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Synchronous Power Control for PV Solar Inverters With Power Reserve Capability

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Abstract— **The increasing penetration of renewable energy systems force the grid-connected power converters to use advanced active power controls, which needs to add more functionalities to their control strategies. A power reserve control is being required for grid support capabilities on Renewable Energy Sources (RES). Classical algorithms as the Maximum Power Point Tracking (MPPT) cannot withstand power reserve on its control, due to this, different control strategies have to be formulated to gain the power reserve capability. On this paper a cost-effective solution to perform the power reserve is presented, which provide a good solution for frequency regulation as well as for general grid fault conditions. Simulation test have been performed to verify the control capacity of this cost-effective solution.**

Keywords—Power reserve control; maximum power point tracking; PV systems; grid-connected power converters; Syncrhonous power control.

I. INTRODUCTION

In recent decade, renewable energy sources (RESs) has been continuously increasing, especially for grid-connected applications. The uncertain behavior of PV systems make the power reserve on those system a challenging control issue, mainly due to the extended control algorithms such as MPPT [1] where the maximum power point tracking (MPP) of each PV is achieved.

Energy sources such as photovoltaic panels (PVs) and wind turbines (WTs) has imposed new challenges in grid operation control, forcing the grid code to add some new requirements to those systems [2],[3], where those systems are not allowed to immediately disconnect from the grid in case of grid perturbations. The main goal is to achieve a power reserve on PV modules that provide the capability of frequency regulation on the system. Classical control strategies presented on the literature are mainly generated without knowledge of solar irradiance and temperature. If the PV system are equipped with irradiance measurement, it is possible to use a maximum power point estimator (MPPE) as presented in [4]. However, it is not common of residential or commercial scale PV systems.

In order to fulfill grid code specification and power reserve capability, the complementation of a PV system with energy storage [5] helps to keep the power generation of the system, as well as grid fluctuation and faults [6]. The use of energy storage also introduce additional control challenges, such as accurately limit the State of Charge (SoC) of the battery within safe operation ranges. Mainly focusing on the idea of having a power reserve on the PV panels different approaches can be obtained. On [7] a sensorless power reserve is achieved by application of both and MPPT control strategy and a Constant Power Generation (CPG) strategy, on [8] a similar approach is taken to fulfill grid regulations. On [9] an MPP estimation is shown, where a capacity to reserve some power generation on the PV unit is possible.

On this paper a power reserve control on PV systems is presented, on which a joint action of two inverter units provide the ancillary reserve needed on grid support specifications. On section II an introduction of power reserve is going to be shown, afterwards on section III the proposed power reserve control strategy is going to be presented. Finally some simulation results are shown on section IV and discussed on Section V.

II. POWER RESERVE CONTROL STRATEGY

Power reserve among PV units has been increasingly imposed to this variety of energy resource by the grid codes, in order to provide frequency and voltage support on grid perturbations. Grid frequency support is demanded to this system that cannot longer disconnect when a fault occurs. This addition to the controllability of the PV power converters has added new challenges in managing to reserve some of the generation capability of its energy resource. This means that common algorithms used in PV power control such as MPPT cannot be used any longer. Enhanced structures for MPP location capable of reserve active power generation have to be generated. Fig. 1 shows the idea of power reserve during steady state operation of PV systems. Most of the enhanced control strategy to add power reserve to the system use an indirect power reserve strategy, meaning on adding energy storage to the system [10] for primary power reserve control.
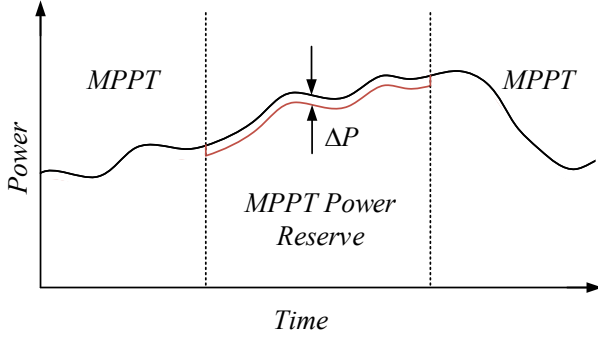
Fig. 1: Maximum Power Point Tracking with power reserve capability

By means of controlling the active power reserve on each PV inverter the actual power output of each module will be determined by (1):

$$P_{output} = P_{available} - \Delta P_{reserve} \qquad (1)$$

The value of the $\Delta P_{reserve}$ should be determined by the amount of active power reserve demanded on the grid code for stability purposes. This leads to generate different approaches where there is a possibility of generating an active power reserve out of PV modules.

As in [4], [11] and [12] an MPP estimator is possible through regression analysis or neural networks, for those kind of systems irradiance and temperature measuring is vital, and may require much more calculation processing to obtain an accurate result.

Other proposals for active power reserve are presented in [5] and [6] where battery integration is done. Those energy storage elements are the ones providing the active power reserve. However, those techniques have two main drawbacks, the first one is the high cost of the battery. The second one is the short lifetime of the battery. This reduced lifetime and high cost make those techniques not be a cost-effective solution. Due to this other solutions are implemented using MPPT strategies as a sensor of the MPP and using this information to generate a $\Delta P_{reserve}$ which means that the MPPT is being used as a sensor and as a power reference generator [8], [7].

III. PROPOSED POWER RESERVE CONTROL STRATEGY

The proposed control strategy for active power reserve in PV systems is a cost-effective solution. By means of joining two PV inverters as a unit, it is possible to both provide active power generation to the grid while maintaining some power reserve for grid fluctuations.

Fig. 2 presents the joint unit of two power converters. One of those is controlled by a classic MPPT control and the other power converter is controlled by a Synchronous Power Controller (SPC).
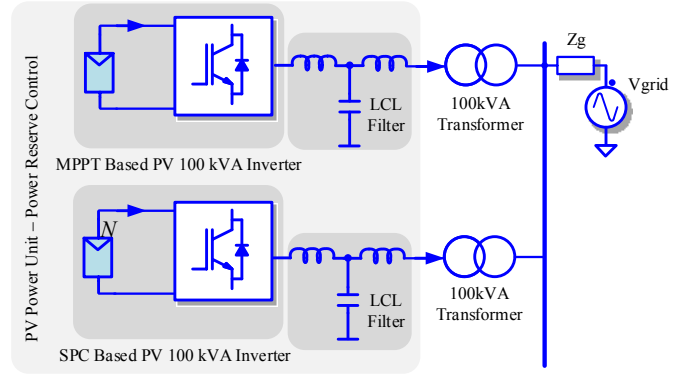

Fig. 2: MPPT based PV Inverter + SPC based PV Inverter power unit

The MPPT unit is controlled by a classical MPPT strategy, where Vdc and Idc are measured from the PV system and a P&O [13] algorithm is used to generate the voltage reference. The generation of a power references through an MPPT make it possible to send this signal with a curtailment value to other units.

The second unit is an SPC power converter unit, this unit has many functionalities. However, on this case the synchronous control is being used mainly for frequency control deviations, acting as a power reserve to the PV system.

A. MPPT POWER REFERENCE

By means of this, two power references are generated. One is the power reference from the MPPT algorithm, the second is the one send to the SPC inverter unit. This second power reference is the reference generated by the MPPT with some power reserve.

$$P_{MPP} = I_{MPP} \cdot V_{MPP} \qquad (2)$$
$$P_{SPC} = P_{MPP} \cdot k_{curtailment} \qquad (3)$$

Providing the power reference from another unit may become an issue when adding this control into a PV system, which is highly unpredictable and may have difference from one point to another. The addition of an external control to maintain the Vdc voltage within safety limits is vital for this control approach.

B. VDC LIMITATION POWER REFERENCE

Voltage limitation on the dc bus of the power converter is needed to ensure the safety operation of the SPC unit. By means of this a double PI control strategy is implemented on the SPC unit, which will be focused on maintaining the Vdc voltage within safety levels. On Fig. 3 the PI controllers and its limitations are shown, one controlling the upper part of the dc voltage and the other one the lower limitation. It is important to understand that both limitations and PI parameters are not the

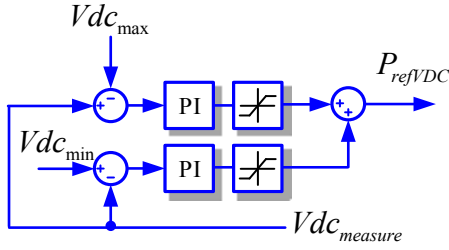same, mainly due to the different characteristic found on the PV panel.

Fig. 3: Vdc Voltage Control for SPC unit to mitigate the effect of the power reference from the MPPT unit

The PI controllers will have different tuning depending on the dynamic characteristic of the PV panel. Due to this, upper and lower limitations on the PI will have different parameters resulting into different performance. Fig. 4 presents the idea of voltage limitation, due to the dynamic characteristic of the PV panel, the PI controller parameters set on the $V_{dc_{MIN}}$ is different from the one on the $V_{dc_{MAX}}$. Those two PI will maintain the V_{dc} within a safety level, while maintaining power MPP tracking from the other unit.
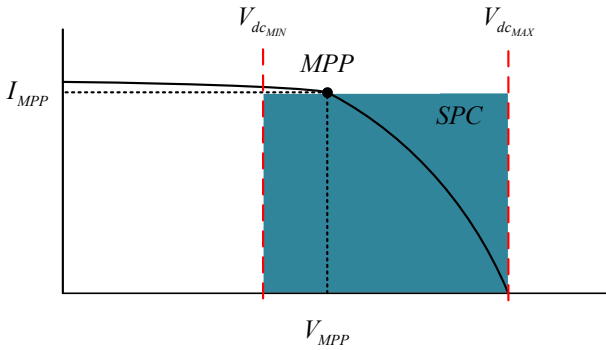

Fig. 4: SPC voltage limitation and actuation zone and MPPT actuation zone

The inertia of the SPC may be a drawback when controlling the Vdc voltage on the upper and lower limitation. To overcome this issue a feedforward parameter is added into the equation. This feedforward is added directly to the Voltage Oscillator Control (VCO) which is much faster than the inertial power control.

C. Droop Frequency Control

The fundamental idea of the droop control is to have a control of the active power extracted from the power converter. This power has a straight relation with the frequency of the grid. So, in order to maintain the frequency on a stable value the power converter have to be able to change its power output, which will be decreasing when the frequency is above the nominal value, and will be increasing when it is under the nominal value.

$$\omega = \omega^* - k_{droopP} \cdot \left(P - P^* \right) \qquad (4)$$

$$E = E^* - k_{droopQ} \cdot \left(Q - Q^* \right) \qquad (5)$$

Equations (4) and (5) are the typical for implementing the droop control in a power converter, represented on Fig. 5. On this case a PV system cannot absorb active power, which means that its Vdc value cannot surpass the voltage limitations set by the PI, so the droop curve will be adding power reference to the one send by the MPPT until it reaches voltage limitations.
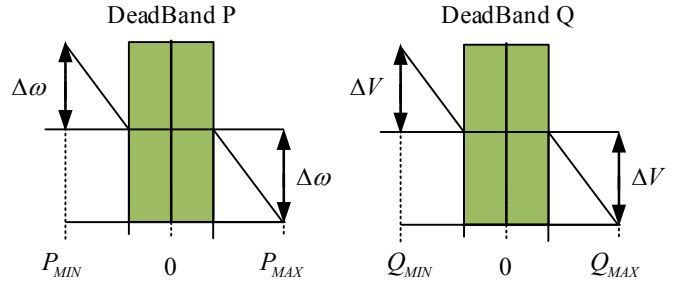

Fig. 5: Classical frequency and voltage droop control with deadband implementation

The final control algorithm is presented in Fig. 6, where the two power converter units are joined to provide power reserve control into the system as well as frequency regulation capabilities. On this case, one of the converters has been programmed with an MPPT algorithm based on P&O. This power reference generated by the MPPT and is send to the SPC unit with a curtailment value, this curtailment will represent the power reserve added into the unit. In addition to this reference, the PI limitation, which ensures that the power converter is working within safety limits of its Vdc voltage levels, and droop control for frequency regulation are aggregated. By means of this it is possible to provide a power reserve on the MPPT unit by terms of adding an SPC unit with frequency regulation capabilities.
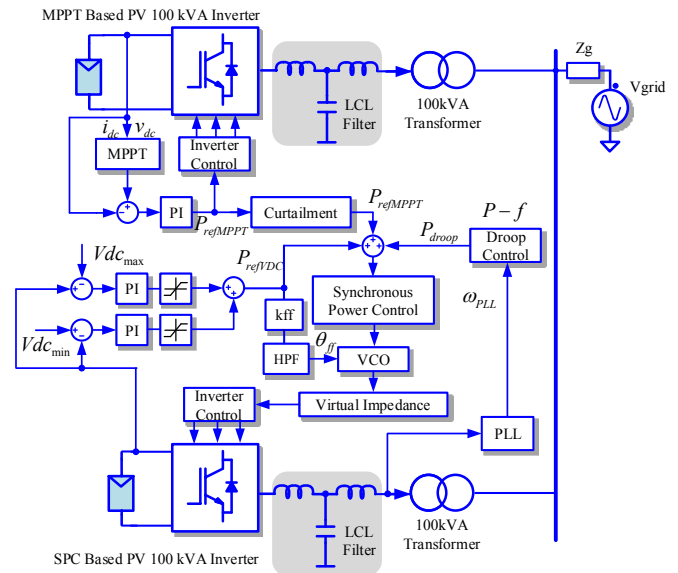

Fig. 6: PV Power Unit – Power Reserve Control

IV. SIMULATION RESULTS

Firstly on this section, a test on the MPPT strategy is going to be produced to validate the MPPT algorithm. Next the whole unit is going to be tested under different scenarios. Irradiance variation, power reserve modifications and frequency regulation are the main tests, with those simulations it is intended to validate the control algorithm structure.

On Table. 1 the elements composing the PV Inverter unit are presented. Each PV Inverter has the same elements connected but different control strategy. Two 100 kVA PV Inverters are going to be tested, the configuration is the one presented in Fig. 2, where one of the power converters is focused on MPPT algorithm, while the other power converter is focused on a synchronous control.

Inverter 100 kVA – Elements	
Fs	3150 Hz
Ts	6300 Hz
L1	777 µH
Rc	0.5 Ohm
C	66 µF
L2	294 µH
Transformer	400 µH
Lg	400 µH

Table. 1: PV Inverter elements

Before testing the two units working as a one, it is important to test if the MPPT strategy is working properly. To test the MPPT strategy a modification on the irradiance of the PV panel is made during the simulation in order to test if the MPPT algorithm is capable of adapting its power generation to track the MPP.

In order to test the MPPT and the SPC power converters working as one joined unit, the parameters of the PV panel emulated are the ones presented in Table. 2

Emulated PV Panel	
Voc	815 V
Icc	150 A
Impp	144 A
Vmpp	690 v

Table. 2: PV Panel characteristic points

In order to provide an acceptable power reference to the SPC based inverter, the MPPT has to be able to withstand irradiance variation. Due to this, a first test where the MPP tracking strategy is simulated under a variation of irradiance is performed. On Fig. 7 an irradiance variation from $1000\ W/m^2$ to $800\ W/m^2$ is performed, the algorithm is capable to overcome the irradiance variation and provide an acceptable power reference for the SPC based inverter.
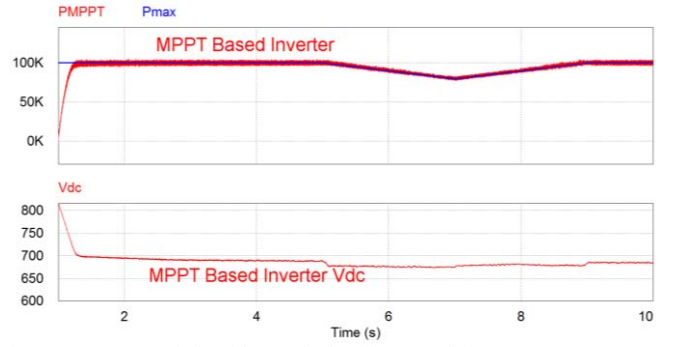

Fig. 7: MPPT control algorithm under irradiance variation

Once the MPPT is working properly it is a matter of setting the power reference of the SPC based inverter by means of adding a power curtailment gain to its reference value. If more than two units are considered, the equivalent equations for power reference and power reserve are written for *n* power converters, where power converter is MPPT based and the rest are SPC based power converters:

$$P_{SPC_n} = P_{MPPT} \cdot k_{curtailment\,n} \qquad (6)$$

$$\%P_{reserve} = \frac{P_{SPC(n-1)} + P_{MPPT}}{P_{MAX}} \cdot 100 \qquad (7)$$

On Table. 3 the values of the limitations of each PI controller on the dc bus is settled to its maximum and minimum value. Above those values the power reference from the MPPT will be attenuated until a value that matches the voltage level on the specification is achieved.

Those PI controllers have more weight on the power reference than the MPPT power reference and the droop control reference, due to its feedforward value on the VCO control. As a result the SPC based inverter will be focused on maintaining its dc voltage level within safety levels, and then provide power reserve and frequency regulation. If voltage levels get to the safety limits the power reference will be mainly controlled by the PI controllers.

SPC Based Inverter	
Vdc Max	815 V
Vdc Min	670 V

Table. 3: SPC Based Inverter PI limitation on upper and lower voltage of the dc bus

A. POWER RESERVE CONTROL STRATEGY

On this test, a power reserve is going to be settled for the SPC inverter. By means of this, the SPC unit is going to provide the 80% of the power provided by the MPPT. To validate the power reserve strategy a test with both units connected is performed. On Fig. 8 the power reserve control is tested, where on t = 1 s the power referece of the SPC unit is set to the 80% of the MPPT power reference value. On t = 5 s the power reserve is changed from 80% to 90% of the capacity of the MPPT, while maintaining the dc bus into safety.
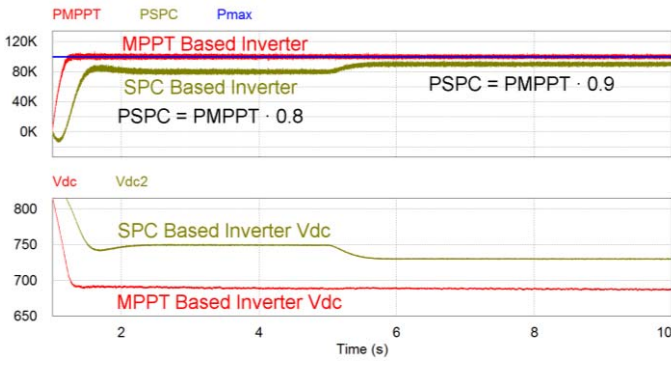
Fig. 8: MPPT based unit with SPC based inverter with power reserve capability. Change from 80% to 90% of power reserve capacity.

B. IRRADIANCE VARIATION

Fig. 9 demonstrates the capability of the system to withstand irradiance variation over time. From t = 4 s to t = 6 s there is a decreasing value of the irradiance, from $1000 \ W/m^2$ to $600 \ W/m^2$. As shown in Fig. 7 the MPPT strategy has no issue on following the MPP when irradiance vary. This modification on the MPPT power reference affects the SPC output power generation and it reduces its output power value. From t = 6 s to t = 8 s the irradiance has an increasing value from $600 \ W/m^2$ to $1000 \ W/m^2$. The power reserve on Fig. 9 is maintained to a 20% of the MPP of the tracking unit.
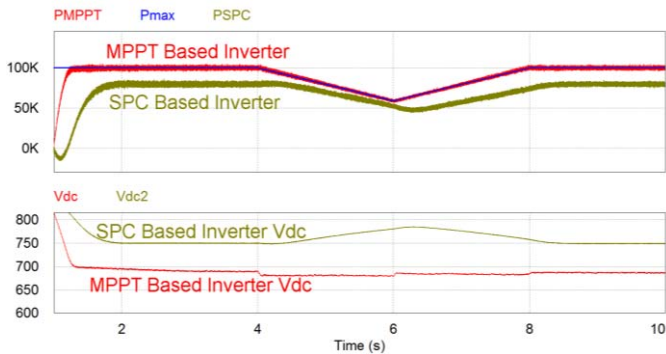

Fig. 9: Irradiation variance from $1000 \ W/m^2$ to $600 \ W/m^2$ and recovered to $1000 \ W/m^2$. 20% Power reserve control

When irradiance is not recovered to the nominal value ($1000 \ W/m^2$), the power reserve control has the capability to maintain a power reserve even during irradiance variation, as shown in Fig. 10. On t = 4 s there is an irradiance modification from $1000 \ W/m^2$ to $600 \ W/m^2$, which provoke a decreasing value of both units power generation, but the power reserve is maintained even during the irradiance variation.

Due to possible distance between units, irradiance level may not be equal on the PV modules, this lead the units to differ from the MPP point. This difference may provoke irregularities on the output power and on the Vdc voltage. Presented in Fig. 11 an irradiance change of the SPC PV module is done from t = 6 s and $1000 \ W/m^2$ to t = 8 s and $800 \ W/m^2$.
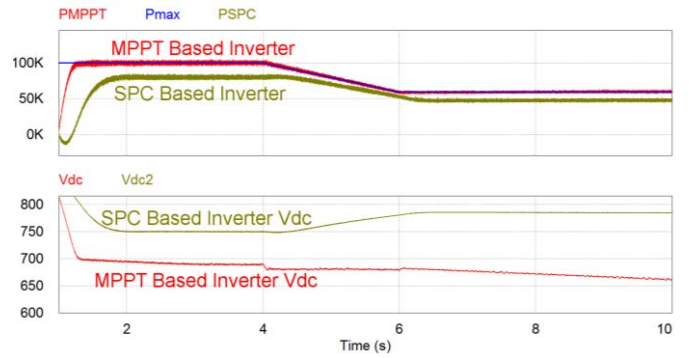

Fig. 10: Irradiation variance from $1000 \ W/m^2$ to $600 \ W/m^2$ maintaining the power reserve to a 20% value.

As it is possible to see there is no modification on the power output of the SPC although there is a rapid change of the Vdc voltage due to irradiance change. If the SPC is capable to maintain its output power generation, the power reference will not be changed. The variation of the irradiance is not enough to lead the SPC system change its power output generation.
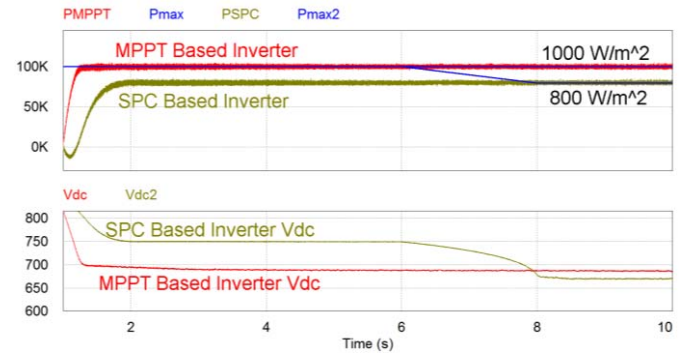

Fig. 11: Variation of the irradiation of the SPC Based inverter from $1000 \ W/m^2$ to $800 \ W/m^2$

On the other hand, if power reference is above the minimum Vdc limitation on the SPC power converter, there is going to be a modification on the power reference on the SPC unit. Fig. 12 presents the results when the Vdc lower limitation actuates. From time t = 6 s to t = 8 s the irradiation is modified from $1000 \ W/m^2$ to $500 \ W/m^2$. Meaning that there is not enough capacity on the SPC power converter to withstand the power reference from the MPPT. The PI controllers actuate in order to maintain the Vdc voltage within the safety range.
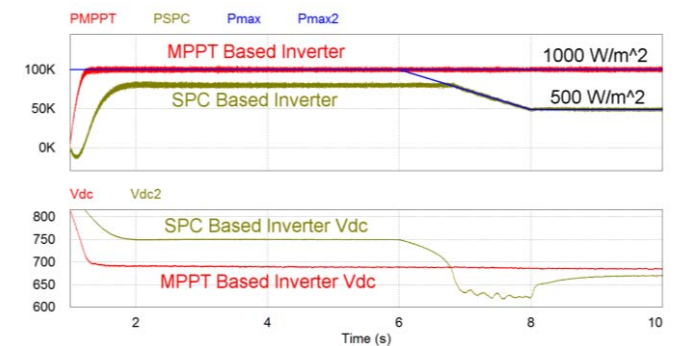

Fig. 12: Variation of the irradiation of the SPC Based inverter from $1000 \ W/m^2$ to $500 \ W/m^2$

C. DROOP CONTROL

Finally, the droop control is going to be simulated to validate its capacity. On Fig. 13 a frequency deviation occurs, frequency is above the nominal value, which means that there should be a power reduction. The SPC power converter is able to observe the frequency deviation and with the droop control provide the needed reference to overcome this dynamic transient, and recover from the grid frequency fluctuation. On t = 5 s the frequency of the grid has an event which make it surpass the nominal value of frequency. The SPC provide the frequency regulation by decreasing its power generation. As it is possible to see on Fig. 13, when the power from the SPC power converter is decreased, the Vdc voltage increases with the same dynamic. However upper limitation of the Vdc bus is not reached, which means that no additional power reference is added in order to maintain the Vdc bus into safety levels.
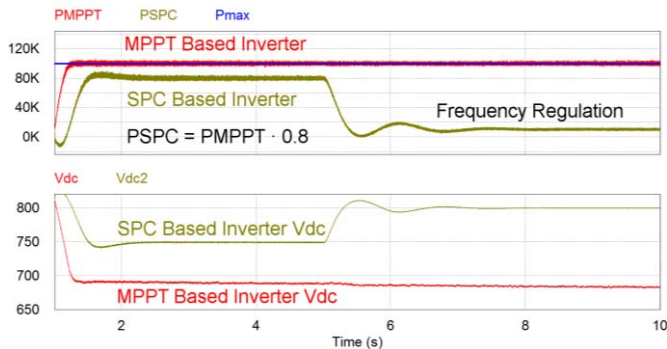

Fig. 13: SPC Based inverter droop control for frequency regulation.

V. CONCLUSION

A power reserve control strategy for PV systems has been discussed in this paper, without the need of energy storage systems for indirect power reserve. The solution is joined with an SPC power converter which provide inertia and fault ride through capabilities to the PV system. Vdc limitation has also been discussed in this paper, which is vital in order to avoid power losses and ensure the safety operation of the power converters.

REFERENCES

[1] V. M. Tovar-Olvera, A. Loredo-Flores, and E. Bárcenas, "Improved P&O algorithm for distributed MPPT PV configurations," *2016 IEEE International Autumn Meeting on Power, Electronics and Computing (ROPEC)*. pp. 1–6, 2016.

[2] "ENTSO-E Network Code for Requirements for Grid Connection Applicable to all Generators 2015," *Eff. Br. mindfulness Interv. acute pain Exp. An Exam. Individ. Differ.*, vol. 1, 2015.

[3] M. Altin, Ö. Göksu, R. Teodorescu, P. Rodriguez, B. B. Jensen, and L. Helle, "Overview of recent grid codes for wind power integration," *2010 12th International Conference on Optimization of Electrical and Electronic Equipment*. pp. 1152–1160, 2010.

[4] A. Hoke, E. Muljadi, and D. Maksimovic, "Real-time photovoltaic plant maximum power point estimation for use in grid frequency stabilization," *2015 IEEE 16th Workshop on Control and Modeling for Power Electronics (COMPEL)*. pp. 1–7, 2015.

[5] T. D. Hund, S. Gonzalez, and K. Barrett, "Grid-Tied PV system energy smoothing," *2010 35th IEEE Photovoltaic Specialists Conference*. pp. 2762–2766, 2010.

[6] L. Pan, J. Gu, J. Zhu, and T. Qiu, "Integrated Control of Smoothing Power Fluctuations and Peak Shaving in Wind/PV/Energy Storage System," *2016 8th International Conference on Intelligent Human-Machine Systems and Cybernetics (IHMSC)*, vol. 02. pp. 586–591, 2016.

[7] A. Sangwongwanich, Y. Yang, and F. Blaabjerg, "A Sensorless Power Reserve Control Strategy for Two-Stage Grid-Connected PV Systems," *IEEE Transactions on Power Electronics*, vol. PP, no. 99. p. 1, 2017.

[8] A. Sangwongwanich, Y. Yang, F. Blaabjerg, and D. Sera, "Delta Power Control Strategy for Multi-String Grid-Connected PV Inverters," *IEEE Transactions on Industry Applications*, vol. PP, no. 99. p. 1, 2017.

[9] E. Batzelis, G. Kampitsis, and S. Papathanassiou, "Power Reserves Control for PV Systems with Real-Time MPP Estimation via Curve Fitting," *IEEE Transactions on Sustainable Energy*, vol. PP, no. 99. p. 1, 2017.

[10] R. Hollinger, L. M. Diazgranados, F. Braam, T. Erge, G. Bopp, and B. Engel, "Distributed solar battery systems providing primary control reserve," *IET Renewable Power Generation*, vol. 10, no. 1. pp. 63–70, 2016.

[11] T. Hiyama and K. Kitabayashi, "Neural network based estimation of maximum power generation from PV module using environmental information," *IEEE Transactions on Energy Conversion*, vol. 12, no. 3. pp. 241–247, 1997.

[12] M. Taherbaneh and K. Faez, "Maximum Power Point Estimation for Photovoltaic Systems Using Neural Networks," *2007 IEEE International Conference on Control and Automation*. pp. 1614–1619, 2007.

[13] N. Femia, G. Petrone, G. Spagnuolo, and M. Vitelli, "Optimization of perturb and observe maximum power point tracking method," *IEEE Transactions on Power Electronics*, vol. 20, no. 4. pp. 963–973, 2005.