

Challenges and opportunities towards adaptive inverter sizing in Bifacial PV systems

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Abstract: Solar Photovoltaic (PV) installations world-wide is currently going through transition from monofacial to bifacial technology. The bifacial photovoltaic (bPV) is replacing its counterpart modules as per the global market shares of the PV technologies. However, with the introduction to the superior technology of generation from both the sides in the bPV systems design aspects of the complete systems needs a critical attention. This is due to the fact that the generation from a bPV system can be 30% more than that of the monofacial PV systems. Nevertheless, the formulation of the inverter sizing in most of the installations is based on the static Direct Current/ Alternating Current (DC/AC) ratio as the design decision criteria. A comprehensive literature review of various domains in bPV technology has provided detailed insights of various aspects of the system bPV design as the research gaps. The unsolved problems in bPV system design to address the issues of bifaciality with inverter clipping losses and estimation of dynamic DC/AC ratio provides opportunity of further research in this direction. This paper presents such unexplored areas of bPV system design alongside the framework towards the transition from fixed inverter sizing to adaptive sizing thereby minimizing the clipping losses and increasing the generation from the bPV system.

Keywords: Adaptive inverter sizing; Albedo; Bifacial PV (bPV); Clipping Losses; DC/AC ratio; Power sizing ratio

Introduction

Bifacial Photovoltaic (bPV) panels differs from the mono-facial panels with respect to its ability to generate electricity from both the sides of the panel i.e front as well as rear surfaces. The concept of bifacial cells originated in the early 1980's [1] from where the initial development in this technology started. Further research in this domain showed some experimental validations where the rear surface was able to provide a substantial addition in the generated power along with tilt angle optimization [2]. The new age installations had invented the technology to optimize the system parameters such as the elevation, row spacing, tilt, string sizing etc., for the optimum energy yield [3-7].

One of the important variables when it comes to the system design of the grid connected PV power plants, the DC / AC ratio plays a major role. This ratio is also expressed in terms of the Power Sizing Ratio (PSR) i.e the PV to inverter PSR. Whereas an oversized DC array can improve inverter utilization during low and moderate irradiance, it increases during the high irradiance period. On contrary to this, an undersized array reduces clipping leaving the inverter underutilized [8]. Conventional inverter sizing therefore

compromises using the long-term energy, cost and inverter utilization. Recent literatures have demonstrated optimum ratios dependency on the several environmental factors in unison with the inverter efficiency curves, clipping and economic assumptions rather than the universally accepted thumb rules. [9-10].

This sizing problems becomes more complex in case of bPV based PV power plants due to the rear surface energy generation in this case. The increase energy yield due to the rear side irradiance has to be accounted in the inverter sizing for its effective utilization [11]. Rear irradiance is affected by albedo, the surface conditions, elevation of the module and the row spacing between the arrays of the string [12]. Studies on the various techniques associated with yield of bPV based systems shows that the field measurements of the site may vary with the actual outputs as the mathematical formulations do not account the real time weather parameters which makes a considerable difference between the actual and predicted outputs [13 - 16]. Consequently, fixed DC/ AC ratio-based design configurations of inverter sizing may be impacted for a real time outputs in case of bPV based plants [17].

This paper presents the research hypotheses as why there is a need to shift the focus from a fixed DC/AC ratio towards an adaptive DC/AC ratio in case of a bPV based solar power plants.

Summary of the related literature studies

The study of the bPV based Solar PV systems is mainly classified into five different streams, namely; (i) fundamental characterization of bifacial behavior, (ii) mathematical modeling of bifacial and electrical parameters (iii) optimization techniques and system design using bPV panels (iv) inverter sizing related characteristics and (v) intelligent and digitalized operations. This classification of the study is considerably useful for the in-depth analysis of finding the knowledge gaps which has evolved into the study of the optimum inverter sizing for the bPV based solar power plants.

As per the finding of the studies of the literatures, there must be systematic review of technologies that emphasize on the optimization of the irradiance modeling, electrical behavior and techno-economic as well as application specific geometry of the bPV based system designs. Recent literature in these streams have significantly proved that the spatiotemporal anisotropy plays a vital role in the bifacial gain estimation from a bPV based systems.

The fourth literature stream significantly emphasizes on the inverter sizing and the PSR integration with the optimization studies in the bPV systems. The existing PSR reviews and optimization studies compares methods based on annual yield, clipping losses and the Levelized Cost of Energy (LCOE). The techno-economic study in [18] explicitly incorporates real weather data and inverter efficiency curves and identifies a site-specific optimum PSR rather than a universal value. However, such formulations generally return one optimum ratio for a design case. They do not continuously update the ratio or inverter operating limit as the bPV rear-side contribution changes.

An important bridge is emerging from reliability research in [19] wherein the generation from a bPV system can increase the inverter utilization thereby the loading of the inverters may considerably rise causing the reduction in lifetime of the inverters. More recent literatures in [12-15] reports similar issues with the inverter when the DC/ AC ratio is increased without making any changes in the inverter sizing. This clearly indicates that the inverter sizing should be evaluated not only against the energy yield and clipping losses but also other technical parameters that includes thermal cycling, component lifetime and maintenance costs also needs simultaneous consideration while designing the system.

Research on clipping losses provides another critical connection. The study on oversized bPV systems explicitly examines electrical and financial impacts of inverter clipping under different weather and ground-reflectivity conditions [20]. Thus, clipping is no longer simply an unavoidable loss but it is a controllable design trade-off. The remaining challenge is to determine whether the clipping boundary itself should be adaptive when rear-side irradiance and operating conditions are changing [21-24].

Knowledge gap analysis

The analysis of the recent articles in the represented streams have identified as much as thirteen gaps that can be grouped into four higher- level research deficiencies: i.e static sizing, incomplete physical coupling, limited intelligent adaptation and insufficient validation. The gaps are summarized below and formulated.

Table 1. Representative literature streams for adaptive inverter sizing

Sr. No.	Knowledge gap	Current Status	Research Opportunity
1.	Fixed DC/AC Ratio	System design uses a fixed PSR for a design case	Developing condition dependent flexible DC/AC Ratio
2.	Bifaciality modeling in dynamic conditions	Rear irradiance depending on the albedo of the site and geometry	Real-time integration of rear irradiance with the with decision on flexible DC/ AC Ratio
3.	Bifacial gain – clipping interactions	Clipping and bifacial gain are often analyzed separately	Jointly optimize rear gain, clipping and inverter utilization
4.	Single time-scale optimization	Annual or representative periods dominate conventional sizing.	Use hourly to seasonal hierarchical optimization
5.	No adaptive supervisory layer	Inverter sizing is primarily a project design variable	Create an adaptive supervisory controller for operating limits.
6.	Limited AI for sizing	AI is increasingly used for MPPT and EMS but not directly for PSR adaptation	Use interpretable ML/RL for ratio and curtailment decisions.
7.	Lifetime degradation coupling	Degradation is considered in some performance studies but rarely as a dynamic sizing variable.	Include degradation and aging in lifetime optional sizing.
8.	Climate Variability	Site studies demonstrate strong climatic dependence.	Test robust sizing under climate and weather uncertainty.
9.	Limited long-term validation	Field studies validate bPV performance, but inverter –	Validate with high- resolution field measurements.

		aware long- duration datasets are limited.	
10.	Digital-twin integration	Digital – twin work is emerging	Couple physical models, measurements and adaptive optimization.
11.	Static economic assumptions	Techno-economic studies optimize fixed scenarios	Evaluate lifecycle cost under adaptive operation.
12.	Grid-support constraints	Smart- inverter studies focus on grid operation rather than bPV sizing.	Co-optimize energy yield with voltage/ reactive/ grid – support services.
13.	No unified framework	Module, inverter, reliability and grid variables are mostly treated separately.	Develop a unified multi-objective adaptive architecture. Develop a unified multi-objective adaptive architecture.

Key Contributions

This section describes a structured roadmap towards an adaptive control experiment for the identified gaps from the literature studied in these streams. The key contribution is to the explicit coupling of four domains that are investigated independently: bifacial irradiance modelling, PV/inverter sizing, inverter reliability and intelligent control. The proposed framework treats DC/AC ratio as a design variable with a corresponding operating envelope rather than as an immutable project constant.

First, the paper establishes a gap taxonomy that distinguishes physical, optimization, control, economic and validation gaps. Second, it defines a mathematical structure for condition-dependent sizing. Third, it specifies a validation hierarchy progressing from analytical equations to PVsyst/ MATLAB/ Simulink comparison and finally to field measurements. Fourth, it identifies reliability and grid -support constraints as explicit objectives, preventing an energy- only optimizer from selecting an operating point that may increase thermal stress or violate grid requirements.

The central hypothesis for subsequent experimental work is that an adaptive inverter- loading strategy can improve the balance among energy capture, clipping, inverter utilization, lifetime stress and lifecycle economics when compared with a fixed DC/AC ratio, particularly under high and variable rear – side irradiance.

Proposed design of experiments and methods

The proposed experimental design and methods are defined so that the identified gaps can be tested quantitatively and convert into opportunities. The proposed experiment design framework is explained in next sections.

i) System and Data layer

The first layer should construct a time resolved bPV dataset for the training and validation of the model. This includes front and rear irradiance, ambient temperature, module temperature, wind speed, DC

power, AC power, inverter efficiency, clipping events, grid operating variables and most importantly the albedo of the site. Hourly meteorological datasets from NASA POWER/ NSRDB or other validated solar-resources datasets is to be used to train the model. Primarily the experiment has to be focused on the rear irradiance as total bifacial excitation can obscure the very phenomenon that motivates the adaptive sizing.

ii) Bifacial PV system modeling

In a bifacial PV system, the mathematical model is represented with effective irradiance as a function of front and rear contributions.

$$G_{total} = G_{front} + b \cdot G_{rear} \quad \dots\dots (1)$$

Where G_{total} is the summation of G_{front} and G_{rear} i.e the front and rear surface incident irradiance respectively. The effective utilization of the bPV depends on the 'b' which is the bifaciality factor also known as the bifacial gain. The bifacial gain is largely dependent on the albedo of the site and other weather parameters of the site. The model is largely simulated using MATLAB Simulink or other standard software such as Pvsyst or Python library (Pvlib).

iii) Adaptive DC/ AC ratio modeling

Here in the case of a bPV systems, a condition dependent specific and effective DC/AC ratio has to be developed rather than the fixed ratios as in the case of the mono-facial systems. This can be developed by using the formulation as mentioned below;

$$R_{DC/AC} = f(G_f, G_r, T, \alpha, S, D) \quad \dots\dots (2)$$

Where, G_f and G_r stands for front and rear irradiance respectively, T for the module temperature, α is the albedo, S is the seasonal index, D is the degradation factor.

The output from equation (2) would be the dynamic DC/AC ratios, annual clipping losses and inverter utilization factor.

iv) AI based adaptive optimization

In order to design a bPV system, a multi-objective optimization problem should minimize clipping energy and lifecycle cost while maximizing the useful AC energy and inverter utilization subjected to thermal, voltage, current and grid code constraints. Classical optimizers such as PSO and GA, while Bayesian optimizers can be used when the design space is expensive to evaluate. Reinforcement learning has to be introduced as a sequential decision making tool. Several parameters can be included in the state such as G_{total} , G_f , G_r , T etc. The optimized variable can be then used to combine energy, clipping, thermal stress and economic objectives.

Conclusions

1. Existing bifacial PV and PV/inverter sizing literature provides strong foundations but largely treats the DC/AC ratio as a fixed design parameter. The interaction among rear irradiance, clipping, inverter loading and lifetime reliability remains insufficiently integrated.

2. A structured synthesis of the supplied DOI-based literature was combined with a proposed methodology comprising bifacial irradiance/electrical/thermal modelling, dynamic DC/AC ratio estimation, multi-objective optimization, AI-assisted adaptation, digital-twin implementation and field validation.
3. Thirteen knowledge gaps were identified, with the most consequential being static sizing, incomplete bifacial-gain/clipping coupling, limited multi-timescale adaptation, inadequate lifetime and grid constraints, and scarce long-term experimental validation.
4. The most promising pathway is to treat adaptive inverter sizing as management of an effective operating envelope rather than physical real-time replacement of inverter hardware. This enables a practical bridge between PV design, smart-inverter control and digitalized energy management.

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