Chapter 1

Introduction

1.1 Historical Background

Inverters form a crucial part of electrical system which converts the Direct Current (DC) type electrical energy into Alternating Current (AC) type. This converted energy is useful in fulfilling the demand of industrial loads, domestic loads, and commercial loads [1–3]. The inverter is helpful in getting the converted form of electrical energy as well as monitoring the electrical system. The performance of the electrical system is indicated by the current and voltage signals from the inverter. For monitoring the power quality and fault diagnosis of the electrical system, the inverter's output is taken as diagnostic information. Moreover, inverter is very much helpful in giving supply from a battery to the load in case of unavailability of grid supply or Renewable Energy (RE). Inverters are significantly used in the power industry, transportation systems, distribution systems and etc. Thus increasing the reliability of inverters that provide power to the motors is very important. In order to increase the reliability of inverters, we need a fault identification and diagnosis system. This causes less damage occurs to the power system [2]. In power plants, the energy is generated from the generators which give AC electrical output. In this system, there is a specific synchronous frequency which is also a good parameter to monitor the power quality and health status of electrical system. When the load changes, the rotating speed of the generator is also changed to maintain that frequency. When PV systems are connected to the grid supply, there is a fixed frequency of PV system as there is no moving turbine to adjust the frequency. Therefore, inverters of PV systems need to be monitored so that these can respond to the change in normal operating condition of the electrical system and change in frequency [3].

Every machine in power electronics are affected by faults. Many kinds of faults can occur in industry which may cause shutdown of the operation of whole system. Due to these unexpected faults, performance of inverter decreases. The cost of these steps can be high. It is necessary to avoid these unexpected inverter faults to improve reliability of the system. Therefore, fault detection of three phase inverter is needed. The Insulated Gate Bipolar Transistors (IGBTs) are used as a switch in many inverters. IGBT has the features like high voltage and current ratings. They can handle short circuit currents for more than 10 micro-s [4] but due to excess electric and thermal stress, IGBTs cause failures. There are various types of faults of switching device in inverter, an open switch fault, a short switch fault and intermittent gate-misfiring fault. These faults can causes problems for other parts in system. Therefore monitoring of switching device faults is important. It is required to identify the faulty switch to improve the stability and reliability of the system. In literature, many methods are presented on single switch faults. There is lack of methods which can detect multiple switch faults. In this thesis, techniques for fault detection are discussed which can detect single as well as multiple open switch faults.

1.2 Inverters in Electrical Power System

Inverters are generally classified into two major categories as stand-alone and grid-tied. The standalone type inverter is used for a particular small application or for personal equipment or home. The grid-tied inverters are used in PV systems which give the generated and/or excess power to the grid. This may be that inverter can play both role simultaneously when one private inverter is feeding power to the grid and earn money.

There are two more special kind of inverters such as battery backup inverters and smart hybrid inverters. In battery backup inverters, the inverters are connected with a battery system to extract energy from the battery and supply to the load. This type of inverters are also used to supply the surplus energy to the grid. The smart hybrid inverters are called as multitasking inverters which control PV array, Energy Storage System (ESS), and grid which are coupled as a single power system.

Figure 1.1 shows the grid-connected hybrid renewable energy system with ESS where inverters play a vital role. The supply and load demand are fulfilled by managing the electrical generation and distribution system. For fulfilling the increased load demand, various other resources are utilized such as electrical vehicles and ESS.

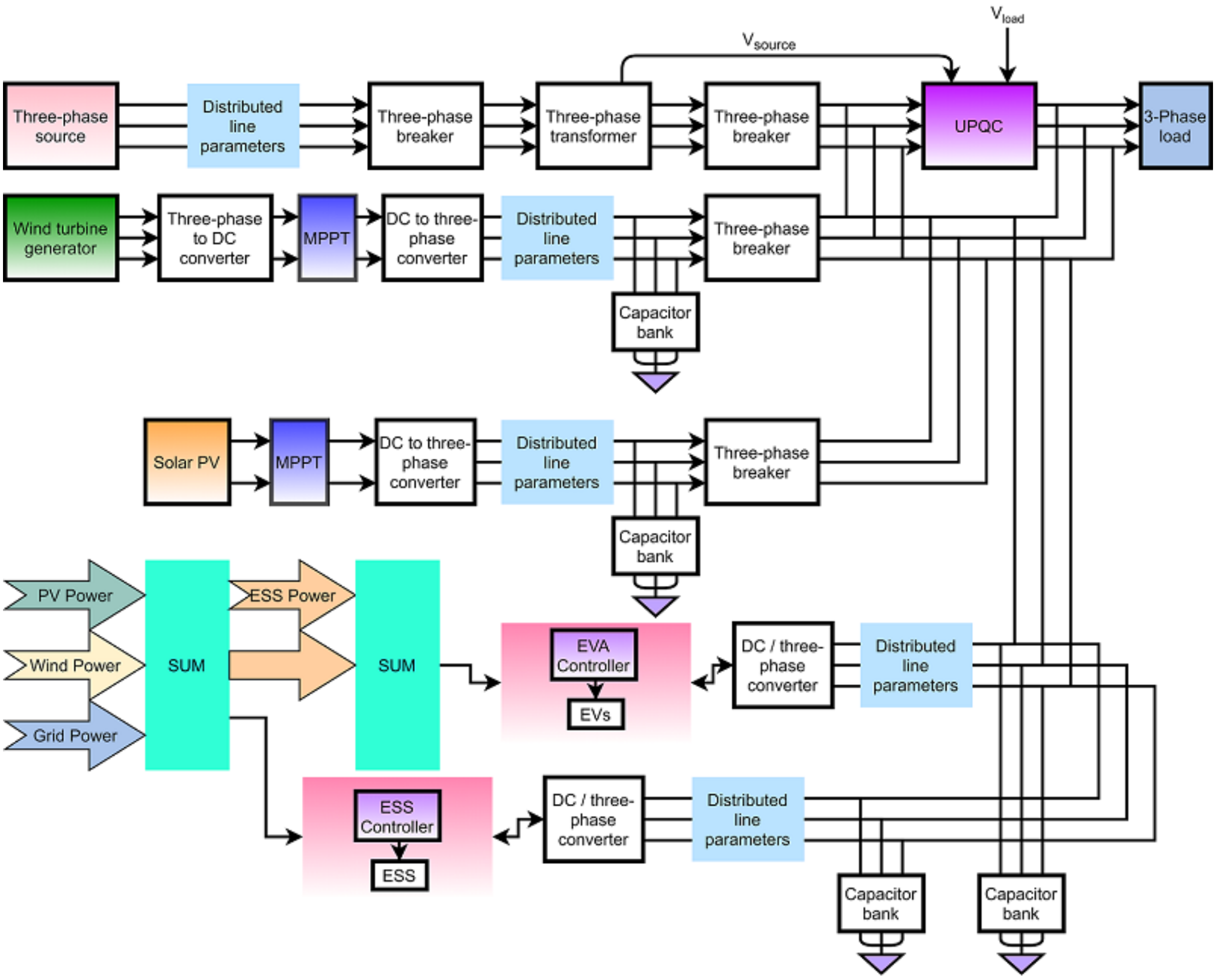

Figure 1.1: Inverters used in electrical power system including wind generation, solar PV panel, EVs, and ESS connected to the grid.

Whenever there is any undesirable condition occurring in the system, the inverter needs to be smart to take appropriate action. Moreover, the condition monitoring system of inverter and other equipment must be good enough to detect the fault condition and to distinguish between normal and abnormal condition for avoiding the false decision.

The grid-connected inverters play a vital role especially when PV systems are connected to the grid. Some major functionalities of inverters are as follows.

1. Power factor improvement: the power factor depends on the type of loads (inductive, capacitive, or resistive). Generally practical loads are combination of inductor and resistor and are called as inductive load as the reactive nature is inductive. For practical inductive loads, the power factor is less than unity and to improve it, the capacitive component is

added to cancel the effect of inductor. The motive is to make the load purely resistive. To do so, the amount of capacitive load to be added depends on the type of equipment and inverter. If inverter allows, then only one can make the power factor close to unity. For this, one must refer the manual of the inverter provided by the manufacturer before changing the nature of load by adding exteral elements. Any mistake in taking the value of capacitive element can damage the inverter.

2. Grid synchronization: two machines of equipment are called to be synchronised when the phase, frequency, and amplitude of both signal are same. For checking the grid synchronization of inverter, the phase-locked loop and zero-crossing detection methods are used.

3. Detection of islanding: for this, there are three methods such as active detection, passive detection, and notification receiving from utility. In active detection, the response of inverter due to change in load is noticed. In passive detection, the change in frequency, phase, and magnitude of voltage is monitored. The inverter is isolated from the grid if any unexpected change is observed. The third method is by notifying the distribution system operators regarding the switching off of grid so that the inverters can be isolated and equipment can be kept safe.

4. Maximum power point tracking (MPPT): the MPPT is built into an inverter when it is used in a system with no backup batteries. The MPPT in an inverter works the same as one in a charge controller of batteries because the inverter input comes directly from the solar array.

5. Condition Monitoring of Electrical Equipment and Drive Systems: the inverters provide current and voltage signature of the connected system and equipment which are very helpful in monitoring the health condition and predicting the fault to occur in the system components.

1.3 Three-phase Inverter Modelling

In today's world most of the appliances and machines work on AC power. In the absence of AC power, there should be some way to convert DC power to AC power. This conversion is done by the power electronic circuit called the inverter. The basic function of a power inverter is to change DC input voltage to a symmetric AC output voltage of the desired magnitude and frequency. These devices find wide applications in uninterruptible power supplies, adjustable speed AC drives, induction heating and standby aircraft power supplies. If the DC input voltage is fixed but not controllable, a variable output voltage is obtained by varying the gain of the converter which is achieved by Pulse Width Modulation (PWM) technique control. There are two types of inverters- voltage source and current source inverters. When an inverter has DC source with negligible resistance, it is said to be a voltage fed inverter. Whereas, when it has a high input resistance, which means it has a stiff DC current source at its input terminals, it is termed as current fed inverter.

In PWM technique, pulses of constant amplitude but different duty cycles are generated by modulating the time periods . This modulation is done by using one carrier and one reference signal. These two signals are fed to a comparator and the corresponding signals are generated based on the logic of the comparator. The reference wave is the desired signal output which may be a sine wave or a square wave. The carrier wave, on the other hand, is generally saw-tooth or triangular wave having frequency significantly higher than that of the reference signal. The higher order harmonics in the load current are eliminated using a series inductor. A selected range of lower harmonics can be reduced by suitably choosing the number of pulses per half cycle. The PWM technique has the following advantages.

1. The output voltage can be controlled without using any additional component.
2. Significant reduction of lower order harmonics.

There are three basic categories of PWM techniques as follows.

1. Single pulse
2. Multiple pulse
3. Sinusoidal PWM

In this thesis only Sinusoidal PWM (SPWM) technique is implemented. In SPWM, the width of each pulse is varied in proportion to the amplitude of the sine wave evaluated at the centre of the same pulse. The gating signals are generated by comparing a sinusoidal reference wave with a triangular carrier wave. Several pulses per half cycle are used and the pulse width is a sinusoidal function of angular position of pulses in a cycle. A high frequency carrier wave is compared to a reference signal having the desired frequency through a comparator. When the sinusoidal wave has a higher magnitude, output is high otherwise it is low. The comparator output is processed in a trigger pulse generator in such a way that the output voltage wave has a pulse width in agreement with comparator pulse width. To provide the gate signals to the switches in an inverter, two types of switching schemes are used- Unipolar and Bipolar voltage switching. If the triangular carrier wave is either in the positive or negative polarity range of changes, the resulting SPWM wave lies only in the polar range, this type of switching is called unipolar control mode. Whereas, if the triangular carrier wave lies in continuous range between both positive and negative polarity, the SPWM wave lies between positive and negative changes, this switching is known as bipolar control.

The three phase inverter is used to provide variable frequency power for industrial applications. The SPWM technique is used for the voltage control of three phase inverters and the corresponding gating signals. The basic circuit diagram of a three phase inverter with 6 IGBTs is shown in Fig. 1.2.

The inverter is fed by a fixed dc voltage V_{DC} and has three phase-legs each comprising two IGBTs. With SPWM control, the switches of the inverter are controlled by comparing a sinusoidal signal and a triangular signal. The sinusoidal wave determines the desired fundamental frequency of the inverter output, while the triangular wave decides the switching frequency of the inverter. Each transistor conducts for 180 degrees. Three of the IGBTs conduct at a time in the order $S_6S_1S_2$, $S_1S_2S_3$, $S_2S_3S_4$, $S_3S_4S_5$ and so on. When S_1 is switched on, the load is connected to the positive terminal of the DC supply voltage. When S_4 is on, the load is connected to the negative terminal of the input voltage. There are six modes of operation and each mode operates for a period of 60 degrees. For IGBTs S_4, S_6 and S_2, the gate signals are just the inverse of S_1, S_3 and S_5 respectively. This is done by adding a NOT gate after each comparator and then the resultant signal is given to the remaining three switches.

1.3.1 Failures in inverters and its causes

Grid-tied three-phase voltage-source inverters are widely used in renewable energy systems, electrical traction systems, etc. Inverters play the key roles of interfaces controlling and transferring power. However, inverters are of the parts with highest failure rate. Unexpected inverter failure may cause considerable loss; therefore, methods to improve inverter availability, protect

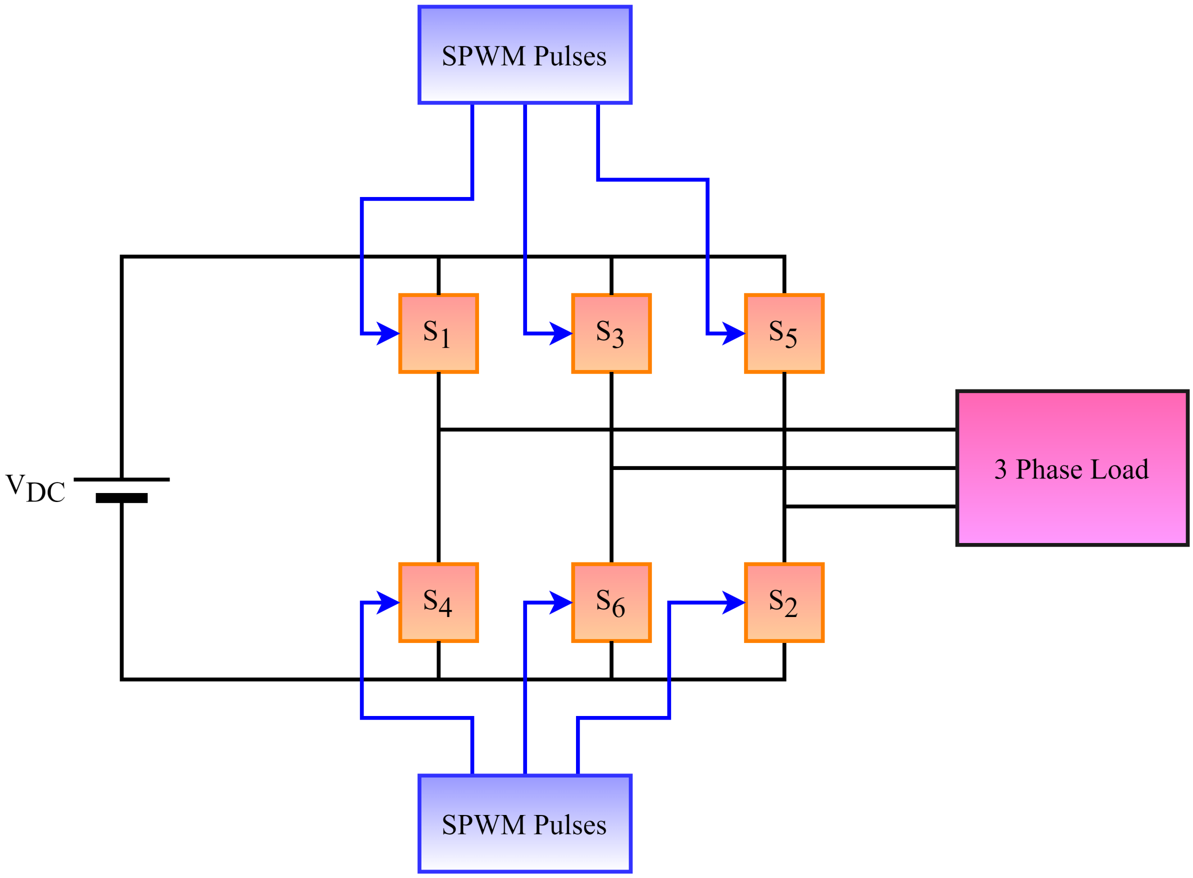

Figure 1.2: Block diagram of three-phase inverter.

systems, and reduce maintenance time are hot topics.

A failure could occur in any part of the electrical power system. According to the study in [5], semiconductor and soldering faults cause approximately 34% of power device failures. However, it is estimated that at least 80% of faults in the converter part are due to semiconductor failures. Power switch faults which are typically caused by high thermal or electrical stress are categorized into two main groups: SC and OC faults. An OC fault in a power converter could occur through a switch failure or a driver breakdown. Gate driver breakdown is the main cause of converter failure (53% of the converter faults) and results in permanent OC of IGBT switches. Unlike an SC fault, which usually triggers the SC protection of the system, an OC can remain undetected for a long time, degrading the power quality in the power system. Problems such as abnormal stress on circuit elements can occur after OC, causing further damage to the system. As OC faults are prevalent in power device failures, OC fault diagnosis is a basic step for increasing the reliability of a power system. In non-fault tolerant systems, using OC fault diagnosis techniques prevents extra system damages. In fault tolerant systems, it also results in continuous operation after an OC fault. Speed, cost, reliability, and independence of the load condition are the main factors for evaluating an OC fault diagnosis method.

In inverters, power semiconductor switches, particularly IGBTs, are the most vulnerable devices. IGBTs may suffer from SC faults and OC faults. Unlike SC fault protection, OC fault protection is not generally included as a standard feature in inverters. However, OC faults also cause malfunction and could lead to failures on other parts. Therefore, it is useful to consider fast and accurate IGBT OC fault diagnosis methods.

1.4 Reliability, Availability, and Condition Monitoring (RACM)

The inverter forms an important part of the solar system. Reliability, Availability, and Condition Monitoring (RACM) evaluation have become the critical area of interest for researchers as the output power quality of PV system depends on the reliability of its components. In this thesis, the RACM of grid-connected PV systems of different ratings is presented. For this, the RBD technique along with exponential probability distribution function is used. The main objective of this work is to identify the weakest subsystem of a system in order to enhance system reliability. Elaborate analysis is presented for these systems beginning from the sub-assemblies to the subsystems and then to the overall system. In addition, the subsystems are ranked based on their impact on the overall availability of the system. This is decided based on the availability importance measures. It is observed that inverter forms the weakest subsystem in the solar system. The reliability of inverter for 100 kW PV system after one year of operation is found to be 88.33% whereas after twenty years of operation, it is 8.36%. The main advantage of the proposed RACM method is that one can monitor the health status or useful life of the system under consideration regularly which is not yet explored in the literature. In literature, most of the papers has considered that the components of PV systems are non-repairable but in this thesis, the affect of maintenance is shown on the life cycle of the component. The reliability, availability, and maintainability of the system are discussed in this thesis. It also discusses the condition monitoring of the inverter of PV systems. The first step in monitoring is data pre-processing in which data is normalized or any other statistical method is applied to make the data useful. The most important factor to be taken care in condition monitoring is that the selected data or parameter must be a good predictor of the health of that system or component. In this case, reliability data, currents and voltages are found to be a good predictor for inverter. After pre-processing of the data set, the smoothed data is sent to the PCA-based monitoring algorithm. The PCA technique gives the current health status of the inverter and helps in knowing the degradation in health by a visualization output.

1.5 Need of RACM of Inverters

The most common fault occurs in IGBTs is OC fault. This fault in a single IGBT may cause interruptions in the converter applications and sometimes it may be harmful for the system components. Therefore, detection with localization of faults in IGBT-based applications are essential for reliable and safe operation of the system. It is necessary to detect and localize the faults in minimum possible time for improved fault tolerant control scheme in IGBT-based applications. So condition monitoring of inverters is necessary.

Condition monitoring of equipment is the process of monitoring the health and operation of the equipment using any of its parameters such as current, voltage, vibration, temperature, pressure or lubrication. The condition monitoring refers to the process in which the system or its components are checked regularly to know whether it is functioning properly or not. It can be online or offline process. Due to advancement in the digital technology, the industries are moving towards industry 4.0 revolution and automation of the processes. Each equipment

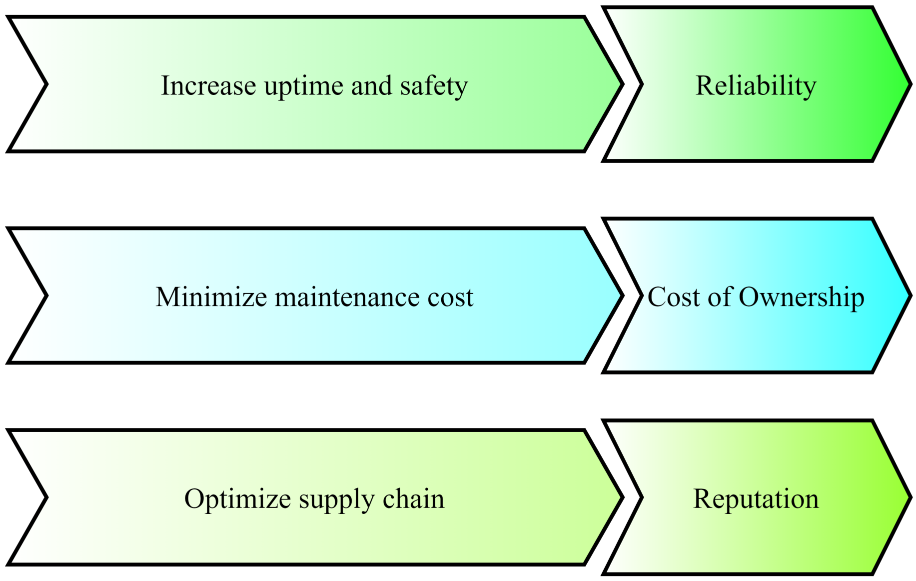

Figure 1.3: Benefits of condition monitoring of system

and its components are monitored from a single monitoring screen which is the visualization of the results obtained from reliability, availability, maintainability, and maintenance process. Once any system or equipment is given maintenance either as per the scheduled maintenance or predictive maintenance, the reliability and availability of the that system must be updated. This system is possible only when there is an integral condition monitoring system which keeps record of each failure and maintenance. For the reliable condition monitoring of the system and components, there is a need for implementing machine learning algorithms which are also helpful for preventive and predictive maintenance of the equipment. The benefits of condition monitoring of system and components are illustrated in Fig. 1.3. As discussed in the earlier sections that inverters are used in almost all the parts of electrical power system and can affect the overall reliability of the system. Therefore, it is very crucial to provide proper condition monitoring to the inverters. This section discusses the need of condition monitoring of inverters used in solar PV system, wind system, EVs and ESS.

1.5.1 Inverters in PV Systems

The important source of renewable energy is solar energy. From the sun the energy can be harnessed as radiant light and heat. From solar energy, we can harness the thermal energy which can be used in space heating. Electrical energy can also be obtained from solar energy which further can be used in various applications. In limiting global warming, the huge step one can take would be solar energy power generation. In particular the adoption of solar energy has accelerated by many countries as energy generation source. In order to balance the changes in climate the implementation of PV systems has been increased.

Inverter is one of the essential parts for any grid connected PV system. Inverter converts the extracted DC power from the solar PV array to the AC power at the proper voltage and frequency to connect the solar PV system to the grid or for offering the supply to the domestic loads. Generally, the failures of inverter subsystem follow the bathtub curve. Almost the failures will occur in the early stage maybe within the two years then after some time they have very low failure rates that is may be for 10 years later on the failure rate increases rapidly. So, it's better to prepare with the spares for the first couple of years as there are chances for 15% failures to occur in early stage. Its better to monitor inverter outputs consistently. By simply replacing the inverter with a spare, most of the failures can be fixed [6].

The layout of the solar power system depends on the architectural design. Based on the number of inverters present in the PV system and the structure of inverter connection with other components, reliability block diagram of inverter is decided. There may be the case when all components are connected to the inverter which is present singly as a central inverter or there may be single inverter present in each line connecting to other components [7]. This affects the overall reliability and availability of the PV system. In case, if only one central inverter is present, the reliability level depends on the availability and reliability of that single inverter. If multiple inverters are present in the system then, groups of strings are counted as per the number of inverters available for each components. From literature [6–10], it is observed that the inverter forms the weakest component among the five major components of the PV system shown in Fig. 1.4 and needs condition monitoring system for improving the overall reliability of the system. The ranking of the subsystems of PV systems based on their effect on the system availability are follows [6].

1. Inverters

2. PV modules

3. Converters

4. System Storage

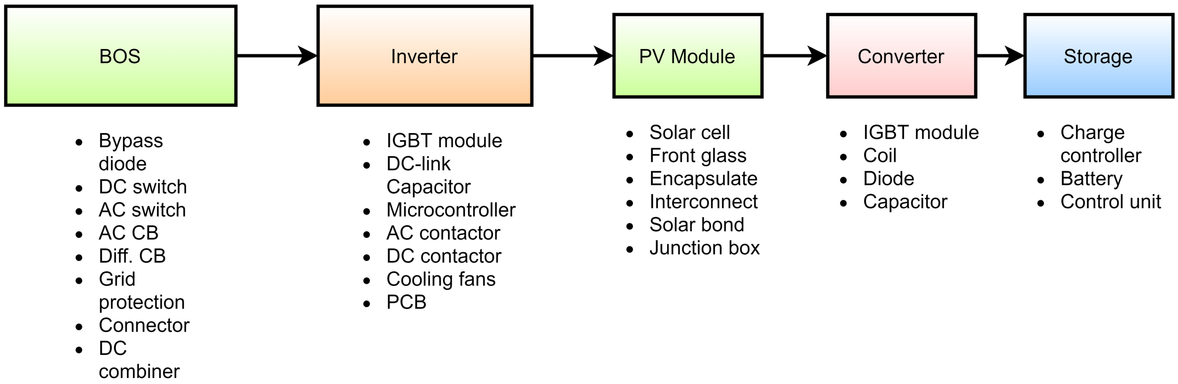

Figure 1.4: Division of PV system into its components and sub-components and reliability block diagram.

1.5.2 Inverters in Wind Energy Systems

In wind energy systems, the inverter is used when MPPT is implemented to extract the maximum power from the system at particular wind speed as shown in Fig. 1.1. In addition to that converter is also used to convert the AC power generated into DC so that it can be used to get the maximum power. After MPPT, the DC is again converted into AC supply using inverter. From literature [11, 12], it is clear that the sensors, converters, and inverters need monitoring system as these components of wind energy system affect the overall reliability and availability of the system most.

1.5.3 Inverters in EVs and other drives systems

The OC faults occurs in power inverters due to high stress in industrial drive systems and also in EVs. Two types of faults mainly occur in inverter's switches: SC fault and OC fault. In SC fault, the current increases by 4 to 5 times of the normal value but in OC fault, there is no such difference is observed for a long time. Hence, detection of OC faults is difficult and crucial too. For the condition monitoring system to be reliable, the faults must be detected at minimum possible time. Otherwise, the OC fault which causes distorted output waveform of inverter, may damage the drive system and the whole process may gets disturbed. For this, fault detection time must be as short as possible. As a result, the focus of this thesis is on the condition monitoring of three-phase inverters.

1.6 Role of Signal Processing Techniques in RACM

The most important task of the electrical energy management system is to maintain the functional continuity even when unwanted events or faults occur. Usually it is very hard or impossible to avoid consequences of equipment failure which results in short-circuits, voltage falls or loss of power. Generally, a system protection is the set of procedures which provide maximum sensitivity to faults and malfunctions and also avoids invalid alarms during normal operating conditions. The faults must be detected as uni-vocally signal difference between normal (or tolerable) and abnormal function of the system. The key point of fault diagnosis is the fault feature extraction. During the past decades the use of signal processing methods in fault feature detection has gained important attention. Performances of these techniques are assessed through simulation experiments and compared for several types of electrical and mechanical faults, broken mechanical parts, power falls or bearing damages. Any significant changes in the parameters of electrical or mechanical signals of equipment can be detected through signal processing methods, especially time-frequency analysis. The signal processing techniques are able to offer the time and frequency information about the studied signal at the same time providing a time-frequency representation of the signal. There are many signal processing methods to detect changes in signals, changes which can be interpreted as consequences of abnormalities in function of a system. Fault detection techniques can be roughly classified into two categories. These include model-based and signal processing based fault detection [13]. The features can be extracted either from three-phase currents or three-phase voltages of the inverter as shown in Figs. 1.5 and 1.6.

1.7 Role of Machine Learning Techniques in RACM

Diagnosis consists of detecting abnormal functioning from sensor data. These data may be noisy or corrupt due to unpredictable events. That abnormal operation may be a failure of process equipment (a sensor, actuator or a component), control system failure (due to operator error or cyber-attack of the system), or change of environment for example resources that are lacking (unavailable operators, exhausted stocks, etc.), or change due to non-conformity product etc. After detecting abnormal functioning, the cause can then be located and identified to make decisions (corrective actions or reconfiguration of the system). There are two main approaches for fault diagnosis: approaches that use an analytic or physical model of the system and approaches

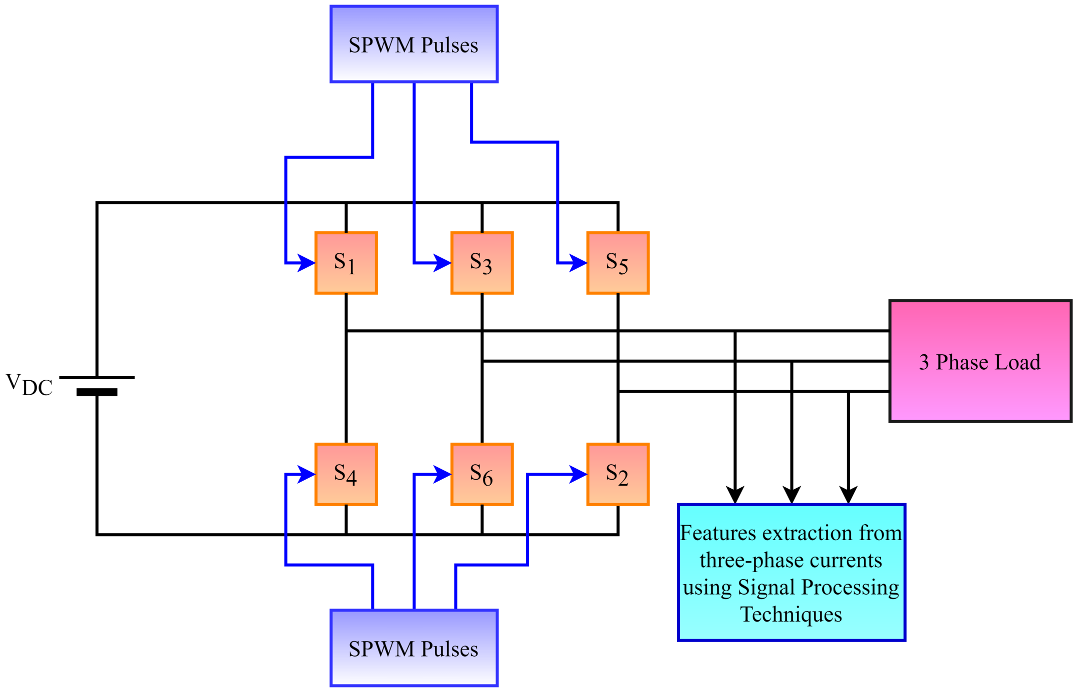

Figure 1.5: Features extraction from three-phase currents using signal processing technique

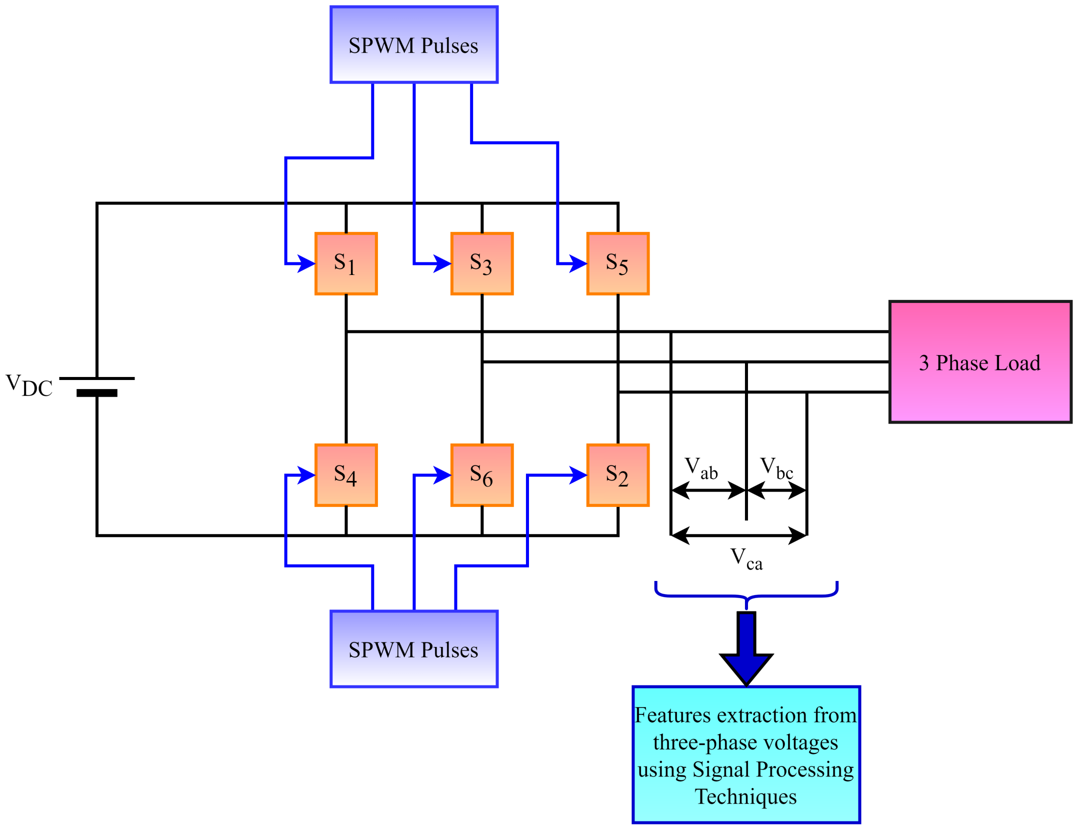

Figure 1.6: Features extraction from three-phase voltages using signal processing technique

that rely only on system observations [14]. The use of the techniques of diagnosis with models seems difficult and expensive, by offering less satisfactory performances. Besides, several industrial applications exist where a model is difficult even impossible to obtain due to increased complexity or several re-configurations involved in the production process.

For this type of industrial application, the only operational monitoring methods are those without analytic or physical models. Among these process history-based techniques, we have signal processing tools and machine learning techniques. However, the approach of signal processing tools is limited to detection and have huge problems with false alarms because they use statistical tests (mean, or variance) to define detection thresholds. In fact, the artificial intelligence offers tools totally decoupled by the structure of the system, not requiring the preliminary modeling of the latter and allowing a real-time follow-up of its evolution. Besides, on-line reasoning makes that the approach of artificial intelligence is stronger in changes in operating modes and have several re-configurations.

In the era of Industry 4.0, the Internet of Things (IoT) technologies is applied in many production systems. One of the important applications of IoT in the industry is monitoring, fault detection, and diagnosis of systems. Most of the IoT systems involve many sensors that collect a huge quantity of data and machine learning methods are applied to analyze them for various goals. The machine learning can be defined as a field of study in computer science that enables personal computers to automatically get more efficient at a given task through experience. In fact, the interesting use of machine learning tools is that they can process many data and are tools of decision-making support for fault diagnosis. The main problem in detection is the setting of a threshold. In fact, setting a low threshold for detection, generate many false alarms. These could disrupt the production system by causing production delays and affect planning and logistics. On the other hand, setting a very high detection threshold may result in the risk of not detecting a slow drift or serious situations. This may not be tolerated for operational safety and security issues. In this context, there are many uncertainties to consider: uncertainties related to lack of process knowledge, data uncertainties in sensors that may be noisy or missing data, uncertainties related to process variability.

In this context, where the system becomes very complex and it is hard to define an analytic model of the system, the machine learning models are used to cope with this challenge. However, the main issues of machine learning tools are the data quality (missing or noisy data), the ability to consider several types of variables (discrete or continuous), the way to consider

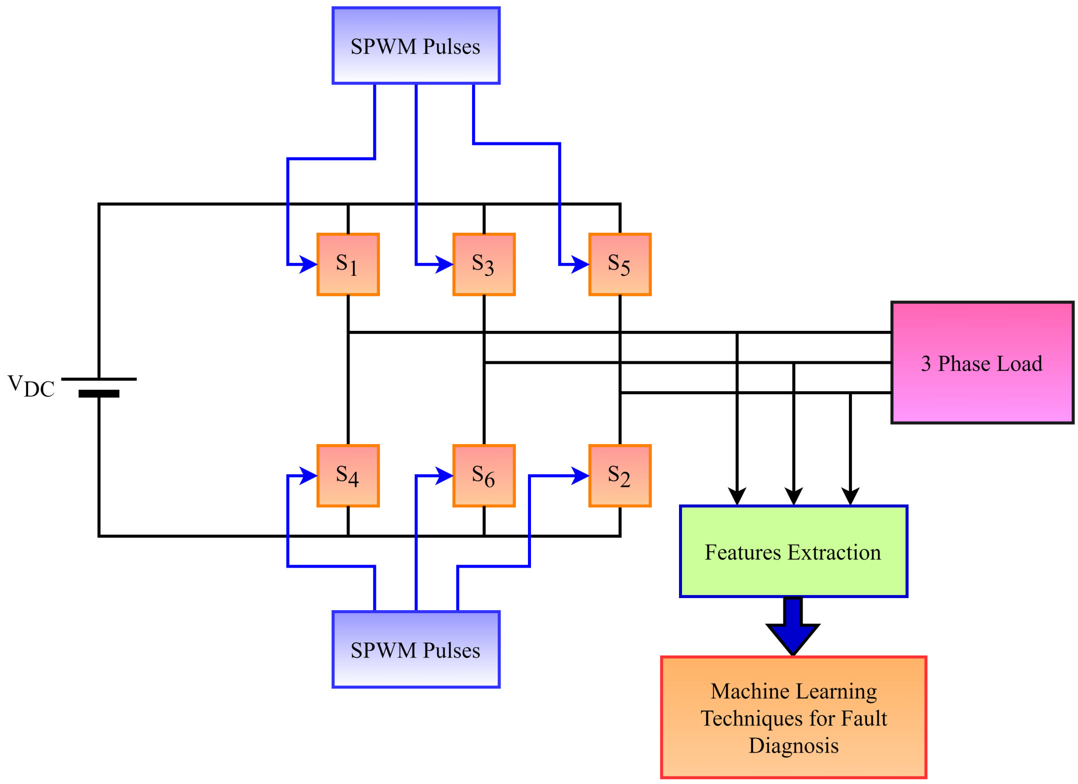

Figure 1.7: Fault diagnosis using machine learning technique.

the time for the dynamic system and the ability to generalize in order the model has the capacity to take a good decision with a new observation.

The application of IoT systems in industries creates a huge amount of data. In addition, these industrial systems have become more and more complex and it is difficult to obtain an analytical model of the system. In this context, the use of machine learning tools comes out obvious and logic to cope with the challenges of diagnosis in these systems. Among the machine learning techniques, there are various supervised and unsupervised type techniques such as SVM, ANN, Fuzzy Neural Network (FNN), DT, KNN, and PCA. These techniques are useful to diagnose the fault condition of inverters using the features extracted from three-phase currents and voltages as shown in Fig. 1.7.

1.8 Thesis Motivation

The reliability assessment of power electronics converters is essential for the secure operation of the converters. The overall performance and reliability of power system depend on the reliability and performance of its components [15, 16]. The converters and inverters are crucial components of the electrical power system. The quality of power is improved by implementing various power electronics-based Flexible AC Transmission System (FACTS) devices that involve power electronic switches [17], and different optimization techniques are also implemented to improve the power [18]. The quality of power is disturbed with RE penetration due to the variable outputs and interfacing converters [19]. The fault in the converters switches leads to the distorted output current waveforms [20] and hence results in reduced power quality. The distorted waveforms lead to heating losses in the converters or may change the response of the system [21–23]. Therefore, to avoid these distorted waveforms, it requires an adequate operation of converter switches. The OC faults must be detected and isolated to achieve the switches' adequate operation in the minimum possible time. Therefore, fault detection and diagnosis must be reliable and fast.

The authors in [24, 25] have discussed the structure of the multilevel converter for getting fault-tolerant operation of the converter with improved performance. The faults in three-phase output lines of converters are easy to identify but detection of OC faults in IGBT switches is complicated work. The localization of the faulty switches is a more difficult task. The fault in a single switch may lead to undesirable operation of power electronics-based drives and control systems. Therefore, detection and localization of faults of IGBTs are too essential.

The fastest OC fault detection techniques observed in literature are observer-based techniques. For minimizing the detection time in the order of microseconds, the algorithm should involve less computational burden. The detection algorithm becomes slow while considering more processing parameters of the system. Moreover, the selection of features and their extraction is essential for fault diagnosis. The most commonly used features proposed in the literature include entropy [26], Wavelet Transform (WT) [27], mean value, phase angle [26], [28], [29] and dq0 transformation of the time series current or voltage waveform [26]. These features sometimes do not accurately detect faults and may result in the wrong classification of faults due to approximately equal values of features under different fault conditions. This thesis proposes different approaches for feature extraction using EWP and WF. These features give accurate results for OC fault detection of IGBTs of three-phase inverter. Furthermore, the classification of faults is significant to distinguish between similar faults. The classification is done using the SVM and KNN based learning techniques. The problem of minimization of fault detection time has also been resolved. The proposed fault detection techniques detect the fault within a few microseconds or in fewer samples of cycle.

1.9 Objectives of the Thesis

The main objectives of this thesis are as follows.

1. To understand the reliability and availability analysis of system and its components.
2. To understand the need of condition monitoring of important part of electrical power system like inverters.
3. To explore the different signal processing techniques and machine learning techniques used for condition monitoring of inverters.
4. To find the best suitable feature and attribute for the inverters to diagnose the fault condition.
5. To propose new and effective methodologies for OC fault detection and localization of IGBTs of inverter.
6. To reduce the OC fault detection time.
7. To increase the accuracy of OC fault localization methods.
8. To provide a comparative illustration between the available techniques and proposed techniques for OC fault diagnosis of inverter's IGBTs.

1.10 Contributions of the Thesis

The significant contributions of this thesis and the steps involved in the proposed algorithms are given as follows.

1. RACM method for inverters is proposed for complete condition monitoring and fault diagnosis.
2. Simulations of three-phase IGBTs based inverter model and Sinusoidal Pulse Width Modulation (SPWM) for pulse triggering in the IGBTs are done using MATLAB Simulink.
3. Fault detection algorithms based on two-sample technique, PCA technique and WF based technique are proposed.

4. The three-phase currents of the inverter are measured for features extraction from the Simulink model.

5. The features including EWP, mean, and Walsh Function Coefficients (WFC) of the three-phase currents and voltages are extracted under different fault conditions generated in the Simulink model.

6. The SVM and KNN model-based fault classification and localization techniques are tested and validated with new data set generated for different fault condition.

7. The classifier-based trained models are validated for fault classification and localization of the single and multiple faulty IGBTs.

8. A comparative analysis of proposed algorithm with the available algorithms in the literature, which are used for features extraction and fault diagnosis, is provided in this thesis.

1.11 Outlines of the Thesis

This thesis is organized into six chapters. The works performed in each chapter are briefly explained as follows.

- **Chapter 1:** This chapter describes the research background, motivation and objectives of the thesis. This chapter also discusses the importance of inverter and need of condition monitoring of inverters.

- **Chapter 2:** The condition monitoring and fault diagnosis techniques for inverters are discussed cumulatively in this chapter. First, the OC fault detection techniques of inverters have been discussed exhaustively. Second, fault localization methods of inverter's switches have also been explored and reviewed using various machine learning based algorithms. The need of RACM is also introduced to highlight the reliability and condition monitoring of the inverters simultaneously.

- **Chapter 3:** The third chapter focuses the role of signal processing and machine learning based algorithms for the proper RACM for inverters. The two samples based signal processing technique for fault detection is proposed and validated. For fault localization, SVM method is used which uses the EWP as feature. The OC faults occurring in switches of Multilevel Converters (MLC) may lead to undesirable operation of the converter. Therefore, fault detection and its localization in minimum time are necessary. This chapter focuses on the fast fault detection algorithm based on the two samples technique and the fault localization algorithm using the EWP as a feature. The EWP feature is used to classify and localize the OC faults in IGBTs of three-phase inverter using SVM based fault classification algorithm. The proposed technique can detect the fault in single IGBT and multiple IGBTs in a lesser time range of microseconds or in lesser than quarter of cycle (less than 10% of cycle). It gives better performance and accuracy (99.70%) than previously proposed SVM algorithms, as the EWP-based feature extraction process used in this chapter is simple and accurate with a less computational burden. The RBD-PCA technique is discussed in this chapter for complete RACM of the inverter.

- **Chapter 4:** In the fourth chapter, the PCA-based machine learning technique is proposed for fault detection and WE feature based SVM technique is used for the localization of fault, which gives results better than the two-samples based technique. The work shows that the fault detection and localization time is reduced, and it improves accuracy using the proposed technique. The output results are compared to the previously available techniques, which show the proposed techniques betterment and shown clear evaluation with theoretical prediction developed. The RBD-WE-SVM technique is discussed in this chapter for complete RACM of the inverter.

- **Chapter 5:** A KNN technique involving WF has been proposed in chapter five, which is found faster than the previous two techniques and giving better results. The work done in this chapter uses a WF-based algorithm to detect OC faults in IGBTs. The WFC of inverter three-phase voltages is used as feature for fault classification using SVM and KNN-based algorithms. The performance effects of KNN and SVM are compared, demonstrating that the proposed KNN-based technique is superior and provide a straightforward evaluation of theoretical predictions. The fault detection and localization time is decreased due to less computing stress, and accuracy is improved. The RBD-WF-KNN technique is discussed in this chapter for complete RACM of the inverter. The method discussed in this chapter is found to give the best outcomes and helps in getting proper RACM system for the inverter.

- **Chapter 6:** This chapter concludes the works accomplished in this thesis, enumerates benefits of the methods, and propose future scopes of the work.