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Photovoltaics and Lithium-ion Battery-based Sustainable Energy Infrastructure

V. POWAR, P. PANIYIL, R. SINGH
Clemson University
USA

SUMMARY

The integration of free fuel-based renewable sources like solar and wind with the existing power grid creates newer challenges and opportunities. Aging grid infrastructure and traditional practices of grid resiliency need to be upgraded to leverage the maximum potential of free fuel-based energy sources. However, the existing grid infrastructure is designed to regulate and condition DC generation to balance reactive power, frequency, phase, and voltages. Numerous research efforts are focused on utilizing Photovoltaics (PV) and Lithium-ion battery storage during peak-load hours while the baseload is met with coal and nuclear power. This approach lacks sustainability and maximum utilization of generated PV power. In this paper, we propose a complete DC-DC architecture for utility-scale PV farms with co-located lithium-ion storage and High Voltage Direct Current (HVDC) transmission. The paper emphasizes the importance of DC architecture required for reduced conversion losses and provides an alternative point of view for a DC-based power network that has PV and Lithium-ion Battery systems at its centre along with an AC grid to supplement it. As existing loads cannot be modified, it is essential to convert DC power back into AC only at the distribution level. The generation, transmission, and storage from PV farms should entirely be based on DC-DC architecture to ensure lower losses and lower carbon footprint.

KEYWORDS

Photovoltaics, Lithium-ion Battery Storage, High Voltage Direct Current (HVDC) transmission

vpowar@g.clemson.edu

INTRODUCTION

The traditional power grid is on the cusp of a comprehensive transformation. Recent developments of 2021 include gas pipeline cyber-attack [1], Texas utility disaster [2], change of US administration leading to US re-joining Paris agreement [3], and President Biden's Pledge to cut greenhouse gas emission in half by 2030 [4] are providing unique challenges and opportunities to develop future US energy infrastructure. Integration of renewable energy sources specifically photovoltaics (PV) and wind have received tremendous impetus owing to declining costs and climate-related challenges. Globally, solar and wind energy account for 90% of the newer power generation capacity added by the end of the year 2020 [5]. As the installation of free fuel-based solar and wind power continues to rise, it is urgently necessary to analyze the most cost-effective way of replacing the aging electricity infrastructure to successfully harness the economic and environmental benefits. Widespread changes in generation, transmission, and distribution, and protection infrastructure are needed to ensure minimal losses, contingent system operation, and increased resiliency. However, the bulk power grid has dawdled with looming concerns of grid reliability, instability, and loss of inertia associated with increasing renewable penetration. The goal of this paper is to address such challenges, rebut traditional claims and propose newer sustainable infrastructure imminent for PV and battery storage integration.

BACKGROUND MATERIAL

Nowadays, majority of the grid-tied PV interactions are based on lossy and inefficient grid system designs. Traditional approaches of injecting active and reactive power into the transmission and distribution corridors for balancing frequency, phase and voltage regulations are extended to newer grid-tied renewable infrastructure. These existing practices are based on the alternating current's (AC) centralized grid topology. They hamper the maximum utilization of free fuel-based sources. PV systems generate direct current (DC) power and require DC storage for the night when solar energy is unavailable. Long-haul AC transmission systems are often retrofitted with Static-var-compensators (SVC) and Static Synchronous Compensators (STATCOM) devices to maintain reactive power thresholds while integrating DC based PV farms [6]. Although arguably such retrofits that balance the transients due to solar variability are essential for reactive grid balance, they also limit the maximum utilization of generated PV-DC power and increase system costs drastically. Moreover, the conversion losses from DC generation to AC transmission need to be minimized in the newer PV infrastructure.

On the other hand, battery energy storage systems (BESS) which are DC sources have found a niche market in several grid-tied AC applications like load-levelling, wholesale arbitrage, spinning reserves, and other ancillary services [7–9]. However, utility-scale BESS are seldom co-located with PV farms as a complementary source to variable PV generation. Instead, battery storage is directly supplemented with newer peaker natural gas plants to provide grid services explicitly during peak-load scenarios. Several storage technologies like redox-flow batteries, lithium-ion batteries, hydrogen fuel cells, etc. are being considered to this end [8]. However, lithium-ion battery storage is the most dominant energy-efficient and cost-effective storage option today [10]. Driven by the advancements in technology (particularly higher energy density), volume manufacturing and the growth of battery electric vehicles, lithium-ion batteries are emerging as a practical low-cost solution. It is therefore important to develop Lithium-ion battery and PV (wind as complimentary energy source) based DC infrastructure solutions that can meet all future needs of electrical power. The dispatchability of wind and solar energy-based systems have been a looming concern due to the temporal variability in generation sources. However, the assumption of renewable energy sources being intermittent and can therefore only suffice the peak-load demands is highly inaccurate. Today, the majority of the baseload power is continued to be fulfilled with coal and nuclear power plants while PV and BESS are only utilized to meet peak-loads. It is necessary to change this approach. With advances in weather modelling and geographical pattern studies, accurate prediction of available PV power is readily available. Appropriate oversizing techniques should be utilized to design PV and BESS systems. Low-cost PV and storage can thereby effectively meet majority of the baseload demand in all U.S. has been proposed by authors from reference [11]. Maximizing the usable integration of PV, Wind and storage into the power grid is essential for cheaper and cleaner electricity generation. For this purpose, we propose an end-to-end DC infrastructure based on PV and battery systems with supplementary grid power. The proposed conceptual system design can provide cheaper $/kWh electricity costs while ensuring minimal water and carbon footprint.

NEED OF BATTERY STORAGE FOR SUSTAINABLE INFRASTRUCTURE

The existing grid infrastructure is designed around grid reliability and to securely operate during a planned or unplanned contingency. However, due to aging grid infrastructure and integration of variable PV and Wind sources, the grid operates near operational limits and stability boundaries. Scheduled outages and load-shedding capabilities are employed by the control-center operators to match the growing demand with variable generation. The rigidity in the grid models need to be altercated with growing variable sources being injected in the generation-mix. The temporal and spatial variations of PV and Wind sources can be leveraged by increasing storage systems. This will mitigate the dispatchability concern with PV and Wind sources. This section addresses the potential of battery storage and also emphasizes the need for distributed control techniques that enable maximum usage of available PV power. For the rest of the paper the term storage is referred to Lithium-ion based battery storage.

A. Storage as a Transmission Asset

Growing distributed generation beckons for expansion of the transmission corridors and advanced planning concepts. Adding high-voltage AC transmission lines to incorporate newer generation facilities is cost-prohibitive. Storage serves as a cost-effective solution for transmission planning [12-13]. Appropriately sized storage can provide congestion relief, voltage stability and reliability. However, utilizing storage for virtual transmission is merely the first step to leverage DC solutions into the grid. It is important to not waste the DC storage merely for transmission capacity operation. High-level system planning of resources is needed that effectively utilize storage while maximizing their energy capacity. Today, most of the storage projects operate for a 4-hour to 6-hour duration. Higher capital cost of battery storage is often linked with this shorter duration of projects. The advancements of Electric Vehicles have created a tremendous market push for innovation in battery storage technologies. As diverse mobility and electrification of automobile fleet continues in the next decade, the battery storage technologies will continue to evolve and become cost-effective solutions. The duration of operation of utility-scale batteries has a direct impact on the $/KWh cost of battery storage. The cost of storage is reduced with increasing the duration of battery storage operation [14-15]. As the Power to Energy (P/E) ratio of battery storage improves, longer duration of discharge (greater than 4-hours) can be achieved thus further reducing cost of storage. As we move towards a digitized grid with fast-switching power electronics circuits, battery storage is the promising storage infrastructure essential for resiliency of the power grid.

B. Grid forming inverter control with storage for virtual inertia

Large synchronous spinning generators are often lauded with providing the grid with inertia— the ability of large spinning masses to react slowly (resisting) thereby allowing extended frequency control for transient periods. With higher level of PV penetration into the grid the loss of system inertia is a major concern for operators. However, with fast-switching power electronics and battery storage applications, virtual inertia can be created when necessary. Inertial parameters can be customized to match specific network conditions. Together with grid forming inverters a complete system can be developed to maintain the Rate of change of frequency (ROCOF) of the grid. This virtual inertial system is deployed widely for providing black-start capabilities for the grid but at the same time can be leveraged in-tandem with PV farms. The real-life test for this system was encountered in Australia, when the coal-fired power plant in Callide Power Station, Queensland exploded resulting in cascaded outages. The Tesla storage batteries along with grid-forming inverters took control and stabilized the ROCOF within 2 seconds [16]. Another such project led by ABB at Dalrymple ESCRI project in South Australia operates with grid-forming inverters that sets the frequency and voltage of the micro-grid structure independently without grid matching [17]. Figure 1 [18] clearly shows the various functions like droop control, virtual inertia and oscillators that can be performed by grid-forming inverters.

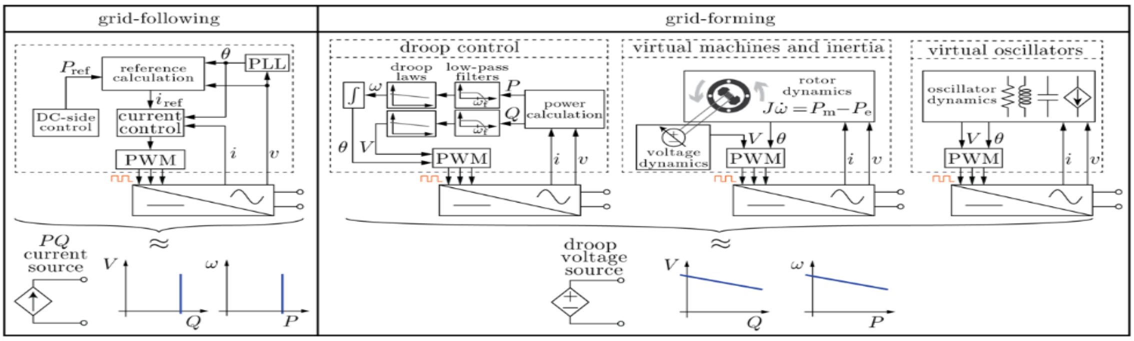

Figure 1. Grid following inverter control v/s Grid forming inverter control [18]

Integrating these technologies with the transmission grid still remains an open challenge in our subcontinent and is a potential research area. However, such developing technologies bolster higher level of PV penetration into the grid and aid in smoother transition from centralized synchronous generation to distributed renewable generation.

C. Concepts of Baseload and Capacity Factor

The power grid is employed to operate with baseload concepts that ensure a certain generation corresponding to a minimum load is always available on the power grid. Baseload Power is usually addressed due to the constant stead-state power output of coal and nuclear power plants. Traditionally, the baseload power generated by aforementioned sources was relatively low-cost power available every time to meet minimum load levels. However, the scenario is rapidly changing today with free fuel-based PV and Wind power. Cost of Coal and Nuclear generated power is no longer the cheapest available power. When coupled with BESS, solar and wind power generation can effectively serve the baseload. With the dynamic nature of loads, smart algorithms for demand-response management and increased renewable penetration, it is necessary to upgrade all the power flow analysis to real-time generation-load balancing techniques [15] while storage serves as the reserve baseload that can be dispatched on-demand. As we move towards more sustainable architecture, newer analysis tools that do not rely on baseloads should be incorporated.

As defined by U.S. Energy Information Administration, the capacity factor is the ratio of the electrical energy produced by a generating unit for the period of time considered to the electrical energy that could have been produced at continuous full power operation during the same period. A higher capacity factor indicates that the generating unit is operating all the time. [19] As PV power is not generated at night, and wind does not blow always, they are assigned a reduced capacity factor of 25% and 35% as opposed to nuclear with 92% and coal with 56% [19]. However, capacity factor is not the accurate measure to represent the viability of the generating source. Most of the generated power from coal and nuclear plants is not often utilized in the power grid. Majority of the loads are satisfied with the most economically viable power resource on the grid. This may be a fuel-mix of various generating sources or merely an exchanged power from the neighbouring pooling resources. Thus, sources with higher capacity factors are not necessarily utilized to their claimed capacity. The metric should be modified to include utilized power from the nameplate generation. Capacity Factor also does not evaluate PV and storage systems working in tandem. With co-located battery storage, PV farms can provide cleaner, cost-effective power to fulfil all load demands in the grid.

PROPOSED DC SYSTEM DESIGN FOR SUSTAINABLE ENERGY INFRASTRUCTURE

In the first quarter of 2021, 99.7% of the new power capacity in the United States was provided by PV and wind turbines [20]. This set of data indicates that combined with storage it is possible to create the future infrastructure based only on solar and wind. As stated earlier we have basically two types of current and future loads. In one case the loads already exist and are served by existing AC infrastructure. In other case new loads are emerging that will provide very high growth of electrical power in the US and rest of the world. Typical examples are electrical vehicle charging infrastructure and new desalination plants. High Voltage DC (HVDC) transmission is superior in all respect to high voltage AC (HVAC) transmission. Even for PV and wind as source of power generation, currently HVDC involves converting DC power of PV or Wind to AC power at generation site and converting to DC at the transmission site and finally back to AC power at the distribution site. In future for the first type of load, we do not need to convert to PV and or wind generated DC power to AC power. For the second type of loads we can have an end-to-end DC case.

The proposed complete end-to-end DC architecture for newer utility-scale PV farms can become a primary source of power as opposed to peak-load satisfaction in the current scenario. Although most of our loads utilized today can be realised as DC loads and therefore achieve 30% improved power and capital savings in a DC system as compared to AC design [21], the prevalent AC infrastructure does not allow the maximum utilization of these benefits. Figure 2 [22] illustrates the current power network scenario, where nuclear/fossil fuel-based power sources are at the centre of the power network with PV power only supplementing it. The end-to-end DC design approach can be utilized in forthcoming countries that are still in the nascent stages of creating a reliable power grid. Separate transmission corridors can be implemented to leverage the growing potential of PV power. An end-to-end DC power network shown in Figure 3 can be realized as a novel design with PV as the source of generation, battery systems as storage, and DC power transmission via High Voltage DC (HVDC) corridors. In developed countries like the US, it will be difficult to overcome the current AC infrastructure and establish a new DC design due to the heavy investments in the existing system. Our approach can be implemented in such a scenario also without major grid infrastructural changes. Instead of the double conversion stages at transmission and distribution, the generated DC power at PV farms along-with co-located battery storage should be converted back to AC at the distribution level. As seen in Figure 2 [22] and discussed in the background section, existing AC grid infrastructure integrates larger PV farms directly into transmission grid with additional conversion stages along-with reactive power injection. This design should be improved to maximize the DC power generation and transmission. To this end, we propose that High voltage AC (HVAC) transmission lines are replaced with High Voltage Direct Current (HVDC) lines to expand the transmission corridors that interconnect PV farms. The need for capital costs for new HVDC transmission infrastructure can be minimized by converting the existing AC transmission lines to HVDC according to the suited project requirements. The following sub-sections discuss this proposed concept in detail and address some potential roadmaps to make it a reality.

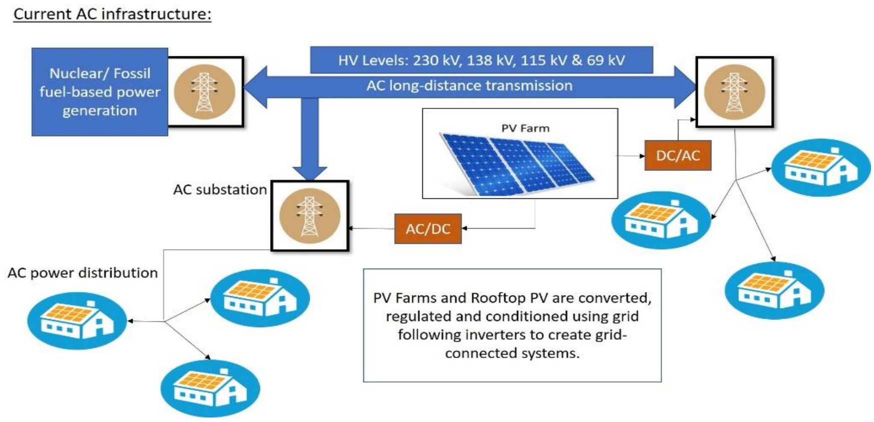

Figure 2. Existing AC architecture for integrating PV farms [22]

A. Role of High Voltage Direct Current topology

HVDC technology has proved to be more cost-effective and comparatively less lossy than the HVAC transmission lines. However, most of the literature on HVDC address the issue of high cost of converter stations needed that eventually make HVDC less lucrative from financial standpoint. HVDC maintains economic viability only after a certain critical distance. This is primarily due to the converter station costs. With longer transmission distance, the converter station costs are compensated for large distances thereby making HVDC lucrative after that critical distance. In an end-to end DC power network, the need for converter station will be replaced by DC-to-DC converters and DC circuit breakers. In utilizing HVDC with the current AC infrastructure also the high voltage converter stations can be eliminated by converting the DC power only at the distribution level. However, transforming the HVDC converter design altogether is needed to justify economic feasibility of the conversion at distribution network level. Current HVDC infrastructure of line-commutated converters (LCC) using thyristors are being replaced with faster-switching IGBT based voltage source converters (VSC). However, due to the limitations of Si IGBTs' operational characteristics, the system complexity and cooling requirements are a concern to be addressed. Another important parameter to be addressed in the DC design is the system protection. The technological innovations required to ensure economic and fault protection stability of the DC design is discussed in the following section.

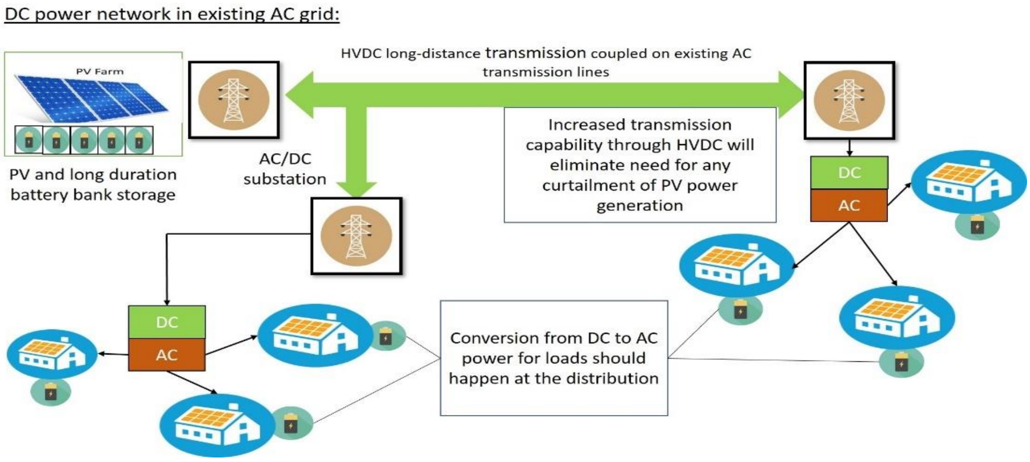

Figure 3. Proposed DC architecture for integrating PV farms

B. Technology innovations in DC-DC converters and DC system protection

Currently we do not have the DC-to-DC convertors that can serve the most cost-effective transmission for future. Thus, there is urgent need to develop HVDC Boost converters and DC-to-DC Buck converters. Due to low thermal conductivity of silicon, large amount of power is dissipated during conversion steps of AC to DC and DC to AC. Power electronics based on silicon carbide devices has several compelling advantages like high breakdown voltage, high operating electric field, high operating temperature, high switching frequency and low losses. Due to these advantages, the sizing requirement of other magnetizing parts like transformers, chokes and inductors etc. in DC-to-DC converters is also eliminated or reduced. The external cooling components like heat sinks is reduced as well, making the packaging density higher. Silicon carbide-based power electronics will save cost in two ways. Firstly, by saving of the dissipated electrical power and secondly by increasing the system life expectancy due to less thermal exposure. Silicon carbide-based components are already being used by many battery electric vehicle manufacturers. As an example, silicon carbide based extremely fast chargers (XFCs) show superior performance as compared to Si based XFCs. The use of silicon carbide-based power electronics in power and mobility sectors will lead to other markets such as high frequency, and ultra-high-power electronics for harsh environments. Since both silicon and carbon are abundant elements, we do not expect any supply-chain challenges. Thus, the cost reduction of silicon carbide-based power electronics can follow the path of silicon power electronics with dedicated R&D and industry demand. As mentioned in the previous sub-section, to implement DC-to-AC conversion at distribution level, there will be an immense need for DC-to-DC converters to enable HVDC voltage conversion to distribution level medium voltage. If these requirements can fuel the need for silicon carbide-based power electronics, it will ultimately emerge as the new technological innovation to reduce the system complexity and costs. The increase in silicon carbide-based power electronics demand will also enable these devices to compete with Si IGBT cost.

The fault isolation and protection systems for DC networks is another important factor to be considered in order to realize any DC-based design. Extensive research efforts are being carried out to establish the best methodology to implement DC fault isolations and protection [23–28]. Since DC systems do not have a natural zero crossing like AC systems, the DC circuit breakers (CBs) are more complicated. With advent of VSC-based HVDC systems, the need for fast DC circuit breakers has increased. The three major technologies that are considered for DC CBs are mechanical switches, semiconductor-based switches, and hybrid switches. Mechanical CBs have the advantage of low conduction losses, but they do not offer faster fault interruption and separation time required by VSC circuits. Semiconductor-based CBs on the other hand offer the exact opposite characteristic, with higher conduction losses and faster interruption and separation times. Thus, hybrid CBs are gaining popularity since they combine the advantages of mechanical and semiconductor-based switches. A major factor to be considered is that the current semiconductor-based CBs are implemented using Si IGBTs owing to their cost advantage over other semiconductor devices, Since Si IGBTs have operating voltage limitations that do not suffice for HV operations, they need to be cascaded which increases system cost, complexity, and losses. However, by utilizing WBG devices like silicon carbide devices, the need for cascading can be reducing which will further reduce cost and system complexity. The device level cost statistics of Si vs SiC devices are shown in [29]. The SiC transistors can catch up to Si IGBTs cost at high power applications with sufficient industry demand in the future. Thus, in our proposed system, silicon carbide-based power electronics adoption is the key to realization of efficient and cost-effective DC CBs and DC-to-DC converters.

CONCLUSION

Photovoltaics (wind as complimentary energy source) and storage-based power networks have the potential to provide sustainable electricity infrastructure not only for US but for the entire globe. In this paper we have analysed the current industry practices and provided pathways that can lead to free fuel-based power networks. As compared to current industry practices two major changes are proposed. Without using the concept of base load, first proposed change is to use free fuel energy sources with storage for as many hours (greater than current practice of 4-6 hours) as the network loads require. The second major change is to use DC power architecture for HVDC transmission. We need to develop new DC to DC convertors based on silicon carbide power electronics. Our proposed changes have the potential to provide sustainable electricity infrastructure that addresses climate related challenges with minimum investments.

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