NTNU

Norwegian University of
Science and Technology

Reliability Analysis of Converter Topologies for Photovoltaic System Inverter

Emmanuel Ayegba Omede

Master of Science in Electric Power Engineering
Submission date: December 2015
Supervisor: Lars Einar Norum, ELKRAFT
Co-supervisor: Amin Hajizadeh, ELKRAFT

Norwegian University of Science and Technology
Department of Electric Power Engineering

Reliability Analysis of Converter Topologies for Photovoltaic System Inverter

Emmanuel Ayegba Omede

November 2015

Master Thesis

Department of Electrical Power Engineering
Norwegian University of Science and Technology (NTNU)

Supervisor: Professor Lars Einar Norum, *ELKRAFT*
Co-supervisor: Amin Hajizadeh, *ELKRAFT*

Preface

This master thesis is written at the Department of Electrical Power Engineering at the Norwegian University of Science and Technology. The master thesis has been carried out during the spring of 2015, and is the final part of my two-year master program in Electrical Power at NTNU. The scope of work for the thesis has been 20 weeks, equivalent to 30 credit units.

The main objective for the thesis is to assess reliability performance of set of inverter topologies for grid-connected PV systems.

I would like to give special thanks to Professor Lars Norum (NTNU) for guidance and supervision of this thesis. I would also like to mention Amin Hajizadeh (NTNU) for guidance contribution with good literature. I have enjoyed working with both academics during the period of this thesis and their inputs have added to me beyond this work.

Emmanuel Ayegba Omede

Trondheim

28. November 2015

Abstract

Application of PV systems in distributed generation (DG) and as renewable sources in the power grid are gaining wide acceptance being favoured by rapid technology development, crave for alternative clean energy, environmental protection awareness, favourable energy policies, regulation and incentives. The power conversion stage of PV systems are considered important components for interfacing, transforming and adapting power from PV to end users and as such, the power quality, efficiency and the reliability of PV inverters are key characteristics to prioritize during development. With an assumption that the PV module has almost achieved peak reliability, the PV inverter is analyzed with overall goal to improving the reliability of the PV system. The technology of PV inverters has thus far mainly focused on improving efficiency, power quality, and ensuring safety which has led to emergence of various PV inverter topologies today. This thesis studies the current PV inverter topologies and analyzes the reliability of two transformerless inverter topologies; Flying capacitor (FC) inverter and the modular multilevel converter (MMC) inverter. It aims to assess the reliability performance of both PV inverter topologies in comparative reliability analysis. The scope of this thesis is limited to transformerless grid-connected PV systems for basic assumptions that simplifies reliability analysis.

Current PV inverter topologies have been studied and a set of transformerless multilevel PV inverters was selected based on fundamental market requirements. Suitable reliability analysis methods have been performed for the selected inverter topologies to assess reliability performance. The reliability performance metrics that have been applied for reliability assessment and ranking of the PV inverter topologies are; survival probability of the inverter over 10 years operation, failure rate, mean life of the inverter, complexity of design and inverter operation and level of redundancy.

The study identified the following PV inverter topologies for reliability assessment based on inverter efficiency, power quality, minimum leakage current, and galvanic isolation; 5-level Flying capacitor transformerless multilevel inverter (topology-1) and 5-level transformerless modular multilevel converter (topology-2). The results and performance ranking from comparative reliability assessment showed that topology-2 gives the highest system reliability performance and rank. The main reasons for the difference between the PV inverter topologies are found in the topologies' number of critical components, fault tolerant ability and ease with implementation of reliability positive redundancy.

Table of Contents

List of Figures

List of Tables

1 Introduction

The world's energy demand is very large and it presents huge challenges as to how it can be met while growing. Meeting this growing demand requires an energy portfolio that is efficient, clean and affordable. This is reason the last decades has experienced growing interests for clean, efficient and affordable energy with massive investments within renewable energy especially those with low or zero greenhouse gas emissions. These understandable interests are coming from governments, several world large companies and the public alike since access to reliable, environmentally friendly and affordable energy is vital for economic prosperity and quality of life of people.

Solar photovoltaic and Wind among other renewable energy sources for electricity have experienced accelerated growth and development owing mainly to large investment, favourable energy policies, and breakthroughs in technology. While the aim is not to compare Solar photovoltaic and wind, but PV is seen to be one of the fastest growing renewable energy technologies and expected to play major role in the global energy and electricity production in future. For electricity production, this is because PV has a tendency to be developed and used at several capacities among all energy stakeholders. The global installed capacity of PV systems have therefore increased rapidly since 2005, being driven by mostly advances in power electronics, attractive policies and incentives. The increasing capacity of installed PV and the maturing policy-driven market have ensured declining cost of PV systems. The consequence is a competitive PV market which is able to drive the industry and technology for specifications and requirements such as higher efficiency, high power quality, and high reliability.

The most effort of the PV industry has been focused on improving the efficiency and quality of output of the PV system with much to be done in reliability. Perhaps to be fair, one could say that reliability has not been effectively applied to PV systems since we mostly see development of highly efficient and reliable PV module but not the PV system. There is need to develop reliability programme for the PV system rather than the subsystem even as they are being designed to address efficiency and safety issues. The reliability work today is mostly isolated improvement of components and subsystems of the PV system. The reliability of a series system is as good as its least reliable component/subsystem, which is the case as seen in the PV System today.

1.1 Background

Most important requirements for PV system may be narrowed to efficiency, reliability and safety. The photovoltaic system technology has undergone rapid development over the past decades and today, innovative breakthroughs and improvement are evident. Most of them are related to improved efficiency, cost reduction (LCOE), efficient MPPT, effective control strategy, and some safety related issues. Reliability of the PV system though taken serious as

the issue of efficiency, has not produced expected result. Wrong application of reliability concepts and perhaps the assumption that increasing efficiency automatically improves reliability. The PV system ought to be designed for reliability through suitable reliability program planned and executed in the PV system development program. Good reliability programs are applied majorly for development of PV modules rather than the PV system and the consequence is we having a high reliability PV module and low reliability PV system despite the achieved high reliability. This may be one of the reasons we have today PV systems offering about 20 -30 years warranty on PV modules with just about 4-6 years warranty on the Inverters. There is need to perform a suitable and planned reliability program for the PV system with measurable reliability targets defined for performance assessment. Power conversion stage of the PV system is very important just as the efficiency. Thanks to advances in power electronics, the efficiency of PV converters is improved comparable to what is achieved for the PV modules. The reality now is that the PV module has been improved in both reliability and efficiency while the PV inverter lags behind in reliability.

Assuming that a reliability program for the PV system is planned and the PV meets the set reliability target, we can now execute a suitable reliability program for the PV Inverter to meet the allocated reliability target. The benefit of such assumption (if it was so) would be a much higher reliability PV system and a cost effective development program. The necessity now is to perform a reliability assessment of the power conversion stage of the PV system. There are several topologies and topology groups of the PV Inverter with each having some advantages over others based on an expected requirement or requirements of PV System power conversion stage.

1.2 Literature

A literature survey was carried out as part of this thesis. The main objective is to find the current topologies for the power conversion stage of PV systems and the relevant concepts, methods for studying the reliability.

One of the fundamental keys for performing a successful reliability analysis of a system is a good understanding of the system's architecture and functions. Several literatures have studied different PV system and inverter topologies. The basic architecture of each topology is normally presented in literatures, the main purpose of the topology, the advantages it has over others or how it compares to previous topologies. In most cases the drawbacks of such topology is also stated. [1], [2] provide insights to emerging PV converter technology for grid-connected PV systems. We have seen the emergence of several novel inverter topologies owing to needs to improve power factor and increase power efficiency. [3] provides good introduction and description of more than 100 topologies of advanced inverters originally developed by their authors. The needs that have created the PV system and Inverter topology groups are mostly industry regulations and the hard-to-meet requirements of PV system market. Attention has turned to the study and development of transformerless PV inverter topologies because they are considered to having greater potential for a most efficient and cost effective PV inverter.

Several articles discussed this category of PV inverter topologies; for example [4], [5], [6] among many others listed in the reference.

Reliability analysis and activities are normally planned, executed and managed as a program for products in technology qualification, development projects, and for complex systems. And in many of such situations, time and the order of activities are important to ensure objectives of each planned activity is achieved and most importantly, the reliability goal of the program. [7], [8], [9] and [10] give introduction to background and concepts in reliability engineering that are relevant for reliability planning, design and management of equipments, systems and events. Several Standards give guidelines to reliability concepts and methods that may be relevant for analyzing PV System reliability. Reliability of the power conversion stage of PV systems is the focus and the reliability of PV system is overall goal in this thesis, therefore concepts and methods that are relevant to PV system's reliability program are discussed. One of the important activities in reliability programs is reliability analysis, which must be systematic and structured in order to achieve measurable metrics to describe reliability performance. Few articles describe reliability analysis of PV inverters. For example; [11] estimates useful life of solar inverters using reliability engineering techniques, and [10] provides framework linking reliability specifications and product performance in product development that may be tailored towards power systems. [12] Predicts reliability of power electronic systems, and [13] estimates reliability and availability of fielded PV systems.

1.3 Objectives

The main objective of this master thesis is to assess the reliability performance of a set of topologies of the power conversion stage for grid-connected PV systems. It should present reliability analysis steps and method to measure the quantitative reliability performance of PV inverters. The assessment should address availability and reliability importance of the various topologies. In achieving the main objective, the thesis shall address the following specific objectives:

1. Describe the grid-connected PV system and requirements for interfacing PV systems with the grid.
2. Perform a technical description of converter topologies. Present the recent and important topologies.
3. Describe suitable methods and approaches for studying reliability of PV systems.
4. Make reliability models of selected PV inverter topologies to be analyzed.

5. Perform an analysis of the selected topologies and compare them using suitable reliability metrics.
6. Recommend the most reliable topology based on the results.

1.4 Scope, Limitations and Assumptions

The scope of this thesis is reliability analysis of the power conversion stage for grid-connected PV system. The following limitations and assumption may have effect on the analysis and results presented in this master thesis.

- It is assumed that the reader has basic knowledge of PV converter technology.
- It is assumed that the reader has basic knowledge within the field of RAMS engineering, equivalent to NTNU course TPK 4120.
- ReliaSoft's BlockSim is used for the reliability analysis.
- Assumptions for reliability analysis are stated in Sections 1.4 and 4.6. These assumptions provide basis for some decisions made in the analysis to simplify computation.
- The circuit for controlling and switching the PV converter switches are assumed similar and allocated the same level of reliability.
- Safety is not given much consideration in this analysis except those as stated in applied standards.

1.5 Structure of the Report

The rest of the report is structured as follows:

Chapter 2: Gives a basic description of the grid connected PV system. The chapter presents an overview of the system configuration and main components. It also highlights the requirements of grid-connected PV system inverters and briefly discuss their control system.

Chapter 3: Presents state-of-the-art literature and overview for the PV inverter topologies. It gives the basic configuration and general topology groups of grid-connected PV inverters with further focus on the transformerless topology group of PV inverters. This chapter also discusses the multi-level group of inverters and the topologies that have developed from the multi-level concept.

Chapter 4: Gives introduction and background to reliability engineering concepts and methods that are relevant for performing reliability analysis. Most importantly the steps to performing a successful reliability analysis as applied to the set of

PV inverter topologies are presented in this chapter. These include relevant results from the reliability tool systematically presented for assessing the various PV inverter topologies by the estimated reliability performance

Chapter 5: Presents assessment of the PV inverter topologies and ranking of the set of analyzed grid-connected PV inverter topologies according to reliability performance.

Chapter 6: Includes the conclusion and recommendation for further work.

2 Overview of Grid-Connected Photovoltaic Systems & Requirements

2.1 Brief Introduction to PV System

PV systems according to [14] are power systems designed to supply usable solar power by means of photovoltaics. IEEE describes PV systems as systems that convert sunlight directly into electric energy and processes it into a form suitable for use by intended load [15].

PV systems may be classified according to their application or use, component composition, and functional/operational requirements. Modern PV systems for terrestrial applications can be divided into two broad categories [16]; off-grid and grid-connected PV systems. Grid-connected PV systems connect to electric power grids (utility grids) and have capability to feed energy directly into the grid. They are not expected to produce 100% of the energy demand of end users, as such the utility grid service is available to the end users as well as the opportunity to feed excess produced energy into the grid. However such end users are not protected from power outages from the utility grid. Off-grid PV systems on the contrary are standalone systems that does not connect or feed energy to the public power grids but to isolated users without access to public grid electricity. Since an off-grid PV system functions independently of the utility grid and expected to supply 100% of electricity demand, it would require a backup source of energy or a storage system. Application of off-grid systems are common in remote locations without access to service from the utility grid. While the two major categories of PV systems can be further classified, focus is given to grid-connected PV systems for terrestrial application in this report. Modern grid-connected PV systems have evolved with rapid technology development from the previous centralized systems to distributed systems in a decentralized architecture application.

Grid-connected PV systems (without battery storage) are considered more efficient, cost effective and less complex than standalone PV systems. Several reasons may be responsible for this but it believed to be probably due to the absence of energy storage subsystems in most grid-connected systems as well as being simple to design, install and cheap to maintain.

2.2 PV System Configuration

All possible design types and applications of PV systems can be classified under the following basic system configurations:

1. Standalone PV system

2. Grid-connected PV system
3. Hybrid PV system

Standalone PV system configuration functions and operates independent of the utility grid and other sources of power supply. They are used for small power applications in remote locations that do not connect to the utility grid or other sources of power supply. Standalone PV systems are required to produce 100% of the energy demand of the load in some cases depending on the type of load or load requirement. Thus Standalone PV systems configuration may be further classified into direct-coupled PV systems for small electrical non-sensitive loads, and standalone PV systems with battery storage for sensitive and non-sensitive loads. The load can be DC or AC which means that an inverter would be required for supplying power to AC loads

Grid-connected PV system configuration on the other hand functions and operates in parallel with the utility grid. A unique characteristic of grid-connected PV system that is beneficial to utility customers is that excess energy produced can be feed into the utility grid with an energy sales agreement. Grid-connected PV systems are popular for large and small power applications. They are not required to produce 100% of energy demand of the load, thus energy storage is not required but may be included optionally for increasing availability of power supply to the load.

In large power applications (centralized generation) where grid-connected PV systems are only required to support the utility grid, energy storage is not required. However in medium and small power applications, the choice for a grid-connected PV system with or without energy storage is mostly influenced by the load requirements and reliability of the utility grid. Thus, a grid-connected PV system configuration may be designed with or without an energy storage.. The main components of the grid-connected PV system without energy storage are the PV module and the power conditioning unit (inverter).

Hybrid PV systems configuration differ from the grid-connected and standalone PV systems in terms of the source of power supply. Hybrid PV systems have more than one power supply with one of the sources being photovoltaic. Therefore a hybrid PV system would have a combination of PV energy source along with one or more of the following energy sources; wind energy, biomass energy (e.g. diesel), micro-hydro, etc. Hybrid systems require a good energy management system to control and optimize the energy flow from the inputs to the output. Further details about hybrid PV systems will not be discussed in this report.

2.3 Requirements for Grid-Connected PV System

There are many definitions for what "requirement" stands for. [14] defines requirement as a singular documented physical and functional need that a particular design, product or process must be able to perform. Some others refer to requirement as a condition or capability that must be met or possessed by a system or system component to satisfy a contract, standard, specification, or other formally imposed document. In some engineering fields, requirement is a specification of what should be implemented. The aim here is not to vote the best definition but to understand the term in simple words as it applies to power systems in order to encourage compliance. In simple terms, grid-connected PV systems requirements should be perceived as conditions or capabilities of the system or system's processes that must be met and should usually be documented.

Grid-connected PV systems are configured to function and connect in parallel to the utility grid, and in order to seamlessly achieve this, it must strive to comply with series of standard requirements and guidelines. There are general specification requirements for designing a PV system, in addition to specific requirements for grid interaction. These two sets of requirements apply in the specification for a grid-connected PV system components' design. The requirements that are specific for the grid interaction are focused as well as the components that interface with the grid which must comply with such requirements.

In grid-connected PV systems, the power conditioning unit is an important component. The power conditioning unit (PV inverter) ensures that the PV system seamlessly connect with the power grid. Design and functional specifications of PV system inverters are as such impacted by the grid requirements.

2.3.1 Grid Requirements & Regulations

Grid requirements are important for maintaining the safety, power quality and reliability of the power grid. It also extends these importance to the grid operators and users alike. Stability of the power grid and safe operation are key priorities for any grid operation. With increased integration of renewable energy generation into the power system, it becomes even more important to formulate excellent grid requirements, guidelines, legislation and regulations.

Most grid requirements and guidelines are stated in standards and technical reports that are further referenced and applied as regulations. Bodies and institutions are saddled with responsibilities for writing standards and technical reports that deal with grid requirements including design, installation and operation of equipments that interface with the grid. Examples of these bodies are IEEE, IEC, and DKE among others. Legislative and regulatory bodies at local, state, and national levels reference and applied these standards together with their local laws to ensure high quality, safe, stable and reliable power grid operation. Manufacturers of grid-connected systems are required by regulation to apply these standards in the design of their equipments including grid operators and users. Governments through their regulatory bodies at various levels ensure the implementation, compliance and management of the regulations to ensure they are executed effectively.

Several grid related standards and guidelines have been developed for equipment design, manufacture, installation and operation:

- **IEEE 1547 Standard for Interconnecting Distributed Resources with Electric Power Systems** [16]**:** This standard was approved in 2003 and establishes criteria and requirements for interconnection of distributed resources with electric power systems or the grid. It provides requirements relating to performance, operation, testing, safety, and maintenance of the grid interconnection. Specific requirements in IEEE 1547 (2003) are presented. The standard, after its approval in 2003 has been expanded through development of complementary standards providing more specific details and expansion of the original standard. A first amendment has been started for the original standard, IEEE 1547. List of the complementary standards developed from the original standards.
- **DIN & VDE German standards for PV power converters and grid connection:**
  - **VDE 0126-1-1:** Automatic disconnection device between a generator and the public low-voltage grid.
  - **VDE 0126-2:** Test procedure of islanding prevention measures for utility-interconnected photovoltaic inverters.
  - **VDE 0126-12:** Overall efficiency of grid connected photovoltaic inverters.
  - **VDE 0126-13:** Data sheet and name plate for photovoltaic inverters
- **IEC 61727 Photovoltaic systems – Characteristics of the utility interface:** This standard provide requirements for grid connected PV power systems that operate in parallel with the utility grid using solid-state non-islanding inverters for DC to AC conversion
- **EN 50160 Voltage characteristics of electricity supplied by public networks:** This is a European standard providing main voltage parameters and corresponding permissible deviation ranges at customer points of connection to public networks.

2.3.2 PV Inverters Requirements and challenges

PV inverters are important elements of grid-connected PV systems for interfacing the PV modules to the utility grid. In order to safely and legally connect a PV system to the grid, specific grid requirements in codes and standards regulated by utility must be complied with. Grid requirements relate to network connection criteria, construction of power generation system, system protection and operation. Expected technical requirements that PV inverters need to satisfy may compose of the following norms [3], [17], [18], [19], [16], [20], [21] :

- Level of injected DC current
- Total harmonic distortion (THD) and individual harmonic current levels.
- Range for voltage and frequency magnitudes for normal operation
- Leakage current values and corresponding disconnection times
- Galvanic isolation
- Power factor
- Detection of islanding and anti-islanding operation
- Automatic reconnection and synchronization
- Grounding of the system

Details of the above requirements are available in standards/guidelines. Some of the standards are international and some are region or country specific in application.

There are few significant challenges with respect to grid-connected PV system requirements. As grid-connected PV systems penetration increases and market continues to mature, customer and grid requirements would continue to evolve and change as grid stabilization becomes even more important. The PV inverter design to meet such increasing requirements would become complex, thus demanding implementation of advanced control system for the inverter or inverter group with advanced energy management. As much as they would be difficult to implement, they are also costly. For existing designs and installed systems, it would mean expensive upgrade if possible or forced decommissioning at worst case.

3 State-of-the-Art Grid-Connected PV Inverter Topologies

3.1 The Inverter

An inverter is an electronic device designed with capability of changing DC electrical power to AC electrical power. An inverter is therefore a DC/AC converter that gives AC output waveform from a DC source. The DC/AC converter have three basic classifications without giving consideration to application areas, efficiency, cost, etc. but the type of DC input. They are Voltage source DC/AC converters, Current source DC/AC converters.

In voltage source inverters, the input is a voltage source and the output voltage may be controlled independently. A voltage source is one that is able to maintain a fixed voltage regardless of current changes or one whose voltage cannot undergo discontinuity due to external variations.

For current source inverters, the input is a current source and the output current may be controlled independently. A current source is one that is able to maintain a fixed current flow regardless of voltage changes at its terminals or one whose current flow does not undergo discontinuity due to external variations.

Another class of inverters may be realized from a voltage or current source inverters. It is called an impedance-source (impedance-fed) inverter. In this type of inverter, a special impedance network is used to couple the main converter circuit to the input which may be a current or a voltage source. Inverters may be classified according to criteria such as the number of conversion stages, ratings of output voltage or power, waveform of output voltage, circuit topology and number of output phases. Ability to control the level of output parameters such as frequency, harmonics, voltage, etc. may also form criteria for classification.

For choice of inverter for connecting to the power utility grid, issues such as efficiency, cost, power quality, safety, reliability and compatibility become very important factors for consideration. Main chapters of this thesis shall discuss various inverter topologies based on these issues or a combination of these issues.

Grid-connected inverters has two basic functions. One of them is to convert DC to AC, and the other is to boost voltage if necessary. Based on these functions, there are two main system configurations for DC/AC converters to connect PV array to the power grid. They are; line frequency transformer configuration and transformerless configuration. The difference would be the number of power processing stage and presence of isolation. The option for the number of power processing stage is dependent on the PV array and other performance requirements.

3.1.1 Line Frequency Transformer Inverter Configuration

The line frequency transformer inverter configuration is show in Figure 1. In this configuration the power processing stage is one and thus usually referred to as the single-stage inverter. This configuration includes a line frequency transformer for galvanic isolation and sometimes for voltage boosting towards the grid. The inverter topologies for this configuration are usually considered efficient and reliable because of few components on condition that required performance can be achieved. Performance requirements may be related to MPPT control, grid-current control, voltage amplification, etc. The application of grid-connected line frequency transformer inverters are usually in low voltage applications.

Galvanic isolation is a safety requirement for some countries but not for others. It is usually implemented either using a low frequency transformer or a high frequency transformer. In the case of the former, the low frequency transformer is placed between the inverter AC terminals and the grid but in the later the high frequency transformer is placed between the inverter DC terminals and the PV array.

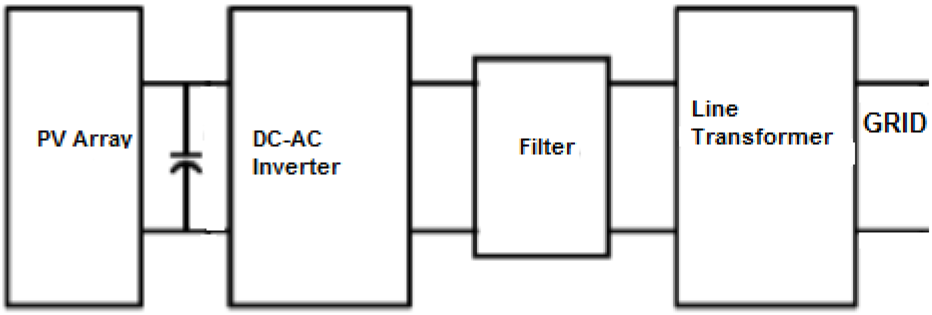


Figure 1: PV System Showing Line Frequency Transformer Inverter Configuration

3.1.2 The Transformerless Inverter Configuration

The transformerless inverter configuration with 2-stage power processing is show in Figure 2. This inverter configuration may have one or more power processing stages depending on the PV array voltage and the required DC-link voltage of the DC-AC converter. In Figure 2 the first stage a DC-DC converter and the second stage a DC-AC converter. As the name of this inverter suggests, this configuration is without a transformer needed to provide galvanic isolation among others. This implies there exist galvanic connection between the PV array and the grid. The consequence is generation of leakage current to ground through the parasitic capacitance of the PV array which if not controlled may lead to voltage oscillation in the PV array.

One of the disadvantages with this configuration is that they are usually considered less efficient and reliable because of switching losses and increased failure points due to increased number of components. Nevertheless considering other advantages offered by this configuration they have found wide application today than the line transformer configuration.

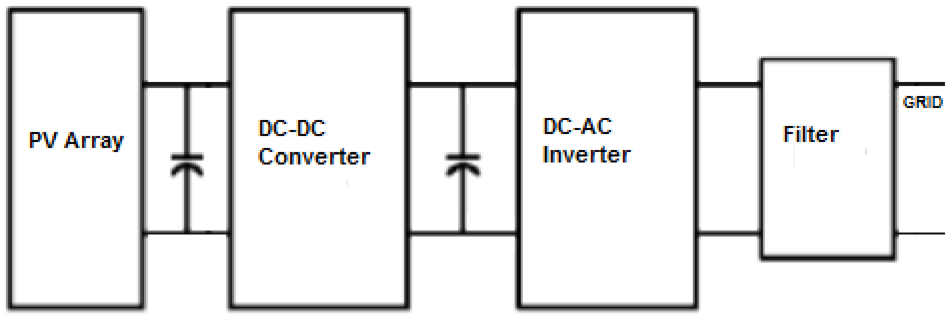


Figure 2: PV System for Transformerless Inverter Configuration

3.2 PV Inverter - General Topology Groups

Inverters that connect PV to the grid normally have unique requirements and to design an inverter in this category, the following issues may need to be addressed in any form possible. Some of the issues are:

- Power quality
- High efficiency
- EMC
- Low cost
- Safety and protection
- Reliability
- Availability
- Environmental conditions
- Low acoustic noise
- Maintainability

Inverters on a generally note have been largely classified according to their application, structure of input rather than type of input source, or even presence of line transformer among others. One general classification of PV inverter have been done according to arrangement of the PV modules of the PV system.

PV modules may be arranged into the following structure:

- Single module
- A string of modules
- Multiple strings
- Array (Multiple strings connected in parallel)

From the above PV module arrangement, the following classification of inverter configuration for PV application may be realized:

1. AC Module Inverter
2. String Inverter
3. Multi-String Inverter
4. Central Inverter

3.2.1 AC Module Inverter Configuration

This inverter configuration gets its name from the PV module arrangement which in this case is a single PV module. In this configuration, one inverter is assigned to a single PV inverters with this configuration are usually called module-integrated inverters. The PV modules having low voltage ratings would inevitably require voltage boosting. Usually a DC-DC voltage boost stage with capability of providing galvanic isolation is designed into the system topology of inverters in this category. It is believed that introducing necessary voltage boost stage reduces the converter efficiency but on the other hand this inverter configuration exhibits highest MPPT accuracy [1].

Advantages of using inverters with this configuration is multi-structure roof and partial shading for small scale applications. Some of these advantages are possible because of flexible and modular features of the inverter configuration. Few inverter topologies can be found with this inverter configuration. Example is an interleaved fly-back converter of Figure 3 developed by Enphase and commercialized by Siemens [1].

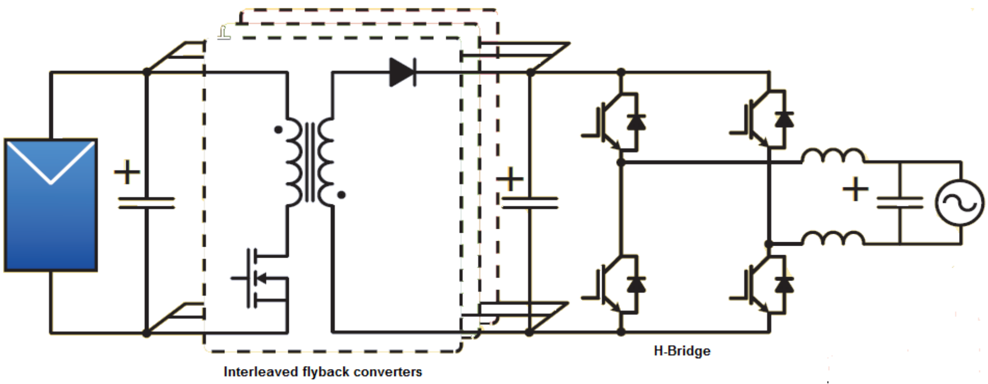


Figure 3: AC Module Inverter Configuration – Interleaved Fly-back Converter [1]

3.2.2 String Inverter Configuration

Similar to AC module inverter that derives its name from arrangement of the PV module, the other inverter configurations such string inverter also does same. In String Inverter configuration, one inverter is dedicated to a string of PV modules. String inverters are usually common with medium scale applications. Depending on the inverter input voltage and PV string, voltage boost by addition of DC-DC converter stage with MPPT may be an option. In such case, the configuration will be a double-stage power conversion inverter. Galvanic isolation may also be introduced through the help of a low frequency or high frequency transformer.

MPPT accuracy of string inverter configuration is considered to be less than AC module inverter configuration but with a higher efficiency and lesser cost per watt for the same power rating of PV system. There are several inverter topologies with wide applications for string inverter configuration. They are; traditional full bridge or H-bridge string inverter, modified and enhanced versions of H-bridge string inverter, 3L NPC string inverter, modified and enhanced versions of 3L NPC string inverter and T-type (3 level transistor clamped) string inverter. An example of a string inverter configuration is shown by Figure 4.

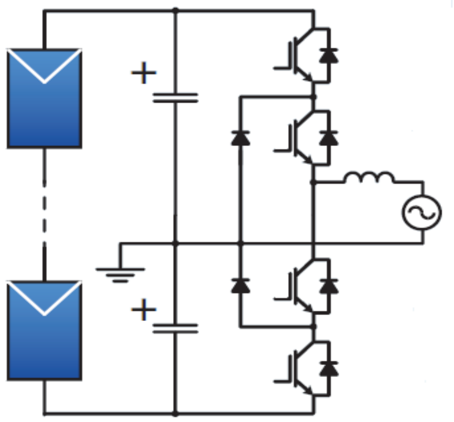


Figure 4: String Inverter Configuration – 3L NPC String Inverter [1]

3.2.3 Multi-String Inverter Configuration

In multi-string inverter configuration, the same name convention applies just as in AC module inverter and string inverter. It is name so because one inverter is dedicated to serving multi-string connected PV modules. Multi-string PV module arrangement is a parallel connection of strings of PV modules to a grid-connected multi-string inverter through DC-DC converters dedicated for each string of PV modules. Two or multiple stage power conversion is also inevitable in multi-string inverter topologies.

What is achieved by this configuration is flexibility, cost effectiveness and increased MPPT performance [1]. They are most relevant in medium and large scale PV applications. Multi-string inverter configuration has capability of partial shading reduction and may be implemented with option of galvanic isolation. Several topologies exist in multi-string inverter configuration and most topologies listed for string inverter configuration also apply for multi-string inverter configuration. The low inverter efficiency and reliability because of more than one power conversion stage and increased failure points are also present in multi-string inverter configuration. An example of multi-string inverter configuration is shown by Figure 5.

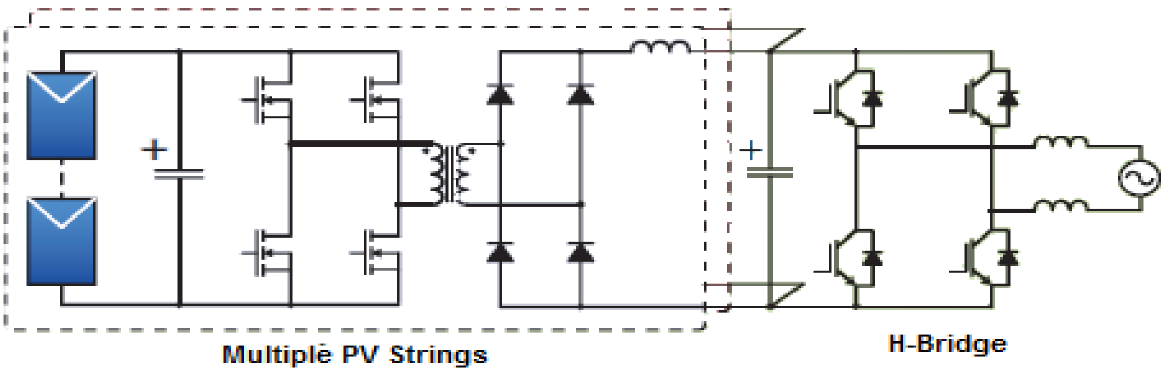


Figure 5: Multi-String Inverter Configuration – H-Bridge Multi-string Inverter [1]

3.2.4 Central Inverter Configuration

This inverter configuration is similar to the other inverter configurations discussed above however in this case the central inverter interconnects the whole PV array to the grid. The PV array is an interconnection of PV modules to achieve parallel-connected PV strings. In this case, a converter is not required for the parallel connection of the PV strings as in the case of Multiple-string inverter configuration. The whole PV array is connected to one central inverter and for each PV string a blocking diode is connected. The shortcoming with this configuration is that it has the lowest MPPT performance and lacks flexibility. On the high side, it is very reliable and simple in structure. It also possesses the highest power conversion efficiency among the inverter configurations discussed. The central inverter configuration is used for large scale applications. One of the central inverter topologies is shown by Figure 6.

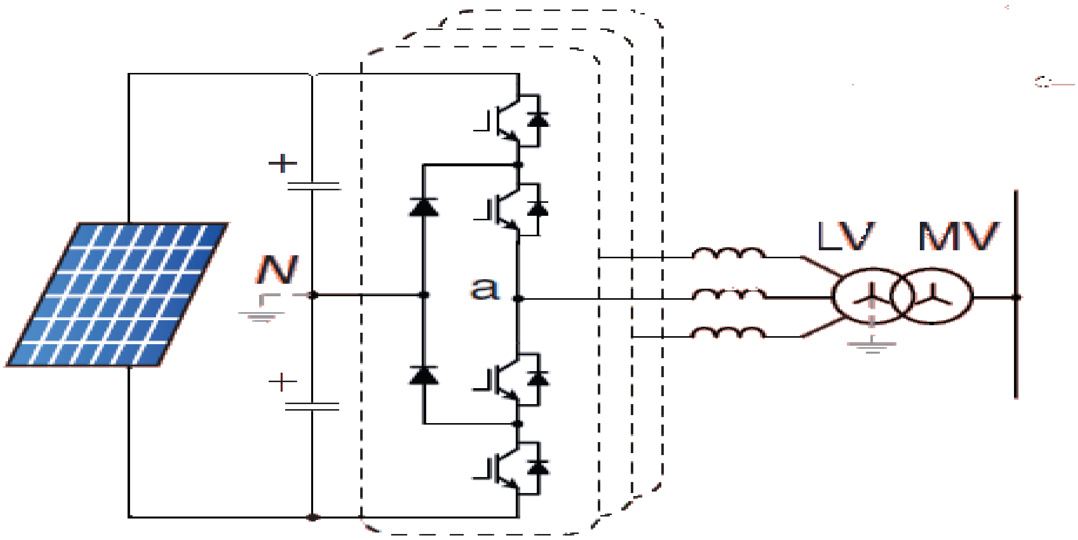


Figure 6: Central Inverter Configuration – 3L NPC [1]

3.3 Transformerless Inverter Topologies

It is discussed earlier the transformer inverter configuration and the transformerless inverter configuration with the structural difference being the presence of a transformer (low frequency or high frequency) to ensure safety and galvanic isolation. It is assumed here that galvanic isolation is necessary for grid-connected PV systems and a requirement even though it may be argued as a safety issue related to what standard is being applied.

For transformer inverter topologies, the life time of the transformer may also an issue but comparison to transformerless configuration would need to be performed to confirm this. Some of the disadvantages of transformer inverter topologies to the PV system and inverter because of grid isolation transformer are:

- Reduced overall efficiency due to leakages and losses in transformer
- Increased cost due to cost of transformer
- Increase size and weight because of transformer (low frequency transformer) leading to installation difficulty

On the other hand with grid isolation transformer removed from the inverter (transformerless inverter topology), the disadvantages listed above would be minimized if not eliminated. When this is allowed, galvanic connection between grid and PV array becomes present and leakage current to ground path due to solar panel parasitic capacitance is introduced. This is the main disadvantage with transformerless inverter topologies but enjoys higher overall efficiency, reduced cost and reduced weight and volume.

Several transformerless inverter topologies have been proposed for connecting PV to the grid. The topologies aim to minimized ground leakage current and DC current injection, improve efficiency, increase reliability among others. Two transformerless PV inverter topology groups have stood out in the industry today in which several inverter topologies are derived. They are:

- H – Bridge topology group
- Neutral point clamped (NPC) topology group

3.3.1 Inverters from H-Bridge Topology

The transformerless inverters derived from this topology group are based on the basic, modified or enhanced structure of H-bridge. Some inverter derivatives in this group are half H-bridge, full H-bridge, HERIC, H5, full H-bridge with DC bypass, full H-bridge zero voltage rectifier, etc.

3.3.1.1 Full H-bridge Inverter

This inverter is composed of 4 switches connected as shown by Figure 7. Three main modulation methods are possible with this inverter [22]:

- Bipolar PWM
- Unipolar PWM
- Hybrid PWM

With bipolar modulation, the full H-bridge inverter yields very low leakage current but with reduced efficiency [22]. As such it is not suitable for PV transformerless inverter applications.

With unipolar modulation, there exist high leakage current but a high efficiency and low filtering requirements. Thus this inverter with unipolar modulation is also not suitable for PV transformerless inverter applications.

With a hybrid modulation the inverter exhibits high efficiency, but an unfortunately high leakage current and filtering requirements.

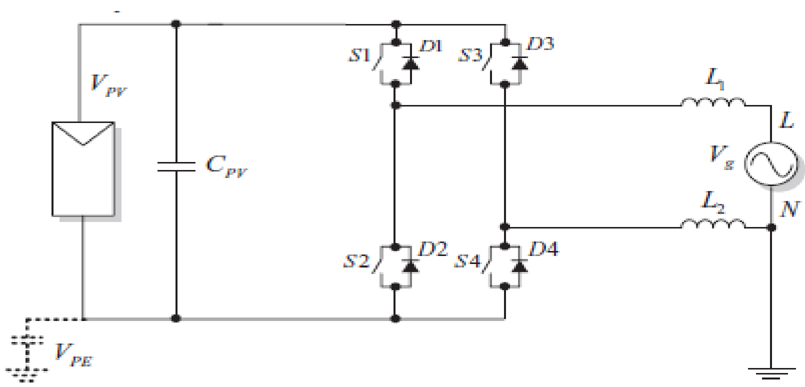


Figure 7: Full H-bridge Inverter Topology [22]

3.3.1.2 Half H-bridge Inverter

The half H-bridge is a reduced form of full H-bridge inverter with only one leg of the bridge (2 switches) and a capacitive divider to the PV array. This inverter has the lowest cost and simplest structure with constant common mode voltage. However it is still not widely used because of high voltage-blocking switch requirement, distorted output requiring high filtering requirements [5].

3.3.1.3 High Efficient and Reliable Inverter Concept (HERIC)

This inverter is patented by Sunways and uses the full H-bridge transformerless inverter topology with an additional branch in parallel with the inverter output filter. The branch is composed of a back-to-back connected IGBTs that switches at the grid frequency. This inverter topology is shown by Figure 8. The function of the additional branch is for isolating the PV array from the grid and provide a third voltage level (0V) at the inverter output [5].

HERIC inverter exhibits high efficiency, low leakage current but with addition 2 extra switches. It is widely used and suitable for PV transformerless inverter applications.

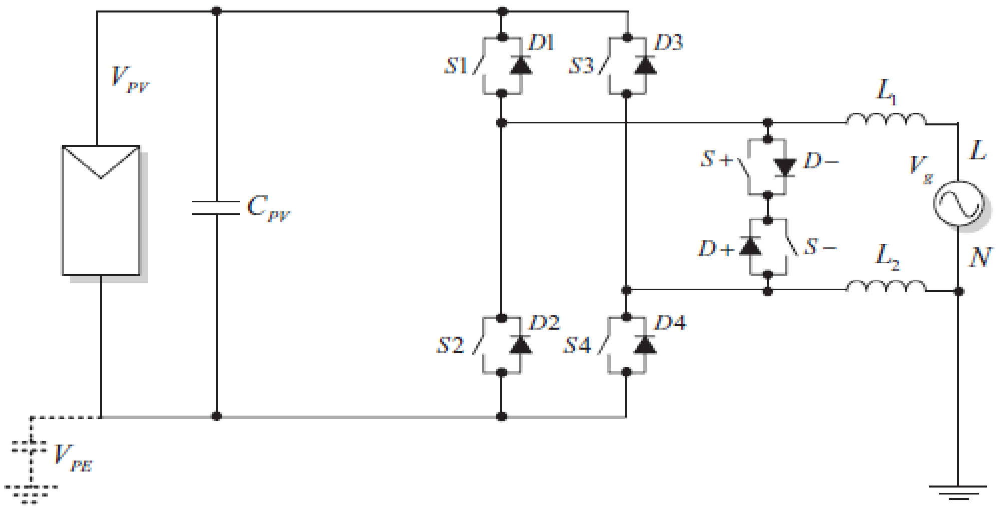


Figure 8: HERIC Inverter Topology [22]

3.3.1.4 H5 Inverter

H5 inverter topology is almost same as the full H-bridge transformerless inverter but with an additional switch in the positive bus of the DC link. It is shown by Figure 9. H5 inverter has a total of 5 switches with S5, S4 and S2 switched at high frequency while S1 and S3 are switched at the grid frequency [22]. The fifth switch (DC bypass), S5 helps to isolate the PV array from the grid during zero voltage state and prevents reactive power exchange between the DC and AC filters.

This inverter exhibits high efficiency and low leakage current. Although it has an extra switch and some level of conduction losses, it is suitable for PV transformerless inverter applications [22].

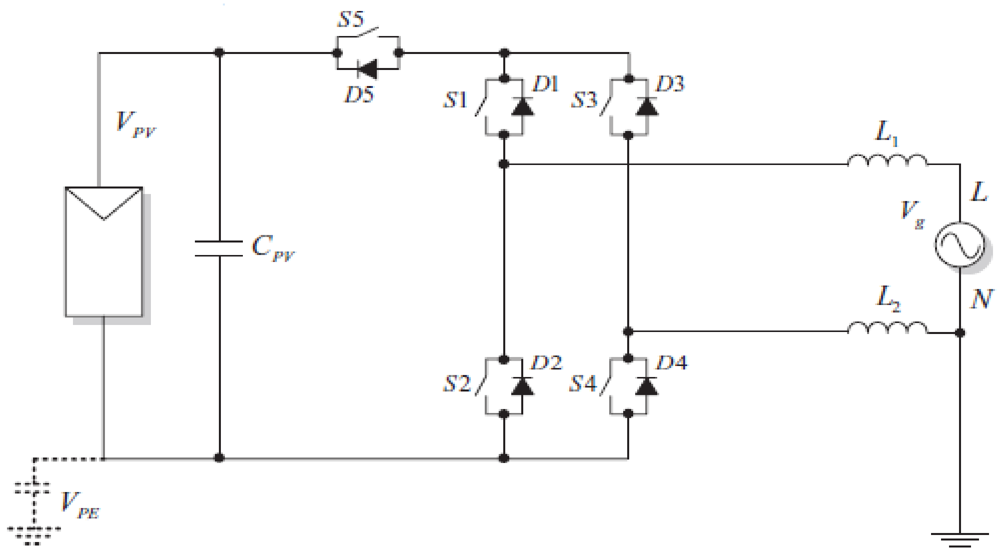


Figure 9: H5 Inverter Topology [22]

3.3.2 Inverters from Neutral Point-Clamped (NPC) Topology

These category of inverters are derived from NPC topology proposed by Nabae, Magi and Takahashi in 1981 [Remus]. They are also widely applied in single phase and three-phase inverter operation. Inverter in this category are; NPC half-bridge inverter, NPC half-bridge with capacitive divider, Conergy NPC, Active NPC, Flying capacitor.

3.3.2.1 NPC Half-Bridge Inverter

This is the version of the diode-clamped half-bridge topology used in low voltage applications. They have 4 switches and two diodes for free-wheeling operation and able to achieve a third voltage level in addition to the two voltage levels in classical inverters. Two of its switches are switched at high frequency and the other two at grid frequency.

Advantages with this inverter is higher efficiency and reduced switching losses than a classical inverter. It also exhibits low leakage current in the PV system. One of the low sides of this inverter is increased component count. Figure 10 shows a schematic of this inverter.

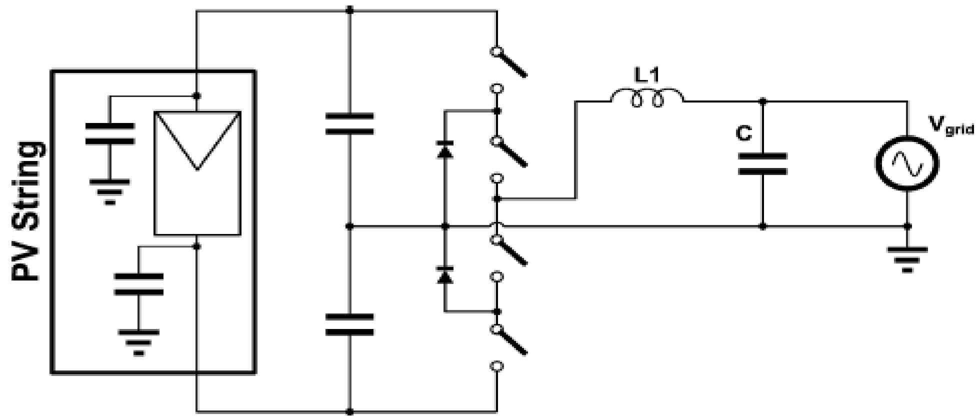


Figure 10: NPC Half-bridge Inverter [5]

3.3.2.2 Conergy NPC Inverter

This inverter is another version of NPC half-bridge with neutral point clamping by a bi-directional switch. It is patented by Conergy and known for its higher efficiency, low leakage current and switching losses. The bi-directional switch is two back-to-back series connected IGBTs. The schematic of this inverter is shown by Figure 11.

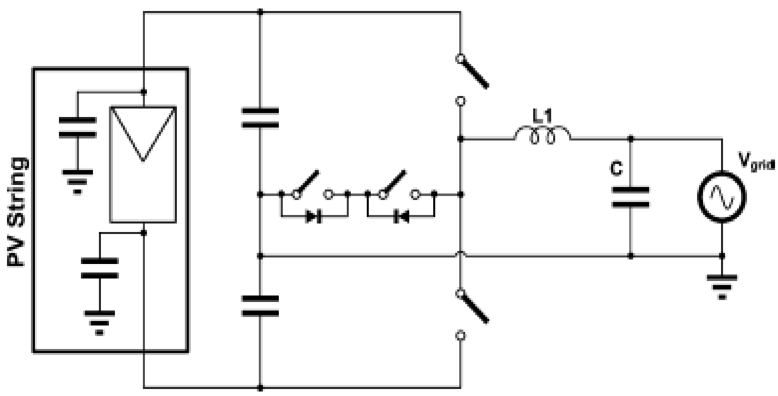


Figure 11: Conergy NPC Inverter [5]

3.4 Multi-level Inverter Topology Group

Multilevel inverters are sets of power inverters capable of generating desired AC output voltage level using several lower level voltages as input. The concept of multilevel inverter horizontally accumulate levels to achieve the desired waveform and does not depend on two voltage level as the PWM concept. Multilevel inverter concept is relevant for wide medium and high voltage applications with several advantages. Some of the advantages derived from multilevel inverter are; low switching frequency, low pulse heights ensuring low harmonic distortion, and simple inverter control circuit.

There are several multilevel inverter topologies which are normally differentiated by the sources of input voltage and switching mechanisms. The following are some types of multilevel inverters [3]:

- Diode-clamped multilevel inverters
- Capacitor-clamped (flying capacitors) multilevel inverters
- Cascaded multilevel inverters with separate DC sources
- H-bridge multilevel inverters
- Generalized multilevel inverters
- Mixed-level multilevel inverters
- Multi-level inverters by connection of 3-phase 2-level inverters
- Soft-switched multilevel inverters
- Laddered inverters

The following sub sections describes few multilevel inverter topologies

3.4.1 Multi-level Inverters Using clamped Diode/Capacitor Topologies

Inverters in this category use the diodes or capacitors to limit voltage stresses. Further description are given below.

3.4.1.1 Diode-clamped Multi-level Inverter

The diode-clamped multilevel inverter is also called the neutral-point clamped (NPC) inverter and was first proposed by Nabae around 1980. In this inverter topology, the switches are connected in series to desired voltage rating and output levels with the inner voltage points clamped by two extra diodes [Hong]. An n-level diode-clamped inverter to operate, it would require (2n-2) switching devices, voltage sources of (n-1) and (n-1)(n-2) diodes.

There are many variants of this inverter topology commercially available for high voltage applications. A diagram of a single phase diode-clamped multilevel inverter is shown in Figure 12.

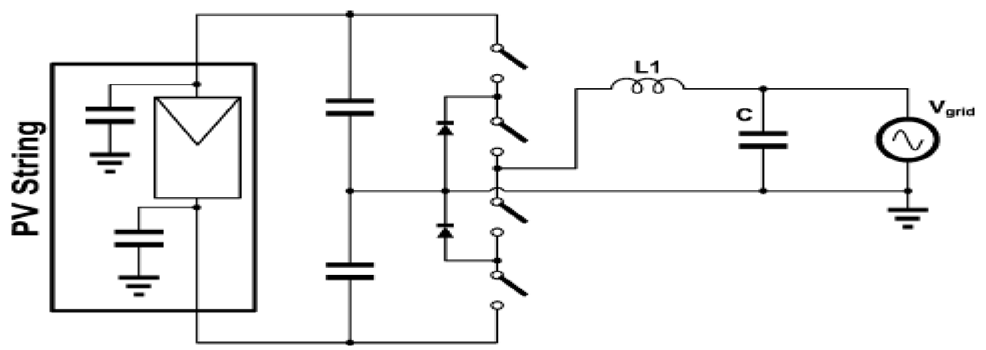


Figure 12: A Diode-clamped Multilevel Inverter [5]

3.4.1.2 Capacitor-clamped Multi-level Inverter

The capacitor-clamped multilevel inverter is a variant of NPC and also called Flying capacitor inverter. Instead of clamping the device voltage by two diodes, a dependent capacitor is used. Many have thought this inverter to a little complex than NPC since a precharge circuit may be required and the need to maintain the capacitor voltage at a reference. Advantage is however gained in the fault-tolerant operation exhibited by the inverter higher levels. A diagram of a capacitor-clamped multilevel inverter is shown in Figure 13.

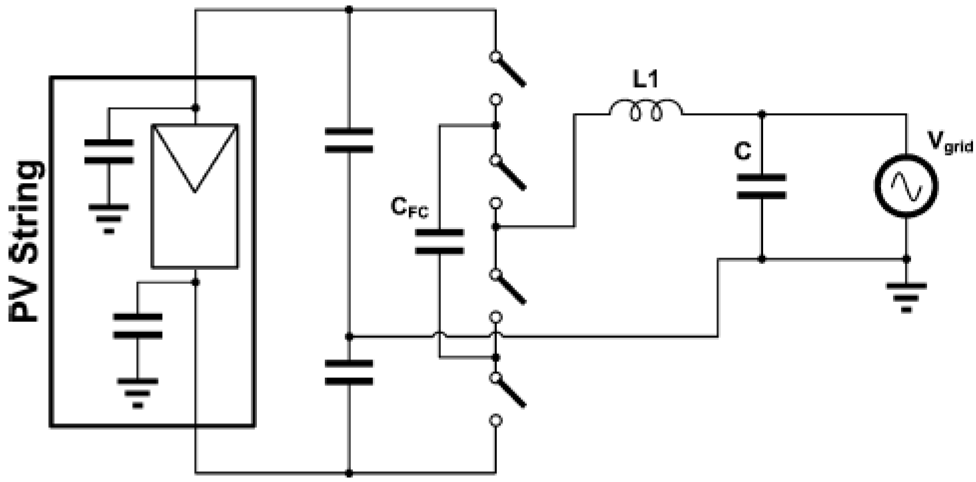


Figure 13: A Capacitor-clamped Multilevel Inverter [5]

3.4.2 Multi-level Inverters Using Cascaded Topologies

Multilevel inverters derived from cascading similar or identical modules may be in the category of those with separate inputs or common input. They are presented in the sub chapters.

3.4.2.1 Cascaded H-bridge Multi-level Inverters

The basic structure of this inverter is series connection of H-bridge cells at the AC-side. Each cell is supplied a different DC source. There are variants of this inverter depending on isolated DC link voltage of the cells. A diagram of a cascaded H-bridge multilevel inverter is shown in Figure 14.

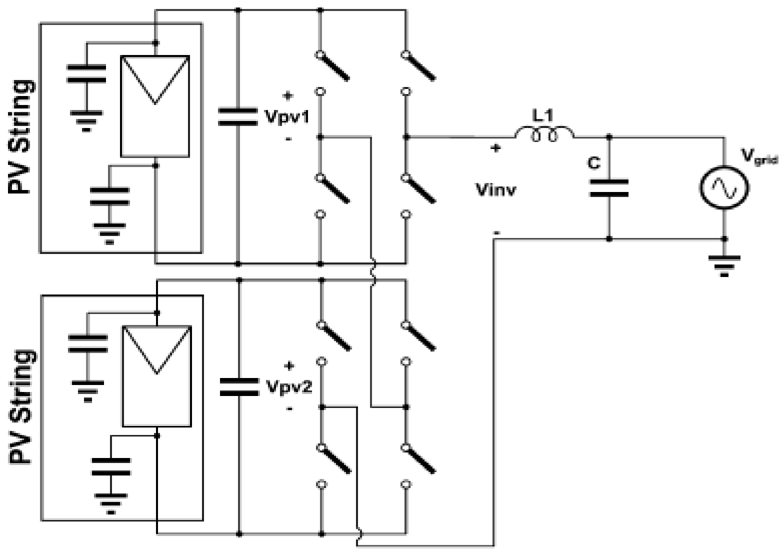


Figure 14: Cascaded H-bridge Multilevel Inverter [5]

3.4.2.2 Modular Multilevel Converter (MMC)

This a one of the recent most attractive multilevel inverters and have received wide attention from literature. This inverter uses modularized setup of submodules (SMs) cascaded on two arms of an inverter leg. The SM may come in several architectures [23]; half-bridge circuit, full-bridge circuit, clamped-double circuit, 3-level converter circuit (NPC or FC), and the 5-level cross-connected circuit. A diagram of a modular multilevel converter is shown in Figure 15.

Some of the reasons why this converter has received attention are [24]:

- Low harmonic output minimizing filtering requirements
- Attainable capacitor voltage balancing independent of load
- Modularized structure allowing easy extension of voltage levels
- Redundancy ability leading up to high reliability and availability of converter system

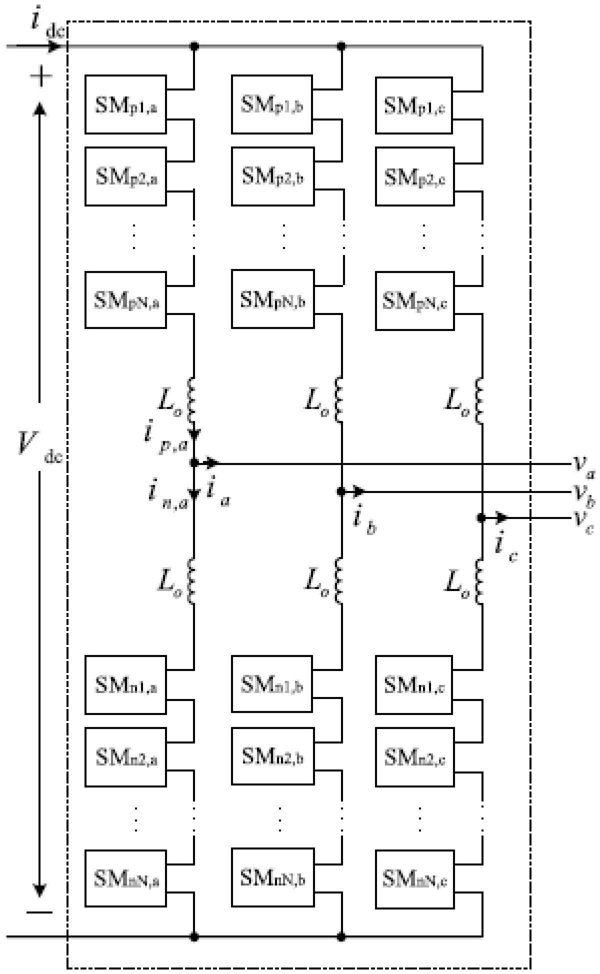


Figure 15: Modular Multilevel Converter [23]

4 Reliability Analysis of PV System Inverter

4.1 Introduction to Reliability Analysis

Reliability in classical terms refer to the probability of providing a specified performance level for a specified duration in a specified environment. In order to better understand and apply reliability modelling techniques, it is important to know some basics of reliability analysis.

Reliability prediction or assessment usually involves application of reliability analysis methods through systematic and structured procedure for evaluating reliability of technical systems. Even as the method is important is also the product that is being analyzed. This will be influential for the type of reliability analysis method or technique to be applied. Reliability analysis is usually performed for different and several purposes which may include but not limited to the following [25]:

- Setting targets and specification
- Comparing options
- Identifying and prioritizing problems
- Indicating fitness for purpose (as in technology qualification)
- Optimizing support (e.g. spares)
- To give input to other analysis (e.g. safety analysis)
- To prioritize areas for improvement with the greatest cost-effectiveness improvement potential

Having a procedure to predict or assess reliability of a system is a welcomed important approach in reliability analysis since products have different suitable reliability method for analysis. The importance is significant when we are analyzing a complex system and product under development or with intention to improve its reliability. At that stage, it will discovered that reliability normally surpasses normal modelling of systems and inputting reliability data to activities such as present for improving reliability. The steps and methods for analyzing system's reliability varies for different systems as there exist many factors to consider during the selection of a suitable reliability prediction or assessment method. A basic general dependability analysis procedure which also applies for reliability performance is described in [26]. The term dependability normally refer to reliability, availability, maintainability, and safety but now it is observed that security and resilience are being accommodated in the term.

Procedure for reliability analysis may be illustrated by the general dependability analysis procedure of Figure 16.

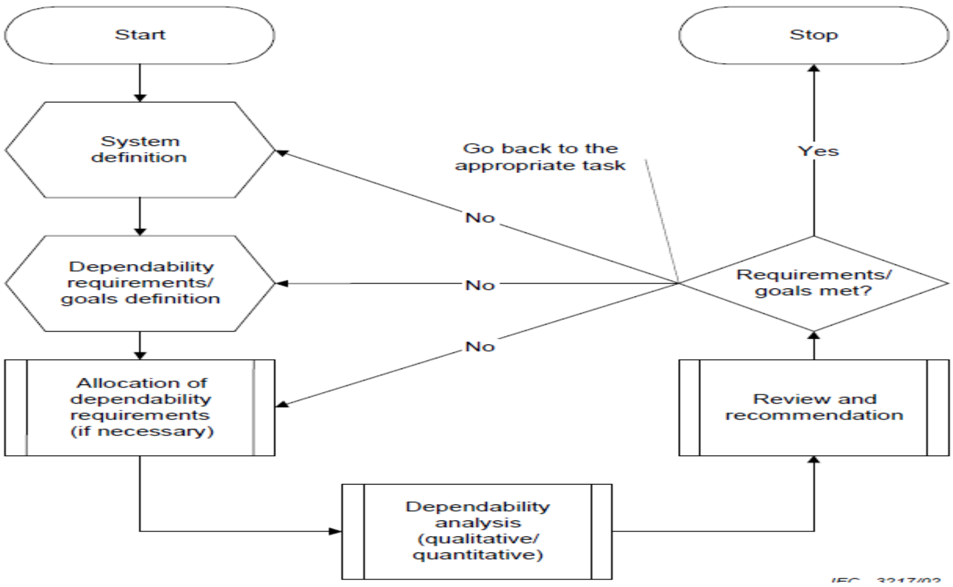


Figure 16: Procedure for performing dependability analysis [26]

System Definition

System definition is very important in performing reliability analysis. It basically involves the breakdown and representation of the system structure and function with goal of understanding the functional responsibilities of the system elements. This step is achieved in system reliability analysis as functional analysis. Relationships that exist between the system and its environment are not left out. The function(s) of the system elements and relationships must be known for all relevant modes of operation of the system in order that proper reliability analysis can be performed. In complex system, representation of the system's elements and functions in a block or functional diagram may be beneficial to the analysis. Boundaries for the system analyzed must be defined before commencing modelling. Other system definitions should include the system interfaces, outputs, inputs and the boundary conditions. The extent of the system definition will solely be dependent on the phase of the product life-cycle and goal of the analysis [7].

System definition are generally achieved from two perspectives [7]:

1. Structural perspective: The focus here is breakdown according to the physical structure of the system. The interfaces between the subsystems or elements of the system in most cases become defining boundaries for the system elements.
2. Functional perspective: The focus here is breakdown according to the system functions or how the system functions are realized. This perspective is mostly considered more

beneficial from reliability angle in a complex system since it is an important input for failure analysis.

Most complex system apply any or both perspectives of the system definition using various representative diagrams. Engineering diagrams and schematics such as circuit diagrams, block diagrams, UML, process diagrams, etc are applied in functional analysis to illustrate the interrelationships within the system structurally and functionally.

Functions and functional analysis:

A function generally indicating a physical behaviour or action is the intended effect of a functional block .System functions may be divided into different classes based on the system's role or use or perceived level of importance of the function. [7] Classified functions in the following way:

1. Essential functions: Functions required to fulfill intended purpose of the functional block. Fundamentals to installing the functional block are because of the essential functions.
2. Auxiliary functions: These functions are required for supporting the essential functions. Their failures are more safety critical than essential functions in some cases.
3. Protective functions: These class of functions are required for protection of people, equipment and environment from damage and injury. They can be further classified into; safety functions, environment functions and hygiene function.
4. Information functions: These category of functions are mainly condition monitoring and warning functions. They are implemented mostly as monitoring and alarm systems.
5. Interface functions: The functions are required for interfaces of the function block and other function blocks.
6. Superfluous functions: These are unnecessary or needless functions in the function block. They are mostly termed "nice to have" functions.

Functional analysis is a tool or systematic process for identifying, describing, and relating the functions a system performs. It is referred to as functional decomposition in some fields. Functional analysis or decomposition is a top-down approach whether it be performed for and existing system or system under development. It is performed for the following objectives [7]:

a. Identify all functions of a system
b. Identify functions required in various operational modes of a system
c. Provide hierarchical decomposition of system functions
d. Describe how each function is realized
e. Identify interrelationships between the functions
f. Identify interfaces with other systems and with the environment

For a reliability engineer to adequately identify all potential failures especially for a complex system, a good functional analysis needs to be first performed. Functional analysis is therefore considered an important step in reliability analysis.

Define analysis goals/requirements and specification

This is the stage where goals and requirements of the system reliability and availability analysis are specified. In product development where reliability program is normally advised, this stage would usually be definition of reliability requirements and targets that the system is expected to achieve. The responsibility of defining requirements and targets can be of the manufacturer, supplier, customer, user or combination of them. Qualitative or quantitative requirements and targets may be defined but important for such definitions is their essential elements or properties. Quantitative reliability requirements and targets should:

- Be simple and unambiguous
- Be measurable
- Possess time element (hours, years, cycles) related to operation or ageing of the product.
- Have confidence level defined (if applicable)
- Include the definition of failure as it relates to the product.
- Include specification of usage and operating environment of the product.

Reliability Allocation

Reliability allocation (if applicable) involves the process of setting reliability goals for individual subsystems and components of a system such that a specified reliability goal can be achieved at the system level. This process (reliability allocation) is mainly relevant in product development design phase and systems where reliability improvement and growth are desirous.

When the reliability goals and requirements at the system level are known or stated, the task remains translating those system goals and requirements to the subsystems and components. This is very challenging because in doing so, the system performance and goal must be achieved along balancing important factors such as development cost, design complexities, and other project issues. There are methods to perform reliability allocation and software tools designed to assist in this task. The following apportionment methods may be applied for reliability allocation [10]:

- Equal apportionment method
- ARINC apportionment method
- AGREE apportionment method
- Feasibility of object method
- Minimum effort algorithm

The choice of apportionment method for allocating reliability may largely dependent on the type of system being analyzed, the stage of product development (if applicable), available product information and complexity.

Dependability (Reliability) analysis

This is a collective term used to describe availability performance and its influencing factors: reliability performance, maintainability performance and maintenance support performance [27]. In the context of this, we refer to dependability reliability for the places dependability procedures and methods have been used.

This step in the analysis procedure involves analyzing the system on basis of suitable reliability analysis method with relevant performance data. It should be noted at this point that system analysis may be qualitative or quantitative but their combination in analysis is been considered a much better approach. The distinction is mostly seen in the presence or absence of numerical reliability data input.

It is advised to first apply qualitative system analysis method such as the FMECA to analyze the components failure modes, mechanism, and effects both at local and system levels. The quantitative system analysis then further cumulates the effects numerically along other specific reliability computations as necessary. Reliability analysis methods are discussed further in Chapter 4.3.

Evaluate, Review, and Recommendation

This step in the procedure requires that the reliability goals and requirements be analyzed against results from the system reliability models. Typical tasks would be to evaluate the results against requirements, and on that basis review the system for design weaknesses and reliability improvement potentials. A recommendation is then proposed for change in design or an alternative design that corrects identified weaknesses or improves the system reliability.

4.2 Reliability Metrics and Terms

[25] defines reliability as a stochastic or probabilistic parameter that cannot be measured exactly or with certainty. Even though it has been stated that reliability cannot be measured with exactness, probability or likelihood of occurrence can be introduced to be able to establish some form of measurement. Thus reliability may be a likelihood of no fault occurring or the probability of survival over time.

There are various metrics for measuring reliability but suitability of a metric to use may be influenced by factors such as the type of equipment analyzed, mode of operation, and type of available reliability data. As defined in the scope, main basis for comparing inverter topologies is the survival probability, mean life and failure rate. There is a note of caution in using results from this comparative analysis. All assumptions must be known as intended before using results and the final results does not reflect the reliability of inverter systems since some components and events are neglected or generalized for ease of computation.

The metrics for analysis are defined below.

Failure rate

Conditional probability per unit of time that the item fails between t and (t + dt), provided that it works over (0, t) [28].

Mean time to failure (MTTF)

Expected time before the item fails. It is used to describe the time to failure for a non-repairable item or to the first failure for a repairable item. When the item is as good as new after a repair, it is also valid for the further failures [28].

Survival Probability (R(t))

Likelihood of the continued functioning of an item, as given by "R (t) = Pr (T > t)" Where Pr is the probability that T, the time to failure of an item, is greater than t, a time equal to or greater than 0. The survival probability is also known as reliability or survival function [29]. This is also known as reliability or survivor function.

Random failure

Failure occurring in a random way. A random failure may be time or demand dependent. Whether it occurs or not is not predictable with certainty but the corresponding failure rate or probability of a failure due to demand may be predictable and this allows probabilistic calculations [28].

4.3 Reliability Analysis Approach and Method

Reliability block diagram (RBD), fault trees (FT), and Markov modelling (MM) are common techniques for modelling systems reliability and availability. They can be used to compute systems expected RAM metrics such as failure rate, survival probability, failure probability, availability, mean down time [30].

The modelling approach adopted is the dysfunctional reliability modelling. The inverter failure behaviour shall therefore be modelled using BlockSim. BlockSim is a reliability and availability analysis software developed by ReliaSoft. The fault tree analysis method of the software will be used to describe the inverter system and components' failure behaviour. Fault tree analysis allows for easy understanding and representation of components failure modes and causes.

Fault tree analysis have similar functionality to RBD in modelling but uses a different principle; items failure. It is deductive technique capable of handling logical combinations of basic events to capture the overall effect at the system level. The logic combinations show interrelationships between potential critical event (TOP event) of the system and the causes for this event expressed in Boolean operation. Fault trees are mostly suitable for modelling non-repairable systems where the sequence of events and dependencies are not critical (traditional fault tree).

The dynamic fault trees (DFT) are capable of handling some kinds of dependencies that may exist in non-repairable systems.

4.4 System Description of the Selected Transformerless PV Inverter Topologies

It is agreed to evaluate transformerless inverter topologies that are widely used or understudied with great potential for PV applications. The inverter topologies selected here for evaluation with respect to reliability are based on good performance exhibited and documented in literature.

Multilevel inverter topologies have unique characteristics that are relevant for medium and high voltage applications. They have high efficiency with low harmonics and suitable for PV applications because of capacity to synthesize sinusoidal AC voltage from different DC voltage levels with minimal harmonics. For reliability and availability evaluation, a standard flying capacitor multilevel inverter is analyzed and compared with modular multilevel converter (MMC).

A basic functional block diagram for a multilevel inverter design is shown by Figure 17. There are several design strategies and architectures possible for implementing a multi-level inverter hence there are many possible functional block diagrams for a multi-level inverter and this would be one of them.

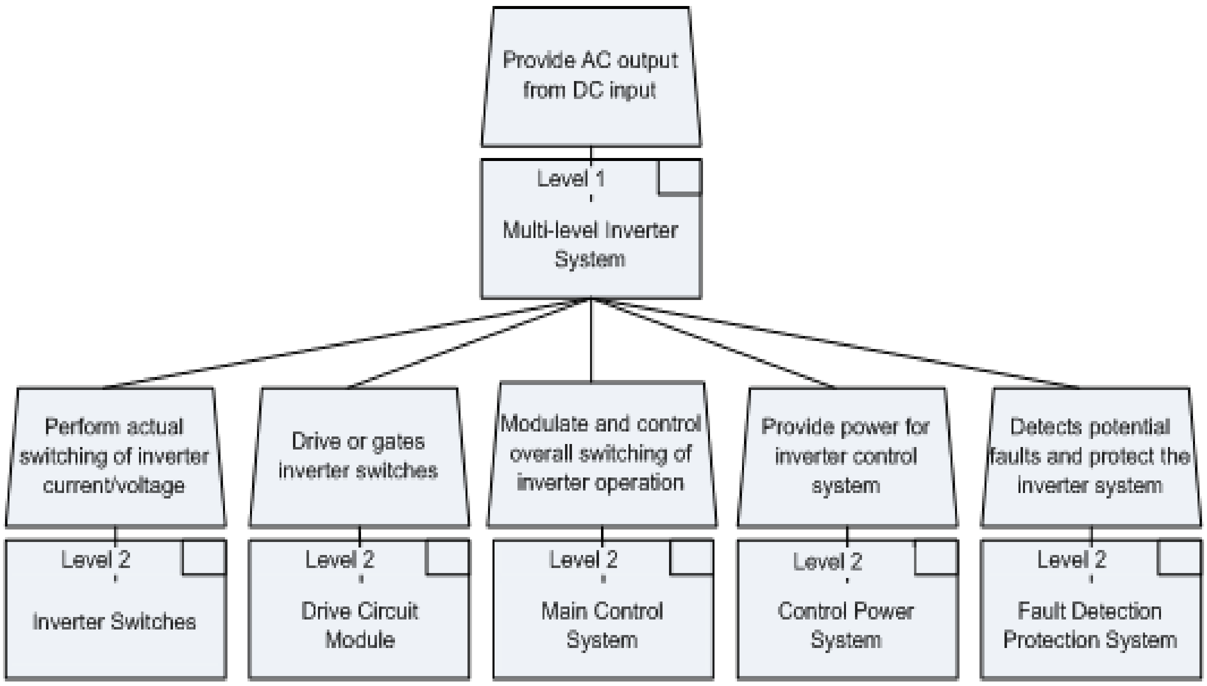


Figure 17: Functional Block of Transformerless Multi-level Inverter

4.4.1 Topology 1 – Flying Capacitor (FC) Multilevel Inverter

The flying capacitor multilevel inverter is similar to the NPC topology in terms of structure and as well as performance. In the NPC topology, diodes are used as clamping components but now in the flying capacitor, floating capacitors are used instead.

In addition to having the NPC topology structure-like, a special circuit is normally included for precharging the capacitors against causing overvoltage situations at the switches. Unique feature of the FC multilevel inverter is the capacity to continue operation at higher number of voltage levels in situations that a switch or capacitor is faulty. It should be noted that this can only exist for higher levels FC inverter and other higher levels multilevel inverters such as the modular multilevel converter inverter. The dc-link capacitors are also numbered and important in the inverter operation.

Figure 18 shows the selected Topology-1 multilevel inverter for comparative reliability analysis. The dc-link capacitors on the PV input are excluded from the analysis but note that they would be contributors to unreliability in the inverter and greater in number than an equivalent modular multilevel converter.

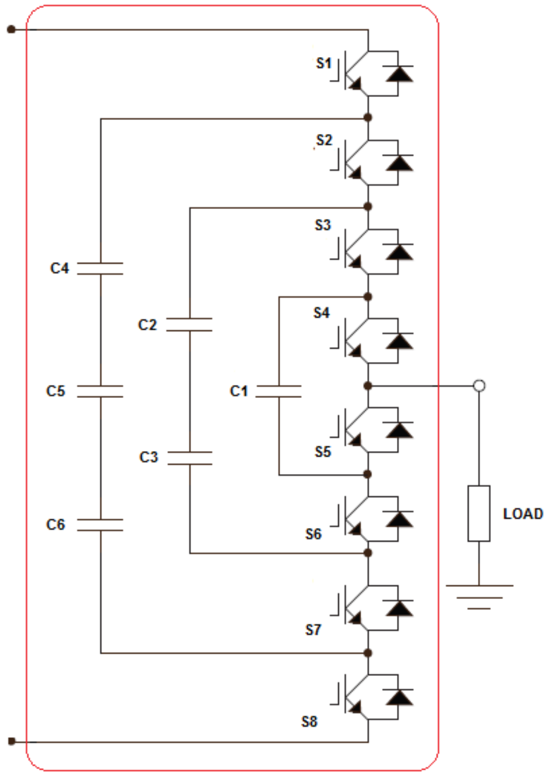


Figure 18: Flying Capacitor Multilevel Inverter with 5 Voltage Levels [31]

4.4.2 Topology 2 - Modular Multilevel Converter

The second inverter (topology 2) selected for comparative reliability analysis with inverter in topology 1 is a modular multi-level converter (MMC) with. This inverter operates 5 voltage levels with 4 converter sub-modules and 2 extra sub-modules on each upper and lower arms for active redundancy. This brings the total number of sub-modules to 6 per arms (12 sub-modules for a phase leg). For a 5-level MMC without redundancy, 2(n-1) sub-modules would give a total of 8 sub-modules; 4 sub-modules each in the upper and lower arms respectively for the modulation strategy adopted.

For the selected 5-level MMC with 50% redundancy, 4 additional sub-modules are included for active redundancy and increased inverter reliability. The extra sub-modules added to each arm do not participate in providing the voltage levels during normal operation bring other added advantages such as increased stored energy in the converter sub-modules, improved thermal management and loss distribution in sub-modules, and deceased switching frequency [32] [33] [34] [23] [35] [36]. However, for improved operational quality and reliability, cost due to additional sub-modules is added with increased control complexity as well. This topology is given by Figure 19.

The modulation strategy and internal control is such that 4 sub-modules out of 6 provide required 5-level voltage output at any one time for the converter leg. Two extra sub-modules are available in case of potential sub-module failure in the converter arm. It is important to note that the extra sub-modules operates normally as any other sub-module in the converter arm and may be selected to provide output voltage by the control and voltage-balancing algorithm. It means that the control and voltage-balancing algorithm has a pool of 6 identical sub-modules with bypass ability but only 4 sub-modules are operated at any time. Each sub-module is designed with a high-speed bypass switch making it possible for the control and voltage-balancing algorithm to completely bypass any faulty sub-module. The converter sub-module with bypass capability is shown in Figure 20.

The control and modulation strategy are only explained and not detailed mathematically since they will not be included in the comparative reliability analysis for the selected inverter topologies. Further details may refer to [37] [32] [33] [34] [23] [35] [36].

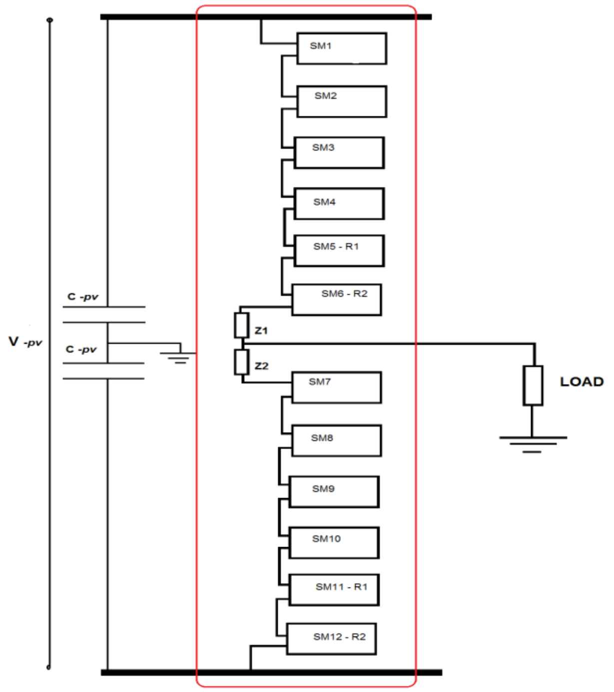


Figure 19: 5-Level Modular Multi-level Converter with 50% Redundancy

The ability of the MMC to continue operation when one or more submodules on the lower or upper arms are failed is dependent on the capability of the fault detection and protection subsystem in the control system to identify and isolate faulty sub-modules without jeopardizing the converter operation. Therefore a robust and fault-tolerant design are required for the control system, fault detection and protection system, and driver circuit. Common cause failure for the identical sub-modules must be mitigated even though it is assumed not present for this comparative reliability analysis.

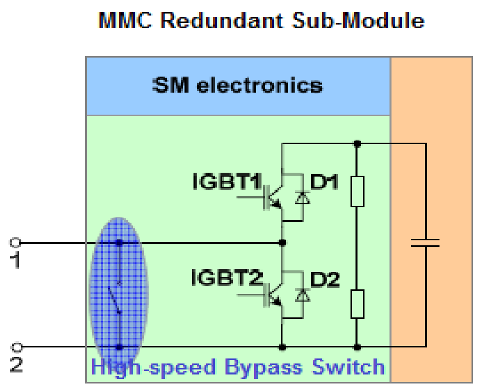


Figure 20: MMC Sub-Module with High-Speed Bypass Switch (modified from [32])

4.5 Failure Analysis - PV Inverter

The procedure for performing reliability assessment can be found in several reliability standards and references. One important step usually performed before reliability modelling is the failure analysis. It is most beneficial to have a type of FMECA carried out or at least a failure analysis at a simple level that will give input to the system reliability modelling. The outcome of such will be knowledge of likely components to fail, the failure progression in terms of the potential failure modes, failure effects, detection method and safeguards. At the most simple level, it may just be the component failure mode, effects and say safeguards.

A sample of how a failure analysis table may be constructed is given by Table 1

Table 1: Sample of Failure Analysis Table for a power system

Component Name	Function	Failure Mode	Failure Mechanism	Failure Detection	Safeguard
Resistor	Limit current flow	Short circuit	overcurrent		Connect two or more resistors in series
			Over voltage		xxxxxx

4.6 Scope and Assumptions for Transformerless PV Inverter Comparative Reliability Analysis

Boundary and scope of reliability analysis are important benchmark in performing reliability analysis. The scope and boundary for the analysis are defined, main assumptions made for modelling and analysis and limitations to the analysis are all documented here.

The scope, boundary, main assumptions and limitations for reliability analysis to compare the two multi-level topologies are defined below.

1. The scope of the reliability analysis is the switching architecture of the transformerless multi-level PV inverter and being that analysis is comparative, some common functions may be neglected as necessary.
2. The boundary of the analysis is the physical boundary of the multilevel inverter described in topologies 1 and 2. It is assumed that functions such as communication interface, connections and input DC from PV array are working properly.
3. Only random failures shall be modelled with the assumption that systematic failures have been accounted for in qualification/test and design. Therefore the constant failure rate portion of the bathtub curve shall be modelled.

4. Reliability analysis shall not include details of the control systems and driver circuits for both inverters since it would be difficult to ascertain such design detail at this stage. Moreover reliability data would be a challenge also.
5. Common cause failures are neglected therefore will not be included in the reliability models.
6. Reliability data from previous studies and expert judgement shall be used. Since details of design components are not available for modelling and analysis because topology design rather than the manufacturing design is assessed. As such other reliability inputs as relevant would be assumed across the compared topologies.
7. Reliability modeling and analysis shall compute the survival probability over 10 years of operation, mean life and failure rate for the comparative analysis. These computation shall be performed assuming an exponential distribution

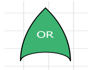
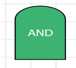
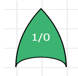
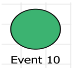
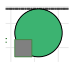
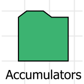
4.7 Reliability Model of Selected PV Inverter Topologies

The reliability models of multi-level PV inverters are presented for comparative reliability analysis. The modelling is performed using ReliaSoft's BlockSim reliability tool.

4.7.1 Reliability Modelling Legend

The legend for the reliability models in BlockSim are given by Table 2.

Table 2: Legend for Reliability Models

Symbol	Name	Description
	OR gate	Gate whose output event occurs if any input event occurs.
	AND gate	Gate whose output event occurs only if all input events occur.
	Voting OR gate/ K-out-of-N	Gate whose output occur if certain numbers of the input events occur.
	Priority AND (PAND)	Gate whose output occurs if the inputs occur in a specific sequence specified by a conditioning event
	Sequence Enforcing gate (SEQ)	Gate whose output occurs if all input events occur only in a specific sequence.
	Basic event	Failure or error in a system component or element.
	Mirrored block	One physical component with one failure instance whose failure may affect more than one sub system operation or scenario for same TOP event. Repeated model event with same failure instance.
	Sub diagram	A fault tree diagram or RBD that may be referenced in a model.

4.7.2 Topology-1 Reliability Model: 5-Level PV Flying Capacitor Multilevel Inverter

The reliability model for the 5-level PV flying capacitor inverter (*Topology-1*) is shown in Figure 21.

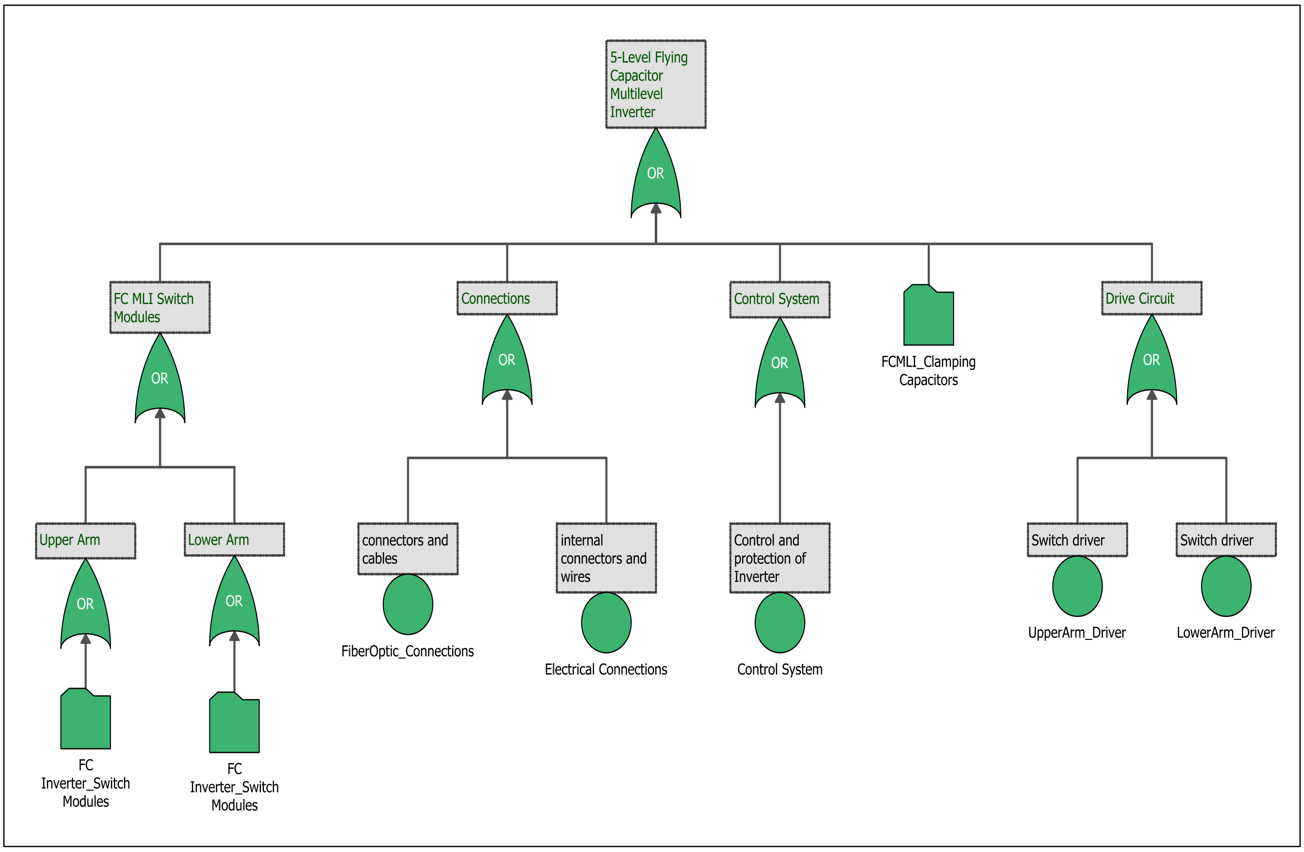


Figure 21: Reliability Model for Topology-1 (PV 5-Level FC Multilevel Inverter)

Submodels "FCMLI_Clamping Capcitors" and "FC Inverter_Switch Modules" are sub trees in the reliability model for *Topology-1* multilevel inverter. Their corresponding submodel details are respectively given in Figure 22 and Figure 23.

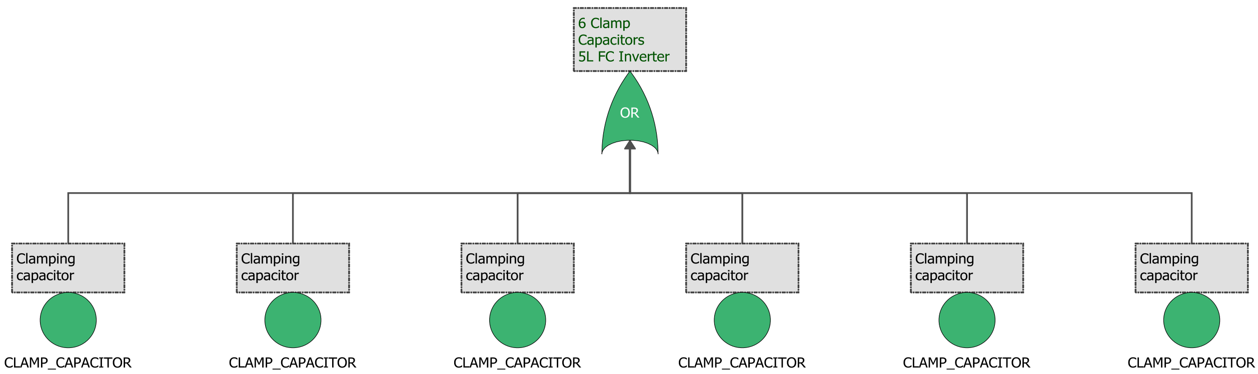


Figure 22: Model Details for Subtree "FCMLI_Clamping Capacitors"

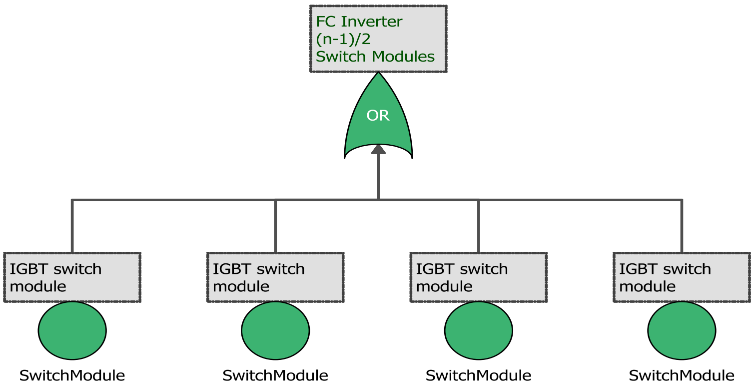


Figure 23: Model Details for Subtree "FC Inverter_Switch Modules"

4.7.3 Topology-2 Reliability Model: 5-Level PV Modular Multilevel Converter (MMC) Inverter

The reliability model for *Topology-2* is given in Figure 24. Topology-2 is a PV modular multilevel inverter with 5 voltage levels. The inverter is capable of redundant switching operation at both arms of the converter through its specialized sub-module with integrated high speed bypass switch.

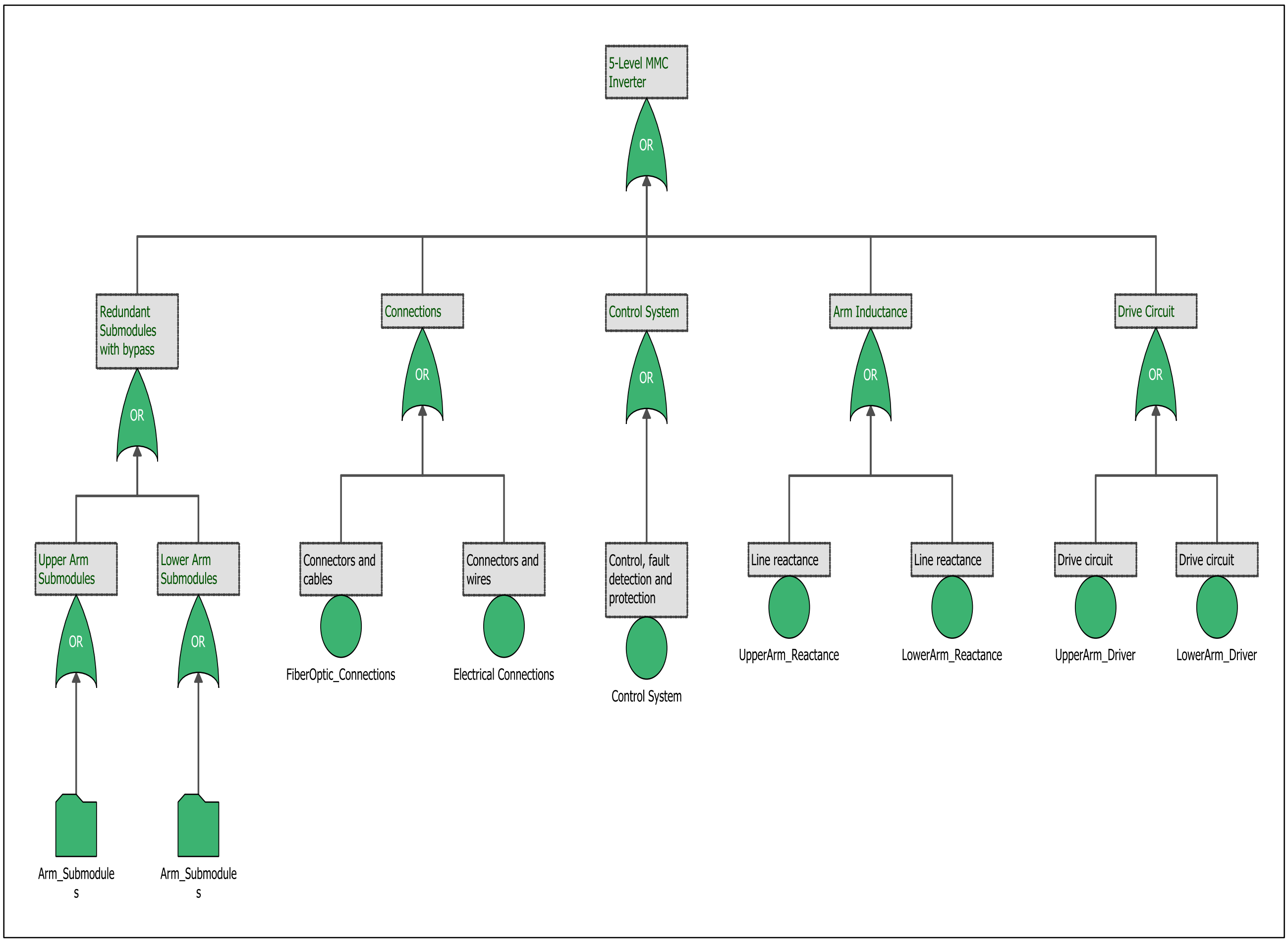


Figure 24: Reliability Model for Topology-2 (PV 5-Level MMC Inverter)

Subtree "Arm Submodules" is a sub model in *Topology-2* reliability model. Details of the sub model are depicted in Figure 25.

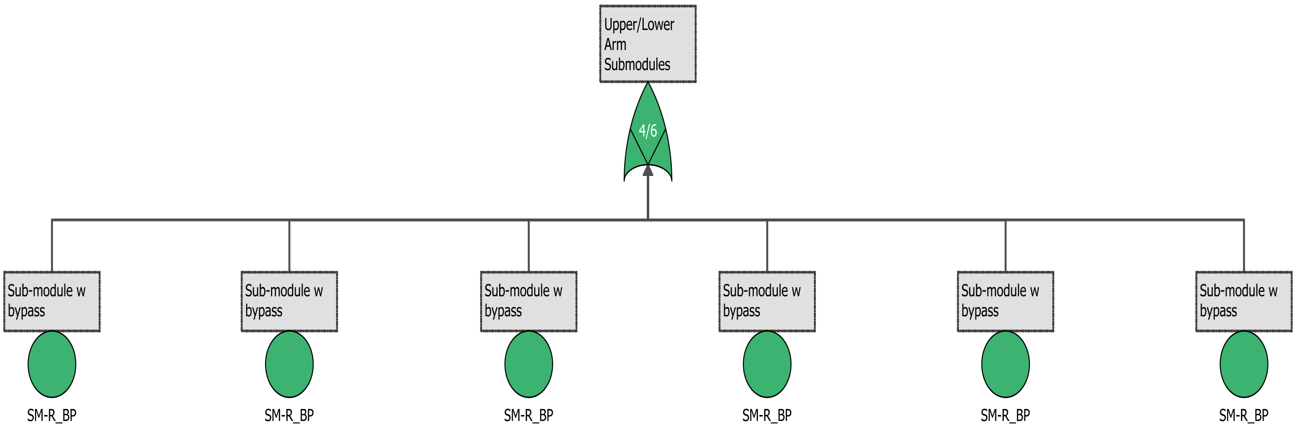


Figure 25: Model Details for Subtree "Arm Submodules

4.8 Reliability Analysis Inputs

Reliability inputs for the comparative reliability analysis are component reliability data, and environmental and operational data as relevant.

The component reliability data are failure rates of equipments/devices collected from field operation, tests, and experience for computing quantitative RAMS characteristics. Reliability data from previous research on PV inverters, reliability database, reliability handbooks, standards, engineering and expert judgements are inputs applied in this analysis. The inputs applied in this comparative reliability analysis are presented in Table 4. Previous research in related topic are also considered to support expert judgement [12] [38]. Reliability data details for the submodule are presented in Table 3.

Table 3: Half-Bridge Submodule (SM) with High Speed Bypass Switch

Submodule Components	FIT	Quantity	Total FIT
IGBT Module – 2 pack	70	1	70
Resistor	0.2	2	0.4
Metallized Capacitor	2	1	2
High speed bypass switch	50	1	50
Total		5	122.4

Table 4: Reliability data for model events/basic components

Model Label	Device Name	Failure rate (FIT)	Data source	Comment
Control System	Control board	250	Expert Judgement	Same failure rate for both models
CLAMP_CAPACITOR	Capacitor	10	SN29500	
UpperArm_Reactance	Line inductor	5	SN29500	
LowerArm_Reactance	Line inductor	5	SN29500	
LowerArm_Driver	Drive board	50	Expert Judgement	Same failure rate for both models
UpperArm_Driver	Drive board	50	Expert Judgement	Same failure rate for both models
Electrical Connections	Electrical connectors/wires	10	SN29500	
FiberOptic_Connections	Fiber optic connectors/wires	10	SN29500	
SM-R_BP	Half-bridge Submodule with bypass	122.4	SN29500	
SwitchModule	IGBT switch module	70	SN29500	

4.9 Analysis Results

Results from reliability analysis of the multilevel inverter topologies are given under the respective topology subsection.

4.9.1 Topology-1 Multilevel Inverter

The results from analysis of Topology-1 reliability model are presented in this chapter. Computed reliability metrics for Topology-1 inverter model are presented in Table 5.

Table 5: Computed Reliability Results for Topology-1 Multilevel Inverter (FC MLI)

Metric	Years of operation	Value
Survival probability	10	92 %
Failure rate	10	0.008672/Year
Mean Life (Constant failure rate)		115 Years

Graph showing the reliability of Topology-1 multilevel inverter over 10 years is given by Figure 26. The failure rate and probability distribution curves are shown respectively in Figure 27 and Figure 28.

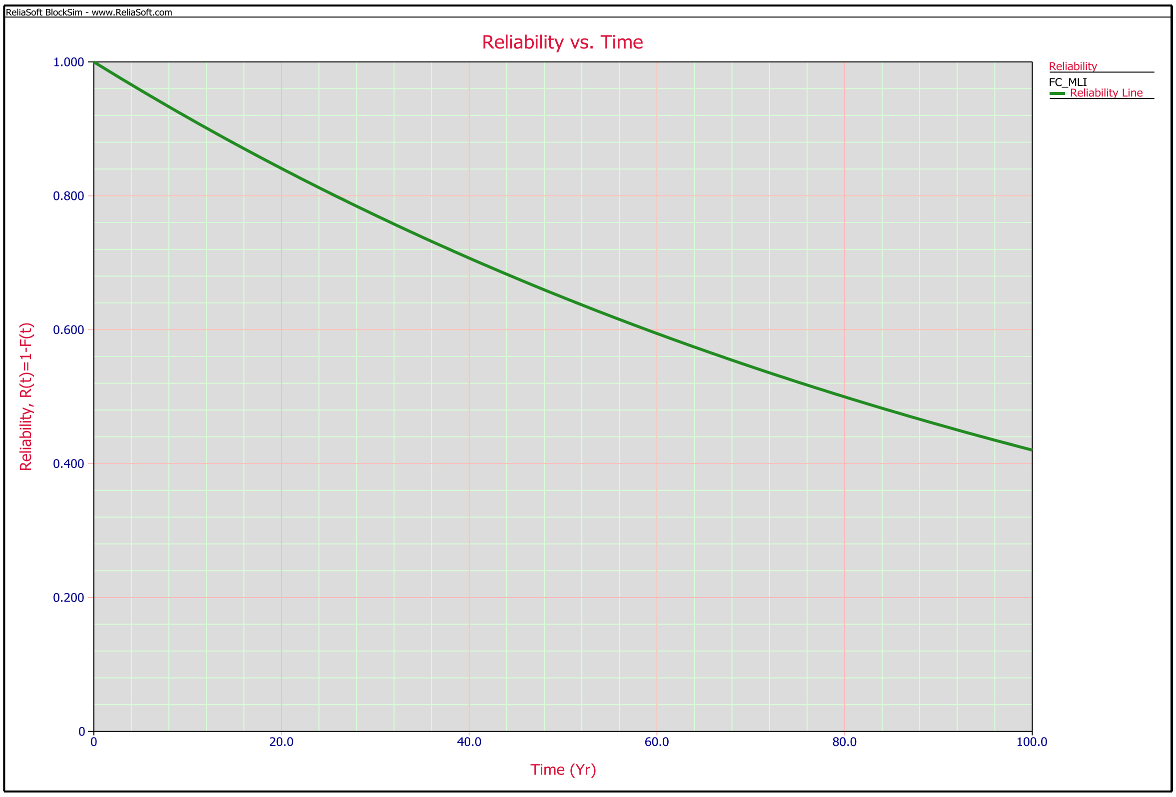


Figure 26: Reliability Curve of Topology-1 Multilevel Inverter

Figure 27: Failure Rate Curve of Topology-1 Multilevel Inverter

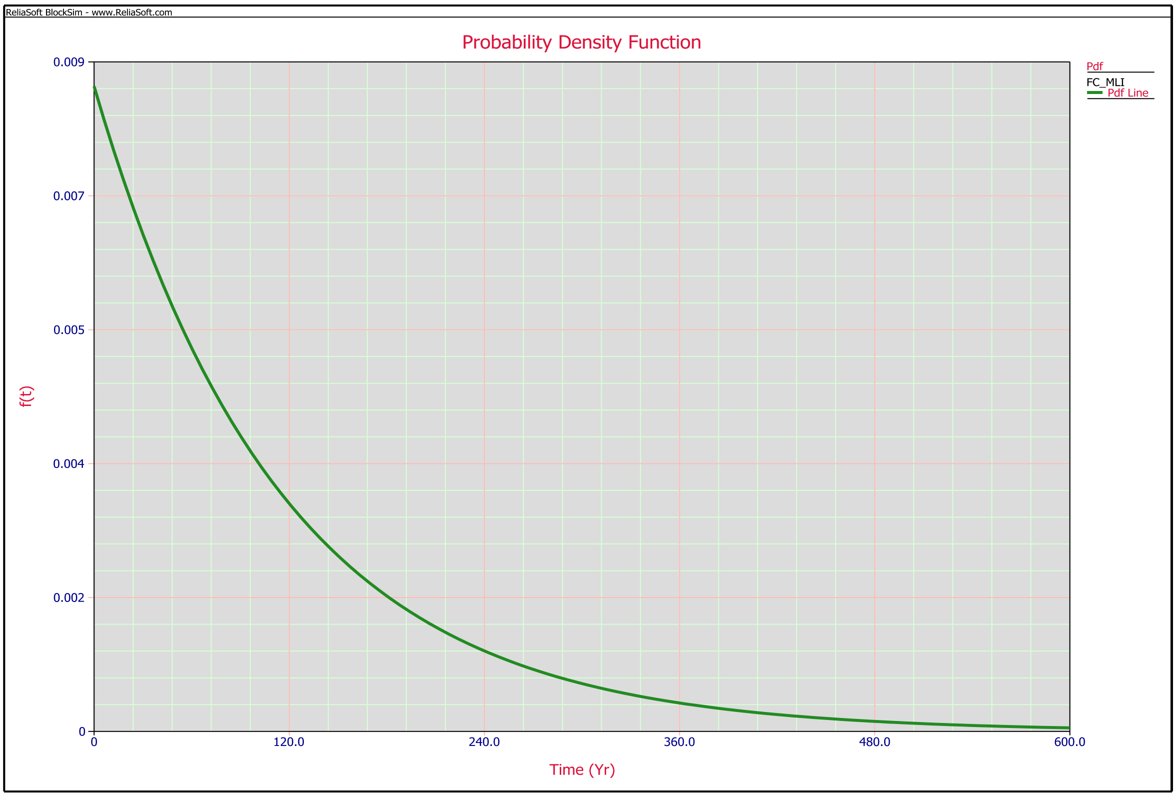


Figure 28: Probability Density Function of Topology-1 Multilevel Inverter

4.9.2 Topology-2 Multilevel Inverter

Results from analysis of Topology-2 reliability model are presented here. Reliability metrics for Topology-2 inverter model are presented in Table 6.

Table 6: Computed Reliability Results for Topology-2 Multilevel Inverter (MMC)

Metric	Years of operation	Value
Survival probability	10	97 %
Failure rate	10	0.003329/Year
Mean Life (Constant failure rate)		248 Years

Graph showing the reliability of Topology-1 multilevel inverter over 10 years is given by Figure 29. The failure rate and probability distribution curves are shown respectively in Figure 30 and Figure 31.

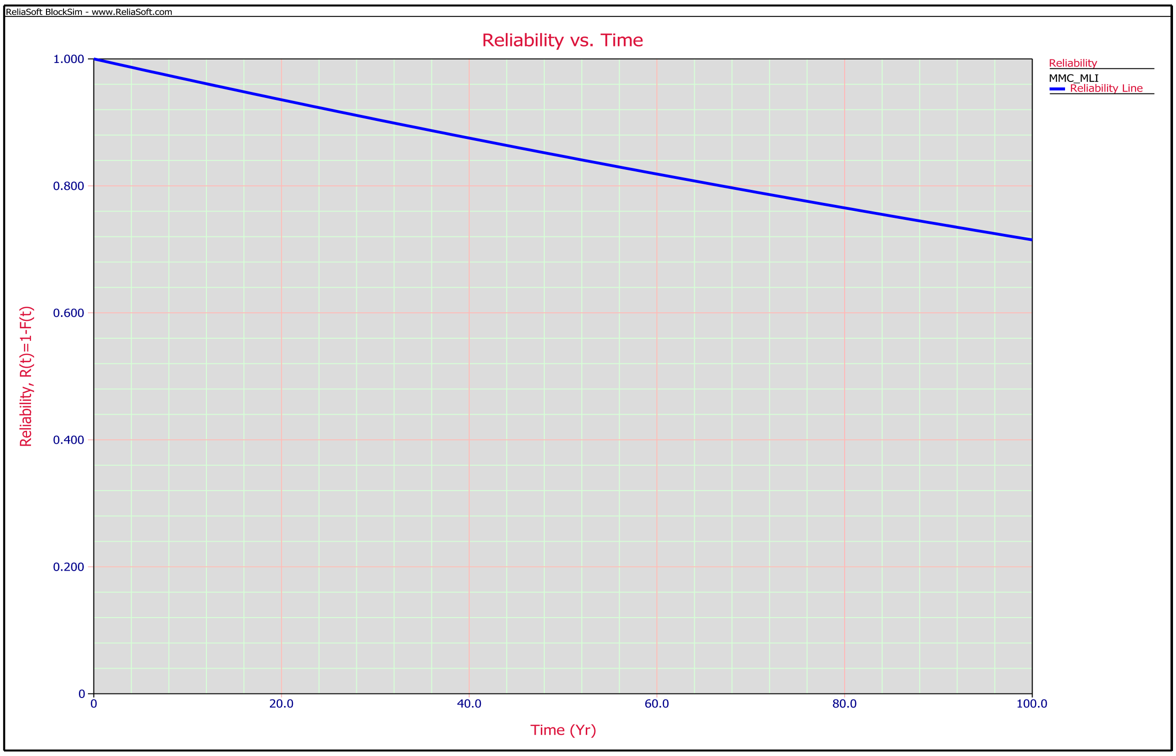


Figure 29: Reliability Curve of Topology-2 Multilevel Inverter

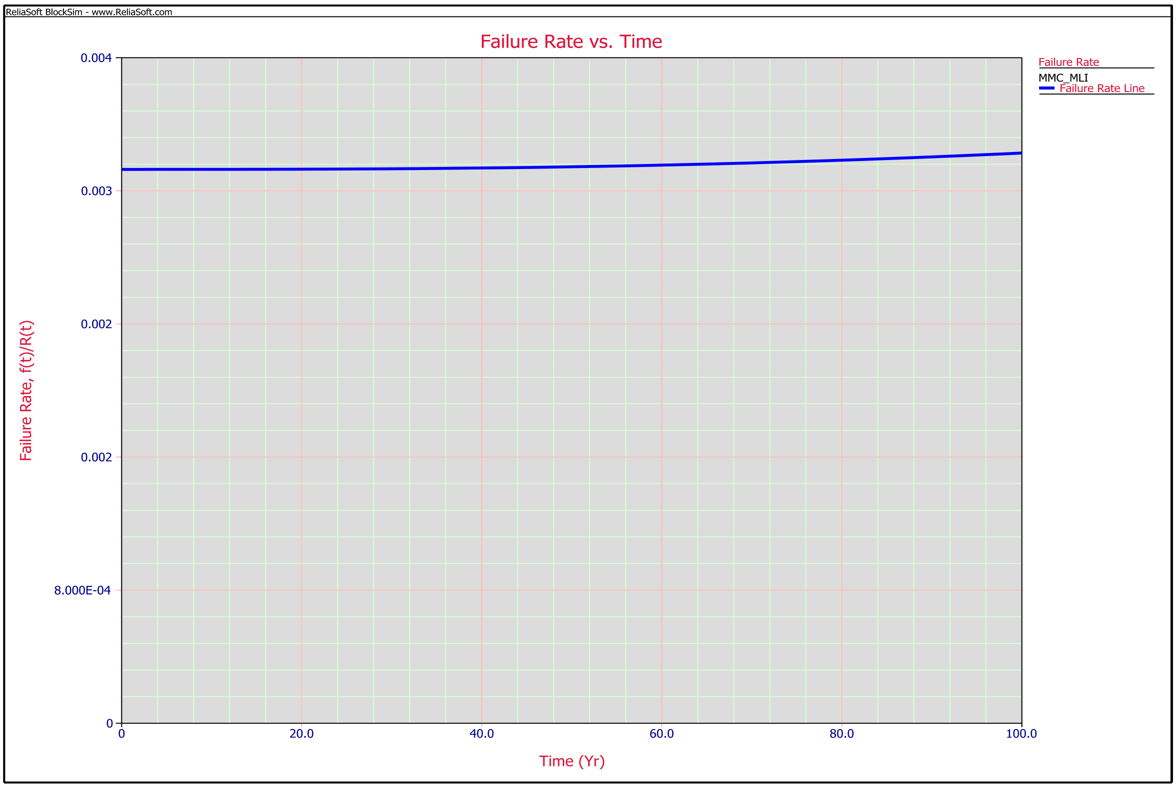


Figure 30: Failure Rate Curve of Topology-2 Multilevel Inverter

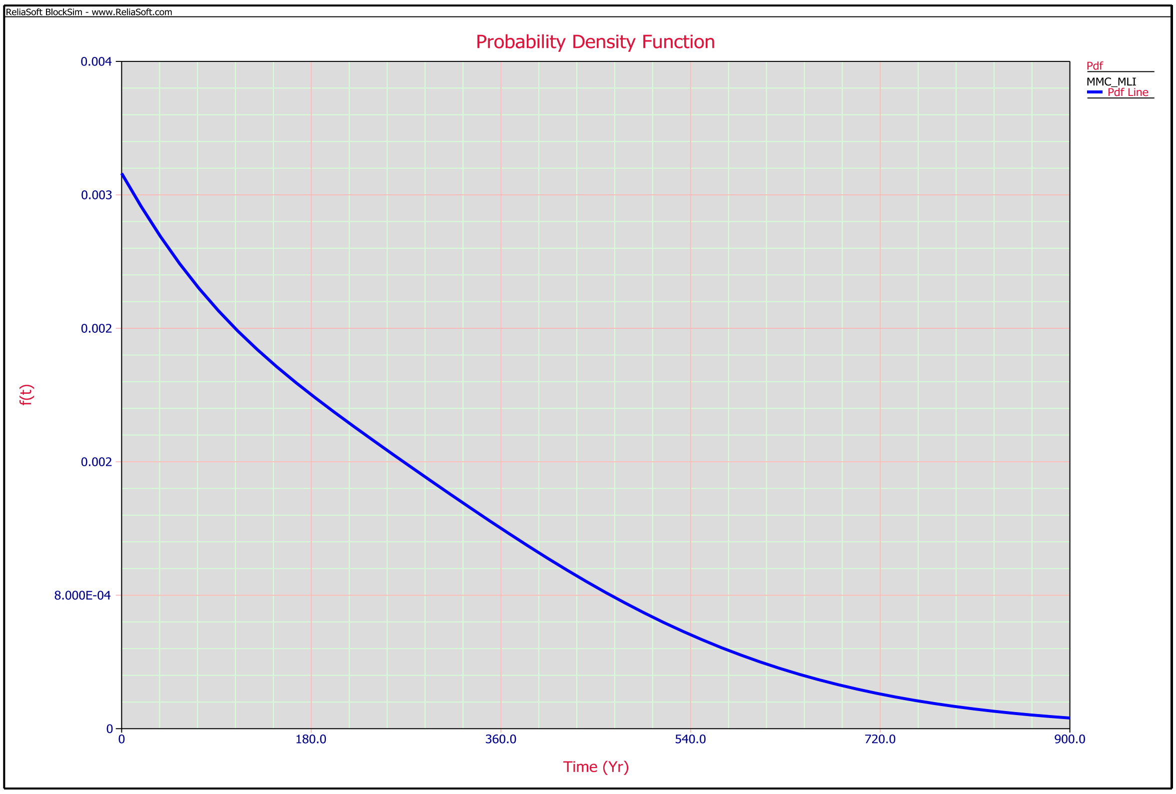


Figure 31: Probability Density Function of Topology-2 Multilevel Inverter

5 Topology Assessment

Topology assessment is done by comparing reliability characteristics of both inverter topologies on the basis of the metrics that has been defined. The comparison is presented in the following section.

5.1 Topology Comparison

Using the results from the analyzed models of the inverters, table xx is constructed to align the similarities, variations and margins between topology 1 and 2.

Table 7: Comparative Analysis Table for Analyzed Inverter Topologies

Metrics	Topology-1 (FC Inverter)	Topology-2 (MMC Inverter)	Comment on topology-2 (topology-1 as base)
Survival probability	92%	97%	5.4% margin increase
Failure rate	0.008672/year	0.003329/year	62% margin reduction
Mean life (CFR)	115 years	248 years	116% margin increase
Redundancy capability	restricted	Little restriction	Redundancy achieved reliability
Complexity	low	high	Complexity in control, fault detection and isolation
Availability	low	high	Reconfiguration is not needed for additional submodules

5.2 Ranking of the Topologies

Ranking the analyzed inverter topologies is difficult to do even though the comparative analysis table favours topology-2. One must assess the assumptions made during the modelling and analysis stage for both inverters. Also high uncertainties exist in reliability data and the models.

Having highlighted some of the obvious to take into consideration in judging by the comparative analysis table, it is easy to rank topology-2 higher for connecting PV to the grid.

6 Conclusion and Recommendations for Further Work

6.1 Conclusion

In this thesis, a review of PV system inverters is presented with main focus on grid-connected, transformerless multilevel inverters. It is evident that many research and analysis have been performed leading to the several topologies now available but most of the studies have focused on performance requirements such as efficiency of the inverter, power density, amount of leakage current and safety related issues when considering optimizing design. Most of the topologies have not considered designing in reliability along with performance or safety, rather if done was carried out in isolation.

Two transformerless multilevel inverter topologies have been modelled and analyzed in a comparative reliability analysis and interesting results obtained. Bearing in mind the assumptions and uncertainties in reliability modelling and data, the modular multilevel converter (MMC) performed better than its corresponding flying capacitor (FC) multilevel inverter counterpart. The MMC inverter showed a higher reliability than FC inverter by a percentage of 5.4%. In terms of failure rate, MMC exhibited a reduced rate in the margin of 62% which is significant. On the basis of the mean life metric assuming an exponential distribution in analysis, MMC showed a mean life twice the FC inverter.

Complexity is also another factor that comes up when implementation of redundancy is performed. Although common cause failure was neglected, it is advised to be critically analyzed to assess the assumption. Complexity is seen in implementing the control, modulation of the switching fabric of the MMC although some level is also experienced with the FC inverter. It is also important to ensure a faulty submodule in the MMC switching arms are detected and isolated properly. This is implemented along the control and modulation system. It is noted from the analysis that the reliability performance margin would be greater for the MMC with higher voltage levels but keep in mind that there is also a limit to increasing redundancy submodules in order to achieve reliability. Once the limit is reached, any increase in redundancy submodules would impact reliability negatively.

In summary, designing redundancy into a classical MMC using fault tolerant submodules for high voltage levels multilevel inverter does achieved increased reliability. In comparative reliability analysis, this has been compared to an equivalent flying capacitor multilevel inverter and has shown remarkable reliability performance.

6.2 Recommendations for Further Work

In performing this comparative reliability analysis, it was noted that many assumptions were made that requires critical analysis to verify their validity. Thus in this respect, it is recommended in future to assess some of the assumptions that have been made in performing this analysis.

Uncertainty in modelling and data are inevitably present in most and every reliability analysis. In the future, it is recommended to perform a suitable uncertainty and sensitivity analysis for the analyzed systems.

7 References

[1] S. Kouro, J. Leon, D. Vinnikov and L. Franquelo, “Grid-Connected Photovoltaic Systems: An Overview of Recent Research and Emerging PV Converter Technology,” *Industrial Electronics Magazine, IEEE,* Vols. 9, no.1, pp. 47-61, March 2015.

[2] N. Marks, T. Summers and R. Betz, “Photovoltaic power systems: A review of topologies, converters and controls,” *in Universities Power Engineering Conference (AUPEC), 2012 22nd Australasian,* pp. 1-6, 26-29 , Sept. 2012.

[3] L. L. Fang and Y. Hong, Advanced DC/AC Inverters: Applications in Renewable Energy (Power Electronics, Electrical Engineering, Energy, and Nanotechnology) 1st Edition, CRC Press, 2013.

[4] M. Martino, C. Citro, K.Rouzbehi and P. Rodriguez, “Efficiency Analysis of Single-Phase Photovoltaic Transformer-less Inverters,” in *International Conference on Renewable Energies and Power Quality, (ICREPQ’12)* , Santiago de Compostela (Spain), 28th to 30th March, 2012.

[5] P. Iván, F. Emilio, G. Fran and G. Gabriel, "Transformerless topologies for grid-connected single-phase photovoltaic inverters," *Renewable and Sustainable Energy Reviews,* vol. Volume 15, no. Issue 7, pp. 3423-3431, September 2011.

[6] I. Monirul, M. Saad and H. Mahamudul, "Single phase transformerless inverter topologies for grid-tied photovoltaic system: A review," *Renewable and Sustainable Energy Reviews,* vol. 45, pp. 69-86, May 2015.

[7] M. Rausand and A. Høyland, System Reliability Theory: Models, Statistical Methods, and Applications; 2nd Edition, John Wiley & Sons Inc, January 2004.

[8] Birolini Alessandro, Reliability Engineering; Theory and Practice, Springer, 2004.

[9] P. O'Connor and K. Andre, Practical Reliability Engineering, 5th Edition, John Wiley & Sons, Ltd., March 2012.

[10] D. N. P. Murthy, M. Rausand and T. Østerås, Product Reliability; Specification and Performance, Springer, 2008.

[11] G. Sanaie and F. Schenkelberg, “Using reliability modeling and accelerated life testing to estimate solar inverter useful life,” *in Reliability and Maintainability Symposium (RAMS), 2013 Proceedings - Annual* , pp. 1-6, 28-31 , Jan. 2013.

[12] Y. Song and B. Wang, "Survey on Reliability of Power Electronic Systems," *Power Electronics, IEEE Transactions,* vol. 28, no. 1, pp. 591-604, Jan. 2013.

[13] E. Collins, M. Dvorack, J. Mahn, M. Mundt and M. Quintana, "Reliability and availability analysis of a fielded photovoltaic system," in *Photovoltaic Specialists Conference (PVSC), 2009 34th IEEE*, 7-12 June 2009.

[14] "Wikipedia," [Online]. Available: https://en.wikipedia.org/wiki/Photovoltaic_system. [Accessed 2 August 2015].

[15] "IEEE Recommended Criteria for Terrestrial Photovoltaic Power Systems," *in ANSI/IEEE Std 928-1986,* pp. 0_1-, 1986.

[16] T. Basso and R. DeBlasio, "IEEE 1547 series of standards: interconnection issues," *Power Electronics, IEEE Transactions* , vol. 19, no. 5, pp. 1159-1162, Sept. 2004.

[17] Solanki Chetan Singh, Solar Photovoltaic Technology and Systems: A Manual for Technicians, Trainers and Engineers, PHI Learning, 2013.

[18] TC 82, "IEC 61727:2004 Photovoltaic (PV) systems - Characteristics of the utility interface," *27.160 - Solar Energy Engineering,* 2004.

[19] TC 61, "IEC 60335-1:2010 Household and similar electrical appliances - Safety - Part 1: General requirements," 2010.

[20] DKE/K 373, "DIN VDE V 0126-1-1: 2013-08 Automatic disconnection device between a grid connected generator and the public low-voltage grid," August 2013.

[21] UL, "UL 1741: Standard for Inverters, Converters, Controllers and Interconnection System Equipment for Use With Distributed Energy Resources".

[22] R. Teodorescu, M. Liserre and P. Rodríguez, Grid Converters for Photovoltaic and Wind Power Systems, John Wiley & Sons, Ltd., January 2011.

[23] S. Debnath, J. Qin, B. Bahrani, M. Saeedifard and P. Barbosa, "Operation, Control, and Applications of the Modular Multilevel Converter: A Review," *IEEE Transactions on Power Electronics (Impact Factor: 6.01),* vol. 30, no. 1, pp. 37-53, 2015.

[24] S. Rajasekar and R. Gupta, "Solar photovoltaic power conversion using modular multilevel converter," in *Engineering and Systems (SCES), 2012 Students Conference*, 16-18 March 2012.

[25] TC 56, "IEC 62308:2006 Equipment reliability - Reliability assessment methods," 2006.

[26] TC 56, "Dependability management –Part 3-1:Application guide–Analysis techniques for dependability –Guide on methodology," 2003.

[27] TC 1, "NEK IEC 60050-191 International Electrotechnical Vocabulary. Chapter 191: Dependability and quality of service," 1990.

[28] ISO/TC 67, "ISO/TR 12489:2013 Petroleum, petrochemical and natural gas industries -- Reliability modelling and calculation of safety systems," 2013.

[29] ISO/TC 67, "ISO 20815:2008 Petroleum, petrochemical and natural gas industries -- Production assurance and reliability management," 2008.

[30] ISO/TC 67, "ISO 14224:2006 Petroleum, petrochemical and natural gas industries -- Collection and exchange of reliability and maintenance data for equipment," 2006.

[31] M. Calais and V. Agelidis, "Multilevel converters for single-phase grid connected photovoltaic systems-an overview," in *Industrial Electronics, 1998. Proceedings. ISIE '98. IEEE International Symposium*, 7-10 Jul 1998.

[32] B. Gemmell, J. Dorn, D. Retzmann and D. Soerangr, "Prospects of multilevel VSC technologies for power transmission," *Transmission and Distribution Conference and Exposition, 2008. T&D. IEEE/PES,* pp. 1-16, 21-24 , April 2008.

[33] G. Konstantinou, J. Pou, S. Ceballos and V. Agelidis, "Active Redundant Submodule Configuration in Modular Multilevel Converters," *Power Delivery, IEEE Transactions,* Vols. 28, no.4, pp. 2333-2341, October 2013.

[34] G. Konstantinou, M. Ciobotaru and V. Agelidis, "Effect of redundant sub-module utilization on modular multilevel converters," in *Industrial Technology (ICIT), 2012 IEEE International Conference,* 19-21 March 2012.

[35] E. Solas, G. Abad, J. Barrena, S. Aurtenetxea, A. Carcar and L. Zajac, "Modular Multilevel Converter With Different Submodule Concepts—Part II: Experimental Validation and Comparison for HVDC Application," *Industrial Electronics, IEEE Transactions* , vol. 60, no. 10, pp. 4536-4545, October 2013.

[36] E. Solas, G. Abad, J. Barrena, S. Aurtenetxea, A. Carcar and L. Zajac, "Modular Multilevel Converter With Different Submodule Concepts—Part I: Capacitor Voltage Balancing Method," *Industrial Electronics, IEEE Transactions* , vol. 60, no. 10, pp. .4525-4535, October 2013.

[37] C. Toh and L. Norum, "Implementation of redundancy control by degrading voltage level in modular multilevel converter," in *Energy Conversion (CENCON), 2014 IEEE Conference* , Johor Bahru, 13-14 Oct. 2014.

[38] S. Yang, A. Bryant, P. Mawby, D. Xiang, L. Ran and P. Tavner, "An Industry-Based Survey of Reliability in Power Electronic Converters," *Industry Applications, IEEE Transactions* , vol. 47, no. 3, pp. 1441-1451, May-June 2011.