

Real-Time Deloading Strategy for PV Systems Based on Voltage Monitoring

Chaouki Messasma¹· Seif eddine Chouaba¹· Bilal Sari¹· Abdallah Barakat²

¹ DAC Laboratory, Electrical Engineering Department, University of Setif1,
19000 Setif, Algeria

²Electrical Energy Research Institute of Nantes-Atlantique (IREENA), Nantes Université,
Nantes, 44000, France

*Corresponding author; Email: chaouki.messasma@univ-setif.dz.

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ABSTRACT

Photovoltaic (PV) systems are emerging as a key solution for clean and renewable energy generation. However, to ensure seamless integration with power grids, they must contribute to frequency stability. This requires maintaining an additional power reserve to emulate the real inertia of traditional synchronous generators (SGs) through virtual inertia. Deloading techniques are commonly used to create this power reserve, but many rely on complex mathematical models or require extra sensors, such as irradiation and temperature sensors. This study presents a novel deloading strategy based on a power reserve control (PRC) method that prioritizes simplicity, stability, and accuracy without the need for additional equipment. The proposed approach operates through two modes in DC-DC boost converters: one dedicated to determining the maximum power point (MPP) using the perturb and observe (P&O) algorithm and another focused on generating the required power reserve. The effectiveness of this strategy was evaluated using Matlab Simulink under various climatic conditions and benchmarked against an alternative method. Furthermore, its impact on frequency stability was demonstrated in an isolated grid under frequency disturbances, highlighting its potential to enhance PV system inertia similarly to traditional SGs.

I. Introduction

To meet the growing demand for electricity, significant efforts are being made to harness electrical power from alternative energy sources, including wind and solar energy, among others [1]. The large-scale integration of renewable energy sources offers several economic and technological advantages, such as cost-effective electricity generation, reduced carbon emissions, and lower operational and maintenance costs [2].

Among these sources, solar photovoltaic (PV) systems have gained considerable attention and are increasingly integrated into power grids. However, as the installed capacity of PV systems continues to expand, they account for a substantial share of total energy generation [3]. This increased penetration introduces several technical challenges, including harmonic distortions, frequency fluctuations, voltage instability, reverse power flow, and coordination issues among network protection devices, potentially compromising grid reliability [4].

Moreover, PV systems inherently lack rotational inertia, making them susceptible to frequency instability and high

uncertainties due to unpredictable variations in solar irradiation and temperature [5]. Addressing these challenges is crucial to ensuring the stable and reliable operation of power systems with high PV penetration.

Grid codes include frequency response requirements and auxiliary services for the decentralized generation, including renewable energy sources. PV systems must have active power reserves that allow them to alter their output power upwards or downwards in response to control system requests in order to meet these criteria [6].

To incorporate PV systems into frequency regulation, some of their active power must be reserved beforehand [7]. The fundamental concept is to emulate the rotational inertia of synchronous generators (SG) with virtual inertia (VI). Virtual inertia is achieved by controlling the power injected through electronic power converters in response to frequency changes. In recent years, research on synthetic inertia has gained prominence, with two primary methods to obtain this additional energy [8]:

- Energy storage: a portion of the energy delivered by the PV will be stored in storage systems such as batteries or ultra-capacitors. In case of disturbance, this power can be used in inertial response [9–11];
- Power reduction or deloading: the maximum power point tracker (MPPT) can be adjusted to operate outside the maximum power point (MPP) to keep a power reserve [12–14].

The cost and complexity of adding an energy storage device to the grid may grow, making techniques like "reduce power or deloading" more appealing. Constant power generation control (CPGC) and power reserve control (PRC) are two categories under which these techniques might be categorized. In CPGC, the system abides by a predetermined power limit that is less than the maximum power output (usually set by the operator). The PV system, however, runs in maximum power point tracking (MPPT) mode if the PV power supply (P_{pv}) reaches this threshold. In PRC, a pre-defined deloading gain is used to determine the reference power (P_{del}), which must be continually monitored [14].

Numerous studies have been undertaken to develop control strategies and generate power reserves under diverse climatic conditions for PV plants. Initially, we present and describe the operating principle of some already-developed strategies. Next, we identify some of the requirements and assumptions of these strategies that may be weak points, and based on these, we propose a new PRC strategy.

A power reserve strategy was developed in [15] composed of two blocks: the first block, called the MPPT block, estimates the maximum power (P_{mpp}) of the PV system using adaptive neural control. The second block, known as the PRC block, utilizes a proportional and integrator (PI) controller to monitor the PV plant and maintain it operating around a deloading power reference (P_{del}) calculated by multiplying the P_{mpp} estimate with the deloading gain (G_{del}).

The artificial neural network (ANN) model used is trained using a dataset of inputs and outputs obtained from the PV system's operating conditions under various weather conditions.

Another strategy is presented in [8], which is also divided into two blocks. The first block estimates P_{mpp} using a linear regression model based on different irradiation and temperature values. The output P_{mpp} of this block is calculated using the equation:

$$P_{mpp} = A_1 + A_2 G_i + A_3 T_i + A_4 G_i T_i \quad (1)$$

where A_1 , A_2 , A_3 , and A_4 are the linear regression model coefficients, and G_i and T_i represent the instantaneous irradiation and temperature, respectively. The second block is similar to the previous strategy, and it generates the desired power reserve using a simple PI controller.

These are valid weaknesses of the two strategies presented [16]. The first weakness limits the applicability of the strategies in real-world situations where partial shading or varying module temperatures can occur. The second weakness adds extra costs to the system as sensors, making it less attractive from an economic perspective. The third weakness mentioned is also a valid concern as offline models may not be able to capture all the variations in climate scenarios. These weaknesses highlight the need for more robust and accurate strategies for power reserve generation in PV systems.

In the temporal periodic switching strategy presented in [18], a different concept of PRC is used. This strategy involves switching between two operating modes periodically. The first mode is the MPPT mode, where the P_{mpp} is calculated using a real-time perturb and observe (P&O) algorithm [17]. The second mode is the PRC mode, which is activated after the MPPT mode is completed. In this mode, the P_{mpp} calculated in the previous mode is stored, and the PV plant is monitored around P_{del} to generate the desired power reserve. This strategy does not require additional sensors, and it is based on real-time operation. However, this strategy has limitations related to the switching time between the two modes, which may affect the system's stability, reduce the lifetime of some

electrical components, and affect also the accuracy of the P_{mpp} calculation, and the PRC performance [16].

The present study proposes a novel PRC approach that overcomes the limitations discussed above. The proposed method generates a power reserve by monitoring changes in the weather conditions (G and/or T) using the voltage fluctuation of the PV system (V_{pv}) as an indicator. This approach ensures grid stability and eliminates the need for additional equipment or control blocks, such as dc link conductance [18]. Furthermore, this technique guarantees that the desired power reserve is accurately produced without requiring any supplementary sensors.

The paper is organized as follows: Section II explains the underlying concept of the proposed PRC approach, including its trigger and control signal and the frequency regulation (FR) principle. Section III presents and discusses the simulation results of different tests carried out using the proposed PRC method and its integration in FR. Finally, the paper concludes by summarizing the contributions of this study and outlining potential future research directions.

II. Proposed PRC strategy

The proposed approach operates through a loop consisting of two successive phases in the DC-DC boost converter, as illustrated in figure 1: MPPT mode and PRC mode. A monitoring device continuously detects variations in the photovoltaic (PV) voltage, denoted as $E_v(t)$, by comparing it to a predefined threshold (S). This process generates a signal, SIG E_v , which initiates the operational loop. The activation of this loop indicates the onset of a climatic change related to temperature (T) and/or irradiance (G).

The following subsections provide a detailed examination of each component of the proposed PRC strategy.

II.1. DC-DC boost cycle modes

(1) Maximum power point tracking mode

In MPPT mode, the PV system operates with the objective of determining P_{mpp} in real time using the perturb and observe (P&O) algorithm. This algorithm is widely adopted due to its simplicity and ease of implementation. It functions by perturbing the operating point of the PV system and observing the corresponding change in power output. If the power output increases, the perturbation continues in the same direction; however, if the power output decreases, the perturbation shifts in the opposite direction. This iterative process continues until the MPP is accurately identified [20].

To ensure the P&O algorithm has sufficient time to accurately compute P_{mpp} , the duration of MPPT mode (denoted as T_1) is experimentally adjusted using a timer. This adjustment considers several factors, including the PV system's characteristics, environmental conditions, and other parameters that may influence system performance.

(2) Power reserve control mode

The power reserve control (PRC) mode is initiated once the MPPT mode is completed, which is marked by reaching the duration T_1 . In the first step of this mode, the previously attained P_{mpp} and corresponding voltage (V_{mpp}) values are stored. These values are then used in Equation (2) to compute the deloading power (P_{del}).

Next, a proportional-integral (PI) controller is employed to adjust the PV system's operation around P_{del} . The controller regulates the duty cycle of the DC-DC boost converter, thereby modifying the PV system's operating points to maintain the required power reserve (P_{res}). The values of P_{del} and P_{res} are determined using the following equations:

$$P_{del} = G_{del} P_{mpp} \quad (2)$$

$$P_{res} = P_{mpp} - P_{del} \quad (3)$$

Here, G_{del} represents the deloading gain, a parameter set by the grid operator to define the maximum power a PV system can supply to the grid while operating in PRC mode. It also determines the acceptable margin of power loss that the grid can tolerate.

To regulate the PRC mode duration (T_2), a second timer is used. This duration corresponds to the time required for

the PV system to adjust its operation around P_{del} and stabilize at that power level. The total cycle duration, T_{cy} , is the sum of the two mode durations ($T_{cy}=T_1+T_2$).

The variation detection block remains disabled throughout the cycle period (T_{cy}) to prevent voltage fluctuations caused by the transition between the two modes, ensuring system stability at the designated P_{del} (as illustrated in figure 1). Once the cycle period concludes, the variation detection block is reactivated, and the system continues operating in PRC mode until a new climate change event occurs, triggering the start of another cycle.

The following subsections provide a detailed explanation of the triggering and switching signal technique used to initiate the two-mode cycle.

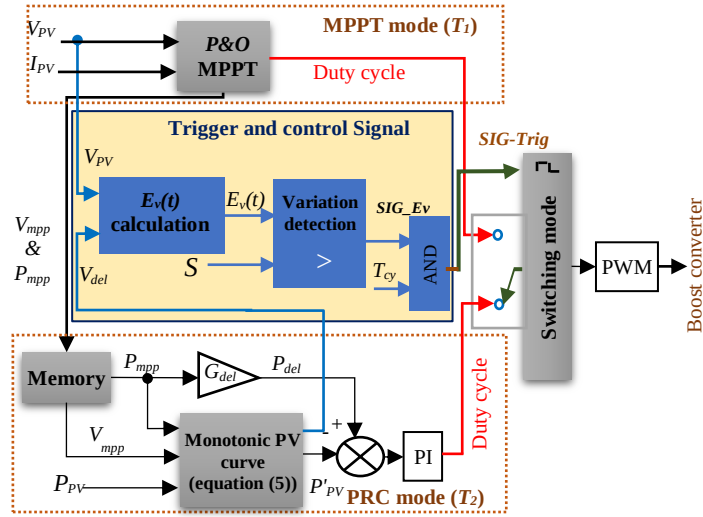


Figure 1. Power reserve generation using voltage variation detection

II.2. Switching cycle signal

The cycle is triggered or switched using a signal known as SIG_Trig (figure. 2a), which is generated by a block responsible for determining the variation in PV voltage as:

$$E_v(t) = (V_{del} - V_{pv}) / V_{pv-max} \quad (4)$$

With $E_v(t)$ the signal represents the instantaneous relative error of the PV voltage, while V_{del} is the voltage value corresponding to the operating power reference P_{del} that has been previously stored in memory. V_{pv} is the instantaneous voltage of the PV system, while V_{pv-max} is the maximum voltage that can be reached by the PV planet

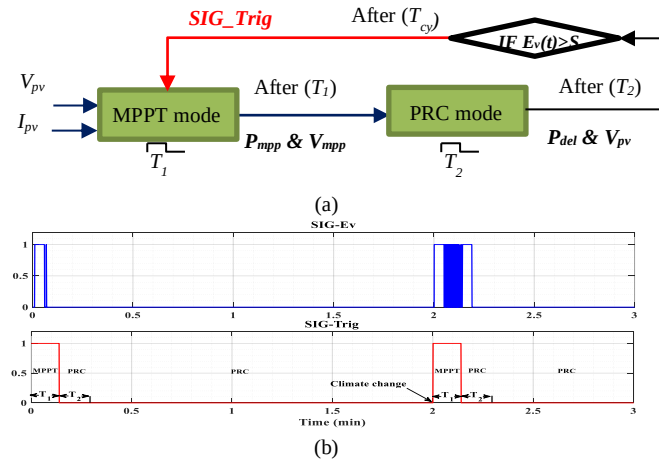


Figure. 2 Trigger cycle signal (SIG_Ev voltage variation detection signal, SIG_Trig trigger signal)

The calculated $Ev(t)$ value is compared to a threshold S , which is set higher than the error margin tolerated by the voltage sensor used to measure V_{pv} . In this study, S is defined as 0.2%, corresponding to the tolerance level of the sensitive voltage sensor integrated into the system.

Figure 2b illustrates an example of a cycle trigger signal. The first cycle is initiated when the PV system is coupled to the grid at start-up, with a total duration of 0.28 minutes ($T_1 = T_2 = 0.14$ minutes). The system remains in PRC mode until $t = 2$ minutes, at which point a climatic change is detected by the SIG_Ev signal, triggering the second cycle.

The following subsection describes the principle used to determine the region where the PV system will enter deloading mode.

II.3. Deloading Region

As illustrated in figure 3, each deloading point on a PV panel corresponds to two distinct voltage values: one on the left side of the MPP (V_{del-L}) and the other on the right side of the MPP (V_{del-R}). When adjusting the PV panel to reach the desired P_{del} , selecting the correct deloading region is critical to preventing oscillations between these two positions.

As illustrated in figure 3, the right side of the MPP corresponds to higher voltage values than the left side. This characteristic enhances the efficiency of the DC-AC converter by reducing power losses and improving overall system performance. Therefore, this study selects the right-side region of the MPP for deloading, following the approach adopted in [21].

To ensure that deloading is performed on the correct side (right), a monitoring algorithm is implemented. This algorithm modifies the actual PV curve (represented by the black line in figure 3) by generating a new curve, P'_{pv} (depicted as a green dotted line). On the right side of the MPP, the new curve retains the original shape. However, on the left side, it is replaced by its reflection across a horizontal line passing through the MPP (red line), effectively mirroring the original curve. This transformation ensures that deloading is correctly applied on the appropriate side of the PV curve.

During the deloading process, the PI controller receives the voltage value corresponding to the left side of the modified curve (V'_{del-L}), obtained through the mirroring process. However, this value introduces a significant negative error in the controller, leading to its rejection. As a result, only the voltage value on the right side of the modified curve (V_{del-R}) is considered valid and retained for further processing.

The P'_{pv} curve is given by [21]:

$$P'_{pv} = \begin{cases} P_{pv}, & V_{pv} \geq V_{mpp} \\ 2P_{mpp} - P_{pv}, & V_{pv} < V_{mpp} \end{cases} \quad (5)$$

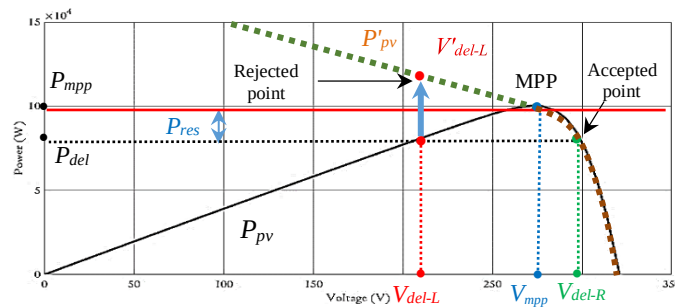


Figure . 3 Deloading region principal using 100 kW PV plant

II.4. Frequency regulation (FR)

The behavior of SGs can be replicated in PV systems using virtual inertia (VI) control and droop control. VI control emulates the inertia of SGs by incorporating a virtual inertia constant into the control scheme. This constant represents the energy stored in the system and is proportional to the power output. Droop control, on the other hand, regulates frequency by adjusting the power output based on the deviation between the measured frequency and the nominal frequency.

A combination of both control methods is often employed to enhance the frequency regulation performance of PV systems. In this work, the additional power used for frequency regulation through the combined VI and droop control method is calculated using Equation (6) and illustrated in figure 4.

$$P_{FR} = K_{VI} \frac{df}{dt} + K_{droop} \Delta f \quad (6)$$

Where P_{FR} is the extra power used to regulate the frequency, K_{VI} is the virtual inertia constant and K_{droop} is the droop coefficient. $\frac{df}{dt}$ and Δf are the Rate of Change of Frequency (RoCoF) and frequency variation respectively.

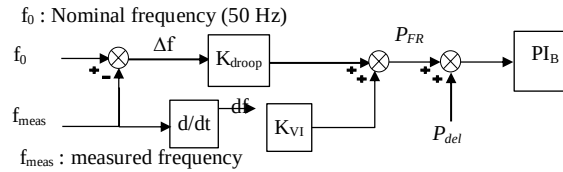


Figure. 4 Frequency regulation integration

In the following section, we will describe the different simulation tests that were conducted to evaluate and demonstrate the efficiency and effectiveness of the proposed strategy.

III. Simulation tests, results, and discussion

III.1. PRC validation

The proposed PRC strategy was tested under two different climatic scenarios to evaluate its effectiveness. The first test was performed under varying irradiation levels, while the second test considered varying temperatures. To highlight the advantages and improvements of the proposed approach, a comparison was made with the temporal switching technique [18] discussed in the introduction. The results of these MATLAB Simulink simulations will be presented and analyzed in the final section.

The simulation was conducted on a two-stage, three-phase PV system, as illustrated in figure 5. The system consists of a 100 kW PV power plant composed of 66 parallel strings, with each string containing five SunPower SPR-

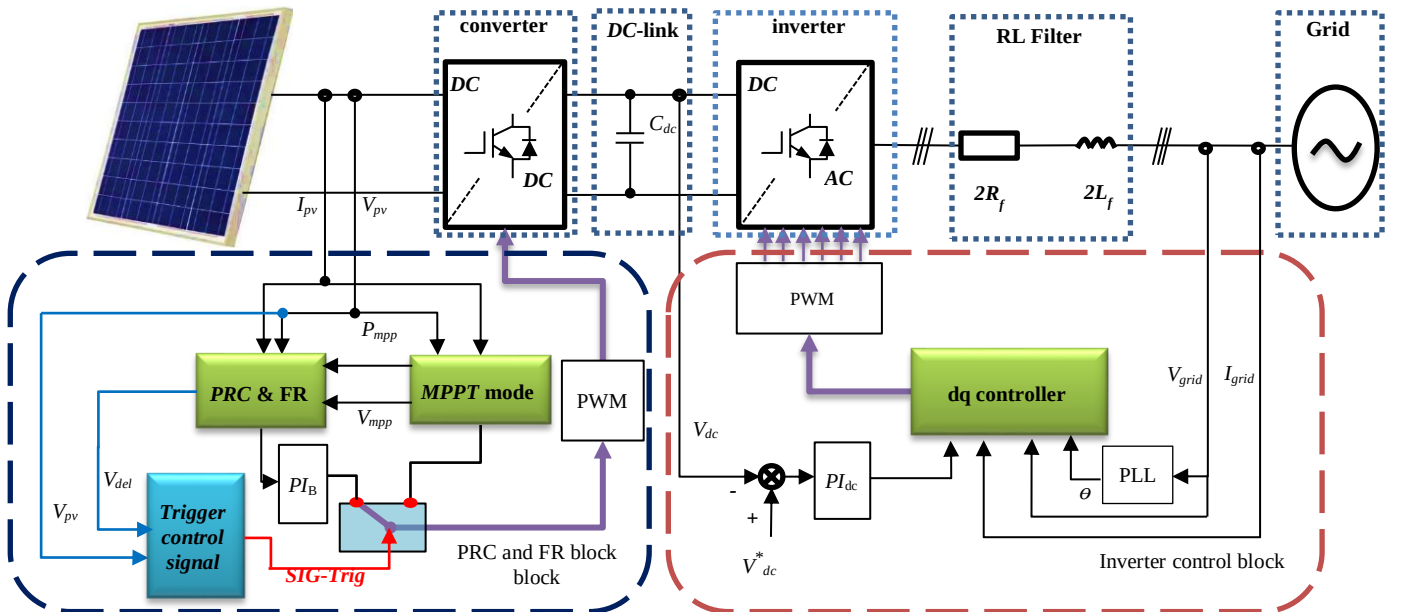


Figure. 5 System of a two-stage three-phase PV with the proposed PRC strategy and inverter control 305E-WHT-D modules [5] connected in series. The PV panels are linked to a DC-DC boost converter, which is

regulated by the proposed PRC strategy to generate a power reserve while operating in deloading mode.

To ensure the transfer of all active power extracted from the PV system without generating any reactive power, the boost converter is connected to a DC-AC inverter. This inverter is controlled using an active and reactive power control technique [22,23]. Additionally, all components of the PV system are connected to the grid through an LR filter [24].

Table 1 lists the values of the various components and parameters of the system.

Table 1. Parameters of the two-stage three-phase PV system

Parameters	Description	Value
PV parameters		
P_{pv}	PV array power	100 kW
V_{pv-max}	Maximum voltage reached by the PV	350 V
Boost converter parameters		
L_{boost}	Inductance of boost converter	0.54 mH
C_{boost}	Capacitance of boost converter	1400 μ F
C_{dc}	DC link capacitance	6000 μ F
V_{dc}^*	DC-link voltage reference	600 V
F_B	Boost converter switching frequency	5 kHz
Filter and grid parameters		
V_{grid}	Rated grid voltage (line-to-line RMS)	300 V
F_{inv}	Inverter switching frequency	25 kHz
F_0	Grid frequency	50 Hz
L_f	Inductance of the filter	0.85 mH
R_f	Resistance of the filter	1 m Ω
(K_{pb}, K_{ib})	Converter PI controller parameters	(5 ; 80)
(K_{pdc}, K_{idc})	DC-link PI controller parameters	(10 ; 0.1)

III.2. Comparison with online PRC

To evaluate the effectiveness of the proposed deloading PRC strategy, a comparison was conducted with an online-mode strategy based on the same principle, utilizing the temporal switching technique. Both methods were implemented on the same system shown in figure 5 and tested within a simulated climatic scenario featuring simultaneous variations in temperature and irradiance.

The climatic scenario included two instances of decreased irradiation: the first droop from 1000 W/m² to 900 W/m² at t=2 min, followed by a further reduction to 800 W/m² t=4.5 minutes. Additionally, two temperature increases were applied: the first from 25°C to 30°C at t=2.5 min, and the second from 30°C to 35°C at t=6 min. In this test, the proposed approach utilized a cycle duration of $T_{cy}=0.2$ min, whereas the temporal switching technique employed a fixed switching period of one minute ($T_{sw}=1$ min). The value of G_{del} was set to 0.9. The corresponding simulation results are presented in figure 8.

The comparison results indicate that the proposed approach effectively generates the required power reserve while reducing the number of switching operations compared to the temporal switching technique. In contrast, the temporal switching technique requires a higher switching frequency and may fail to guarantee the necessary power reserve in certain conditions. These findings highlight the effectiveness and superiority of the proposed PRC strategy over the temporal switching technique.

III.3. Frequency regulation integration

The proposed PRC and its effectiveness in improving frequency stability were demonstrated through its implementation in an isolated PV grid system. As depicted in figure 9, this system consists of a SG representing the primary grid, a 100 kW PV plant coupled in various configurations, and a main load of 200 kW representing consumption. It should be noted that during the tests, the G_{del} parameter was set to 0.8, corresponding to a 20% power reserve. Implementing the PRC in this system allowed for an assessment of its benefits in enhancing frequency stability, a critical factor in ensuring the overall reliability and performance of the grid.

To evaluate the system's performance, tests were conducted in three stages. In the first stage, a 400 kW SG was connected to the main load without integrating the PV plants. Subsequently, an additional 100 kW load was sequentially connected and disconnected at $t=80$ s and $t=140$ s, respectively. This procedure was designed to simulate temporary variations in power demand and to analyze the system's response to such fluctuations.

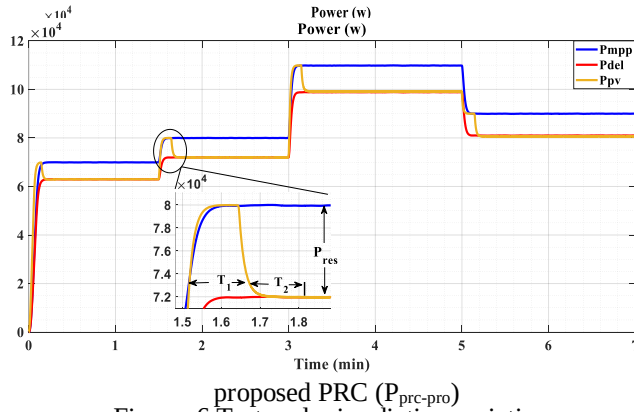


Figure. 6 Test under irradiation variation

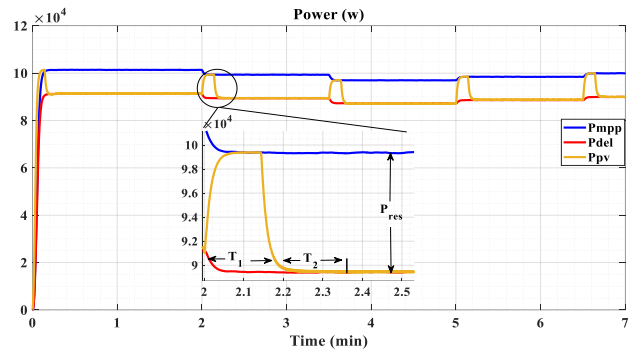


Figure. 7 – Test under temperature variation

In the second stage, the SG was configured to 300 kW, and a 100 kW PV system was integrated into the power system, replacing 25% of the total power. The same power variation scenario from the first test was applied to this configuration. However, in this case, the power reserve was not utilized for frequency regulation. This step was essential for evaluating the impact of PV system integration on the power system and analyzing its response to changes in power demand without the use of a power reserve for frequency stabilization.

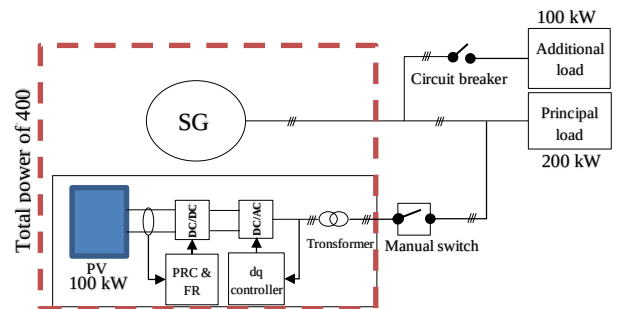


Figure. 9 PV plant connected to an isolated grid

The third and final stage built upon the second configuration by incorporating the PV system along with the power reserve to demonstrate the benefits of the proposed control loop, leading to a more stable frequency response, crucial in highlighting the effectiveness of the proposed PFR as a reliable power supply.

The isolated grid frequency under various scenarios is graphically depicted in figure 10. Understanding the behavior of the isolated grid under different operating conditions is critical for assessing its overall reliability and stability.

III.4. Discussion

Based on the simulation results presented in the various figures mentioned earlier, several key conclusions can be drawn. Firstly, the proposed PRC strategy has been successfully validated and tested under different climatic conditions, including variations in irradiation, temperature, and simultaneous climatic changes. In all these scenarios, the proposed technique efficiently generated the planned power reserve P_{res} (10%), demonstrating its robustness and effectiveness.

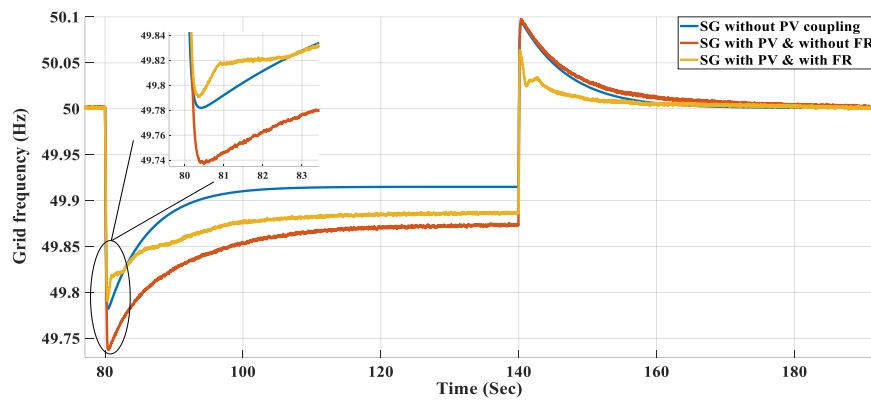


Figure. 10 Grid frequency in different configuration

Secondly, the comparison between the proposed PRC strategy and the temporal switching strategy revealed that the latter resulted in a higher number of switching cycles (7 cycles) due to its fixed switching time and failed to generate the desired power reserve correctly in all test scenarios (P_{res1} and P_{res3}). In contrast, the proposed PRC strategy resulted in fewer switching cycles (5 cycles), matching the number of climatic changes, while accurately producing the required power reserve in all situations (P_{res2} and P_{res4}). This underscores the clear advantages of the proposed PRC strategy over conventional methods.

Thirdly, the significant benefits of the proposed PRC in frequency regulation were demonstrated in both load impact and load shedding scenarios. The integration of PRC substantially improved frequency stability, reducing the frequency nadir from 49.74 Hz (0.26 Hz of droop) without frequency regulation, and from 49.78 Hz (0.22 Hz of droop) in the case of an SG without PV coupling, to 49.79 Hz (0.21 Hz of droop). This improvement in frequency stability is a crucial advantage of the proposed PRC, ensuring the stable operation of the power system under dynamic conditions and unexpected disturbances, such as load impact and load shedding.

Overall, the simulation results highlight the effectiveness and advantages of the proposed PRC strategy in enhancing the stability and reliability of isolated PV grid systems. Its ability to efficiently generate power reserves, reduce switching cycles, and improve frequency regulation makes it a promising solution for future power systems.

IV. Conclusion

This study introduced a novel deloading strategy utilizing a power reserve control (PRC) method based on a two-mode cycle. The first mode enables real-time maximum power point tracking (MPPT), while the second mode generates the power reserve (PR) using a PI controller through a mirror system, ensuring deloading on the correct side of the PV curve. This cycle is initiated by a trigger signal that monitors variations in PV panel voltage, which reflect climate changes, ensuring adaptability to any environmental variations.

Simulation tests conducted on a three-phase PV system under various climatic scenarios, along with validation against literature strategies, highlight its superiority in accurately providing the desired power reserve without complex calculations or the need for additional equipment. Furthermore, the proposed deloading technique has demonstrated its effectiveness in improving frequency stability in an isolated grid, addressing a key challenge in achieving high PV penetration in power networks.

As a perspective, the proposed strategy's contribution to grid stability can be further optimized by fine-tuning parameters such as K_{VI} , K_{droop} , and G_{del} using advanced techniques. Future work may also focus on enhancing the approach by replacing conventional PI controllers with more sophisticated and intelligent control methods. Overall, this study presents a significant advancement in power reserve strategies for PV systems and provides a foundation for further research and development in this field.

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