Hybrid Electric Power System Generation: Current Perspectives and Future Trends

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***Abstract*—In this paper, a comprehensive review and qualitative analysis of studies and solutions for applications of stand-alone solar photovoltaic (PV) and wind farm systems, as well as hybrid power plants is presented, pointing out the current panorama and potential trends regarding the optimization processes typically used for sizing, allocating and dispatching from these systems. From the carried out studies, combined artificial intelligent-based techniques have appeared as a tendency to solve multi-objective optimization functions, which are often applied to individually optimize the combination of size, allocation and dispatch from hybrid plants. On the other hand, optimizing approaches capable of combining all these aspects are still scarce in the literature, even such procedures being able to assist industries in the network planning and operation tasks.**

***Index Terms*—Hybrid power plants, optimization techniques, PV systems, wind farms.**

I. Introduction

With the continuous growth in energy demand and the concern about environmental issues, the use of renewable energy sources (RESs) to produce electricity have been increased worldwide, reaching amounts of total installed capacity of about 2.8 TW in 2020, which represents an expansion of approximately 110% from 2011 to 2020, considering the different types of RESs [1]. In this scenario, the biggest increases were from wind and solar photovoltaic (PV) plants [1].

Similarly, in Brazil, for example, despite an increase in the installed capacity of hydro sources could naturally be considered as the immediate solution to be adopted to meet the load demand growth, significantly increases in the use of wind and PV technologies have been noticed, reaching growth levels of about 15.8 GW and 7.9 GW, respectively, from 2011 to 2020 [1]. In fact, although Brazil is a country of continental dimensions and typically has great hydrographic potential, the possibility of long periods of water scarcity, combined with possible environmental and social conflicts that may arise due to the construction of new hydropower facilities, have led to the search for a greater participation of other types of RESs [2], [3], [4]. In Figs. 1 and 2 it is shown the evolution of the power installed capacity of different types of RES in the world and in Brazil, respectively [1]. As presented in both figures, the expansion of wind and solar photovoltaic plants along the years is evident, which highlights that the technological advancements and more efficient power conversion systems have boosted the use of more cost-effective RESs [5].

With the integration of such low-inertia resources into the grid, challenges arise in maintaining the system stability and resilience, mainly due to their inherent intermittent characteristic [4], [5], [6]. In order to complement the alternative sources operation, an increasing use of energy storage systems (ESS) has been a trend in recent years [7], [8]. As a result, the combined use of wind, photovoltaic and storage plants in the same space, or close to each other, have been boosted, allowing the system expansion projects to be postponed and reducing some impacts caused by the availability and randomness of each RES. Thus, to allow a better performance of the joint operation of these hybrid resources, utilities have invested in projects to properly determine the sources sizing, to allocate them according to the natural resources available in the region, and to use the transmission transfer capability of the operating facilities [6], [7], [9].

To do so, the use of optimization routines is usually reported, whose applications depend on parameters such as: source types, load profile, technical-economic feasibility, ob-

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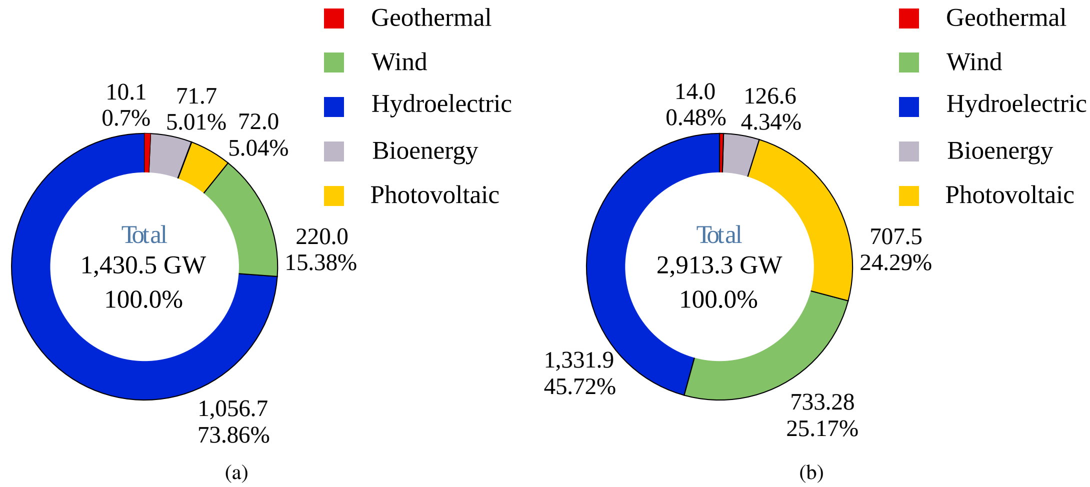

Fig. 1. Power installed capacity according to the type of source in the world, in GW: (a) scenario of 2011; (b) scenario of 2020.

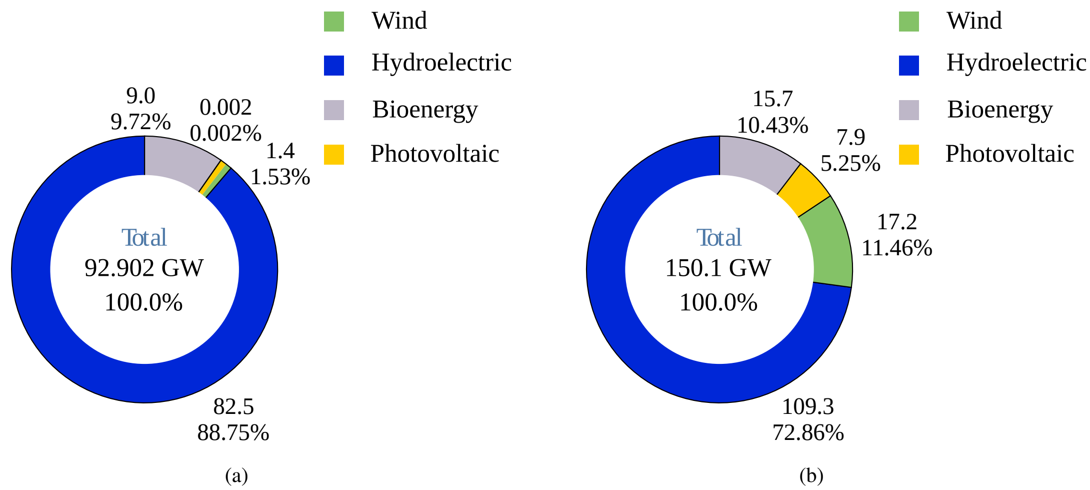

Fig. 2. Power installed capacity according to the type of source in the Brazilian system, in GW: (a) scenario of 2011; (b) scenario of 2020.

jective functions etc. Despite the use of the most varied optimization techniques to plan and operate the generation plants, most of the reported works are aimed at optimizing individual processes. As a consequence, solutions designed to the joint implementation of these optimal sizing, allocation and dispatch processes are configured as a search target by utilities to increase their competitiveness in the generation and transmission scenarios.

Therefore, in this work, a comprehensive review and qualitative analysis of studies and solutions for applications of hybrid power plants is presented, highlighting the current panorama and trends regarding the impacts and benefits of the joint integration of RES and the optimization techniques typically employed for sizing, allocating and dispatching from these systems. These studies are part of a R&D project carried out with the São Francisco Hydroelectric Company (Chesf) and partner institutions to develop a methodology that optimally estimates the allocation and energy dispatch of a hybrid system. As a result, this work may gather scientific information that will help in the development of such solution and other ones of interest to the electric sector, highlighting the algorithms typically used along the years for optimization processes and identifying the trends applied for hybrid power plants.

II. Applications of Optimization Techniques with RESs and Hybrid Plants

Irrespective to the used RES type and hybrid power plant, the essential idea behind the application of optimization techniques is providing a more efficient procedure to generate electricity [10]. To do so, researchers and engineers build the optimization problem as a function of different characteristics, which may depend on the availability of natural resources, transmission power loss, operating and maintenance costs, or even on social aspects, i.e., the optimization goals typically depend on technical parameters, environmental issues, economic factors or social indicators, in which they may be individually formulated or combined to each other [6], [10], [11]. A general flowchart about the building process of an optimization procedure is shown in Fig. 3.

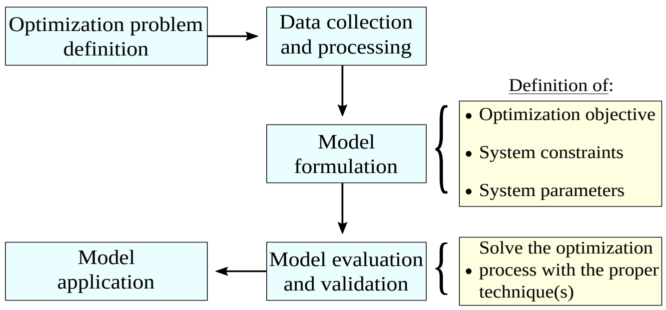

Fig. 3. Basic flowchart about an optimization technique modeling.

In the following subsections, details about the optimization processes typically used in applications with RESs and hybrid power plants are presented, outlining the perspectives along the years and pointing out potential future trends. It is worth mentioning that, although a lot of papers have been analyzed, it will be shown in the next subsections a summary of the works that properly represent the conclusions obtained from the carried out studies, which have allowed to identify the current panorama and trends about RESs and hybrid plants.

A. *Solar photovoltaic systems*

As depicted in Figs. 1 and 2, the use of solar photovoltaic plants has increased in recent years. The benefits of such growth is even more evident due to the application of optimization procedures to properly sizing and allocating this type of RES, as well as minimizing the effects of weather parameters on the PV system performance [6], [10].

The PV output power is highly dependent on weather parameters, such as solar irradiation and temperature. As a consequence, the unpredictability and intermittent weather characteristics may affect the proper sizing and operation of solar photovoltaic systems. In this way, the use of optimization techniques has been extensively applied in the literature and in practical applications to improve the PV system performance, reliability and allocation [12].

It is shown in Table I a summary of some optimization techniques typically applied in solar photovoltaic systems, pointing out the optimization goals, constraints, input parameters, used method(s) and the main contributions of each presented work.

Basically, from Table I, the general optimization goals were related to optimize the load matching process or the PV modeling. However, several techniques have been proposed in such field over the years and suitable PV system representations were reached to be used in steady-state studies. Thus, the PV system analysis moved toward the optimization of its size and allocation. As a result, non-technical optimization constraints, such environmental and economic indicators, started to be often used in the optimization process.

On the other hand, different approaches have been proposed to take into account climate variability constraintsand optimally size and place stand-alone PV systems. In this scenario, by considering that the optimal size and placement tasks of solar photovoltaic generators are properly carried out, the recent works are focused on enhancing the PV output power by means of extracting the optimal maximum power point (MPP). Therefore, it can be mentioned that the historical optimization procedures of PV system have passed through to suitably feed the load, moving to sizing and allocation tasks, and currently to extract the best generator performance for a minimum cost.

B. *Wind farms*

Similar to PV systems, the wind farms installed capacity has considerably increased worldwide. Particularly in Brazil, such growth reached approximately 16 GW in less than a decade, as shown in Fig. 2. In fact, wind energy has been considered as one of the most profitable RES to meet the load demand growth for the coming years [21].

The wind power efficiency in generating electricity is also dependent on some environmental parameters, such as wind speed and direction, as well as on geographical data (land availability to its construction etc.) and wind turbines technical characteristics [21]. Nevertheless, optimization routines are typically employed to minimize such effects, as shown in the summarized works presented in Table II.

From the works presented in Table II, there are a variety of algorithms to optimize the wind farms sizing and placement, which are typically advancements from previous works whose optimization goals were related to predict the wind power output to meet the load demand. In general, the optimization constraints are varied, which can be individually categorized as technical, environmental or geographical data, or a combination between them.

Different from PV systems situation, the optimal stand-alone wind farms sizing and allocation still has attracted attention from researchers and engineers, mainly due to challenges that may arise on both on- and off-shore operation.

C. *Hybrid plants*

Although the stand-alone application of different types of RESs have increased around the world, their intermittent behavior due to the unforeseeable variation on climate conditions may avoid the system to efficiently operate, which can even lead to PV and wind farms over-sizing choices and increase the investment and operating costs [12]. In this scenario, the hybrid power plants have gained space in practical applications as a cost-effective solution to minimize technical losses and capital costs [6], [12], especially with the integration of ESS [7], [9], [30]. Indeed, storage systems integrated with RESs play an important role for maintaining the system stability and regulating frequency, which improves the network operation efficiency [8].

To run the optimization process for hybrid power plants applications, it is usual to consider data from the different types of RESs and/or ESS, or the complementary weather conditions (for cases of PV + wind farms), as input parameters to the model formulation, in order to take into account the distinct characteristics required to each source to operate. It is shown in Table III a summary of the evaluated works

TABLE I
PANORAMA OF THE OPTIMIZATION PROCESSES USED IN SOLAR PHOTOVOLTAIC SYSTEMS

Ref.	Year	Optimization objective	Constraints	Input parameters	Method(s)	Contributions
[13]	1988	Optimally match PV generation and load	Daily generation	Load data	Nonlinear optimization routines	Optimization of PV output
[14]	2007	Optimal PV modeling	Weather conditions	Meteorological data	Artificial neural network (ANN)	ANN-model predicts PV performance
[15]	2013	Optimal PV sizing	Loss of power probability	Meteorological and load data	Analytical method	Optimize the PV-inverter size ratio
[16]	2016	Optimize the extraction of PV peak power	Partial shaded conditions (PSC)	Maximum power point	Particle swarm optimization (PSO)	PSO was effective in dealing with PSC
[17]	2018	Optimal PV sizing	Economical indicators	PV module database	Dolphin echoloca-tion algorithm (DEA)	DEA can maximize the net present value
[18]	2019	Minimize real power losses	System stability	PV real power	MultiVerse optimization algorithm	Avoid the system congestion
[19]	2020	Optimal voltage level	Irradiation and temperature level	Maximum power point	Fuzzy logic	Increase the PV-output power
[20]	2022	Extract the global maximum point	PSC	PV system volt-tage and current	Adaptive neuro-fuzzy inference	Distinguish between global and local MPP

TABLE II
PANORAMA OF THE OPTIMIZATION PROCESSES USED IN WIND FARMS

Ref.	Year	Optimization objective	Constraints	Input parameters	Method(s)	Contributions
[22]	1996	Prediction of wind farm power output	Model architec-ture parameters	Wind turbine and meteorological data	Neural network model	Develop of a short-term forecasting model
[23]	2011	Solve the economic load dispatch problem	Physical and operational constraints	Wind data	Craziness-based shuffled frog leaping optimization	Minimize the overall costs
[24]	2013	Optimal wind farm allocation	Transmission security and power system stability	Wind, load and grid data	Linear optimization	Reduce investments and improve system stability
[25]	2017	Optimal wind farm allocation	Geographic and turbine characteristics	Study area and wind data	Multi-Criterial Deci-sion Making method	Optimal screening in wind farm siting
[26]	2017	Multiple-Objective opti-mization for wind siting	Limits of generation and transmission elements	Load and wind data	Pareto optimal method	Maximization of wind farm energy injection
[27]	2019	Optimal wind farms sizing and allocation	Limits of transmission lines and power balance	Load, generation and grid data	Binary PSO and selective method	Minimize the system operation cost
[28]	2021	Optimal wind farms sizing and allocation	Wind uncertainty and wake effect	Wind data	Clustering-based Monte Carlo simulation	Reduction of network loss
[29]	2022	Optimal wind farms allocation	Wind data and geographical location	Wind and grid data	Combination of artificial intelligent algorithms	Reduction of costs and energy-related losses

to identify the current panorama and future trends of such application field.

As presented in Table III, the optimal design of hybrid power plants (PV + wind farms) was a cause for concern since the last decades, even being a time period in which the applications were more concentrated in stand-alone RESs installations. However, with the possibility of integrated operation of RESs and ESS spreading around the world, the researches have focused on how to optimally size and allocate hybrid plants, since the complementary aspects of the distinct RESs bring additional challenges to the optimization process. As a consequence, the optimal sizing and placement of hybrid plants is still an open field, and new solutions are sought by researchers and industries. Despite that, the benefits of the existing processes indicate that the integration of distinct sources have brought more benefits than stand-alone applications.

TABLE III
PANORAMA OF THE OPTIMIZATION PROCESSES USED IN HYBRID POWER PLANTS

Ref.	Year	Optimization objective	Constraints	Input parameters	Method(s)	Contributions
[31]	1997	Optimal design of a hybrid plant	Environmental factors	Load, solar and wind data	Linear programming techniques	Reduction on the average production cost
[32]	2015	Optimal sizing of a hybrid plant	Life cycle cost	Geographical data	Combination of PSO techniques	Optimally design a hybrid plant for a remote area
[33]	2016	Optimal sizing of a remote hybrid plant	Seasonal variation of load	Study area and weather data	Cuckoo search and Monte Carlo methods	Most reliable and economic hybrid system
[34]	2018	Design and sizing concentrated solar and PV systems	Limits of PV technical characteristics	PV and storage characteristics	Multi-objective genetic algorithm and Pareto method	Lower levelized cost of energy than in stand-alone plants
[35]	2018	Optimal sizing of an off-grid hybrid plant	Loss of power supply probability	Weather data and load demand	Hybrid genetic algorithm with PSO	Reduced levelized cost of energy
[9]	2021	Optimal sizing and location of a hybrid plant	Power loss-sensitivity factor	Wind speed and solar radiation	Rider optimization algorithm	Reduced total power and energy losses
[36]	2022	Optimal planning of a hybrid system	Operational and economic factors	Wind and solar data	Artificial hummingbird algorithm	Maximization of voltage stability margin and energy savings
[30]	2022	Optimal sizing of RES and storage systems	Economic factors	Weather data and load demand	Multi-objective distributionally robust shortfall risk optimization	Reduce the load shedding risk and investment costs

D. Analysis and Discussions

From the carried out studies, it is noticed that the application of optimization techniques have been typically done for minimizing individual technical aspects, such power loss, or economic ones, as production costs. In this way, single objective functions have been formulated to run one specific algorithm, as linear programming, nature-based routines etc. However, as the need for RESs increased along the years, the grid planning and operation have become more complex, in such a way that using a single function to represent a combination of technical and economic, or even environmental and social, objectives was quite difficult. Thus, multi-objective functions have been addressed to better represent real-world cases, which may combine different characteristics of the desired study.

In this context, the number of constraints also increased in the optimization process along the years, especially when multi-objective functions were taken into account. In these cases, it was usual to consider utility capacity and RESs limitations, as well as some economic indicators to the optimization function.

Regarding the optimization techniques, the first works usually applied classic approaches to solve the desired goals, such as linear and nonlinear programming. Such procedure had yielded reasonable results for the considered applications. However, the slow convergence rate and the time-consuming approach for solving only single objective functions with few constraints have led such technique to lose space. In this scenario, artificial intelligent-based routines have been employed to solve the optimization problems, but some issues may have arisen regarding difficulties in mapping the global optimum point or the need of many setting parameters, for example. Then, to overcome such concerns, the combination of distinct artificial intelligent-based routines, or classic and artificial intelligent-based algorithms, have been used to provide a faster and more efficient solution, in such a way that these hybrid methods may appear as a potential trend to optimize the objective functions.

Finally, it is noticed that for stand-alone PV systems, the future trends aim to optimize procedures to maximize their power output, whereas in wind farms scenarios the most recent works are still reporting solutions to optimally size and allocate them in both on- and off-shore grids. On the other hand, hybrid power plants appear as a tool to enhance the power system resilience and stability, whose facilities are expected to increase over the years. However, even in hybrid power plants applications, the optimization processes are regarded to size and allocate them, or to provide their load scheduling, being the reported solutions designed to perform these tasks individually. Therefore, there is still a scarce number of works that provide methodologies to optimize the size, allocation and dispatch of hybrid power plants in a practical-scientific way, whose procedures could assist industries in the network planning and operation.

III. CONCLUSIONS

In this paper, a comprehensive review about applications of hybrid power plants and stand-alone PV and wind farm systems is presented, pointing out the current panorama and potential trends regarding the application of optimization techniques for sizing, allocating and dispatching from these systems.

The application of hybrid methods (combination of different artificial intelligent-based approaches or classic and artificial intelligent-based algorithms) has appeared to provide the best solutions for the optimization objectives in the most recent works. In the same way, the use of hybrid power plants has brought several benefits to the system resilience and stability, but the optimal sizing and allocation of such systems is still a search target by researchers and industries.

From the carried out studies, solutions that provide combined optimal processes for sizing, allocating and dispatching from hybrid plants are scarce, whose tasks would certainly benefit facilities during the planning and operation activities.

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