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PROTECTION COORDINATION OF PHOTOVOLTAIC POWER PLANT IN THE TIME DOMAIN

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Abstract:
The safety of workers and equipment in the power grid requires the shutdown of power plants in case of maintenance or malfunction. The shutdown relies on protective devices that must be properly coordinated to isolate only the part of the grid affected by the malfunction. Using the DIgSILENT PowerFactory software, an analysis was conducted on a model of an accurate real grid integrating a photovoltaic power plant with a capacity of 390 kW. Protection coordination testing was carried out for three-phase, two-phase, and single-phase short circuit currents at arbitrarily selected locations at medium and low voltage levels. Protection in the time domain is coordinated on lines and busbars to determine the speed and selectivity of protective devices. The analysis results indicate that adequately adjusting the three-phase short circuit at the main transformer output 110/10 kV with an impedance of 0 Ω and an allowed protection operation time of up to two seconds can be correctly addressed within 36.7 ms.

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1. INTRODUCTION

Since the early days of electricity use, the flow of electricity has been from the source to the consumer. With the emergence of renewable energy sources, such as photovoltaic power plants, connecting at the point of consumption for end consumers of electrical energy on the low-voltage grid, the flow of electrical energy is no longer unidirectional. With the increasing number of photovoltaic power plants on the low-voltage grid connected on the consumer side, the reliability of electrical energy supply is enhanced. Distributed generations are beneficial in reducing network losses, increasing network reliability, and improving power quality [1-3]. However, such a large penetration of distributed energy resources may bring several challenges for coordinated control, system reliability, and proper protection coordination [4-5], which becomes increasingly challenging as selective protection must be ensured from the substation to the consumer, as well as from the consumer (source) to the substation [6-7]. By connecting new photovoltaic power plants, power flows changes, leading to an increase in short-circuit currents. The short-circuit current of photovoltaic sources (I_{ks}) is 10% higher than the rated current, and due to the large number of photovoltaic power plants, there is a significant contribution to the short-circuit current [8-10]. With a significant contribution to the short-circuit current, all photovoltaic power plants with a 50 kW or higher capacity must meet grid connection requirements. Coordination verification of protection must be performed because protective devices are set up before the grid configuration changes and are adjusted according to previous power flows, which may

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differ significantly from the new situation. In this paper, protection coordination is carried out on an example of a 390 kW photovoltaic power plant according to HEP-DSO (Croatian Electricity Compay, HEP - Distribution System Operator, in future reference HEP) guidelines. The selectivity of protection is tested, and the course of changes of short-circuit current value provided by the power plant is monitored. The current value at the point of disconnecting the power plant from the grid (displayed on the main bus of the power plant) is monitored, as well as other parameters required by HEP. To verify proper protection coordination, simulations are conducted using the DIgSILENT PowerFactory software package [11].

2. PROTECTION OF DISTRIBUTION GRID

The photovoltaic power plant connects to the existing grid with its pre-defined protection. Therefore, to understand how the protection of the photovoltaic power plant must be coordinated, it is necessary to know the protection of the distribution grid.

The electrical power system is susceptible to disturbances and faults, and protection devices must be installed to safeguard its components. Proper protection settings protect system components and the entire system, ensuring the shutdown of the parts of the grid affected by the fault while the rest of the grid remains energized.
The fundamental properties of protection include [12]:

- ✓ Speed of protection operation.
- ✓ Selectivity of protection.
- ✓ Sensitivity of protection.
- ✓ Reliability of protection.

One of the most crucial aspects is the speed of protection operation. Faster protection operation eliminates faults in the grid, reducing or completely avoiding destructive mechanical and thermal effects of fault current. In modern electrical power grids, the following fault-clearing time values are recommended [12]:

- ✓ 400 kV grids – fault clearing time is typically in the range of 50–120 ms.
- ✓ 110 and 220 kV grids – fault clearing time is typically in the range of 150–300 ms.
- ✓ 10, 20, and 35 kV grids – fault clearing time is typically in the 1–2 s range.

Selectivity of protection is the ability to automatically disconnect and isolate only those parts of the grid affected by the fault while the rest of the system continues to operate normally. Selectivity is achieved through [12]:

- ✓ Setting protection time in steps from the end-protected part of the grid to the power supply source
- ✓ Additional criteria (phase angle, power direction)
- ✓ Special relays with limited operating zones (differential relays).

The sensitivity of relays ensures reliable operation according to the set value. Relay operation must occur for all faults within the set operating value. The sensitivity of overcurrent relays must be such that the relay reliably operates for faults where minimal fault currents occur but does not operate for maximum operating currents of loads.

Reliability of relay protection is also a critical criterion for protection quality. While there are no faults, relays remain in a state of rest, which can be for an extended period, but in case of a fault, they must reliably perform disconnection. In the event of unnecessary operation or protection failure, the consequences can be catastrophic [13-14].

Research on faults in the grid essential for setting, operation, and selection of protection aims to determine characteristic values of various types of faults that may occur [12]:

- ✓ In converters (static generators).
- ✓ On low-voltage manufacturer's buses.
- ✓ On low-voltage buses where the power plant connects to the grid.
- ✓ On low-voltage buses of the encounter plant SPMO (stand-alone connection-measuring cabinet).
- ✓ On low-voltage buses of the MV/LV transformer where the photovoltaic power plant is connected.
- ✓ On the low-voltage side of the transformer station.

Based on the characteristic fault values, the validity of existing protection settings is checked. Changes in selecting other operating values or characteristics and introducing other protection possibilities are proposed based on fault research. The research includes the operation of appropriate protections:

- ✓ In converters (static generators).
- ✓ In the power plant low-voltage grid.
- ✓ At the interface of the power plant and the low-voltage grid (encounter plant SPMO).
- ✓ In the transformer 10/0.4 kV on the low-voltage side towards the encounter plant and the power plant.

- ✓ In the transformer 10/0.4 kV at the transformer medium-voltage connection (transformer protection) [15].

The selection of operating level and time of operation of appropriate protection must be chosen to meet all fundamental requirements for protection operation (speed, sensitivity, reserve, selectivity) while respecting the short-term permissible and rated currents of equipment in the power grid and power plant.

Research on short-circuit current flows (maximum and minimum) through the contribution of the power plant and the grid is used to adjust overcurrent protections (*I*>, *I*>>) in any configuration, ensuring the achievement of basic requirements set for each short-circuit protection and efficient separation under inappropriate conditions of parallel operation of the grid and the power plant [16-17].

Particular attention should be paid to the selectivity of fuse operation in the low-voltage grid when fault current flows through them from the grid and the power plant converter. According to Grid Code (Ministry of Economy, PP 036/06, reference [13]), islanded operation must be specially permitted, providing the conditions for this kind of operation and if the distribution system operator, and producer conclude an agreement on keeping the operation. Generally, HEP never allows islanded operation of distributed generation [18].

3. MATERIAL AND METHOD

3.1. Protection Coordination

The photovoltaic power plant protection coordination will be conducted using the PowerFactory DIgSILENT software package. A part of the grid to which the 390 kW photovoltaic power plant is connected will be modeled, and the operation of protection on simulated grid faults will be demonstrated according to the guidelines for the preparation of Protection Setting Studies (in future reference EPZ) provided by HEP. As the photovoltaic power plant alters electrical quantities that are influential to the protection operation in the grid, research is necessary to select optimal settings for existing protections in the grid, those at the interface of the power plant and the grid, and those within the power plant. Three-phase, two-phase, and single-phase short circuits are simulated at multiple locations in the grid, along with islanded operation to test protective devices in the grid.

The grid model on which protection coordination will be performed is shown in Fig. 1.

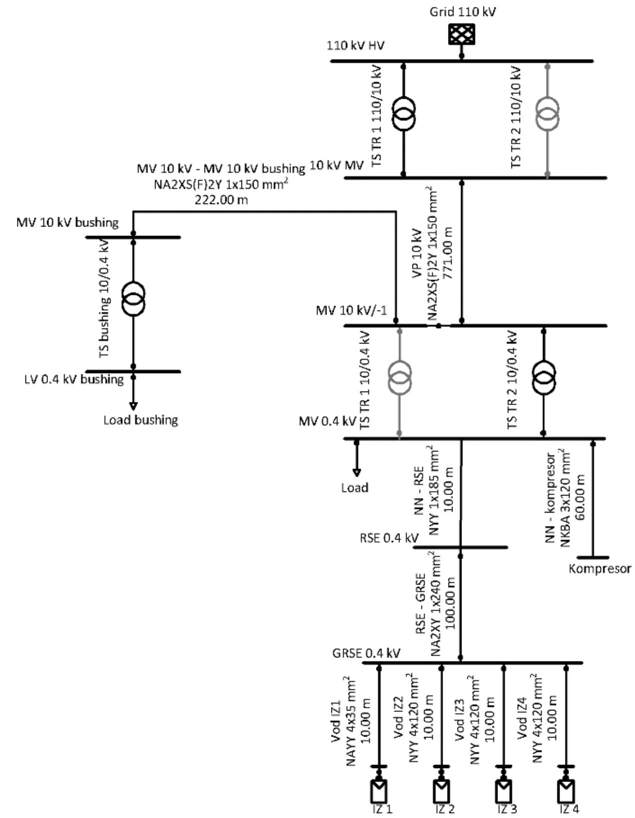

Fig. 1. Photovoltaic power plant connected to MV grid

The three-phase, two-phase, and single-phase short-circuit faults and islanded operation are simulated according to the HEP guidelines EPZ and presented in diagrams. The following diagrams are shown:

- ✓ The course of changes in the short-circuit value provided by the power plant is displayed at the separation point between the power plant and the grid.
- ✓ The course of changes in the short-circuit value provided by the superordinate grid according to the location of the fault.
- ✓ For all short circuits, the course of phase voltage values at the power plant, and the point of separation of the power plant from the grid.

Fault 1 – Short circuit on the medium-voltage feeder supplying the grid user. Characteristic quantities:

- ✓ The progression of zero sequences of voltage and current.

Fault 2 – Short circuit on one of the outputs in the consumer installation.

Fault 3 – Short circuit on the low-voltage main buses of the grid user.

Fault 4 – Short circuit on the terminals of the generator/inverter.

Grid-tied dispersed generation islanding takes place when a portion of the network that encompasses generators is detached from the central system, while independent distribution generation keeps on powering the utility lines in the isolated segment (termed as an island) [19]

To protect the power plant against the islanded operation, according to the Grid code [20], it is necessary to:

- ✓ Identify all possible scenarios for the occurrence of the power plant's islanded operation with part of the grid, considering the grid's allowed connection states.
- ✓ Depending on the method used to determine the islanded operation and the application's features in the power plant provide an interpretation of the power plant's behavior in case of a long-term stay in islanded operation with part of the grid.
- ✓ Perform a simulation of islanded operation with part of the distribution grid at the moment when the available electrical power of the power plant is closest to the consumption of the islanded grid, and determine whether passive methods (U>, U<, f>, f<, df/dt> ROCOF>, Voltage shift, Δθ>) are sufficient for detecting islanded operation [18], or if additional communication or similar methods in the power plant protection system are required [21-23].

Guidelines for preparing the Protection Setting Studies for Solar Power Plants with a capacity > 100 kW connected to the low-voltage grid define places where faults need to be simulated and results need to be observed to verify protection operation. Fig. 2 gives a general overview of fault locations in the Solar Power Plant.

Table 1 displays the location of installed protection along with their settings [24].

Another aspect of distribution power network protection is that inverter-based energy resources also have their own protective devices, which can be programmed to respond to internal and external faults in different ways [25].

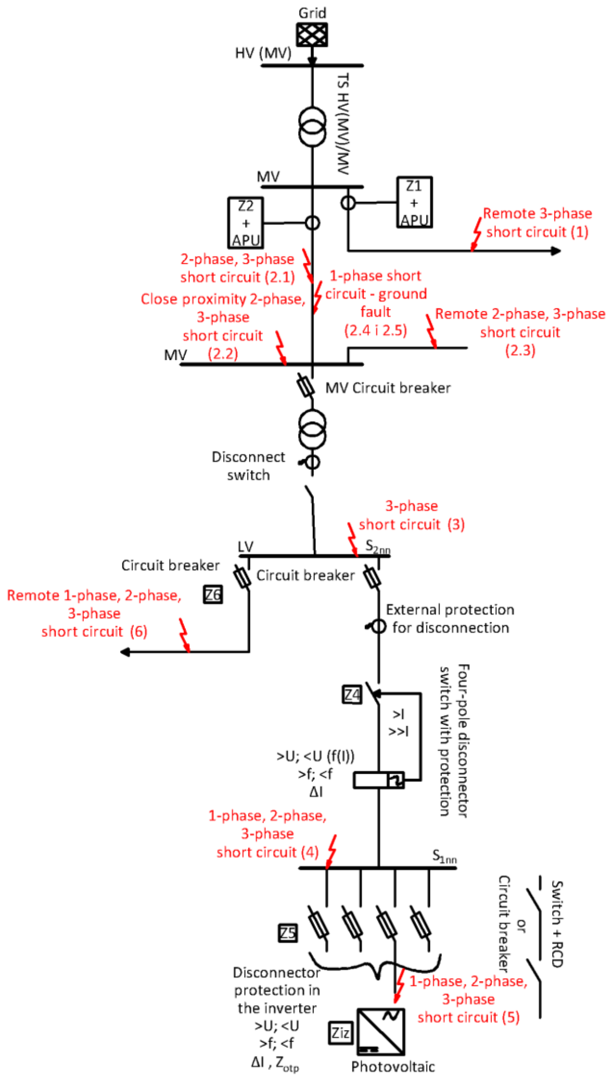

Fig. 2. General overview of faults in the Solar Power Plant

Table 1. Display of protective device

Protection name	Installation location	Settings
Z1 – Siemens 7SJ6226-5EB32-3HH3	VP 10 kV	I > 300 A; DT; 0,5 s I >> 1020 A; DT; 0 s I_E > 18 A; DT; 0,4 s I_{EE} > 3 A; 0,2 s; sinφ
Z2 – IKI 30	Bus SN 10 kV	In = 60 A; EI – Extremely inverse characteristic; v = 0,5 I > 1,1 x In = 66 A I >> 20 x In = 1200 A
Z3 – HV fuse	Transformer primary TS TR 2	VV 125 A
Z4 – ABB SACE 57H 1600 AA	Secondary of Transformer TS TR 2	In = 1600 A I > 0,9 x In = 1440 A; t = 6 s I >> 6 x In = 9600 A; t = 0,01 s
Z5 – fuse	RSE	NVO 4 x 200 A

Table 1. Display of protective device - *Continuation of the table from the previous page*

Protection name	Installation location	Settings
Z11 – fuse	Output compressor	NVO 250 A
Z6 – Schrack M4 800 A with thermomagnetic relay TM IEL VR–50	GRSE	In = 800 A I > 1 x In = 800 A I >> 10 x In = 8000 A; t = 0,01 s IEL VR–50 U > 1,10 p.u.; 60 s U >> 1,15 p.u.; 1,5 s U < 0,80 p.u.; 1,5 s f > 51,50 Hz; 0,3 s f < 47,50 Hz; 0,3 s
Z7 – Schrack MCB B 125 A	GRSE	In = 125 A with RCD protection 125/0,1 A
Z8, Z9, Z10 – Schrack MCB B 200 A	GRSE	In = 200 A with RCD protection 200/0,1 A

The meaning of symbols used in Table 1:

SN - Medium-voltage level.

TS - Transformer.

RSE - Solar Power Plant Divider.

GRSE - Main Solar Power Plant Divider.

Fig. 3 shows the tripping characteristics of protective elements.

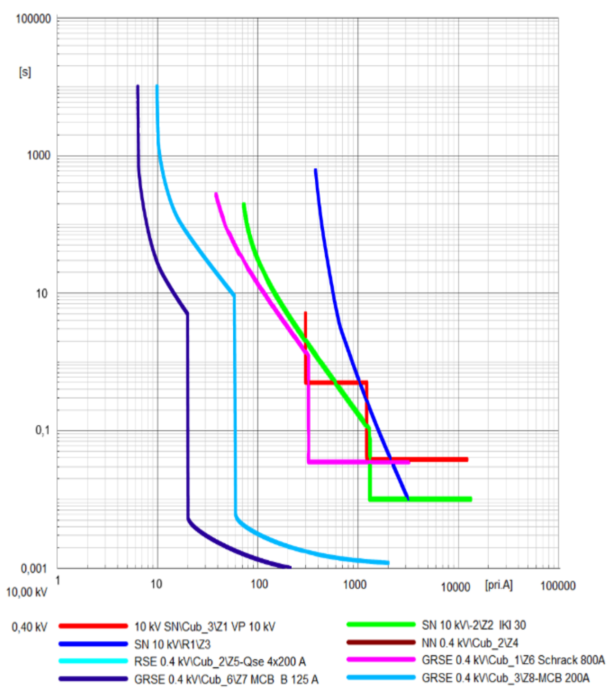

Fig. 3. Switching characteristics

Table 2 displays the protection of the inverter with under-voltage, over-voltage, sub-frequency, and over-frequency protection incorporated into the inverter. Also, specific values are given for each protection module.

Table 2. Adjustment of the inverter

Ziz	**Inverter**	U > 1,10 p.u.; 30 s U >> 1,15 p.u.; 0,2 s U < 0,90 p.u.; 1,5 s U << 0,80 p.u.; 0,2 s f > 51,50 Hz; 0,1 s f < 48,00 Hz; 1,0 s f << 47,50 Hz; 0,1 s

4. RESULTS AND DISCUSSION

The photovoltaic power plant is connected to the LV grid using four inverters. Fig. 4 depicts an equivalent grid diagram with plotted grid protections indicating their locations and settings. It models a grid section from the primary power source to the photovoltaic power plant and displays fault locations required by HEP ODS. All faults are shown, and protection operation in the event of fault 1 is illustrated. Fig. 4 and fault location 1 with Tables 3 and 4 are small pieces that are analyzed in master teases [24].

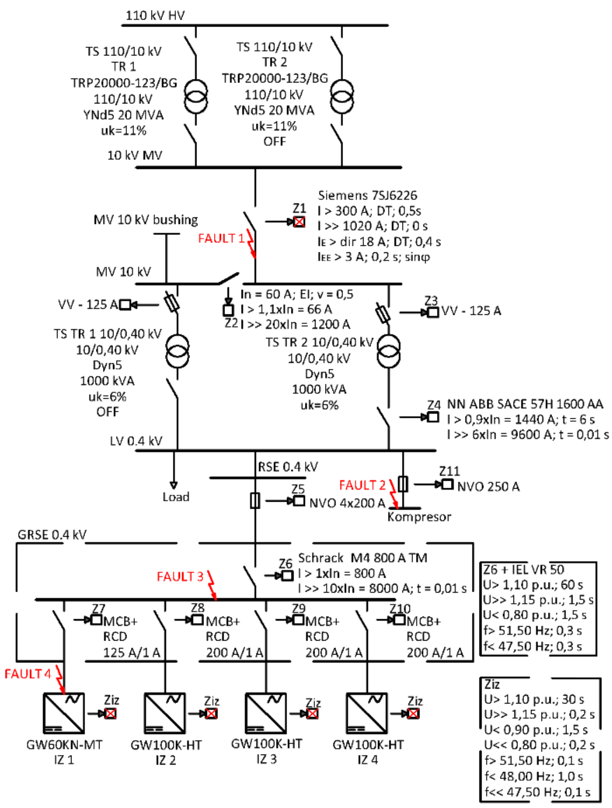

Fig. 4. Equivalent diagram with protective elements plotted, showing all faults and illustrating protection operation in the case of Fault 1 [15]

4.1 Fault Location 1: Three-Phase Short Circuit

The selectivity of protection settings for the case of a three-phase short circuit at fault location 1 was analyzed for a fault with an impedance of 0 Ω. The short circuit occurs at time t = 0.1 s after the start of the simulation. Results obtained from the event recorder of the DIgSILENT 23.0 software package and results are shown in Fig. 5:

- ✓ After 36.7 ms, protection Z1 - SIEMENS 7SJ6226 activates in the 10 kV switchgear.
- ✓ The inverters are grid-connected and disconnect from the grid after the loss of grid supply.
- ✓ The inverters will restart once the fault is cleared.

Figs. 5, 6, and 7 depict the values of currents and voltages at locations in the grid requested by HEP ODS.

The operation of protection is selective (Figs. 5, 6 and 7).

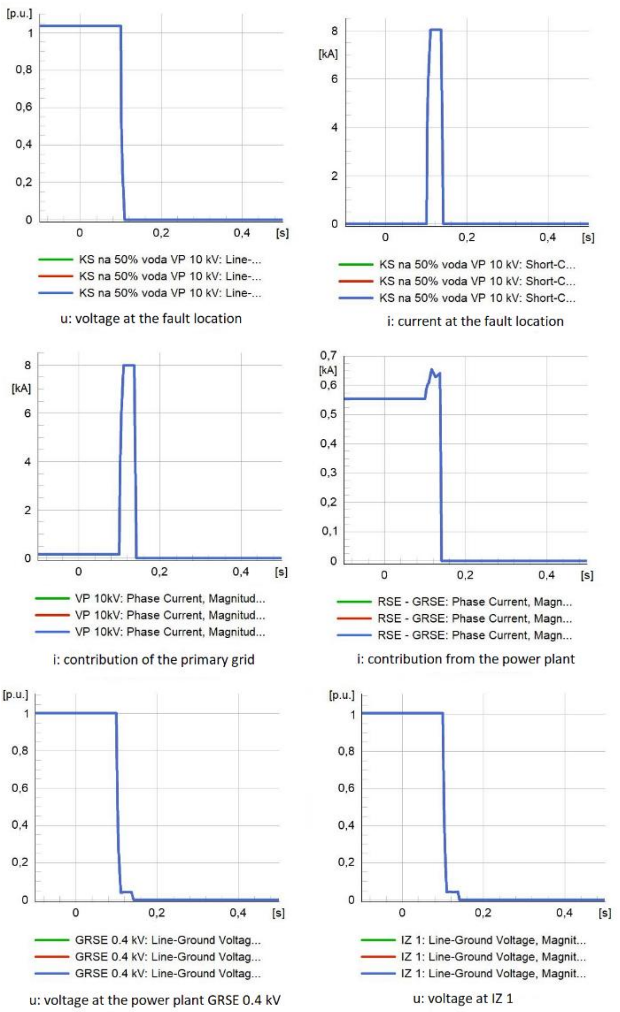

Fig. 5. RMS values of currents and voltages: Fault 1 and Three-phase fault

4.2 Fault Location 1: Two-Phase Short Circuit

The selectivity of protection settings for the case of a two-phase short circuit at fault location 1 was analyzed for a fault with an impedance 0 Ω. The short circuit occurs at time t = 0.1 s after the start of the simulation. Results obtained from the event recorder of the DIgSILENT 23.0 software package and results are shown in Fig.6:

- ✓ After 35.4 ms, protection Z1 - SIEMENS 7SJ6226 activates in the 10 kV switchgear.
- ✓ The inverters are grid-connected and disconnect from the grid after the loss of grid supply.
- ✓ The inverters will not restart until the fault is cleared.

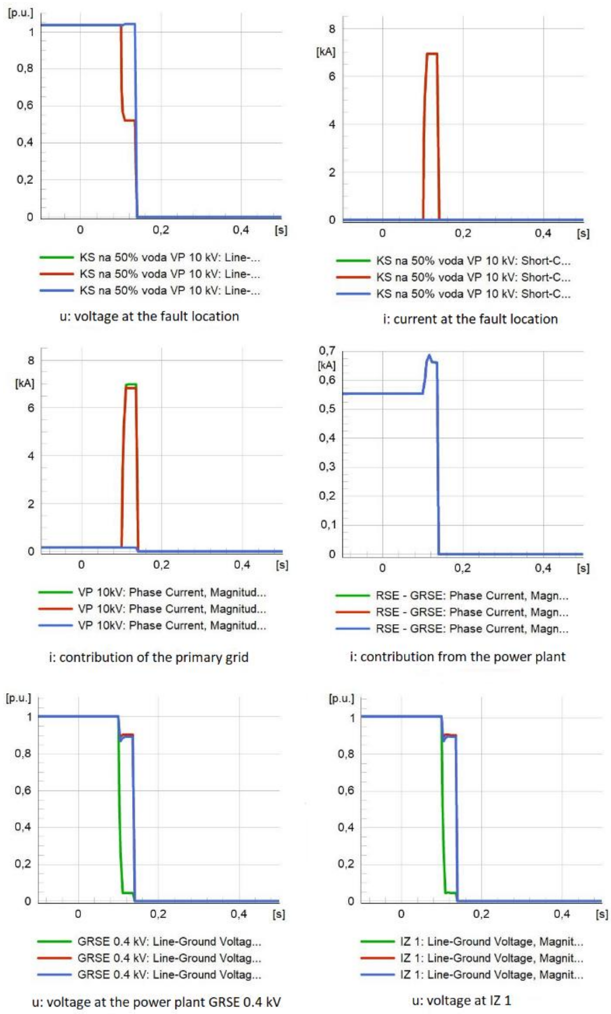

Fig. 6. RMS values of currents and voltages: Fault 1 – Two-phase fault

4.3 Fault Location 1: Single-Phase Short Circuit

The analysis of the selectivity of protection settings for the case of a single-phase short circuit at fault location 1 was conducted for a fault with an impedance of 0 Ω. The short circuit occurs at time t = 0.1 s after the start of the simulation. Results, shown in Fig. 7, are obtained from the event recorder of the DIgSILENT 23.0 software package:

- ✓ After 25 ms, protection IEE > Z1 - SIEMENS 7SJ6226 activates in the 10 kV switchgear.
- ✓ The inverters are grid-connected and disconnect from the grid after the loss of grid supply.
- ✓ The inverters will restart once the fault is cleared.

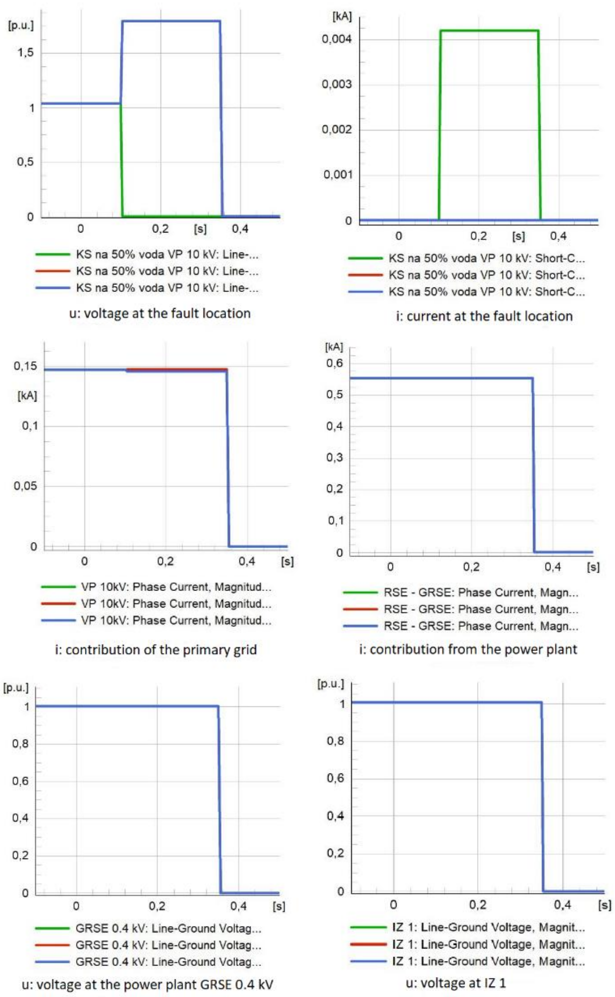

Fig. 7. RMS values of currents and voltages: Fault 1 – Single-phase fault

Fig. 8 shows the value of the zero sequence components of voltage and current.

In Table 3, fault locations are shown along with the type of fault simulated at those locations, including the operating times of protection for each location. Protective devices were properly configured, and there was no need to change their settings after installing the photovoltaic power plant.

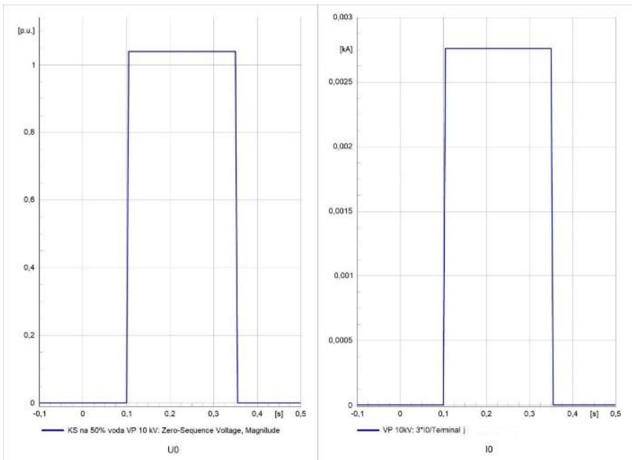

Fig. 8. Zero sequence components of voltage (left) and current (right)

Table 3. Time for the protective devices to activate

Fault design-ation	Fault type	Protective device and trip time
SC 1	3p	Z1 – Siemens 7SJ6226; t = 36,7 ms
	2p	Z1 – Siemens 7SJ6226; t = 35,4 ms
	1p	Z1 – Siemens 7SJ6226; t = 25,0 ms
SC 2	3p	Z11 – Fuse NVO 250 A; t = 2,80 ms
	2p	Z11 – Fuse NVO 250 A; t = 4,02 ms
	1p	Z11 – Fuse NVO 250 A; t = 6,70 ms
SC 3	3p	Z6 – Schrack M4 800 A; t = 35 ms
	2p	Z6 – Schrack M4 800 A; t = 35 ms
	1p	Z6 – Schrack M4 800 A; t = 35 ms
SC 4	3p	Z7 – Schrack MCB 125 A; t = 0,150 ms
	2p	Z7 – Schrack MCB 125 A; t = 0,330 ms
	1p	Z7 – Schrack MCB 125 A; t = 0,359 ms

Table 4 and Table 5 display the current and voltage values read from the RMS diagrams.

Table 4. Display of RMS current values

Fault designation	Fault type	Current from the upstream grid 10 kV [A]	Current from the power plant at the separation point LV RSE – GRSE [A]	Current at the fault location [kA]
SC 1	**3p**	7973	655	8.023
	2p	6975	68	7.597
	1p	147	553	0.004
SC 2	**3p**	555	543	12.207
	2p	555	603	10.485
	1p	294	561	8.242
SC 3	**3p**	651	14480	15.089
	2p	673	12571	13.058
	1p	410	11117	11.603
SC 4	**3p**	501	10595	10.969
	2p	224	3124	3.210
	1p	162	2993	3.386

Table 5. Display of RMS voltage values

Fault designation	Fault type	Voltage at GRSE 0.4 kV [p.u.]	Voltage on IZ 1 [p.u.]
SC 1	**3p**	0.039	0.041
	2p	0.868	0.872
	1p	1.004	1.007
SC 2	**3p**	1.006	1.009
	2p	1.006	1.009
	1p	1.007	1.010
SC 3	**3p**	0.000	0.000
	2p	0.517	0.521
	1p	1.167	1.171
SC 4	**3p**	1.005	0.000
	2p	1.020	1.019
	1p	1.020	1.023

5. CONCLUSION

In order to ensure selectivity, the activation of the appropriate protection needs to be enabled. The protection is tested by simulating faults and the operation of protective devices. In this particular case, testing is done using the DIgSILENT PowerFactory software package. A grid model with existing protective devices has been created in the program, and by simulating three-phase, two-phase, and single-phase short circuits at various locations in the grid, the selectivity of protection operation and the settings of protective devices are examined. If a protective device does not trip for the simulated fault after the simulations, a change in relay settings must be made, and the same fault must be simulated again. Once the fault trip is ensured with the new protection settings, these settings must be applied to the protective device to ensure selectivity.

The simulation of short circuits has yielded results regarding the operation of individually installed protective devices. It can be concluded that the installed equipment for the protection of the photovoltaic power plant ensures complete protection of all plant elements and protection of the distribution grid from the power plant's back feed impact during a plant or grid fault. Further research could be conducted in the direction of system monitoring and improving the simulation model in accordance with the collected data.

Conflicts of Interest

The authors declare no conflict of interest.

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