A Comprehensive Overview on PV based Hybrid Energy Systems

Pradip.C*, Vinoth Kumar.K**‡, Lydia.M***

* Research Scholar, Karunya Institute of Technology and Sciences, Coimbatore – 641114, Tamil Nadu, India

** Assistant Professor, Karunya Institute of Technology and Sciences, Coimbatore – 641114, Tamil Nadu, India

*** Associate Professor, Department of EEE, SRM University, Delhi-NCR, Sonepat, Haryana

‡ Corresponding Author; +919446224500, E-mail: cherukadpradip@gmail.com

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Abstract- The need for usage of renewable energy resources is gaining significance due to the depleting fossil fuels and its effect on climate change. Photovoltaic (PV) based power generation is gathering momentum due to the decrease in its cost of components. However solar energy is diurnal and highly uncertain which makes inclusion of storage element indispensable. This will enhance the cost of PV based energy systems. A grid tied PV energy system with proper backup will be a more economical alternative. This paper aims in reviewing the various objectives in designing such a PV based hybrid system to make it convenient and economical. An overview of optimization techniques, energy management methodologies and modeling of PV based hybrid energy systems has been presented. The research challenges in these areas have also been included.

Keywords Photovoltaic systems; Optimisation; Home energy management; Battery energy.

1. Introduction

Power demand has increased in recent years in developing countries due to industrialization, urbanization and increasing population. The demand for producing cleaner and greener energy to meet this increasing need for energy can only support the sustainable development. Harvesting solar energy is the best solution to this increasing energy demand. The energy generated by sun has more energy than our energy needs, and no one can monopolize the sun's energy. Also, the usage of solar power is the safer, cleaner and easier path to contribute to a sustainable future. Technological advancements and reduction in generation costs have made solar power generation popular. Many utility companies and domestic consumers have opted for solar power generation. As per the Renewables 2018-Global status report, 98GW of solar PV capacity has been added in the year 2017 and the global cumulative capacity has reached 402GW. This is 3% of global power output. Out of this utility-scale projects contributed over 60% of total PV installed capacity, with the rest by distributed applications (residential, commercial and off-grid). In the next five years, solar PV is expected to expand leading renewable electricity capacity growth, by about 580 GW [Renewables 2018-Global Status Report].

India too is marching to achieve a renewable energy capacity target of 175 GW by 2022. There was an exponential increase in solar energy generation, it was 2650MW in 2014 which has reached 20GW by end of January 2018[MNRE]. By offering various incentives, contribution of Solar PV generation has gained momentum.

Survey on recent literature has been carried out to explore the various researches done in the area pertaining to cost-effective PV systems and to study the possibilities of obtaining an optimal energy management strategy. Five major areas have been reviewed to find the research updates. These areas are Optimization of solar PV systems, Energy management in solar PV systems, Battery and storage technologies and usage, Hybrid PV systems and Modeling of PV systems.

2. Optimization of PV Based Hybrid Systems

The economics of solar PV generation depends mainly on its optimization of size, type, capacity and operation. Many research works are done considering various combinations and capacities of solar PV systems. A comparison on the optimal sizing of grid-independent hybrid photovoltaic–battery (PV/B) power systems for domestic

sector is done [1]. Here the PV/B system and PV/B/fuel cell (FC) stem were compared varying PV module number, tilt angle and battery capacity. The household demand is assumed and estimation on the optimum size of solar array, the best PV module tilt and optimum value battery capacity were arrived. Thus, energy exchange from the grid is minimised. Here the life cycle cost of electricity is not taken into consideration.

Optimization is done by scheduling the usage of battery storage assessing customer benefit [2]. The scheduling is done using a quadratic program-based scheduling algorithm. This algorithm is applied to measured load and generation data and reschedules the PV power usage during peak loads and peak billing time. In the scheduling algorithm the battery size, financial policies and metering topologies are not considered while arriving at the savings.

The sizing of energy storage systems for micro grids is optimised by simultaneously optimising Energy Management Strategy (EMS) and Energy Storage System (ESS) [3]. EMS is done using fuzzy expert systems. It is used in setting up the power output of the ESS. This work is applied to optimization of micro grids. Implementation of time of use tariff by the utility companies makes such an optimisation suitable for grid tied systems as well.

A grid independent hybrid renewable energy system is optimised by considering three decision variables namely total swept area by the rotating turbine blades, total area occupied by the set of PV panels, and the number of batteries [4]. A case study is conducted in Iran by the authors. The optimisation is done using Particle Swarm Optimization (PSO) and some of its variants.

It is found that PV/Wind turbine and battery-based hybrid system is most reliable and cost effective. The life cycle cost of electricity for ascertaining the economics of the hybrid system can be considered.

For an off grid hybrid renewable energy system, Planning, configurations, modeling and optimization techniques were reviewed [5]. Optimization techniques using different mathematical models build on objective functions, reliability studies and economics involving design parameters proposed by researchers were analysed. A customised design with optimised system size for a standalone hybrid renewable energy generation can be proposed based on the comparison of results of various mathematical models.

Optimisation is done for normalised storage. The normalised storage is expressed as a portion of annual demand and energy returned on energy invested (EROEI) [6] on domestic photovoltaic-plus–battery systems in islanded mode. The role of secondary load in obtaining energetic and economic perspectives of different PV combinations can be added as a part of investigation.

A methodology was proposed for optimization of the complementarities between solar PV systems and small-hydropower plants [7]. Here the optimization algorithm is developed associating hydrological with solar irradiation information which investigates the degree of time complementarities between small hydro power systems (SHPS) and adjacent solar photovoltaic systems (SPVS). The locational and spatial aspects, variation in climatic conditions and variations in stream flow profiles that affect the degree of complementarities can yield better results.

A reliable grid connected PV- based power plant with/without energy storage system was optimized [8]. Harmony search method is used for optimization for solar PV system with and without storage element. The net present value of the system is minimised considering the reliability of power as the constraint. Optimum capacity of solar power with sufficient storage element can make the system reliable and profitable.

For designing standalone PV system an optimisation method was proposed [9]. For determining the optimized benchmark all possible PV array and battery capacity a loss of power supply probability (LPSP) analysis was done. The sizing of charge controller, inverter sizing and battery connection were also considered. This method considers the entire load connected to the system. The system can be tried out to a grid tied system to meet the emergency loads only thereby the cost can further be optimized.

Design and Optimization for Hybrid Micro-Grid System (HMGS) was done using, HMGS Particle swarm optimisation method [10]. This method identifies the sizing of PV module, wind turbines (WT), battery energy storage system (BESS) and diesel generator. This technique computes the optimal configuration of HMGS, Renewable Factor (RF), the lowest Price of Electricity (POE) and LPSP. Price of electricity is dependent on the performance of wind turbines. However, the cost of electricity (COE) can be reduced by enhancing the number of solar panels. Thus, a hybrid scheme with more contribution from solar power can reduce the COE.

Optimisation techniques of distributed generation with renewable energy sources were reviewed [11]. Most of the researches have addressed the static models for optimal sizing and placement on distributed generation. However, for long term planning due to the uncertainties in various parameters like solar and wind energy generation, fluctuations in load, prices of conventional energy etc., dynamic models are needed.

The latest size optimization methodologies for standalone solar and wind hybrid renewable energy system were reviewed. A comparison of various algorithms and software tools for optimization were analysed [12]. The latest developments in sizing stand alone and wind hybrid renewable energy systems were analysed with due consideration to size optimisation methodologies. A critical comparison of single / hybrid algorithms and software tools were made. The assessment parameters namely economical, reliability, environmental and social aspects were evaluated on all possible combinations of standalone solar and wind energy systems. The sizing optimization problem considered various assessment parameters such as economical, reliability, environmental and social parameters. The load profile and metrological data also affects the size optimization problem. The multi-objective optimization

problem can be solved using modern methods such as hybrid and artificial algorithms since these can give more accuracy for the optimization results than software tools.

Optimal operation strategy and sizing of battery energy storage systems (BESS) is obtained through a stochastic mixed integer nonlinear programming (MINLP) method [13]. In home energy management systems equipped with solar photovoltaic panels this method is applied to obtain optimal battery storage sizing and scheduling. The method also considers the battery charging time, usage, PV usage and usage of grid power based on the cost of energy during peak and off-peak hours. The uncertainty of PV energy is also taken into consideration. This MINLP is solved by advanced adaptive particle swarm optimisation (AAPSO) algorithm. The problem can be considered as a multi-objective optimization including several objectives at the same time such as well-being, cost, reliability and environmental pollution.

For optimizing a solar PV system for domestic application many parameters have to be considered. These parameters include levelised cycle cost of electricity (LCOE), optimum capacity of storage element which makes the system reliable and economical, cost of electricity from utility grid, efficient energy management strategies, environmental conditions and economics in setting up hybrid systems. Thus, a solution to multi-objective optimization problem can bring optimised solar PV system.

3. PV Based Hybrid Systems

PV based Hybrid systems are becoming very popular now a days due to its reliability, stability in daily output, less expensive than on-grid systems and higher return for solar energy generation.

The switching and its effect on the performance of a hybrid solar PV system to obtain optimal system performance were done [14]. The system performance is obtained by suitably optimising PV energy generation, storage of energy and load pattern. A switching control parameter is defined as function of normalized excess PV power generation. Based on modelling and simulation a switching technique was developed on a hybrid PV (HyPV) system. The simulation is done for the typical day time load pattern, local climate and for HyPV system design. To study system performance and to do economic analysis a simulation can be carried out and an optimal system can be designed.

An optimized operation strategy of PV/Fuel cell/Battery based system is evolved for a grid-connected hybrid PV/fuel cell/battery energy system for residential applications, based on mixed integer linear programming theory, considering economic information such as electricity tariff, natural gas price and other policy issues [15]. Optimisation of system configuration, super structure and operating structure of this hybrid energy system considering multiple objective functions so as to obtain an integrated optimisation framework can yield better results. Uncertainties due to change in demand, energy and environment policies need to be taken into consideration.

Multi-objective line-up competition algorithm (MLUCA) is used to optimise economic multi-objective size optimisation problem. Hybrid power generation systems subjected to the constraints of battery capacity, energy supply and component sizes were considered for optimisation [16]. This optimisation strategy can be tested with other combinations of Hybrid power generation with constraints of relevance to that combination so that techno-economic and reliability analysis can be obtained.

A reliability analysis on quantitative hardware was performed. The effect on overall system reliability by energy storage configuration was analysed for a PV-battery hybrid power system (HPS) [17]. A decentralized controller manages the control strategy of the proposed HPS. Simulation is done on the proposed system using realistic irradiance data and a battery model. The performance of the system with the control strategy was verified using simulation results. In this analysis the temperature effect was also considered. Better performance to the HPS can be achieved by developing detailed control approaches for a grid connected HPS and examining the effect with different energy storage technologies.

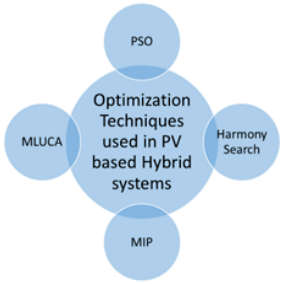

Fig. 1. Optimisation techniques used in PV based hybrid systems

Effective and efficient utilization of renewable energy can be achieved by setting up hybrid systems. These systems can be designed considering economic analysis with different load pattern, uncertainties in energy demand, energy and environment policies of the government, techno economic feasibility in selection of hybrid systems, reliability of the hybrid system, efficient and cost-effective storage techniques and energy returned on energy invested (EROEI).The different optimisation techniques used in PV based hybrid systems is depicted in Fig. 1.

4. Energy Management Techniques

Energy management is the most important in order to determine how effectively the power generated from renewable sources are utilized. The choice of various sources of generation based on the power cost and life cycle cost of electricity has to be taken care for efficient energy management. The power requirements have to be assessed based on social life style and power needs of the people.

A PV based power plant for remote residential applications is modelled in power system simulation tool

DlgSILENT [18]. The model considers socio-technical and economic perspectives. Hourly generation estimated and the performance of the power plant estimated by life cycle cost analysis. Economic comparison was done with diesel generating set. The cost of generation varies with the autonomy selected. This will have an impact on the life cycle cost. Instead of depending on a single power source a hybrid power generation model can be more economical.

Demand side management under intermittent primary energy source conditions with a PV-battery backup system designed and implemented in real time [19]. A PV-battery backup system will back up the blackout period of the grid. The demand side is managed using a DSM algorithm which sets setting priorities for different loads and estimates the availability of energy in the PV-Battery system. The load is predicted such that discomfort layer to the customers is minimal. However, it is seen that high autonomy is given in de-selecting unpredictable loads. Such a scenario may lead to de-selection of intermittent loads which are important.

The grid connected PV system for households with feed in tariff and time of day tariff regulation in New Delhi was technically and economically evaluated [20]. HOMER software is used for techno-economic analysis of grid tied solar PV system. How the best use renewable energy system through decentralised grid connected system can benefit the society, can be analysed by this method.

A grid-connected hydrokinetic system under Time of Use (ToU) tariff was subjected to an energy management technique [21]. The objective is to minimize the cost of electricity within the demand side management framework. An optimal power flow management algorithm of the proposed hybrid system was developed to minimise the cost of electricity. Objective function taken into account was energy cost and ToU tariff. The solution to this optimization problem is arrived using the "linprog" function from MATLAB (R2016a) optimization toolbox. Reduction in operational cost reduction by maximising the use of RES was proposed. However, the maintenance cost of battery can also be taken as a parameter in optimization.

An optimum community energy storage (CES) for renewable energy and demand side load management was subjected to energy management technique [22]. For assessing CES systems the key performance indicators selected were community demand, PV generation, battery characteristics as well as the management of CES systems. An optimisation method is activated as a function of the size of the community. This optimization method can be performed for local communities/ grid tied systems where the uncertainty in the input data is the least.

Two storage methods namely vanadium redox flow battery and lithium ion battery used in a hybrid system were compared by calculating the levelised cost of electricity [23]. These comparisons can be extended to other PV hybrid systems to obtain a techno-economic evaluation of PV based hybrid system with storage.

The dynamics of source and load were considered to decide the best home energy management [24]. The changes occurring to load, tariff of electricity and renewable energy sources were considered at 5-minute intervals to obtain a forecasting model of home energy management (HEM). The economic consideration in setting up grid tied PV system with battery backup can be obtained using the model.

A photovoltaic-battery hybrid power system within demand side management for domestic application was subjected to techno-economic and environmental optimization [25]. This optimization method suggests a control system model for power dispatching level and home appliance scheduling level, which will minimise the residents' energy cost and consumption from the grid satisfying the constraints. A multi-objective optimization problem considering operating cost, energy consumption and customer inconvenience were developed. The peak potential benefit for different configurations and capacities of PV-BT system can be analysed and an improved investment plan for residential applications can be evolved.

A dynamic home energy management proposal capable of incorporating load and source side dynamics were considered for decision-making [26]. The real time pricing and local renewable energy generation forecasts were considered while executing a dynamic energy management system. The power consumption of appliances, tariff of electricity and power received from renewable sources were taken on real time at 5-min interval. The forecasting model is thus assimilated into the HEM system for better matching between energy consumption and renewable energy generation. HEM algorithm thus developed is successful in regulating the sources and loads dynamically under varying renewable generation and price of electricity. This model can be used as a tool for short-term energy management. The long-term energy management can be achieved through proper modification of the HEM algorithm.

Potential social benefits of mini grid with solar contribution were studied [27]. The data obtained from five different mini-hydropower installations were taken and three solar PV technologies were simulated. Energy return on investment (EROI) was computed for three different solar PV technologies. The different battery options were reviewed. The potential social benefits were only considered in the study. The environmental effects need to be considered while computing EROI.

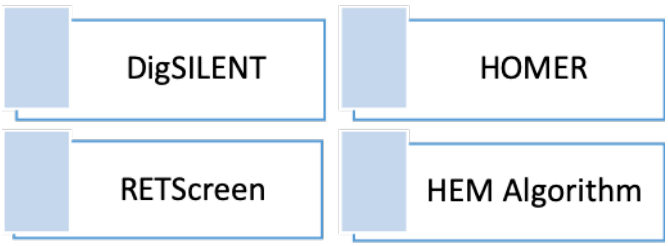

Fig.2. Software's used in Energy Management Techniques

Successful energy management techniques can make the PV based power system more efficient. The approach to energy management should take care of the socio-technical, economic and environmental requirements. The different energy management software's used are presented in Fig. 2.

It is observed that proper energy management can be achieved by considering the following parameters like selection of generation mix, life cycle cost, reliability, priority loads, optimal use of storage element and maximum the use of RES.

5. Battery and Storage in Hybrid PV Systems

Many research works in the recent past developed models that attempts to provide insights into the techno-economic benefits of PV generation system with battery storage. In developing system models of PV – with backup battery where feed-in tariff (FiT) incentive, where differential tariff exists, the cost of storage element and has to be minimised to bring down the life cycle cost of electricity.

A technical and economical design proposal was developed for a photovoltaic and battery energy storage system. This analytical model determines the PV system rated power and the battery energy storage system (BES) capacity sufficient to minimise the LCOE [28]. The model is built on a power flow control algorithm and confirms to meet the energy load profile with the system. The model can be used for developing a system which can minimise the levelised cost of electricity by designing a system computing the PV rated power and the battery capacity with due consideration on environmental factors.

For a micro-grid operation management, the optimal sizing of battery energy storage performed by using an optimisation algorithm namely new improved BAT algorithm [29]. Here the multi objective optimisation problem is solved using this robust and strong optimization algorithm, and corrective strategies required for least cost dispatches were arrived. The performance of the approach is estimated by one grid-connected low voltage micro grid and the optimal size of BES is determined. Optimisation can be performed by considering the intermittency of RES, and optimal sizing of battery considering cost and emission objectives.

Daily Solar Energy Production (DSEP) is assumed and an off-line Linear Programming (LP) optimization algorithm was developed [30]. This algorithm takes into account the battery size, the battery state of charge and maximum battery charge/discharge powers. The daily solar energy production is assumed to be constant, which cannot be true in real time. The optimisation can include the real time production of solar power instead of assuming a constant value.

Different configurations and sizing methodologies of a standalone PV energy system were considered. The different parameters such as technological, economical, and socio-political factors are encapsulated and arranged in sizing a practical standalone PV system [31]. The relative advantages of different sizing methods namely numerical, software based and AI methods were reviewed. Comparison of various sizing methods for a standalone revealed that hybrid method yields optimal solution.

Customer damage function was considered in optimisation of practical battery size in a PV system [32]. Battery size for a 110kW PV pant supplying 550kW load in a commercial building, is obtained through Monte Carlo simulation considering the damage costs during power outages and compared with the battery size determined by stochastic methods. The optimum capacity of storage element in a PV system coupled to the grid over the life cycle of the PV system has to be estimated for consumers whose usage pattern is similar.

An optimization model in which there exists an optimally sized PV system with battery backup for residential and non-residential customers of electric power using stochastic mixed integer optimization method was proposed [33]. Probabilistic scenarios are formed considering the oscillation associated with load, solar radiation and electricity price. Here the load, the solar radiation, and the price of grid power are treated as random variables. The randomness of these variables are represented by scenarios. This model can be used with different grid pricing programs and can also be applied where no net metering or net metering exists. This optimisation model highlights the need to use an optimisation model for PV system with battery backup. It can be used to arrive at suitable optimisation model for storage enabled PV system.

Storage element being the costliest part in a Solar PV system selection of storage element and capacity of the storage element required has to be ascertained. It is seen that selection of type and capacity of storage element directly depends on the size of storage element, pricing schemes of the utility power, cost of storage element, type of storage element, levelised cost of electricity and economy with usage of hybrid power using storage element.

6. Modeling of PV Systems

There are many methodologies followed in modeling and optimisation of PV based renewable energy systems. These modeling methods use genetic algorithm, fuzzy logic and artificial neural network in optimising the systems. An optimisation based on genetic algorithm for design and modeling of hybrid renewable energy systems was proposed [34]. Here optimisation is done using genetic algorithm and the sizes of the various components of the hybrid system with objective function to minimise the cost of electricity is obtained. The component parameters namely PV tilt and azimuth angle have also been optimised. Load is shielded with 100% reliability. Cost of global warming emissions was also considered. Cost of electricity being higher than that of utility grid optimizing the cost of energy (COE) with utility grid and solar PV can be an option to reduce the COE.

The control of a grid connected PV system was implemented using fuzzy-sliding mode [35]. A fuzzy simulation is done for a grid connected PV system. This is a real time work which extracts maximum power from PV system and supplies power to the load. This can be combined with an energy management technique to obtain better results with lesser cost of energy.

An energy management was done on photovoltaic solar home [36]. Here the fuzzy logic was used to construct the energy management algorithm, where state of charge, PV energy produced and energy imported from grid were managed to satisfy the prioritised home energy demand. The work is based on simulation results, however in practical

situations the assumptions on the PV energy produced may not be as expected. Hence the real time study can only reveal the actual advantages of the proposed energy management strategy.

The modeling can thus be done by selecting parameters with due consideration in its contribution in attaining optimal results. The method of modeling may be selected undertake a real time study so that results can be used for implementation too.

7. Research Challenges in PV Systems

Research works are on to make solar power generation cost-competitive as compared as to utility power. Many countries including India have promoted the domestic consumers to install roof top solar power plant. It is seen that rooftop, off grid, solar photovoltaic (PV) based inverters are being popularly used in for home-based backup power supply. However, when the battery is in fully charged condition the solar power generated gets under-utilized as the solar energy is only partially used for charging the battery. Reliability of the power supply and effective utilization of solar energy have to be addressed to attain economy in operation. This in turn will reduce the payback time of the photovoltaic (PV) system, decreases the life cycle cost and makes it financially attractive.

A renewable energy backup which is cost effective electrical energy source for the consumers suffering from grid scheduled blackouts (GSBs) supplying all critical loads have to be designed. As investment cost of the storage system being considerably high, obtaining an optimal technology, size, and configuration needs emphasis. In a domestic PV system, the battery backup should be suitably selected to meet this objective. The energy management should be done in such a manner that the life cycle cost of electricity can be considerably reduced by operating such a hybrid system.

The increase in energy contribution to the grid from PV system has reduced the cost of electricity during its contributing hours of the day. However, during peak load hours where solar energy contribution to the grid is zero, other conventional sources of energy have to be depended on for generation of power. This makes cost of energy production higher during the peak hours of the day. It is here the utility companies go in for differential pricing or the so-called time of the day tariff. The power received from the utility grid during this timing will increase the energy bill.

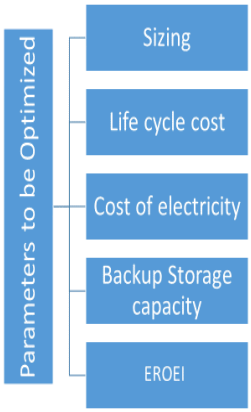

Fig.3. Parameters to be optimised.

There are various parameters that are to be considered while designing a PV based hybrid system to make it cost effective and efficient. Solar PV systems provide the best solution to the increasing energy demand. The depleting fossil fuels, depletion of natural resources and pollution caused to the environment makes solar energy the best choice for power generation. Decreasing cost of PV panels and better conversion efficiencies of the equipment will enhance its suitability. However solar power is temporal and affected by climatic conditions. Hence energy has to be stored. This has increased the life cycle cost of electricity of solar PV systems.

Roof top standalone solar PV systems have been installed in many houses. Due the subsidies offered by the government during installation many have opted for the same. The battery, which is a costly component in the system, have to be replaced after five to six years of service. This makes grid tied system more attractive. However, the comfort of zero outage in standalone system has to be compromised. Better management of energy by optimising the storage element and setting up a hybrid system by connecting the solar power to the grid can bring down the cost and enhance the convenience and reliability to the consumers. The different parameters to be optimised are represented in Fig. 3.

8. Conclusion

A review on various parameters of this multi-objective energy management problem is done. The various models discussed highlights the various considerations to be made in setting up of a PV based Energy generation. It is seen that a hybrid system is more suitable for domestic application since it can address both convenience and economy to the customers. The need for a suitable energy management technique becomes significant in reducing the energy bill of the domestic customers. By proper selection of critical loads and taking into consideration of time of the day tariff, the storage element can supply power to the load. Thus the customer can avoid power outages as well as reduce their energy bill. A properly managed grid connected PV system with backup storage element to supply critical loads can

address both these issues. Due to the lower capacity of storage element the lifecycle cost of PV system can be reduced.

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