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Verifikacija modela distribuiranih izvora energije za proračune kratkih spojeva mikromreža

Verification of Distributed Energy Resource Models for Microgrid Fault Calculations

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Rezime - Mikroreže se uglavnom napajaju obnovljivim distribuiranim izvorima energije, poput sunca i vetra, sa baterijama kao rezervnom snagom. Ovi distribuirani izvori su odvojeni od mreže pretvaračem, pa su njihove struje kvara uslovljene upravljačkim strategijama programiranim u samom pretvaraču. Strategije upravljanja pretvarača u većini slučajeva diktiraju Pravila o radu elektroenergetskih sistema, kako bi ovi distribuirani izvori pomogli pri lakšem oporavljanju mikromreže od kvara. Dakle, da bi se dobili tačni rezultati za proračun kvarova u mikromreži, što je presudno važno za podešavanje relejne zaštite i zaštite cele mikromreže, ovi distribuirani izvori moraju biti precizno modelovani. Nažalost, ovi modeli još uvek nisu u potpunosti razvijeni niti standardizovani. U ovom radu, nedavno razvijeni modeli distribuiranih izvora energije zasnovanih na invertorima integrisani su u proračun struje kvara na osnovu IEC 60909 standarda i testirani u savremenom „Hardware-In-The-Loop (HIL)" okruženju. Rezultati ispitivanja su obećavajući, što otvara mogućnost za standardizaciju ovih novih modela.

Ključne reči - distribuirani izvori energije, mikromreže, proračun kvarova

Abstract **-** The emerging microgrids are mainly powered by renewable distributed energy resources (DERs), such as solar and wind, with batteries as a backup power. These DERs are decoupled from the grid by inverters and thus, their fault currents are dictated by the control strategies programmed in the inverter itself. The inverters' control strategies are in most cases dictated by the Grid Code requirements, in order to help the microgrid ride through the fault as painless as possible. Thus, in order to have accurate results for microgrid fault calculations, crucially important for setting the relay protection and protecting the entire microgrid, these DERs must be accurately modelled. Unfortunately, these models have not yet been fully developed nor standardized. In this paper, a recently developed model for inverter-based DERs are integrated into the fault current calculation based on the IEC 60909 standard for fault calculations and tested in the state-of-the-art hardware-in-the-loop environment. The test results are very promising, which opens the possibility to standardize these novel models, filling the seriously dangerous gap of not having the standardized fault models for inverter-based DERs.

Index Terms - distributed energy resources, microgrids, fault calculations

I INTRODUCTION

In traditional power systems, synchronous and asynchronous machines (SMs and AMs, respectively) are the main contributors to the fault currents and steady-state models of this type of sources (in sub-transient, transient or steady state period) are standardized in IEC 60909. Because of proven efficient performance and simplicity of this standard, a common practice in many countries is to execute Short-circuit calculation (SCC) in accordance to IEC 60909 standard [1].

Nowadays, there are microgrids with high penetration of distributed energy resources (DERs) which represent the new emerging concept in power systems [2]. These DERs are, in most cases, fully decoupled from the grid by inverters - inverter based DERs (IBDERs). IBDERs have a different behaviour during faults compared to SMs and AMs, because their fault currents are dictated by control strategies programmed in the inverter itself. The inverters' control strategies are in most cases dictated by the grid code requirements, in order to help the microgrid ride through the fault as painless as possible. Generally, their fault current is limited to low levels (i.e. around the rated current of the converter) [3]. Therefore, their fault currents were usually ignored in steady-state fault calculations. However, due to the increased penetration of IBDERs, most grid codes require such resources to remain connected during the faults and to dynamically support the voltage by injecting reactive current. This concept is referred as fault ride through (FRT) or low voltage ride through (LVRT) [4]. Consequently, the fault current contribution from the IBDERs cannot be ignored anymore in steady-state fault calculations of power systems with high penetration of IBDERs.

At the beginning, in IEC 60909 standard for fault calculations, fault current contribution from IBDERs had been neglected. After that, a new version of IEC 60909 has provided two ways to consider the fault contribution from IBDERs [5]:

1. A static-fed drive model which only contributes to the symmetrical three-phase fault current that equals to 3 times of the rated value of the converter interface,
2. A SM model which represents the IBDERs as a SM with a limited fault current contribution (i.e. a voltage source behind a reactance). In practice, these models provide misleading results in most cases, as discussed in [3].

The latest version of the IEC standard has upgraded modelling for the IBDERs in fault calculations [6]. It has recommended neglecting the fault contribution from the IBDERs when their fault current contribution is less than 5% of the total fault current. Otherwise, a current source model is suggested for such resources that contribute to the fault current according to its maximum overrating capability during the fault. According to [7], this model might be efficient in cases where the converters inject their maximum fault currents in response to a fault near to the source, otherwise this may overestimate the fault current specially in high microgrids with high penetration of IBDERs. Hence, there is a need for enhancing the methodology used in the IEC 60909 standard to better consider the fault current from the IBDERs in steady-state fault calculations especially on nodes within microgrids with high penetration of IBDERs or on nodes which are electrically near to the point of common coupling of microgrid.

In [3] a detailed explanation of IBERs modelling is presented. These models are based on Reactive Current Injection and Fault Ride Through requirements defined in the grid codes. Unfortunately, these models are not yet standardized.

The main objective of this paper is to verify recently developed models for IBDERs in the transient period, integrated into the fault calculation procedure based on the IEC 60909 Standard for fault analysis, as compared with the state-of-the-art hardware-in-the-loop setup.

The motivation for this research is to propose upgrade of the insufficiently accurate models of DERs which exist in IEC 60909 standard with more accurate and more precise models which are integrated into the SCC procedure based on IEC 60909 and verified in this paper.

The contributions of this paper are:

1. Integration of IBDER models form [1] into the SCC procedure which is in accordance with the IEC 60909 Standard for fault calculations.
2. Verification of the SCC results in the state-of-the-art hardware-in-the-loop environment.

The results from this research can hopefully lead to the eventual substitution of the insufficiently accurate IBDER models from the IEC 60909 Standard with much more accurate models as proposed in this paper. As results of SCC are used for Relay protection setting and coordination, inaccurate SCC results can cause inadequate relay settings which can be dangerous for the safety of the entire power system, which further validates the importance of this research.

The remainder of the paper is organized as follows. In Section II, IBDER models are presented. Section III presents Fault current calculation procedure. In Section IV, verification setup is depicted. Results are presented and discussed in Section V. The paper is concluded in Section VI. Conclusions and directions for future research are presented in Section 5.

II Inverter Based DER Models

IBDERs are fully decoupled from the grid by an inverter, and their fault currents (after a short initial sub-transient period) are limited by an inverter to typically no more than 1.5 of their rated values [3],[8]. Moreover, in order to satisfy various grid-code requirements for voltage stabilization, IBDERs should inject reactive current component proportional to the voltage drop caused by the fault [3],[8]. Thus, contrary to synchronous and induction machines directly connected to the grid, IBDERs' fault currents are not dictated by the physical characteristics of the machines, but rather by the power electronic components and control strategies of the inverter. A very short sub-transient period in which the IBDER's fault current is not limited is beyond the scope of this paper. However, this period is very important for the planning and selection stage of the protection equipment in the microgrids and will therefore be addressed in the authors' future research. In [3],[8] accurate fault models for IBDERs are proposed. The proposed models in the transient period consist of limited current sources with the ratio of their active to reactive parts dependent on the voltage drop on the IBDER's terminals. These models are briefly summarized as follows:

$$\delta_{Ireact\ i} = \delta_{V\ i} + \frac{\pi}{2}\ , i = 1, \dots, N_{IBDER} \tag{1}$$

Where:

- $\delta_{V\ i}$ represents known angle of $V_{PCC\ i}^{+}$
- $V_{PCC\ i}^{+}$ represents voltage at bus where IBDER marked with *i* is connected which is calculated in pre-iteration step [3], [8].
- N_{IBDER} represents total number of IBDERs in the system.

$$\Delta V_i = 1 - \frac{V_{PCC\ i}^{+}}{V_{rated\ i}}, i = 1, \dots, N_{IBDER} \tag{2}$$

Where:

- $V_{rated\ i}$ represents rated voltage at bus where IBDER marked with *i* is connected.

$$I_{IBDER\ i}^{react} = 2 \times \Delta V_i \times I_{IBDER\ i}^{rated}, i = 1, \dots, N_{IBDER} \tag{3}$$

Where:

- $I_{IBDER\ i}^{react}$ represents magnitude of reactive component of fault current from the IBDER marked with *i*.

$$I_{IBDER\ i}^{react} \begin{cases} > I_{IBDER\ i}^{max} \Rightarrow I_{IBDER\ i}^{\prime\, fault} = I_{IBDER\ i}^{max} e^{j\delta_{Ireact\ i}} \\ \leq I_{IBDER\ i}^{max} \Rightarrow I_{IBDER\ i}^{\prime\, fault} = I_{IBDER\ i}^{act} e^{j\delta_{V\ i}} + I_{IBDER\ i}^{react} e^{j\delta_{Ireact\ i}} \end{cases} \tag{4}$$

Where:

$$I_{IBDER\ i}^{act} = \sqrt{(I_{IBDER\ i}^{max})^2 - (I_{IBDER\ i}^{react})^2} \tag{5}$$

As mentioned above, these models depend on FRT requirements. In this paper, authors have chosen FRT requirements from the German Grid Code [3].

III Fault Current Calculation Procedure

This Section describes the way of modelling IBDERs and calculation procedure according to the latest IEC 60909 standard.

A. Modelling of IBDERs according to the latest IEC 60909 standard

In steady-state fault calculation in the latest version of the IEC 60909 standard, IBDER is modelled as ideal current source in positive sequence domain [6], [9] as shown in Fig.1. Such modelling method might be appropriate considering the fast response of the inverter controller [3]. However, this way of modelling assumes a fixed fault current contribution equal to maximum injection current provided by manufacturer, regardless the voltage drop level at the node in which IBDER is connected, during the fault. This might overestimate the fault currents for case where the fault occurs far away from the IBDER because in this situation relative voltage drop in node where IBDER is connected is low and because of that injection current will not be at maximum value. It should be defined by FRT requirements from grid-code standards and it probably will be lower than maximum value provided by manufacturer.

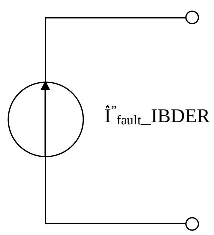

Figure 1. Ideal current source model for IBDER according to the latest version of IEC 60909 standard

B. Calculation Procedure in the latest IEC 60909 standard

The procedure for SCC in power systems from the IEC 60909 standard is based on the Thevenin equivalent method. As Thevenin equivalent is serial connection of Thevenin impedance which represents equivalent impedance of whole system seen from node with the fault and ideal Thevenin voltage source, it is obvious that such calculation does not consider contribution of IBDERs. However, in presence of IBDERs, their fault contribution will be calculated using the current source model. Sum of both contributions from SMs and IBDERs will represent the total fault current. The calculation procedure for the fault current is explained in the following steps:

1) Calculating the fault current without considering the IBDERs:

i. Calculate the equivalent impedance seen from the node with fault.

There are many ways to calculate this equivalent impedance. One of the mostly used ways implies creating and inverting admittance matrix of the entire power system.

ii. Determine a pre-fault voltage of the node with the fault.

This voltage equals the nominal pre-fault value (phase voltage) multiplied by a correction factor, as follows:

$$V_n = \frac{c \times V_{line}}{\sqrt{3}} \tag{6}$$

Where:

- c represents correction factor
- V_{line} represents phase to phase (line) voltage

iii. Calculate the fault current as follows:

$$I''_{fault\_grid} = \frac{V_n}{Z_k} \tag{7}$$

Where:

- Z_k is representing Thevenin impedance

2) Calculating the fault current of the IBDERs:

i. Obtain the value of the j-th current source,

ii. Calculate the transfer impedance between the faulty buses i, and j, where the IBDER is connected, Zij.

iii. Apply the following equation:

$$I''_{fault\_IBDER} = \frac{1}{Z_k} \sum_{j=1}^{j=N} Z_{ij} \times I_{\max\_j} \tag{8}$$

Where:

- $I_{\max\_j}$ represents the IBDER's maximum value of injecting current from the manufacturer
- N represents the total number of IBDERs connected to the power system
- Z_{ij} represents the transfer impedance between node with fault i, and node in which IBDER is connected j.

3) Calculating the total fault current as follows:

$$I''_{fault\_total} = I''_{fault\_grid} + I''_{fault\_IBDER} \tag{9}$$

In this paper, instead of IBDER models which are described above, IBDER models from [3] are used. These models have been integrated into the SCC procedure described in this section. Using the fault calculation procedure from the latest IEC 60909 standard with new, more accurate, IBDER models from [3], SCC has been performed on test microgrid with high penetration of IBDERs in grid-connected mode and results obtained in this way have been verified on state-of-the-art HIL setup. The HIL setup will be described in the next section

IV Verification Setup

Hardware-in-the-loop (HIL) which is used in this paper as a verification setup is a technique for real-time digital emulation (simulation) which makes it possible to replace a physical system with a computer model for the real-time control, design, testing, and optimization (a "digital twin" of the power system). It is possible to connect real, physical, inverter controller to HIL setup inputs and from the controller perspective there is no difference between the physical system and its real-time simulation [10]. Indeed, the real controller (also the high-speed part of the controller which includes the modulator and the protection functions) "feels" that it is controlling the real physical system [10]. HIL emulator interacts with the real physical controller, via fast input/output signals in real-time. This controller takes some signals for HIL platform and based on them and the implemented control algorithm, it generates the appropriate control signals. There are many possibilities for which the described HIL setup can be used for. Because of ultra-low latency high-speed processor architecture (extra small simulation time-step) and high-fidelity feature in real time, one of the possibilities for using HIL setup is development, testing, and optimization of real-time control algorithms for grid-connected power electronics converters for DERs and smart grid applications. Another possibility is development and real time analysis of small-scale power systems, even in time domain, especially of microgrids with high penetration of DERs in both modes of operation - grid-connected and islanded.

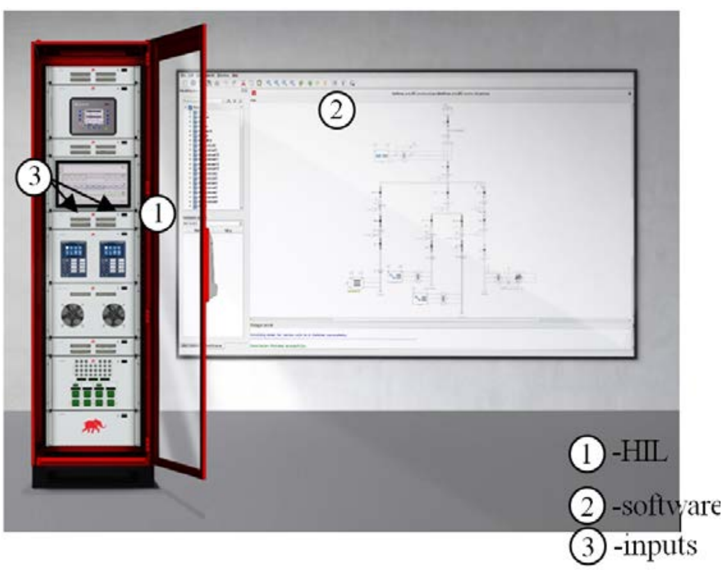

Figure 2. HIL setup

For the purpose of verifying the results from this paper obtained by the SCC procedure which is in accordance with IEC 60909 and upgraded with new, more accurate, models of IBDERs from [3], authors have used HIL setup which is shown in Fig 2. HIL setup's software has its own library with highly accurate models of all types of DERs on both levels (electrical part and signal processing part). Signal processing part of IBDER's model from HIL setup's software library can give the same response with response from real controller which can be connected to the HIL. It also can take into consideration FRT requirements of grid codes for 5 countries and besides that, it gives a possibility to the user to create custom FRT requirement curves. Because of the identical responses of both, real and modeled IBDER's controller, for the purposes of verifying the results from this paper, authors have used IBDER's models from the HIL setup's software library.

V Results and Discussion

To test and measure short-circuit current level for various fault types and locations, a small-scale microgrid testbed is developed. The microgird testbed consists of modified IEEE 33 test feeder with 4 IBDERs located in 18, 22, 25 and 33 busses and a SM located in buss 1 as depicted in Fig. 3. All lines from the microgrid testbed have original resistance and reactance parameters from IEEE 33 test feeder. Modifications are made as follows. All line lengths are reduced from 1 km to 0.5 km. Further, instead of the original equal loads from IEEE 33 test feeder, there are equal loads of 100kVA in all busses, except in busses with IBDERs. The busses with IBDERs are without loads. The specific DER technologies are described for each DER in Fig. 3. The DER powers are as follows: SDG = 1 MVA, SPV = 200 kVA. The utility grid's equivalent impedance is Z = (0.09220 + j 0.04700)Ω.

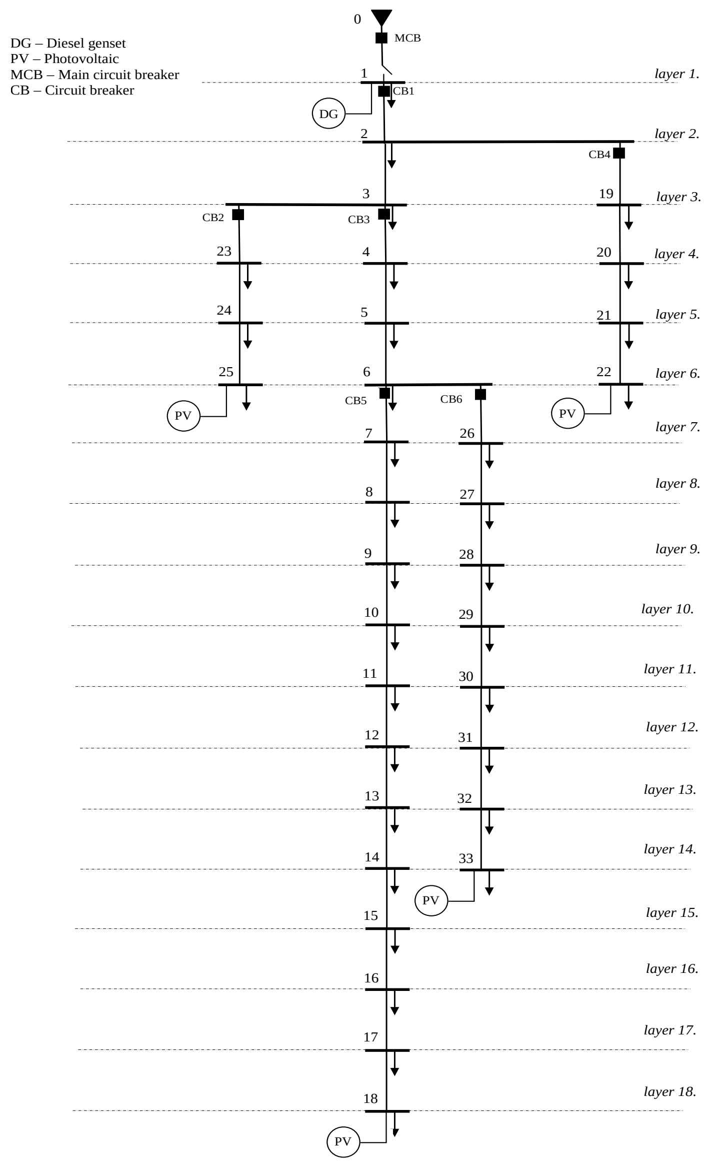

Figure 3. Microgrid testbed

The bus 1 is the microgrid's point of common coupling (PCC) in which the microgrid is connected to the utility grid. The main circuit breaker that connects the microgrid to the utility grid is marked with MCB in Fig.3, while six other breaking devices, located at the critical positions, are marked with CB1, CB2, CB3, CB4, CB5 and CB6, respectively. The nature and technology of these devices (breaker, fuse, etc.) are beyond the scope of this paper.

Different fault types in various busses are analysed, but due to space limitations, the results are presented only for the following borderline cases (maximal and minimal fault currents): three-line-to-ground (3LG) and single-line-to-ground (SLG) faults in bus 32. Results for faults in other busses are available upon request. Only grid-connected mode of operation is analysed. Islanded mode of operation is beyond the scope of this paper, and will be analysed in the authors' future research.

The fault calculation procedure which is in accordance with IEC 60909 standard with upgraded IBDER models from [3] was used for all tests. IBDER models are made with considering the FRT requirements from German grid code [3]. All calculation procedures were in-house developed and programmed in FORTRAN 2008. The results for the complete faulted states of the microgrid are presented in tables 1 and 2, for 3LG and SLG faults, respectively. Fault currents at the breaking devices' locations as well as IBDERs' locations are presented in the tables bellow.

Table 1. The SCC Results for 3LG Fault at the Bus 32

Fault type	3LG		
Phase	A	B	C
I_2 [A]/angle[˚]	1855.98/-36.70	1855.94/-156.70	1855.94/83.30
I_4 [A]/angle[˚]	1852.05/-36.70	1852.01/-156.70	1852.01/83.30
I_7 [A]/angle[˚]	23.05/-13.89	23.05/-133.89	23.05/106.11
I_{18} [A]/angle[˚]	13.78/-150.43	13.78/89.57	13.78/-30.43
I_{19} [A]/angle[˚]	0.65/-117.76	0.65/122.24	0.65/ 2.24
I_{22} [A]/angle[˚]	13.68/-177.31	13.68/62.69	13.68/-57.31
I_{23} [A]/angle[˚]	5.54/-159.74	5.54/80.26	5.54/-39.74
I_{25} [A]/angle[˚]	13.67/-171.28	13.67/68.72	13.67/-51.28
I_{26} [A]/angle[˚]	1822.49/-37.20	1822.45/-157.20	1822.45/82.81
I_{33} [A]/angle[˚]	13.63/-90.30	13.63/149.69	13.63/29.70

Table 2. The SCC Results for LG Fault at the Bus 32

Fault type	LG		
Phase	A	B	C
I_2 [A]/angle[˚]	1852.41/-36.62	76.95/-127.95	76.95/112.05
I_4 [A]/angle[˚]	1849.55/-36.66	72.16/-127.59	72.16/112.41
I_7 [A]/angle[˚]	20.90/-3.73	37.67/-124.59	37.68/115.41
I_{18} [A]/angle[˚]	13.84/-169.32	13.84/70.68	13.84/-49.32
I_{19} [A]/angle[˚]	0.39/-143.38	0.30/155.25	0.30/35.24
I_{22} [A]/angle[˚]	13.68/-178.74	13.68/61.26	13.68/-58.74
I_{23} [A]/angle[˚]	5.37/-173.05	4.56/70.22	4.56/-49.78
I_{25} [A]/angle[˚]	13.67/-176.63	13.67/63.37	13.67/-56.63
I_{26} [A]/angle[˚]	1823.71/-37.23	21.19/-137.79	21.18/102.22
I_{33} [A]/angle[˚]	13.72/-152.60	13.72/87.40	13.72/-32.60

To validate the accuracy of the obtained results, the same microgrid testbed is developed in the HIL setup. Same as in calculation done in FORTRAN 2008, models of real IBDER's controllers with FRT requirements from German grid code standard are chosen. As mentioned above, because of equality of responses of these models and real inverter controllers, real behaviour of IBDERs in fault condition are simulated in this way in order to compare fault current values obtained from HIL setup with values obtained from the calculation procedure based on IEC 60909. Results from HIL setup are obtained in time domain and after that they are transformed into steady-state domain in order to be comparable with results obtained from FORTRAN. The comparison of the results from FORTRAN and HIL setup, along with the highest differences in the results obtained by two platforms, are presented in table 3 for 3LG and SLG faults.

Table 3. Comparison of the SCC Results

	Fault type	3LG	LG
I_2[A]	Fortran	1855.98	1852.41
	HIL setup	1837.42	1833.88
I_4[A]	Fortran	1852.05	1849.55
	HIL setup	1833.52	1831.05
I_7[A]	Fortran	23.05	20.90
	HIL	22.81	20.69
I_{18}[A]	Fortran	13.78	13.84
	HIL setup	13.64	13.71
I_{19}[A]	Fortran	0.65	0.39
	HIL setup	0.64	0.39
I_{22} [A]	Fortran	13.68	13.68
	HIL setup	13.54	13.54
I_{23}[A]	Fortran	5.54	5.37
	HIL	5.48	5.31
I_{25}[A]	Fortran	13.67	13.67
	HIL setup	13.53	13.53
I_{26}[A]	Fortran	1822.49	1823.71
	HIL setup	1804.26	1805.47
I_{33}[A]	Fortran	13.63	13.72
	HIL setup	13.49	13.58
The highest difference	**1.5%**		

From the presented results, the following can be derived:

1) Based on the results from table 3, we can conclude that the results of SCC in transient period for the microgrid in grid-connected operation mode, obtained by in-house-developed software solution with implemented procedure for SCC, which is in accordance with IEC60909 standard,

and with new IBDERs' models from [3], match well with the results from HIL setup. The differences are less than 1.5%.

2) It is important to notice that IBDERs' models from [3] are more precise then IBDERs' models from IEC60909 because of consideration of FRT requirements from grid code standards. As it is presented above, these new models from [3] are verified in this paper with HIL setup which is even more precise. In case when there is not significant number of IBDERs connected to the network, differences of results obtained from calculation procedure according to IEC60909 with actual IBDERs' models and proposed models form [3] might not be so noticeable, but in microgrids with high penetration of IBDERs differences can be very significant, especially in islanded mode of operation. Based on this, we can conclude that there is potential for changes in IEC60909 standard, in order to take into consideration new, more accurate and precise, models from [3].

3) One of the future research directions for the authors will be the short-circuit analysis in microgrids with high penetration of IBDERs which are in islanded mode of operation.

4) Because of time-domain results which can be obtained from HIL setup, the other direction of the authors' future research will be a short, initial time-period immediately upon the fault occurrence, in which the fault currents of IBDERs are not limited, as well as the influence of these currents on the protective equipment selection and planning process.

VI Conclusion

In this paper, a thorough analysis of the fault current values in the emerging microgrids with high penetration of IBDERs is performed in order to analyse IBDER models form [3] and their contribution to the fault current. Comparison of the results obtained by in-house-developed short-circuit calculation based on the IEC60909 standard, with new more accurate and precise IBDERs' models from [3] and results obtained by HIL setup is carried out.

Results from this paper prove that there is a need for changes in IEC60909 standard, in order to accurately consider the IBDER models. Results which can be obtained with actual IBDERs' models from IEC60909 might not be accurate for calculations in microgrids with high penetration of IBDERs, because these models do not take into consideration FRT requirements form grid code standards. IBDERs' contributions to the fault current can be overestimated. In case when there is significant number of IBDERs connected to microgrid, it is very important to use precise and accurate models because difference between obtained results that demonstrate IBDERs' contributions with actual models from IEC60909 and models from [3] can be very noticeable. These differences can negatively influence the relay protection of the microgrid, causing the microgrid to be vulnerable and unprotected in some critical cases. As DERs are increasingly installed nowadays, it is of the crucial importance to have more precise and more accurate models of all types of DERs in order to have protected and secured microgrids.

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