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Published in:
2023 IEEE PES/IAS PowerAfrica

DOI (link to publication from Publisher):
10.1109/PowerAfrica57932.2023.10363159

Publication date:
2023

Document Version
Accepted author manuscript, peer reviewed version

Citation for published version (APA):
Jamroen, C., Pannawan, A., Sangwongwanich, A., & Motahhir, S. (2023). Self-Consumption Evaluation for Grid-Connected Photovoltaic Systems Considering Ramp Rate Limit. In *2023 IEEE PES/IAS PowerAfrica* (pp. 1-5). Article 10363159 IEEE Press. https://doi.org/10.1109/PowerAfrica57932.2023.10363159

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Self-consumption Evaluation for Grid-connected Photovoltaic Systems Considering Ramp Rate Limit

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***Abstract*—Grid-connected rooftop photovoltaic (PV) systems are a promising solution to reduce electricity bills and support sustainable development in residential areas. Although excess PV power can be sold to the grid at attractive tariffs, premium feed-in tariffs have been discouraged in many countries. Instead, self-consumption policies have been encouraged to promote local generation and consumption. Rooftop PV systems are connected to the grid; thus, local grid codes are applied to maintain a stable and reliable system operation. A high PV power ramp rate (fluctuation) typically imposes several difficulties: voltage fluctuation problems and shorter electric appliance lifetimes. However, previous studies have failed to consider the PV power ramp rate limit when evaluating self-consumption. In addition, neglecting the ramp rate limit leads to a PV system with a lower self-consumption rate in practical implementation due to ramp rate limitations. Therefore, this study focuses on a self-consumption evaluation in grid-connected PV systems considering the ramp rate limit. A modified inverter-based ramp rate control method is considered to maintain PV power fluctuations within ramp rate limits. Several ramp rate limits are assigned to the ramp rate control method in a comparative study, where two scenarios are considered: low and high PV power fluctuations. The comparative results reveal that PV ramp rate limits positively affect the self-consumption rate but negatively affect the self-sufficiency rate.**

***Index Terms*—photovoltaic, ramp rate, self-consumption, self-sufficiency.**

I. INTRODUCTION

Due to population and economic growth, growing electricity consumption leads to an increase in energy resource provision. Conventionally, electricity is generated using fossil fuels, such as natural gas, lignite, or diesel fuel. However, electricity tariffs increase significantly due to the depletion of fossil fuels. Moreover, fossil fuel-based electrical generation inevitably releases greenhouse gases, causing global warming. Renewable energy (RE) has produced electricity without emitting greenhouse gases in recent years [1]. Photovoltaic (PV) energy has considerably contributed to the global RE share due to its substantial cost reduction. Consequently, rooftop PV systems have been installed globally and connected to distribution grids to reduce electricity bills and enhance sustainability [2]. Today, governments worldwide have encouraged consumers to maximize the use of local RE generation instead of selling excess energy to the grid [3]. This policy, called self-consumption, aims to provide environmental, economic, or social benefits at the community level, helping countries become energy-independent and propelling nations toward a climate-neutral future [4]. In many countries, PV technology adoption is approaching grid parity, making self-consumption an attractive measure [5]. Therefore, numerous studies have focused on evaluating the self-consumption of grid-connected rooftop PV systems or determining their optimal capacity based on a techno-economic assessment to improve or maximize self-consumption rates.

Tazarine and El Omari [6] designed an optimal PV system for self-consumption at the Faculty of Technical Sciences in Settat, Morocco. The study indicated that a PV capacity of 200 kWp was selected with the minimum expenditure and a payback period of 8.5 years. Ettalbi et al. [7] comprehensively evaluated energy management strategies for PV self-consumption. The study identified key benefits and disadvantages of energy measurement, communication protocols, and PV self-consumption optimization methods. Garcia-Villalobos et al. [8] presented a methodology to analyze the influence of PV self-consumption on voltage levels and power losses in medium-voltage distribution networks in Murcia, Spain. The study revealed that a unity power factor setting for PV installations mitigated power losses but increased effects on voltage levels. Additionally, Garcia-Villalobos et al. [9] used a uniform geographic distribution of PV self-consumption installations to evaluate energy loss. The study revealed that energy loss increased significantly even though low PV penetration was considered. Fialho et al. [10] conducted an economic evaluation of nonresidential PV self-consumption at the Polytechnic Campus of Viseu, Portugal. The study demonstrated that a PV capacity of 250 kWp was the optimal PV installation based on the net present value and payback period. Nemes et al. [11] analyzed the self-consumption of a grid-connected PV system installed at the Faculty of Electrical Engineering, Technical University of Iasi, Romania. The study suggested that increasing self-consumption was dependent on the installed PV capacity. Jager-Waldau et al. [12] introduced an overview of collective self-consumption, a relatively new development facing considerable administrative and regulatory challenges. The study revealed that appropriate regulatory and legal conditions, which enabled secure and fair financing, were necessary to enable the participation of people living in buildings. Jately et al. [13] conducted a techno-economic

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assessment of the PV self-consumption system using a case study of Malta. The study suggested that policies must be revised to further incentivize self-consumption systems for residential applications. Liu et al. [14] focused on the influence of the microgrid scale and the capacity of rooftop PV systems on self-sufficiency. The study indicated that increasing the microgrid scale or PV capacity could improve self-sufficiency. Herrera-Perez et al. [15] presented a comparative analysis of self-consumption regulations in Spain, Romania, and Ecuador. The study demonstrated that the annual economic savings for the three countries were around 42% (Lasarte, Spain), 85% (Riobamba, Ecuador), and 70% (Brasov, Romania) for a PV installation of 4.3 kWp.

Although PV systems are an affordable RE technology to improve self-consumption, their intermittent nature inevitably affects grid stability through power and voltage fluctuations [16], [17]. Based on the current literature, previous studies have focused on evaluating PV self-consumption systems or exploring optimal PV system capacity to maximize self-consumption in various locations. A high PV power ramp rate imposes several difficulties, such as voltage fluctuation problems and shorter electric appliance lifetimes, and several countries have included ramp rate limits in their grid codes [18]. Conventionally, power ramp rate control can be realized through active power curtailment by modifying the maximum power point tracking (MPPT) algorithm at the PV inverter level [19]. Consequently, PV systems with ramp rate limits are vulnerable to having a lower self-consumption rate in practical implementation. However, previous studies have failed to consider a PV-power ramp rate limit when implementing PV self-consumption systems. Therefore, this study conducts a self-consumption evaluation for grid-connected rooftop PV systems, considering the influence of PV power ramp rate limits. A modified inverter-based ramp rate control method was considered to maintain PV power fluctuations within ramp rate limits. Several ramp rate limits were assigned to the ramp rate control method in a comparative study, where two scenarios were considered: low and high PV power fluctuations.

The remainder of this paper is organized as follows. Section II describes the methodology. Next, Section III provides the simulation results. Finally, Section IV summarizes the key conclusions.

II. METHODOLOGY

A. Grid-connected rooftop PV system design

This study considers a grid-connected rooftop PV system connected to an inverter to supply PV power to residential loads or inject excess PV power into the grid. The inverter used in this study is equipped with an MPPT controller. Residential load profiles in an urban area of Bangkok, Thailand, are obtained from the Metropolitan Electricity Authority. The load profiles for 2020 were averaged to obtain a single residential load profile, as illustrated in Fig. 1. The electricity consumption gradually decreases after 22:00 until 4:00. Afterward, the electricity consumption marginally increases in the morning (around 5:00) and gradually decreases. The electricity consumption reaches the minimum level before noon. In the afternoon, the electricity consumption gradually increases and significantly increases after 18:00. Notably, the electricity consumption reaches the maximum level at around 22:00.

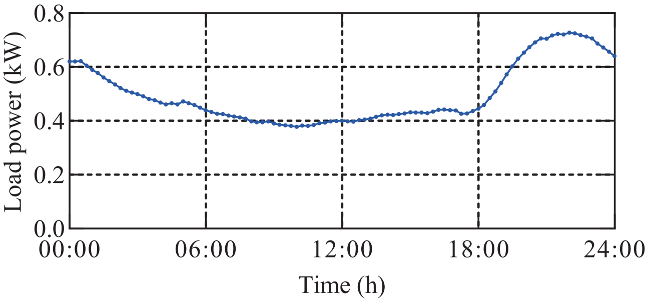

Fig. 1. Daily average electricity consumption for a single house in an urban area of Bangkok, Thailand in 2020.

B. PV-power ramp rate limitation

Grid-connected rooftop PV systems can sell excess PV power to the grid when PV generation exceeds load consumption. However, injecting PV power fluctuations with a high ramp rate adversely affects grid operation and stability. Consequently, several countries have introduced additional regulations and restrictions associated with ramp rate limits in their grid codes. A PV power ramp rate is expressed as follows [20]:

$$\mathrm{RR}(t) = \frac{dP_{\mathrm{pv}}}{dt} \tag{1}$$

where $\mathrm{RR}(t)$ indicates the ramp rate (kW/min), and P_{pv} represents the PV power (kW).

Conventionally, PV power ramp rate control can be realized through active power curtailment by modifying the MPPT algorithm at the PV inverter level. This study uses a modified ramp rate control method based on the inverter-based ramp rate control proposed by de la Parra et al. [21] and Sangwongwanich et al. [22]. The ramp rate control method is expressed in (2), where P_{pv}^{*} indicates the PV power reference considering ramp rate limits, $P_{\mathrm{pv,mpp}}$ denotes the maximum power point of a PV system, P_{rated} represents the rated PV capacity, and $\mathrm{RR}_{\mathrm{th}}$ indicates the ramp rate threshold. The inverter-based ramp rate control method can mitigate PV power fluctuations during ramp-up events.

C. Self-consumption indicators

This study uses the self-consumption rate (SCR) and self-sufficiency rate (SSR) proposed by Luthander et al. [23] to display the self-consumption level of an RE energy system, where the local PV generation is consumed directly by the prosumer.

1) Self-consumption rate: The SCR is described as a proportion of the total local PV generation used directly by the prosumer. Hence, the SCR is expressed as follows:

$$P^*_{\text{pv}} = \begin{cases} P_{\text{pv,mpp}} & \text{if } \text{RR}(t) \le \text{RR}_{\text{th}} \\ P_{\text{pv,mpp}} - \left(P_{\text{rated}} \times (\text{RR}(t) - \text{RR}_{\text{th}})\right) & \text{if } \text{RR}(t) > \text{RR}_{\text{th}} \end{cases} \tag{2}$$

$$\text{SCR} = \frac{E_{\text{du}}}{E_{\text{pv}}} \times 100\% \tag{3}$$

where E_{du} is the consumption directly supplied by PV generation (kWh) and E_{pv} denotes the PV generation (kWh). Typically, the SCR is always greater than 0%, and SCR $>$ 0% indicates that the local PV generation partially fills the consumption when a certain amount of PV generation is injected into the grid. In addition, SCR = 100% indicates that the total PV generation is fully consumed locally.

2) Self-sufficiency rate: The SSR is described as the proportion of the total consumption directly supplied by local PV generation. Hence, the SSR is expressed as follows:

$$\text{SSR} = \frac{E_{\text{du}}}{E_{\text{load}}} \times 100\% \tag{4}$$

where E_{load} represents the load consumption (kWh). Similarly, the SSR is always greater than 0%. Moreover, SSR $>$ 0% indicates that the local PV generation partially supplies a load, and energy imports are required to meet the remaining load. In addition, SSR = 100% indicates that the PV generation fully covers a load without energy imports from the grid.

D. Cases and scenarios

Three cases were used to evaluate the influence of various ramp rate limits on the SCR and SSR. Hence, three levels of RR_{th} were given: Case 0 (without a ramp rate limiter), Case 1 (with RR_{th} = 10%), and Case 2 (with RR_{th} = 1%). In addition, two scenarios were considered: Scenario 1 (low PV power fluctuations) and Scenario 2 (high PV power fluctuations). Once all three cases were applied to each scenario, the SCR and SSR can be determined using (3) and (4), respectively. The daily PV power and ramp rate variations of those two scenarios based on a PV capacity of 1 kWp are illustrated in Figs. 2 and 3. Fig. 2 represents a PV power variation on a high-visibility day with some clouds. The PV power could reach the maximum PV power around noon. Moreover, most ramp rate levels were below the ramp rate level of 10%. Very few ramp rates exceeded the ramp rate level of 10%. In contrast, the maximum PV power in Fig. 3 was less than in Fig. 2 because Fig. 3 represents a PV power variation on a low-visibility day with frequent clouds. The ramp rate level frequently exceeded 10%.

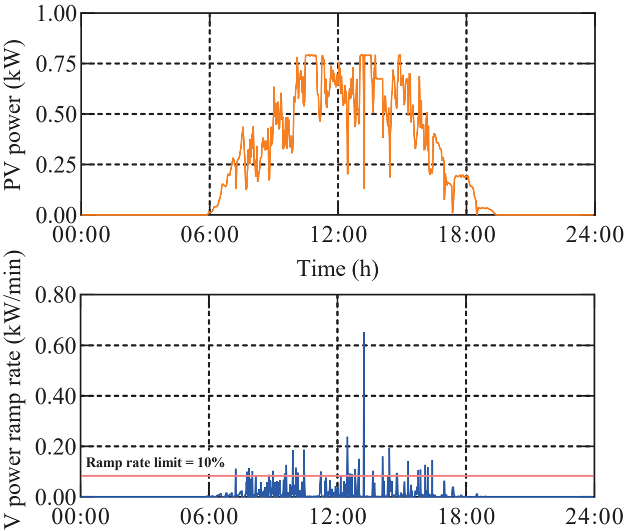

Fig. 2. Daily PV power generation and ramp rate variation in Scenario 1 (low PV power fluctuation).

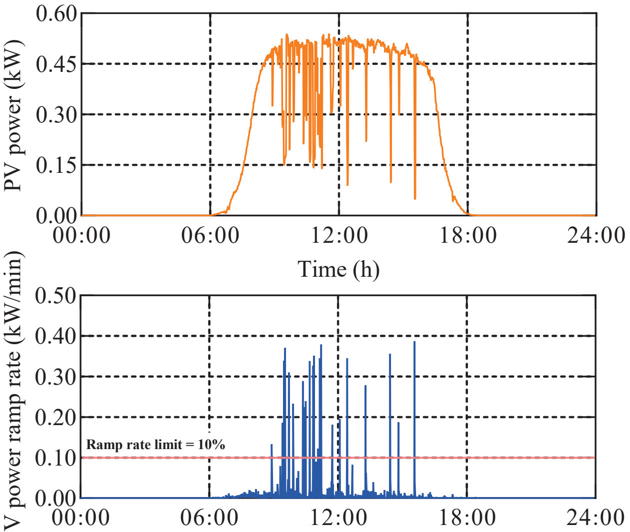

Fig. 3. Daily PV power generation and ramp rate variation in Scenario 2 (high PV power fluctuation).

III. RESULTS AND DISCUSSION

A. Scenario 1

This scenario focuses on the low PV fluctuations in Fig. 2. Changes in E_{pv} and E_{du} were plotted in Fig. 4(a). Moreover, the SCR and change in SCR were plotted against the PV capacity in Fig. 4(b), and the SSR and change in SSR were also plotted against the PV capacity in Fig. 4(c). In Fig. 4(a), diminutive negative changes in E_{pv} and E_{du} (less than –0.6%) were observed in Case 1. The change in E_{pv} was constant at –0.55%, but the change in E_{du} decreased as the installed PV capacity exceeded 0.6 kWp. Consequently, the SCR in Case 1 remained unchanged when the installed PV capacity was less than or equal to 0.6 kWp, whereas it increased diminutively (less than 0.25%) when the installed PV capacity was greater than 0.6 kWp (see Fig. 4(b)). This outcome was because the decrease in E_{pv} was greater than that of E_{du}. Furthermore, higher negative changes in E_{pv} and E_{du} were observed in

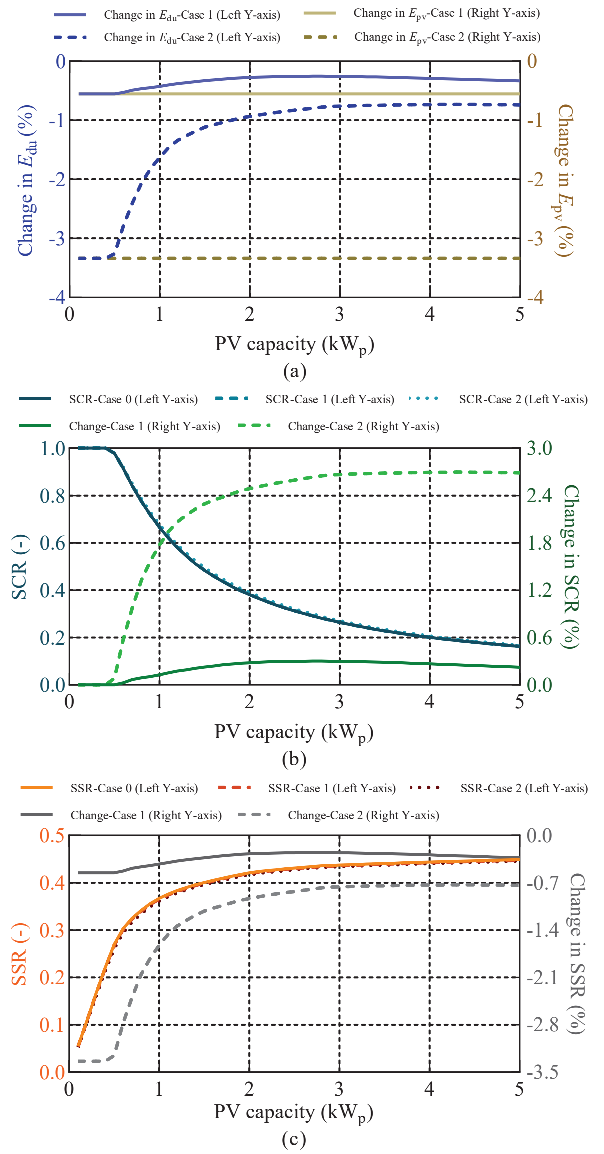

Fig. 4. Comparative self-consumption results of Scenario 1 with different ramp rate limits: (a) change in E_{du}, (b) SCR and change in SCR, and (c) SSR and change in SSR.

Case 2 (Fig. 4(a)). A similar trend was that the change in E_{du} decreased as the PV capacity increased, whereas the change in E_{pv} was constant. Hence, the SCR increased by 2.70%. In contrast, the SSR reduced when implementing the ramp rate control, as depicted in Fig. 4(c). The SSR with Case 1 decreased negligibly ($< 1\%$) due to the diminutive decrease in E_{du}. Notably, it was observed that ramp rate control had a greater influence on the SSR obtained with a small PV capacity than that with a large PV capacity because it significantly reduced E_{du}. Furthermore, the 1% ramp rate limit (Case 2) had a greater influence on the SSR, decreasing it from –3.34% to –0.71%.

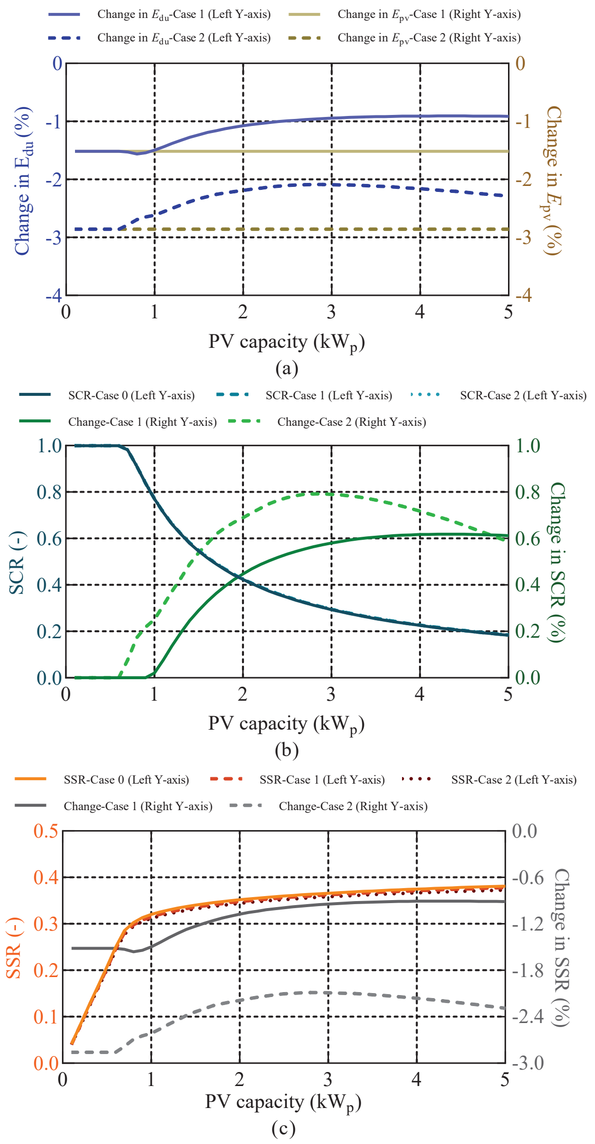

Fig. 5. Comparative self-consumption results of Scenario 2 with different ramp rate limit: (a) change in E_{du}, (b) SCR and change in SCR, and (c) SSR and change in SSR.

B. Scenario 2

Furthermore, the high PV power fluctuations in Fig. 3 were considered in this scenario. Fig. 5(a) illustrates changes in E_{pv} and E_{du} against PV capacity, whereas Figs. 5(b,c) display variations of the SCR/SSR and changes in the SCR/SSR against PV capacity. A similar trend was observed for the SCR and SSR. The ramp rate control had a greater influence on the decrease in E_{pv} and E_{du} for the high power fluctuation scenario than that for the low power fluctuation scenario, particularly in Case 1 (Fig. 5(a)). Fig. 5(b) reveals that the ramp rate control had a minor effect on changes in the SCR, although the ramp rate limit was assigned to 1% for Case 2. This result was because the difference between E_{pv} and E_{du} was mild (less than 1%) for all cases. Thus, the SCR increased slightly (less than 0.8%) as the PV capacity increased. Moreover, when the ramp rate control was implemented, the SSR decreased. In Case 1, a change in SSR reached –1.51% when the PV capacity was small but tended to decrease by –0.91%. Furthermore, the SSR in Case 2 decreased by greater than –2% even though the PV capacity was increased.

IV. CONCLUSION

This study conducted a self-consumption evaluation for grid-connected rooftop PV systems considering the influence of the PV power ramp rate limit. The SCR and SSR were used as technical indicators that display self-consumption levels. Two scenarios were considered: Scenario 1 (low PV power fluctuations) and Scenario 2 (high PV power fluctuations). Three ramp rate limits were assigned in a comparative study. The simulation results reveal that ramp rate control positively affected the SCR. When a ramp rate limit was implemented, the SCR slightly increased for both scenarios. In contrast, ramp rate control negatively influenced the SSR due to the decrease in E_{du}. Hence, the SSR decreased for both scenarios when a ramp rate limit was implemented. Moreover, the influence of the ramp rate control on the decrease in the SSR was higher in the scenario with the high PV power fluctuation than with the low PV power fluctuation. This study investigated the effects of the ramp rate control on two technical indicators: the SCR and SSR. Therefore, future work should evaluate its effects from an economic perspective. Moreover, considering the ramp rate control, the optimal PV capacity should be determined based on techno-economic assessments.

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