Developing Solar Photovoltaic Systems - Investigating Modeling and Sizing Techniques and Power and Technical Challenges

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Abstract:
These days, solar photovoltaic (PV) plants are getting into the limelight because of their inherent quality to turn solar energy into electricity directly. However, the power that PV plants generate can rarely meet load demand quickly as they don't have proper supply that can meet consumer demand immediately. Grid-connected solar photovoltaic plants have recently gotten immediate attention for using energy storage and making load management flexible while dealing with major power quality issues in grids. This way, solar PV panels are more effective and useful. Various battery management techniques are used to come up with more price-responsive demand and to ensure effective integration of PV plants into the power grid. Vast deployment of solar PV systems has been affected with the growth of power policies. This study is aimed to discuss various sizing and modelling techniques for effective operation of solar PV systems. In addition, we also discuss the strategies to make the most of stored energy in PV systems financially apart from optimization techniques. We have also covered some of the technical and power quality issues on the state of the art of PV systems as per various cell technologies, energy policies, and inverter/converter technology, control and power quality challenges.

***Keywords*: Solar photovoltaic systems, Solar PV plants, solar PV systems, sizing techniques, energy storage, grid-connected PV panels**

1. Introduction

Emission of greenhouse gases (GHG) from the sweltering of fossil fuels is highly responsible for climate change in the world. Over 80% of GHGs come out of consumption and generation of electricity. The demand for primary energy across the world is going to have a 60% rise by 2030 from 2002, i.e. a 1.7% year-on-year hike, which further raises carbon footprint leading to the phenomena of global warming and climate degradation (Moosavian et al., 2013). Technologies like low-carbon and sustainable energy will be very important in the revolution of energy needed to make change in the chosen path.

Various types of green energies with carbon capture, energy efficiency, and storage, new transport mediums and nuclear power should be deployed widely in order to achieve a new low CO2 target related to energy in future and deal with the issues of global warming (Hoeven, 2015a). Without fully devoted and immediate action, climate change will drastically affect the world and it would be irreversible, according to the "International Panel on Climate Change (IPCC)". Similarly, "long-term average temperatures" should be reduced to 2°C to pre-industrial levels. Global commitments and sustainable solutions will be needed to control all emission levels (Hoeven, 2015b). The "International Energy Agency (IEA)" is developing some technology footprints with all shareholders which enable industries, governments, and financial stakeholders together to define the steps required to boost technology changes.

1.1 Background

Solar photovoltaic systems make one of the most emerging and promising technologies. The levelized electricity of "decentralised solar photovoltaic panels" is going down the variable part of retail energy prices that are paid by system owners in some commercial and residential markets (Hoeven, 2015a; 2015b). Over the past decades, a lot of solar PV systems have been added. In 2013, 100 MW installed each day was used to show this increasing phenomenon of demand for PV units. In 2015, a total of 177 GW of Photovoltaic power was recorded (Hoeven, 2015a). PV is estimated to have a 16% share by 2050 across the world in energy demand, i.e. rising steeply from 11% in 2010, according to the IEA 2014 roadmap.

PV Generation would deliver 17% of completely clean energy while all renewable sources are proposed to generate 20% of energy across the world. China will have 37% share in global capacity and emerge as the PV market leader by 2050 (Hoeven, 2015a; 2015b). The newly developed PV systems have evaluated a variation of US$90 to US$300 per MWh of cost, which varies as per solar type, resource, cost and size of systems, costs of capital, and maturity of markets (Hoeven, 2015b).

PV energy sources are usable as simple, stand-alone solutions and grid-connected platforms and can be used in battery charging, pumping water, street lighting, powering home appliances, heating up swimming pools, refrigeration, telecom, hybrid vehicles, satellite power, military space, and hydrogen production. Decentralised systems have covered around 60% of the market across the world, while utility-scale, centralised systems have 40% of market share. Off-grid or standalone systems now have only 1% contribution to the international market, which were once the leader on a very small market. Whether "multi-crystalline (mc-Si)" or "single-crystalline (sc-Si)", the "crystalline silicon (c-Si)" modules have 90% share in the PV market. Different kinds of "thin films (TF)" have only 10% share, which gone down from 16% in 2009, and there is only 1% share for "concentrating PV (CPV)" (Hoeven, 2015a).

Solar resource also relies on weather like wind energy and poses serious issues. Hence, it is important to determine all flexible solutions for the consistency of power supply like storage, demand-side response, flexible generation, and inter-connections to meet the targets of generating solar energy by 2050. PV must be able to balance all renewables. For example, wind energy is supposed to be stronger in winters and can balance the needs for solar irradiance in moderate countries. Hydro energy can compensate solar energy in wet and hot countries.

Major applications for storage has been defined well but it is still important to quantify dispatch strategies of solar energy which is stored to enhance the financial value of combined energy and generation systems in an operational context (Nottrott et al., 2012). Reliability is a major challenge to make the most of PV energy in smart grids and there is a huge demand for battery systems (Eltawil and Zhao, 2010). In order to attract consumers for getting indulged in demand response, several schemes for retail pricing have been proposed like "critical peak pricing (CPP)", "time-of-use (TOU)", and "real-time pricing (RTP)" to enhance economical value of PV systems. This study has been organized as follows – Section 1 is based on the foundation of solar PV systems and key indicators for its development, Section 2 is based on the review of related literature on solar PV systems, key issues and challenges, and several other technologies to find the research gap. Section 3 deals with methodology of this study, Section 4 discuss the data gathered from various studies, Section 5 discusses the results obtained from this study and Section 6 concludes the paper.

Literature Reviews

2.1. Introduction

The solar resource relies completely on weather, which poses a serious issue. Hence, it is important to determine all flexible options for consistent power supply, such as storage, demand-side response, flexible generation, and interconnections to meet PV generation targets by the year 2050 in the IEA roadmap. PV must be able to balance all renewable. For instance, wind energy can compensate for reduced sunlight as it is likely to be stronger in winters in temperate areas.

2.2. Hydropower and Solar Energy

As a renewable resource, hydropower can compensate for solar energy in wet and warm countries. With integrated thermal storage in arid and hot countries, solar thermal energy can generate electricity at night and compensate for the PV fluctuation and supply more energy to systems. This way, solar energy might be the prominent source by 2040 to generate electricity (Hoeven, 2015a).

2.3. Key Issues of PV System

The sources of solar PV are not able to provide consistent power supply and may cause imbalance in demand and generation of electricity, especially during off seasons when more energy is generated by PV and during peak months when there is extremely high load demand. Due to its irregular and intermittent nature, PV units make it difficult to manage the grid. At the same time, the production of PhotoVoltaic into the grid is limited. The matching of the production of intermittent energy with demand for dynamic power is one of the key issues of Photovoltaic systems (Riffonneau et al., 2011). Adding storage to those power sources can solve the problem. Intermittent energy sources can fulfil load demand on a timely basis and make load management flexible with batteries and other storage devices.

Even though important storage applications have been identified well, there is a lack of understanding and quantification for dispatch strategies for stored energy to enhance financial value of energy storage and renewable energy generation systems in operation and it should be investigated further (Nottrott et al, 2012). Reliability is a major issue in smart grids and ample use of PV energy, along with the rise in demand for battery solutions (Yoon & Kim, 2014). In order to attract customers, a lot of retail schemes like "critical peak pricing (CPP)", "time-of-use (TOU)", and "real-time pricing (RTP)" have been proposed to boost economic benefits of PV battery solutions. Yoon & Kim (2014) and Eltawil & Zhao (2010) studied controlling grid PV systems to improve system output and their efficiency and optimise the process for quality electrical energy.

2.4. Grid PV Systems

Grid PV systems can work together and are connected with the power grid. The inverter or "power conditioning unit (PCU)" is an important component of grid-based PV systems. DC power can be converted and produced by an array of PV into AC power with consistent power quality needs and voltage for either sending the power to the utility grid or direct use of appliances to earn feed in compensation of tariff. When there is no power in the grid, the power supply is stopped automatically to the grid from the PCU. At the on-site panel for distribution or service entrance, a bi-directional interface enables AC current generated by the PV system to either back-feed the grid or supply loads on-site when PV output is higher than the demand for onsite load. When there are greater electrical loads than output of a PV system, especially during cloudy weather and at night, the power balance needed by the loads is received from the utility. It refers to a safety feature in case the grid is down for repair or service to ensure that it would not feed back or operate in the utility line (Zhou et al, 2010).

2.5. Research Gap

There are two categories of solar PV systems – grid-connected "utility interactive" and "standalone" systems. They rely on their functional and operational needs, configurations of their components, and their link with power sources and power loads. In addition, they might be interconnected or interdependent with the utility grid. They can provide DC and/or AC power service and can be linked with various alternative sources of energy and energy storage solutions. Without backup "energy storage (ES)", grid-connected photovoltaic systems are high on demand as they are eco-friendly and sustainable because of low cost and maintenance. However, the system needs to shut down in case of power cut during cloudy weather or night time. This study is aimed to discuss environmental and economic benefits of grid-connected PV systems and some of the technology and power quality issues to tackle.

2.6. Research Objectives

- To discuss different modelling, sizing, and "maximum power point tracking (MPPT)" techniques for smooth running of PV systems
- To explore control technology and power quality challenges of grid-connected Photovoltaic systems

Research Methodology

In order to fulfil the above research objectives, this study will be based on secondary data collected from various sources like research journals, articles, studies, publications, online databases, online libraries, and other sources.

3.1. Research Design

PV Systems are subcategorized into grid-connected and stand-alone PV systems. Their classification relies on their functional and operational needs, configurations of their components, and their connection to various power sources and electrical loads. In addition, they can work with utility grid or independently. They can provide DC and AC power source and be connected to various alternative sources. Hence, this study is designed to further discuss the emerging sizing and modeling techniques used in solar photovoltaic systems.

3.2. Research Approach

Without backup storage, the grid-connected solar systems are eco-friendly and widely used by people as they don't rely very much on cost and maintenance. The system needs to shut down on cloudy days or night time due to power outage until the grid power is connected. The approach of this research is to further explore technical and power challenges and find solutions by opening further research path.

Analysis of Study

Effectual modelling for components of solar PV systems would make it efficient. It consists of modelling of storage devices, photo-voltaic power generator, power loads, and electronic interface. Various models of solar cells consist of a more accurate model, a PV cell model known as the "2-diode model". A 1-diode model is accepted widely for modelling of PV panels. Using an existing source along with a diode illustrates a simple model of a PV cell. The light on the cell directly affects the output of the existing source (Ajayi-Obe et al, 2019). A typical PV cell doesn't show any serious loss or leak on the circuit and shunt and series resistances are equivalent to infinite and zero, respectively (Tsai et al., 2008). There is constant output charge under constant temperature and solar energy.

The "open-circuit voltage" and "short-circuit current" are the most important parameters of a PV cell. The datasheet of the maker usually provides their values. When PV cell terminals are connected, it is possible to achieve the "short-circuit current". It means the voltage is equivalent to zero across terminals. On the other hand, if the terminals are not linked or open, it is possible to achieve the "open-circuit voltage" and current "*I*" is equivalent to *0*.

As per the "Kirchhoff's law" on the common circuit cell, here's how to calculate the output "I_0" -

$$I_o = I_{sc} - I_d \tag{4.1}$$

Here, I_{sc} refers to "short circuit current" at "*T*" temperature and I_d is diode current as per this "Shockley's diode" equation (24-26) –

$$I_d = Irev(e^{qV/kT} - 1) \tag{4.2}$$

Here, q is electron charge "(1 eV = 1.602 e^{-19} J)", V refers to "diode voltage", k is "Stephen Boltzmann's constant" "(1.381 e^{-23} J/K)", T refers to "Junction Kelvin temperature (*K*)" and *I_rev* is "reverse saturation current" at "*A*" reference temperature. Here is the "PV cell" current-voltage equation after replacing (1) and (2) equations –

$$I_o = I_{sc} - Irev(e^{qV/kT} - 1) \tag{3}$$

There is a similar value of output current either for cell or panel and cells are linked in a range of solar PV systems. The power of the solar PV system changes because of fluctuations in temperature and solar irradiation. In addition, with direct connection between the load and solar panel, the delivered power is not optimal. The operation of the PV panel is influenced by the load impedance. The operating point moves on the curve of voltage as the load changes. In the real method of "PV direct couple", the operation point coincides barely with "maximum power point (MPP)". There is a risk of mismatch in configuring load in the PV panel. Hence, PV panels must be outsized in case of low irradiation. There are significant implications of cost. Hence, the "maximum power point tracker" is important to enhance efficiency. The techniques of "maximum power point tracking (MPPT)" are useful in extraction of the right supply of power to run an MPP system.

The "input impedance (R_i)" and "load impedance (R_L)" can rarely match in a PV panel. The tracking process is supposed to match these parameters with the right duty cycle adjustment in Figure 4.1. (Enrique et al., 2010)

Benefits of Solar PV Panels	Objectives	Findings	References
Economic benefits	Energy and design control	Various situations have been studied in PV power, power prices, and profiles for load demand	Zhu et al. (2014)
	To study economic benefits	Calculated "Internal Rate Return (IRR)" and NPV	Dahlan et al. (2013)
	To evaluate technological and economic benefits	Several areas where PV was installed had levelized electricity cost	Marinopoulos & Bakas (2014)
	To do cost analysis of microgrid generation	"Probabilistic costing analysis"	Tsikalakis & Hatziargyriou (2005)
	To do financial analysis of grid system	IRR, NPV and "discounted payback period"	Kornelakis & Koutroulis (2009)
	To take design decisions in PV system like battery storage, PV, inverter models, and charge controller	Economic analysis to find out levelized energy system cost	Nordin & Rahman (2014)
	To determine the impact of hybrid power storage in smart grid	Peak shaving achieved optimal control mechanism	Wang et al. (2013)
	To determine output of grid-based PV/storage	Load shifting and peak shaving	Gitizadeh & Fakharzadegan (2013)
	To analyse profitability of hybrid storage	Cost savings are achieved on daily basis with specific limitations	Zhu et al., (2013)
Environmental Benefits	To determine both ecological sustainability and financial viability of PV electrification in rural areas	"Retscreen" program is used for saving carbon emission and cost as compared to traditional technology used for power generation	Adam et al. (2015)
	To study photovoltaic power plant	Energy predicted with reduced Greenhouse gases and RET emission	Harder (2010)
	To analyse "techno-economic feasibility" of PV systems	Three methods have been suggested for designing several PV systems	Jamil et al. (2012)
	To analyse importance of storage on PV system	Studied energy cost and NPV, GHG etc.	Arif et al. (2013)
	To study investment on PV	Achieved optimal capital cost and capacity with less CO_2 emissions	Ren et al. (2009)

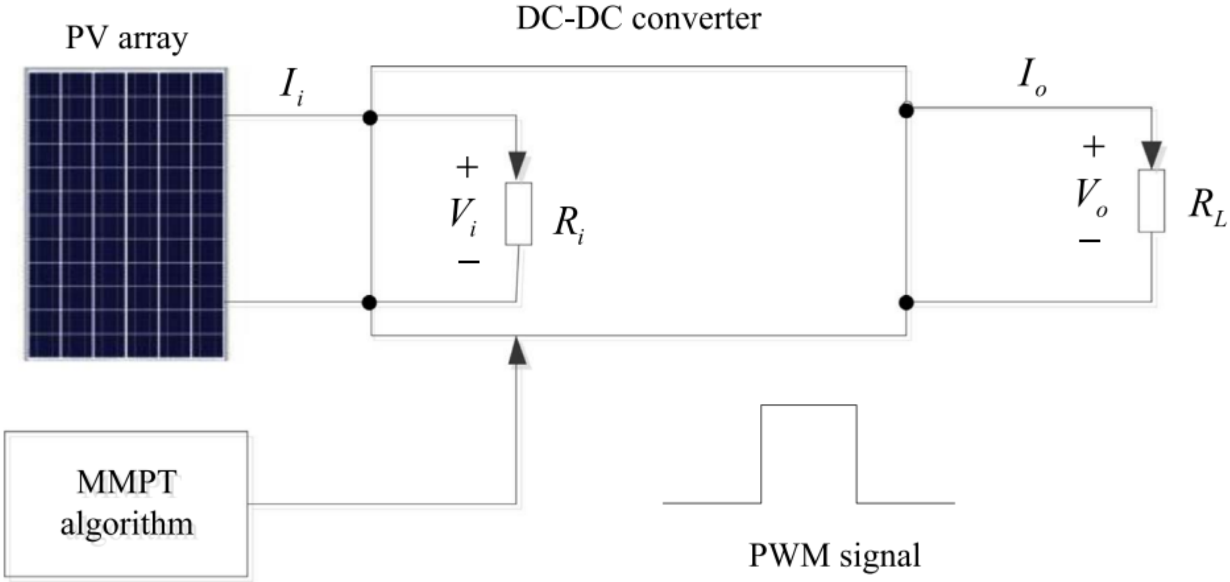

Figure 4.1. MPPT Method in PV panel

The "Incremental Conductance (IC)" and "Perturb and Observe (PO)" are the most prevalent MPPT models. The PO model is one of the most common models that can be implemented easily and are simple. This MPPT model is also called the "Hill Climbing (HC)" model. HC needs "converter duty cycle" to be changed while the operating voltage is perturbed by PO in the PV panel, despite having the same working principle (43). It is possible to update and track this MPP to solve the "mathematical equation" of "*dP/dV = 0*". One can calculate "*dP/dV"* slope online with sampling of "*I*" output current in PV panel and "*V*" voltage at the existing and last time intervals "(i) and (i-1)" –

$$\frac{dP}{dV}(i) = \frac{P(i) - P(i-1)}{V(i) - V(i-1)} \qquad \textbf{(4)}$$

In Equation (4), the power product of "*I(i)* and *V(i)"* measurements are "*P(i)"*. The PO can be implemented easily as it needs just measurements of current and panel voltage. After reaching the MPP, the operating point equivalentes constantly around MPP and it causes power losses of PV.

4.1. Environmental and Economic Benefits of PV Systems

It is possible to do cost analysis to find out the "net present value (NPV)" of "battery storage system" as designed to determine feasible PV system by determining the amount saved in electricity bills over the lifetime of battery against the capital costs of solar power storage panel, interest rates, and annual cost of "Operation and Maintenance (O&M)". Table 4.1 illustrates economic and environmental benefits of solar PV systems for sustainable operation -

Table 4.1. Economic and Environment Benefits of PV systems in various studies

4.2. Control Technology and Power Quality Issues of PV Systems

Solar PV systems are known to be very intermittent and highly concerned as sources for renewable energy in power systems. It may lead to issues like voltage control, stability, and power quality. Energy storage solutions are utilised widely to deal with them in power systems. A lot of energy storage solutions like electrochemical, electrical, mechanical and thermal systems are widely used for dealing with PV systems. It is important to compare them in terms of capital cost, merits, applications, and lifecycle. Table 4.2 illustrates various maintenance and power quality issues of PV plants.

Objectives	**Findings**	**References**
To determine operating expertise on PV power plants with 4.9 to 5 MWdc capacity	Costs, performance, and maintenance for operation period of 5 years	Moore & Post (2008); Moore et al. (2005)
To determine the effects of new technologies and tools on PV grid solutions	Barriers on PV-DG interconnection and grid power quality are reduced	Katiraei & Agüero (2011)
To perform cost analysis of scheduled maintenance	Cost-based criterion for optimization	Canto (2014)

To investigate RO plant powered by PV	3-phase induction motor has been found more economical than DC motor on RO plant powered by PV helped in reducing power consumption	de Carvalho et al. (2004)
To study the stability of frequency	Measures of mitigation of grid-code needs and unusual conditions	Jahn & Nasse (2004)
To determine operational outcome of PV systems connected by grid	Reliable data has been observed on performance monitoring	Boemer et al. (2011)
To investigate operation of PV for commercial purposes	Helpful for decision makers with cost, installation, maintenance, and operation indicators	Borja et al. (2005)
To discuss PV maintenance and operation	Resulted in cost savings and plant downtime, workforce safety and greater output	Enbar et al. (2016)

Results

Solar PV panels have gained immense attention as a promising technology to mitigate the reduction of fossil fuel, rise of power demand, and need for lowering Co2 emissions. PV energy can be very competitive when there is peak demand but there are enough options for improvements as given in "IEA tech roadmap" for enough energy on grid. On the basis of above analyses, renewed proposals on regulatory and legal issues, system integration and technology can overcome several environmental and economic issues. AI techniques can be beneficial to size grid-connected and standalone PV systems optimally. It is also possible to cover reduction techniques to reduce losses of shading and mismatch in PV arrays.

We have also discussed grid-connected and standalone hybrid PV solutions with power management issues (Table 5.1). Hybrid power storage solutions have been cost effective as compared to homogenous technologies but they are more complex to model and analyse.

Table 5.1. Applications of Hybrid PV Systems

Types of Hybrid systems	**Objectives**	**Findings**	**References**
Off-grid	To form control strategies	Found solid performance of "Fuzzy Logic Control (FLC)"	Singh et al. (2010)
	To study economic design and feasibility	Reduced carbon emissions and operating costs	Ismail et al. (2012)
	To review optimization, simulation, and control approaches in hybrid systems	Found optimised techniques with battery storage	Zhou et al. (2010)
On-grid	To perform simulation and modelling of microgrid	Grid-connected, islanded modes improved power quality	Reddy et al. (2013)
	Hybrid PV system	Small PV size, lower fuel consumption and cost-effective	Singh & Snehlata (2011)
	Optimal sizing of hybrid PV	Better reliability and safety along with cost-savings	Zhang et al. (2012)

A lot of power generation methods and plants have been evil to the local environment in communities worldwide. Traditional means for power production have made local flora and fauna suffer, especially birds. Plants are removed for space and habitat for animals is lost. These ecosystems can recover and start flourishing again with solar energy. Solar panels installed at the top of buildings and in villages can keep other habitats safe and healthy without any air or water pollution. Water is among the most important and scarce natural resources. It is very hard to survive without fresh water in dry areas and this scarcity will be more dangerous and devastating.

Drilling, mining, and burning of fossil fuels constantly release carbon and other pollutants in the environment and it leads to air pollution. These pollutants are harmful to the environment and public health. Solar energy can avoid this issue and reduce pollution in the air. Renewable resources can lessen dependence on limited resources that affect the environment. Solar energy doesn't release any toxins in the river or atmosphere. Hydro-electric plants, nuclear power plants, and coal plants need a lot of land and water, but solar systems don't have many requirements for land. They can be installed in remote lands or on rooftops.

Conclusion

This study has made it clear how financially and economically beneficial solar PV systems can be when load forecasts and power output can be used for storage of energy with several optimization techniques. This article has also investigated issues of grid-based PV battery solutions like voltage stability, power outage, reliability, islanding detection, etc. with solutions studied. We have analysed sizing and modelling techniques in the context of hybrid and homogenous PV systems. We have discussed environmental effects of greenhouse gases with implications related to NPV cost. Finally, we have presented maintenance and operation findings of hybrid systems. Technical challenges like different cell technologies, energy policies, MPPT technology, reliability, and other issues have been addressed.

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