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Internal active power reserve management in Large scale PV Power Plants

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***Abstract*— Active Power Reserves (APRs) provided through curtailment (iAPRs) or through auxiliary storage systems (aAPR) with Large scale PV Power Plants (LPVPPs) becomes a reality in the near future with high penetration levels of Photovoltaic (PV) power into the grid. Therefore, this paper analyzes the solutions for iAPR fulfillment in central inverter based - LPVPPs in terms of their layout, configuration and control architecture. During iAPR supply, the LPVPP has to operate under its Maximum Power Point (MPP), which means that the MPP algorithm has to undergo several changes. For this purpose, the paper proposes to supply iAPRs by means of a sweep function distributed over the PV inverters used in the central inverter station which has the potential to guarantee a maximum energy extraction along with a secured supply of the APR in any given meteorological condition.**

Keywords-LPVPP, iAPR, ENTSO-E;

I. INTRODUCTION

PV power became extremely popular in the recent years reaching impressive penetration levels in several parts of the grid (e.g. Germany, Italy). When the total installed capacity began to cause grid instabilities, system operators started to impose strict Network Codes (NCs). For example, the NCs proposed by the European Network of Transmission System Operators for Electricity (ENTSO-E) show an increased interest over the technical requirements of every grid connected application during transient grid conditions. At the same time, the NCs require the supply of ancillary services which is a new feature added to the future grid connected medium and LPVPPs [1-3].

Frequency support became a subject of interest recently due to several triggering events. Also, an increased number of downward regulations forced ENTSO-E to impose the Frequency Sensitive Mode (FSM) operation and sharing of Frequency Containment Reserves (FCR) requirements.

To participate with APRs, LPVPPs have to produce the APR by curtailment (iAPR) or to provide it from auxiliary sources (aAPR), such as batteries. Both methods can offer proper solution to the need of FCR supply but iAPRs represent a more flexible solution given the fact that aAPRs require maintenance, have limited lifetime and necessitate long recharging periods.

The decentralized power production by means of LPVPPs implies a strong TSO process of grid reinforcement, but sharing the responsibilities, part of the extra costs can be saved. Thus, grid support functions and the supply of APRs becomes a necessity and its deployment has to consider:

- **Network frequency requirements**– the main target of the TSO is to synthetically enforce LPVPPs with frequency support functions such as the FSM operation and highly encourage them also for the supply of IR during frequency excursions [2, 4, 5].
- **Power ramp-rate requirements** – these requirements are seen as the next step to correct LPVPPs power fluctuation and are already demanded in island power systems [4, 6, 7].
- **TSO APR requirements** – LPVPPs have to share part of the total APR necessity and has to guarantee its security and reliability during the participation period on the reserve energy market.

Compared with the classical power system approach in which conventional power plants had well defined APRs in terms of coal, gas or oil, in modern power systems having LPVPPs as the main supplies of power, active power reserve (iAPR or APR) management and supply becomes a topic of extreme interest. Therefore, flexible and reliable methods of iAPR management are needed in order to ensure LPVPPs with constant iAPR in every cloud cover scenario present at the production level or TSO APR request.

In consequence, this work considers for the first time several iAPR management methods depending on different characteristics present in the LPVPP layout, and it proposes a sequential sweep based method, which can ensure the pre-set iAPR level to a high degree of accuracy. This article is structured as follows: section II shows the system description, section III presents several proposed methods iAPR management along with the design and implementation of a proposed sweep method, section IV presents the study cases and in section V the conclusions are drawn.

II. SYSTEM DESCRIPTION

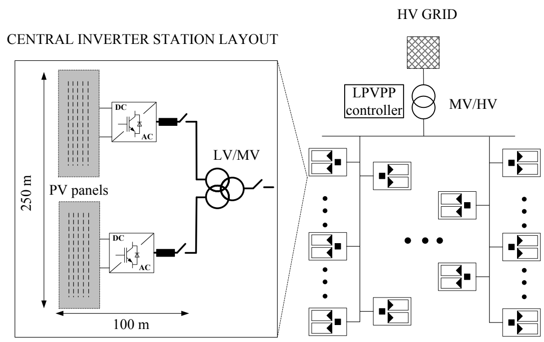

Fig. 1 Central inverter based LPVPP layout

The modeling process of central inverter based LPVPPs starts from the basic statement that the plant has to accurately reproduce the effects induced by the irradiance and temperature in the injected active power.

The design of central inverters shown in Fig. 1 starts from the power production level –the PV panels, which are modeled as current sources sensitive to irradiance and temperature changes, while for the PV central inverters, average sources are used to reproduce their response and to reduce the calculation effort.

The LPVPP layout consists of multiple MV feeders to which central inverter stations are connected and can handle the power extracted from the panels and through a MV/HV transformer, inject the produced power into the HV grid [8].

III. iAPR Management in PV central inverters

The APR demand for LPVPPs becomes a necessity in order to increase the percentage levels of penetration into the grid. In consequence, plant owners have to manage their development either by curtailment either by adding extra equipment to the LPVPP.

In consequence, this works proposes to analyze several iAPR management methods which haven't been discussed in the literature yet and might have the potential to become feasible candidates which can ensure central inverter – based LPVPPs with reliable active power reserves.

A. PV panel characteristic method for iAPR generation

The method presented in Fig. 2 takes into consideration the characteristics of the PV panels connected to the DC input of the PV central inverter. Based on the cloud cover conditions, the algorithm dictates the MPP operating point and dynamically creates the iAPR used for ancillary services. To ensure a certain amount of iAPR, the central inverter has to operate under its MPP condition imposing an increased DC voltage reference. Moreover, the references for the inner loop current control (i_α and i_β) are set using the inverse matrix (M^{-1}) used in the instantaneous power theory.

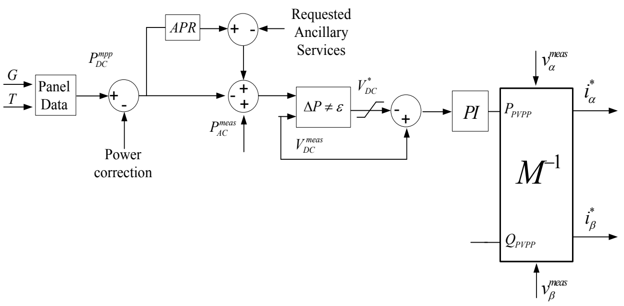

Fig. 2 Proposed control architecture for dimensioning iAPRs based on PV panels characteristics

A major disadvantage of this proposed method is the dependency on the PV panel characteristics. Therefore, the method needs to consider that ageing and partial shadowing effect has a direct impact over the long term power production.

B. Central inverter configuration based iAPRs

The method presented in the figure below relies on the fact that the PV central inverters have multiple DC inputs and their configuration is based on a parallel operation of several converters. This configuration can provide a proper iAPR management since one of the inverters is operating at its MPP and becomes the reference for the rest of the inverters. The iAPR is divided among the remaining inverters in order to ensure the desired iAPR.

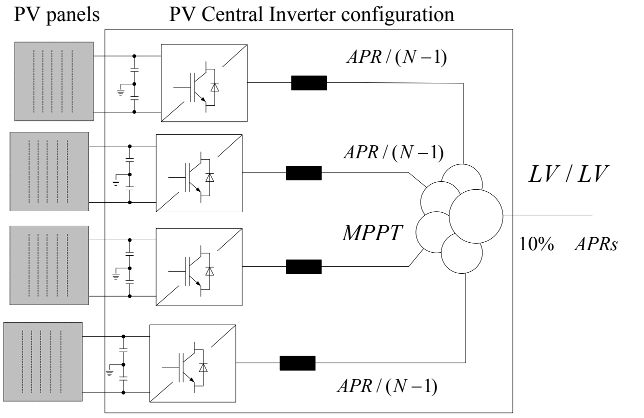

Fig. 3 Central inverter configuration based iAPR generation

C. Central inverter station layout based iAPRs

Using this method, the iAPR is created based on the topology of the entire central inverter station. One central inverter is operating in its MPP mode and becomes the reference for the other central inverter, which has to reduce its output power accordingly in order to fulfill the APR requirements.

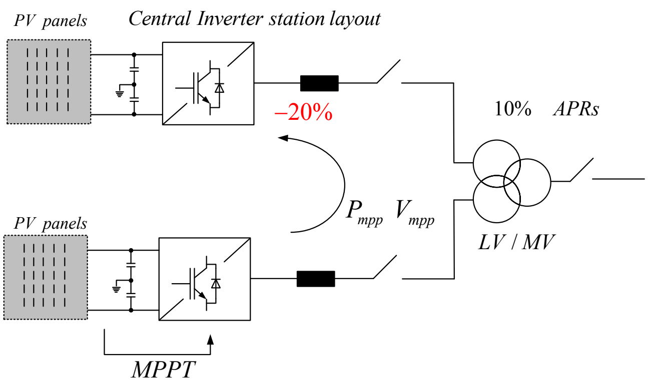

Fig. 4 Central inverter station layout configuration iAPR generation

The main drawback of this method is in terms of reliability which means that the irradiance might differ from one central inverter to another and can have a decisive impact over the total APR generated.

D. Proposed sweep method for iAPR generation

Another method to internally generate iAPRs is by the use of a sweep function after both converters have reached their MPP conditions. The proposed sweep method aims towards a synchronized operation among the converters used in the station with the purpose of providing a constant and reliable iAPR by considering also the changes in irradiance.

The basic operation principles of the proposed sweep method are listed as follows:

- **MPP mode** – the sweep function scans for the MPP condition by measuring the produced power and adjusts the DC voltage reference accordingly
- **iAPR mode** – from the MPP conditions, the method searches to fulfill the iAPR requirement (e.g. 10% from P_{max}) and in order to accomplish this, the method forces the inverter to operate at higher DC voltage than the V_{mpp}
- **Synchronized swing operation** – the PV inverters used in the topology of the central inverter station have a synchronized operation between the above mentioned modes. This means that the converters continuously swing their operation between MPP mode and APR mode to provide a constant iAPR.

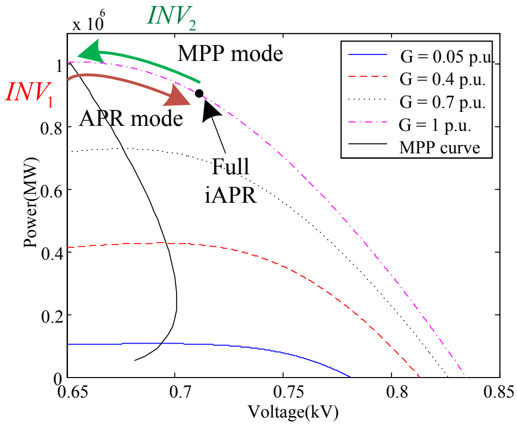

Fig. 5 Proposed sweep function operation for iAPR generation

To successfully provide the iAPR, the proposed sweep function relies on the following parameters:

- **Sweep function frequency** – operation frequency for both MPP and APR mode. This frequency dictates how often the DC voltage is updated in order to meet with the set conditions of the present mode.
- **Applied voltage step** – during each time step, the DC voltage reference is modified with a preset voltage step imposed by the sweep function

IV. Results

The entire system was developed, tested and evaluated over a Real Time Digital Simulator (RTDS) platform that offers superior advantages in terms of calculation effort and accuracy of the obtained results.

The iAPR management studies of central inverter-based LPVPPs are reduced to a PV central inverter station with an installed power of 2 MWp.

A. Normal operation

In normal operation conditions with constant power production and with the grid frequency within the rated values, the proposed sweep method function starts to impose different operation modes for the participating inverters.

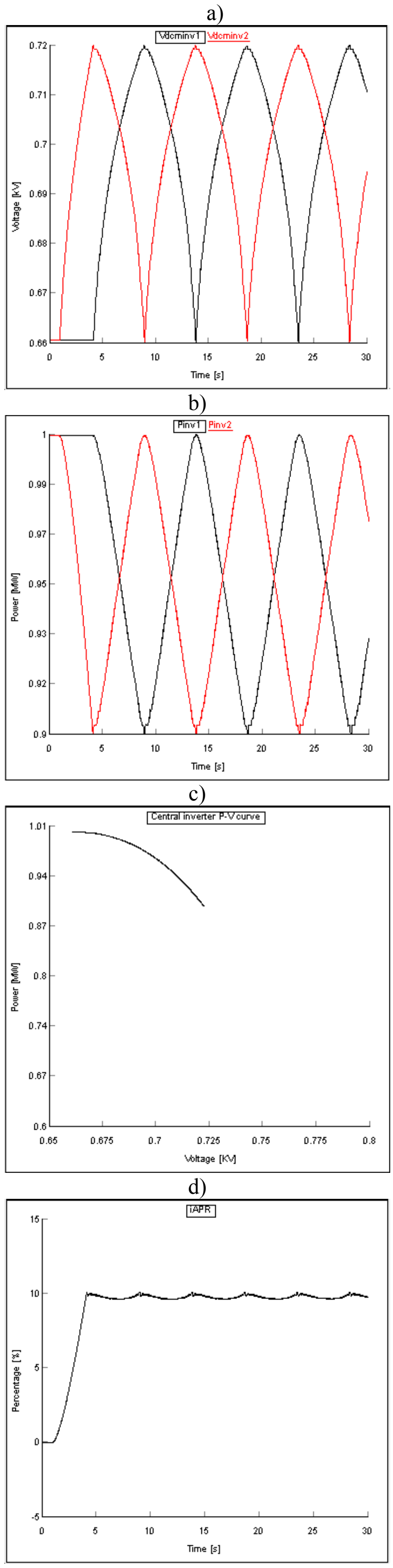

Fig. 6 Proposed sweep operation: a) DC voltage during sweep b) Central inverter power production c) P-V characteristic of the PV central inverter d) iAPR time domain evaluation

In consequence, the DC voltages are continuously changed (see Fig. 6a) which consequently forces the converters to modify their output power (see Fig. 6b).

The swing character of the proposed sweep method can be observed in Fig. 6c which shows the operation principle applied to the power converter. The produced power oscillates between the MPP and APR conditions and, as a result, a constant desired iAPR is obtained (e.g. 10% from P_{max} see. Fig. 6d).

B. *Irradiance changes*

The most challenging and decisive factor which highly influences the iAPR generation process, remains the nature of the PV central inverter station primary energy resource - the irradiance.

For this purpose, the proposed sweep method was tested for irradiance variations at the production level. As it can be observed from Fig. **7**a, the power production is directly influenced by the irradiance and consequently the nature of the iAPR changes.

During high slopes of irradiance, the sweep method operates in the MPP mode in order to decide the maximum available power, followed up by the APR mode which dynamically restores the iAPR in the system.

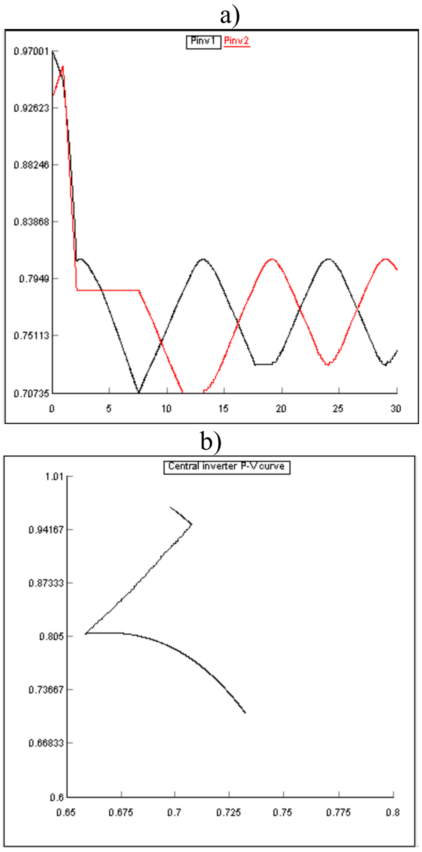

Fig. 7 Irradiance changes present at the power production level: a) Active power output of the inverters b) P-V characteristic during irradiance changes

C. *iAPR deployment*

The main purpose of creating iAPRs is to enhance LPVPPs with more grid support functions such as frequency and ramp rate control capabilities. Thus, plant owners have to be able to flexibly operate their iAPRs according to TSO requirements in case the LPVPPs participate to the total APR need.

In order to test the iAPR deployment based on the proposed sweep operation, both cases of upward and downward regulation procedures were analyzed and considered (see Fig. 8 and Fig. 9).

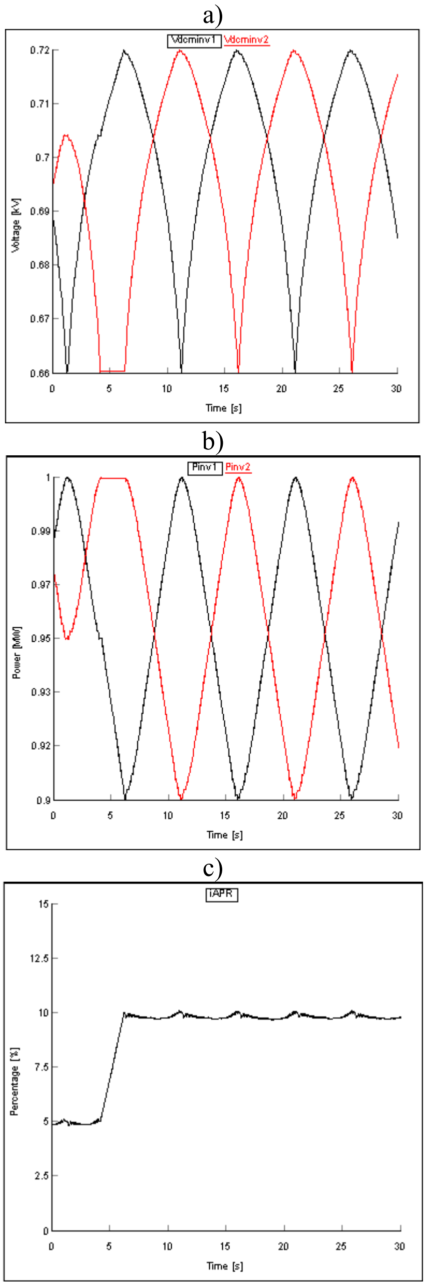

Fig. 8 iAPR upward deployment: Time domain evaluation of the DC voltage in PV central inverters used b) Active power output of PV central inverters c) iAPR management during iAPR demand increase

To operate the iAPR in a downward manner, the sweep method increases the value of the DC voltage at the input of the inverter accordingly (see Fig. 8a), until the iAPR requirements are met.

For this study case, the central inverter was considered to operate with 5% of iAPR from the total available power (see Fig. 8b) and the iAPR references was modified to a value of 10 % as seen in Fig. 8c.

On the other hand, during upward regulation procedures, the iAPR is reduced from a value of 10% towards a value of 5%. As expected, the sweep method continuously regulates the DC voltage level until the desired amount of iAPR is obtained (see Fig. 9).

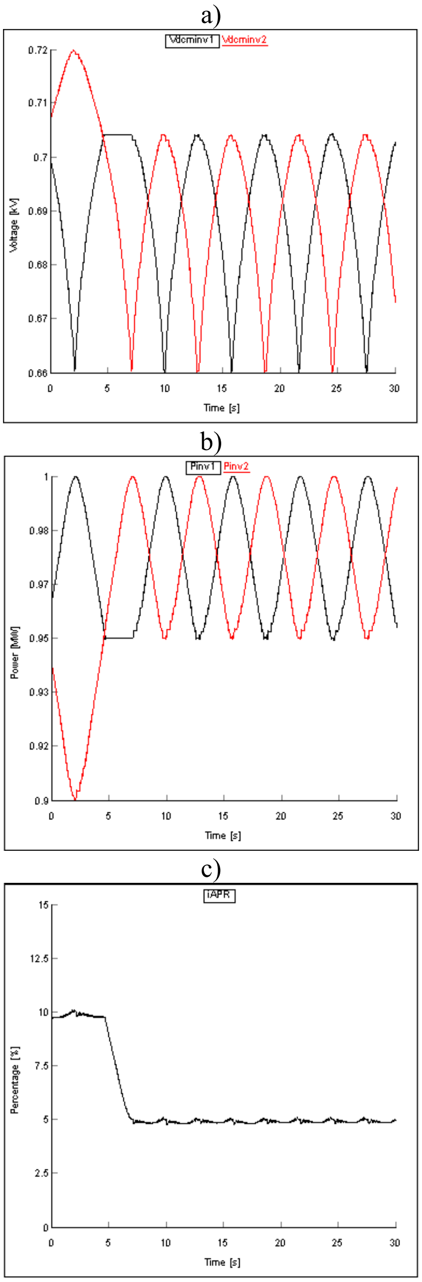

Fig. 9 iAPR downward deployment: Time domain evaluation of the DC voltage in PV central inverters used b) Active power output of PV central inverters c) iAPR management during iAPR demand increase

V. Conclusions

In order to fulfill different NCs, the management of iAPRs and their supply has to be evaluated first at plant level, followed up by a dispatch process over the production units.

The technical analysis performed in this paper over the PV central inverters, showed that iAPRs can be generated only by operating under the MPP conditions taking into consideration the topology, configuration and the control architecture of the entire PV central inverter station.

The focus of the paper was to propose a novel control architecture which enables the possibility of having reliable iAPRs in any irradiance change condition or grid instability scenario. For this purpose, a sweep method was used in order to enhance PV central inverters with a synchronized swing operation between MPP and full APR conditions which in the end guarantees a secure amount of iAPR.

The obtained results have shown that the proposed sweep method has a flexible nature, dynamically adjusting the magnitude of the required iAPR which can easily adapt to changes in demand and deployment of iAPR during instabilities.

VI. References

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