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Grid Connected-Photovoltaic System (GC-PVS): Issues and Challenges

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Abstract. Smart grid is the key technology for an effective utilization of the Renewable Energy Sources (RES). The utilization of RES for the generation of electricity is increasingly gaining interest of researchers during the last decades. The main reason behind this is global incentivization, the increasing price of petroleum products, climate issues and deregulations in the energy market. As the Government of India, (MNRE i.e. Ministry of New & Renewable Energy) is targeting to generate 20000 MW power through grid-connected solar PVS by the year 2022 therefore, the main focus in this paper has been presented on power generation through grid-connected PVS. The emerging smart grid technology has enabled the grid-connected PVS as an evolving process in today's world for electrical power generation. However, apart from so many advantages, there are several issues and challenges associated with the integration of PVS to the electric utility grid hence, the investigation to find out available possible solutions to overcome these issues becomes essential in order to enhance the performance of grid-connected PVS. The most severe constraint associated with this emerging technology is it high penetration level. If during low load conditions there is some mismatch found between the real power output and the load profile characteristics of PVS then it may result into large reverse power flow, high power losses or severe voltage violation. In this paper, several issues and challenges associated with the integration of solar PVS with the electric utility grid are presented.

1. Introduction

Utilization of RES for electrical power generation is increasing drastically due to depletion of Conventional Energy Sources (CES) and associated environmental problems. The integration of RES into the current electric utility grid is become a challenging task because most of the RES are variable and uncertain in nature, they lead to several technical and environmental issues while integrating. In order to maintain a reliable as well as economically effective power supply, new efforts need to be considered in order to manage the energy networks, integration of RES to the current electric utility grid, demand management as well as for a variety of some other technical and cost-effective aspects of decentralized energy markets.

Recently, utilization of RES in smart grid system has been continuously increasing. Numbers of programs have already been implemented in different parts of the world; most of them are in those countries which either developed or developing countries. Various studies show that these already adopted technologies can provide reliable electricity service comparatively at low cost. To feed the electrical energy demand of the world, RES offer excellent options that enable the impact on the environment, social and economic factors in to consideration.

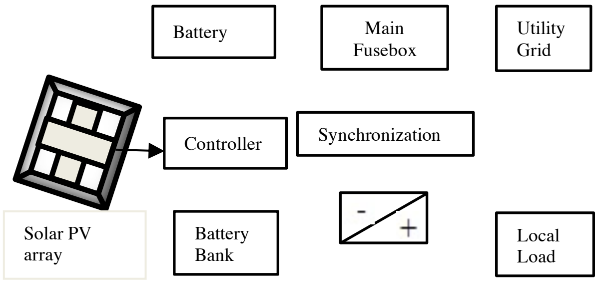

Fig. 1. Grid-connected hybrid power system (PV/Battery)

Further, during the last decades, the use of RES has increased by the development for RES in grid-connected technology. The interest of industries and academia is attracting increasingly towards Grid-connected solar PVS primarily encouraged by the capability to deliver a substitute to the power generation by conventional fossil fuels. It helps to achieve the energy demands which are increasing day by day and to limit the environment pollution due to fossil fuel emissions. The Grid-connected solar PVS configurations are growing consistently in the solar market over the last 20 years by 20–25% PA and that is why they are gaining interest.

The PVS is an array of PV cells which are combined with the controlling device, power electronic equipment and some additional related accessories which convert solar energy received from the sun directly into the electrical energy [1-3]. The output received from the PV cell is subjected to the solar insolation, position of PV modules and temperature of PV cell. The operation of PVS can be either in integration with the existing electric utility grid for peak shaving during the extreme load conditions or as a stand-alone unit to supply demand of a specific load. The configuration and connection of PVS to the existing electric utility grid can be either through net-metering or through feed-in. As the operation of grid-connected PVS is in parallel with the connected utility grid so they do not require any energy storage system. Regardless of the fact that there are some variability and uncertainties always associated with the traditional electrical power system, it is still in the process to know how to tolerate with the diversity and the requirements of high power quality in case of DER sources particularly PVS. Out of the several concerns in the integration of PVS with the electrical power system, the major one is the great trend of a divergence between load profile characteristics and the output of the PVS, which might cause severe violation of voltage regulation, high transmission losses and, during low load conditions a large amount of reverse power may flow. This inconsistency might be the effect of unpredictable cloud movements and sometimes hardware failures [4-6].The grid-connected solar PVS (GCPVS) might be building integrated (BIPVS) or terrestrial (TPVS). TPVS could be located in desert area, tidal area, and saline-alkali land [7].

This paper ultimately presents a comprehensive overview of assembly, benefits, issues and challenges, and the control strategies adopted to overcome the challenges associated with grid-connected photovoltaic systems (PVS). In this paper we have reviewed over 50 research publications including journal papers, conference papers, research articles and magazines. We have also presented the recent trends and developments in the adopted control strategies to overcome the various issues and challenges associated with grid-integration.

2. Benefits of Grid-Connected PVS

A survey has been conducted by World Energy Council in 2007 on several available Energy Resources and according to the survey it has been found that the energy received from sunlight is directly converted into the electrical energy only in the photovoltaic energy conversion process. It has also been studies that there is no interference of heat engine involved in this process. The design of PVS devices are very robust and simple so they possess biggest advantages on a very little maintenance cost. They are capable to produce power outputs ranging from microwatts to megawatts as stand-alone systems. In this way, they are utilized tremendously in variety of applications e.g. for water pumping, interchanges, remote structures, invert osmosis plants, sun oriented home frameworks, space vehicles, satellites and for even

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control plants on megawatt scale. As a result, the interest in the application of PVS is expanding each year. Solar energy is almost everywhere available and need not to be imported from different regions of the country or across the world as a result it reduces the environmental impacts associated with transportation and also reduces the dependence of consumers or power system engineers on the imported fuels. The PVS are modular; their installation is not complicated, compatible to the environmental conditions, no fuel consumption, pollution free with a long life-span and minimum operation and maintenance costs. Among all grid-connected RES, the grid-connected PVS are coming as the top leading source for the electricity generation and meeting demand. Regardless of abundant benefits of using grid-connected PVS, it suffers from high capital requirements for installation therefore; governments of several countries have taken a step to encouraging the customers for the installation of PVS at their respective locations by offering support in the form of feed-in-tariff (FIT) and net-metering (NEM) [8].

Unlike isolated photovoltaic systems, the operation of the PVS connected to the grid is parallel to the electric utility grid, so they do not need any kind of storage devices to store electrical energy. The PVS connected to the grid help to overcome the issue of greenhouse gas emissions by displacing the required electricity by local connected load and providing supplemental power to the electric utility grid. This is because when generated electricity is more than the demand of local connected load, the grid-connected PVS fed power back into the grid. As such during maximum solar irradiance (peak solar hours), few plants for conventional power generation are required. Additionally, it has also been studied that the transmission and distribution (T&D) losses are also reduced in grid-connected PVS [9]. Therefore, in modern power system, applications of PVS or Distributed Generation (DG) connected to the grid help to meet the load requirements of the consumers and applications of DG technologies are more efficient and reliable to supply additional power to the grid on the appropriate quality and continuity.

The PVS can be of any size depending upon the energy requirements. The small scale solar power plants up to 2 KW of capacity can be mounted on the unused space on rooftops of small buildings like homes, shops etc. In case of large scale solar power plants, the advantage of unused space on rooftops of large buildings can be taken e.g. universities, industries or unused agriculture land. Further, the owner of PVS can move or enlarge his/her system with changes in energy needs. If the energy usage and financial resources grow then owners can add modules or move the whole system to some other relevant place. In comparison with the operating and maintenance costs of other renewable energy based systems, the solar PVS are considered to be low, almost negligible. The PVS can sometimes produce more than needed electrical energy especially during the hot summer months; this excess amount of energy can either be stored in a storage device called battery or sometimes fed directly back into the locally connected electric utility grid if the PVS is grid-connected. The main advantages of connecting the PVS to the local electric utility grid is its simplicity, reducing electricity bills of the owner and low operating and maintenance costs. Further it also reduces the consumption of conventional energy sources to produce electricity since a part of required energy is met by feeding back the excess generated power by the grid-connected PVS. Table 1 represents the technical, environmental and economic benefits of using grid-connected PVS [10, 11-14].

3. Challenges and Impacts of PVS on Grid

Since the overall costs of owing grid connected PVS are decreasing these days therefore, the rate of adoption of this technology at residential, industrial, commercial and utility scale is increasing. Apart from many of the benefits associated with the adoption of grid connected PVS, such as its low operating and maintenance costs and long lifespan of around 25-30 years also, environmental benefits to overcome the massive use of fossil-fuels, this technology have its own set of issues and challenges. Various research scholars and industry researchers are working on this and have suggested the rapid rise in adoption of this technology could produce huge stress on the electrical utility grid. Xin et al. stated that if the infrastructure is not technically proper then a large number of grid-connected PVs will have a negative impact on power network of electrical utility grid [15]. Zarina et al. in [16] explained that if the grid-connected PVS are not dispatchable then it will become difficult to control the effects of PVs on the grid. Omran et al. in [17] stated that in the upcoming stage, many independent system operators and utilities may start implementing more rigorous rules on the application of PVS in grid integration mode because of its high penetration level and unpredictable output power. All of these conclusions made on the basis that the function of grid-connected PVS is inherent in nature. It is well known fact that the power output generated by PVS decreases with the decrease in solar irradiation. Also, the stand alone grid-connected PVSs are unable to contribute adequately when demand increases mainly at the time of sunset which is generally the time of peak demand. During this time period, the electrical utility grid import generation from conventional power plant in order to meet the surge in demand. In addition, Wang et al. argued in [18] that energy storage systems are essential to smooth the operation of grid-connected PVS to provide more reliable and stable system for adequate capacity. Walawalkara et al. in [19] stated that the applications of large scale storage have its own barriers in technical as well as marketing areas that often rise the capital costs in comparison to conventional peak power generation.

Table 1. Benefits of grid-connected photovoltaic systems (PVS)

Technical Benefits					**Economic Benefits**	**Environmental Benefits**
Improvement in Reliability	Improvement in Voltage profile/quality	Reduction in Line/energy losses	Improvement in Security	Benefits in Operations		
1. Power system reliability could be improved 2. Capacity release could be reduced 3. Generation diversity could be improved 4. Reduction in peak power	1. Improvement in voltage quality 2. Improvement in voltage profile 3. Reduction in voltage flicker 4. Better regulation and voltage support	1. Line losses are reduced 2. Control of reactive power is better	1. Security of the critical loads could be enhanced 2. Security risks to the grid could be reduced 3. Power utilities security is improved 4. Reduced impacts of cyber-attacks 5. Reduced Vulnerability of terrorist attacks	1. Facility of ancillary services 2. Productivity is increased 3. Installation is quick and easy 4. Maintenance and operation is easy 5. Reserved requirement is reduced 6. Improvement in total efficiency and infrastructure resilience	1. Reduced operation and maintenance cost for a long time 2. Reduction in cost associated with losses 3. No fuel cost	1. Effects of land use are reduced 2. Improvement in health 3. Reduction in green house gas emission pollutants 4. Reduction in emission of CO_2

3.1 Impacts on voltage stability.

On the other hand if we talk about technical issues then most important is the voltage instability is generally caused by the grid-connected PVS because of its high penetration level, several studies have been carried out about this issue out of which Yan et al in [20] and Thomson et al. in [21] both have concluded that the voltage at the distribution level is mainly affected by the cloud transient as the action of tap changing transformers is not as quick as required to maintain the desired voltage level at distribution level.

Apart from cloud coverage, the second very most important factor to consider is the distance of feeder, according to the studies in [22] the performance of the system at distribution end is mostly affected by the voltage level at the feeder which ultimately depends on the size and location of PVS.

Therefore, the optimum location is desirable for the PVS at the distribution level in order to achieve reduced power losses and voltage stability.

The study about voltage stability affected by large scale PVS has not been carried out broadly till date, however, Omran et al. in [23] and Wang et al. in [24] have investigated the effects of large scale PVS on voltage profile which are installed at different sites and connected to the grid. Their studies show that when the power generated by the PVS crosses the desired limit of 0.2-10 MW, the voltage profile at the feeder varies as a parabolic trend. The overall impedance of the PVS including impedance of the transmission line decides the peak of this curve. These studies do not consider the output power variation of the PVS during the day but they have considered that the PVS supplies maximum possible power output. However, if we talk about low voltage networks, Rylander et al. in [25] investigated the response of two feeders on PVS at different penetration levels, they have found that the response on the penetration level of PVS is unique in each feeder case and it is depends on the power factor of the inverter, size of PV and its location characteristics. Pompodakis et al. in [26] presented that in low voltage networks, the reactive power regulation in the inverters can modify the overvoltage. The impacts of penetration level on the traditional voltage regulation devices and voltage profile has been investigated by Liu et al. in [27] and reported that the capacitor banks connected to support the voltage across the feeder can be replaced by the overvoltage at high penetration level (30-50%) in the secondary circuits with PV inverters. Shahnia et al. proved in [28] that PVS may responsible for the variation in voltage profile depending on their location, size, and the interconnected load. They have also presented that the impact of PVS on voltage imbalance installed at rooftops will be more severe at the end of the feeder as compared to the starting point of the feeder in case of low voltage distribution network.

Therefore, today, the most important challenge is to investigate how the voltage profile is affected by the large scale PVS connected to the grid due to cloud coverage, solar irradiation and temperature as there are no deep studies have been carried out on how the environmental effects affects the performance of the grid in grid-connected large scale PVS.

3.2 Impacts on frequency stability.

The frequency of generation in current electrical system depends upon the rotating speed of the active synchronous generator. The operation of these synchronous generators is controlled by the difference between demand and generated electrical power of each machine governs by the acceleration or deceleration to increase or to decrease. To control the frequency in the electrical system, most important role is played by the inertial response of the generators. The supply of kinetic energy can limit the initial rate of frequency, if the demand and generation imbalance occurs in the electrical system. Seneviratne et al. and Rahmann et al. in [29-30] argued that a big difference in the operation compared with the conventional power plants can be made by the involvement of inverter and PV array in the case of large scale PVS. They said that in the electric utility system, the reduced number of rotating machines and the power variability during the day time could be responsible for the several problems from the frequency point of view. Yan et al. carried out a study on Australian network in [31], in this network a wind and solar power plant were integrated. They concluded that the frequency regulation problems in the electrical utility system are caused by the low inertia and variation in PVS. They have considered a small PVS integrated with electrical utility grid, the grid has a net installed capacity of 500 MW. Abdlrahem et al. investigated in [32] that how the interconnected system of 200 MW made up of four large scale PVS of 50 MW each in an electrical utility system affects the frequency. The study is carried out to see the response of electrical system to the increased and decreased radiations on each PVS. They conducted the analysis with constant conventional power generation and made conclusions that the frequency stability is not drastically affected by the penetration level of PV however, on the basis of simulation results they commented that the frequency stability of the electrical power system is better in a grid-connected PVS. Also, the frequency oscillations damped out faster with an increasing level of PV penetration. On the other hand another investigation based on statistical evaluation of the European continental electrical utility system in [33] says that the high penetration level of PV affects the frequency stability.

The detailed studies and analysis about this phenomenon are still not achieved till date however, it is important and necessary to investigate that how the lack of inertia in PVS affects the electric utility grid as the large scale PVS have been installed and in operation throughout the world. The switching from conventional power plant to grid-connected PVS requires that the synchronous generators must be re-designed to accommodate the variation in power output of solar PVS in order to maintain the connected electrical utility system stable. The investigation carried out by Rahmann et al. in [34] could be considered as initial step to understand that how the lack of inertia creates problem in the current electrical utility system. Moreover, it is suggested that a power reserve is not at all required to control the frequency stability if the large scale PVS works at MPP. Today, the most important challenge associated with the large scale PVS is to overcome with the primary and secondary control of frequency which is generally affected by the lack of inertia. However, the challenge is not limited up to large scale PVS but also for conventional power plants.

3.3 Impacts on active power regulation.

The peak of active power varies non-linearly depending on the solar irradiance. To track this point called as MPP, many researchers have developed and implemented various tracking algorithms, some most widely used are named as Particle Swarm Optimization (PSO), Perturb and Observe (P & O), Hill Climbing HC), incremental conductance (IncCond), artificial neural network, fuzzy logic control. There are many more as they are explained in [35]. Their time of response, the time delay to notice the variation in solar radiation and the required number of sensors are considered as their limitations. However, under these techniques, the large scale PVS will always be operating at MPP in any solar radiation. Sometimes, large and quick active power fluctuations are experienced by the electrical power system due to cloud transients. This response in result affects the power balance of the grid as well as economic dispatch. In [36] the authors have analyzed the impact of the PVS connected to the grid on the active power dispatch during the day, in the PVS which is installed at the distribution network, the PV production due to variation in solar radiation shows higher ramp rates more than 2.5 MW/min.

Therefore, for active power control: ramp rate control and power curtailment are the two types of grid codes which are necessary to be implemented. As per the literature, it would be necessary to continuously track the power required by the Transmission System Operator (TSO) instead to ensure that the PVS to be work at MPP all the day. The MPP of the PVS must be less than the overall power handling capacity of the large scale grid-connected PVS otherwise the installation of a storage system is required.

3.4 Impacts on reactive power regulation.

The PQ control is not available with the recent advancements of PV inverters which are implemented at the distribution end as inverter itself can perform it however this control is also not required by IEEE1547. The MPPT technique implemented in normal operation of PVS limits the performance of the system as it does not allow the complete control of the reactive power during the day. The PV inverter connected in large scale PVS are required not only to control the active power but to control the reactive power as well due to the increased development of grid-connected PVS [37]. The limitations of temperature, dc solar radiation and dc voltage are not reflected by the developers of PV inverter in their capability area.

Thus, to understand the limitations of the inverters connected in PVS considering the variation in temperature, dc solar radiation and dc voltage is a big challenge for today.

3.5 Impacts on equipment loading and power losses.

The power flows as a function of current through the transformers, lines and loads therefore, in the electric utility grid the power losses are generally ohmic in nature. Power losses and equipment loading both are related to each other as they vary as a function of rms value of the current. An installation scheme is presented by Weckx et al. in [38] in which central and local converters control the two balancing inverters, which results in the reduction of distribution losses in the electric utility grid. The absolute values measured for the local voltage are considered in local controller whereas the line current which controls the voltage drop over the line is considered in central controller. The grid losses in the distribution network were reduced by 10%. Also, the high nodal voltages are noticed as a result of high PV penetration systems which may lead to rise the feeder section loading and no-load distribution transformer losses.

Moreover, the resultant increment or decrement in power losses by the integration of PVS with the electric utility grid depend on location and size of PVS on the grid. In [39] authors reported that non-optimal size or location of a PVS may lead to rise in grid power losses. To find out the optimal size and location of the PVS for the distribution network, various methods have been presented in the existing literature which are employed to minimize the system losses. Additionally, in [40] authors have done an exhaustive review on the methods used to optimize the performance of the current electric utility grid interconnected with the PVS.

3.6 Impacts on voltage regulation devices.

An innovative attempt is made in [41] to show that how the voltage regulation devices are affected by the high penetration level of PVS in the distribution system. Garret et al. in [41] have experimentally obtained the switching operations performed by the voltage regulation device when integrated with a relatively large PVS, 90 operations were observed by the authors. Hariri et al. in [42] performed simulation using QSTS (Quasi-Static Time Series) to show that the traditional system control is an essential requirement because the operations of voltage regulator might increase whenever the PV inverter system is permitted to participate in voltage regulation operations. The on load tap changers (OLTC) and operation of the voltage regulator is affected by the PVS as a result the increased number of operation and runaway issues arises. Hence, Agalgaonkar et al. in [43] developed a new control methodology by taking reactive power supply from the inverter system. With this strategy authors have alleviated the negative impact of the PVS. Investigation has also achieved the voltage control when the PVS and OLTC operated at set points which are required for optimum control.

Sandia National Laboratory recently conducted a study on the impact of grid-connected PVS on the operation of conventional voltage regulation devices. The verities of impact have been noticed on various devices such as line voltage regulators, OLTC and switched capacitor banks and it was found that all depend on operational settings of the device, location and level of load. It has been noticed that the operations of the devices are reduced for the first capacitor adjoining to the substation as well as for the OLTC and increased for the rest of the capacitors.

3.7 Impacts on Harmonics.

According to the previous studies, it has been found that one of the harmonics delivery source in to the electric utility grid including inter-harmonics may be the PVS connected to the grid, which is also found as one of the reason for worst power quality [44-45]. In the latest research, to study and investigate the impact of grid-connected PVS inverters on harmonics, many attempts have been made. It has been found that since, the interaction between different controllers such as the current controllers and the dc link voltage as well as the switching behavior of the power devices are non-linear in nature hence, PV inverters are generally responsible for the introduction of harmonics [46-47]. Moreover, the issues related to inter-harmonic in PVS are hardly observed. However, the conclusion given in some of the recent articles shows that inverters connected in PVS may responsible for the introduction of inter-harmonics as well in the electric utility grid currents, resulting flickering and overloading.

In the most terrible conditions, inter-harmonics may result in triggering the protection circuit, and as a result isolates the PVS unintentionally from the electric utility grid [48]. Impacts of such actions comprise challenges from the system stability point of view and substantial energy losses in case of large-scale grid-connected PVS. Sangwongwanich et al. in [48] has defined the concept of inter-harmonics as “frequency components with non-integer times of the fundamental frequency”. In [49], it has been investigated experimentally that MPPT device which is used to track MPP for the PVS to operate at maximum power output sometimes imposes variations in the dc power and as a results produce inter-harmonics. During the investigation, a significant amount of inter-harmonics has been measured from PV inverters during the steady-state operation of MPPT controllers. Particularly, it is recommended that "the inter-harmonic frequency spectrum is somehow correlated with the MPPT frequency".

A brief discussion has been presented in [50] on the inter-harmonic emission mechanisms through various simulations, an in-depth analysis is still not achieved about this mechanism and has not been validated experimentally either.

4. Conclusion

The PVS in integration with the electric utility grid is one of the most emerging tool in the field of DERs. Some most important issues of PVS that affects the performance of the connected grid are discussed which are available in the literature and the challenges to overcome these issues are also highlighted. The environmental issues like cloud transients and solar irradiation leads to challenging issues regarding instability in voltage and frequency profile. The Power electronic devices are found as feasible solution to minimize the problems associated with the variability and uncertainty in the grid-integration. Further, to overcome with the variation in power generated by the PVS, MPPT controllers and energy storage devices could be employed. However, the involvement of PV inverters in the PVS also leads to challenging issue regarding harmonics. Moreover, the up gradation in stability of the system by incorporating some new materials and storage equipment may employed to enhance the performance of the grid-connected PVS. Therefore, the developments in grid-connected PVS are still needed that incorporates technical and financial aspects. This would be useful to assess the balance of the electricity price for grid-connected PVS.

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