HYBRID CSP-PV ADVANCED CONTROL, INTEGRATION AND REAL-TIME OPTIMIZATION: REVIEW AND FUTURE LINE OF RESEARCH

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Abstract

According to some recent studies, the development and improvement in Concentrated Solar Power (CSP) – Photovoltaic (PV) hybrid technology is considered to be an important future research trend in solar energy field. Its development was accelerated in recent years with the fast technological maturation in both CSP and PV systems. Recent works inquiries on optimal sizing, long term performance evaluation and technical-economic analysis of hybrid CSP-PV plants. Otherwise, it is well know that a proper operation of such large scale complex system relies on a development and implementation of accurate advanced control and real-time optimization methods. This paper surveys recent works related to Hybrid CSP-PV power plants. Later, some important issues related to advanced control, integration and real-time optimization are discussed, open problems are pointed and a roadmap for future research topics is provided.

Keywords: Hybrid CSP-PV, Advanced Control, Real-time Optimization, Game Theory, Deep Learning

1. Introduction

In the last decade, renewable energy sources have experienced significant growth on its rate of deployment and investments on the development of new efficient generation units, establishing itself as a sustainable alternative for conventional power sources. In this scenario, the Sun is the most abundant sustainable source of energy. The irradiance in the Sun is about 63 MWm−2 and on the Earth's surface, it is around 1 kWm^{-2}, providing considerable power when collected by means of different technologies. (Fernández-García et.al. 2010).

Photovoltaic (PV) and Concentrated Solar Power (CSP) plants are being used for generating electricity from the sun's energy (Cocco, 2015). Some factors such as efficiency, reliability, cost, power quality, and grid integration decide the future trends of these plants. A solar power plant needs to deal with problems of cloud cover, humidity, and air transparency. Moreover, the main source of energy cannot be manipulated as in other power generating processes. In this scenario, scientific research has been developed for improving the efficiency of solar power plants from the control and optimization viewpoints (Sigarchian et. al. 2016).

CSP plants are used to produce alternating current (AC) energy, which is of high power quality and matches the frequency and phase of the existing power grid. In addition, the integration with Thermal Energy Storage (TES) systems allows the successful production of stable and dispatchable energy from intermittent solar energy. Moreover, the CSP-TES plants provide more flexibility and reliability for power scheduling and it can play an important role in future energy systems, with high penetration of renewable energy resources (Mehos et. al. 2016).

Concentrated Solar Power systems are represented as a complex grid, where each element has stationary and transient losses with changing dynamics, nonlinearities, and uncertainties. The use of control can improve the efficiency and increase the operational hours, reducing the cost per kilowatt-hour produced. There are numerous examples in the literature, about advanced control techniques in solar fields using Model Predictive Control (MPC), adaptive control, gain scheduling, time-delay compensation, optimal control, robust control, fuzzy logic control, and neural network controllers (Camacho et. al. 2007b).

PV units have a low cost which allowed this technology to be converted into a relevant player in renewable electricity markets. Nonetheless, it presents dispatchability and stochasticity problems in a short period of time.

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These issues can be overcome by the using of suitable energy storage systems. If compared to PV plants, CSP plants have better conversion efficiency and the possibility of efficient storage of thermal energy to be subsequently converted into electricity (Andrade et. al. 2013). A promising solution to mitigate the effects of variability and intermittency of renewable sources is the use of hybrid storage systems. In the case of solar energy coupled thermal-electrochemical technologies rise as potential candidates (Xing et. al. 2017).

Research efforts have been devoted to techniques that may help to collect, convert, store and utilize solar energy (Camacho et. al. 2012, Jebasingh 2016, Camacho et. al. 2007a). In order to answer the following question: "How to manage solar thermal plants to maximize energy production, minimizing losses, production cost and equipment wear?", some solutions based on hybrid model predictive control (HMPC) was proposed for the case of control of solar large scale fields subject to the action of clouds in parts of the field (Elias et. al. 2019a) and seeking to use the control of solar collector defocusing as a second degree of freedom (Elias et. al. 2018, Elias et. al. 2019b). Regarding solar collector defocusing application, recent advanced control techniques based in state-space MPC and event-based MPC was proposed in Sánchez et. al. (2019b) and Sánchez et. al. (2018), respectively.

Recently, the combination of the CSP and PV systems has been studied in order to offer fully dispatchable power at lower energy production costs reaping advantages of both technologies (Xing et. al. 2017). As noticed in Platzer (2016), in the year of 2016 three projects of this kind were announce for Chile combining in one case a 130 MW CSP project with a 150 MW PV project by Solar Reserve, and in the other, two cases 110 MW CSP plus 100 MW PV by Abengoa. As mentioned in Starke et. al. (2018a), the hybridization of CSP and PV plants is a potential solution to reduce the operational and installation costs and increase significantly the capacity factor. Indeed, a proper integration between photovoltaic systems, characterized by relatively low cost, and CSP systems, typified by a certain dispatch capability during low insolation periods, could achieve several benefits for the new hybrid energy system. The purpose of the hybrid CSP-PV systems is to provide a cost-effective and reliable energy conversion system. According to Xing et. al. (2016), the CSP-PV hybrid system has several advantages over the PV or CSP standalone system: better power quality, higher electrical efficiency, and lower cost. In a CSP-PV hybrid system, PV and CSP subsystems can be independently planned and constructed, and the hybrid system is integrated together by the electric power dispatching and management system. A detailed technical-economic analysis of the jointly CSP-PV system can be found in Zhai et. al. (2017).

In CSP units, predictive control strategies use the future prediction of solar irradiation and the effect of its future variance in the field output temperature and/or energy to decide the best control action to take at the present time to optimize an objective function. Thus, the better the accuracy of the prediction, the more assertive the decision making will be, which positively impacts the energy utilization and stability of solar field operation. With respect to photovoltaic units, solar forecasting can assist in the energy management of storage and demand response plans (in the case of small and medium-sized micro-grid connected units) and in intra-day market trading (in the case of large generating units). As exposed in IEA (2013), there exist two main techniques in evidence in the last years: the all-sky camera methods that are suitable to short-term forecasting (Ravinesh 2017) and the satellite-based methods generally used for short-term forecasting (Ravinesh 2017), but recently applied for long-term forecasting (Ravinesh 2017).

Advanced control and real-time optimization of this complex integrated power plant are essential in order to guarantee a stable and dispatchable operation to produce high-quality electricity with scheduled profiles and to reduce energy losses. Additionally, improvements in the solar radiation forecast systems are desirable in order to provide an accurate prediction, which is indispensable for an adequate intra-day and daily energy management/trading planning. In this work, a recent literature survey is first performed in order to point out the last developments and studied topics in the scientific community with respect to CSP-PV Plants. In sequence, some uttermost relevant future research "hot" topics in the field of advanced control and real-time optimization of CSP-PV systems are discussed.

2. Recent Literature Review

Recently, the scientific community has presented several studies on hybrid CSP-PV plants. Topics such as optimal design, techno-economic analysis, and energy dispatch have been shown to be the main topics of interest. Some industrial applications of such new technology are addressed in Cocco (2016), Starke et. al. (2016) and Pan (2017).

In Starke et. al. (2016) a power generation and economic analysis of two hybrid CSP- PV plant models were carried out considering parabolic trough or central receiver plants, combined with a PV system and the Atacama Desert (located in Chile) environmental conditions were considered. Parametric analysis and optimization was performed to determine the storage and power block sizes for the CSP plants taking into account the Levelized cost of energy (LCOE), considering a constraint on the capacity factor for supplying baseload energy to the electricity grid and assuming the PV plant with varying nominal capacity. According to the authors, the combination of both types of CSP with PV plants had shown a high potential to be implemented in the Atacama Desert due to the high levels of irradiation available in northern Chile. It was concluded that the main advantage of the hybridization of a CSP plant with a PV array is reducing the size of the CSP solar field while maintaining a high capacity factor and lowering the LCOE.

Starke et. al. (2018a) and Starke et. al. (2018b) presented a methodology for design and sizing the same CSP-PV plant located in Atacama Desert, based on the implementation of a transient simulation model coupled to an evolutionary optimization algorithm, addressing the tradeoff between costs and capacity factor which leads to a multi-objective optimization problem. As in previous work, the proposed procedure was applied to analyze two types of CSP systems: parabolic trough collectors (PTC) and a central receiver system (CRS), coupled to a PV array. Three objective functions were considered in the multi-objective optimization procedure: the Levelized Cost of Energy (LCOE), total investment and capacity factor, which yield a Pareto frontier. The decision variables of this problem were the size of the solar field, thermal storage capacity, PV tilt angle and PV power ratio. As reported by the authors, the obtained capacity factor was higher than 85%, and the LCOE is lower than the ones observed for single CSP plants.

A concept of a central receiver concentrating solar power plant operating jointly with a PV unit located in South was approached in Pan (2017). Various simulation studies under different weather conditions were carried out for single PV and CSP plants and comparison with hybrid CSP-PV was performed. For this specific case, the LCOE varied in the range of 0.133–0.157 $/kWh for base load-capable configurations. The enthusiastic result is due by the high solar irradiation levels found in South Africa and presents the hybrid CSP-PV plants as a sustainable solution capable to replace the old coal-fired power plants reducing emissions and increasing the share of renewable sources.

Sigarchian et. al. (2016) proposed a Particle Swarm Optimization (PSO) algorithm as a global optimizer applied to a hybrid PV-CSP-LPG Microgrid optimal design and sizing problem. A comparison with data from an exhaustive search, presented in previous work, was performed in order to test and validate the proposed technique. The proposed PSO method rises as an efficient technique determining a high-quality design solution with a lower computational cost.

The potential improvements of power dispatchability achieved integrating of Concentrating Solar Power and Concentrating Photovoltaic (CPV) plants in order to mitigate the effects of solar radiance variability and intermittency was investigated in Cocco (2016). The studied CSP–CPV plant is the Ottana Solar Facility, located in the industrial district of Ottana (Sardinia, Italy). The facility consists of a CSP plant based on linear Fresnel collectors using thermal oil as heat transfer fluid, a two-tank thermal energy storage system (capacity of about 15 MWh), a 600 kWe ORC power plant, a 400 kWe CPV power plant, and an electrochemical storage system with a capacity of 430 kWh. For this application, the authors assumed a constant daily power demand (which is not true in most of real-world cases) and compared the usage of two different energy management strategies, fully and partially integrated. It was shown that the fully integrated strategy obtained better performance in terms of annual energy production and maximized the operation time.

Cau et. al. (2015) proposed an algorithm for the optimal management of a hybrid CSP-PV plant with thermal and electrochemical storage systems using weather forecast data to schedule the optimum generation profile by maximizing the power production of the integrated plant, while different constraints due to equipment limits are satisfied. It was presented a comparative analysis between deterministic and stochastic (to take into account the uncertainties in weather forecast) strategies. As demonstrated, the use of a stochastic approach allowed generating more robust solutions those results in an improvement of about 3-5% in the yearly power production.

The optimal design of a hybrid CSP-PV plant was investigated in Petrollese (2016a) in order to evaluate the optimal design parameters that minimize the energy production cost of the hybrid plant while the plant is constrained to follow a power output curve characterized by a constant power level. For the same plant, a techno-economic analysis was carried out in Petrollese (2016b) to evaluate the dispatch capabilities of hybrid CSP-PV. Authors have shown an enhancement in the ability of the hybrid CSP-CPV power plant to provide fixed power curves with respect to PV power plants, moreover, the presence of two energy storage sections improves the ability of the hybrid plant to produce power with programmable profiles.

With respect to the CSP role in the energy market, some recent works can be highlighted. A methodology to build offering curves for a concentrating solar power plant as a price-taker producer that participates in a pool-based electricity market with the aim of maximizing its expected profit was presented in Dominguez et. al. (2012). In Usaola (2012) an optimization method that aims to maximize CSP plant revenues by taking into account daily electricity prices was proposed. A general model framework on the optimal offering strategy for CSP plants in joint day-ahead energy, reserve and regulation markets, which is robust for solar energy uncertainty and stochastic for market price uncertainty was discussed in He et.al. (2012). Shafiee et. al. (2017) proposed an information gap decision theory (IGDT)-based risk-constrained bidding/offering strategy for merchant compressed air energy storage (CAES) plant that participates in the day-ahead energy markets considering price forecasting errors. In Yuan et. al. (2017), risk-constrained day-ahead (DA) scheduling strategies for a virtual power plant (VPP) integrating a CSP with some responsive residential and industrial loads was proposed considering the uncertainties from electricity price, thermal production of the solar field of the CSP, and participation factor of residential demand response (RDR). Zhao et. al. (2019) introduced a stochastic mixed-integer linear programming model, where the objective function is the maximization of the expected profit that can be obtained by selling the energy generated by the CSP plant in the day-ahead electricity market.

All of the previously cited works consider the CSP unit as a price taker. With respect to the CSP playing price maker role, the bi-level optimization based on a non-cooperative game method proposed in Nieta et. al. (2018) can be highlighted. The competitive behavior among power plants was formulated as a non-cooperative game and the profit of power plant was scheduled by adjusting generation and bidding strategies in both day-ahead markets and intraday markets. Another recent work depicted a stochastic formulation of a storage owner's arbitrage profit maximization problem under uncertainty in day-ahead (DA) and real-time (RT) market prices Krishnamurthy et. al. (2018). The proposed model helps storage owners in market bidding and operational decisions and in the estimation of the economic viability of energy storage.

From up to the author's knowledge, none of the previous cited works addressed the problem of integration CSP and PV plants focused on the spot market. So there exist a gap in this scientific field with many open issues to be investigated.

With respect to image-based forecasting methods, Cheng et. al. (2014) proposed a short-term solar irradiation prediction scheme via support vector repressors. Using clarity index conversion and appropriate features, support vector regression models are capable of generating satisfactory prediction results. In Montesinos et. al. (2015), a method for predicting Direct Normal Irradiance (DNI), Diffuse Horizontal Irradiance (DHI), and Global Horizontal Irradiance (GHI) irradiations was proposed. In this method, the digital image captured from the sky is converted into an irradiance grid and then the maximum cross-correlation method is applied to obtain future predictions. Cervantes et. al. (2016), presented an intra-hour cloud prediction methodology for distributed solar generation, predicting irradiance changes at five-minute intervals throughout the day. In Caldas (2019), a hybrid prediction methodology was proposed to predict average solar irradiation from one minute to ten minutes in advance. The methodology combined the use of all-sky images and irradiance measurements that are processed in real-time to produce the forecast.

Recently, in Siddiqui et. al. (2019), a new application of the deep neural network approach to observe and estimate short-term irradiation from sky videos was presented. Specifically, videos obtained from sky-cameras were used to directly estimate and predict solar irradiance. Compared to satellite-based approaches, the proposed deep learning approach significantly reduced the normalized mean absolute percentage error for forecasting solar irradiance for a future horizon of up to 4 hours. In Kamadinata et. al. (2019), two methodologies based on artificial neural networks were used to predict global horizontal irradiance with a horizon of 1 to 5 minutes in advance from sky images. These methodologies do not require cloud detection techniques, were able to capture solar irradiance trends with small discrepancies and require much fewer image data compared to existing techniques.

Regarding satellite forecasting techniques, Perez et. al. (2014) presented and evaluated a new operational solar radiation forecast model to be deployed on a prototype basis as part of the SolarAnywhere (SA) data service. The proposed forecast model consisted of an optimum mix of satellite-derived cloud motion forecasts, the National Digital Forecast Database's (NDFD) cloud cover-derived irradiance forecasts, and several operational numerical weather prediction (NWP) models. The authors reported forecast time horizon ranges from one hour to five days ahead, with spatial and temporal resolution data of 10 km and 1 h, respectively.. Miller et. al. (2018) described the use of geostationary satellite observations jointly with operational cloud masking and retrieval algorithms, wind field data from Numerical Weather Prediction (NWP), and radioactive transfer calculations to produce short-term forecasts of solar insolation for applications in solar power generation. Watanabe (2019) depicted a method for predicting time series of the surface solar irradiance (SSI) from one-granule cloud properties data obtained by satellite observation. The proposed method is divided into two parts: the prediction of time series features from cloud properties and the prediction of a time series from time-series features.

Srivastava (2018) applied Long Short Term Memory (LSTM) neural networks in forecasting day-ahead global horizontal irradiance with satellite data and compares its forecasting accuracy to alternative methods with a proven track record in solar energy forecasting. The results suggested that LSTM outperforms a large number of alternative methods with substantial margin and average forecast skill of 52.2% over the persistence model. Cornejo-Buenoa et. al. (2019) evaluated the performance of several Machine Learning regression techniques in a problem of global solar radiation estimation from geostationary satellite data. The work analyzed different types of neural networks, support vector regression and Gaussian processes. Wang et. al. (2019) proposed a convolutional neural network, long short-term memory network, and hybrid model based on convolutional neural network and long short-term memory network models for the solar radiation forecast problem applied to the data from DKASC, Alice Springs photovoltaic system. The authors depicted that when the input sequence is increased, the prediction effect of the hybrid model is the best, followed by that of the convolutional neural network and LSTM model.

As noted in the previous paragraphs, the topic of short/long-term solar radiation prediction is an open research topic in the academic world with great importance for practical application to improve solar power plant performance. Of the most promising existing technologies is the prediction through sky imagery. As deep learning techniques are the most indicated and currently used for image processing, there is great potential to use deep neural networks for solar irradiance prediction through images. Of all the studies cited above only the recent works Siddiqui et. al. (2019), Kamadinata et. al. (2019), Srivastava (2018), Cornejo-Buenoa et. al. (2019) and Wang et. al. (2019) used deep learning techniques, which makes this field few explored and with great potential for future research and development.

3. Open Fields and Future Research

The effect of passing clouds, load variability, voltage unbalancing, frequency stability, short, medium and long term dispatch, CSP operating modes, coordination among hybrid storage systems (electrochemical and thermal), stochasticity of irradiation predictions, and integrated energy management in a hierarchical framework are of great importance to provide an optimized real-time operation and improve reliability of CSP-PV systems. From up the author's knowledge, there is no published work addressing advanced control, integration and real-time optimization of Hybrid CSP-PV plants taking into account the related topics.

The frequency stability and power factor characteristics of the CSP can be used as a reference for the PV subsystem, while its DC/AC converters can be used to correct the voltage unbalance among the phases in the AC bus, usually caused by different load values in each phase of the system. A voltage unbalance correction algorithm can be used in conjunction with the short-term Energy Management System (EMS) to improve the quality of energy delivered by the hybrid plant. This way the CSP-PV system can provide ancillary services to the grid.

With respect to energy management systems, Model Predictive Control (MPC) appears as a powerful technique that can deal with system constraints, nonlinear dynamics, CSP operating modes and stochasticity of predicted data. Hybrid and Stochastic MPC approaches can treat properly the issues from different time scales, providing an optimized and reliable operation of the CSP-PV system. MPC based EMS can be applied both in secondary local and tertiary levels for short and long-term management taking advantage of problem distributed hierarchical natural structure. Although there exist many publications in this area, jointly hybrid stochastic distributed and hierarchical formulations lack theoretical stability and convergence guarantees, which configures itself as an important challenge and open research topic with real-world application.

Once the system dispatchability and reliability are achieved, the most important research focus is to study the capability of high power Hybrid CSP-PV plants in negotiating the energy price in future renewable energy markets (day-ahead and intraday), becoming a price maker actor (not only price taker). At this point two main questions arise: "How to integrate several CSP and PV units in order to improve the resilience, dispatchability and energy quality of the units array?" and "How to improve CSP trading's in SPOT Energy Market?".

To answer the first question, the use of Game Theory techniques applied to advanced control of networked systems can be investigated. In this case, a scenario with several geographically spaced CSP and PV units operating in an integrated manner can be explored. It is essential for the generation units to be capable of meeting the expected energy values determined by previous market transactions. Individual features of each unit such as response time, storage capacity, available instantaneous power, cloud covering, voltage unbalance correction capability and reactive generation shall be taken into account by the integrated operation management system. One potential way is to explore cooperative games to show that users can always benefit from cooperating with one another. This is the main idea behind coalitional control (Fele et.al. 2018), a novel theory inspired by cooperative games, where the control strategy adapts to the varying coupling conditions among the agents (CSP and PV units), promoting the formation of coalitions, clusters of controllers that cooperate to benefit from a jointly optimized control action.

Regarding the second question, a good possibility is to investigate the use of Game Theory techniques applied to peer-to-peer (P2P) energy trading. One potential way is to investigate the use of Stackelberg games to manage to trade among the Distribution Network Operator (DNO), consumers and several CSP and/or CSP-PV units (leader-follower game) (Pilz 2017). The problem can be considered as a constrained dynamic pricing Stackelberg game taking into account finite energy resources as constraints. Thus, game-theoretical approaches can be investigated to determine an agreement of dynamic energy prices among the players. On the one hand, we have the generating units seeking to maximize the profit and the time of supplying energy. And, on the other hand, we have the consumers making demand bids aiming at reducing the energy cost. As an intermediary, we have the DNO managing the transaction rules and seeking to guarantee a feasible and advantageous operation for the large scale networked system.

Another important issue is the coordination of the hybrid electrochemical and thermal storage units in order to avoid the short term fluctuations of solar irradiation and demand, and provide a long-term dispatchability of the hybrid CSP-PV plant. As depicted previously deep learning techniques can play an important role in order to forecast solar irradiation. One promising strategy for solar irradiation nowcasting, convolutional neural networks can be used to generate direct and global irradiation maps from images obtained with all-sky cameras and satellites. The goal is to create a new method for generating these maps based on deep networks and validated based on recognized methods. Once in possession of the irradiation maps generated by the convolutional network, the next step is the training and validation of recurrent neural networks for direct and global irradiation prediction. These networks can use the maps generated in the last Np time steps to predict Nf time steps ahead, with Np and Nf parameters to be determined during the project. Another important research line is to design hybrid convolutional recurrent deep neural networks to perform the nowcast and forecast with one jointly structure. The challenge here is to propose new deep learning topologies to improve the accuracy of image-based solar radiation forecast systems.

4. Conclusions

The main goal of this work is to survey the recent existing literature, discuss the open issues and point out the open research trends in the field of advanced control and real-time optimization of CSP-PV units. Most of the existing works focused on designing and sizing of such hybrid units and few authors explored the integrated operation from the control point of view. In advanced control systems based in MPC, solar radiation forecasts can be useful for better decisions using feedforward action, and to achieve this purpose different research lines are being carried out highlighting deep learning techniques. The insertion of CSP-PV units in spot markets is still an unexplored field with potential game-theoretic solutions to be proposed. Finally, it can be concluded that the integration of CSP and PV power plants trough advanced control and real-time optimization is a complex research topic with several open points, involving hybrid, stochastic, distributed, hierarchical MPC approaches, game theory techniques and deep learning algorithms.

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