2.1 INTRODUCTION

This chapter reviews the research works carried out by different researchers about the PV-Diesel hybrid power generation system and the components of the hybrid power generation systems.

The review of literature is carried out in the following areas:

- PV-Diesel Hybrid power generation system
- DC-DC converters
- DC-AC inverters
- MPPT techniques
- PV panels
- Storage batteries

2.2 HYBRID SYSTEM

Abdiun (1999) designed a Proportional Integral (PI) controller for a standalone PV-diesel hybrid system to control the continuous variation of load voltage and frequency on the output side and Maximum Power Point (MPP) tracking from the PV panel on the input side with the objective of
reducing the consumption of diesel fuel. The simulation results of the above system confirmed that the closed loop control system maintained the frequency variation and output voltage variation within the limit and MPP extraction control was also appreciable.

Shaahid and Elhadidy (2003) focused on the consciousness about greenhouse gas emissions and global warming by the usage of fossil fuels and the consequent depletion of fossil fuels. This effort in turn led to interest in renewable sources of energy. As Saudi Arabia receives high solar radiation, installation of PV systems for power generation offers a better solution for power generation problems. However, PV systems cannot meet the load demands due to poor solar radiation in the period of June to September. This issue could be managed effectively by enhancing storage batteries or diesel generators or a combination of both to satisfy load requirements. The hybrid system formed by PV/diesel/battery enjoyed the benefits of enhancing the diesel generator efficiency, reducing the battery autonomy and maintenance requirements of the diesel generator.

Shaahid & Elhadidy (2007) analyzed the performance of a hybrid PV- hybrid power generation system for the climatic conditions of Dhahran whose monthly mean daily global solar radiation varies between 3.61 to 7.96 kWh/m². The simulation analysis was carried out using the Homer software. The results indicated that for a 80 KWp PV system, 175 kW diesel generator with battery storage with autonomy of 3 hours, the diffusion of PV system is 26% and the cost of generation of power was found to be 0.149 US$/kWh with the assumption of diesel cost as 0.1 $/L. From the simulation results, it was inferred that the increase of PV capacity in the system results in the reduction of the operating duration of diesel generators. The deployment of battery further pulls down the run time of the diesel generator. It was found that 27% of fuel saving occurred in the hybrid system compared to a diesel-
only system. Further, the percentage decline in CO₂ emission was found to be 27% in the hybrid system. In the hybrid system, the efficiency of the diesel generator was maximized with a minimum maintenance requirement. Further, the possibility of a cut back in the entitled capacity of diesel generator and battery was also noted.

Manoj Datta et al. (2009) analyzed the variations in power output of a PV system caused by variations in weather conditions. The variation in power was found to result in variations of frequency and the reliability of the system. Power adjustment was carried out using fuzzy reasoning, considering solar radiance, variation in solar radiance and average frequency variation.

Varun et al. (2009) performed an assessment by considering generation cost, GHG emissions and energy payback period as indicators of sustainable development. Based on the analysis, it was found that wind and small hydro stations are more suitable for sustainable growth. In case of unavailability of the above sources, solar thermal and solar photovoltaic systems can be considered. It was found that the cost of generation of renewable power is high now and is expected to reduce due to technological progression.

Tamer Khatib (2010) reviewed the design and installation of PV power systems to arrive at the best design and installation procedures for PV systems. In this paper, a detailed procedure for load estimation and sizing of PV system elements namely PV array, controller, batteries and inverter were discussed. The procedures for connection and installation of the system were also discussed. Finally the method for economic evaluation was presented.

Tamer Khatib et al. (2012) proposed a new method for the optimal sizing of a standalone PV system from the perspective of sizing the PV array and battery storage. They analyzed the flow of energy using the MATLAB
fitting tool to fit the sizing curves and to obtain a general formula for sizing the PV array and battery. Data from five sites of Malaysia were used for deriving the formula and the designed system was installed in Kuala Lumpur. The obtained results were validated and found acceptable.

Abdulqadiri Bello Abdulqadiri & Elwan Abubakar Ahmed (2012) performed a comparison of both wind-diesel and PV-diesel hybrid power generation systems using the Homer software simulation based on economical and technical considerations. It was concluded that the wind-diesel system costs less when compared to the PV-diesel system. Nonetheless, considering technical factors such as design complexity and ease of access of the source, PV systems were determined to be the best suited in comparison to its counterpart. Ease of maintenance and installation were the other aspects favoring PV-diesel systems. The system was designed for an output of 96 kW.

John Kaldellis et al. (2012) designed a PV-diesel hybrid configuration on the basis of long-term power generation (20 years) and minimum cost and compared the hybrid system with a diesel-only system. They concluded that an autonomous hybrid system is more cost-effective than a diesel-only system.

Nitin Agarwal et al. (2013) developed a standalone PV-diesel-battery based multi-objective hybrid model with the goal of minimizing both the life cycle cost and CO₂ emission from the system. The constraints for the goals are the system reliability, power generation by the specified components of the system and State of Charge (SOC) conditions of the storage battery system. The variables incorporated with the system optimization are area of PV modules, number of PV modules, number of batteries used and power of diesel generator, and fuel consumption of the diesel generator per annum. The hybrid system components specifications are calculated by the utilization of C programming language program code.
Abdelhamid Kaabeche & Rachid Ibtiouen (2014) attempted to create a method for the size optimization of a standalone PV/Wind/diesel hybrid system with storage battery for rural electrification. Two models namely Total Energy Deficit (TED) and economic model based on the calculation of Total Net Present Cost (TNPC) and Energy Cost (EC) was designed for this analysis. Total system autonomy was obtained by combining these two models. The simulation results concluded that the PV/Wind/diesel/battery system is economically better than the standalone diesel generator and PV/Wind/battery systems.

Makbul Ramli et al. (2015) performed an economic analysis of PV/diesel hybrid systems with different combinations such as diesel/flywheel hybrid, PV/diesel/flywheel hybrid and PV/diesel/flywheel/battery systems using Homer simulation software and found that the PV/diesel/flywheel/battery system has the lowest cost of energy and CO$_2$ emission. The usage of flywheel improves battery and utilization time.

2.3 DC-DC CONVERTERS

Hong Mao et al. (2007) performed an analysis with regard to the current sharing in the case of interleaved converter and Half Bridge Current Rectifier doubler (HB CDR) circuits and found that the sharing of current is based on DC resistance and value of duty cycles in the steady state condition. In interleaved mode buck converter, the total dc resistance is the sum of its switch ON resistance and inductor direct current resistance (DCR). The input voltage has influence in sharing of current only when the duty cycles of the switches are different. In the case of CDR, current sharing is decided by inductor DCR. Here transformer secondary winding DCR comes into picture during the time when diode D$_1$ is not equal to diode D$_2$. The practical analysis concluded that current sharing in interleaved buck converter was carried out by adjusting the duty cycle. However, in the case of HB CDR a modified
circuit is constructed to adjust the current sharing and tested for exact current sharing.

Tomonobu Senjyu et al. (2002) performed a comparative study on the performance of PV based boost and interleaved converters for operating a separately excited DC motor. The implementation of interleaved boost converter minimized ripple in the input current and output voltage and size of the filtering components.

Syafrudin Masri & Pui-Weng Chan (2010) carried out a design and testing analysis of boost converter with PV input to produce a constant voltage output of 24V. The gate Pulse Width Modulation (PWM) pulses are produced using a microcontroller PIC16F877. It was found that the converter unit is simple and weightless and can be directly fixed in the PV panel. The inverter can be used for grid connected or standalone systems.

Thounthong & Davat (2010) planned for a parallel converter to boost the low DC voltage of fuel cells to the required level using the interleaving concept. The usage of the interleaving concept requires a low value of output capacitor owing to the lower output current ripple which in turn results in less power dissipation and lower cost. Further, spreading of the dissipated power over a large area leads to efficient thermal management. Two-phase and Four-phase interleaved converters were implemented for a 1.2kW fuel cell unit and good dynamic and static performances of the system were validated.

Gulam Amer & Sandepudi Srinivasa Rao (2010) performed reliability calculation and simulation analysis for three modes of operation of interleaved boost converter: Continuous Conduction Mode (CCM), Discontinuous Conduction Mode (DCM) and Critical Conduction Mode
(CRM). They found that the reliability of the interleaved boost converter in CCM is superior to the reliability in DCM and CRM.

Seyezhai (2011) explored the operation of 2-phase IBC and boost converter in terms of ripple in the phase current and input current ripple with variation of duty cycle. The equations related to the IBC design were provided. It was confirmed that IBC reduces the current ripple more effectively than the boost converter. Further, the SiC diode & CoolMOS transistor combination were observed to have reduced switching losses.

Wuhua Li & Xiangning He (2011) reviewed the need for DC-DC converters, and discussed isolated and non-isolated converter types and their advantages and disadvantages. High-step-up, low voltage converters of different configuration were analyzed. The challenges to be expected while designing the high-step-up converters were clearly listed for guidance and thus a clear idea about the types of next-generation non-isolated high-step-up high efficiency DC-DC converters was provided.

Duran et al. (2011) conducted a theoretical and practical analysis of different types of non-isolated DC-DC converters and found that the single-ended primary inductance converter was the most suitable for fuel cell applications. However, the analysis helped to select converters based on CCM mode of operation and duty cycle variation for various applications.

Ahmad Saudi Samosir et al. (2011) described the different modes of operation of IBCs and the variation of output voltage with variation of duty cycle. The system was simulated using MATLAB and the results were compared with the results from the hardware. The authors concluded that IBC is capable of providing current sharing with reduced ripple.
Ainah Priye Kenneth (2012) simulated and constructed a DC-DC boost converter working in CCM with maximum power point tracking utilizing the microcontroller control. 555 timer circuits were implemented for generating PWM signal for the switch in the boost converter. PSIM and Spice software were used to simulate the boost converter. The behavior of the system with different solar irradiation was analyzed using the developed prototype model.

Seyezhai & Mathur (2012) analyzed the design of three phase direct coupled IBC for fuel cell applications. The performance analysis concluded that the operation of the direct coupled inductor minimized the ripple more than the operation of the uncoupled inductor. Further, the comparative study concluded that CoolMOS transistor & SiC diodes are better than MOSFET IRFP460A and Si diode MIR1560.

Mohammed Elgendy et al. (2012) used a 1080 Wp practical model to study P&O reference voltage and direct duty ratio methods and concluded that the direct duty ratio control method shows better performance in energy utilization and remains stable during slower transient response. However, the performance worsens during fast changing solar irradiance.

Taghvaee et al. (2013) reviewed non-isolated DC-DC converters for PV power generation systems. After the analysis it was concluded that the boost and buck converters were economical and efficient. However, the difficulty of following the variation of load, radiation and temperature are problems with buck and boost converters compared to buck-boost, Cuk and Single Ended Primary Inductance Converter (SEPIC) converters whose operations are independent of the above said variations. The buck converter is suitable for situations where the load impedance is less than R_{MPP} (optimum resistance) and boost converter is suitable for situations where the load
impedance is greater than $R_{MPP}$. The Cuk and SEPIC converters are costly, hence buck-boost converters are found to be suitable for PV applications.

Weerachat Khadmun & Wanchai Subsingha (2013) studied the IBC for PV power generation and determined that IBCs can boost DC voltage from 24V to 130V with a power rating of 350W. Four-phase IBC uses a 90 degree phase angle of gate signal $(360/n, n$- number of phases). The IBC can be used in association with any non-conventional energy sources.

Deepika (2014) compared the performance of boost and IBCs and found that IBC shows low input current ripple and output voltage ripple compared to boost converters. The comparison was carried out between simulation and prototype hardware results.

## 2.4 DC-AC INVERTERS

Juan Carlos Floriani (2004) performed both theoretical and practical analysis on the performance of single phase H-bridge inverter with two PWM techniques namely unipolar and bipolar techniques. In bipolar PWM technique, the switching devices of the bridge are controlled diagonally where as in the unipolar PWM technique each arm is controlled separately. In case of Bipolar PWM, the maximum ripple value obtained will be four times that of the maximum ripple of unipolar PWM. The experimental setup using DC drive was constructed and tested for varying conditions and the results were found to be matching with the theoretical values obtained.

Arab et al. (2014) designed and developed a microcontroller based PWM signal by associating two transistors as switching devices for generating PWM. The inverter with PWM and filter were simulated, a prototype was constructed and tested. The generation of pure sinusoidal
output implies that this PWM generator can be used along with half bridge and H-bridge inverters for renewable power generation systems.

Anuja Namboodiri et al. (2014) offered a MATLAB simulation comparison between unipolar and bipolar PWM techniques and found from the Fast Fourier Transform (FFT) analysis waveforms that the unipolar inverter circuit performance was better than bipolar inverter performance in terms of Total Harmonic Distortion (THD).

Deshmukh & Jadhav (2015) expressed the Power factor (PF) and THD variations of half bridge, full bridge and multilevel inverters using MATLAB simulation for different load conditions. The phase disposition technique was used for gate pulses. It was found that the multilevel inverter shows the minimum THD compared to the half and full bridge inverters.

2.5 MAXIMUM POWER POINT TRACKING

Moacyr Aureliano Gomes de Brito et al. (2013) evaluated various MPPT techniques namely, constant voltage method, P&O method, modified P&O method, incremental conductance (IC) method, modified Incremental Conductance method, IC based on Proportional Integral (PI), Temperature method, Beta method, Oscillation method and Correlation method. Based on the simulation results using MATLAB and space Simulation software, it was found that the Beta method was the best because of its small steady state ripple voltage, good transient response and low complexity during implementation. However, this method depends on PV characteristics for operation. Modified IC, Modified P&O, IC based PI, P&O based PI had excellent performance and do not depend on the type and producer of the PV panels.
Pallavee Bhatnagar & Nema (2013) examined six on-line, four offline and six more MPPT techniques including intelligence control methods based on the efficiency of tracking, complication, number of control variables considered, fastness in tracking, and hardware assembling and expenses for each method of implementation. Their findings are tabulated to facilitate the ease with which the user can select suitable methods based on their requirements.

Lian et al. (2014) proposed a hybrid MPPT using P&O and Particle Swarm Optimization (PSO) method, in which P&O MPPT method is used for the detection and the Local maximum point (LMP) and PSO methods are used for finding the Global Maximum Point (GMP). The proposed MPPT was tested with a prototype model. The results obtained proved that the hybrid MPPT showed a faster convergence and good dynamic response.

Moein Jazayeri et al. (2014) analyzed the performance of P&O and IC MPPT with boost converter for PV applications and found that P&O tracking is the simplest and most efficient algorithm for MPPT of PV systems. Furthermore, they found that the addition of MPPT had raised the output of the PV system by about 70% more than the system without MPPT.

Lyden & Haque (2015) performed review analysis by classifying MPPT techniques as conventional methods, modified conventional MPPTs to meet partial shading conditions, global maximum power point tracking (GMPPT) methods, and methods using power electronics devices to handle partial shading conditions. The simulation for P&O, PSO and simulated annealing (SA) methods were carried out, compared and concluded that the GMPPT cannot be reached by using a single MPPT method.

Zainal Salam et al (2013) appraised the performance of MPPT techniques such as P&O, PSO, Fibonacci search (FS), Ant Colony
Optimization (ACO), Artificial Neural Network (ANN), Chaotic Search, Cuckoo Search (CS) and Differential evolution (DE) and concluded that the hybrid system formed by combining conventional and soft computing techniques can be implemented in future to obtain better performance.

Boualem Bendib et al (2015) focused on the response of P&O, IC and FLC MPPT techniques under slow and fast varying illumination and temperature using MATLAB simulation and found that FLC was better than P&O MPPT and IC MPPT in terms of stability of operation, fastness in reaching MPP and accuracy.

2.6 PHOTOVOLTAIC PANEL

El Chaar et al. (2011) carried out a study on different PV technologies and found that the first generation PV technology constituted single junction silicon-based mono-crystalline and poly-crystalline solar cells of high cost and efficiency. The second generation thin film based single junction devices like Cadmium Telluride (CdTe), CIC (Cadmium Indium Carbide) and a-Si showed less efficiency compared to the first generation type. Reduced cost was the added benefit of the second generation PV technology. The third generation technology is related to double junction, triple junction and nano technology related types with high efficiency and low cost devices which are under development.

Ugwuoke & Okeke (2012) carried out an analysis on the performance of mono-crystalline, poly-crystalline and amorphous silicon panels under varying illuminations and found that the efficiency of the panels reduces as the irradiance levels increases from 600w/m² to 1000w/m² and the maximum power outputs and efficiencies of the modules are below the rated value given by the manufacturer.
Ndiaye et al. (2013) performed a review of the degrading factors affecting the performance of PV panels and concluded that the major factors are corrosion, discoloration, delaminating and breakage. Corrosion and discoloration are the major degrading factors. Temperature variations, moisture, ultraviolet radiations are also responsible for degradation of the PV panel. Predicting the occurrence, speed and frequency of degradation is not possible even though the degrading factors are known.

Keshav Pratap Singh & Bhupendra Gupta (2014) analyzed the performance of mono-crystalline and poly-crystalline panels with stationary, single axis, dual Axis and hybrid Axis tracking systems and found that the mono-crystalline panels produced higher output compared to poly-crystalline panels in all the tracking methods. Hence, it was concluded that the automatic hybrid axis tracking systems is the best of the three tracking methods.

Saban Yilmaz et al. (2015) performed a comparison of mono-crystalline, poly-crystalline and thin film panels of 3 kWp grid connected system and found that payback and production of poly-crystalline is better than mono- and thin film types. Thin film is best situated for high ambient temperature variations but occupies large space and has huge weight compared to other panels, mono-crystalline, on the other hand, has the advantage of small size and less weight.

2.7 STORAGE BATTERIES

Nirmal-Kumar Nair & Niraj Garimella (2010) carried out a study on different storage devices such as batteries, flow batteries, fuel cell, flywheels, super conducting magnetic energy storage (SMES) devices, super capacitors, compressed air energy storage (CAES) and pumped hydro power plants for energy storage in small scale renewable energy systems. Storage devices such as CAES and pumped hydro power plants are not suitable for
small scale renewable energy systems due to their large size and high initial cost. Although SMES and super capacitors are high power devices, due to high installation cost they are not suitable for this application. Flywheels are capable of supplying short duration high power by storing kinetic energy in magnetic bearing supported rotating cylinders. Their limitation is the requirement of large construction and maintenance costs. Batteries are considered as the most suitable energy storage devices for small renewable energy systems. Four types of batteries namely lead-acid, nickel cadmium, nickel metal hydride and lithium ion batteries were considered in this analysis and they were simulated using Simulink and Homer software for standalone PV systems. It was found that the most suitable battery for small renewable systems is nickel metal hydride battery. However, its high cost is the limiting factor. Lead-acid batteries are mostly suited for small renewable energy systems due to their low cost and easy availability.

Fernao Pires et al. (2014) studied various storage devices such as electrochemical energy storage, fluid storage, mechanical and electromagnetic. They found that electrochemical storage devices such as batteries, super capacitors and fuel cells were used in standalone power supply systems. The pros and cons of all type of batteries and fuel cells were discussed. Further, the types of single stage, two stage, multilevel and multi-input port converters and control techniques were analyzed. Two stage inverters enjoy the independent control of energy sources and good reliability. Multilevel inverters have the advantages of modular construction, reduced fabrication cost and high reliable operation. Similarly multiport topology has the favor of central control and compactness in packing.

2.8 SUMMARY

This chapter presents the review of various research works related to PV-Diesel hybrid systems, DC-DC converters, MPPT techniques, PV systems and DC-AC inverters. It was learnt that the PV/diesel/battery hybrid
system has the benefits of reducing the battery autonomy and maintenance requirements of diesel generator and a diesel saving of 27% is possible in the hybrid system compared to diesel only system. Further IBC is capable of providing current sharing with reduced ripple in input current and output voltage. In MPPT techniques review, P&O MPPT technique has oscillation of the operating point around MPP under steady state condition and the inability to respond to rapidly changing atmospheric conditions and fuzzy method has the fastest tracking capacity for MPP. The above points lead to the choice of selecting hybrid PV/Diesel/battery system with interleaved boost converter incorporated with hybrid P&O fuzzy MPPT technique.