Solar Photovoltaic Output Smoothing: Using Battery Energy Storage System

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***Abstract*— Battery Energy Storage System (BESS) is widely being implemented along with Solar PV to mitigate the inherent intermittencies of solar power. Solar smoothing is one such application of BESS. In this paper, different techniques for solar power smoothing is compared. An energy compensation based smoothing technique is proposed in this paper. The smoothing method not only ensures an optimal sizing of the battery but also keeps the state of charge of the battery same at the beginning and end of any random day. The different techniques are simulated on a typical moving cloud day output of a 5 MWp solar power-plant.**

Keywords— Battery Energy Storage System (BESS), Smoothing, State of Charge (SOC), Moving Window, Solar Photovoltaic, Renewable Energy, Intermittency

I. Introduction

With increasing penetration of renewable energy the grid is becoming increasingly weather dependent. The variable cloud-cover or wind speeds on a typical day results in intermittency of renewable generations. This in turn leads to permanent fluctuation of power at the terminals of conventional generating units. The fast change in power requirement at the generator terminal causes higher stress of generator components and faster ageing and wear of components. The sudden change in the power input to the grid has also detrimental effect on the connected load.

In case of micro-grid systems, such as an electricity grid in an island the result of such variation may result in significant changes in frequency. In a grid with a high contribution of solar power, the fast changes in power output must be negated by changing the governor position of conventional generators. This results into significant wear and tear of the governor system of the generators. Further, the quick variation of solar power through-out the day also means fast variation of loads on the conventional generators. As a result, Generators are not in a steady thermal condition in the grid. Due to fluctuating thermal cycle and increased number of stop/start cycles the thermal fatigue of the generators are increased which have adverse effect on the life of the conductors and insulation. When renewable energy penetration increases in a grid the inherent intermittencies may result in voltage instability of the grid in case of weak distribution networks.

To mitigate the energy variation from solar power output Battery Energy Storage System is being used. Several authors [1]-[3] in the past have described the effect of increasing Renewable energy penetration in the grid. Methods such as use of Battery Energy Storage, use of dump loads and curtailment of solar PV output power has been suggested to reduce the fluctuations from solar power in the grid [4].

In small grid the renewable intermittency brings in frequency changes. However, researchers have shown in case of distribution networks with high R/X ratio increase of Renewable Energy penetration can lead to instability in the network-voltage [2].

To handle the issues of renewable energy intermittencies Battery Energy Storage System (BESS) is being implemented widely. Several studies dwell on design and modelling of Battery Energy Management System for reduction of power in solar PV [5]-[6]. Some researchers have also suggested use of Hybrid Energy Storage System (HESS) along with Solar PV for power-fluctuation mitigation [7]. In this paper authors have proposed a super-capacitor bank along with Vanadium Red-Oxide Battery as a part of the HESS.

The different applications of BESS with Solar PV integration are energy time shift, frequency regulation and solar PV output smoothing. In energy time shift application of BESS the solar energy is stored in the battery during day time. The energy stored in the battery is discharged during peak-load hours at a later time of the day. The battery sizing is typically large for this application. The frequency regulation application of BESS is to provide energy support to the grid by charging the battery in over-frequency situations and discharging it while the grid frequency is less than the nominal frequency [8]. In this paper the authors describe a control strategy for BESS tailored for Indian grid conditions. In smoothing application, the fast variations in solar PV output are negated using BESS. The result is a smoother power output with a relatively small size of battery.

From the above literature survey it is understood that, application of BESS along with solar PV is common for frequency regulation, output smoothing and energy time shift. In this paper the different strategies for solar PV output smoothing is carried out. Further, the State of Charge (SOC) of Battery at beginning and end of the day is also carefully considered. A smoothing technique which ensures an optimal size of battery and almost same SOC at beginning and end of

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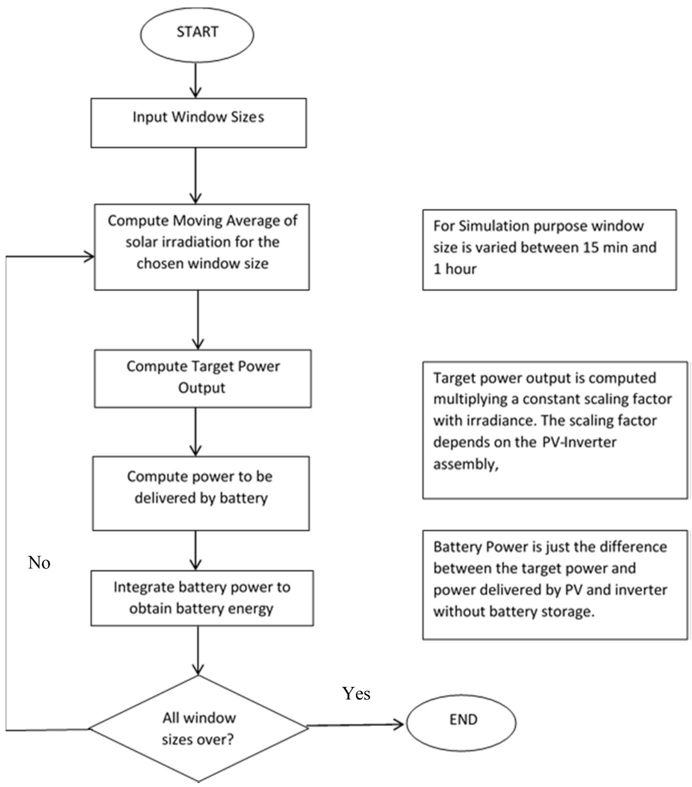
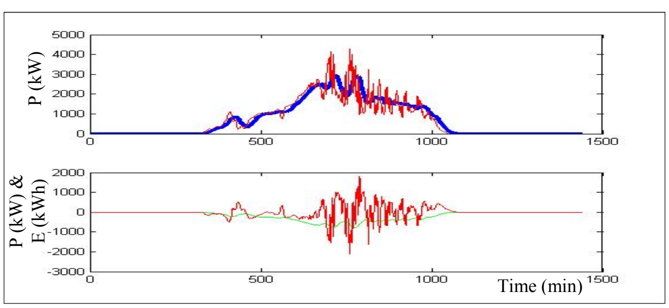
the day is proposed. The studies are carried out for a sample 5 MWp solar power-plant.

II. PROPOSED TECHNIQUES

A. SIMPLE MOVING AVERAGE BASED SMOOTHING

For solar-smoothing a moving window based algorithm is proposed. At each point of time the algorithm decides a target power. The difference between the target and actual power output from the solar PV inverter is the battery power.





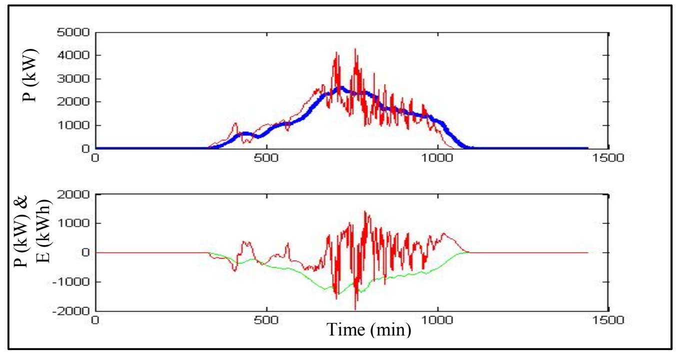
The smoothing curves, obtained using simple moving average from simulation, on a typical moving cloud day are presented in this section.

Figure 1 Smoothing Results with Simple Moving Average and 30 min window period

The figure presents two sets of curves. The first set of contain two curves (Red- Actual solar PV output & Blue-Total System Output). The next set of curves represents Power supplied by BESS (Red) and Energy supplied by BESS (green).

The smoothing results are obtained for variable window size. It may be noted that higher the window size smoother the curve and lesser the variations in the output of the solar PV and battery system. A curve is presented as follows for a 60 min smoothing window period.

Figure 2 Smoothing Results with Simple Moving Average and



60 min window period

The energy supply curve of the battery can be inversely correlated with the State of Charge of the battery. Higher the energy supplied lower the state of charge of battery. It can be seen from the above curves that total energy supplied by the BESS over a 24 hour period is zero.

It is further observed, with a higher averaging window size the smoothing curve obtained is smoother. However, higher window sizing results into a higher size of battery. The green curve in the second set of curves in the above figures the energy requirement from the battery. With an increase in window size from 30 min to 60 min battery sizing increases almost by 100%. Hence the window size is to be judiciously chosen as a trade-off between the smoothing desired and the battery size.

One major limitation of this method is the target power always lags behind or leads ahead the actual power output curve. As a result the difference in the power between the two curves keeps on integrating over time and the energy sizing of the BESS is much more. Higher the window size higher the lag/lead and higher sizing of battery.

B. SINGLE AND HALF WINDOW BASED MOVING AVERAGE

To tackle the problem of lag/lead in simple moving average based algorithm a single and half window based moving average is chosen. In this method moving average is calculated for the whole window period and also for the second half of the window period. Let, the average over the entire window period be x and average over the last half of the window period be y. Then the estimated output at the end of window period will be y+(y-x)=2y-x.

The example of the following sequence can be taken for understanding purpose: {0,1,2,3,4,5,6,7,8,9}. In this case the average over the entire period x=4.5 and over latter half of the window period y=7. Hence the modified moving average is 2y-x=9.5 which is closer to the real-time value of 9.

The simulation result with this modified algorithm and 30 min integration period is presented below.

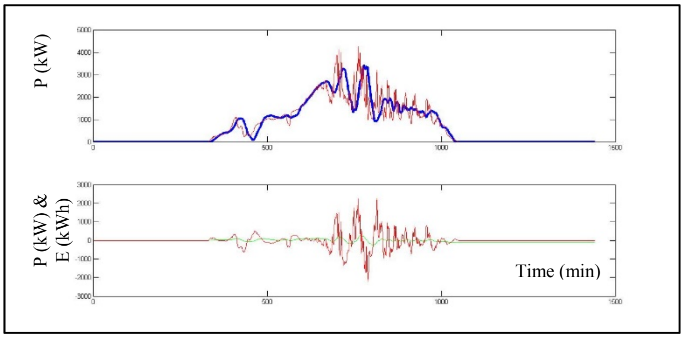


Figure 3 Smoothing with Single and Half Window Algorithm

It can be observed the lag and lead of the previous method has been completely omitted in this method. Similar to the previous algorithm a smoother curve has been obtained with a 60 min window period.

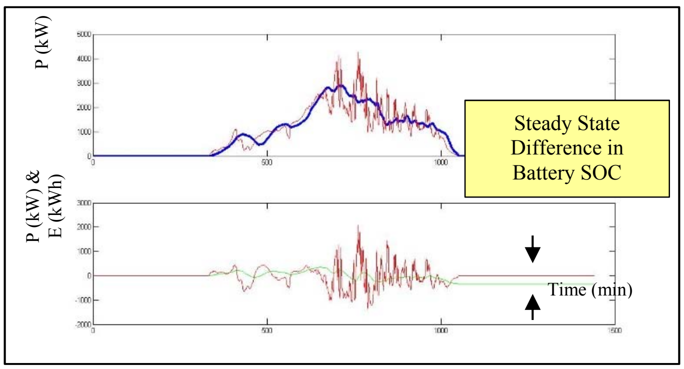


Figure 4 Smoothing with Single and Half Window and 60min Window Size.

However, a closer scrutiny of the curves presents a hitherto unprecedented problem. The single window and half based moving average algorithm removes the lag and lead between the target power and actual solar PV output. As the target power closely follows the solar PV output the battery storage requirement is also reduced. The problem with this method is that the SOC of the battery changes over the entire day. It is observed from the curve that the net energy supplied over the entire course of the day is non-zero. This means application of this technique makes the battery gain/lose some net charge over the course of a day's operation. Hence, the starting state of charge (SOC) of the battery changes to a different level at the end of the day. A change in the algorithm is hence proposed to tackle this problem.

C. SINGLE AND HALF WINDOW BASED SMOOTHING WITH ENERGY COMPENSATION

To negate the end of day change in SOC an integral control is incorporated in algorithm. The change incorporated in the algorithm monitors the difference in energy between target energy and actual energy over a certain period of time (20 minutes in the simulated problem). This energy is then compensated over the next period of time.

The pseudo-code annexed to the algorithm can be written as follows:

For (t=1 to end)

{

Revised Target Power (t) =Target Power (t) +Difference (t);

If (t<=20)

{Difference (t) =0 ;}

Else

{Difference (t) $= \frac{1}{20}\sum_{k=1}^{20}[Actual\ Power(t-k) - Revised\ Target\ Power(t-k)]$;}

End if;

End For;

The results of the novel method are shown as follows:

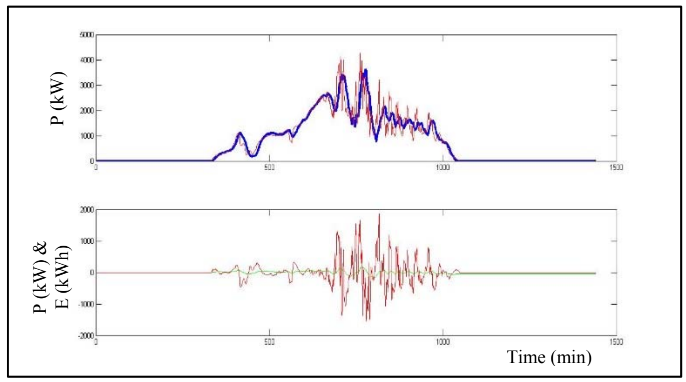


Figure 5 Smoothing Results with Novel Method and with 30 min Window Period

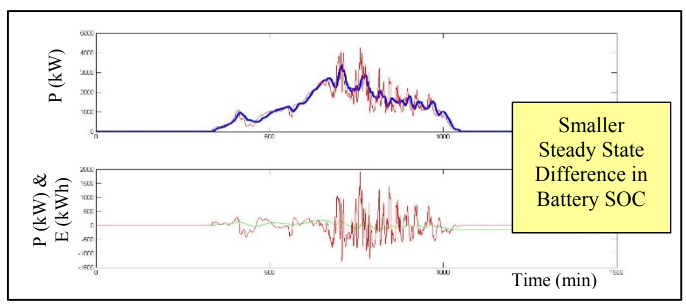


Figure 6 Smoothing Results with Novel Method and 60 min Window Period

III. RESULTS AND DISCUSSION

The results of the different techniques used for solar PV output technique is compared in this section. The criteria on which the fitness of algorithm are judged are Battery Sizing in terms of Energy and the final SOC of the battery.

A. Simple Moving Average- 30 Min Window Period

- *Battery Sizing in terms of Energy*: Maximum energy exchange through BESS is 600 kWh.

- *State of Charge*: Unaltered at the end of the day.

B. Simple Moving Average- 60 Min Window Period

- *Battery Sizing in terms of Energy*: Maximum energy exchange through BESS is 1200 kWh.
- *State of Charge*: Unaltered at the end of the day.

C. Single And Half Window-30 Min Window Period

- *Battery Sizing in terms of Energy*: Maximum energy exchange through BESS is 200 kWh.
- *State of Charge*: Changed at the end of the day

D. Single And Half Window-60 Min Window Period

- *Battery Sizing in terms of Energy*: Maximum energy exchange through BESS is 300 kWh.
- *State of Charge*: Significant change at the end of the day.

E. Single and half window based with energy compensation-30 min

- *Battery Sizing in terms of Energy*: Maximum energy exchange through BESS is 200 kWh.
- *State of Charge*: No change in SOC.

F. Single and half window based with energy compensation-60 min

- *Battery Sizing in terms of Energy*: Maximum energy exchange through BESS is 250 kWh.
- *State of Charge*: Small change in SOC.

From the above discussion, it is clear that simple moving average based smoothing results into a higher sizing of battery. The battery sizing is typically 3-4 times the battery sizing required with any other smoothing technique.

With Single and half window based smoothing the battery sizing is reduced significantly. For a Solar power-plant of 5 MWp the typical sizing for BESS is 200-300 kWh. This method does not guarantee same state of charge at the end of the day.

With the introduction of energy compensation in the above problem the change of SOC is restricted. In the novel method, there is marginal change in Battery Sizing for 30 min and 60 min integration period. However, there is small change in SOC for 60 min period using the novel technique, whereas there is no change in SOC for 30 min window period using the novel technique.

Hence, it may be suggested that, the Single and a Half Window based Smoothing using Energy Compensation technique and a 30 min window period is most suitable for Solar Smoothing application of a 5 MWp solar power plant.

IV. Conclusions

The Government of India has set an ambitious target of generating 175 GW power by 2022 from Renewable Energy Sources (RES), including 100 GW from solar. To accommodate the intermittencies associated with the RES, grid connected storage is needed. As a proof of concept, POWERGRID is implementing 500 kWh BESS at Puducherry with Frequency Regulation and Energy time shift applications. In the above project, the benefits and suitability of two BESS technologies- Lithium Ion and Lead Acid (250 kWh each) are being studied extensively. Further, it is prudent to explore additional applications of BESS, such as solar PV output smoothing which will facilitate integration of Renewable Energy in the grid.

The paper presents a comparative analysis of different solar power smoothing techniques. The starting point is a simple moving window based algorithm using Battery Energy Storage System. The simple Moving Window Average smooths the power output significantly but however presents with a high sizing of battery. The reason for the high sizing of battery is that the time difference between the actual power from PV and target power. To reduce the lag a single window and half moving average is proposed. This algorithm reduces the lag and consequently reduces the battery sizing. However, the SOC of the battery changes significantly over a day's operation. To solve the issue an integral control based strategy is incorporated in the same algorithm. This has reduced the battery sizing as well as the change in SOC over a 24 period operation

The proposed methodology for smoothing is suitable for any size of solar PV installation. Application of the novel-technique with similar window periods will result into similar smoothing results and proportionate battery sizing.

V. Acknowledgement

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