

# Relay Protection Coordination for Photovoltaic Power Plant Connected on Distribution Network

Case Study

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**Abstract** – This paper presents a procedure and computation of relay protection coordination for a PV power plant connected to the distribution network. In recent years, the growing concern for environment preservation has caused expansion of photovoltaic PV power plants in distribution networks. Numerical computer simulation is an indispensable tool for studying photovoltaic (PV) systems protection coordination. In this paper, EasyPower computer program is used with the module Power Protector. Time-current relay curves will be computed and plotted for all protection devices in the network and the PV power plant. Protection relay AREVA Micom is placed on the secondary side of a 10 kV feeder and has overcurrent and ground fault protection. The HV side of the transformer station where a PV power plant is connected has an HV fuse. On the secondary side of the transformer there is a low-voltage (LV) circuit breaker Končar 400A with overcurrent, under/over voltage, under/over frequency and ground fault protection. Furthermore, the fuse in the supplying cable for the PV plant is installed as well as the LV breaker in the PV switchboard. Each SMA Tripod inverter is protected with the fuse and the RCD relay. All these relays are modeled and short circuit analysis is performed on several places in the network and the PV power plant and the transformer station. Three phase and single phase to ground faults were considered. Time-current plots were presented and a relay setting is suggested in order to satisfy selectivity and backup protection.

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**Keywords** – distribution, inverter, PV power plant, relay protection, short circuit

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## 1. INTRODUCTION

In recent years, installation of PV power plants in the distribution network has increased significantly. In order to provide safe operation of a PV power plant, relay protection coordination must be carried out. Numerical computer simulation is an indispensable tool for studying photovoltaic (PV) systems protection coordination. In this paper, the procedure and computation

of relay protection coordination for a PV power plant connected to the distribution network is presented.

## 2. TECHNICAL DATA OF SOLAR POWER PLANT DOMI AND THE SURROUNDING DISTRIBUTION NETWORK

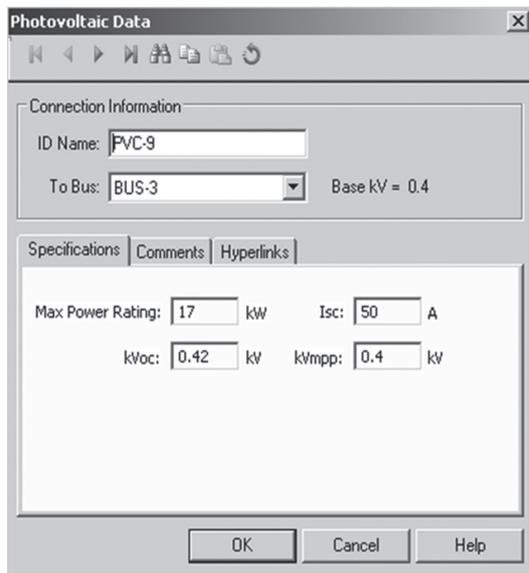
A solar power plant is built on the existing building as a structural system area of 1,088 m<sup>2</sup> on which 636

photovoltaic modules (of type SMA ST 245E) are set to produce electricity. Each photovoltaic module consists of 60 solar cells. The main parts of the solar power plant, i.e., a photovoltaic array and a photovoltaic inverter, convert solar energy into electricity and deliver it to the electricity network. Solar power plant Domi is presented in Fig.1.

Photovoltaic modules are connected to nine 17 kW three-phase inverters with the total power of 153 kW. The entire PV field contains 636 modules with the total power of 155.82 kWp. Photovoltaic modules are grouped into a photovoltaic string and presented as nine individual units of the output power 17 kW, the short-circuit current of 50 A, and the open-circuit voltage of 0.42 kV. Voltage at which the maximum power is achieved amounts to 0.4 kV. The characteristics of a photovoltaic string are given in Fig. 2.



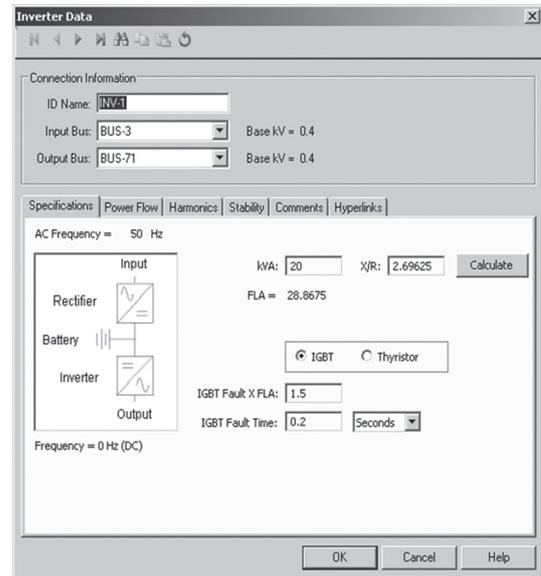
**Fig. 1.** Solar power plant Domi



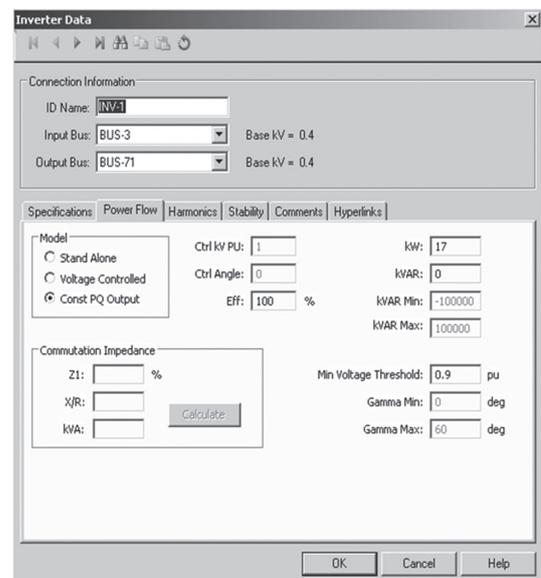
**Fig. 2.** Characteristics of a photovoltaic string

The generated direct current is inverted into alternating current using the inverter. Voltage is synchronized on the grid voltage by the amount and frequency. Nine production units are connected to nine equal three-phase inverters of rated power of 20 kVA. Inverters do not pro-

duce reactive power, i.e., power factor value amounts 1. Due to Croatian Utility Grid Rules, isolated operation of the solar power plant in respect of the power grid is forbidden. The IGBT inverter is modeled with a constant output power of 17 kW and a lower voltage limit of 0.9 pu, as can be seen in Fig. 2. and Fig. 3.



**Fig. 3.** Inverter characteristics, specification tab



**Fig. 4.** Inverter characteristics, power flow tab

The solar power plant is connected to the 10 kV distribution network at the 0.4/10 kV substation Majeđe Gajec. The supply substation 35/10 kV Varazdin 2 powers the observed 10 kV distribution network. Substation data are shown in Table 1. and Table 2. In both parallel connected transformers in the substation 35/10 kV Varazdin 2, the star point is grounded through a small impedance value of 40 Ω. The purpose of star point grounding in electric power networks is to limit the fault current as well as the level of internal surges in case of a single line-to-ground fault.

**Tab. 1.** 10/0.4 kV transformer substation Majerje Gajec

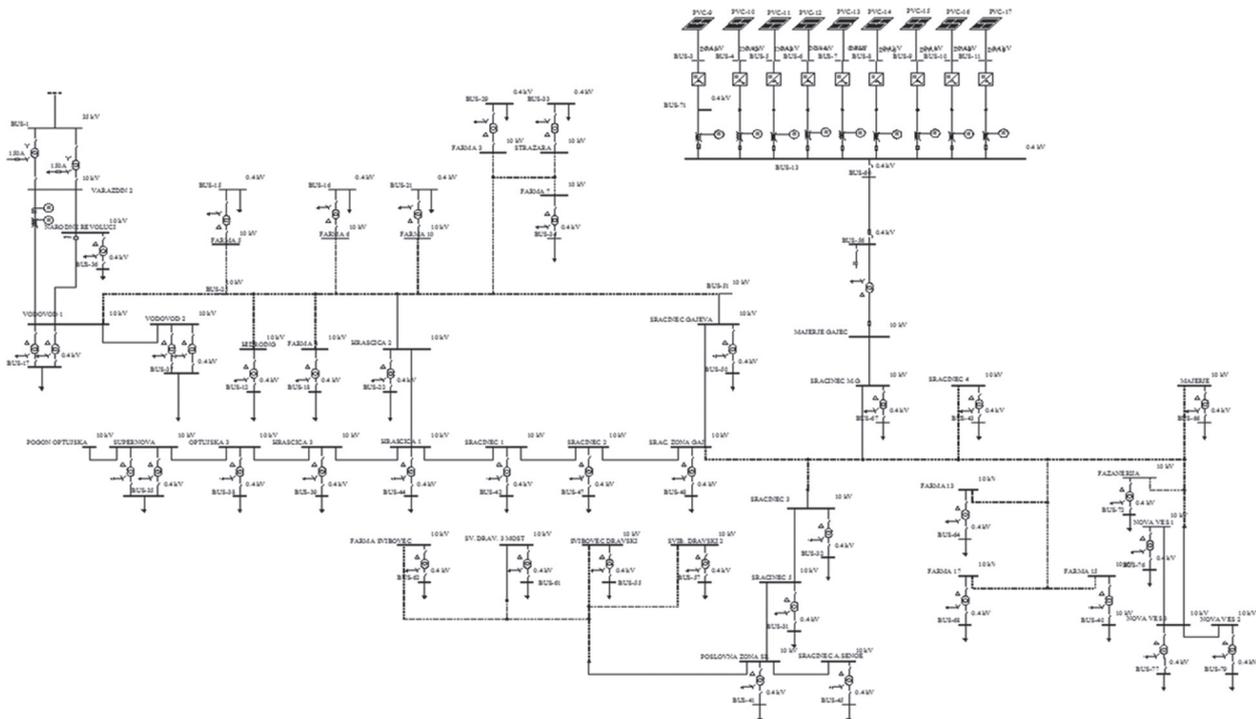
Transformer station name	TS 10/0.4 kV Majerje Gajec
Transformation	10/0.4 kV
Rated power	400 kVA
Short circuit voltage	4 %
Three phase short circuit power	7.9 MVA
Transformer star point grounding status	Star point is grounded directly
Voltage tap position	-1
Vector group	Dyn5
Core losses	610 W
Copper losses	4,600 W
Rated power of capacitor bank	50 kVAr

The amount of inrush current and the duration of the transient state in case of energizing the transformer as well as amounts of single line-to-ground short-circuit impedance (high-impedance faults) are important parameters that determine the proper operation of relay protection. A false protection response results in disconnection of the element or the entire distribution feeder, which makes it difficult to establish normal operation.

**Tab. 2.** 35/10 kV transformer substation Varazdin

Transformer station name	TS 35/10 kV Varaždin 2 - VP 10 kV DV Vinica
Transformation	35/10 kV
Rated power	2 x 8 MVA
Short circuit voltage	7 %
Three phase short circuit power	164 MVA
Transformer star point grounding status	Grounded through a small impedance of 40 Ω in order to limit ground fault currents to 150 A
Voltage tap position	0

By increasing the value of the current protection settings, sensitivity to single line-to-ground faults reduces which can result in damage of the grounding resistor due to overheating. An increase in the fault duration can lead to high touch voltages in the power network and can damage the grounding system, especially if the fault current is greater than a few kA. Single line-to-ground fault current in the 10 kV distribution network is limited to 150 A. In this particular case, single line-to-ground fault current is limited to 143.5 A by grounding the star point of transformers in TS 35/10 kV Varazdin 2 through resistors. In Fig. 5, a computer model of the observed 10 kV distribution network and the solar power plant is presented. The computer model is made in Easy Power software.



**Fig. 5.** Model of the observed 10 kV distribution network

### 3. POWER FLOW CALCULATION AND FREQUENCY RESPONSE

Since load values of 10/0.4 kV transformer substations are not available, for the purpose of power flow calculation, linear load distribution on the feeder is assumed with respect to transformer rated power in each substation, with the assumed power factor  $\cos \varphi = 0.95$  according to:

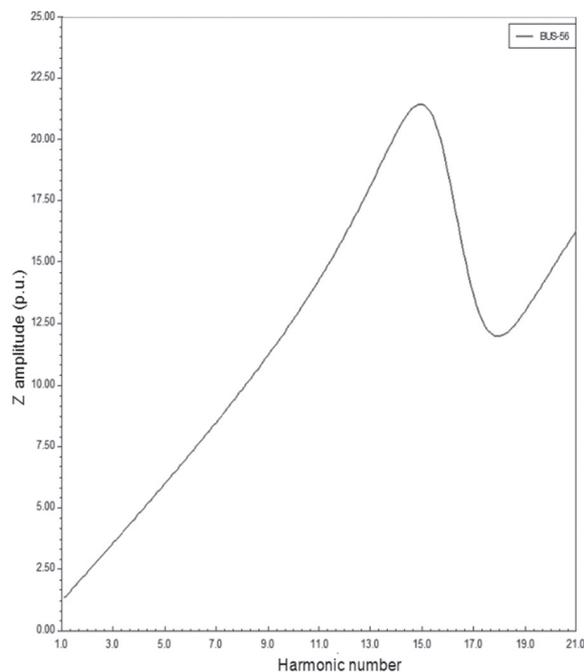
$$S_i = S_f \cdot \frac{S_{r,i}}{\sum_{i=1}^N S_{r,i}} \cdot f_g, \quad (1)$$

where:

- $S_i$  – apparent load power of transformer station  $i$ ,
- $S_f$  – total apparent power of the observed feeder,
- $S_{r,i}$  – rated power of the transformer in substation  $i$ ,
- $f_g$  – loss factor.

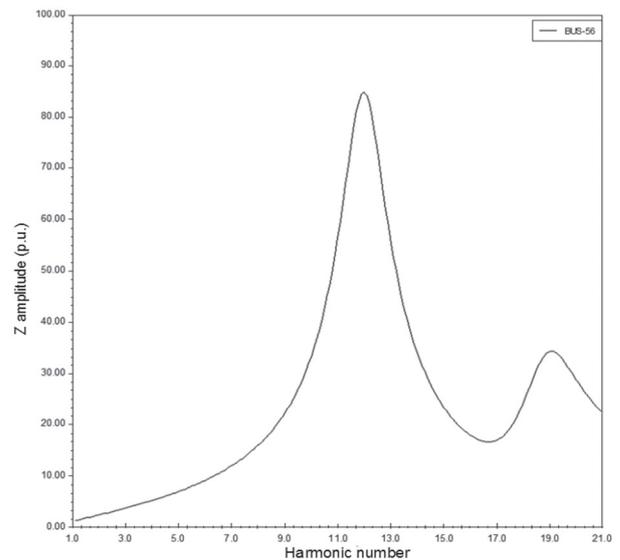
The loss factor  $f_g$  takes into account power losses in transmission lines and transformers, depending on the network topology and voltage profile in the network. The value of the loss factor in the modeled network is assumed and it amounts to 0.8. In order to determine the total apparent power of the observed feeder for scenarios of the maximum and the minimum load, maximum and minimum values of current measured on the transformer in the 35/10 kV Varazdin 2 substation are used.

Frequency responses when a capacitor bank is switched off and switched on are presented in Fig. 6. and Fig. 7., respectively.



**Fig. 6.** Frequency response when the capacitor bank is switched off

The frequency of the ripple control signal in the distribution network is 316.66 Hz and it can be concluded from Fig. 6 and Fig. 7 that the capacitor bank does not affect the ripple control signal.



**Fig. 7.** Frequency response when the capacitor bank is switched on

Power flow calculation results for scenarios of the maximum and the minimum load of the observed feeder are presented in Table 3. The results show that voltage values do not violate the limits defined by the Grid Rules.

**Tab. 3.** Power flow calculation results for scenarios of the maximum and the minimum load of the observed feeder

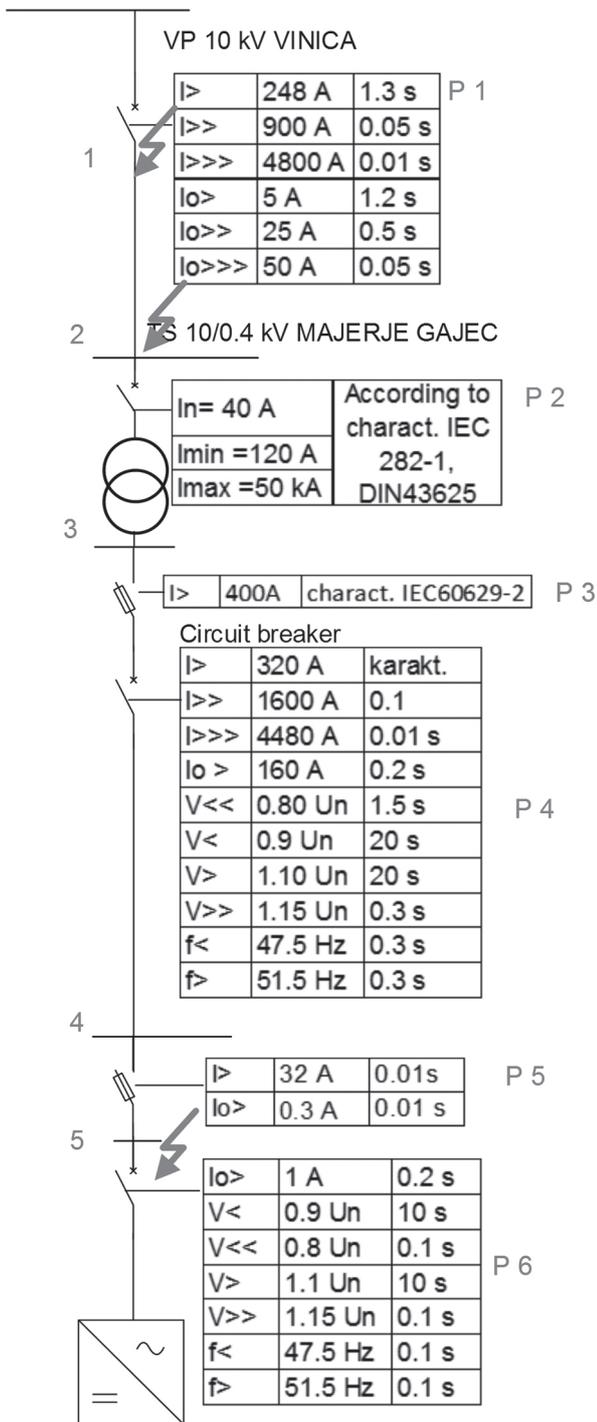
Scenario	Active Power (MW)	Reactive Power (MVar)	Total Power Losses (MW)	Maximal Voltage Drop (%)
Maximum load	6.945	2.241	0.369	5.7
Minimum load	3.806	1.068	0.120	3.3

### 4. SHORT-CIRCUIT ANALYSIS AND PROTECTION COORDINATION

A computer model of a PV power plant and a local distribution network created in EasyPower (Fig. 5.) is used for short-circuit simulations. A simplified single-line diagram of a PV power plant and its connection to the local distribution grid is shown in Fig. 8. Three-phase and single-phase to ground short-circuits were simulated at different locations. All locations are marked with numbers in Fig. 5. The obtained values of short-circuit currents are listed in Table 3.

**Tab. 4.** Short circuit calculation results for different locations in the network

Location	Current of single line to ground short circuit Ik1	Current of three-phase short circuit Ik3
1	0.287 kA	5.531 kA
2	0.255 kA	1.697 kA
3	12.734 kA	11.229 kA
4	8.633 kA	8.801 kA
5	7.272 kA	7.741 kA



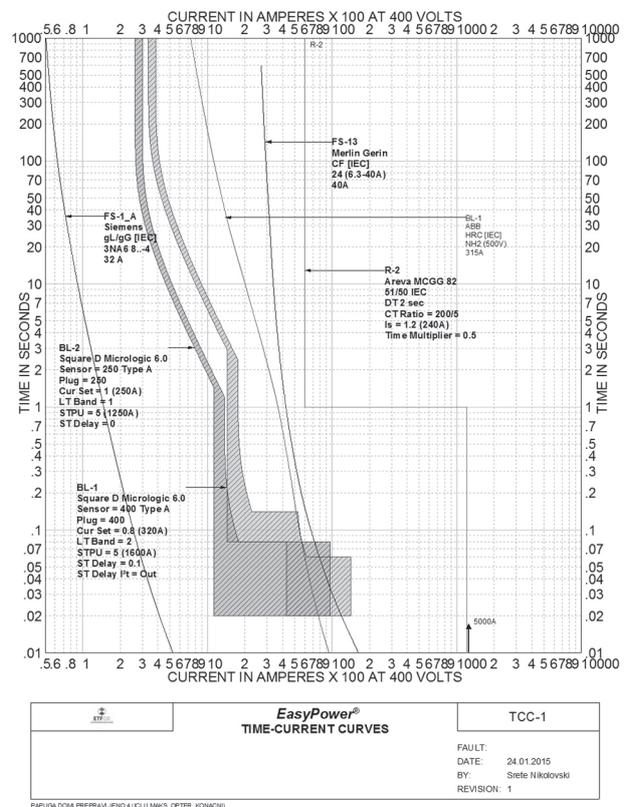
**Fig. 8.** A simplified single-line diagram of the PV power plant and proposed protection settings

Besides the impedance of network elements, the three-phase short-circuit current is dependent on the voltage level (the largest three-phase short-circuit current is on the LV side of the 10/0.4 kV transformer – location 3). The single-phase short-circuit current, *inter alia*, depends on the grounding system of the network transformer. The star point of the 35/10 kV transformer (location 1) is grounded through small impedance and thus the single line-to-ground short-circuit current is smaller than 300 A.

The star point of the 10/0.4 kV transformer (location 3) is directly grounded and thus the single line-to-ground short-circuit current is significant.

### 5. OVERCURRENT PROTECTION SETTINGS

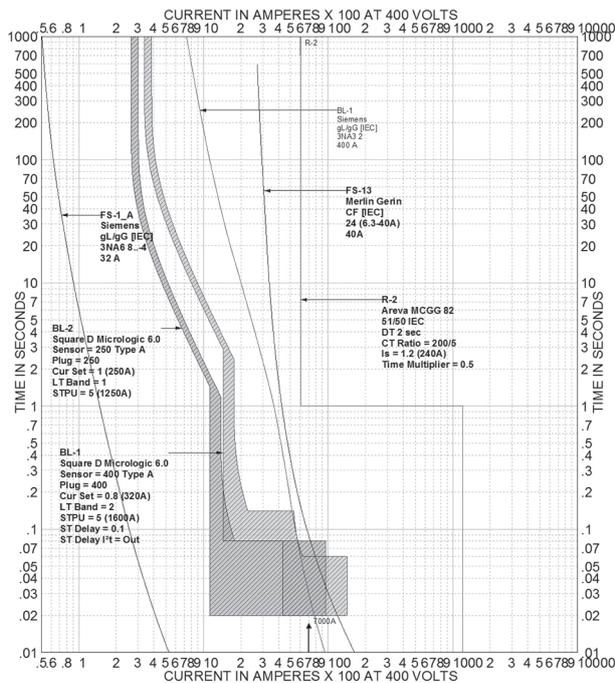
The proposed settings of overcurrent protection are shown in tables marked with letters (P1, P2, etc.) in Fig. 8. In order to test the proper functioning of overcurrent protection, simulations of the three-phase short circuits are performed and time-current curves of protection devices are plotted. Due to limited space of the paper, only two curves for two cases of short-circuit simulation are shown. Time-current curves for the case of a three-phase short circuit at location 1 are given in Fig. 9. According to Table 3, the three-phase short circuit current is 5.531 A.



**Fig. 9.** Time-current curves of protection devices for the case of a three-phase short circuit at location 2

As can be seen in Fig. 9, the fault be isolated from the 35 kV feeding network by protection device P1 (it will trip after 0.01 s) and from the side of the PV power plant by protection P3 (circuit breaker I> will also trip after 0.01 s).

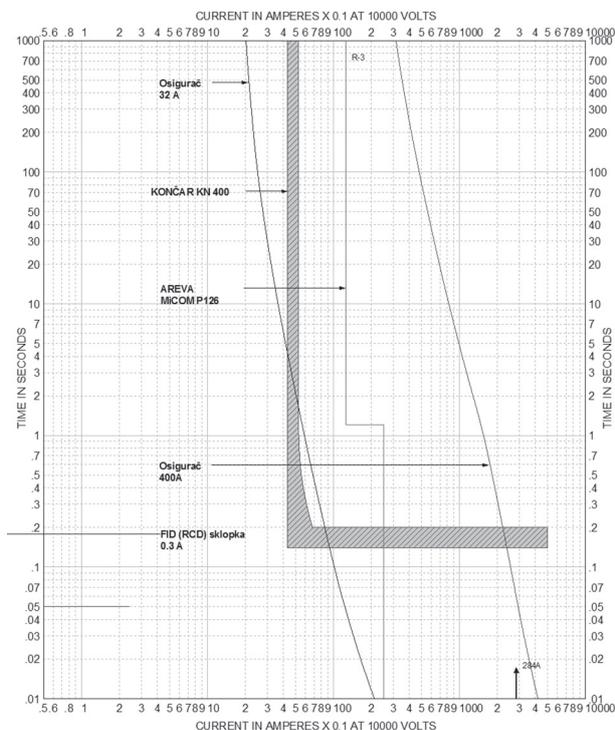
Time-current curves for the case of a three-phase short circuit at location 5 are given in Fig. 10. According to Table 3, the three-phase short circuit current is 7.741 A. The fault is isolated by protection device P5 (I>32 A).



**Fig. 10.** Time-current curves of protection devices for the case of the three-phase short circuit at location 5

## 6. GROUND FAULT PROTECTION SETTINGS

In order to test the proper functioning of ground fault protection, simulations of SLG short circuits are performed and time-current curves of protection devices are plotted. Due to limited space of the paper, only one example is shown. Time-current curves for the case of the single line-to-ground short circuit at location 1 are given in Fig. 11.



**Fig. 11.** Time-current curves of protection devices for the case of the single line-to-ground short circuit at location 1

According to Table 3, the three-phase short-circuit current is 287 A. The fault is cleared by protection device P1.

## 7. CONCLUSION

A computer model of the PV power plant and the surrounding distribution network is created by means of computer software EasyPower. Installed power of the PV power plant is 153 kW. The created computer model is used to simulate power flows in order to examine the impact of the PV power plant on voltage profile in the distribution network. A power flow analysis performed for cases of the minimum and the maximum load in the distribution network shows that the PV power plant does not have any negative impact on voltage profile in the distribution network. In the second part of the paper, a short circuit analysis is presented. Short circuit simulations are performed in order to check settings of protection devices. Examples of time-current curves of protection devices obtained for the three cases of different short circuits at different locations show that protection devices are well-tuned and that the faults are cleared properly and on time.

## 8. REFERENCES

- [1] Electrical installation for PV Power Plant Domi, Project, MTB Engineering Ltd., Macinec, 2012.
- [2] S. Nikolovski, Zaštita u elektroenergetskom sustavu - udžbenik (Power System Protection), Faculty of Electrical Engineering, Osijek, 2007.
- [3] S. Nikolovski, T. Barić, Programski paketi za analizu i simulaciju rada elektroenergetskog sustava : upute za rad (Power System Analysis - 2<sup>nd</sup> edition), Faculty of Electrical Engineering, Osijek, 2003.
- [4] PV Power Plant Influence on Electrical Network, Project, Solektra Čakovec, 2013.
- [5] M. Primorac, L. Jozsa, V. Papuga, "Maintenance of Photovoltaic Power Plants", 23<sup>rd</sup> International Scientific-Professional Meeting OTO 2014, Požega, Croatia, April 2014.
- [6] S. Nikolovski, D. Šljivac, I. Provči, "Simulation of Numerical Protection REF 541 in Transformer Station TS 35/10 kV Using Power Protector Software", International Council on Large Electric System – CIGRÉ Croatian National Committee, VI Symposium, Vol. B5 - 17, Cavtat, Croatia, 2003, pp. 141-150.
- [7] EasyPower 9.0 User Manual, Easypower LLC, Gladstone, Oregon, 2014.