Grid-connected photovoltaic system with power smoothing

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Abstract. This paper analyzes the power smoothing of grid-connected photovoltaic (PV) systems under fast irradiance changes. The analyzed converter is composed of a triple active bridge series-resonant (TABSR) DC-DC converter cascaded with a voltage source inverter (VSI). Two controlled variables are considered: battery current and the PV voltage. The TABSR DC-DC converter is modeled as controlled current sources for the battery and the PV ports. The ramp rate (RR) control algorithm is used to smooth the PV output power profile enhancing the power delivered to the grid. Four ramp rates (10%, 5%, 2% and 1%) are used to evaluate the RR control algorithm and the battery state of charge (SOC) response. Therefore, the battery can be sized appropriately. Real data for irradiance and temperature in an overcast day is used to verify the effectiveness of the proposed system.

1. Introduction
The grid-connected PV systems have been increased in the last years, contributing to electricity generation [1]. However, the generated PV power might fluctuate due to the changes in solar irradiance for hours, minutes or even seconds. According to the solar irradiance conditions, the days can be classified into three groups: clear sunny days, overcast days and partly cloudy days [2]. On sunny days, there is no power fluctuation problem, while on overcast days, the PV output power profile completely loses its typical shape (bell shape). Indeed, the maximum power point tracking (MPPT) algorithm allows the PV array to supply the maximum available power [3], which depends on atmospheric conditions like irradiance and temperature. On the other hand, on partly cloudy days, the PV array is shaded for a few minutes or seconds, leading to an intermittent PV output power. In grid-connected PV systems, these power fluctuations are prejudicial to the grid, causing unintentional islanding, frequency variations outside the allowed range and economic penalties [4].

The PV power profile can be improved by adding storage elements to smooth the PV output power. Several smoothing techniques such as moving average (MA), low pass filter (LPF) and ramp rate (RR) control have been proposed in the bibliography [5]. The RR control technique is the most popular, limiting the power variations to be less or equal to 10% of nominal power per minute.

Usually, non-isolated buck or boost converters are used to model these systems. However, these converters have limited gain to reach the DC-Link voltage. In contrast, isolated converters such as the TABSR DC-DC converters have a HF transformer with high gain and allow the interconnection of the PV array and batteries with the AC grid [6]. However, this converter has not been studied for PV power smoothing. This paper is focused on modeling the TABSR DC-DC converter for PV power smoothing under different irradiance and temperature conditions on a cloudy day with fast irradiance variation.
2. PV system modeling
The analyzed system is shown in figure 1. The converter consists of a TABSR DC-DC converter cascaded with a voltage source inverter (VSI), which allows to interface the PV and the battery with the grid.

![Figure 1. Analyzed TABSR DC-DC converter to interface PV and battery with the AC grid.](image)

In the TABSR DC-DC converter shown in figure 1, the power flow is controlled by the phase-shift angles ($\varphi_{13}$ and $\varphi_{12}$) between modulated voltage signals which are shown in figure 2.

![Figure 2. Modulated voltages in the DC-DC TABSR converter.](image)
According to [7], in a switching period, the average current on the PV side is a function of $\varphi_{13}$ and $\alpha_1$, while the average current on the battery side is a function of $\varphi_{13}$, $\varphi_{12}$ and $\alpha_1$, it means:

$$I_{PV} = f(\alpha_1, \varphi_{13}) = K_1 \sin\left(\frac{\alpha_1}{2}\right)V_B \sin(\varphi_{13})$$

(1)

$$I_{BP} = f(\alpha_1, \varphi_{13}, \varphi_{12}) = K_1 V_{PV} \sin\left(\frac{\alpha_1}{2}\right) \sin(\varphi_{13}) + K_2 V_{DC} \sin(\varphi_{13} - \varphi_{12})$$

(2)

Where $K_1$ and $K_2$ are constants that depend on the characteristics of series-resonant circuit 1 (SRC1) and series-resonant circuit 2 (SRC2), respectively (figure 1). Therefore, the converter can be modeled on the PV and the battery sides as source currents which is shown in figure 3.

3. The MPPT implementation

In figure 4 is shown the implemented MPPT control strategy. The irradiance and temperature are the inputs for the PV array model. The MPPT step voltage changes every twenty seconds. Besides, the PV voltage is controlled by a PI controller. The MPP algorithm used is the P&O MPPT algorithm [8].

4. The RR control algorithm

The smoothing PV power control strategy is shown in figure 5. The battery current is controlled by a PI controller. The battery is sized according to its state of charge at the end of the day, which depends on the PV output power profile and the chosen ramp rate. That means that using a low ramp rate, the battery...
provides or receives a more significant amount of energy than using a high ramp rate throughout the day.

Figure 5. Battery current control loop.

The RR algorithm is shown in figure 6. Typically, the ramp rate of PV power must be lower than 10% of nominal power ($P_{nom}$) per minute. If the condition is not satisfied, the RR control algorithm imposes the power variation equal to the maximum power allowed ($r\%P_{nom}$).

Figure 6. RR control algorithm flowchart.

5. Simulation results and discussion
For PSIM® simulation, real irradiance and temperature data in text format collected from the PV station was used. The irradiance and temperature profiles are obtained using a counter and two lookup tables (figure 4). These variables are used as inputs on the PV array model. The irradiance and temperature data were extracted in Lima, Peru, on February 26, 2017, sampled every 15 s. The rated power is 2 KW, and the PV array consists of eight solar panels of 250 W, each one arranged in series and the rated voltage of the battery is 48 V.
Figure 7. Atmospheric conditions: (a) irradiance and (b) temperature profiles.

Figure 8. Power profile of each port under fast irradiance changes using (a) 10%, (b) 5%, (c) 2% and (d) 1% of ramp rate.
The energy delivered by the battery at the end of the day is greater using a low ramp rate, as shown in figure 8. For example, the energy capacity of the battery must be at least 88 Wh using a RR of 5%, while using a RR of 2% with the same conditions of irradiance and temperature, this capacity must be at least 249 Wh. Indeed, the battery needs to be pre-charged at the beginning of the day or at night to ensure the correct operation of the PV system. The power smoothing limits the fast PV power variations removing these power peaks in power delivered to the grid.

The power peaks shown in all cases of figure 8 were occasioned by the instant PV voltage variation when the irradiance step happened. When irradiance transition occurs, the current source \( I_{PV} \) starts from its previous value and acts according to the control loop; on the other hand, the PV current changes quickly, almost immediately, according to the PV model of the PSIM simulator. This difference of currents results in a PV voltage jump. In addition, some voltage jumps are more emphasized throughout the day when the irradiance step is large.

\[
V_{PV} = \frac{1}{C_{PV}} \int_{t}^{t+7} (I_{PV} - I_{PV,0}) dt
\]  

(3)

In figure 9, the behavior of PV voltage in a certain period of time is compared between the system working with a value of 240 \( \mu F \) and 1mF of capacitance. According to equation 3, these voltage jumps can be attenuated, increasing the capacitance \( C_{PV} \). Another method to attenuate these jumps is increasing the sampling frequency of irradiance and temperature; in this way, the irradiance step would not be large. However, the control loop should also increase its dynamic response and more memory resources would be needed.

![Figure 9. Photovoltaic voltage using (a) 240 \( \mu F \) and (b) 1 mF of capacitance in \( C_{PV} \).](image-url)
6. Conclusions
This paper presents a method to implement the PV power smoothing applied to grid-connected converters. The storage element to the power smoothing is a Lithium battery. The analyzed converter is a two-stage converter composed of a TABSR DC-DC converter cascaded with a VSI. The TABSR DC-DC converter is modeled using controlled current sources. The MPPT algorithm is used to get the maximum available power from the PV array, which is smoothed by the RR control algorithm. The modeled PV system was evaluated for different ramp rate values. The profile of the power delivered to the grid is smoother with a lower ramp rate. However, the battery capacity needs to be higher. The proposed model for the PV system allows to size the battery for a chosen ramp rate using real data of irradiance and temperature collected from the PV station.

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References
[1] REN21 2021 Renewables 2021 Global Status Report chapter 3 pp 117-132
[2] Salehi V and Radibratovic B 2014 Ramp rate control of photovoltaic power plant output using energy storage devices Proc. Int. Conf. & Exp. 2014 IEEE PES General Meeting (National Harbor: IEEE)
[3] Xiao W, Elnosh A, Khadkikar V and Zeineldin H 2011 Overview of maximum power point tracking technologies for photovoltaic systems IECION 2011 – 37th Annual Conf. of the IEEE Industrial Electronics Society (Melbourne: IEEE)
[4] Shivashankar S, Mekhilef S, Mokhils H and Karimi M 2016 Mitigating methods of power fluctuation of photovoltaic (PV) sources – A review Renewable and Sustainable Energy Reviews 2016 59 pp 1170-84
[5] Sukumar S, Marsadek M, Agileswari K R and Mokhlis H 2018 Ramp-rate control smoothing methods to control output power fluctuations from solar photovoltaic (PV) sources – A review Journal of Energy Storage 20 pp 218-229
[6] Yong H, Li X, Wu X, Li M and Wang Y 2020 Stability control design for TAB-based three-port bidirectional DC-DC converters in PV-battery grid-connected applications IECION 2020 The 46th Annual Conf. of the IEEE Industrial Electronics Society (Singapore: IEEE)
[7] Sal y Rosas D, Frey D, Schanen J L and Ferrieux J P 2017 Close loop control to bidirectional isolated single stage DAB with resonant circuit DC-AC converter to connection of batteries to the single-phase grid 2017 IEEE applied Power Electronics Conf. & Exp. (APEC) (Tampa: IEEE)
[8] Kollimalla S K and Mishra M K 2014 Variable perturbation size adaptative P&O algorithm for sudden changes in irradiance IEEE Transaction on Sustainable Energy 5 pp 718-728