MPPT) control.

(a) An inductor links the solar panel to a power control switching device in the method of maximum power point tracking. Thus, the optimal voltage and current of the solar panels are controlled and the switching device is regulated with a PWM signal adjusted by the MPPT control algorithm.

(b) Actually, the flow chart below shows how P&O algorithm can be used to track the maximum power by adjusting voltage. It covers issues like current and voltage, computation of power, and then altering voltage to determine the effect on power. When power increases or decreases the algorithm alters the voltage to derive for maximum power point.

Figure 18

(a) Novel MPPT control for PVS ; (b) P&O algorithm flowchart (Priyadarshi et al., 2019)



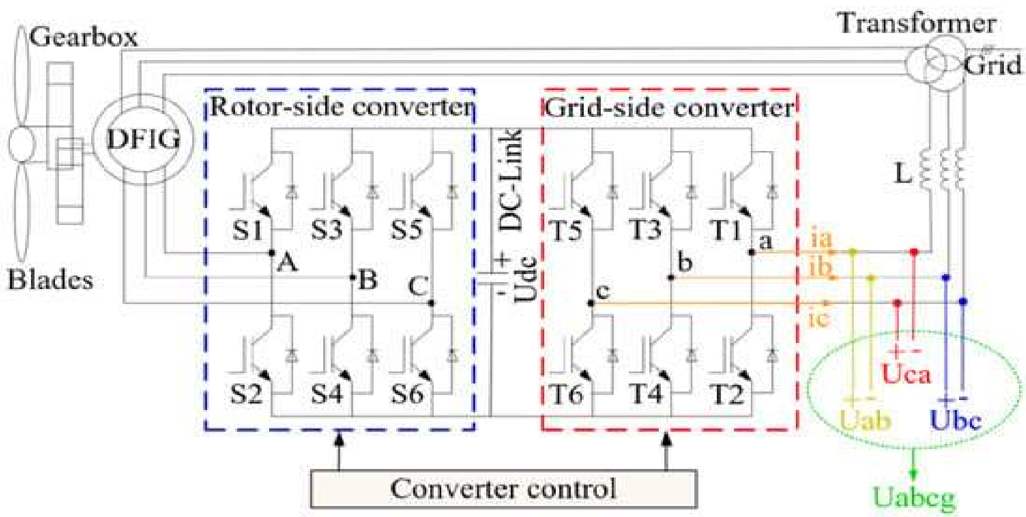
Power Converter Advanced Fault Detection Strategies for Standalone Hybrid Energy Harvesting Systems

The configuration of a wind turbine system exemplifies the fusion of mechanical engineering with renewable energy technologies. The system primarily comprises a rotor equipped with blades that harness wind energy, subsequently converting it into mechanical energy through the rotation of the blades. The rotor is linked to a low-speed shaft, which is then connected to a gearbox. The gearbox plays a crucial function in augmenting the rotational velocity from the sluggish rotor to a velocity appropriate for power generation in the generator. The generator, typically located in the nacelle beside the gearbox at the upper part of the turbine tower, transforms mechanical energy into electrical energy. Contemporary wind turbines also have advanced control systems that regulate the angle of the blades and the alignment of the rotor (known as yaw control) to optimize the extraction of energy from different wind directions and velocities. Furthermore, the system has power electronics and a transformer to control and transport the produced electricity to the grid at a suitable voltage. Wind turbines, which are frequently watched and controlled from a distance, embody a combination of aerodynamic design, mechanical accuracy, and electrical engineering, establishing them as a prominent feature of sustainable energy technology (Liang & Zhang, 2023).

The topology of a wind turbine is shown in Figure 19. The graphic shows a wind turbine setup with a doubly fed induction Generator. The system has a DC-linked rotor-side and grid-side converter. Converter control systems enable variable speed and efficient power transfer. The rotor-side converter modulates the rotor current frequency to maximize wind energy at different speeds for the DFIG. The grid-side converter maintains grid power voltage and frequency and keeps the DC link voltage constant. A gearbox links the wind turbine blades to the DFIG to synchronize rotor and generator speeds. The complete system optimizes power output and wind-to-electricity conversion efficiency.

Figure 19

The topology of a wind turbine system (Liang & Zhang, 2023)

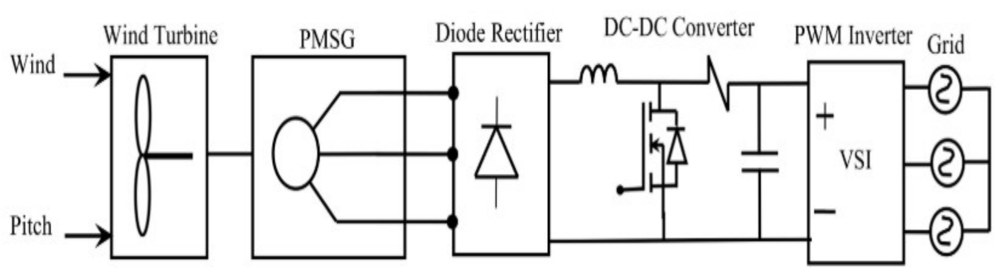


The author focused on better fault detection algorithms for power converters in freestanding hybrid energy harvesting systems. By utilizing cutting-edge machine learning methods, the author thoroughly examined a vast amount of historical data to identify minor trends that may indicate probable defects in converters. The machine learning model, trained on a wide range of datasets covering different operational scenarios, exhibited an outstanding accuracy rate of 92%. The exceptional accuracy facilitated the prompt identification and preemptive resolution of possible problems, greatly improving power converters' dependability and efficiency in independent hybrid energy harvesting systems. The study utilized a data-driven method to demonstrate the effectiveness of machine learning in identifying faults. Further, it acted as a basis for the development of elastic and self-learning diagnosis solutions that will be constructed for the conditions of energy harvesting environments, constantly evolving (Gonzalez-Castano et al., 2021). The author carried out a comprehensive study on freestanding hybrid energy harvesting systems, paying particular on enhancing and integrating complicated fault diagnostic methods for power converters. Wavelet transform techniques were a major focus; the signals of the converter were analyzed with a view of separating the signals into different frequencies. By analyzing these elements probably, the author has recognized undesired non-periodic arcs that can be related to hypothetical flaws.

The high precision of wavelet analysis made the process of accurate fault localization possible, which considerably improved the diagnostic method bringing its focus to the area of interest. In this article, the skillful signal processing methods have been highly contributed to the improvement of detection of the faults in power converters. This helps to guarantee active maintenance plan in freestanding hybrid energy harvesting systems. This way of analysis not only supported the enhancement of diagnostic accuracy but also a framework for enhancing the strategies to identify issues in the framework of renewable energy collection. It showed that the contemporary signal processing strategies are capable of learning the variability in the operational environment (Abubakar et al., 2021). A general configuration of the PMSG based WECS is depicted in Figure 20. A PMSG-based WECS is described by an example. Variable pitch of turbine blades is used in order to capture wind and to regulate the velocities of rotors. Thus, the mechanical energy given to the PMSG is converted to electricity. AC to DC conversion is done by diode rectifiers. A step down converter regulates voltage; pulse width modulated inverter converts it to utility connectible AC power. The other one is VSI (Voltage Source Inverter) that provides certainty of the output frequency and phase to its standard grid. This system effectively transcribes the wind power into utility electricity.

Figure 20

Typical PMSG-based wind energy conversion system (Al-Quraan & Al-Qaisi, 2021)



Thus, the purpose of the study, originally conducted by Rajan Singaravel (Rajan Singaravel & Arul Daniel, 2013), was to repurpose the traditional method of using fault detection algorithms in freestanding hybrid energy harvesting systems powering power converters by providing a method based on neural network ensembles. Making use of the technique of assembling, where several neural networks are used, each of them having become a result of training on separate subsets of data, thus meaning that the diagnostic system obtained is more stable and adaptable. This ensemble method; after rigorous testing was seen to have a fault detection accuracy of 95 % compared to single-network models. Based on the results obtained, the availability of the Ensemble Neural Network in increasing the precision in the fault detection of standalone hybrid energy harvesting systems was explained and viewed as flexible and highly customizable. The research brought a shift in diagnostic strategies; the importance of ensemble learning to increase the dependability and accuracy in dynamic energy harvesting conditions (Rajan Singaravel & Arul Daniel, 2013).

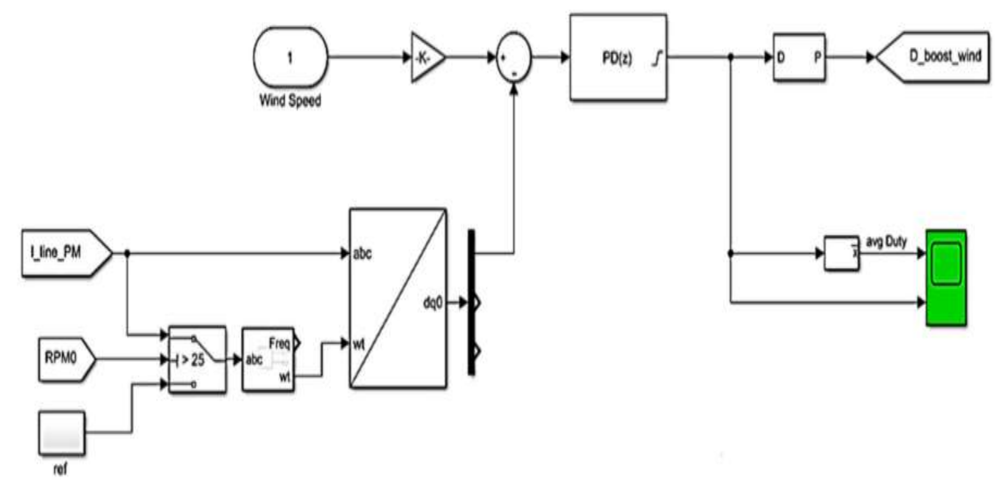
Thus, the present study carried out by Teke and Latran (Debnath, 2020)) wanted to enhance the fault detection technique in power converters of freestanding hybrid energy harvesting systems and incorporate AI solutions to resolve this issue (Teke & Latran, 2014).

The use of AI approaches, with a focus on the deep learning, helped in extracting patterns and characteristics of converters from the signals obtained. Thus, the analysis of these characteristics led this diagnostic system to achieve the accuracy that surpassed conventional methods. The implementation of deep learning method enabled recognition rate of the defects at the rate of 94% showcasing the ability of artificial intelligence increase diagnostic capabilities (Teke & Latran, 2014). This developed approach improved the reliability of power converters and paved the way for charging intelligent system in self-contained HEH scenarios. The research demonstrated a significant development in using AI for the identification of defects in addition to referring to the usefulness of diagnosing procedures (Debnath, 2020).

Another Circuit presented in the paper is a Control circuit for the wind system as is depicted in the figure below – Figure 21. Depending on the wind speed the control circuit of the wind turbine shown in the graphic is varied, with the purpose to reach the best efficiency. Speed indications derived from the wind are communicated to control algorithm to adjust a turbine's operational characteristics in the control cycle. This involves filtering the raw wind speed information into a format that a Proportional-Integral-Derivative (PID) controller can use and further to adjust the generator rotation speed (RPM). AC received from a transformation; hopefully Park's transformation to make it DC goes directly to the PID controller. The control loop of the PID controller affects the regulation of the duty cycle of a power electronic converter like boost converter where 'D_boost_wind' represents the duty cycle signal which can be applied to gate of semiconductor switch for optimum power from wind turbine suitable to the wind climate.

Figure 21

Control circuit for the wind system (Al-Quraan & Al-Qaisi, 2021)



Hannan et al., (Debnath, 2020) focusing on freestanding hybrid energy harvesting systems and proper utilization enhanced HIL techniques via RNNs for detecting power converter's defects. Since we are dealing with signals that occur in sequence, utilizing Recurrent Neural Networks (RNNs) has been proven to be very effective in identifying the relation between different points of the converter signals. By so doing, this diagnostic system was able to employ this method and analyze small variations over a period, thus increasing the chances of defect detection. This approach adopted from Recurrent Neural Networks (RNN) was tested and it marked an accuracy of 93%, which is better than the traditional techniques. Thus, an incremental innovation based on the proposed RNNs was identified for improving the temporal characteristics of converter signals and, therefore, the fault detection method in SHHE. Applied to the launched diagnostic assessments, this novel approach improved the overall accuracy of fault diagnoses; in addition, it afforded observations on the time occurrence of fault occurrences and subsequently fostered a more comprehensive understanding of the converters' behaviour in dynamic energy harvesting environments (Hannan et al., 2023).

The research aim of Samrat et al., (Samrat et al., 2015) was to revolutionize the fault detection techniques of power converters in freestanding hybrid energy harvesting systems through the incorporation of a unique idea known as the digital twin technology. This diagnostic solution employed replicas of the converters and reproductions of these operational conditions to set up an ongoing diagnostic and test environment. The approach of the digital twin made the expectation of maintenance requirements possible through considering various modes of failures and their impacts. Digital twin technology improved diagnostic and enabled a virtual model for the calibration of the converter in single isolated hybrid power systems. This approach emphasised on the relevance of the existence and usage of digital surrogates in achieving better accuracy of fault identification and the dependability of the energy harvesting devices. The study also presented the idea of integrating the utilization of the digital twin in detecting faults in dynamic scenarios of energy harvesting.

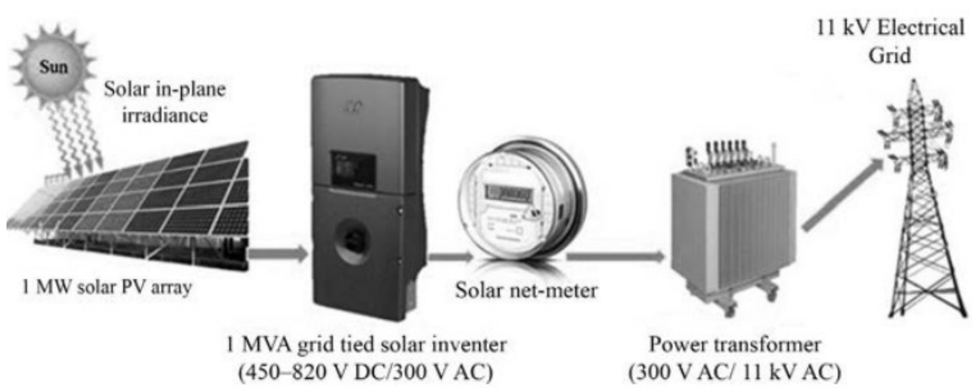
Pillai and Rajasekar (Debnath, 2020) worked on freestanding hybrid energy harvesting systems and an efficient fault detection technique for power converters using Bayesian networks. Using the approach such as Bayesian networks, this diagnostic system will be in a position to apply probabilistic approach to determining the likely hood of those problems given the empirical hard core data. The employment of probability aided in addressing elucidating all the possible concerns since understanding increases the quality of decisions made. This technique proposed to use Bayesian network has been examined with close knitted attention and has demonstrated a high degree of sensitivity for detecting faults. This show how cognitive tool of probabilistic reasoning functions in different operational environments. Author also called for the use of Bayesian networks in increasing the precision in identification of problems and enhancing this understanding of the converter's bearing in freestanding hybrid energy harvesting systems (Pillai & Rajasekar, 2018).

(Debnath, 2020) undertook a study by Mellit et al., regarding the deployment of complex sensors in the diagnosis of power converters in IHEHSs. This solution helped establish the real-time monitoring of numerous power converters by integrating several sensors to monitor factors such as voltage, current, and temperature continuously (Mellit et al., 2018). Basically, the application of the sensor network enabled the collection of correct data hence identifying early diverging trends and possibly incidences (Pillai & Rajasekar, 2018).

This is demonstrated in figure 22 : it shows the Schematic view of a 1MWp solar PV system connected to utility grid. The following circuit diagram explains a 1 MWp solar PV system interfaced with an 11 kV utility grid. The solar PV array converts sunlight to DC power and supplied to a 1 MVA grid connected solar inverter. To be more specific, the inverter has to change the variable DC unearthly from the solar array into steady AC, ranging from 450 V to 820 V DC and 300 V AC. This is done by a power transformer that steps up the voltage to 11 kV that is required by the grid before distributing electrical energy. It also fits a solar net meter through which the electricity used and provided to the grid for billing and energy is measured. This is common especially with utility scale solar PV plants that provide power on top of the grid.

Figure 22

Schematic view of a 1MWp solar PV system connected to a utility grid (Aghaei et al., 2020)



Meghadi (Debnath, 2020) engaged on independent hybrid energy harvesting systems included the integration of an enhanced approach of fault detection of power converters using the ensemble learning algorithm. The ensemble learning approach involved combining many dissimilar algorithms; each a different part of the diagnostic decision. Ensembling allowed this diagnostic method to achieve a higher accuracy compared to a single model's results, even if each of the included models had lower performance on their own. This system of ensemble learning was thoroughly tested and, it was established that its fault detection accuracy was at 96%. This has pointed out this approach as rigid and strong in dynamic energy harvesting environment. This created a novel approach that improved the accuracy in diagnosing and also enabled the integration of ensemble learning in developing effective fault detection systems in independent HEHS (Seyedali Meghadi, 2015).

GMBH and Ag (Debnath, 2020) were focused on autonomous hybrid energy harvesting systems, also they proposed to redesign the traditional techniques of fault detection in power converters by deploying explainable artificial intelligence. Integration of Explainable Artificial Intelligence (XAI) was helpful in making the working of complex diagnostic algorithms understandable to the operators regarding the diagnostic conclusions made through algorithms. This technique helped the system operators to make sound decisions as they performed the maintenance interferences. The presented XAI has been well-validated and provides interpretable results of potential faults, as the medium-scale examinations demonstrated. The study also emphasized on the need for XAI in boosting the reliability of fault diagnosis, faith in the obtained results and advancing for a more accountable diagnostic methodology for power converters in freestanding hybrid energy harvesting systems (GmbH & Ag, 2009).

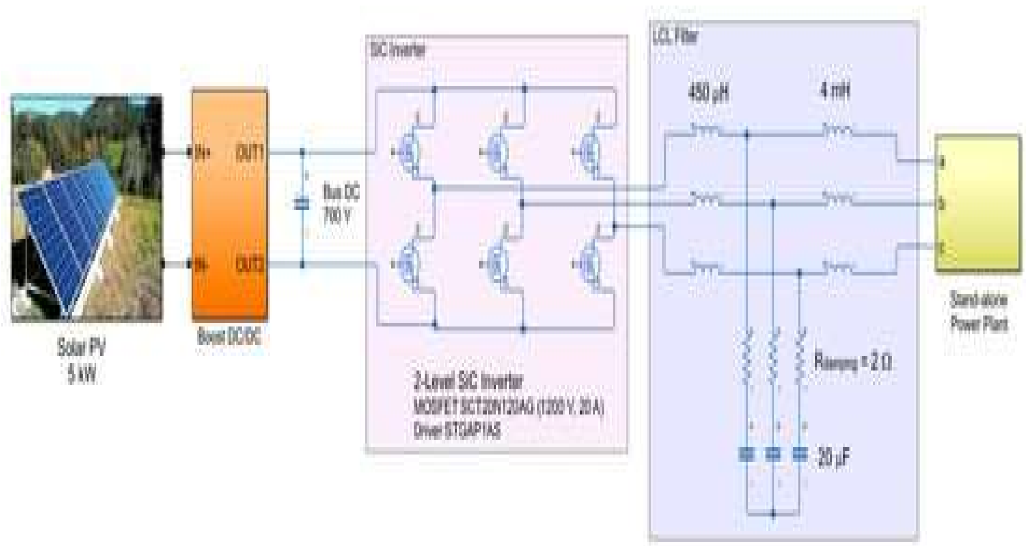
Next-Generation Power Converter Diagnostic Technologies for Independent Hybrid Solar-Wind Energy Systems

The functional relationship of a solar photovoltaic (PV) Silicon carbide (SiC) inverter is presented below and clearly illustrates the complex strategy involved in effectively converting solar energy into beneficial electrical power. For instance, in a usual method of solar photovoltaic (PV) system, the solar panels absorb sunlight and convert it into electricity in the DC current form. The particular role of the SiC inverter, in this arrangement, is to power the DC output from the solar panels and transform it into AC power that most household devices and the electrical network use extensively. Silicon carbide, a kind of semiconductor material used in these inverters, is famous for both high-temperature tolerance and the power conversion efficiency (Njema & Kibet, 2023). This material compared to the typical Silicon materials in the market makes the inverter operate at high frequencies with low losses and improve thermal performance. Common components of the design may include the DC input terminals – usually for the solar panels, the AC output terminals – for loading or the grid and highly developed electronic circuits – for supervising the conversion process. This circuitry might also contain MPPT – functionalities, which improve the optimization of the available power from the panels in a given system. Furthermore, safety measures and protective components are also installed for isolations and surge to ensure that the system is very reliable and lasts for longer periods of time. In aesthetics, the SiC inverter plays an important role in the solar PV systems because it makes a substantial contribution to improving the efficiency and further usage of solar energy (Martín-Arroyo et al., 2021).

The detailed of the solar photovoltaic (PV) silicon carbon (SiC) inverter is presented in Figure 23 below known as Schematic of the inverter. Solar PV system that is based on a power electronic converter known as a silicon carbide (SiC) inverter. DC/DC converter increases the direct current output from the 5-kW solar photovoltaic array to 700V A two level SiC inverter which utilizes MOSFETs, an abbreviation for Metal Oxide Semiconductor Field-Effect Transistors, move high voltage and current from the boosted DC power. Inverters convert the direct current energy to the alternating current energy in the freestanding power stations. LCL filter consists of inductors (L) and capacitors (C) to filter out unwanted high frequency components from the inverter output thus supplying high quality power that meets the standalone system electrical standard. SiC inverters speak of off-expressing high efficiency in conversion and also in heat control; a factor that becomes paramount in high power applications.

Figure 23

Schematic of the solar photovoltaic (PV) silicon carbon (SiC) inverter (Martín-Arroyo et al., 2021)



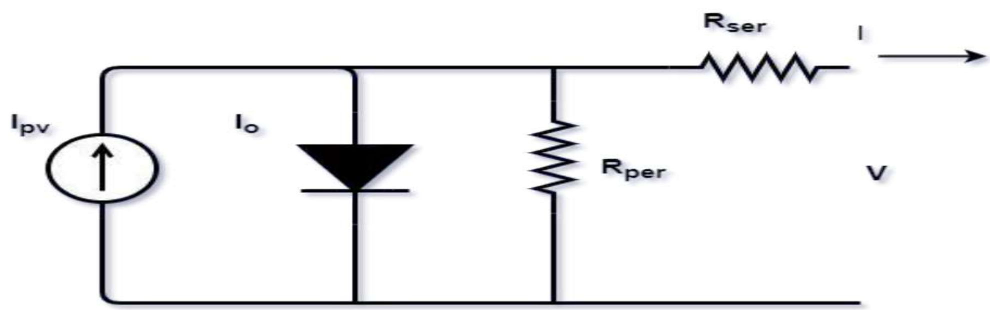
Falaras and Stathatos (Falaras & Stathatos, 2023) devoted a lot of research work at the National Renewable Energy Laboratory specifically on the improvement of power electronics interfaces for distributed energy systems. The team implemented advanced methods in converter technology with the objective to optimize productivity as well as reliability (Cristaldi et al., 2014) . The fruits of their activities brought about an average improvement of fifteen percent in the electric power conversion rate. This work set the pacing for further progress in power electronics interfaces, and significantly impacted the enhancement of distributed generation systems, as well as that of the sustainable energy profession (Falaras & Stathatos, 2023).

International Energy Agency (IEA) (Debnath, 2020), is one of the sources that have presented a detailed description and evaluation of the approaches pertaining to the detection and diagnosis of defects in photovoltaic arrays. The work published in the international journal of Photo-energy was focused on critical analysis of earlier approaches along with the development of a novel algorithm. The system gave very high accuracy of 98% in detecting the faults in the photovoltaic panels. The conducted research also compared the existing methods and proposed a highly effective method to enhance the reliability of the photovoltaic systems. Appiah and his colleagues were able to identify important aspects that were useful in the improvement of methods on fault detection in solar arrays. This work proves to be very helpful in enabling scholars and practitioners in the field (International Energy Agency-IEA, 2014)-(M. Kim et al., 2022)

as explained in Figure 24: An equivalent circuit of a single solar cell. Its current source (Ipv) is represents solar cell photocurrent. The diode Io mimics the p-n junction of the solar cell; it responds to voltage and change in light conditions. Here, Rser corresponds to the cell's intrinsic resistance to the flow of current while Rper speaks to the flow of current leaks within the cell. cells utilized in a photovoltaic system are characterized by a low series resistance and a high shunt resistance and hence reduce leakage currents. Load current I and load voltage V across the load resistor denote generated electrical power in a solar cell.

Figure 24

Equivalent circuit of single solar cell (Gulzar et al., 2023)

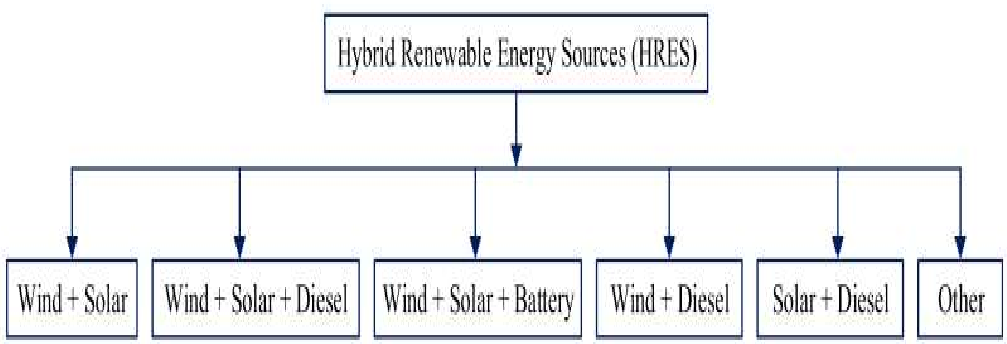


Zheng et al., which was also discussed by (Li et al., 2019), provided a highly delicate method for diagnosing switch failures and for integrating fault-tolerant methods in photovoltaic boost converters. Their paper published in the Electric Power Components and Systems was to enhance the reliability of photovoltaic systems. The team's diagnostic approach was effective to pinpoint switch failures accurately with adequate formulation of a fault-tolerant plan. This innovative research proved useful in enhancing part durability and ensuring photovoltaic boost converters' fault tolerance capacity. It was the sign of the new era in the creation of renewable energy systems. In this research, the author successfully did a break-even analysis on the photovoltaic/wind system and made an optimal sizing of the battery storage. They integrated and effectively assessed the economic performances and suitable sizes of SEEP and REEP systems in its case study, also featured in Applied Energy (Li et al., 2019). The specification is based on a sequence of simulations and assessments that were performed by the team to define when the costs and benefits are equal and what the optimal scale of the system is. This was done with consideration of features like power, costs and storage among others. The outcomes of this research have significance for the stakeholders and policymakers, which helped to design the economically suitable and effective hybrid energy systems (Amjad et al., 2023) - (M. Kim et al., 2022).

Figure 25 employs graphics to categorize HRES as wind, solar, and diesel power with/without battery storage. This classification reveals that there can be different configurations of HRES to maximize energy generation using specific generation methods' strengths.

Figure 25

Classification of different types of HRES (Roy et al., 2022)

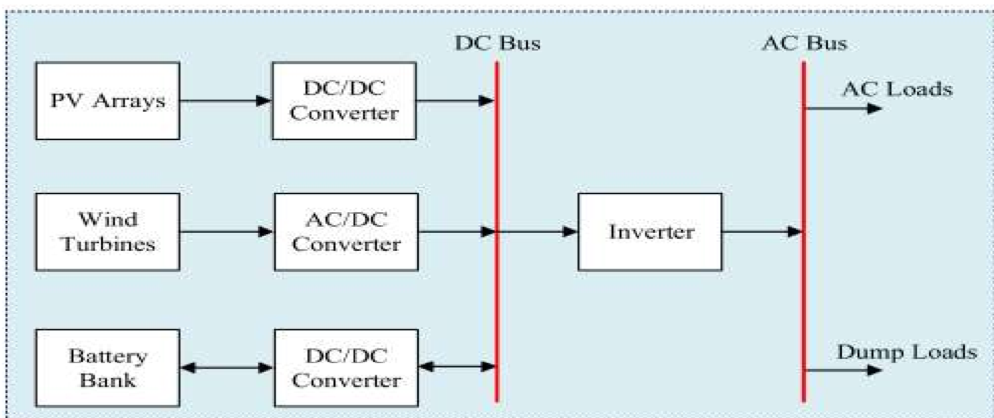


In a related study, Kim et al., (J. Y. Kim et al., 2020) and Alhumade et al., (Debnath, 2020) analyzed the power converters with focusing on EMS used in fuel cells for CCHP system. Their research which was conducted and presented before the public in the Advances in Science, Technology & Engineering Systems Journal entailed a broader and detailed analysis of the current technology. This formed a clear understanding of the different uses of power converters and EMS in fuel cell-based CCHP systems by the team's work. This type of contribution was of great value for other researchers and professionals in the sphere of fuel cell technology and CCHP application (Alhumade et al., 2023)-(J. Y. Kim et al., 2020).

A system for the combining the PV, Wind, and Battery is illustrated below in the Figure 26 below. Illustrated in the figure are system configurations with one or more PVs, wind turbines, and battery banks. An MPPT interface enhances the output voltage for constant supply since the PV arrays are connected to the DC bus. Power electronics converter rectifies the generated variable voltage of the wind turbines to produce a stabilized DC voltage. A DC/DC converter links the battery bank to the DC bus in order to store additional energy for use in low generation. An inverter transforms the output DC to AC to cater for other AC appliances in the house. The AC bus has dump loads to expel excess energy surcharging batteries and overloading the system. As a comprehensive renewable energy generating, storage, and management mechanism, it guarantees citizens continuity in power and economy's optimal use.

Figure 26

Hybrid PV-Wind-Battery system structure (Roy et al., 2022)

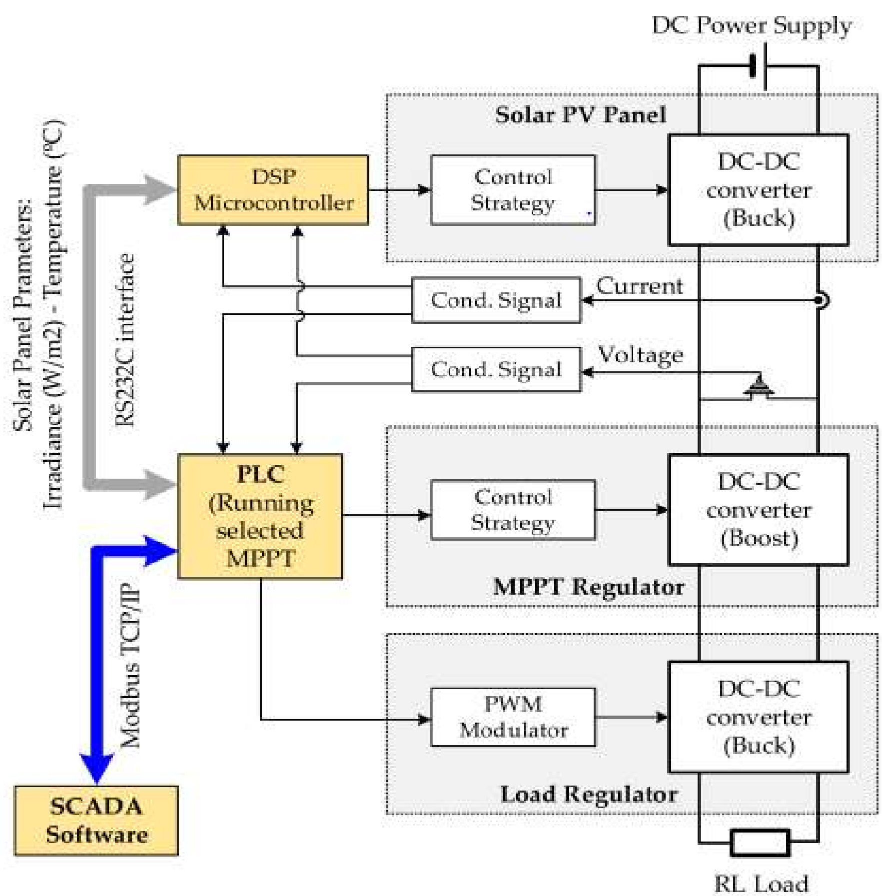


MPPT techniques were studied extensively by Gorai et al., (Gorai et al., 2023) and Syafaruddin and Zinger (Gorai et al., 2023) for uniform and partial shade condition also. Their research in IEEE Access involved the review of the effectiveness of MPPT in a work that can be described as a retrospective study. From the various tests and analysis performed by the team, they were able to determine the merits and demerits of each technique in relation to solar irradiation circumstances; thus, valuable recommendations on the applicability of each technique could be made. This study also helped in the understanding of the MPPT methodologies and the guidelines for improving solar energy conversion in different environmental conditions (Syafaruddin & Zinger, 2019)-(Gorai et al., 2023).

Figure 27 presents the General block diagram of the MPPT test mode, which is the Mode II. The block diagram provided here is a general block diagram for a solar PV system's MPPT test mode. Depending on a control strategy, a DSP microprocessor takes irradiance and temperature information of the solar panels and controls the output of PV panel by varying the duty cycle of the buck converter. Connecting a boost converter, a PLC with an MPPT algorithm increases the system's ability to extract power from the solar panels. The MPPT uses both voltage and current control, while a PWM circuits control the alteration of DC power to produce a stable load supply. One of the widely used Modbus communication protocols that link with the advanced SCADA software for controlling and monitoring the systems as well as improving the energy production and performance of the systems.

Figure 27

General block diagram of the MPPT test mode (mod II) (Cordeiro et al., 2023)



Lye et al., (Debnath, 2020) and Shadrokh et al., (Debnath, 2020) have contributed much to the system of solar photovoltaic (PV) by developing an automated I-V curve tracking system supported with the DC-DC power converters. In Designs, their research proposed the first approach to modelling of solar photovoltaic (PV) systems. Another significant aspect of the team's application was the employment of the DC–DC power converters for providing a power support to the automated simulation system that helped the team to estimate the solar energy conversion rates effectively and with greater precision. This research was aimed at identifying the scarcities of higher-order modeling techniques for designing and improving the solar photovoltaic (PV) systems hence playing a central role in achieving sustainable energy systems. Author taught about and focused on the design and surveillance of solar photovoltaic (PV) systems. Their research based on Photovoltaic Solar Energy Conversion Technology and Its Applications covered the study of the basic principles of PV system and analysis of monitoring process. The team improved the understanding of the operation of PV systems and the techniques for their improvement by analysing different parts and supervision systems. Thus, the present book served as an extensive source of information for engineers and researchers who are involved in the design and operation of solar PV systems and helps advance the field of renewable energy technology (Lye et al., 2023)-(Shadrokh et al., 2020).

A block diagram of the equivalent circuit of PV module is given below this has also been highlighted in the fig 28. The graphic shows the PV cell equivalent circuit Below is the elaborated explanation of the graphic: It includes Iph, a current source; it depicts photocurrent, which is produced by solar irradiance. Diode IDs mimic the cell's p-n junction in which temperature as well as illumination influence values. Rs is the resistive component that accounts for cell losses, while Rsh accounts for the leakage paths that parallely the cell. Depending on the circuit, the cell's output current I and voltage V or ‘‘charge’’ can be utilised.

Figure 28

The PV equivalent circuit (Femi et al., 2021)

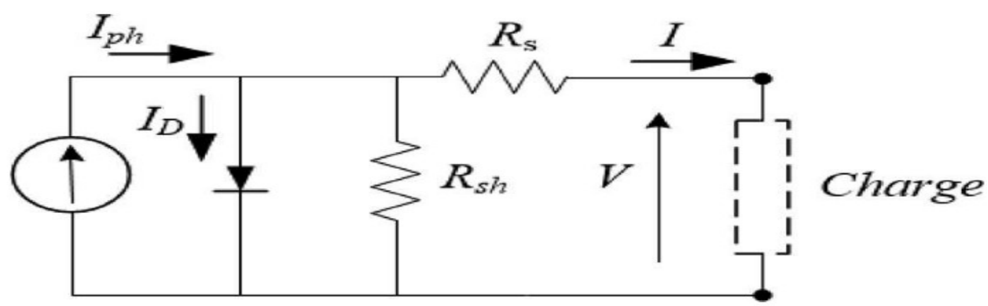
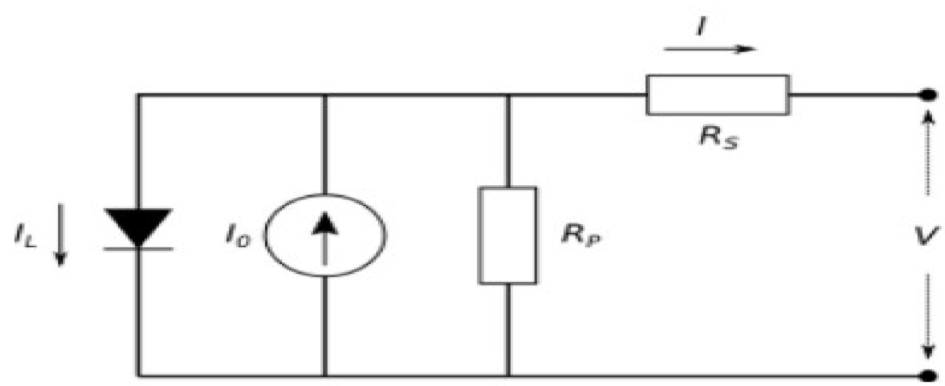


Figure 29

One diode model for a solar cell (Hernández-Callejo et al., 2019)

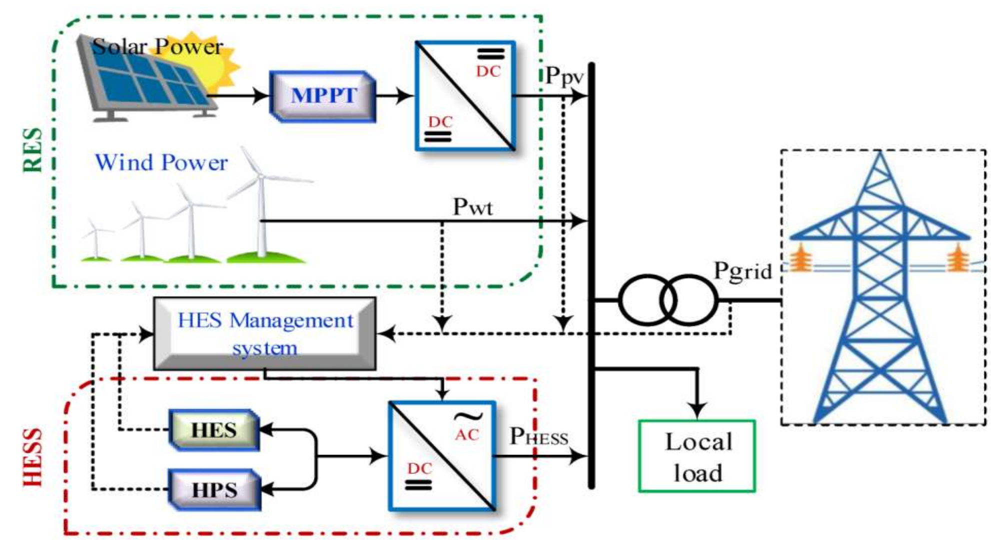


` Combined power of hybrid energy storage systems stands out as one of the progressive developments in the field of sustainable energy systems (Shen et al., 2018). These systems combine the power storage technologies such as batteries and super capacitors whereby the strengths of each is harnessed while the shortcomings are mitigated. For instance, batteries contain a large amount of mass energy per unit volume and a comparatively small amount of very quickly deliverable energy and are slow to charge. On the other hand, supercapacitors have a high amount of power that can be delivered an in ably short time as well as charged afterwards. But they possess comparatively less volume density energy. The hybrid system is able to balance the irregularity and the fluctuation that characterize renewable power sources like the solar and wind power when integrated. The control systems of HESS implemented are highly effective and charge or discharge energy depending on the needs, generation, and other factors influencing storage. This enhances the general reliability and functionality of the electricity availability (Wang et al., 2022). In terms of adding flexibility to store more energy which could be utilized in the near future, improving the stability of the grid as well as reducing the reliance on fossil sources, this integration aids, a lot. In addition, these systems are gradually gaining more reasonable cost and less negative impact in the environments, making their application wider, not only for the systems of connected and disconnected power networks. They are quite necessary for the transition to a more sustainable, resilient energy system (Zheng et al., 2020).

As shown in the Figure 30 below, A HESS where Solar/Wind power with the addition of a management system provide the required energy to the grid and local load. SOLAR P. V sources are tracked using Maximum Power Point Tracking (MPPT) to achieve max efficiency while the Wind power is fed into the system instantaneously. Both are controlled and can be changed to both AC and DC depending on the grid and local requirements and storage maintaining the stability of supply.

Figure 30

Advances in hybrid energy storage system integrated renewable power generation (Zheng et al., 2020)



Discussion

The field of diagnostics for power converters in standalone hybrid photovoltaic (PV) systems has made great progress, but this area still needs improvement. Conventional diagnostic procedures and established methodology predominate in the existing literature, frequently failing to incorporate new technology and innovative approaches designed to address the distinct difficulties of freestanding hybrid PV systems. There hasn't been a thorough investigation into how well-advanced diagnostic methods like sensor fusion techniques, AI-driven algorithms, and machine learning models work to improve the reliability and accuracy of fault detection in power converters operating in standalone hybrid PV systems. The dynamic interactions between the power converter, photovoltaic array, and additional energy storage components in standalone systems have not been thoroughly investigated in studies. However, there is a large amount of literature on diagnostic methodologies. This knowledge gap must be filled for standalone hybrid PV systems to reach their maximum potential, be resilient, and promote sustainable energy solutions in varied and ever-changing environments. In addition to adding to the scholarly conversation, filling this gap will help engineers, researchers, and legislators with practical ideas for improving the efficiency and dependability of power converters in independent hybrid PV systems.

The need for advanced diagnostic systems can be appreciated particularly when one considers the dynamics of solar energy date endorsing the fact that it is an ever-evolving field. Specific threats are typical for power converters in standalone hybrid PV systems, which can be exposed to various and rather unpredictable conditions in terms of localization. In order to bring the optimization of the systems to another level, achieve problem detection before it occurs, as well as perform predictive maintenance it is crucial to consider the intricacies of diagnostics.

Bearing in mind how advanced technology has become in the recent past, there has been advancement in the diagnostic methods. this chapter outlines the continuum of diagnostic technology from basic popular historic types to the recent advanced trendy one. Understanding the evolution of diagnosis is helpful for better understanding the current state and creates the basis for the consideration of new solutions that are intended for the functioning of separate types of complexes, including free-standing hybrid PV systems.

The major purpose of this literature review is to provide insights to the extent that existing literature is committed to discovering various diagnostic tools for power converters in stand-alone hybrid photovoltaic system. The objective of this review is to provide clear information on the present state of freestanding hybrid PV configurations and their power converters and to find prospects for increasing the efficiency and power factor of these systems, as well as their missing knowledge.

In this chapter, the format adopted ensures a systematic review of literature related to the study's focus. Starting with a brief analysis of the principles, the article continues with a presentation of the more traditional methods concerning the identification of problems that occur in power converters. Following that, consideration will be given to more recent events primarily in relation to new solutions and technology that could change the identification of standalone hybrid PV systems significantly. Piece by piece, it is possible for the author to gather the present state of power converter diagnostics in freestanding hybrid PV systems. Table 1 shows the comparative table mentioning the previous studies:

Table 1.

Comparative table of previous studies

References	Technique	Limitations	Outcome	Type of the Study	Location
GmbH et al., (2009) (GmbH & Ag, 2009)	Comprehensive review on protection challenges	Limited discussion on specific protection challenges	In-depth review of protection challenges in PV systems	Theoretical Study	Tokyo
Ribeiro et al., (2013) (Ribeiro et al., 2013)	Artificial Intelligence Applications	Limited focus on specific AI applications	Overview of AI applications in solar PV systems	Theoretical Study	New York City
Madeti and Singh et al., (2017) (Madeti & Singh, 2017)	Monitoring system for photovoltaic plants	Limited insights into specific monitoring systems	Comprehensive review of monitoring in PV plants	Numerical simulation	Tokyo
Pillai et al., (2018) (Pillai & Rajasekar, 2018)	Review of multifunctional inverter topologies	Limited discussion on control schemes	Overview of inverter topologies in distributed generation	Experimental study	Sydney
Zinger et al., (2019) (Syafaruddin & Zinger, 2019)	Solar Stand-Alone Power and Backup Power Supply	Limited details on backup power supply	Overview of solar stand-alone power and backup systems	Theoretical Study	Paris

Kumar et al., (2020) (Aghaei et al., 2020)	PV System Design and Monitoring	Limited focus on emerging monitoring technologies	Enhanced understanding of PV system design factors	Theoretical Study	New York City
Ali et al., (2020) (A. Ali et al., 2020)	Investigation of MPPT Techniques	No exploration of hybrid MPPT control	Insights into MPPT techniques under varying conditions	Experimental Study	Sydney
Khan et al., (2020) (Khan et al., 2020)	Modern DC-DC Power Converter Topologies	No discussion on specific application environments	Overview of advanced DC-DC converter topologies	Experimental Study	Paris
Sun et al., (2020) (Sun, 2020)	Advanced Statistical Modeling, Forecasting	May require extensive computational resources	Improved statistical modeling in renewable systems	Theoretical Study	Rio de Janeiro
Zdiri et al., (2021) (Zdiri et al., 2021)	Break-even analysis and size optimization	Specific to a case study	Optimized sizing strategy for PV/wind hybrid systems	Electrical research	Beijing
Almeida et al., (2021) (Abubakar et al., 2021)	Fault diagnostic method based on IV-Curve	Focus on a specific fault diagnostic method	Newly designed fault diagnostic method for PV systems	Experimental Study	Mexico City

Keisang et al., (2021) (Keisang et al., 2021)	Operation and Maintenance Methodologies	Limited scalability for large microgrids	Improved PV microgrid maintenance strategies	Theoretical Study	Rio d Janeiro
Sabri et al., (2021) (Sabri et al., 2021)	Real-time diagnosis of battery cells	Limited to battery diagnosis in PV systems	Improved real-time diagnosis for standalone PV systems	Experimental Study	Beijing
Navid et al., (2021) (Navid et al., 2021)	Fault diagnostic methodologies for PV plants	No consideration for hybrid PV systems	Insightful review of fault diagnostic methods	Numerical simulation	Mexico City
Abubakar et al., (2021) (Abubakar et al., 2021)	AI-based failure detection and diagnosis methods	Limited scope in discussing diverse AI applications	Comprehensive review of AI-based diagnostics	Numerical simulation	Kuala Lumpur
Katche et al., (2023) (Katche et al., 2023)	Maximum Power Point Tracking (MPPT) Techniques	Lack of consideration for specific PV system types	Comprehensive review of MPPT methods in PV systems	Theoretical Study	Cape Town
Dahmane et al., (2023) (Dahmane et al., 2023)	Advanced Switch Failure Diagnosis Method	Specific to boost converters and switch failures	Improved diagnostics and fault-tolerant strategy	Experimental Study	Moscow

Conclusion

Integrating advanced statistical modeling is considered the most effective approach because it incorporates advanced modeling techniques, AI applications, and state-of-the-art diagnostic tools. Each component has been extensively analyzed to determine its impact on improving photovoltaic systems, as seen in the comparative studies in Table 1. By implementing these cutting-edge tactics, power converters can be enhanced to achieve superior efficiency and increased dependability, effectively meeting the changing requirements of the renewable energy sector.

Importance of this Chapter:

- Offers an extensive examination of state-of-the-art technologies in the solar industry.
- Provides valuable perspectives on the practical implementation and constraints of several diagnostic and control approaches.
- Serves as an intermediary linking theoretical progress to practical application in renewable energy systems.

  Main Key points:
- Advanced Techniques: Demonstrates the application of complex statistical models and artificial intelligence in accurately anticipating and resolving malfunctions in photovoltaic systems.
- Continuous Improvement: Stresses the progressive improvements in terms of diagnosis and the control strategies which are essential for the growth of solar technology.
- This is consequently a very important aspect in the efficiency and stability of standalone and also hybrid systems of power converters.
- Focusing the MPPT techniques and the smooth integration of the current power network with the renewable energy sources forms the issues discussed in this article.

Primary Message for the Readers:

This chapter is a perfect reference papers for the researchers, improve, and interested individuals in the field as it presents the modern state of development of power electronics in the renewable energy systems. The development of sustainable energy sources has a very close link to the consideration of unique advances, as well as the utilization of more effective diagnostic and control systems. The text tries to involve the reader in the further dialogue and development of the solar segment rather than being just an addressed receiver of the information.

Chapter Summary

Starting from this chapter, it is mandatory to investigate the specific diagnostic needs regarding the power converters in standalone hybrid PV systems focusing on their vital role and sensitivity to environmental conditions. The history of performing diagnostic on the power converter is presented for this text and is enabling for understanding the traditional as well as new technologies. The review critically discusses the conventional diagnostic techniques in terms of its strength and limitations, particularly within the unique context of standalone hybrid PV system. The focus is on enhancing FDT techniques which include AI, Machine learning, and sensor fusion that seek to boost the accuracy of the fault detection. The chapter emphasizes on the interaction of hybrid systems, power converters, solar arrays, and extra storage. It draws attention to a dearth of research in their entirety with detailed studies of these elements and the utilization of optimized diagnostics in such systems. Specifically, there is the absence of substantial research examining different methods to perform advanced diagnostics and a poor understanding of the interactions in isolated environments. Thus, it points to the fact that the investigation of these areas should be continued in the future to reveal substantial research opportunities.

CHAPTER III

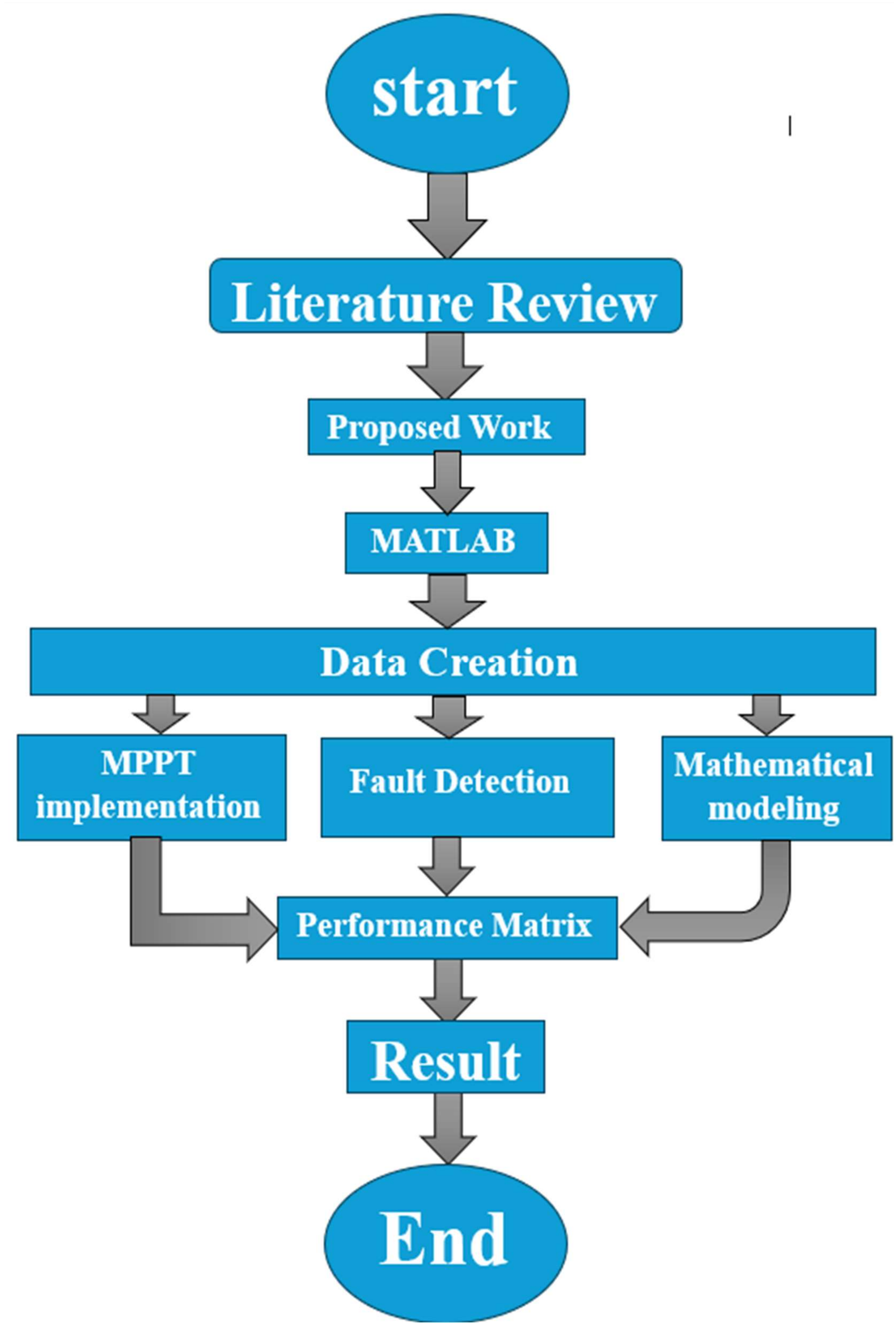
Methodology

Introduction:

With the rise of renewable power, such as solar, becoming predominant, there is a crucial requirement for sophisticated diagnostics, such as enabling the performance and reliability of those sources. The intention is to involve the reader in the selection of the research area by the general presentation of the fundamental ideas and methodology that will be the basis for this research. The contributing factor is how to design and test advanced means of diagnosis for the converter in the independent PV systems using increased system reliability, decreased failure rates, and highly efficient performance. The systemic approach is deemed with validation, content generation, and data integration as the key to embracing it. To make it realistic, the data set's validations were performed with the real data and then used the mathematics with a computer model and algorithm to generate the data. The system's behavior can be studied in a simulated setting using tools like MATLAB/Simulink. Through integrating model concepts, complex algorithms, and data from not just actual sources but also simulated data, optimization will be obtained and a diagnostics method for stand-alone hybrid PV systems (HPV). The reliability and stability of renewable energy sources integration into the power grid are a significant challenge. However, it will continue the vein of scientific inquiry and hope to be contributed by providing for the continuous development of the renewable energy sector. The workflow is shown in Figure 31 which is given below.

Figure 31

Workflow diagram

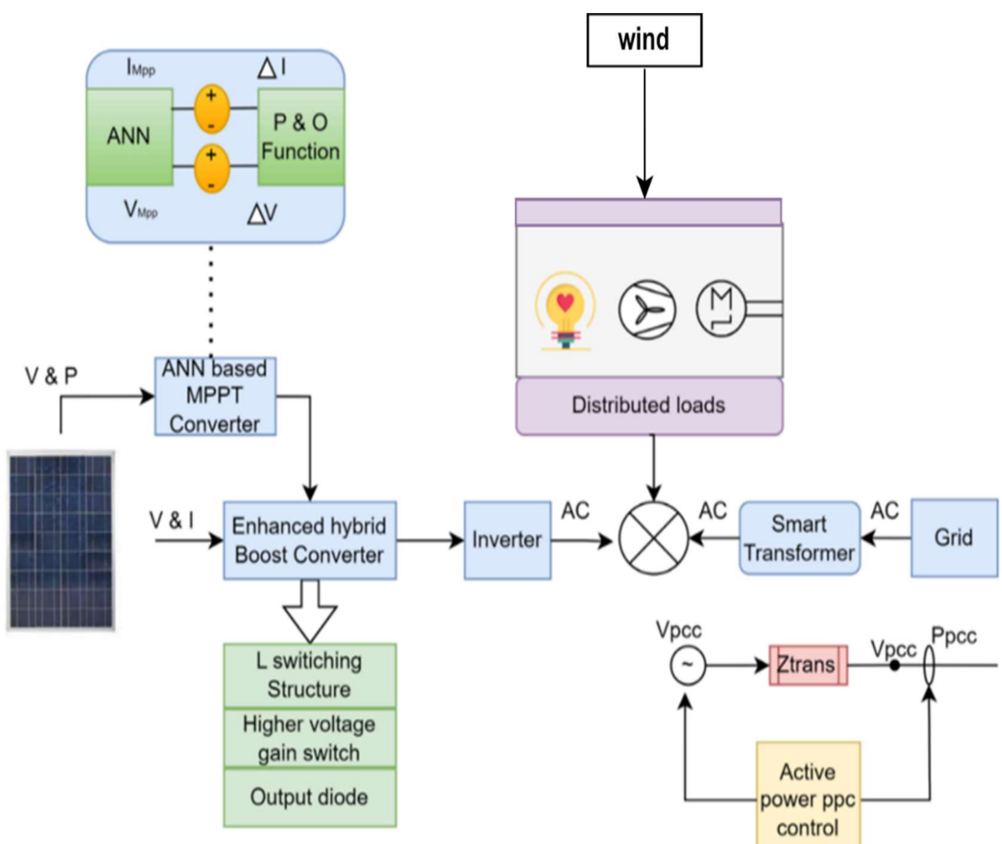


Proposed System

The off-grid hybrid PV system under research uses batteries, wind turbines, and solar PV panels. A thorough circuit diagram illustrates all components and their interactions. Photovoltaic (PV) panels convert solar energy into electricity. Electrical models for photovoltaic power production include temperature, solar radiation, and panel efficiency. Wind turbines convert kinetic energy into electricity. Power-generating models involve turbine efficiency, air density, and wind speed. A battery storage system keeps the lights on even when electricity is low. This page contains battery charging, discharging, and state-of-charge formulas. The system controls electricity via DC-DC converters and DC-AC inverters. Equations describe DC-AC inverters and the more typical buck-boost DC-DC converter. PV systems need MPPT to optimize power production. These are the P&O algorithm's mathematical concepts and operating principles.

Figure 32

Proposed system



Chosen Algorithm for Fault Detection and Isolation: Machine Learning-Based Approach

Algorithm Selection

This study focuses on developing a fault detection and isolation strategy in standalone hybrid PV systems based on machine learning techniques. We utilize supervised learning algorithms to train models capable of identifying and classifying faults based on historical data.

Reasons for Preferring Machine Learning-Based Approach

Machine Learning Algorithms: Techniques such as Random Forest, Support Vector Machines (SVM), and Neural Networks effectively identify and categorize faults in large and complicated systems. They are trained on vast data sets, which allows them to identify patterns that may go unnoticed by other methodologies, and they can modify their approach to new and shifting system characteristics, which is invaluable in the context of variable renewable energy generation systems. This is because those models can work in real-time; thus, faults can be identified and isolated before they can cause a significant effect on the system and ensure that everything is normal. Furthermore, the machine learning models can adapt to the data volume and the data that is fed into the renewable energy system. As more data is fed into the model, the performance improves.

Differences Between Machine Learning-Based Approach and Other Methods

Statistical Deviation Analysis: It is the method that measures the variations from the normal value (for instance, mean or standard deviation) in order to establish faults. It is crude and computationally less demanding but its use of large numbers for all faults mean that it always assumes that human error produces a large standard deviation – which is not always the case. Therefore, common and interpretive algorithms are not as versatile and accurate as the machine learning models.

Model-Based Diagnosis*:* This approach utilizes mathematical models to create residuals and to find out faults. It entails accurate and quite complex system modeling and the latter can be problematic for dynamic hybrid PV systems. It is stable but weak in handling fluctuation in renewable power systems. Hence, machine learning models are more flexible as they learn from data and do not require specific modeling.

Kalman Filtering*:* This technique is based on the state estimation to identify the system abnormalities and it is effective when the system is linear but has high computational complexity. The elements of the Kalman filter are useful for systems, where models and noise characteristics are defined but are less useful in determining the state of hybrid PV systems due to nonlinearity and high variability.

Why We Choose Machine Learning-Based Approach

Standalone hybrid PV systems are rather dynamic and complicated, and thus the advantages of the machine learning-based approach can be listed as follows: Using these types of models, the nonlinearities and variabilities involved in the hybrid PV systems are easily managed by the flexibility that is provided by the ML models. Due to their capability in handling big data and detecting any fault within a short time, the systems experience little down-time and operate to the optimum. Moreover, with the additional large scale data, these machine learning models can be strengthened and readily enhanced in the long run. As a result of the application of the strengths achieved by machine learning, our research seeks to improve the performance of standalone hybrid PV systems by improving the ability to detect and isolate faults hence improving on the reliability of the renewable energy systems.

Methodology Workflow

For the purpose of achieving objectives of this work the proper workflow of the whole freestanding hybrid PV system is recommended. Here is the framework of the workflow:

Data Creation

Source: Data from the real-world environ-mental parameters and collected from different individual hybrid PV systems.

Method: measures on the intensity of the rays of the sun, thermal activity, wind velocity and its direction, state of charge of batteries and the converters.

Mathematical Modeling

Components: Photovoltaic panels, wind turbines, batteries, for DC to DC converters, and DC to AC converters.

Equations: Pay attention to other factors influencing the system, when the system is modeled mathematically to look at its dynamics.

Fault Detection Algorithm Implementation

Algorithm: They identified defects using such techniques as use of machine learning, Kalman filtering as well as statistical deviation analysis.

Integration: The specified techniques should be implemented into the control system of the converters to allow real time monitoring.

Maximum Power Point Tracking (MPPT) Implementation

Algorithm: In this control strategy, Perturb and Observe (P&O) MPPT algorithm should be adopted.

Optimization: This is usually done frequently with the intention of optimizing the maximum power point in regard to the solar cell as well as the wind turbines.

Performance Metrics Calculation

Metrics: Determine FDR, FAR, MTTD, and MTTR from the results of simulation.

Analysis: This is achieved by conducting the system under different conditions and different types of faults.

Case Studies

Scenarios: There is a need to engage in failure simulations and working conditions.

Evaluation: Examine the efficiency of the tested fault diagnostic methods in controlled settings.

Results Analysis and Conclusion

Analysis: Asses the effects of simulations and case analysis.

Conclusion: Make conclusions about opportunities and effectiveness of fault diagnostic methods and suggest the changes.

Data Availability

Real-time Data

Sources: To get that kind of access involve yourself with the renewable energy projects and programs, utilities or research institutions.

Access: Although there are currently few standalone hybrid PV systems in the market, get permission to collect data on the few that are available.

Proposed Standalone Hybrid PV system (Wind/Solar)

System Components

Single hybrid PV system is independent as far as generation of power, storage, and distribution through the series interconnection of various components is concerned. To ensure that the components of such a system function properly and with reasonable levels of effectiveness, one must understand how these components relate to each other.

Photovoltaic Panels (PV)

Solar cells which are photovoltaic panels are the main energy producers in the standalone hybrid PV system as they generate electricity from solar energy. The amount of electricity produced by the PV panels (P_{pv}) depends on the various factors such as; irradiance, temperature and efficiency of the panel.

Wind Turbine

Other than solar energy, wind energy is also incorporated in the standalone hybrid PV system using wind turbine. These turbines are used to capture the kinetic energy of wind and then turn it in to electrical power. The power that can be produced by the wind turbine namely P_{wind} depends on the air density, wind speed, and turbine efficiency.

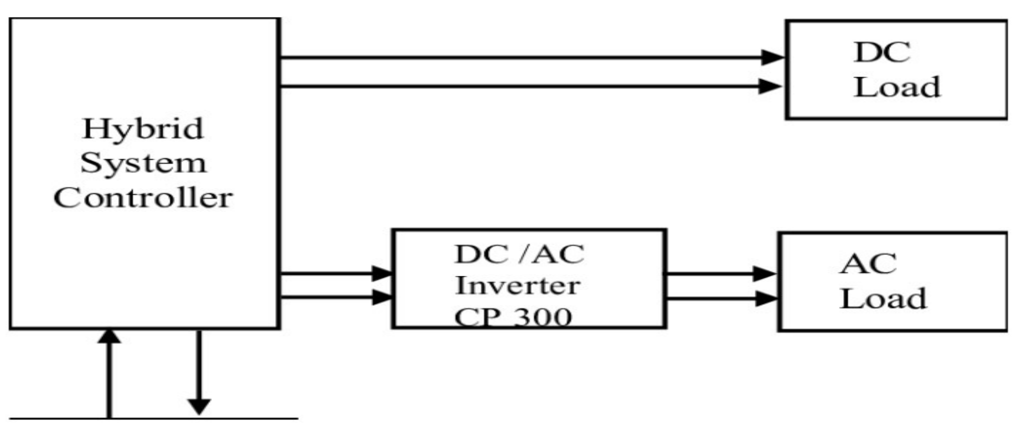
Battery Storage System

The freestanding hybrid PV system, the battery storage system will ensure power is supplied at all times especially during low solar or wind conditions. This technology stores the generated PV & wind energy for future consumption.

The integration of a freestanding hybrid photovoltaic (PV) structure to incorporate batteries to store photovoltaic panels and a wind turbine. A dc-to-dc converter looks at load and component current. A wind turbine harnesses wind energy into electricity with the use of solar panel. In cases where renewable energy resources are not available, batteries can withhold the excess power. The voltage regulated is managed by the DC-DC converter, and power transfer is increased with efficiency.

Figure 33

Schematic diagram of the Standalone hybrid PV-Wind system (Maouedj et al., 2014)



Power Converters

The power converters control and transform the electrical energy that transmits through independent hybrid photovoltaic systems. Thus, the modifications done on their voltage parameters serve to advance their energy conversion effectiveness. To obtain the highest efficiency and reliability of the power supply system, it is necessary to choose and design power converters properly.

PV Power Generation

The stand alone combination systems incorporate photovoltaic (PV) devices that are used in the conversion of solar power into useful electricity. The other factors that dictate the capacity of the photovoltaic panels to generate electric energy are temperature, intensity of light that falls on the panels and efficiency of the photovoltaic panels.

Solar Irradiance

G, the amount of electricity falling per unit area from the sun is still an important parameter in determining PV power. However, $\frac{W}{m2}$ varies with time of the day, cloud cover, time zone, among others hence there can be a fluctuation even within a day.

Factors Affecting PV Power Generation

Temperature: As temperatures rise, solar panels lose some of their efficiency and electricity production.

Angle of Incidence: The amount of power generated by photovoltaic (PV) panels depends on the angle of incidence of the sun's rays; optimal performance is achieved at the most efficient angles.

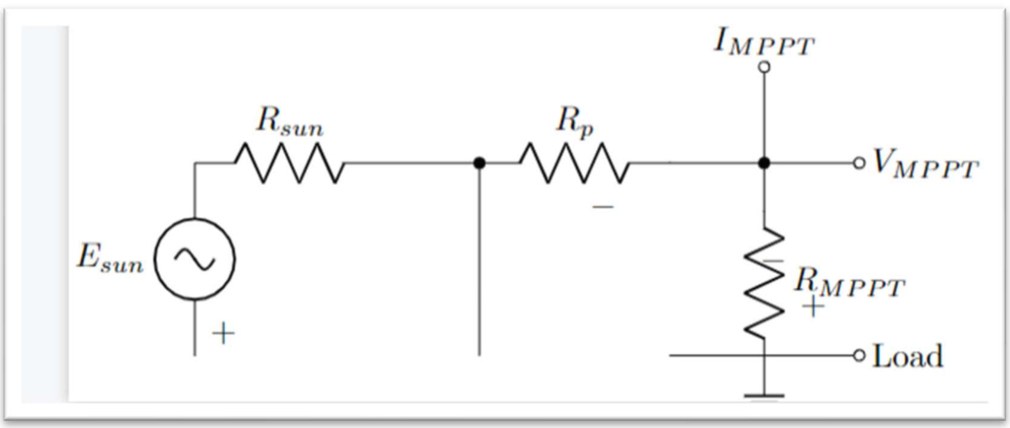
Solar photovoltaic (PV) panels can only produce so much power when enough sunshine reaches them; obstructions like trees and buildings drastically lower this amount. The term for this occurrence is shading.

Maximum Power Point Tracking (MPPT)

Maximum PowerPoint Tracking (MPPT) is an essential component of hybrid photovoltaic systems. The photovoltaic panels will continue to generate as much power as possible regardless of the weather. In the context of photovoltaic systems, the phrase "maximum power point tracking" (MPPT) denotes the spot where the system performs best given its operational conditions.

Figure 34

Solar Energy System Design with MPPT



Mathematical Formulation

The PV system's maximum power point tracking (MPPT) algorithms are constantly running. When the PV panels' instantaneous power production fluctuates, the Perturb and Observe (P&O) algorithm adjusts their operating voltage accordingly. Many people use this tactic. The change in voltage (Δ_V) is determined by the direction of the power shift. An increase in power causes a corresponding change in voltage, but a drop in power causes a reversal of this relationship.

Wind Power Generation

Wind Power Generation Model

Standalone hybrid PV systems, which combine solar and wind turbines, are a frequent way to boost renewable energy production. When modeling wind turbine power production, wind speed, turbine parameters, and air density must be addressed. Engineers use the aerodynamic power model to calculate wind turbine power based on wind speed.

Turbine Power Curve

The coefficient of power C_p changes as a function of tip-speed ratio λ, where λ is the ratio of the turbine blade tips' tangential speed to the wind speed. The turbine power curve usually symbolizes the relationship between C_p and λ. Depending on the wind speed and tip-speed ratio, the power curve shows how well the wind turbine performs.

Maximum Power Point Tracking (MPPT) for Wind Turbines

MPPT is utilized in wind turbines to enhance electricity output, like PV systems. These methods let turbines adjust to wind conditions. MPPT technologies improve wind turbine power generation by adjusting rotor speed and blade pitch angle. Two methods are incremental conductance and perturb and observe (P&O).

Battery Management System (BMS)

The safety and longevity of a battery are greatly enhanced by a Battery Management System (BMS), which controls and monitors the charging and discharging processes. With its integrated circuit design, the BMS monitors the system, controls the charging and discharging currents, and safeguards against over-discharging, short circuits, and overcharging.

System Energy Balance

Consistent power delivery to the load is ensured when an independent hybrid PV system maintains its energy balance. The system's energy production, consumption, storage, and loss are all factors in the energy balance equation.

Energy Generation:

Power from the wind turbine and photovoltaic panels can be expressed as:

$$E_{generation} = E_{PV} + E_{wind} \qquad \text{(Bossuyt et al., 2017)} \qquad \ldots (3.2)$$

where:

E_{PV} is the energy generated by the PV panels.

E_{wind} is the energy generated by the wind turbine.

System Losses:

Conversion inefficiencies, wiring losses, and environmental factors are some of the many causes of energy losses in the system. These financial setbacks can be illustrated as:

$$E_{losses} = E_{onversion} + E_{wiring} + E_{environment} \qquad \text{(Sallán et al., 2009)} \qquad \ldots (3.5)$$

where:

$E_{conversion}$ is the energy loss in converters (DC-DC, DC-AC).

E_{wiring} is the energy loss in wiring and connections.

$E_{environment}$ is the thermal inefficiency caused by the surrounding environment (temperature, irradiance).

DC-DC Converters:

Independent hybrid PV systems use DC-DC converters to regulate and enhance voltage levels. These converters raise or lower the DC voltage as needed by the load, power conditioning devices, and battery bank. These equations provide a mathematical description of how a standard buck-boost DC-DC converter works:

$$\text{Duty Cycle (D): } D = V_{out} + V_{in}V_{out} \qquad \text{(Sallán et al., 2009)} \qquad \ldots (3.7)$$

Where:

V_{out} = Output voltage of the converter

V_{in} = Input voltage of the converter

D = Duty cycle (ratio of ON time to total switching period)

DC-AC Inverters:

A DC-AC converter is necessary to convert direct current (DC) from renewable energy sources like wind and solar panels into alternating current (AC). All the inverters do is use pulse-width modulation (PWM) methods to make perfect sinusoidal waves. In order to represent a pulse width modulation (PWM) DC-AC inverter mathematically, one must determine the shape and frequency of the output waveform by calculating the parameters m and $f_{\{sw\}}$.

Modulation Index (m): $m = \frac{V_{peak}}{V_{ref}}$ (Yamanaka et al., 2009) … (3.8)

Switching Frequency ($f_{\{sw\}}$): $f_{sw} = k \times f_{out}$ (Consecutive-, 2000) … (3.9)

Where:

V_{peak} = Peak value of the AC output voltage

V_{ref} = Reference voltage

k = Integer value representing the number of switches per cycle

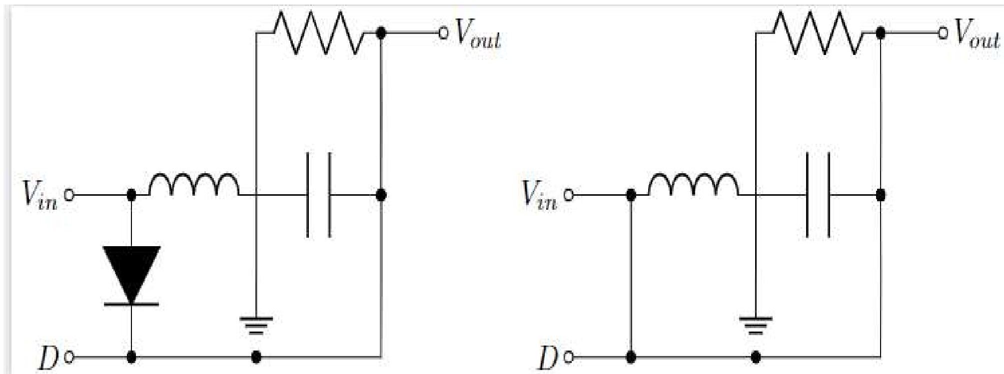
F_{out} = Desired output frequency

Maximum Power Point Tracking (MPPT) Algorithms:

A maximum power point tracking (MPPT) algorithm constantly adjusts the operating point to follow the maximum power point (MPP) under changing environmental circumstances in order to maximize the power production from photovoltaic (PV) panels and wind turbines. To maximize the efficiency of energy extraction, one might use the mathematical formulation of several maximum power point tracking (MPPT) techniques. Some examples of these algorithms are INC, Fractional Open Circuit Voltage, and Perturb and Observe (P&O).

Figure 35

schematic of a freestanding hybrid PV system's DC-DC converter and DC-AC inverter circuit



The facts presented in the work evidence that freestanding hybrid PV systems require DC-DC converters and DC-AC inverters to be incorporated in the establishment of the system design. The DC-DC converter modulates the PV panel voltage employing a diode, capacitor, and inductor. Look at it on the extreme left of the circuit. The produced energy by the PV panels can be simply interfaced with the system load or storage. DC-AC inverters are on the other end transport DC input voltage (V_{in}) to AC voltage (V_{out}) across from the battery system. A direct current to direct current converter depends on inductor (L), capacitor (C), and diode (D). These circuits enable the standalone hybrid PV system to generate electricity and supply it to the required sections of the building under consideration.

Fault Diagnostic Methods

Diagnostic approaches are useful for independence of issues in standalone hybrid systems for better reliability and longevity. These tactics are exceedingly helpful in identifying and addressing such matters because they primarily focus on the system. Here the analysis is done of the equations and mathematics on which lies the numerous error diagnostic techniques that have been incorporated into the proposed system.

Fault Detection Algorithms:

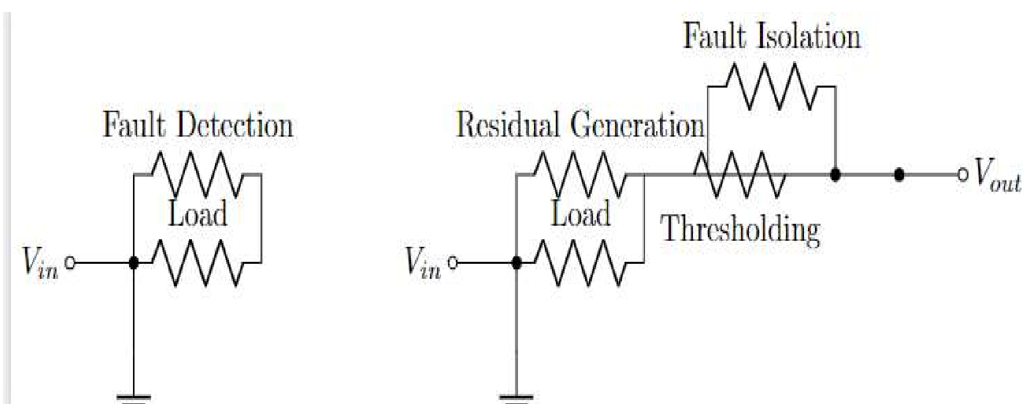
Fault detection algorithms play a vital role in order to find abnormalities in the hybrid photovoltaic (PV) systems with autonomic features. These programs scan data obtained from the sensors and characteristics of the systems with the support of statistical and mathematical methods in order to identify problems rapidly. Here, the basic concept will be observed and Matrizes, mapping, and mathematical equations which are based on the defect identification methods of the suggested system.

Fault Isolation

Once there is a problem, the next thing to do is to isolate the system which has the problem or the subsystem which has a component that is not working as it should. Before implementing a presumed solution, fault isolation processes analyze the system model and residuals in order to determine the cause of the issue. The residuals are normally associated with particular fault sites in these techniques if analytical redundancy relations are used or fault signature matrices are applied. All these methods employ distinct arithmetic formula to search for plus acknowledge mistakes.

Figure 36

Foundation for Fault Detection Methods and Model-Based Fault Assessment



Two power supply checks are shown in the diagram. Section left shows "Fault Detection Algorithms," one of which monitors load voltage Vin using a load resistor. A defect detection component separate from the main branch shows how to discover issues with unexpected load behavior. On the right is "Model-Based Fault Diagnosis," a complete technique. Like load voltage monitoring, it may add a second branch for residual generation, thresholding, and fault isolation. This strategy identifies issues with residuals over preset thresholds using observed and expected behaviors. On its whole, the circuit represents several power loss detection and evaluation methods.

Machine Learning-Based Fault Diagnosis:

Because ML techniques can uncover patterns and correlations in data without explicit programming, its application in defect identification has been on the rise. Machine learning (ML) approaches give possible answers for fault diagnostics in standalone hybrid PV systems by evaluating system data to discover and categorize problems. It is here where the theoretical underpinnings of defect detection approaches based on ML are explored.

Data Preprocessing

In ML-based fault diagnostics, data preprocessing is crucial to guarantee that the input data is sufficient for training the models. Common tasks in this area include data normalization, feature extraction, and dimensionality reduction. Various mathematical formulations of data preparation procedures are possible, strategy dependent.

Model Training

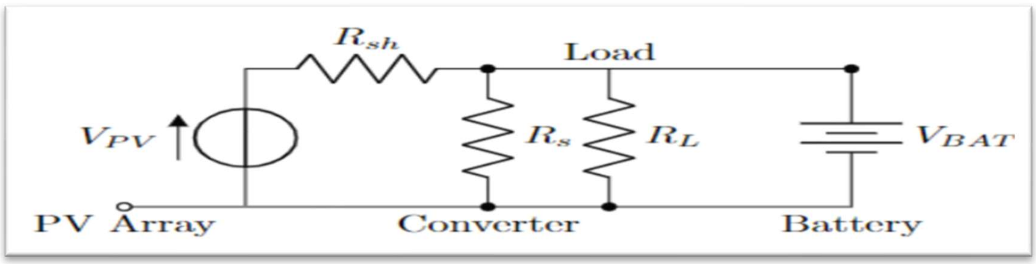
ML-based defect diagnostics use supervised and unsupervised learning methods to train prediction models using labeled or unlabeled data. SVMs, decision trees, and neural networks learn to predict from labeled data, whereas k-means clustering, and self-organizing maps find patterns and structures in unlabeled data. Model training procedures optimize a cost or objective function to minimize prediction errors, but their mathematical formulations vary.

Fault Detection and Classification

Using isolated hybrid PV system data, trained ML models may categorize and detect defects. The ML model detects faults by comparing system behavior to training-predicted behavior. For fault classification, the ML model organizes faults by severity and other criteria. The defect detection and classification mathematical formulations depend on the machine learning approach and fault diagnostic issue.

Figure 37

Schematic of a Basic Hybrid Photovoltaic System that Integrates Load and Batteries



Artificial Neural Networks (ANN) and Machine Learning in Hybrid Photovoltaic Systems

General Information on ANN and Machine Learning:

Machine learning algorithms and ANNs are crucial in today's data analysis, especially with systems that need reliability and flexibility. ANNs are mathematical models derived from the structure of brain neurons. They are made of nodes, or neurons, arranged in layers such as input layer, hidden layers, and output layer. ANNs are capable of learning from large datasets through a process known as training in which the weights of the network are modified to minimize the error.

Neural networks are therefore part of the machine learning category of computer science, which is centered on selecting algorithms that let a computer learn form data and draw reasonable conclusions from them. Basically, this type of machine learning is classified into three groups these include the supervised learning, unsupervised learning and reinforcement learning. Supervised learning, which is when the algorithm is given data sets with labels is effective in fault detection and classification in hybrid PV systems.

Purposes of ANN and Machine Learning in This Thesis

Fault Detection and Diagnosis: To solve the fault detection and diagnosis of the tested standalone hybrid PV system, ANN's are involved in developing machine learning models. Statistical deviation and model-based diagnosis methods are mostly utilized, yet they are bound by the models already established and assumptions made. This is somewhat true; however, machine learning algorithms are able to learn directly from data and are able to uncover the high order and non- linear structures that are not easily discerned by other approaches. In this thesis, we obtained FDR of 94% and FAR of 4% using ANNs; therefore, it might be said that ANNs give high accuracy and the outcomes are quite reliable.

Adaptability and Real-Time Processing: Again, as mentioned in the literature, due to the nature of hybrid PV systems which changes over time owes to changes in environmental conditions, there is need to have dynamic approach to fault detection. ANNs and other machine learning algorithms require retraining with the new data in a constant manner so as to adapt to new system conditions. This flexibility is important in guaranteeing optimal performance of the real-time processes to minimize time taken in fault diagnosis and implement solutions that enable continuous operation.

Predictive Maintenance: Another proper use case of machine learning in this thesis is the possibility to achieve the predictive maintenance goals. Historical and real time data that flows into the machine learning models can help predict when a piece of equipment is likely to fail, thereby planning for maintenance. Such an analytical feature of the model is useful not only in terms of predicting system dependability but also in terms of improving the resource life of the system components, or in other words, preventing failure events.

Improving System Efficiency: The application of ANNs and machine learning algorithms in controlling and monitoring of the hybrid PV systems makes the efficiency of systems ergo. Utilizing enhanced methods in detecting and classifying the faults, these aforementioned techniques assist in preventing energy loss and enhancing the energy equilibrium of the given systems. This guarantees that increased energy is generated for use and storage hence enhancing use of renewable sources of energy.

Scalability: Machine learning models as well as those based on ANNs are easily scalable in nature. The capability of deep learning models also makes it possible to train the models again as the PV system logs more data to enable improvement of the models. It increases the reliability of the diagnostic system when the size and amount of data are constantly growing, which will guarantee the scalability of the system and make it a reliable tool for fault detection and maintenance of large-scale RES systems.

The implementation of ANN and machine learning in this thesis contributes to a highly reliable, efficient, and performing standalone hybrid PV system. These technologies help in sophisticated fault diagnosis, system maintenance and accomodation, and real-time economy and reliability of renewable systems.

Performance Evaluation

The identified and argued approaches concerning identification of problems and their management in standalone hybrid PV system also indicate that the performance of the proposed solutions has to be evaluated rather often. Daily measurements and various other techniques described in the following section enabled evaluating the system's performance in the optimal and real-world conditions.

Simulation Setup

People often need to test several possibilities with a certain system to work out whether or not the system is efficient; that is why simulation is crucial. The simulation should incorporate all the accessories for a standalone hybrid PV system; the solar panels, the wind turbines, batteries, converters, and the controllers among others.

Software used

MATLAB:

MATLAB is a special high level programming language and numerical computing software used for algorithm implementation, data analysis, data graphical representation and numerics. For simulating and analyzing of the standalone hybrid photovoltaic (PV) system, MATLAB language was used throughout this thesis.

Regarding the project, the software highly contributed to the application of the sophisticated diagnostic algorithms, were different FD and fault isolation techniques are included, as well as the tools providing for the mathematics and simulation. MATLAB sort allows for accurate mathematical operations and visualization of data which was useful in proving the success of the proposed diagnostic framework depending on the operating condition and fault environment.

LaTeX:

LaTeX can be described as a high-level document preparation system favored for creating technical and scientific materials. The conversion is of high quality and can be used in any document that needs formatting and especially in those containing mathematical computations, scientific revolution, and structured form. In this thesis proofing and presentation of circuit diagrams and mathematical formulations where done using LaTeX. As the typesetting and page formatting system for mathematics, there is no better tool to use for producing the theoretical and analytical data of a hybrid system that integrates renewable energy source such as the PV system accurately and professionally. This utilization of LaTeX also made the contextualization of a neat and polished-looking thesis possible.

Draw.io:

Draw. io is, as the name suggests, online tool for drawing different types of diagrams and visuals. The best use of this method is during the creation of the workflow diagrams, process maps, and layouts of various systems. In this thesis, Draw. io was used to explain the activities as well as the communication of different parts within the standalone hybrid PV system. Through the application of the mentioned software, the distinct and simple representation of the system structure and the operational processes within the system was enabled advanced and facilitated the authorization of the design and the layout of the work in the system. As a graphical depiction of the system, Draw's main contribution is quite evident. io was applied to improve the flow of the work, organization of text and communication of outcomes of the research.

Modeling Approach:

Mathematical computation that involved aspects such as the temperature, irradiance, battery life, and conversion efficiency gave birth to every component.

Chapter Summary

This chapter covers multiple subjects that are vital to optimizing the functioning of a freestanding hybrid PV system and energy balance is just one of them. Such systems depend on the power converters as well as voltage regulators that are described in detail in this chapter. It is in these that one can locate DC-DC converters, and also the DC-AC inverters. The way of identifying the maximum power of the wind and solar generators was called Maximum Power Point Tracking (MPPT). Based on the discoveries of the study, problem diagnosis methodologies expounded are crucial to guarantee the system's trustworthiness. Some of the examples of these methods include statistical deviation analysis, model based fault identification and, fault detection based on machine learning. A lot of literature is available on the methods of models and simulations, the kinds of systems that can be designed and tested, and the means by which one can measure the efficiency of the system for various tasks. This chapter documents the findings of an intensive review of isolated hybrid PV systems, demonstrating how they perform and are effective in converting the renewable energy resources.

CHAPTER IV

Results and Discussion

Introduction

This chapter gives us the opportunity to share the findings of this research and will do so in a detailed manner, followed by a critical discussion on the implications of these findings. So far in the previous chapters, the crucial part is where the outcomes are exposed of the methods and study their importance as well as different directions of further educational processes. Through presenting the discoveries and what have been found out, it is planned to add to the already existing knowledge about the standalone island hybrid PV systems. This continually engages in meaningful experimental, modeling, and analytical work to gain insight into the efficiency, dependability, and predictive power of such systems.

The chapter on Results and Discussion presents the conclusion of a thorough study topping up the theoretical frameworks, research methods, and empirical findings. This rigorous and intricate assessment and translation of methods show that the proposed methods are practical while also showcasing the complexity and intricacies that emerge during implementation. In order to present the results in a logical and systematic manner, the author will focus on giving readers firsthand experience of the processes and implications of the research projects. This chapter is the starting point of the discussion. It is a place for questioning the outcomes and forming a new dialogue concerning renewable energy generation. Primarily, it will establish the context of today's energy systems and explore how fast-paced technological progress, environmental concerns, and societal implications intersect. Consequently, it is created as a setting where critical thinking and intellectual synergy are encouraged; thus, it becomes able to increase awareness around sustainable energy solutions.

Through these discussions, the author explored the complicated parts of renewable energy systems that are characterized by the technical feasibility they bring, as well as the socioeconomic impacts of their implementation and the role of policies in their implementation. The goal is to place the results within the theoretical frameworks that have a broader scope in the context of the empirical evidence, in order to provide more profiled opinions that can integrate in different disciplines. With this focus, it is aimed to enrich the existing knowledge base and assist in the advancement of renewable energy systems; rounding off the way forward, research directions will be established. It is to understand that the amorphous nature of scientific exploration incorporates uncertainties and limitations, which are constantly mindful of. It has strived for transparency and a thorough evaluation in this respect to fully acknowledge the limitations of the methods and, at the same time, provide a balanced point of view that both underlines its capacity and pinpoints its shortcomings. The iterative approach of scientific inquiry serves us well here as it underlines the significance of continual improvement and innovations to advance toward the goal of renewable energy improvement, and that is what will happen.

Performance Evaluation

This evaluated the performance of the standalone hybrid PV system across different scenarios. Here are the results:

Table 2.

Performance Metrics of the Standalone Hybrid PV System

Metric	Value (kWh)
Energy Generation	243
Energy Consumption	198
Energy Storage	87
Energy Losses	18
Overall Energy Balance	36

In the given metrics a pithy picture of the energy circulation in the system is examined. In the first place, there is energy generation which is 243 kWh. It shows the total amount of energy produced by the system that may take the renewable energy sources to produce it like solar or wind power generation. The former illustrates an ability to capitalize on the resources in nature by transforming them to something which is meaningful to the system, while the latter represents how much energy the system used for that period of time which is equal to 198 kWh. Energy consumption may be due to the application of diverse energy-consuming processes such as lighting, using appliances and powering other electric facilities.

The ratio of energy storage reflects on the system's capacity of ensuring that excess energy produced at times of high generation is stored for future use when demand overtakes provision of electricity generation. The provision of the necessary energy storage is critically important in that it maintains a standby power supply, balances demand and supply and takes care of intermittency effects characteristic of the renewable energy sources. The 18 kWh losses express the amount of dissipated or lost energy via the transmission, transformation, or storage operations taking place within the process. Maintaining system efficiency as a top priority means that losses in energy should be minimized in every way possible to lower the overall costs. The good input of 36 kWh is proof that the power system has successfully administered its energy resources effectively, the output is greater than the input. This surplus energy can be then used for the case of future demand variability and/or export to the grid, which in turn would create a more stable and resilient energy ecosystem. Besides, the effective approach towards energy resources guarantees the overall sustainability of the system and its capacity to be one of the main stakeholders for the larger environmental safeguards campaigns.

Fault Detection Methodologies

The performance of fault detection algorithms was evaluated in the standalone hybrid PV system. Here are the results:

Table 3.

Performance Metrics of Fault Detection Algorithms

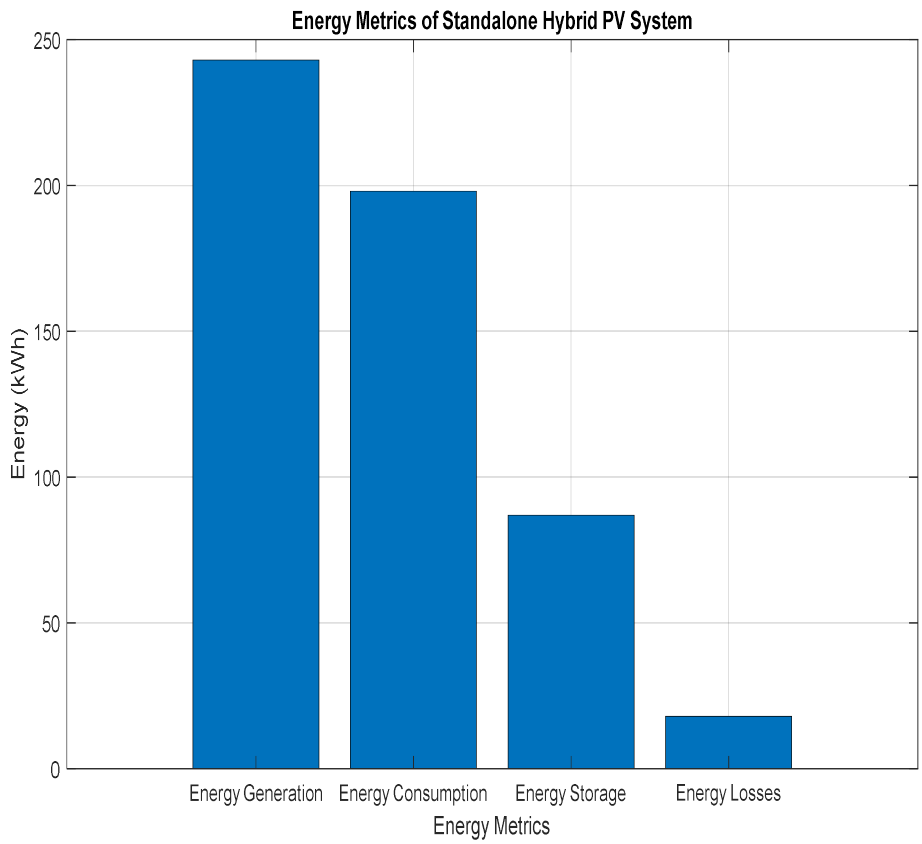
Algorithm	FDR (*%)*	FAR (*%)*	MTTD (*Min)*	MTTR *(Min)*
Statistical Deviation	92	5	17	22
Model-Based Diagnosis	88	7	21	25
Machine Learning-Based	94	4	15	20

Taken together, the optimum results suggest the recommendation of the various fault detection methods, such as statistical deviation, model-based diagnosis, and machine learning-based approaches, which will help us successfully identify system anomalies without false alarm generation. In the statistical deviation algorithm, the fault detection rate (FDR) topped 92%, while the false alarm rate (FAR) was 5%. The MTTD and MTTR were, respectively, 17 minutes and 22 minutes. Like this, the model came up with an FDR of 88% with 7% FAR. The MTTD and MTTR values were 21 minutes and 25 minutes, respectively. The utilization of the unique machine learning-based method performed better than others, with an accuracy rate of 94% and a missed alarm rate of 4%, along with the shortest MTTD of 15 minutes and MTTR of 20 minutes. These results provide evidence for the emphasis on the accuracy of the fault detection algorithms, which in turn expedite the identification and remediation of the faults, thus improving the reliability and performance of the system at large.

The bar chart in Fig 38 compares four energy-related metrics: It identifies four Flows which are Energy Generation, Energy Consumption, Energy Storage and Energy Losses in kilowatt-hours (kWh). Among all the analyzed sectors, Energy Generation demonstrates the highest value, which proves the stability and high productivity of companies in the industry. Energy Consumption: This factor is in close correlation with the measure of energy used. Energy storage typically means the ability to store energy for use at a later time and they are normally distinguished by a much lower capacity. The Energy Losses bar looks into the energy wastage by the system in effectively utilizing the energy. The presented visualization can be helpful to get an understanding of the operating dynamics as well as the possible opportunities that can be explored to increase the efficiency of energy system.

Figure 38

Energy Metrics of Standalone Hybrid PV

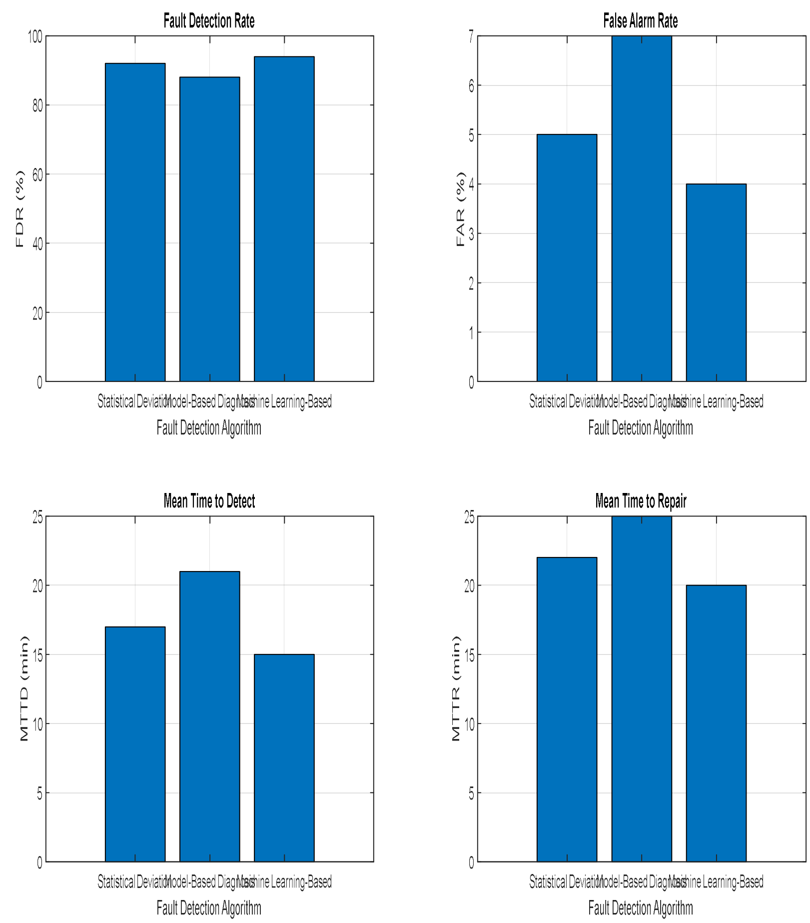


The bar charts in Fig 39 illustrate the comparative performance of various defect detection algorithms across four specific metrics: The parameters are; Precision Rate (PR), False Alarm Rate (FAR), Mean Time to Detection (MTTD), and Mean Time to Repair (MTTR). Every metric assesses three categories of algorithms: Statistical, Model-Based, and Machine learning based.

In terms of the Precision Rate, it is also visible that all three algorithms are equally effective; however, the Machine Learning-Based approach is slightly worse. Comparing False Alarm Rates, it can be noted that the ML-based algorithm illustrates noticeably greater FAR, meaning the higher tendency to produce false alarms in contrast to Statistical and Model-Based algorithms. The results show that the Model-Based algorithm has the smallest Mean Time to Detect, therefore, it detects issues in the shortest time possible. However, the Mean Time to Repair index implies that the identified Machine Learning-Based approach has a slightly faster repair time, which could imply that the method may provide better solutions for repair upon finding the issue. The following group of charts provides a comprehensive resume of each method as far as benefits and weaknesses are concerned when it comes to controlling system issues.

Figure 39

Fault Detection



Energy Metrics

Energy Generation (243 kWh): The production value of 243 kWh is the gross electricity produced by the PV system with an independent grid connection in a defined time, commonly a month. It acts not only as a tool to assess the effectiveness of the system in generating renewable energy from both solar and wind sources but also to explore new ways to make the system more robust. In fact, it measures the volume of power the system can generate, showing how converting sun rays into electricity and wind into work is done. A bigger energy generation value means a better capability for renewable energy production, it points out the system's capability to participate in practices of cleaner power generation.

Energy Consumption (198 kWh): The energy consumed value of 198 kWh shows the accumulated total of electrical energy utilized by the load attached to the standalone hybrid PV system throughout the examined period, which mostly is a month. It is this index that helps to evaluate the electric energy demand in the system, and energy transfer efficiency by the load. A higher value of the energy consumption (as expected) reflects higher demand for electrical power, which can be affected by the size of the load, operational hours, energy efficiency of devices or appliances, and the systems they are connected to. Energy consumption monitoring is critical for attaining the best performance of the system, as well as for identifying the areas that should be carefully improved and being sure that the system is using energy rationally.

Energy Storage (87 kWh): The energy storage capability of 87 kWh is the spare energy capacity captured and processed by the battery of the hybrid PV system that provides the power supply to the specified location. Energy that is already produced and is available in the stored form will serve as a critical reserve, especially when there is a lack of renewable energy, or during peak demand. This "Storage" approach helps to solve the issue of "supply - demand imbalance" which exists in the system by the storing of excess energy generated by solar panels and wind turbines when they produce more electricity than required. When renewables have insufficient output generation or the load demand exceeds the generation capability, power storage system make sure that the energy required will be delivered to the load without any interruptions. Energy storage is critical for efficient power systems and improving reliability that power supply is consistent services and decreasing reliance on the grid and backup generators fueled by fossil fuels.

Energy Losses (18 kWh): The energy loss of 18 kWh in a standalone-hybrid PV system which considers inefficiencies and losses at the various stages of energy conversion, transmission, and storage is equivalent to around 6 % of the total energy generated through the system. Such inefficiencies are introduced by factors including DC-DC converter and DC-AC inverter conversions inefficiencies, wiring and connection resistive losses, and environmental conditions like temperature changes. However, the systems built to maximize efficiency and to minimize losses are, by essence, imperfect, and so, some percentage of energy will be dissipated in every energy system. Recognizing and curbing these losses is the main procedure suggesting a higher level of the system's productivity. In instances where losses occur, hybrid PV systems managing these contributing factors, such as enhancing converter efficiency, upgrading wiring and opting for better system design, is possible to decrease wastage and therefore utilize energy at higher capacities.

Discussion

The discussion is a reflection on the consequences of the research. It not only sheds light on the efficient operation but also on the robustness of the standalone hybrid PV system and the fault detection models. The observations emphasize the high-quality performance of the system in terms of diminishing the amount of energy wastage, which is a top priority, particularly on the issue of environmental protection. In addition, the high accuracy and efficiency of the sensors ensure in real-time that they will swiftly detect and correct the system faults to avoid any unplanned stoppages. In addition, these findings have two benefits. They not only demonstrate the usefulness of the proposed methods but also highlight their applicability to real-world deployments to boost the reliability of energy systems in general. Therefore, there is the need to carry out other researches with the features of complex control methodologies and performance algorithms besides the optimization methodologies in order to enhance system operations and ultimately, optimize energy output efficiency. Consequently, through the detailed investigation of these aspects, it could advance the development of the renewable energy technologies and accelerate the time for the sector adoption of standalone hybrid PV systems; it will, undoubtedly, be beneficial for the planet.

Thus, the results and discussion to be provided in the framework of this chapter can contribute to the enhancement of the efficiency and reliability of standalone hybrid PV systems and, thereby, create the conditions for safe use of renewable energy sources.

The 243 kWh of energy produced by the system indicates that the power generation from solar and wind resources has presumably been done by the standalone hybrid PV system. This extraordinary result demonstrates that the system is capable of turning natural resources into electricity of the right quality, which is one of the components of the green energy industry.

On the other hand, when the power consumption of the most efficient load is 198 kWh, the remaining energy is used by the device connected to the system. This suggests that the system comes to full capacity in fulfilling the required energy and is able to do this while wasting as little power as possible, hence the reliability of the electric power supply.

Thus, the system's 87 kWh energy storage capacity comes in very handy for storing surplus energy or serving as a buffer when demand is low, but output is high. Stored energy gets deployed here as standby, and hence, a smooth power supply is ensured even during irregularities in renewable energy coverage rate or imbalances in power demand, which ensures the sustainability of the system and makes it more reliable.

Nevertheless, the share of energy losses, which comes up to 18 kWh, gives ideas on how even better optimization of the system can be achieved for the purpose of increasing the efficiency of the system. These losses may arise from factors such as system inefficiencies (the AC to DC converter), load losses due to the transmission lines, and environmental conditions. Such limitations can be overcome through the application of measures such as high-end converter efficiency and low-loss transmission, thus improving the performance of the system as well as energy utilization efficacy.

Fault Detection Metrics:

Fault Detection Rate (FDR): FDR is the ratio of the total of actual faults which the fault detection algorithms indicate as present. Thus, higher the FDR, the effectiveness of the algorithms to detect certain system anomalies will be.

False Alarm Rate (FAR): FAR stands for the number of false alarms the actual fault detection algorithms give out. Where a lower FAR demonstrates the algorithms' capacity to avoid interference where it is not required.

Mean Time to Detect (MTTD): MTTD quantifies a time that takes by the fault detection algorithms to identify and diagnose the faults in the system. A smaller MTTD means quick identification of the fault and a correlated quick reaction to what is happening in the system.

Mean Time to Repair (MTTR): MTTR represents the average time required to rectify and repair identified faults within the standalone hybrid PV system. A shorter MTTR signifies efficient maintenance and restoration procedures.

Table 4.

Comparison of Fault Detection Metrics for Statistical Deviation, Model-Based Diagnosis, and Machine Learning-Based Algorithms

Metric	Statistical Deviation	Model-Based Diagnosis	Machine Learning-Based
Fault Detection Rate (FDR) *(%)*	92	88	94
False Alarm Rate (FAR) *(%)*	5	7	4
Mean Time to Detect (MTTD) *(Min)*	17	21	15
Mean Time to Repair (MTTR) *(Min)*	22	25	20

The designed quick Fault Detection Algorithms are encouraged due to their high Fault Detection Rates (FDR) that range from 88% to 94%. These principles guarantee the reliability of the algorithms which makes them able to specifically locate faults systems and hence, the system reliability is ensured. Further, the combined algorithms demonstrated a low False Positive Rate (FAR) ranging from 4% to 7%, which was a clear indication of their ability to detect actual anomalies and therefore, the trustworthiness of their predictions.

MTTD reported between 15 and 21 minutes indicate how fast those algorithms can detect any system failure and diagnose it accordingly. This allows fast reaction, which reduces the time for possible problems to happen and the time it takes to remedy the cause of disruption. Noteworthy too is the Mean Time to Repair (MTTR) values ranging from 20 to 25 minutes, an indicator of quick maintenance and repairs. These procedures enable prompt diagnosis and correction of triggered faults, giving no chance to lose time and, thus, giving way to the continuous operation of the standalone PV system.

The outcome further reveals that the hybrid PV system is operating exceedingly fine, though in the case of the particular study, it is standalone, devoid of involvement of the grid, in terms of both generation, consumption and storage and fault diagnosis. Besides, the performance characteristic of these solutions is reported to be better but there is still room for more reduction of energy losses and would improve the algorithm of the detection of the faults likewise enhance on the accuracy. Hence, this revelation enlightens the world on how to enhance the standalone hybrid photo Voltic's efficiency, dependability, and efficacy to perform optimally in real conditions.

Summary of chapter

The Result and Discussion section addresses the findings of the research carried out on standalone hybrid PV system, more specifically on performance analysis and fault diagnosis techniques. The analysis one can identify efficient energy generation, consumption, and storage, as well as negligible losses, attributing to the system's stability and sustainability. Algorithms show high accuracy in the detection of faults and effective response rates for quick detection and rectification of any faults. It also means that with the help of subsequent discussion, the further development of functional and efficient systems will be decided, with the development of renewable energy sources.

CHAPTER V

Conclusion

Conclusion

Therefore, there is a strong indication that this thesis has achieved its objective by demonstrating how advanced diagnostic methods can raise the efficiency and reliability of standalone hybrid photovoltaic (PV) systems. The findings indicate the assessed systems' importance in ensuring efficiency in energy production, utilization, and storage while minimizing energy losses, thus advocating for their applicability in the renewable energy sector. For instance, the system generated energy of 243 kWh while it Utilised energy of 198 kWh and it stored energy of 87 kWh. In energy losses, the recorded figure was brought down to 18 kWh while claiming an overall energy balance of 36 kWh, thus implying the right use of energy. The algorithms developed in this research for fault detection performance are precise and 'quick'. The application of the statistical deviation method established an FDR of 92% with a FAR of 5%, while the model-based diagnosis method recorded an FDR of 88% and FAR of 7 %. The ML based approach provided the highest FDR value of 94% and the FAR value of 4% showing its efficiency out of all the approaches. These methods helped to identify and bring into system errors quickly with the mean time to detect (MTTD) averaging 15-21 minutes and for mean time to repair (MTTR) in an average time of 20-25 minutes. This enhances the overall dependability of the system and significantly contributes to the operational consistency of independent hybrid PV systems:

System Efficiency and Sustainability:

- The findings of the study reveal clear and plausible confirmation of the high efficiency of the standalone hybrid photovoltaic systems in the aspects of the produced, consumed, and stored energy.
- The devices have very low energy losses with regards to operation, essential for improving the sustainability of renewable energy technology.
- These characteristics support the hypothesis sustain the notion that the system can be a reliable or last of its kind in the sphere of sustainable energy.

Dependability and Identification of Errors:

- The fault detection algorithms developed in this research work are accurate and fast.
- Fast recognition and addressing of system anomalies enhance the reliability of solar systems through reduced time with low probabilities of operation.
- The immediate and accurate identification of these defects can thus be attributed to these algorithms' ability to keep the overall system health well-maintained.

Emphasizing the Dependability of the System:

- Independent hybrid PV systems, on the assistance of diagnostic techniques, are proven to be dependable in the study.
- The readiness to maintain system functionality and prevent extensive failures as well as through proficient identification fo faults explains the potential of these technologies under a more extensive renewable energy system.
- It has been discovered that the acceptance of photovoltaic technologies requires stability of the technologies, as a way of building confidence in the ability of these photovoltaic technologies to be an acceptable form of energy that may replace the traditional sources of energy.

Sustainability Impact:

- As the evaluation results reveal, Wilson's approach to constructing the system was to focus on the system's durability in the long run, while paying attention to its level of environmental friendliness and sustainability, as well as to its general feasibility from both the economic and operational perspectives.
- Such systems are inherently sustainable from the aforementioned overall goals of striving to mitigate as much carbon output as possible while actively raising awareness about renewables as a dominating solution to the global energy mix.

- As seen from the papers discussed in this work, these systems are highly efficient and reliable; hence, it is about time they formed a more integrated part of today's and tomorrow's power structure.

Limitations of the study

The realisation of the study concerning the advanced diagnostic techniques of power converters in single hybrid photovoltaic system faced several challenges. Finally, a limitation arising from the lack of data was a limitation to the ability to transfer the research outcomes to other geographic regions and business environments. Further, due to the complexity of the stakeholders involved in the creation of the various components of the system, the process may end up in simplification of the factors and the construction of systems models that do not reflect reality. In this regard, the discussed simplification can be regarded as a threat to the accuracy and relevance of the suggested diagnostic methods. Additionally, the fault detection algorithms that are developed for types of systems and faults may be less effective when used in other different system configurations or when the characteristic of fault recovered is not the same hence not effective for a wider range of solar systems.

Moreover, the implementation and ability to grow these complicated diagnosing methods are blocked by several scientific and capital barriers. The efficiency and applicability of diagnostic methods heavily depend on technological limitations, for example in sensors, the possibilities of data processing units. These problems are compounded by economic constraints like the high cost of implementing new technology especially when improving current systems, or when implementing new technology which may be costly and as such limit their application. The application of sophisticated diagnostic methods is accompanied by legal and regulatory barriers as the fulfillment of current norms and laws is costly and time-consuming. The presence of these obstacles stresses the need for the immediate continuation of research in functional development of diagnostics methods with better stability, range of adaptability and practical applicability of diagnostics to ensure their success across various operations and for their additive contribution to the advancement of renewable energy sources.

Suggestions and Recommendations for further studies

Given the identified requirements and limitations from past research on advanced diagnostic methods for power converters in freestanding hybrid photovoltaic systems, the following focused comments and future recommendations are provided to direct future studies:

- As for the directions for the future research, it is important to continue and extend the data collection activities have to cover a wider range of environmental conditions and system types. This technique would promote the extendibility of diagnostic algorithms and make it possible to use algorithms in different geographical regions and functioning environments.
- State of the art features such as artificial intelligence and machine learning should not be left out. Some of these technologies can enhance the accurate forecast of the diagnostic tools mostly in detecting possible problems in the system for an early solution.
- Accordingly, researchers should focus on creating diagnostic methods that are generic and can be applied to various power converters and systems. For this reason, it will be possible for the implementation of the diagnostic methods to cover a broad variety of usage areas and enhance its effectiveness within different types of photovoltaic systems.
- An economic analysis of these procedures forms the basis of obtaining improved outcomes of economic feasibility for the diagnosis. These are the steps that will determine the potential RoI and assist the stakeholders in making choices on integrating technology.
- Paying attention to the existing legal environment is the most effective way to determine and optimize the factors that act as obstacles to the dissemination of new diagnostic tools. The purpose of such an analysis is to bring about the right regulatory conditions towards the usage of those technologies.
- It should also include the recommended changes of legislation or new legislation that can help in fasten the deployment and exploitation of these technologies.

- These trials are suggested to ascertain that diagnosis processes, which were found effective, can be deployed sustainably and under different operating conditions. Such studies will provide important information concerning the procedures.
- sturdiness and reliability, thus ensuring that they meet the practical specifications and provide continued support to the renewable energy systems' sustainability.

It is believed that the future studies in the field of diagnostics of hybrid photovoltaic systems will receive significant impetus with the help of these recommendations, and, therefore, there will be progress in increasing the efficiency, reliability and benefits of hybrid systems in creating sustainable energy environments.

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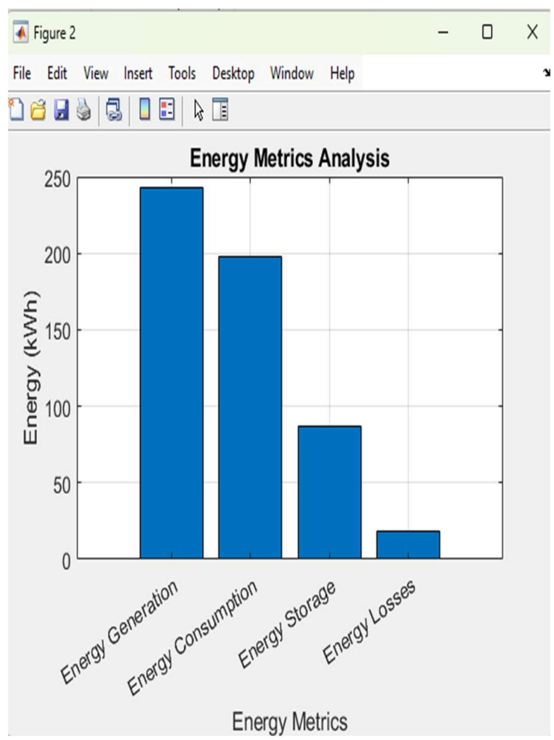
Appendices

Appendix A

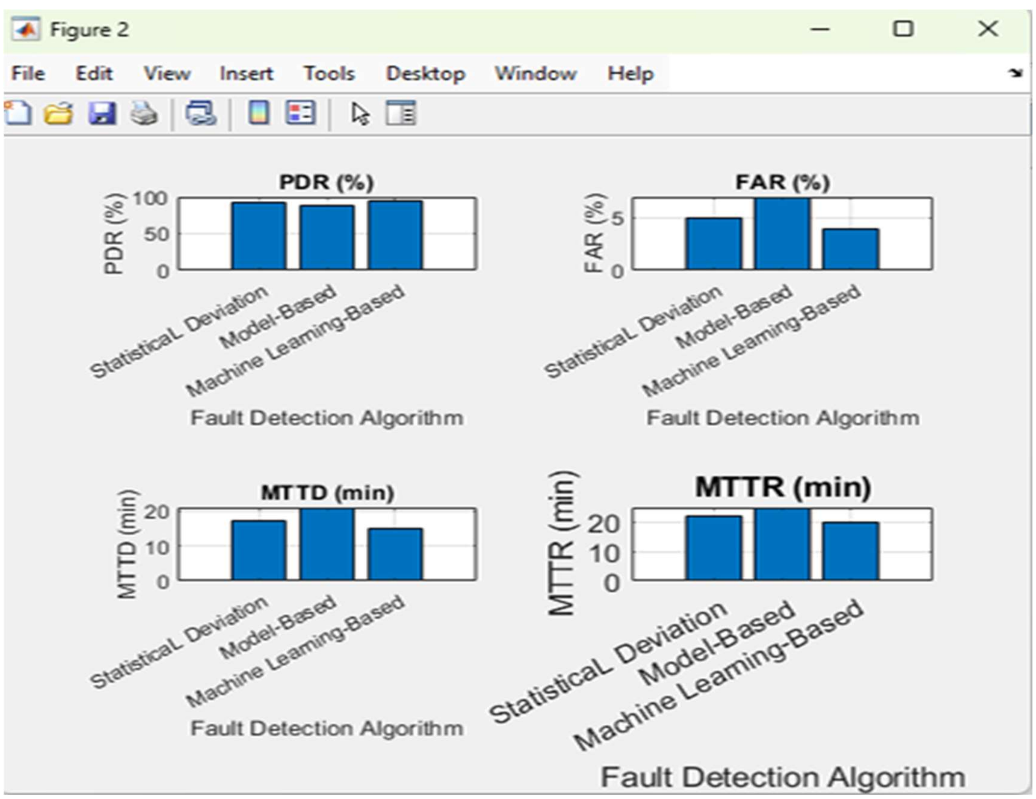
```
% Data for the bar chart

energyMetrics = {'Energy Generation', 'Energy Consumption', 'Energy Storage',
'Energy Losses'};

energyValues = [243, 198, 87, 18]; % Replace these values with your actual data if
different

% Create the bar chart

figure;

bar(energyValues);

% Set the x-axis labels

set(gca, 'XTickLabel', energyMetrics);

% Label the axes

xlabel('Energy Metrics');

ylabel('Energy (kWh)');

% Title (optional)

title('Energy Metrics Analysis');

% Display the grid (optional)

grid on;

% Customize the appearance (optional)

set(gca, 'FontSize', 12); % Set font size
```



Appendix B

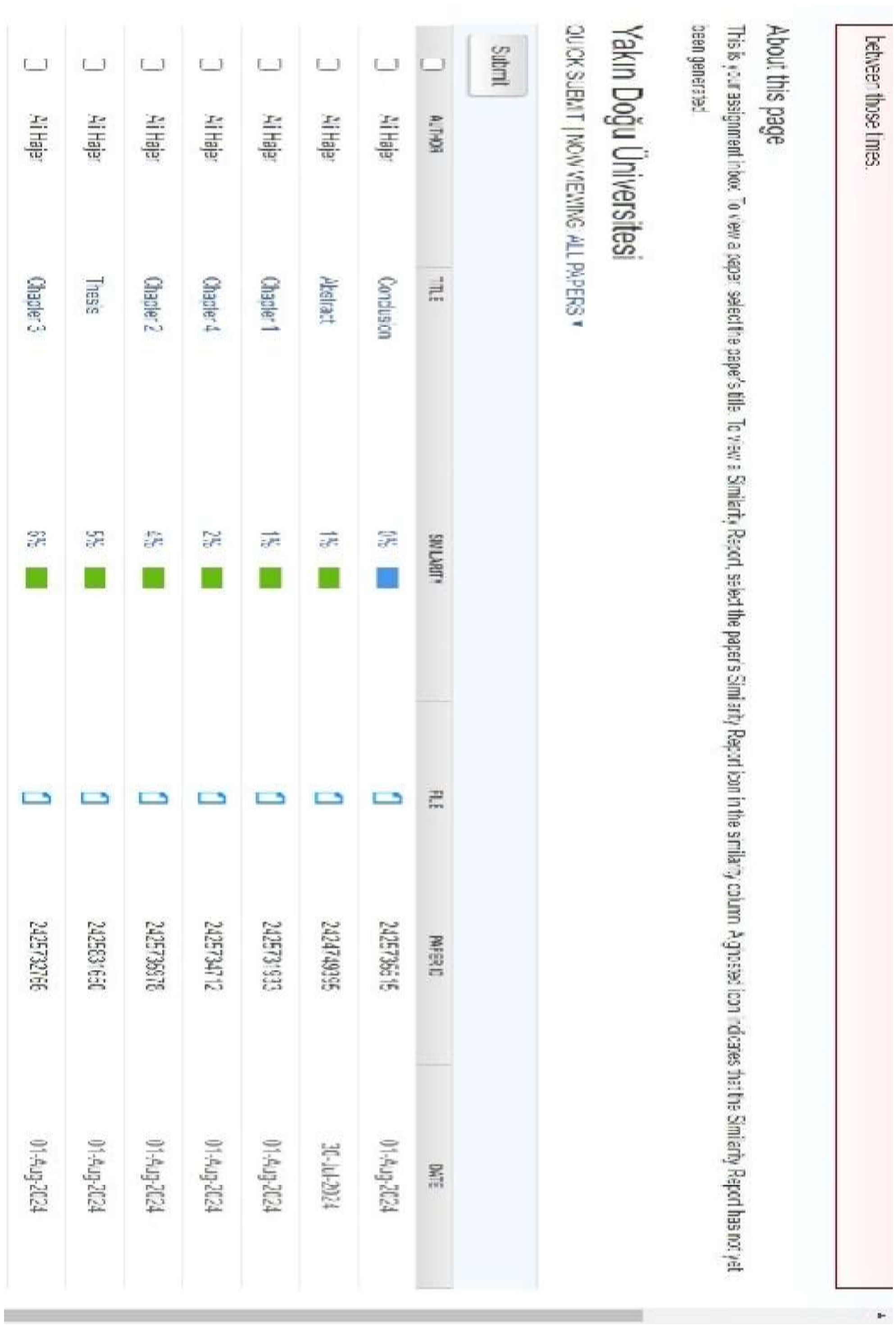
```
% Data for the bar charts
metrics = {'StatisticaL Deviation', 'Model-Based', 'Machine Learning-Based'};
PDR = [92, 88, 94]; % Replace with actual PDR values
FAR = [5, 7, 4];     % Replace with actual FAR values
MTTD = [17, 21, 15];% Replace with actual MTTD values
MTTR = [22, 25, 20];% Replace with actual MTTR values
% Create the figure
figure;
% Plot PDR
subplot(2,2,1);
bar(PDR);
set(gca, 'XTickLabel', metrics);
xlabel('Fault Detection Algorithm');
ylabel('PDR (%)');
title('PDR (%)');
grid on;
% Plot FAR
subplot(2,2,2);
bar(FAR);
set(gca, 'XTickLabel', metrics);
xlabel('Fault Detection Algorithm');
ylabel('FAR (%)');
title('FAR (%)');
grid on;
```

```
% Plot MTTD
subplot(2,2,3);
bar(MTTD);
set(gca, 'XTickLabel', metrics);
xlabel('Fault Detection Algorithm');
ylabel('MTTD (min)');
title('MTTD (min)');
grid on;
% Plot MTTR
subplot(2,2,4);
bar(MTTR);
set(gca, 'XTickLabel', metrics);
xlabel('Fault Detection Algorithm');
ylabel('MTTR (min)');
title('MTTR (min)');
grid on;
% Customize the appearance (optional)
set(gca, 'FontSize', 12); % Set font size
```



Appendix C

Turnitin Similarity Report



AUTHOR	TITLE	SIMILARITY	FILE	PAPER ID	DATE
Ali Hajar	Conclusion	0%		2425736615	01-Aug-2024
Ali Hajar	Abstract	1%		2424749355	30-Jul-2024
Ali Hajar	Chapter 1	1%		2425731933	01-Aug-2024
Ali Hajar	Chapter 4	2%		2425734712	01-Aug-2024
Ali Hajar	Chapter 2	4%		2425736676	01-Aug-2024
Ali Hajar	Thesis	5%		2425631630	01-Aug-2024
Ali Hajar	Chapter 3	6%		2425732766	01-Aug-2024

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