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*grid-connected PV power plant,*
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*overcurrent protection*

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# SHORT-CIRCUIT CURRENT CONTRIBUTION FROM LARGE SCALE PV POWER PLANT IN THE CONTEXT OF DISTRIBUTION POWER SYSTEM PROTECTION

The interconnection of distributed generators (DG) to existing network may give rise to many technical problems. To ensure appropriate power quality and stability of the grid these problems should be recognized and solved. For this purpose, behaviour of such energy sources, under various disturbances, must be studied and known to the distribution grid operators. In this paper fault current contribution from large scale photovoltaic (PV) power plant as well as protection issues concerning such DGs are discussed. The mentioned problems were investigated in PSCAD model of 50 MW grid--connected PV power plant where various operating condition of the network and penetration levels of PV were considered.

## 1. INTRODUCTION

Due to growing requirements related to environmental and economic objectives imposed on energy sector, cause that renewable energy sources are more and more frequently employed. Solar energy belongs to one of the important and very resiliently developing sources of non-polluting energy. Significant increase of photovoltaic industry is observed not only in small scale systems (power range of kilowatts) but also in large scale ground-based arrays of tens of MW. Since the number of large scale photovoltaic systems has increased in the past several years many issues related to integration of this sources of energy into power system need to be discussed. There are many papers and reports that analyse the following aspects [5,6,8,9,10]:

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– design, construction and operation of PV systems;
– environmental and economic analysis;
– interaction with distribution network,
– operation of PV array (I-V and P-V characteristics) under variable weather conditions;
– enhancement of controllers' performance;
– anti-islanding protection;
– reduction of harmonic distortion;
– energy storage systems.

However, from the viewpoint of both power protection vendors and power system utilities, another issue should be analyzed as well. Since a large scale PV power plant of dozens of MW may be a significant source of short-circuit current, therefore, the following question arises: whether influence of such power source should be taken into consideration when protective system performance is analyzed. Because the fault contribution from PV power plant is limited by the maximum current level of the applied inverters, it may seem that the short-circuit current of the PV modules may have insignificant impact on MV protections [1,4,11]. Nevertheless, various issues of protection operation due to grid-connected PV systems are still reported [2]. Furthermore, in case of large scale photovoltaic power generation (in the above referred papers, only small scale PV systems have been considered) when PV system power is substantial, short-circuit current contribution from PV may lead to false relaying operation despite above mentioned limiting of the inverter current. Thus, such problem should be thoroughly investigated.

In this paper, short-circuit current contribution from large scale PV power plant in the context of distribution power system protection performance is discussed. In order to investigate the problem, appropriate power system model of a real distribution network has been prepared with the use of PSCAD simulation tool. Using the prepared model, a wide range of fault disturbances that may occur in a distribution network have been simulated. Finally, the most interesting cases are presented in the paper, conclusions are drawn and appropriate recommendations are made.

## 2. SIMULATION MODEL OF THE GRID-CONNECTED PHOTOVOLTAIC POWER PLANT

In this section a PSCAD model of a typical distribution network with interconnected PV power plant is presented. The following subsections contain comprehensive model description of: solar cell, maximum power point tracking controller, power inverter, radial distribution grid and protection devices.

## 2.1. PHOTOVOLTAIC POWER PLANT

The basic element of a PV system is the photovoltaic cell. Cells are grouped to form modules, and these modules can be grouped to form photovoltaic arrays. The term array is usually understood as a numerous PV cells connected in series and/or parallel. In Fig. 1 equivalent circuit model of a PV array is presented.

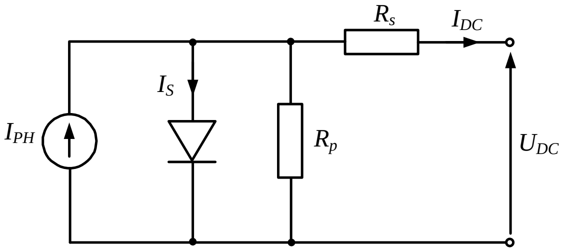


Fig. 1. Equivalent circuit of a PV array

This model consists of an ideal current source, a diode and shunt resistor connected in parallel with the current source and a series resistor.

The output terminal current of modelled photovoltaic array $I_{DC}$ and thereby the I-V characteristic of a practical array may be described by the following equation [6,7,12]:

$$I_{DC}=N_p \cdot I_{PH}-N_p \cdot I_S\left(e^{\left(\frac{U_{DC}+R_s \cdot I_{DC}}{a \cdot N_s \cdot V_T}\right)}-1\right)-\frac{U_{DC}+R_s \cdot I_{DC}}{R_p} \tag{1}$$

where: *Np* is a number of solar modules arranged in parallel, $I_{PH}$ is a photocurrent (light-generated current), $I_s$ is a cell saturation current, $R_s$ is a series resistance, a is an ideal factor (diode constant), $N_S$ is a number of solar modules arranged in series, $V_T$ is thermal voltage, $R_p$ is a shunt resistance.

Photovoltaic current is calculated according to following equation [6,7,12]:

$$I_{PH}=\left(I_{SC}+K_I \cdot \left(T_C-T_{ref}\right)\right)\cdot \lambda \tag{1}$$

where: $I_{SC}$ is a short-circuit current, $K_I$ is a short-circuit current temperature coefficient, $T_C$ is cell's working temperature, $T_{ref}$ is a nominal cell's working temperature, $\lambda= G/G_n$ is an insolation level, $G$ is a working irradiation and $G_n$ is a nominal irradiation.

The cell saturation current, in turn, is given as [6,7,12]:

$$I_S=\left(I_{SC}+K_I \cdot \left(T_C-T_{ref}\right)\right)\cdot \left(e^{\left(\frac{V_{OC}+K_V\left(T_C-T_{ref}\right)}{a \cdot V_T}\right)}-1\right)^{-1} \tag{1}$$

where: $V_{OC}$ is a cell open-circuit voltage, $K_V$ is a open-circuit voltage temperature coefficient.

It has been assumed that main parameters of a single PV module are [7]:

$P_m$=53W; $Isc$=3.35A; $V_{OC}$=21.7V; $V_m$=17.4V; $I_m$=3.05A

Therefore, 50 MW plant requires 943400 pieces of such PV modules. To simplify the PV model, all modules were arranged in one array. Such model offers a good compromise between simplicity and accuracy. To confirm accuracy of the model, *I-V* and *P-V* characteristics under various operating conditions are presented. In Fig. 2 both *P-V* and *I-V* characteristics of modelled array under nominal insolation and cells temperature are shown, whereas Fig. 3 presents *P-V* characteristics of power plant operating under various irradiance and cells temperature.

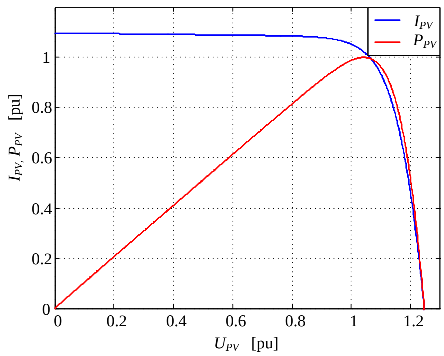


Fig. 2. I-V and P-V characteristics of modelled PV array for nominal insolation and modules temperature

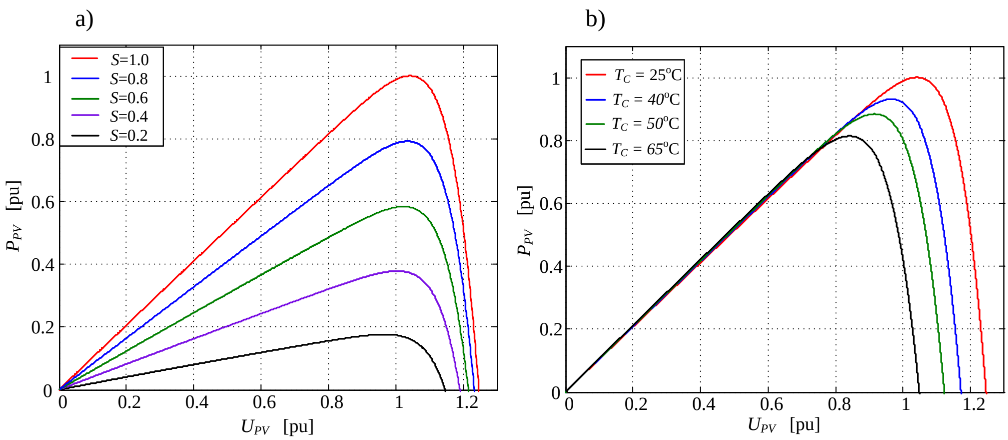


Fig. 3. P-V operation characteristics of modelled PV plant at: a) different insolation conditions; b) different cells temperature conditions

It can be seen that behaviour of the modelled PV power plant showed close approximation of the model characteristics to the real characteristics based on experimental data which are presented in other papers [6,7,12].

The complete photovoltaic generation system consists of: a PV array, a full bridge switching converter, AC filter, active and reactive power controllers, Pulse Width Modulation (PWM) module and step-up transformer, as depicted in Fig. 4.

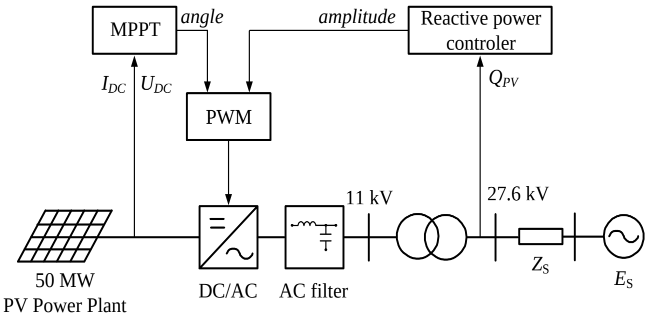


Fig. 4. I P-V operation characteristics of modelled PV plant at different cells temperature conditions

The grid-connected 6-pulse IGBT inverter converts the DC into AC voltage, at frequency equal to the nominal utility grid one. To generate firing signals of the inverter, PWM method was employed. The PWM module was governed by two controllers. The first was responsible for appropriate reactive power generation (it was assumed that reactive power generated by PV power plant should by equal to zero). To generate maximum real power available under actual operating conditions (temperature and irradiance), PWM module was controlled by MPPT block. For tracking the maximum power point (MPPT) of the PV power plant, current (IDC) and the dc-link voltage (UDC) are monitored. Incremental conductance (IncCond) method was used to realize MPPT [3,6]. Additionally, maximal current converted by inverter was limited to 1.5-2.0 times rated current of the PV power plant. To achieve appropriate quality of generated energy (reduce THD factor), LC low-pass harmonic filter was employed.

Such photovoltaic power generation model approximates dynamic response of a large number of channels (sets of PV array, inverter and low voltage transformer) at a point of common coupling [7,12]. To study operating performance of prepared model, two disturbances scenario was simulated.

In Fig. 5, plots of PV power change observed behind the step-up transformer under sudden changes of insolation are presented. First the irradiance decreased from 1000 W/m2 to 600 W/m2 at 0.7 s and then went back up to the initial value at 1.2 s. A stable operation of the PV system can be observed.

The grid-connected PV power plant responded promptly to sudden change of ambient conditions without any significant overshoot.

In Fig.6, PV power plant phase currents under a persistent three-phase fault at the step-up transformer busbar are presented. It may be observed that right after fault inception short-circuit current form PV plant was limited to the preset value (1.6 times the rated current in this case). If the pickup current of the overcurrent protection is set above this level, PV plant will supply this fault until undervoltage protection operate. In the presented case, fault was cleared after about 0.3s from the beginning of disturbance.

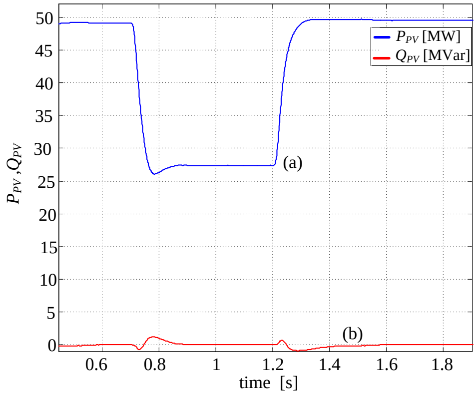


Fig. 5. PV power plant response during sudden change of insolation: a) active power; b) reactive power

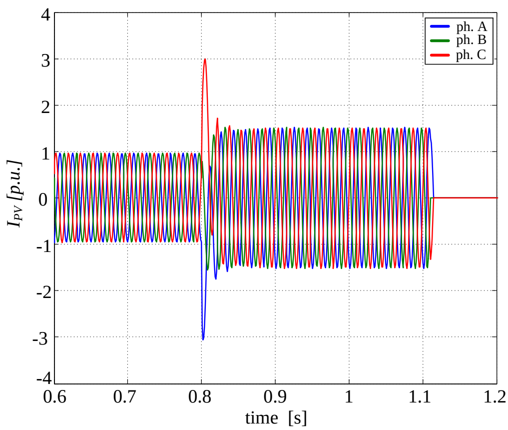


Fig. 6. PV power plant current under long-lasting three-phase fault at the PV station busbar

## 2.2. TEST DISTRIBUTION NETWORK

Single line diagram of full modelled MV network is presented in Fig. 7. It contains a 50 MW PV power plant – described earlier – connected to a 27.6 kV distribution feeder. The distribution feeder is supplied by a substation of 70 MVA transformer.

Power is transmitted to customers through both cable and overhead lines of lengths varying between 0.5km and 5.0km. In the investigations, various impedances of system $E_s$ were considered, to analyse three cases of varying level of PV penetration (i.e. 10%, 30% and 45%).

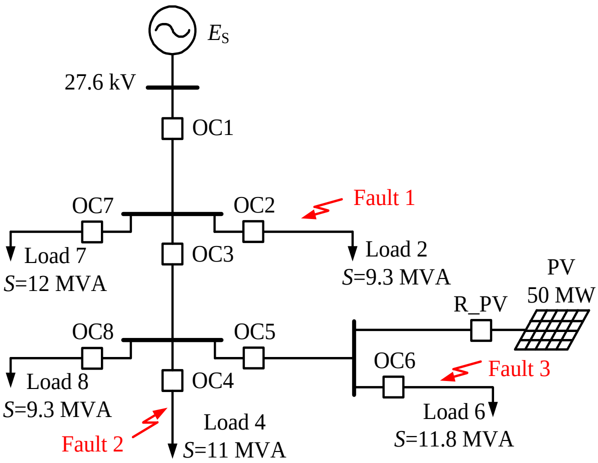


Fig. 7. Schematic diagram of distribution network with PV generation system used in the PSCAD

The model was used for studying three fault scenarios: $F_1$, $F_2$ and $F_3$, as shown in Fig. 7. Overcurrent relays OC1-OC6 were set to operate as fast as possible for faults in the primary zone, and with appropriate delay for faults in the backup zones. Moreover, the settings must be below the minimum fault current for which they should operate, but not operate on all normal and other load conditions. All relays were set according to these requirements and properly coordinated for system without PV power plant. Fig. 8 shows the time-current characteristics of the relays.

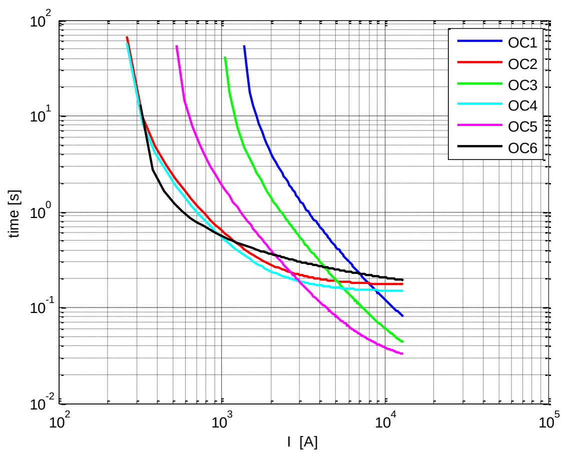


Fig. 8. Time-current curves of overcurrent relays in the distribution system

## 3. TEST RESULTS

In this section, the fault contribution of PV grid-connected generation was surveyed. To make results more realistic, various operating conditions of PV arrays have been taken into account such as, operating cells temperature that affects PV characteristics shape as well as insolation that has essential effect upon the maximum of PV power. Since the basic aim of the research was to analyse influence of the PV system on distribution system protection performance (i.e. overcurrent protection), these simulations were done with and without photovoltaic power generation. A large number of fault scenarios have been simulated and relay performance has been investigated. The results for system with and without PV power generation were then compared to assess the performance of the distribution system protection. In this paper, only two cases are shown because of space limitations.

Case 1 is for a three-phase fault at point Fault1. The level of the PV penetration was equal to 30% and overcurrent protection settings remained unchanged as for the system without PV power plant. Figure 9 shows that even if the inverter would continue to feed the fault, it would be at a level below 2 times rated current of the unit. Obviously, this current affects the short-circuit current, as observed when Fig. 10a and Fig. 10b are compared.

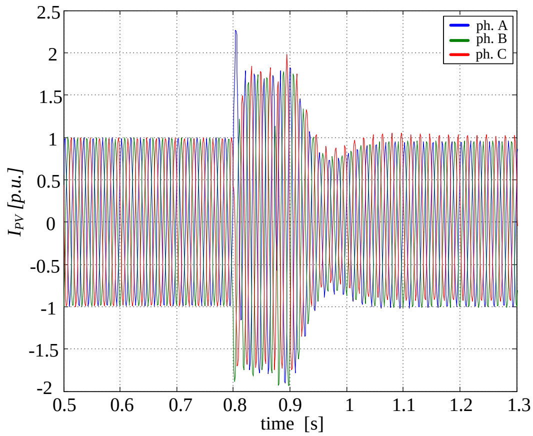


Fig. 9. PV power plant current for Case 1

As far as protection performance is concerned, it has been noticed that even if overcurrent relays settings had not been changed, protection relays were still well coordinated and no maloperations were observed. As shown in Fig. 11, relay OC2 properly cleared the fault. Obviously, tripping time is shorter when fault is fed both from the utility and from PV power plant. Basically, in most of the investigated cases, connection of the PV power plant to the grid did not require any changes of OC relay settings.

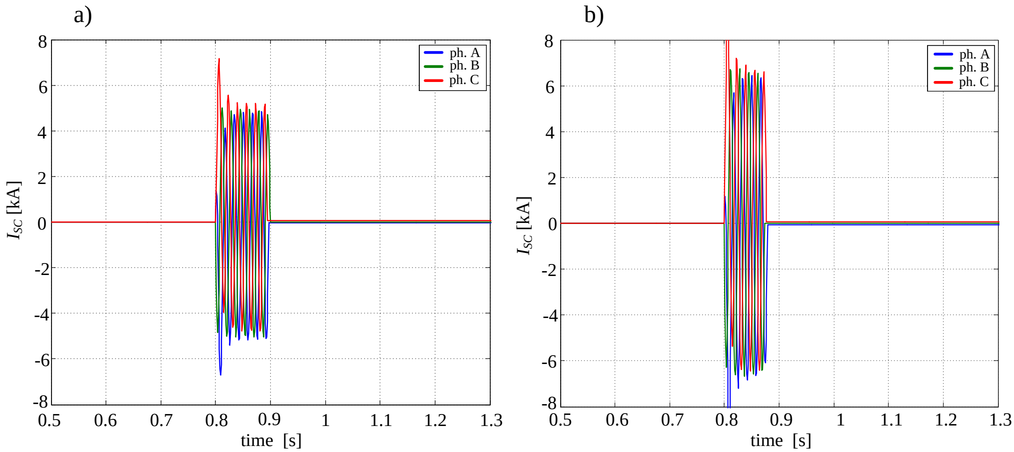


Fig. 10. Short-circuit currents for Case 1: a) without PV power plant; b) with PV power plant

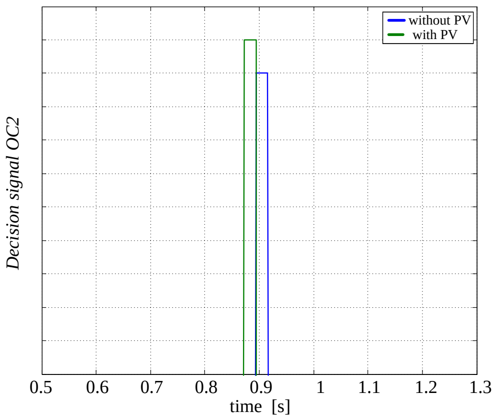


Fig. 11. Decision signals of overcurrent protection OC2 for Case 1

Case 2 is a three-phase fault at point Fault3. The level of the PV penetration was equal to 45% and overcurrent protection settings again remain the same as for the system without PV power plant. In Fig. 12, short-circuit current contribution from grid-connected PV power plant is shown. Although PV current is once again less than twice the inverter's rated output current as seen in Fig. 13, but the contribution is relatively higher as compared to Case 1. But, there is no unselective tripping. The fault was cleared by the relay OC6, as shown in Fig. 14. However, because of this clearance, PV power plant started transferring all generated power through OC5. Since OC5 was not set for such scenario, it can be observed that after few seconds a trip signal is issued, as shown in Fig. 15. This kind of situation should be taken into account. To prevent undesirable tripping in the mentioned case, OC5 should be set properly or a directional time-overcurrent relay may be applied.

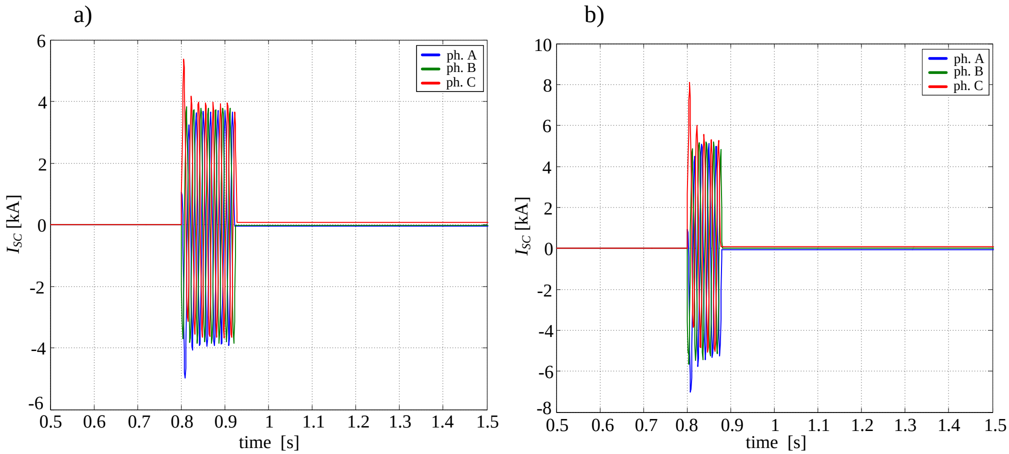


Fig. 12. Short-circuit currents for Case 2: a) without PV power plant; b) with PV power plant

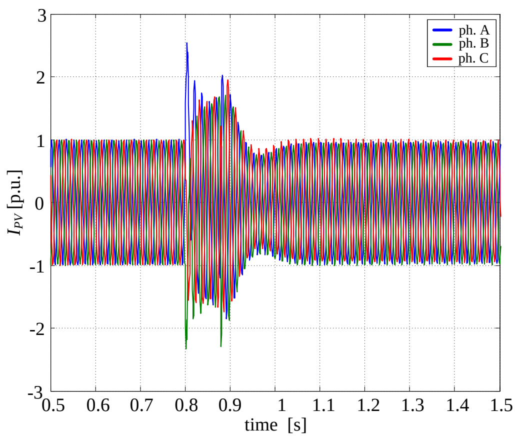


Fig. 13. PV power plant current for Case 2

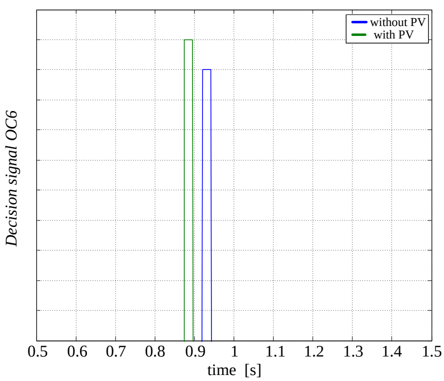


Fig. 14. Short-circuit currents for Case 2: a) without PV power plant; b) with PV power plant

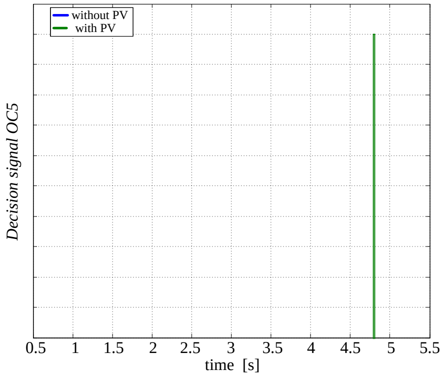


Fig. 15. Short-circuit currents for Case 2: a) without PV power plant; b) with PV power plant

## 4. CONCLUSION

In the paper, the fault contribution of the grid-connected photovoltaic power plant is discussed. The dynamic model of a PV power plant interconnected to radial distribution network is presented. Using this model, it was possible to investigate issue at hand.

Large number of simulation cases confirmed that even for large scale PV power plant fault contribution is insignificant. Due to limitation of maximum power inverter current, it can be assumed that total fault contribution from PV power plant does not exceed twice the PV power plant rated current. Additionally, when PV system is properly protected (i.e. overcurrent, overvoltage and anti-islanding protections) its fault contribution is also limited in time. For these reasons, there should not be any problem with relays coordination when large scale PV power plant is connected to the grid. Undoubtedly utility service should be careful when the level of the PV power plant penetration is high. Then, a dedicated study is recommended and sometimes coordination with directional units may be required.

Although impact of grid-connected PV power plant on the protection performance is not significant, it must be noted that short-circuit current levels will increase. This must be taken into consideration when short-circuit capacity requirements of power system devices (e.g. circuit breakers) are analysed.

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