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Editorial

Solar PV and Wind Power as the Core of the Energy Transition: Joint Integration and Hybridization with Energy Storage Systems

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The availability and accessibility of renewable energy in locations worldwide make it play a leading role in the decarbonization process of the energy sector. Moreover, this 'wide availability' makes renewables the most suitable type of energy source to stop depending to a large extent on fossil fuel exporting countries; countries that often have a high degree of social and political instability. Thus, power systems are transitioning towards a renewable-based model that allows the use of fossil fuels to be abandoned. However, this implies a number of technical and operational challenges that need to be addressed by society in general and energy companies and governments, in particular, to efficiently and safely integrate this growing renewable energy generation capacity into power systems. The most remarkable challenges to be met are those related to the intermittency of these clean sources and the maintenance of the system's reliability and stability. Electricity is not always generated during the periods of time when it is most needed, and its production results in power systems that are less predictable, more difficult to control and less synchronous. These challenges give rise to the proposal of a number of solutions, such as energy storage, the development of new energy carriers such as green hydrogen and the establishment of virtual power plants.

Energy storage is crucial in balancing network generation and demand and providing support to the network—it is even being designed to conduct power-frequency regulation tasks in the power system, so large-scale energy storage systems based on cutting-edge technologies will have to be deployed [1]. Countries are also focusing on the production of green hydrogen because it can be stored and later used as a fuel or even also help to balance energy production and consumption curves [2]. Finally, given the advantages of distributed generation and the commitment that countries are making to evolve towards a power system based on this production model [3], virtual power plants are also emerging as key entities in the integration of renewables into the power system [4]. Virtual power plants are virtual units that aggregate the power and energy storage capacities of a set of electricity generation and storage power plants, are coordinated by a single entity and provide energy and ancillary services to the electricity system.

The global figures also highlight the importance of renewables. According to the International Energy Agency (IEA), renewable capacity additions in 2021 reached almost 295 GW, breaking a new record. In addition, and although the effects of the Russian invasion of Ukraine have not yet been accurately assessed, installed renewable capacity is expected to set a new record in 2022, with an 8% increase. In this scenario, the competitiveness of the two most important renewable energy technologies, wind and solar photovoltaic (PV) power, continues to improve, especially in light of the high coal and natural gas prices [5].

The 94 GW of new installations added at the end of 2021 brings the total wind power capacity installed worldwide up to 837 GW [6], while the solar PV market also grew

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significantly again in 2021, breaking a new record, as a total of 175 GW was installed [7]. Furthermore, the European Network of Transmission System Operators for Electricity (ENTSO-E), forecasts scenarios in which renewable generation targets are significantly increased [8].

Under this framework, the present editorial paper summarizes the contributions of a number of scientific articles related to the integration of renewable energy into power systems, and in particular related to the integration of solar PV and wind power. The main objectives of the selected papers are included, as well as the most important results obtained. The topics of the articles range from the implementation of virtual inertia control techniques in renewable installations [9], to the review of PV systems [10] and their components [11]; from the assessment of the impact of faults on PV systems [12], to the study of standalone energy systems based on renewable energy [13,14]; and from the development and simulation of hybrid energy systems formed by PV power, wind power and energy storage systems [15], to the study of hybrid systems formed only by solar PV power and batteries [16–18]. Their information is presented below.

Among the articles reviewed in this editorial paper, the only one that deals exclusively with wind energy is [9]. In Aluko, Anuoluwapo Oluwatobiloba et al. [9], authors address a topic that is currently of special relevance, such as frequency control in electrical power systems. Until now, frequency control in power systems was mainly conducted by synchronous generators, since their 'natural inertia' -due to the kinetic energy stored in their large rotor masses, allowed frequency deviations to be damped, giving these generation units sufficient time to increase or decrease their production and thus contribute to correcting those frequency deviations. However, as the integration of renewable energy grows, inertia is reduced and the 'dynamics' of power systems become faster. This situation highlights the need for generation units based on renewable sources to also contribute to frequency regulation in networks by means of the known as synthetic, hidden or virtual inertial responses [19]. Based on this, the work carried out in [9] focuses on the development of a virtual inertia control strategy for wind energy systems connected to the grid, based on the artificial bee colony algorithm. The authors validate the model proposed by defining three different real-life scenarios, and the results show that the control model developed allows frequency deviations to be reduced and the performance of the system to be improved.

The rest of the studies either focus on the study of solar PV energy exclusively or on the study of hybrid models that include solar PV and wind energy and, in some cases, also energy storage systems. Among the contributions that only address PV power, there are two [10,11], conducting a review, and another focusing on a technical issue in PV arrays [12].

In Mohamed Hariri, Muhammad Hafeez et al. [10], being aware that solar PV power is one of the most promising types of technologies and is experiencing unstoppable growth, authors conduct a review of grid-connected PV systems, focusing on certain aspects that were not covered by other similar scientific publications. Thus, the contribution specifically addresses the development of each of the main components that form part of a PV system, such as the modules or the inverters, and reviews the main Maximum Power Point Tracking (MPPT) techniques implemented in PV systems and even the mechanisms conducted to achieve their grid synchronization. With this review, the authors aim to lay the groundwork for identifying the key challenges to be overcome in order to achieve more efficient, safer and smarter PV systems.

A more specific review also related to solar PV power is carried out by Ali Khan, Muhammad Yasir et al. [11], since authors focus on analyzing one of the most important devices that form part of a PV system, the power converter. First, the authors make a classification of the main types of inverters, depending on the commutation process these implement, distinguishing, as well, the different types into which the above can be divided according to their conduction mode. Then, based on the type of inverter, further classification is made, this time of the PV array configurations. The study goes on to classify

grid-connected inverters according to the structure of their power circuits. In addition to the classifications just mentioned, the modulation techniques implemented in inverters are reviewed, as well as the different control reference frames used and control strategies applied. The completeness of the study makes it very useful for any researcher, engineer, or company that needs to choose an inverter based on the different criteria addressed.

As mentioned above, PV power is evaluated from a more technical perspective in Gul, Saba et al. [12]. Given the criticality of faults in the operation and efficiency of any type of generation technology, including renewable-based ones such as wind power [20–22], or PV power [23], authors in [12] consider different PV configurations to assess the impact of a number of faults, namely open-circuit, short-circuit and non-uniform shading faults, on these PV systems. Moreover, the authors contemplate several PV technologies -in reference to the layout of the silicon material used- to analyze the impact of the above-mentioned faults. One of the main conclusions drawn from the study is that the use of PV arrays of Thin-film technology, as long as they are used with the appropriate configuration, can minimize the impact of faults. All the analyses conducted, mainly focused on obtaining power-voltage (P-V) curves in each of the case studies, are performed by means of the simulation software tool MATLAB/Simulink.

The two most important types of renewable energy generation sources currently available, wind and solar PV, are jointly studied in Al-Quraan, Ayman, and Muhannad Al-Qaisi [13], in Yang, Yong, and Rong Li [14], and in Antonio Barrozo Budes, Farid et al. [15]. These articles also consider the use of batteries in combination with the hybrid wind-PV systems proposed.

The lack of resources and adequate political measures, coupled with poverty and poor planning strategies, are the main causes of why many rural areas around the world do not have access to electricity. Authors in [13] deal with this problem by developing a standalone micro-grid hybrid system powered by PV and wind power and equipped with batteries. The electricity generation facility proposed is simulated based on a control system developed by the authors, which intelligently manages power to either feed the loads considered in the different study scenarios or charge the energy storage system. A control mechanism to protect the batteries based on their state of charge is also developed, and the disconnection of loads is considered an option in certain circumstances.

In line with the work developed in [13], authors in [14] also focus on the study of a standalone hybrid system formed by solar PV and wind energy and a battery to supply power to an island area, Xining, in China. In the article, a multi-objective differential evolution algorithm is proposed to obtain a precise Pareto set. The algorithm is applied to optimize, both considering technical and economic parameters, the standalone hybrid system object of study. The effectiveness of the algorithm implemented is carried out by comparing its performance with other types of control algorithms. A sensitivity analysis is also performed, and some of the conclusions obtained include, on the one hand, that if the reliability requirements of the system are reduced, the economic benefits are increased, and on the other hand, that the initial capital of the PV module has the greatest impact on the known as levelized cost of electricity (LCOE).

In order to minimize the negative environmental impact produced by conventional power plants during operation and to reduce electricity costs, authors in [15] propose a hybrid power plant based on renewable energy sources and connected to the grid to supply a certain amount of the total energy demand. The facility, located in Colombia, is formed by PV panels and wind turbines, and the definition of the hybrid power plant is based on several steps, namely the identification of a suitable location both from an economic and resource availability point of view, and the estimation of the optimal renewable capacity to be installed. To support these tasks, the software HOMER pro® is used.

In the last part of this editorial paper, three research articles that assess hybrid systems formed only by PV power and energy storage systems are reviewed. In Ciocia, Alessandro et al. [16], authors focus on enhancing the benefits of prosumers in Italy. The way we consume and produce energy is changing, and with it, the players are involved in

the electricity market organization. Energy prosumers are either individual citizens or small or medium-sized companies that consume and produce electricity using renewable energy sources. Prosumers also have the capacity to store energy and even to make their demand more flexible [24]. In this context, ref. [16] defines a case study representing a prosumer in which the self-sufficiency and cost-effectiveness of the hybrid system implemented are maximized through the application of a specific methodology, also developed in the article. The results of the study show that PV power is already such a mature technology that compensates for the installation of batteries, which are more expensive, although the paper also shows that the cost of batteries greatly influences the results obtained. It should also be noted that the prosumer energy self-sufficiency level achieved in the case study is around 64%.

In Żelazna, Agnieszka et al. [17], authors compare two small-scale power generation systems, one consisting exclusively of solar PV panels and the other a hybrid system consisting of both solar PV power and a battery-based energy storage system. Both systems are supposed to be in Poland, and several respects are assessed, covering from economic and environmental aspects to technical ones. To analyze the different aspects mentioned above, the lifecycle of the systems is considered. The results show, among other things, that the location of the installations and the electricity prices have a strong influence on the economic viability of the facilities.

Finally, in Subramaniam, Umashankar et al. [18], authors consider a solar PV–battery hybrid system to implement a power balancing control that aims at efficiently managing power between the different devices that form part of the system and interact with each other, including the grid and the load. One of the most interesting aspects of the proposed hybrid system is that it is capable of operating not only connected to the grid, but also in standalone mode. Moreover, the response of the energy generation and storage system is simulated and analyzed under both steady-state and transient conditions. Among the conclusions drawn from this article, it can be highlighted that the hybrid system presents a good dynamic response when the irradiation conditions on the solar PV modules vary rapidly.

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References

1. Hannan, M.; Wali, S.; Ker, P.; Abd Rahman, M.; Mansor, M.; Ramachandaramurthy, V.; Muttaqi, K.; Mahlia, T.; Dong, Z. Battery energy-storage system: A review of technologies, optimization objectives, constraints, approaches, and outstanding issues. *J. Energy Storage* **2021**, *42*, 103023. [CrossRef]
2. Schrotenboer, A.H.; Veenstra, A.A.; uit het Broek, M.A.; Ursavas, E. A Green Hydrogen Energy System: Optimal control strategies for integrated hydrogen storage and power generation with wind energy. *Renew. Sustain. Energy Rev.* **2022**, *168*, 112744. [CrossRef]
3. Xu, X.; Niu, D.; Peng, L.; Zheng, S.; Qiu, J. Hierarchical multi-objective optimal planning model of active distribution network considering distributed generation and demand-side response. *Sustain. Energy Technol. Assessments* **2022**, *53*, 102438. [CrossRef]
4. Marinescu, B.; Gomis-Bellmunt, O.; Dörfler, F.; Schulte, H.; Sigrist, L. Dynamic virtual power plant: A new concept for grid integration of renewable energy sources. *IEEE Access* **2022**, *10*, 104980–104995. [CrossRef]
5. International Energy Agency. *Renewable Energy Market Update—Outlook for 2022 and 2023*; Technical Report; International Energy Agency (IEA): Paris, France, 2022.
6. Global Wind Energy Council. *Global Wind Report 2022*; Technical Report; Global Wind Energy Council (GWEC): Brussels, Belgium, 2022.
7. International Energy Agency—Photovoltaic Power Systems Programme. *Snapshot of Global PV Markets 2022*; Technical Report; International Energy Agency (IEA): Paris, France, 2022.
8. European Network of Transmission System Operators for Electricity. *Ten-Year Network Development Plan (TYNDP) 2022—Scenario Report*; Technical Report; European Network of Transmission System Operators for Electricity (ENTSO-E): Brussels, Belgium, 2022.

9. Aluko, A.O.; Dorrell, D.G.; Pillay Carpanen, R.; Ojo, E.E. Heuristic optimization of virtual inertia control in grid-connected wind energy conversion systems for frequency support in a restructured environment. *Energies* **2020**, *13*, 564. [CrossRef]
10. Mohamed Hariri, M.H.; Mat Desa, M.K.; Masri, S.; Mohd Zainuri, M.A.A. grid-connected PV generation system—Components and challenges: A review. *Energies* **2020**, *13*, 4279. [CrossRef]
11. Ali Khan, M.Y.; Liu, H.; Yang, Z.; Yuan, X. A comprehensive review on grid connected photovoltaic inverters, their modulation techniques, and control strategies. *Energies* **2020**, *13*, 4185. [CrossRef]
12. Gul, S.; Ul Haq, A.; Jalal, M.; Anjum, A.; Khalil, I.U. A unified approach for analysis of faults in different configurations of PV arrays and its impact on power grid. *Energies* **2019**, *13*, 156. [CrossRef]
13. Al-Quraan, A.; Al-Qaisi, M. Modelling, design and control of a standalone hybrid PV-wind micro-grid system. *Energies* **2021**, *14*, 4849. [CrossRef]
14. Yang, Y.; Li, R. Techno-economic optimization of an off-grid solar/wind/battery hybrid system with a novel multi-objective differential evolution algorithm. *Energies* **2020**, *13*, 1585. [CrossRef]
15. Antonio Barrozo Budes, F.; Valencia Ochoa, G.; Obregon, L.G.; Arango-Manrique, A.; Ricardo Núñez Álvarez, J. Energy, economic, and environmental evaluation of a proposed solar-wind power on-grid system using HOMER Pro®: A case study in Colombia. *Energies* **2020**, *13*, 1662. [CrossRef]
16. Ciocia, A.; Amato, A.; Di Leo, P.; Fichera, S.; Malgaroli, G.; Spertino, F.; Tzanova, S. Self-Consumption and self-sufficiency in photovoltaic systems: Effect of grid limitation and storage installation. *Energies* **2021**, *14*, 1591. [CrossRef]
17. Żelazna, A.; Gołębiowska, J.; Zdyb, A.; Pawłowski, A. A hybrid vs. on-grid photovoltaic system: Multicriteria analysis of environmental, economic, and technical aspects in life cycle perspective. *Energies* **2020**, *13*, 3978. [CrossRef]
18. Subramaniam, U.; Vavilapalli, S.; Padmanaban, S.; Blaabjerg, F.; Holm-Nielsen, J.B.; Almakhles, D. A hybrid PV–battery system for ON-grid and OFF-grid applications—Controller-in-loop simulation validation. *Energies* **2020**, *13*, 755. [CrossRef]
19. Fernández-Guillamón, A.; Gómez-Lázaro, E.; Muljadi, E.; Molina-Garcia, Á. A review of virtual inertia techniques for renewable energy-based generators. In *Renewable Energy—Technologies and Applications*; IntechOpen: London, UK, 2021.
20. Artigao, E.; Ballester-Arce, J.M.; Bueso, M.C.; Molina-García, A.; Escribano, A.H.; Lázaro, E.G. Fault evolution monitoring of an in-service wind turbine DFIG using windowed scalogram difference. *IEEE Access* **2021**, *9*, 90118–90125. [CrossRef]
21. Lorenzo-Bonache, A.; Honrubia-Escribano, A.; Fortmann, J.; Artigao, E.; Gómez-Lázaro, E. Fault transient response of generic Type 3 wind turbine models: Limitations and extension of the validation methodology. *Int. J. Electr. Power Energy Syst.* **2020**, *121*, 106001. [CrossRef]
22. Villena-Ruiz, R.; Honrubia-Escribano, A.; Jiménez-Buendía, F.; Sosa-Avendaño, J.; Frahm, S.; Gartmann, P.; Fortmann, J.; Sørensen, P.; Gómez-Lázaro, E. Extensive model validation for generic IEC 61400-27-1 wind turbine models. *Int. J. Electr. Power Energy Syst.* **2022**, *134*, 107331. [CrossRef]
23. Pillai, D.S.; Rajasekar, N. A comprehensive review on protection challenges and fault diagnosis in PV systems. *Renew. Sustain. Energy Rev.* **2018**, *91*, 18–40. [CrossRef]
24. European Environment Agency. *Energy prosumers in Europe—Citizen participation in the Energy Transition*; Technical Report; European Environment Agency (EEA): Luxembourg, 2022.