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Review Article

UNDERSTANDING SOLAR POWER SYSTEM AND ITS CONTRIBUTION TO FREQUENCY REGULATION – A REVIEW

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Abstract *Thirst for renewable power systems is gaining popularity in recent times. Solar power system due to its inherent advantages and availability is one such renewable energy system that is gaining penetration in power system sectors. The penetration of renewable energy sources in power systems is what is making the systems more concerned in terms of voltage and frequency stabilities. Overall understanding of solar power system is crucial in terms of construction, operations and possible means for enhancing the system stabilities where possible. This study covers the basic understanding of solar power in terms of construction, types along with a clear indication of solar power as one of the promising renewable energy options. Furthermore, the concept of the energy storage system and different options for energy storage are discussed as it is an essential requirement of the solar power system. The role of the energy storage system along with the basic concept of frequency regulation, the need for frequency regulations and the possible aspects of using solar PV plant for frequency are compared in this study.*

Keywords *Solar Power, Renewable Energy, Grid, Storage System, Frequency Regulations, State of Charge*

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1. Introduction

Global demand for electrical energy is on the rise due to population growth as well are increasing developmental activities. On one hand, there is stress on power system networks to meet the growing load demands and on the other hand, there is a need for judicious extraction and use of energy sources. The pressure is also mounting from the concern pertaining to impacts of climate change where the holistic shift in renewable energy sources should be the priority. Almost 26% of the global electricity is from renewable sources and there are predictions that it will rise to 30% by 2024 [1]. There are commitments in line with realizations of 'Sustainable Development Goals (SDGs)' whereby countries are committing and shifting towards renewable energy initiatives. This is in the thirst for decarbonization of power system networks and initiatives towards becoming carbon neutral. Commitment from different countries in its strategic plan for going renewable has been realized with meaningful actions towards these directions. Penetration of solar and wind energy systems is quite significant in recent times along with hydropower.

One more reliable and user-friendly approach are driven towards solar power which has wider scales of growth starting from rooftop to solar farms which are contributing to meeting individuals' electricity demands and in many extends its connection and contributions to the power grid. Researchers have also found out that substantial rural communities depend on lighting and heating loads from renewable energy [2]. A deeper understanding of solar energy, radiation, solar power system, energy storage system and the frequency regulation concepts are thus crucial while exploring renewable energy

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sources as an option. It is critical to review the work done especially in the domain of energy storage as well as frequency regulations as solar power systems are variable power generations that are subjected to multiple factors. The best of the best energy storage system and the frequency regulation techniques are appropriate for given situations and conditions thus be key indicators for specifically realizing the potential of solar power system for its contribution to electrical power system networks.

The electric power system must meet two distinct challenges: maintaining a near-real-time balance between generation and demand, and adjusting generation (or load) to regulate power flows through particular transmission facilities. Because loads and generators are continually varying, it's challenging to balance generation and load in real-time. Regulation, contingency reserves (spinning reserve, supplemental reserve, replacement reserve), and voltage support are all services that storage technologies should be able to provide [3].

2. Understanding Solar Power System and their roles in power system networks

2.1. Why Solar Energy?

Energy from the sun is enormous and most of it goes untapped. The daily solar energy radiations are more than that of the energy used in a world for a year and it is a renewable source of energy. Furthermore, solar energy is freely available, environmentally friendly, sustainable and has strength for energy independence, the choice for it is most favorable. The solar radiation can be turned into thermal energy as well as electrical energy and realize the appropriate requirements [4].

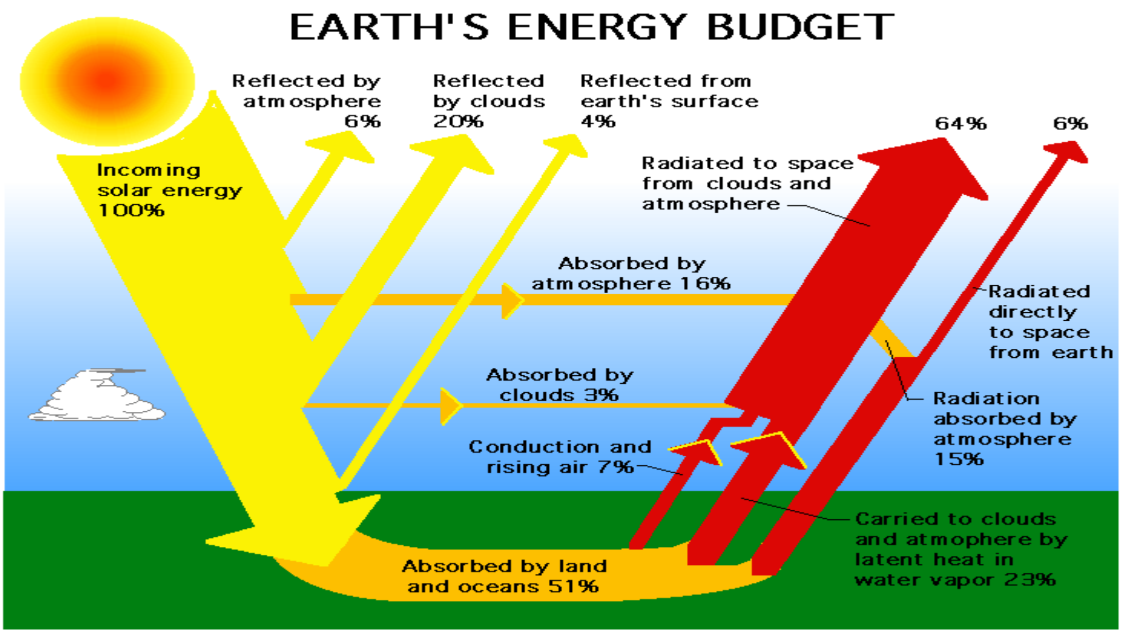

Fig.

Figure 1. Earth Energy Budget [5]

It is noted that major portions of solar radiation that reached the earth's surface are just radiated back and despite its numerous advantages it is hard to believe that it has not gained major penetration in power sectors where some pertaining issues related to higher cost involved in collecting, converting and storing.

Still, the use of solar electrical energy is rising fast in current times which are largely due to the attributes of positive aspects derived in terms of technologies, cost and ease of implementation. The lifespan of solar panels is 30 years and it can be customized based on size, colors and materials being used [6]. The construction of solar panels is such that it meets the requirements of energy generation as well as its conditions for usage in the exposed atmosphere.

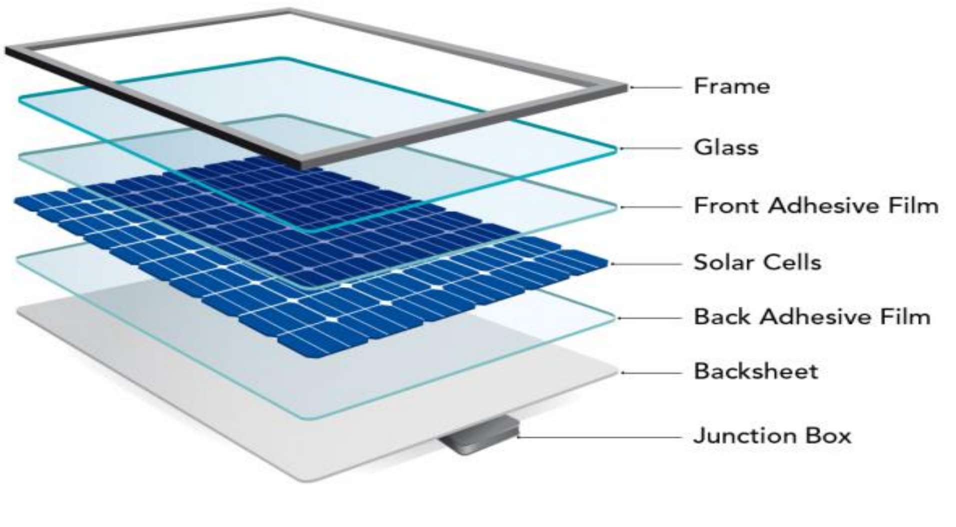

Figure 1. Solar Photovoltaic (SPV) Layers [7]

There are two common types of solar energy systems like 'Utility Intertie PV Systems (Grid Connected)', 'Stand Alone Solar Electric System'. The grid-connected solar energy system provides simple and cost-effective integration of solar power to utility power for energy requirements in smaller scales in residential/other buildings. Whereas the stand-alone system can well be applied in isolated building/structure or setup where there is no connection to utility power. The requirements can be implemented without or with usages of battery system (storage where necessary and feed in night time or in the case of cloudy weather).

Figure 3. On-grid and Off-grid components [8]

The mounting of solar panels can be either 'Fixed Mount' or 'Track Mount' based on the situation. the former is less costly as compared with the latter whereas the latter is most efficient as compared to the former as it has the capability of tracking the sun direction so as to achieve maximum solar radiation hitting the solar panels surface. In the majority of rooftop solar power systems, the use of fixed mounts is common due to price as well as other associated technical and practical difficulties.

The need to have greater insight into energy storage and frequency regulation is critical while talking about solar power systems. The penetration of solar power systems in the power utility grid will be more materialized when possible storage systems are incorporated as well there is special attention given to the frequency regulation when it is connected to the grid. Unlike hydropower, the fluctuations and weather dependency is high in the case of solar power system and more so it will generate D.C. voltages while the grid mostly/always is A.C in nature.

3. Why energy storage system is needed?

The need for energy is round the clock whereas the possibility of generating solar power is during the daytime. This has demanded the requirement of a storage system that can stock the excess power during the daytime and can be utilized during nighttime or even during cloudy weather. The grid-tied net-metered solar panels system is seen as more viable when there are bidirectional energy flow conditions can be realized. This will facilitate the excess energy if produced can be contributed to the grid and in other instances draw the required energy from the grid. The researcher has found that the extra energy can be used to charge the energy storage whereby the stored energy can safely be used after sunset so that the need for grid-connected utility power demand does not arise [9]. There are several types of energy storage technologies, including electrochemical, mechanical, and electrical/ magnetic fields as shown below;

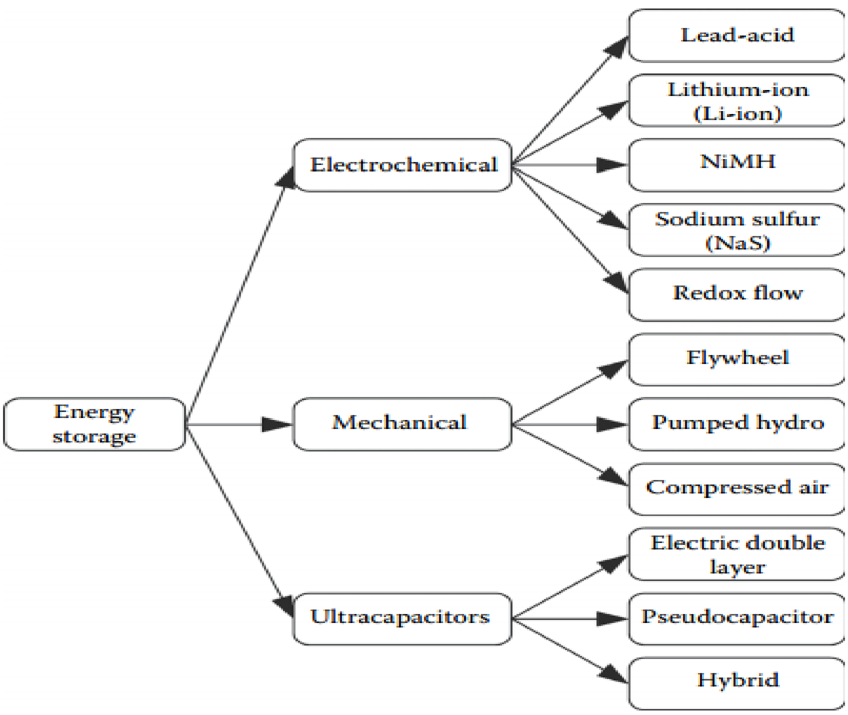

Fig. 4. Different types of Energy Storage Systems (ESS) [10].

Solar PV plants require short term support during clouding, load shedding and short-circuits. Such support can be provided by energy storage with high power capabilities rather than high energy capabilities [10]. Also, ESS with a faster discharge rate is preferred for such purposes. Modern ESS such as flywheels, ultracapacitors, Compressed Air Energy Storage and superconducting magnets are designed with such characteristics [11]. The characteristics of some of the commonly used ESS are shown below in figure;

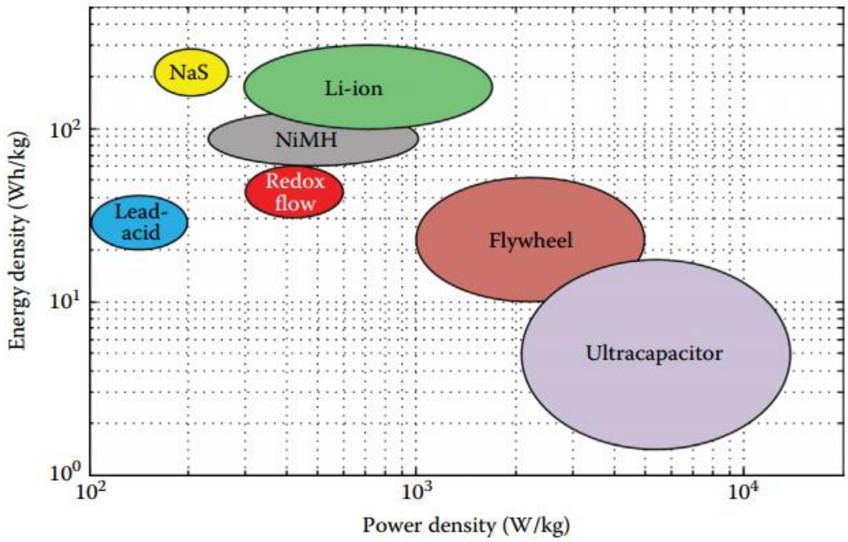

Fig. 5. Ragone plot for various types of Energy Storage Systems [10].

While consideration for frequency regulation, ESS with higher power density is preferred. There is a need for understanding the different options available for the energy storage system that are already in place and have their strength and weakness.

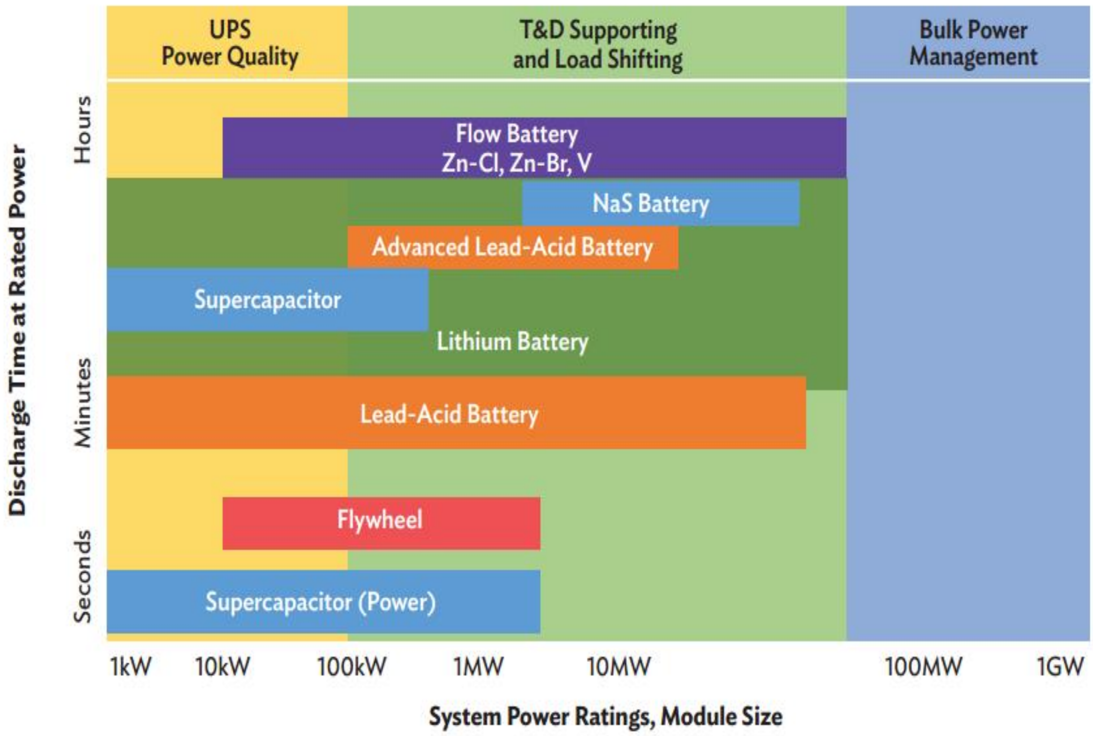

Fig. 6. Comparison of Power Output (in watts) and Energy Consumption (in watt-hours) for Various Energy Storage Technologies [12].

4. Frequency regulation

In a power system, frequency is a constantly changing variable that represents the balance between generation and demand. The regulation of frequency to have power system on permissible frequency range is crucial when there are constant changes in generation as well as load is observed in power system. With the growing need for renewable energy, conducting primary frequency management alone on the generation side has become not only prohibitively expensive but also technically complex. Demand-side frequency response is an innovative technique to address the growing demand for traditional power sources [13]. Also with solar power systems penetrating in power systems and their fluctuating generating situations, the thirst for 'Maximum Power Point Tracking (MPPT)' technologies are incorporated to achieve maximum possible generation. Solar photovoltaic power generation (PV generation), on the other hand, does not engage in any frequency regulation or oscillation damping function for the bulk power grid when operating in MPPT mode because the panels' output is maximized rather than coordinated with the grid. PV operations could be modified to include it in frequency support and small-signal stability control for bulk power systems as penetration grows [14].

4.1. Frequency regulation using solar PV system

With the increasing growth of renewable energy generation technologies making its impacts on global power system networks there are issues of frequency stability [15]. If operated as a stand-alone system, a solar PV system, as a renewable energy source, is often unable to follow load demand or participate in frequency regulation [16]. When a PV system is connected in a large power grid the issues pertaining to the impacts related to system frequency is neglected due to its capacity being much smaller as compared to power plant capacities but this issue is of concern when the larger-scale solar power system is connected to power grid [17].

By using reserve power from the array [16] and using interconnection with other renewable energy or non-renewable energy [18-19] the frequency is being regulated in the solar PV system. With the increase in the use of solar power plants all around the world, modern power plants demand not only generation support but also the need to use solar power plants for ancillary support. Solar power plants usually do not contribute to system frequency due to their decoupled nature from system dynamics [20]. In addition, the intermittent nature of solar power plants limits their ability to provide constant power as and when required [21]. However, with the use of ‘Energy Storage Systems (ESS)’, energy from the solar power plants can be stored and utilized as and when the system parameter changes. ESS can help to stabilize the electric power system by providing voltage and frequency support, load leveling and peak power shaving, spinning reserve, and other ancillary services.

Although BESS are among the oldest technologies, they are the most matured and developed ones as shared by ADB [12], but other researchers highlighted that BESS is not only capable of regulating frequency but also in improving them for both load-shedding and load increase cases [22]. Some of the BESS such as Li-ion batteries have a flexible characteristic because of which they can be used for multiple purposes including frequency regulation [23].

Mechanical storage devices are also employed for the ancillary service of both islanded and grid-connected systems. Flywheel is one such device that has shown considerable improvement in system stability by reducing frequency fluctuation [24]. Flywheels possess higher power density and lower energy density which makes them superior and suitable for frequency stabilization in RES technologies [25].

‘Battery Energy Storage Systems (BESS)’ is an economic choice and has a wide range of characteristics feasible for frequency regulation (such as fast ramp rate and power density). In addition, they are the most commonly used ESS as it is a matured technology. Hence, BESS is a good choice for frequency regulation. In the case of the battery, the commonly preferred ones are a Lead-acid battery, Li-ion battery and Sodium Sulphur (NaS) battery.

4.2. Frequency regulation using BESS with SPVP

When the grid frequency falls below a specified threshold, BESS can supply the PFR service by discharging (delivering active power) or absorbing active power from the grid (charging) when the frequency rises over that threshold. Between 0 and the maximum storage power, the necessary charging or discharging power is proportional to the frequency deviation and is linearly increased. Because of their quick response and high-power capabilities across time scales of up to 15 minutes, Li-ion BESS is well suited for PFR duty. Furthermore, when operated at 50% SOC, their calendar lifetime is extended.

One research shows how a battery energy storage system (BESS) with a frequency sensor controller may improve the frequency of an isolated island microgrid (FSC). The case has a Solar Photovoltaic Plant (SPVP) of a total installed capacity of 410 kWp, with over 50% instantaneous penetration. To mitigate the impact of SPV power production volatility on the microgrid, a BESS with the planned FSC was deployed. After that, load flow and transient stability analyses were performed with and without the use of the BESS. A simulation of transient stability was used to investigate the events of the greatest SPVP power plant tripping and all SPVP output powers with a ‘Ramp Rate (RR)’ of 70%/s. During these events, the frequency decreased below 57.3 Hz without being compensated by the BESS, which caused the load to trip. However, using the planned FSC of the BESS to support the microgrid's operation, the system frequency was well maintained [26].

In another study, it showed that the operation and control of hybrid photovoltaic power, ‘Diesel-Engine Generator (DEG)’, and BESS connected to an isolated power system a case study was conducted on the impact of BESS operations on the frequency stability of the hybrid system. Due to limited storage space, constraints on ‘State Of Charge (SOC)’ have also been introduced. In two scenarios, steady-state analysis of a hybrid system using step load response with PI controller and real-time performance analysis for a typical day with random fluctuation in load demand was carried out. The Genetic Algorithm is used to optimize the parameters of controllers. Matlab / Simulink platform is used to simulate a hybrid system model. According to simulation studies, the BESS system can contribute to frequency stability when the load increases and when the load decreases. This aspect of the BESS system will come in handy if it is used in conjunction with a hybrid Wind-PV system [22].

A flow chart depicting the hybrid system model's operational approach is shown in the figure below. A grid or an isolated power system can be used with the hybrid system. Variable loads are connected to the electricity system. The frequency of the electrical system changes whenever the load demand changes.

Changes in frequency are proportional to changes in load demand, therefore as load demand rises, system frequency falls, and vice versa.

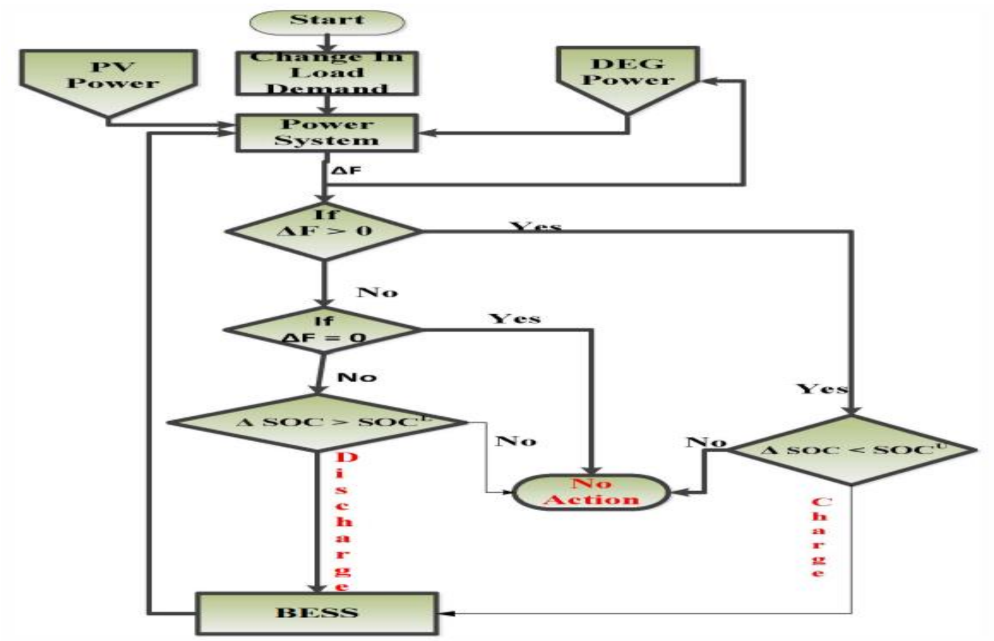

Fig. 7. illustration of operation strategy [22]

The frequency stability of the system must be constant. So, in order to achieve a change in frequency of zero, the power supply should be changed, which implies that if load demand increases, the power supply should be raised, and when load demand lowers, power should be reduced. On this basis, systems proceed as follows: when the change in frequency becomes negative, BESS supplies power to the system; however, before BESS can operate, it must go through a procedure in which the battery's state of charge (SOC) is compared to its lower limit of a state of charge (SOC^L). If the battery's SOC is higher than the SOC^L, BESS will deliver power to the grid or system before being discharged; otherwise, BESS will not produce power. In another scenario, if the frequency change is positive, BESS does not deliver power and reduces total power. Before charging the BESS, some of the surplus power was supplied to the battery system and its SOC as compared to its upper limit of a state of charge (SOC^U).

If the SOC is less than the SOC^U, the battery is charging and drawing power from the system; otherwise, the battery is not charging.

Furthermore, if electricity system resiliency is to be considered which is essential when there are issues with the grid during grid outrages as a consequence of any emergencies as well as extreme weather, the distributed solar photovoltaic systems can serve the purpose. This requires design consideration with ESS, hybrid fuel-use and microgrids but has to be supported by favorable regulatory measures so that power access during such circumstances be materialized [27].

4.3. Frequency regulation using De-loading method

In this method, effective control over the active power below the maximum power point (MPP) of the PV plant is achieved for numerous variations in solar irradiation and temperature to regulating the frequency of the plant [16]. This method is known as de-loading. A frequency droop control mode similar to that of synchronous generator's has also been developed following the same de-loading method [28]. This model uses a droop characteristic for varying irradiation to control the frequency for any loading condition as shown in the figure 8 below.

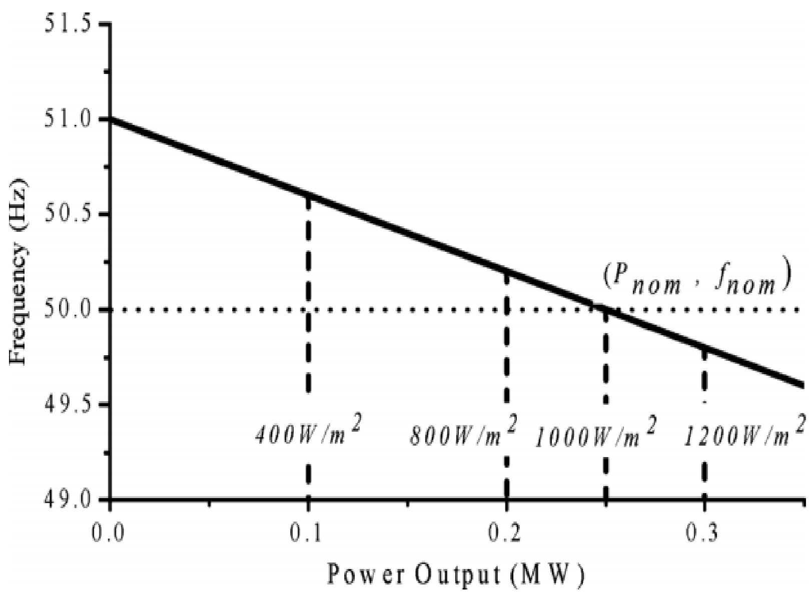

Fig. 8. Frequency drop for PV array [28]

De-loading techniques for the SPV plant by creating a power reserve in its MPPT curve are shown below in figure 9. This is achieved by changing the maximum power point 'V_{MPP}' to 'V_{deload}'. At 'V_{deload}', the SPV plant operates at normal frequency but as soon as the system frequency reduces, the point will move to the reference as shown as 2.

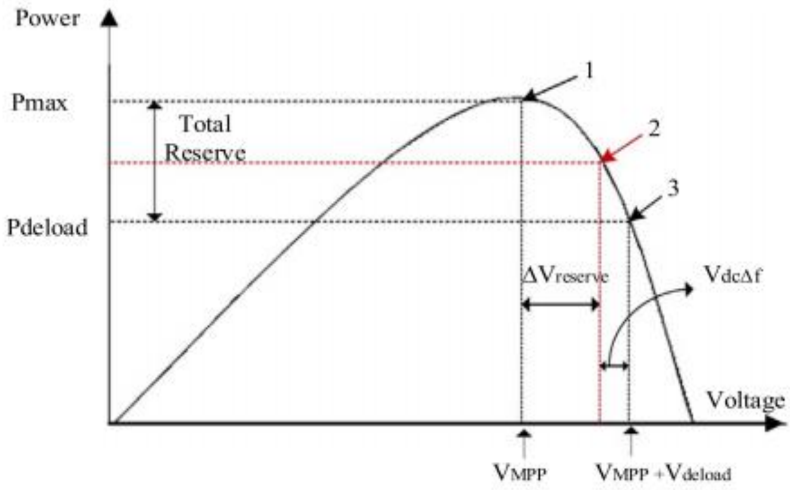

Fig. 9. De-loading technique [29]

A more optimized and intelligent technique to perform frequency control by the de-loading method has also been proposed [16, 30]. These methods involve the implementation of algorithms for the MPPT controller which can regulate the MPPT curve point according to the changes in the system frequency.

One of the studies done in U.S. Eastern Interconnection has reflected having several active power controls along with PV (Inertia control, governor control AGC control and PSS control) that are further employed with user-defined solar PV control that has potential for frequency regulation and oscillation damping in power system [31].

5. Discussion

Power generation from the renewable energy source and its penetration in power grids is gaining momentum whereby SPV plants are one main contributor. The SPV plant understanding thus becomes much crucial. Furthermore, due to the varying power generation nature of SPV as well as wind plants, there is a need to choose the best option for ESS too. From various types of ESSs, mechanical and electrical storage systems were found to have fast response characteristics that would support frequency regulation. However, BESS such as Li-ion and NaS was also found to have similar characteristics in addition to being a mature and cost-effective technology. Hence, BESS could be implemented for both grid and island mode operation of the SPV plant.

From the review of these techniques, it was found that SPV with ESS was more reliable than using the de-loading method. Although, the cost involved in implementing the de-loading method is lesser, however, there would not be full utilization of the energy generated by the SPV plant which could reduce its efficiency. Also, variation in irradiation poses complications in regulating frequency. Hence, using ESS such as BESS along with SPV plant would be a feasible option as it allows full utilization of energy produced, increase reliability and also, have multiple uses of ESS.

6. Conclusion

The solar energy system is growing across the globe and showing major penetration in power sectors in recent times. The need in understanding the solar power system and the trust in its capabilities are worth appreciating in a thirst for renewable energy. It is seen that solar radiation source, different components of an SPV plant and its advancement with modern technologies, various connection methods and other components of SPV farm are worth understanding when we think and act on the solar energy system. As the operating characteristics of the solar power system are weather dependent and there is a need to focus on energy storage systems. Also, the frequency regulations aspects seem important in power system networks when we have penetration of renewable energy sources to the grid network. The focus on SPVs contribution to frequency regulation using ESS is important to consider while working on the solar power system. Moreover, various comparisons and research show that BESS was a preferable choice of ESS for frequency regulation. Also, frequency regulation strategy using BESS shows that there is a relation between load demand, frequency and SOC of the battery and hence, these parameters are considered for maintaining the system's frequency. As a result, more research can be focused on realizing the best possible options capitalizing the potential of above mentions techniques with efficient controller/s and appropriate algorithms for making the reality of efficient frequency regulation using SPV plant.

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