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2016

Tafti, H. D., Maswood, A. I., Pou, J., Konstantinou, G., & Agelidis, V. G. (2016). An algorithm for reduction of extracted power from photovoltaic strings in grid-tied photovoltaic power plants during voltage sags. IECON 2016 - 42nd Annual Conference of the IEEE Industrial Electronics Society, 3018-3023.

<https://hdl.handle.net/10356/84734>

<https://doi.org/10.1109/IECON.2016.7793187>

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An Algorithm for Reduction of Extracted Power from Photovoltaic Strings in Grid-Tied Photovoltaic Power Plants during Voltage Sags

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Abstract—Due to the high penetration of the installed distributed generation units in the power system, the injection of reactive power is required for the medium-scale and large-scale grid-connected photovoltaic power plants (PVPPs). Because of the current limitation of the grid-connected inverter, the injected active power should be reduced during voltage sags. In order to obtain a constant dc-link voltage in a multi-string PVPP, the extracted power from PV strings should be equal to the injected power to the grid in all operating conditions (excluding power losses). Therefore, the extracted power of PV strings should be reduced during voltage sags. In this paper, an algorithm is proposed for determining the reference voltage of the PV string which results in a reduction of the output power to a certain amount. The proposed algorithm calculates the reference voltage for the dc/dc converter controller, based on the characteristics of the power-voltage curve of the PV string and therefore, no modification is required in the controller of the dc/dc converter. Simulation results on a 50-kW PV string verified the effectiveness of the proposed algorithm in reducing the power from PV strings under different irradiation and reference power values.

Index Terms—Photovoltaic systems, Fault-ride through capability, Active/reactive power injection, dc/dc converter, active power reduction

I. INTRODUCTION

Photovoltaic power plants (PVPPs) are one of the most favorable renewable sources for electricity production these days. Such rapid momentum for the total installed PV capacity growth is initiated due to the extreme reduction of the PV panel production expense and is expected to remain like this in the upcoming years. High penetration of distributed generation (DG) units, such as PVPPs, in the power system introduced new challenges for power system operators (PSOs). Therefore, new requirements for the ancillary services, especially during the grid faults have been regulated by PSOs. Large-scale and medium-scale grid connected PVPPs are required to stay connected to the grid during voltage sags and inject active/reactive power to the grid. This capability results in the enhancement of the voltage of point of common coupling (PCC) during voltage sags [1]–[3].

The current of the dc/ac converter of the PVPP should remain within its nominal range during all operating conditions.

During grid voltage sags, the amplitudes of the grid voltages are smaller than the nominal value. Thus, higher currents are required in order to inject the same amount of active power into the grid. However, based on grid codes, grid-connected PVPPs should also inject reactive power to the grid during voltage sags, and as a result, the active power should be decreased for the sake of keeping the inverter current within its nominal range [4]. Therefore, the grid-tied inverter of the two-stage multi-string PVPP, i.e. PV strings with dc/dc converters, should decrease the injected active power to the grid (P_{inv}) during voltage sags. At the same time, if the dc/dc converters continue to extract the maximum power (P_{strTot}) from PV strings, the excessive energy ($P_{strTot} - P_{inv}$) is stored in the dc-link capacitors. This excessive energy increases the dc-link voltage (V_{dc}) which may result in the activation of the over voltage protection [5], [6]. Consequently, P_{strTot} should be decreased in order to be equal to P_{inv} during voltage sags. This study investigates the reduction of the extracted active power from PV strings (P_{strTot}) of a multi-string PVPP to a certain reference power (P_{ref}), during voltage sags.

The current-voltage characteristic of the PV panel changes according to the solar irradiation and temperature. Thus, the output power of the PV panel is dependent on the solar irradiation and temperature and maximum power point tracking (MPPT) is necessary to harvest the maximum power from the PV panel. Several MPPT algorithms are introduced in the literature [7]–[11]. Each method has various advantages and disadvantages in different aspects like computational complexity, fast tracking of maximum power point and power oscillation during steady state. Within various MPPT algorithms, perturbation and observation (P&O) [12], [13] and incremental conductance (INC) [14], [15] algorithms are most commonly used. It is shown in [16] that the tracking performance of P&O and INC methods are similar under both static and dynamic conditions. In this study, P&O method is considered for maximum power extraction of PV strings of PVPP.

Most of the studies in the literature [7]–[16] investigate various algorithms for MPPT operation that is continuously tracking and extracting the maximum power out of the PV

Fig. 1. Grid-connected multi-string photovoltaic power plant structure.

string. However, during grid voltage sags, the extracted power from PV strings should be adjusted to P_{ref} , which is computed based on the current limitation of the inverter. The extracted power can be reduced to zero by short-circuiting or opening circuit of all PV strings during grid voltage sags [17]. These methods are easy to implement, however, the full current capacity of the grid-connected inverter is not used in the injection of active/reactive power during the voltage sag. A power reduction method based on the dc-link voltage control is implemented in [6] and [17]. The P&O method is used to calculate the maximum power point voltage (V_{MPP}). An extra voltage is added to V_{MPP} in order to reduce the extracted power of the PV panel during the voltage sag. However, it requires an extra PI controller and a modification in the dc/dc converter controller.

In this study, an algorithm is proposed to calculate the voltage which leads to a certain output power from the PV string. The proposed algorithm is based on the characteristics of the power-voltage (P-V) curve of the PV panel. During the voltage sag, the P&O method for MPPT is replaced with the proposed method to calculate the reference voltage based on the required reference power. The reference voltage can be fed into the dc/dc converter controller and no modification or extra controller is required for the dc/dc converter.

The rest of the paper is organized in the following manner. Section II provides an overview of the necessity of reducing the extracted power during voltage sags based on the grid codes and structure of the PVPP. Principles of the power reduction strategy for PV strings are analyzed in Section III. The detailed implementations of the reduced power strategy is described in Section IV. The evaluation results of the proposed controller are illustrated in Section V, while the conclusions of the work are summarized in Section VI.

II. PROBLEM DEFINITION

A comprehensive representation of the multi-string two-stage grid-connected PVPP structure is shown in Fig. 1. It consists of multiple PV strings, dc/dc converters and a central grid-connected inverter. The dc/dc converters extract the power from PV strings to the dc-link and the inverter injects the active/reactive power to the grid.

The requirement of the German grid code for the connection of medium and large-scale PVPPs is depicted in Fig. 2 [4]. The shaded area depicts the grid connection requirement for different voltage amplitudes and sag durations. The PVPP

Fig. 2. Limiting curves of voltage at the grid connection point for distributed generation facility [4].

must stay connected to the grid during a voltage drop to 0% of the nominal voltage with a duration of <150 ms. The lowest value of the voltage range for normal operation of the PVPP is 90% of the nominal voltage. For voltage dips with amplitude larger than 70% of the nominal voltage, the PVPP should stay connected to the grid for a longer time according to the voltage amplitude.

In addition to the requirement of the grid-connection, grid codes regulate reactive power injection to the grid during voltage sags. The injection of the reactive power leads to the enhancement of the PCC voltage during the voltage sag. The requirement of grid codes for reactive current (I_q) is [1]:

$$I_q = \begin{cases} 0, & 0.9pu \leq \hat{V}_{min} < 1.1pu \\ k \frac{\Delta V}{\hat{V}_N} I_{Ndq} + I_{q0}, & 0.5pu \leq \hat{V}_{min} < 0.9pu \\ -I_N + I_{q0}, & \hat{V}_{min} < 0.5pu \end{cases} \quad (1)$$

where $\hat{V}_N$ is the nominal amplitude of the PCC phase voltage and $\Delta V = \hat{V}_{min} - \hat{V}_N$ where $\hat{V}_{min}$ is the minimum voltage amplitude. I_{Ndq} denotes the transformed nominal inverter current to dq coordinate ($I_{Ndq} = \sqrt{3}I_N$ where I_N is the nominal rms current of the inverter) and I_{q0} is the initial reactive current of the inverter before the voltage sag. k is a constant value defined according to the agreement between PSO and power producer and is usually larger or equal to 2.

According to (1), for voltage sags with amplitude smaller than $0.5pu$, the injected reactive current is equal to the nominal current of the inverter. Therefore, no active current can be injected to the grid and the extracted power from PV strings should be reduced to zero. During voltage sags with the amplitude between $0.5pu$ and $0.9pu$, I_q is smaller than I_N , therefore the inverter is also able to inject active power to the grid simultaneously. The possible injected active current is computed based on the nominal current of the converter as:

$$I_d = \sqrt{I_{Ndq}^2 - I_q^2} \quad (2)$$

where I_d is d-axis current of the inverter which is related to the active power.

The amount of possible active power (P_{inv}) which can be injected to the grid through the inverter, can be calculated based on (2) and the grid voltage amplitude. Consequently,

Fig. 3. Power-Voltage curve of the PV string: (a) Operation at maximum power point (b) operation at left-side of MPP , and (c) operation at right-side of MPP .

during voltage sags, the total extracted power from all PV strings P_{strTot} should be reduced to P_{inv} in order to avoid increasing the dc-link voltage excessively. The following section provides a detailed implementation of the proposed power reduction method for PV string.

III. PRINCIPLES OF REDUCTION OF THE EXTRACTED POWER FROM PV STRINGS

During normal operation, the dc/dc converter extracts the maximum power (P_{MPP}) from the PV string, referred as $MPPT$ operation mode is this paper (Fig. 3(a)). During the voltage sag, the extracted power from the PV string should be reduced to the reference power (P_{ref}) which is calculated by an external controller. This operation mode is referred as reduced power (RP) operation mode. According to the P-V curve of the PV string (Fig. 3(a)), there are two operation points (A and B) which result in extracting P_{ref} from the PV string.

In order to operate the PV string at point A , the PV string voltage (V_{PV}) should be decreased to V_A which is in the left-side of the MPP . Similarly, the operation of the PV string with V_B , which is the right-side of the MPP , can result in the extraction of the same amount of power (P_{ref}) from the PV string. It can be seen that the difference between V_B and V_{MPP} ($|V_{MPP} - V_B|$) is smaller than $|V_{MPP} - V_A|$. Therefore, moving the operation point from MPP to point B can be performed faster than moving the operation point from MPP to point A . Since fast performance is necessary for achieving low-voltage-ride-through (LVRT) capability for the PVPP, the operating point of the PV string should be moved to the right-side of MPP . Therefore, for extracting P_{ref} from

Fig. 4. Proposed reference voltage calculation for reduction of extracted active power from the PV string.

the PV string, V_B is used as the reference voltage of the PV string. In order to ensure operation of the PV string in the right-side of MPP during RP mode, the characteristics of the P-V curve are analyzed for both right-side and left-side of the MPP .

In this study, ΔV is defined as $\Delta V = V_{new} - V_{old}$, where V_{new} is the PV string voltage in the current time step and V_{old} is the PV string voltage in the previous time step. Also, ΔP is defined as $\Delta P = P_{new} - P_{old}$, where P_{new} is the output power of the PV string in the current time step and P_{old} is the output power of the PV string in the previous time step. By assuming the operation of the PV string at point A in the current time step (Fig. 3(b)), the operation point of the next time step can be A_1 or A_2 . Moving the operation point to A_1 results in $\Delta V = V_{A1} - V_A$ which is a negative value. Also, by moving the operation point to A_1 , ΔP will be a negative value ($\Delta P = P_{A1} - P_A$) which results in $\Delta P / \Delta V > 0$. On the other hand, moving the operation point from A to A_2 results in:

$$\frac{\Delta P}{\Delta V} = \frac{P_{A2} - P_A}{V_{A2} - V_A} > 0 \quad (3)$$

Consequently, $\Delta P / \Delta V$ is always positive in left-side of MPP , as depicted in Fig. 3(b).

Similarly, moving the operation point from point B to point B_1 in the left-side of MPP (Fig. 3(c)) results in:

$$\frac{\Delta P}{\Delta V} = \frac{P_{B1} - P_B}{V_{B1} - V_B} < 0 \quad (4)$$

and in the same way, moving the operation point from point B to point B_2 results in $\Delta P / \Delta V < 0$. Therefore, $\Delta P / \Delta V$ is always negative by operating in the right-side of MPP . This characteristic of the P-V curve is applied in the proposed algorithm to ensure the operation of the PV string in the right-side of MPP during RP operation mode.

IV. PROPOSED ALGORITHM FOR REDUCTION OF THE EXTRACTED POWER FROM PV STRINGS

A comprehensive schematic of the proposed algorithm for reduction of power from PV string is depicted in Fig. 4.

Fig. 5. dc/dc converter controller.

TABLE I
SIMULATION PARAMETERS

Parameter	Symbol	Value
Number of series PV panels in each branch of the PV string	N_p	14
Number of parallel connected branches of the PV string	N_s	15
PV string maximum power	P_{MPP}	50 kW
PV string maximum power voltage	V_{MPP}	420 V
PV string maximum power current	I_{MPP}	120 A
dc-link voltage	V_{dc}	770 V _{dc}
PI controller proportional factor	K_p	0.0003
PI controller Integral factor	K_i	0.15
Simulation sampling time	T_s	5 μ s

The operation mode of the dc/dc converter is determined by an external controller based on the grid voltage and inverter current, as mentioned in Section II. If the operation mode of the dc/dc converter is *MPPT*, the controller calculates $V_{ref} = V_{MPP}$ using an MPPT algorithm.

During *MPPT* mode, the time step (T_{step}) is considered to be large (e.g. 0.1 s) in order to reduce the oscillation of the output power of the PV string during steady-state operation. However, fast performance of the controller in reducing P_{PV} during (*RP*) operation mode is necessary. Therefore, T_{step} is imposed to be a small value (T_{step_RP}) during *RP* operation mode.

As mentioned in Section III, during *RP* mode, the operation point should be moved to the right-side of *MPP*. By calculating $\Delta P/\Delta V$, it can be determined whether the current operation point is in left-side or right-side of *MPP*. If this value is positive, which means the current operating point is in left-side of *MPP*, the reference voltage for next time step will be increased ($V_{ref} = V_{ref_old} + V_{step_RP}$). The increase of V_{ref} in subsequent time steps, moves the operation point of PV string to the right-side of *MPP*. After ensuring that the current operation point of PV string is in right-side of *MPP*, the proposed algorithm should determine the voltage which is related to P_{ref} . Therefore, $\Delta P^* = P_{new} - P_{ref}$ is calculated in each time step. The positive ΔP^* means that the output power is larger than the reference power, hence V_{ref} should be increased in the next time step, to reduce the output power (Fig. 3(c)). Similarly, for negative ΔP^* , the reference voltage for the next time step should be decreased ($V_{ref} = V_{ref_old} - V_{step_RP}$) in order to increase the output power.

As shown in Fig. 5, the calculated reference voltage (V_{ref}) is compared with V_{PV} and the error is fed into the PI controller in order to calculate the duty cycle (D). Subsequently, the switching signal (S) for the dc/dc converter is generated. It can be observed that since the proposed algorithm calculates

Fig. 6. Case I: Simulation results for power reduction of the PV string with constant irradiation and temperature: (a) Reference voltage (V_{ref}) (b) string voltage (V_{PV}) (c) duty cycle (D) (d) string current (I_{PV}) (e) string output power (P_{PV}), and (f) power-voltage curve of the PV string.

V_{ref} during both *MPPT* and *RP* operation modes, no extra controller or modification is required in the dc/dc converter controller to operate at *RP* operation mode.

V. EVALUATION RESULTS

The performance of the proposed power reduction strategy is evaluated on a modeled PV string using Matlab/Simulink and PLECS toolbox. The PV panels are modeled using the SHARP NU-U235F1 model. Each PV panel produces the maximum power of 235 W (30 V and 7.84 A) at 25 °C and 1 kW/m². The parameters of the simulation setup are given in Table I. The proposed controller has been evaluated under three different conditions in the following case studies.

Case I: A power reduction from 50 kW to 30 kW is investigated in this case study. The results are depicted in Fig. 6. Before $t = 0.4$ s, the PV string is at *MPPT* operation mode. In this case study, the irradiation (I_r) is 1000 W/m²

Fig. 7. Case II: Simulation results for power reduction of the PV string with change of irradiation: (a) Reference voltage (V_{ref}) (b) string voltage (V_{PV}) (c) duty cycle (D) (d) string current (I_{PV}) (e) string output power (P_{PV}), and (f) power-voltage curve of the PV string.

while the temperature (T) equals 25°C as the P-V curve is shown in Fig. 6(f). Consequently, the dc/dc converter extracts $P_{MPP} = 50\text{ kW}$. The voltage of PV string is around 420 V and the current equals 120 A . According to the voltage boost factor of the dc/dc boost converter, $V_{PV} = 420\text{ V}$ and $V_{dc} = 770\text{ V}$, the duty cycle (D) is approximately 0.45 , as depicted in Fig. 6(c).

At $t = 0.4\text{ s}$, a power reduction command is received from an external controller which leads into the operation of the dc/dc converter in RP mode. The reference power for this condition is assumed to be 30 kW . It can be observed from Fig. 6(a) that the reference voltage is increased to 490 V , which is related to 30 kW power from the PV string (Fig. 6(f)). Accordingly, V_{PV} also is increased following V_{ref} which results in the reduction of D and I_{PV} . At $t = 0.8\text{ s}$, the voltage sag is cleared and hence the operation mode of the PV string is recovered to $MPPT$ mode. It can be seen that voltage, power and current of the PV string are quickly recovered to their initial maximum

Fig. 8. Case III: Simulation results for power reduction of the PV string with MPPT power smaller than reference power: (a) Reference voltage (V_{ref}) (b) string voltage (V_{PV}) (c) duty cycle (D) (d) string current (I_{PV}) (e) string output power (P_{PV}), and (f) power-voltage curve of the PV string.

power point values.

The time step is equal to $T_{step_MPPT} = 0.1\text{ s}$ during $MPPT$ operation mode. However, it is reduced to $T_{step_RP} = 0.002\text{ s}$ during RP operation mode. The shorter time step leads to fast response of the proposed reference voltage calculation algorithm. The time step values for different operation modes can be seen in Fig. 6(a). On top of that, for the sake of achieving fast recovery response after clearance of the power reduction command from the external controller, the time step is kept at T_{step_RP} for a time delay after the clearance of the voltage sag. The time delay is referred as T_D in Fig. 6(a). The short step time of the reference voltage calculation algorithm, during this time delay, helps the $MPPT$ algorithm to determine V_{MPP} quickly. The duration of this time delay can be adjusted according to the applied $MPPT$ algorithm. The time step of the controller is changed to T_{step_MPPT} after this time delay.

Case II: A sudden change of the solar irradiation is produced during the *RP* operation mode as presented in Fig. 7. Before $t = 0.4$ s, the dc/dc converter extracts the maximum power from the PV string with $I_r = 900$ W/m². During *RP1* operation mode, which is related to $I_r = 900$ W/m², the reference power is assumed to be 20 kW. The reference voltage is increased using the proposed algorithm in order to reduce the extracted power to 20 kW. During this *RP* operation mode, at $t = 0.6$ s, the irradiation is suddenly reduced to $I_r = 600$ W/m² which leads in the change of P-V curve of the PV string as shown in Fig. 7(f). It can be seen from this figure that, in this condition, the reference voltage should be reduced in order to extract 20 kW power from the PV string. Therefore, the proposed voltage calculation algorithm reduces V_{ref} in order to operate the PV string at *RP2*. It can be observed that the proposed power reduction algorithm is able to track the reference power under the step change of the irradiation.

Case III: The irradiation of the PV string is assumed to be 500 W/m² and the temperature is 25 °C in this case study. Accordingly the maximum power of the PV string is 25 kW. The results of *MPPT* operation mode of the converter are shown in Fig. 8. Similar to other two case studies, a voltage sag is occurred at $t = 0.4$ s. Hence, the operation is changed to *RP* mode. The required reference active power (P_{ref}) is 40 kW which is larger than maximum power of the PV string. It can be observed from Fig. 8(a), that although the converter is operating in *RP* mode between $t = 0.4$ s and $t = 0.8$ s, it extracts the maximum power from the PV string. The reason of this performance can be explained as follows.

According to Fig. 4, initially, the proposed algorithm tries to move the operation point to the right-side of the *MPP* by increasing V_{ref} . After moving the operation point to right-side of *MPP*, the proposed algorithm compares the extracted power with the reference power and since the extracted power is smaller than the P_{ref} , the reference voltage is reduced in the next time step. This results into the movement of the operation point to the left-side of *MPP*. Subsequently, in the next time step, V_{ref} will be increased again. Therefore, the operation point will oscillate around *MPP* and extracts the maximum power during *RP* operation mode. The selected simulation results verify that the proposed algorithm performs as expected during different operation conditions.

VI. CONCLUSION

An algorithm for calculation of the reference voltage which results in reduction of the output power of the PV string to a certain value has been introduced and investigated in this paper. It is shown that by operating on the right-side of the maximum power point, the algorithm reaches its target power reference and recovers to the maximum power point faster. The time step operation of the reference voltage calculation algorithm is also reduced during the power reduction mode in order to achieve fast response. The performance of the proposed algorithm has been evaluated under various conditions including the change of irradiance during the power reduction mode. Also it is shown that if the target reference

power is smaller than the maximum power of the PV string, the proposed algorithm operates at maximum power point. The evaluation results demonstrate the fast performance of the proposed algorithm, which makes it interesting for the operation of multi-string PV power plants during grid voltage sags.

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