Evaluation of the Solid-State Breakers on the performance of Power Distribution Grids with high-RES penetration

G. A. Poulimenos[1], E. D. Ellinas[1], E. M. Voumvoulakis[1], S. T. Christoforos[2], C. A. Christodoulou[1], I. F. Gonos[1]

***Abstract* — Electricity is currently one of the most promising components for the future growth of our communities. Energy consumption will skyrocket in the near future, necessitating massive reforms in the energy industry to ensure that contemporary cities have enough electricity. Furthermore, climate change necessitates a greater than ever before energy transition from fossil fuels to greener power generating sources such as wind, solar power, or other more newly discovered technologies such as hydrogen. However, significant improvements to the power distribution and transmission grids are required for high - RES penetration in the energy system. To illustrate, power networks have been built radially, with energy flowing in just one direction, from the original power source to the consumer, with no provision for the penetration of independent power producers (ipps) across power grids. As a result, studying and developing such significant components, including power protection systems, is now seen as a critical undertaking in order to minimize unanticipated breakdowns and optimize grid availability. The goal of this work is to analyze a novel and promising technology in the power protection industry known as Solid State Breakers (SSB) and its contribution to the efficient operation of power distribution networks with high-RES penetration.**

***Keywords*: distribution network, distributed generation, power protection, renewable energy, solid state breakers.**

I. INTRODUCTION

Despite the recent (2020) and ongoing pandemic, energy consumption of various forms of fuel is constantly increasing throughout the world as a result of contemporary societies' continuous industrial and digital growth, with oil and natural gas being the primary energy sources utilized from industrial and transportation sectors not only in Europe (Fig. 1) but worldwide as well. On the contrary, electrification will be critical to modern civilizations' energy transition and decarbonization. To illustrate further, the worldwide proportion of electricity in final energy consumption is climbing, reaching around 20% in 2021, and is predicted to rise considerably higher by 2030 with including Renewable Energy Sources (RES) into the energy balance. However, large-scale development of RES at the european and global levels is likely to accelerate in the next years in order to fulfill the ever-increasing decarbonization objectives and deal with the recent energy crisis [1], [2], [3]. On a more positive note, RES power plants totaling around 10 GW (50% in power distribution grids) are already in service in Greece's interconnected system.

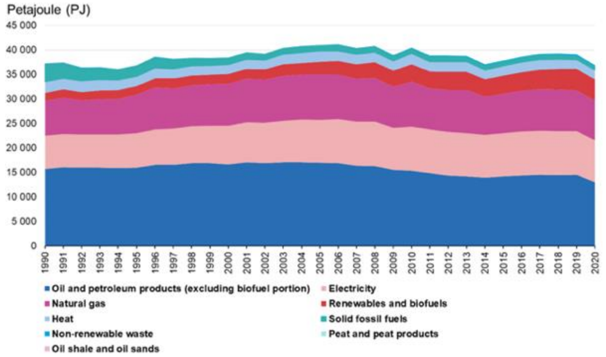

Fig. 1 - Final energy consumption by fuel, EU, 1990-2020 (Source: Eurostat)

However, as power distribution grids are currently overloaded, considerable upgrades in existing infrastructures, despite the multiple technological challenges, are required to incorporate new RES in the energy system while avoiding operational constraints or limitations to the existing ones [1]. Under the scenario of high - RES penetration, one of the most critical components of power distribution networks that must be assessed and revised is the power protection strategy. The primary goals of this are to accomplish protection coordination, isolate the smallest feasible portion of the network in the event of a short circuit and minimize catastrophic islanding events caused by RES contributions to the Short Circuit (SC). To that end, a novel semiconductor - based circuit breaker (SSB) technology has been developed, which allows for virtually instantaneous isolation of a short circuit across a Medium Voltage (MV) line [4], [5].

The performance of such a circuit breaker is studied in this research on a real power distribution network with high photovoltaic park (PV) integration, under various scenarios. Furthermore, the influence of this technology on the performance of the electricity distribution system will be assessed. Power flow and short circuit studies, in particular, have been carried out using the DIgSILENT PowerFactory software tool [20] in order to investigate the advantages of this technology over traditional electro-mechanical circuit breakers by studying transient phenomena depending on the protection device and its fault clearing time. Furthermore, purpose of this paper is to use the SES CDEGS software tool to examine the impact, that arises from a short circuit, on the power network

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1 G. A. Poulimenos, E. D. Ellinas, C. A. Christodoulou, E.M. Voumvoulakis, I. F. Gonos are with the School of Electrical and Computer Engineering, National Technical University, Athens, Greece (e-mail: igonos@cs.ntua.gr).
2 S. T. Christoforos is with Hellenic Electricity Distribution Operator S.A.

and its equipment such as the development of hazardous potentials in medium voltage grounding grids [19].

II. SOLID STATE BREAKERS

Although conventional electromechanical circuit breakers have an established track record as effective and dependable circuit protection devices, future power distribution technologies and architectures, such as dc microgrids, require enhanced interruption performance characteristics (e.g., faster switching speed). The demand for quicker switching operation, along with the most recent advancements in sophisticated power semiconductor technologies, has fueled a surge in solid-state circuit breaker research and development [4].

Solid-state circuit breakers are power semiconductor-based protection devices that have no moving components for fault current interruption and are well-known for their superior operational and system-level advantages. First and foremost, semiconductor devices have a response time that is several orders of magnitude faster than the electromechanical mechanisms used in conventional circuit breakers. Second, unlike electromechanical circuit breakers, which rely on contact separation to stop current flow, semiconductor devices may interrupt current flow without arcing [5],[6]. Moreover, thanks to the extremely quick current interruption capability, semiconductor-based circuit breakers can limit the let-through energy and arc hazard exposure in the event of a fault by multiple orders of magnitude. On top of the aforementioned benefits that are true for most of the power distribution applications, semiconductor-based circuit breakers offer several additional benefits that may be application- specific. Specifically, marine power distribution systems, data centers, aviation power distribution, battery protection, photovoltaic systems, power converter protection, railway power systems, defense power systems, and electric vehicle charging infrastructure have all evolved in recent years [5].

An upsurge in SSB research effort has been observed during the last decade. Researchers have reached manufacturing maturity of low loss, high efficiency, and quick switching wide bandgap power semiconductors enabling a wide range of system applications, which has sparked renewed interest in SSB technology. In general, many different types of SSB technologies have been proposed in the literature, as have various characteristics of SSB subsystems and critical components. Nonetheless, the idea is motivated primarily by the recent revived interest in high performance shielding in developing applications [6], [7].

As illustrated in fig. 2, the conventional electromechanical circuit-breakers have response time of some msec depending on their voltage, current rating, and tripping technology. On the contrary, SSBs have much faster reaction time than conventional ones, due to the extremely quick response of power semiconductor devices. The semiconductor devices are controlled by a relatively low power electrical signal and therefore the triggering of the SSB and the fault current limitation can occur in microseconds or even in tens of nanoseconds. Fig. 2 presents the significant difference in response time and current limitation capability of an SSB in contrast to conventional circuit breaker [4].

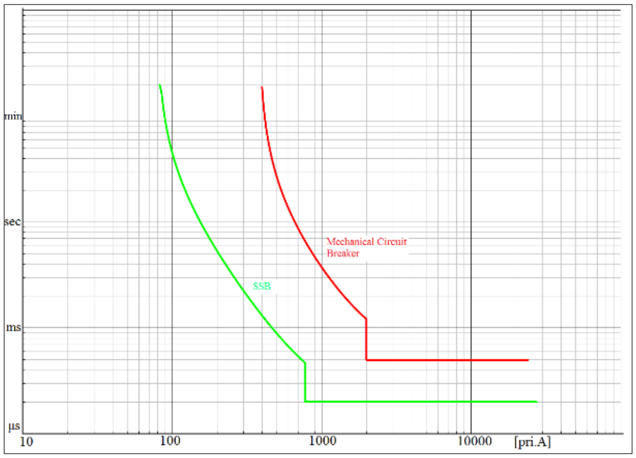


Fig. 2 - Conventional and solid-state time - current characteristics

Ultimately, solid-state circuit breakers are considered as a viable option since they can provide various advantages over traditional electro-mechanical alternatives, such as enhanced voltage quality during short circuit and lower short circuit current levels. However, until now, the majority of SSB research has concentrated on breaker topologies and control techniques. The current paper will investigate the extra value that SSBs may give to an electrical grid in terms of RES penetration.

III. SYSTEM CONFIGURATION

A. Power System Model

A typical HV/MV substation (s/s) with two interconnected MV (21kV) busbars has been simulated (Fig. 3). 5 MV distribution lines depart the first busbar and are connected to a capacitor bank, while 6 MV lines depart the second busbar and are likewise connected to a capacitor bank. On each busbar, PV parks have been linked to MV lines. The distribution network is a three-phase, three-wire network that is grounded at the transmitting end (MV node of an HV/MV substation) through a resistance that allows a single-phase to ground fault of up to 1000 A. Tables I-III show the key features of the MV lines.

TABLE I
INFINITE (HV) EXTERNAL GRID

Characteristics	Maximum Value	Minimum Value
SC Power, S_k''	2078.46 MVA	1715.51 MVA
SC Current, I_k''	8 kA	6.603 kA
c-Factor	1	1
R/X ratio	0.21829	0.29627
Z_2/Z_1	1	1
X_0/X_1	3.15764	3.15764

In Table II, the characteristics of the HV/MV transformers are presented. More specific, the 50 MVA power transformer, TR2, is connected to P2 busbar and the 25 MVA transformers are in parallel and connected to P1 busbar of the substation of the fig 3.

TABLE II
HV/MV TRANSFORMER

Characteristics	Value	
Rated Power	50 MVA ONAN/ONAF	25 MVA ONAN/ ONAF
Frequency (Hz)	50	50
HV Side (kV)	150	150
MV Side (kV)	21	21
SC voltage, u_k	20.09 %	20.15%
Vector Group	Dyn1	Dyn1
Tap Positions	+6-10 x 1.25%, in 17 steps	+6-10 x 1.25%, in 17 steps
Star Point, R_c	12 Ω	12 Ω

TABLE III
CONDUCTORS

Conductor Type	I_{max} (A)	Equivalent symmetrical Resistance, R_e (Ω/km)	Equivalent symmetrical Reactance, X_e (Ω/km)
3x95 ASCR	448	0.264	0.741
3x50 ASCR	296	0.453	0.785
3x35 ASCR	224	0.625	0.796
3x50 Cu	232	0.475	0.785
3x35 Cu	285	0.645	0.8

The typical protection scheme of the MV lines in Fig. 3 includes a Current Transformer (CT), an overcurrent relay, and an electro-mechanical Circuit Breakers (CB). It has one instantaneous operation and three Time Delays, TD, in its concluding operating sequence.

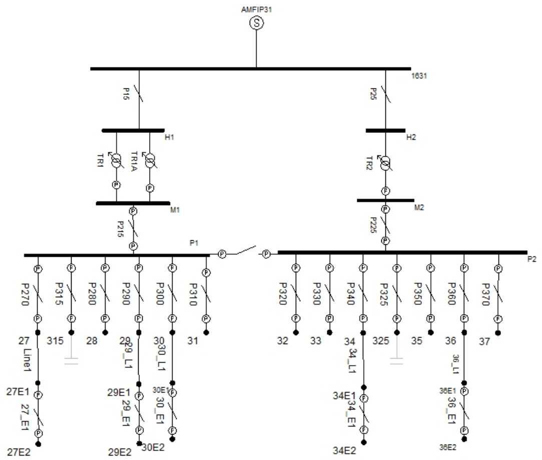
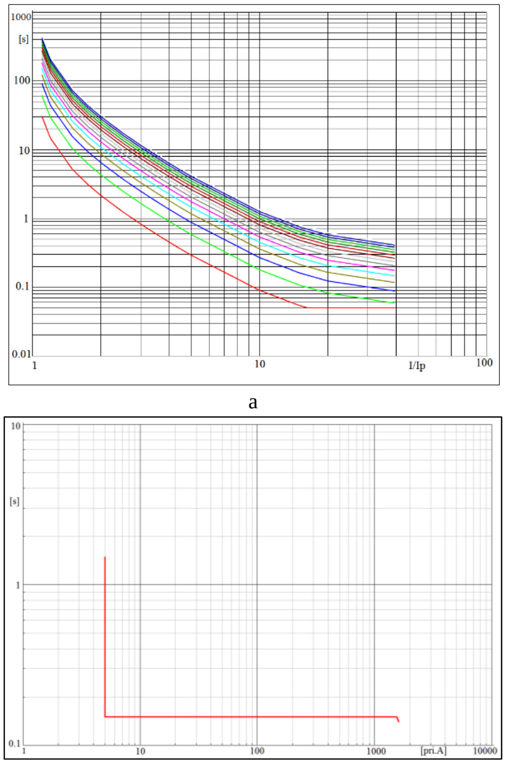


Fig. 3 Single Line Diagram of the HV/MV substation

The CB's instantaneous operation and Time Delays (TD) have been configured in accordance with the necessary Time - Current Characteristics (TCC) given in [16]. In greater detail, as shown in Fig 4, the time current characteristic of the Time Delays follows the Extremely Inverse (EI) curve and the instantaneous operation the Definite Time (DT) [8] - [12]. However, certain scenarios were created by substituting the standard protection mechanism, as stated, with solid state circuit breakers with tripping periods of a few μsecs, particularly on MV branches with high - RES penetration.



a

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Fig. 4 – (a) Extremely Inverse TCCs (TD: 0.1 - 1) and (b) Definite Time TCCs (t=150msec)

To choose appropriate protective equipment, the maximum and minimum short-circuit currents estimated to occur across network portions must be known. The maximum and minimum short-circuit currents are calculated independently for three phase and phase with earth return faults.

A three-phase fault at the beginning of the protective zone is the maximum short circuit which may occur and can be calculated by the following formula [18]:

$$I_{PH,MAX} = \frac{Un}{\sqrt{3}Z_T} \quad (1)$$

The greatest phase with earth return fault occurs at the start of the protective zone, with a current value of [18]:

$$I_{GR,MAX} = \frac{Un}{\sqrt{3}Z_G} \quad (2)$$

Where:

U_n is the rated voltage of the network in kV, Z_T is the total resistance of the network up to the point of the three-phase fault in Ω, and Z_G is the total resistance of the network up to the point of the phase with earth return fault in Ω. It is noted that the previous equations apply to conventional power distribution grids, which supply the loads radially.

B. Grounding Grid Models

The generated potentials on a grounding grid of an MV/LV outdoor compact substation have been evaluated under various scenarios of fault clearing time in case of a short circuit in order to evaluate the performance of the SSBs and compare it to that of a standard electromechanical circuit breaker. The grounding grid should shield qualified personnel operating in the vicinity of the substation from potentially dangerous touch and step voltages. These values must not exceed the restrictions set by the applicable IEEE Guide for a 70-kilogram body [17].

The grounding grid under consideration is described in [9], which is built of 35 mm^2 Cu (Fig. 5). The top portion of the grid is made up of two linked square grids at various depths under the earth's surface.

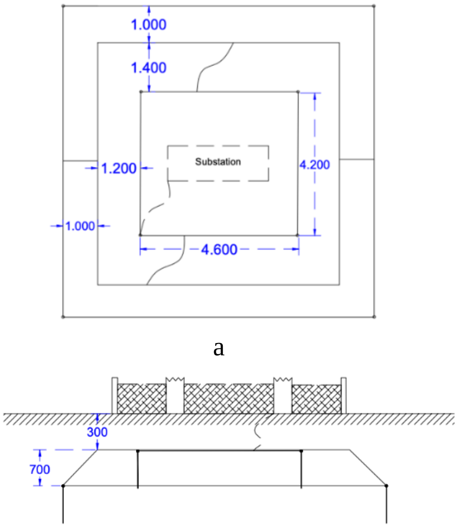

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Fig. 5 – (a) Top view and (b) Side view of grounding grid [9]

IV. METHODOLOGY

Various situations were examined in order to evaluate the performance of the solid-state circuit breakers. More specifically:

- Initially, load flow and short-circuit analyses were performed in an HV/MV S/S and its downstream network, where RES (primarily PVs) are connected. The short circuits were calculated using the complete method. This method is a superposition method of short-circuit analysis which can produce more accurate calculation results given realistic pre-fault loading of the system [19].
- The maximum load and RES generation in service scenario was considered.
- The short-circuit level of the S/S was calculated in this scenario when a three-phase short circuit occurs on one of the two busbars with the existing RES connected, in N and N-1 conditions. (Condition N-1 considered the power transformer 50MVA out of operation and the interconnecting switch between the two busbars closed).
- In both of the aforementioned conditions, various scenarios have been carried out in terms of tripping time of the power protection devices. In particular, tripping times of 250, 150 msec representing the conventional circuit breaker and 20μsec of the SSB have been simulated.
- The RMS simulation function, which can analyze the dynamic behavior of small and large-scale power systems, was also used. This function simulates a wide range of complex systems, including large power transmission or distribution grids and renewable generation plants, while accounting for electrical, mechanical, and control parameters.
- Finally, SES CDEGS [20] was used to calculate the developed potentials of the grounding grids of MV/LV compact substations (Fig. 5) in both cases of conventional CB (150 ms) and SSB (20 μsec) when a phase with earth return fault occurs across the exclusive MV line.

V. RESULTS

The extracted results from DIgSILENT PowerFactory and SES CDEGS simulations are presented in this section [19], [20]. The results will be presented from both the faulting (inside the S/S) and RES sides. Fig. 6 depicts a three-phase short circuit interruption caused by conventional electromechanical circuit breakers with a fault clearing time of 150 msec and an SSB of 20μsec (Fig. 6c).

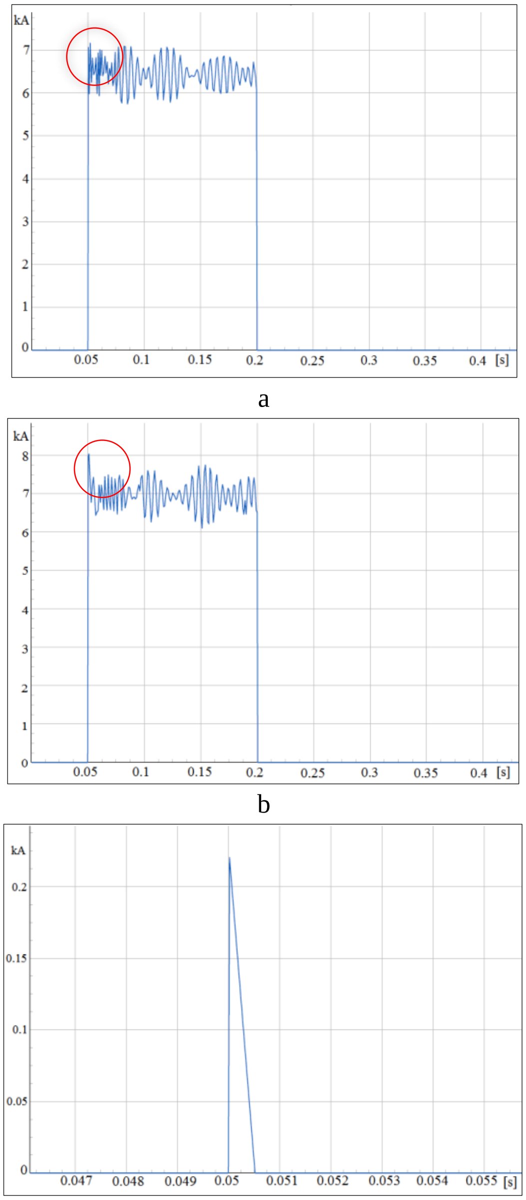

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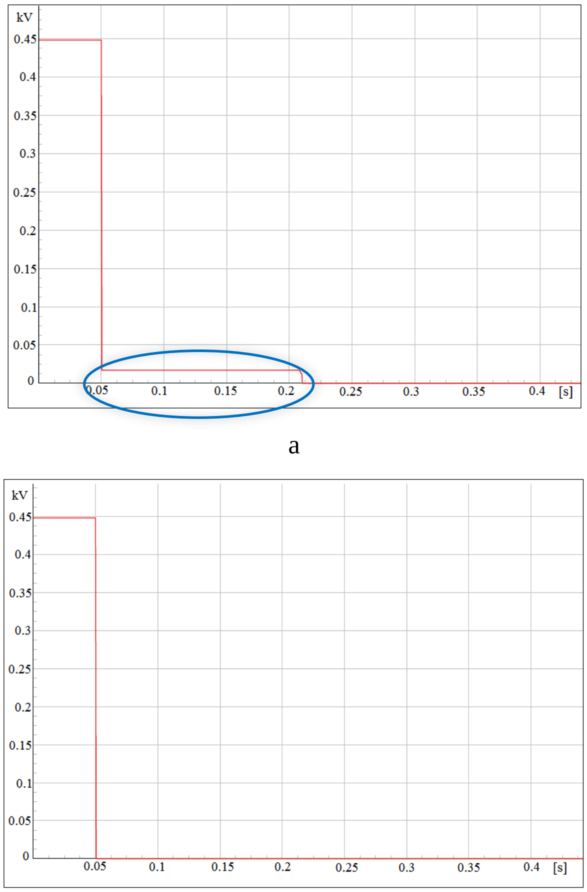
Fig. 6 - Three phase short circuit interruption (a) Conventional CB, n bus, 150 ms (b) Conventional CB, n-1 bus, 150 ms and (c) SSB with 20 μsec fault clearing time.

The voltage output of a pilot PV park connected in the substation under investigation is shown in Fig. 7 under two different scenarios. To elaborate, the first refers to a PV park with a traditional circuit breaker, while the second refers to one with a solid-state breaker.



a

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Fig 7 – Photovoltaic Park voltage output (a) Conventional CB with 160 ms fault clearing time setting and (b) SSB with 20 µsec fault clearing time (almost instantaneous).

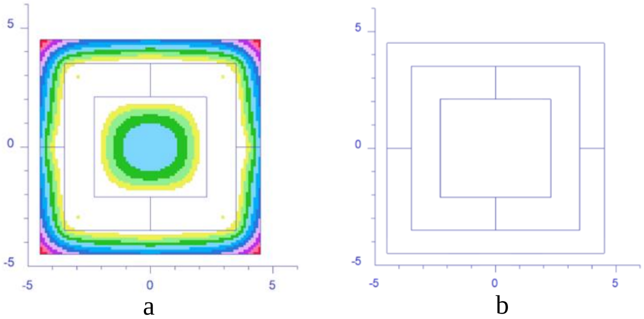
The cumulative power contribution of RES to the calculation of short-circuit current in S/S busbar 1 is shown in the table below. It is worth noting that, for the photovoltaic contribution to the short-circuit level, the maximum sub-transient short-circuit current was set to 100% of the PV system's installed power, and the pre-fault voltages were set to the nominal voltage (C=1.0).

TABLE IV
RES CONTRIBUTION TO SC

Busbar 1 (kVA)	
PVs	6155.88
	4821.35
	4200.89
	7928.15
	6116.685
BIOGAS	3358

The PV modeling has been carried out by using the corresponding PowerFactory (PV System) block element, and the "Full Size Converter" short-circuit model has been considered. Accordingly, the other RES sources were modeled as synchronous generators by choosing an appropriate Xd".

Finally, in Fig. 8, the distribution of developed potentials across the grounding grid of an MV/LV outdoor compact substation (Fig. 5) is shown for a phase with earth return short circuit under two different scenarios in terms of fault clearing time.



a b

Fig. 8 - Developed potentials (touch voltage) on the grounding grid for uniform soil structure with soil resistivity of ρ=500 Ωm, fault current of I_f=319 A, safe touch voltage limit V_t= 458V [17] and (a) fault clearing time of a conventional electro – mechanical CB (150msec) and (b) fault clearing time of a SSB (20µsec)

VI. CONCLUSIONS

The current work compares the performance of a solid-state breaker to that of a conventional electro-mechanical one. To assess the added value of SSBs, the results were presented from both the S/S and RES perspectives. According to the extracted results, the following conclusions are reached:

- Solid state breakers are expected to clear a short circuit much quicker than conventional CBs, resulting in more secure and reliable power distribution grid operation by avoiding transient phenomena that may increase power grids' equipment stress. (Figures 6a and 6b)
- If the S/S is in condition (n-1) mode, higher short circuit current is expected since all RES contribute to the same busbar (Fig. 6b).
- By equipping PVs connected to the power distribution grid with SSBs, we can ensure that they trip immediately in the event of a short circuit across the MV Line. PV parks will not contribute to the short circuit, and the islanding phenomenon will be prevented (Fig. 6c).
- As shown in Fig. 7, the voltage output of a PV park equipped with a conventional CB does not immediately reach zero in the event of a short circuit because the breaker requires some time to open its contacts. In the case of an SSB, however, the circuit is instantly isolated.
- Fault clearing time is critical in reducing the developed potentials across the grounding grids of Medium Voltage grids. In particular, the shorter the time, the lower the developed touch or step voltages (Fig. 8).
- By increasing the installed capacity of the PV systems, which are connected to the busbar 1 of the S/S, with additional 71320.27 kW and by executing short circuit analysis we conclude that the short circuit level rises up to 9 kA in case that the solar portfolio is protected by conventional electro – mechanical circuit breakers. On

the other hand, when using SSB as the main protection device of the PV systems, the short circuit level remains constant and to its initial value of 7.2 kA.

Based on the aforementioned, we conclude that SSBs have the potential to play an important role in ensuring the high availability and safe operation of power distribution grids. It is recommended that further research on the performance of various SSB technologies on power distribution grids be conducted in the near future.

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