A Novel Protection Philosophy in Low Short-Circuit Capacity Distribution Grids with High Penetration of Converter-Interfaced Distributed Renewable Energy Sources

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Abstract: The ever-growing penetration of converter-interfaced Distributed Renewable Energy Sources (CI-DRES) in distribution networks, despite the undoubted advantages, has a profound impact on the traditional protection systems. The protection problem becomes even more complicated as the increase in the CI-DRES penetration level leads to the decommissioning of conventional power plants. Due to the limited current capability of CI-DRES, decommissioning of conventional units will lead to a transmission grid of significantly lower short-circuit level. This paper proposes a novel protection philosophy for distribution grids of low short-circuit capacity and high CI-DRES penetration. According to the proposed approach, CI-DRES are controlled to actively participate in the fault clearing procedure, supporting the short-circuit capacity, in an aggregated form, through the injection of controllable currents. Therefore, conventional overcurrent protection devices can be used, without any additional investments for a protection system upgrade. The CI-DRES fault contribution is based on their relative position to the fault, respecting technical and protection-malfunction constraints. In addition to the short-circuit level, the effect of the feeder parameters and the power factor of the injected fault current on the voltage recovery is also investigated. The proposed protection philosophy is validated via detailed simulations in DIgSILENT PowerFactory.

1. Introduction

Grid protection, in the presence of DRES, has been a conspicuous issue in recent years and needs immediate consideration [1]. Nowadays, it is a common assumption that the transmission grid possesses adequate short-circuit capacity for fault clearing, provided from the large conventional synchronous generators (SG). However, in a future scenario, high DRES unit penetration will lead to the decommissioning of conventional power plants. Nowadays, most DRES units are converter-interfaced, with limited current capability, and they are not intended to participate in the fault clearing procedure [2]. As a result, decommissioning of conventional units will in turn lead to weaker transmission systems. Therefore, a new protection philosophy is required, with the active contribution of CI-DRES to the fault clearing.

In a distribution grid that does not rely on the upstream grid contribution for fault clearing, new protection practices are required. In the literature, there are many studies that investigate the impact of the increasing DRES penetration on protection, but in the frame of a stiff grid [3]-[11]. There are also several papers that propose new protection methods for islanded microgrids, like the differential and the adaptive protection [12] – [22]. Some other studies propose even more sophisticated methods that combine adaptive protection and machine learning [23]. Although some of the aforementioned protection methods could be applied also to distribution grids of low short-circuit level, they are based on extensive communication systems, which increases the investment cost, while their reliability is under question. In [24] – [26] protection methods that are entirely based on local measurements, without the assistance of any communication system are proposed for islanded microgrids. However, these methods are effective only in looped islanded microgrids, or they pose constraints regarding the location a CI-DRES can be installed.

This paper proposes a novel overall protection philosophy, for distribution grids with high penetration of CI-DRES and low upstream grid short-circuit level. Ultimate objective of this paper is to support the short-circuit capacity of the upstream grid, through the aggregated action of all CI-DRES. The proposed method aims to keep the effectiveness of the legacy overcurrent protection devices within the distribution grids (thus defer investments for their upgrade), by developing proper control algorithms that will be embedded in the CI-DRES. It is entirely based on local measurements, without the need of any kind of communication, presenting increased reliability. According to the proposed method, all CI-DRES should actively participate in the fault clearing procedure by injecting controllable fault currents. The current injected by each CI-DRES is based on the relative position to the fault location, taking also into account constraints, like the rating of the converter and the prevention of common protection problems (e.g. sympathetic tripping and protection blinding). A vital part of the proposed method is a fast-acting energy storage system (FESS), e.g. ultracapacitor, that is embedded in each CI-DRES, in order to enhance the fault ride-through (FRT) capability and provide the required fault currents, for the time required [27], [28]. Finally, in the context of this study, the impact that the power factor (PF) of the injected fault currents has on the voltage level during a fault and eventually, on the total fault current, is also examined. In contrary to other studies which focus only on the line parameters [29], [30], this paper introduces in the analysis the upstream grid parameters, in order to study the impact of the PF of the CI-DRES on the voltage recovery within the distribution grid. This analysis is particularly important, since recent Standards [31] require the injection of additional reactive fault-currents

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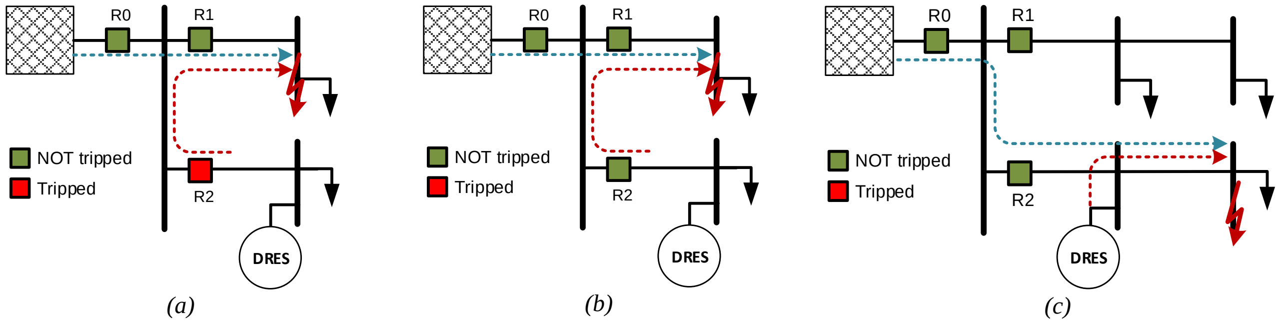


Fig. 1. *Protection problems: a) Sympathetic Tripping, b) Blinding of back up protection and c) Blinding of feeder protection*

by the CI-DRES at distribution system level. Moreover, for the CI-DRES participating in the fault clearing procedure, the PF is estimated, so that it maximizes the voltage level and hence, the fault current for specific line and upstream grid parameters. In addition, by increasing the voltage level during the fault, the FRT of the DRES is increased in terms of time. To the authors best knowledge, there is not such analysis in the current state-of-the-art.

The rest of the paper is structured as follows. In Section 2 the evolution of the protection problems as CI-DRES penetration increases is presented together with an extensive literature review on the protection methods under high CI-DRES penetration. Section 3 presents the proposed protection methodology and performs an analysis that correlates the total fault current to the injected PF. Section 4 presents the simulation results. Section 5 compares the proposed method with the requirements included in the current Standards and with other protection methods presented in the literature. Finally, Section 6 concludes the main findings.

2. Protection problems under increasing CI-DRES penetration

2.1. Evolution of protection problems

This section presents the evolution of protection problems that might appear due to the increasing proliferation of DRES in distribution grids. Nowadays, it is a common assumption that the short-circuit level of the upstream grid is high enough for clearing the faults within the distribution grids, through the tripping of the protection devices. In a Medium-Voltage (MV) distribution grid, such protection devices are usually circuit-breakers, controlled by overcurrent (OC) relays. These devices monitor the current flow through the protected element and generate trip signals to the circuit breaker, if the fault current flow is more than the specified value. There are two levels of protection; *a*) the main feeder protection at the beginning of a feeder and *b*) the secondary protection at transformer level, which is used to protect the transformer against overloading and short-circuits and provides back-up protection to the feeder protection device. The coordinated operation of both the aforementioned levels is significant, in order to keep the selectivity of the protection system.

The protection philosophy of the passive distribution systems is based on the assumption that these are radial in nature and power flow is always unidirectional from the source to consumers [32]. When DRES units are connected to a distribution grid, the system is considered as active. The DRES will change the total fault current in the event of a fault. The change in the fault current level depends on the type, location, and technology of DRES and it can lead to protection blinding (of main or back-up protection), cause sympathetic tripping, force unintentional islanding, mal-operation of auto-reclosers, and loss of protection coordination in the distribution network [33]-[37]. Similarly, in order to interrupt the high fault currents, the revision of short-circuit interrupting capacity of protection devices may also be required. These problems directly affect the safety of equipment, personnel, and continuity of service. The most common protection problems are illustrated in Fig. 1.

IEEE Standard 1547 issued in 2003 [38] identified these problems and proposed the DRES units to stop energizing the distribution system, when there is a fault in the grid. However, as the capacity of installed DRES increases, disconnection of a large number of DRES units is no longer an option. Latest Standards and national grid codes [39], require the DRES to possess FRT capabilities and remain connected to the grid, when the voltage at the point of connection is within defined limits. During the fault period DRES should support the voltage recovery by injecting reactive power.

A further increase in DRES penetration will lead to the gradual decommissioning of conventional power plants, powered by fossil fuels. However, conventional units employing large SGs are the basis for providing large fault currents. Eventually, since most of the DRES that are installed nowadays are converter-interfaced, with a limited fault current capability, decommissioning of conventional units will in turn lead to a distribution grid of significantly lower short circuit capacity. A grid with low short-circuit capacity will face the problem of reduction of "reach" of the protection relays, since the short-circuit level is not enough for activation of the protection devices. In the following sections, the analysis focuses on the protection problems that stem from the reduced short-circuit level of the upstream grid and proposes control methods for the CI-DRES, in order to overcome these problems.

2.2. Review of existing protection methods under high CI-DRES penetration

Section 2.1 has evidenced the problems that CI-DRES proliferation may cause in the operation of conventional protection devices of a distribution network. This section is devoted to outline the main existing trends in the specialized literature to guarantee the protection. The most common protection methods can be summarized as follows [32] - [34]:

DRES disconnection: This protective methodology proposes to disconnect all the DRES in case of a grid disturbance [38]. In this way, the conventional protective systems will not be disrupted by the DRES fault contributions. However, in case of a massive DRES penetration this solution is no longer an option from the reliability and quality of service points of view. Additionally, a stiff grid of significantly high short-circuit capacity is required in order to clear the faults.

Fault Current Limiters (FCL): A FCL is a series device used for suppressing fault current of DRES or branch by increasing rapidly its impedance from zero to a high value. In this way, the DRES fault current contribution does not interfere with the smooth operation of traditional protection devices, preserving the coordination of protection. The use of FCL is also proposed to be used in DRES operating within microgrids, in order to enhance their FRT capability, by limiting the peak current [12], [13]. FCLs present several drawbacks like the increased switching losses, long recovery times and increased cost for the DRES owner or the utility.

Distance protection: This is the traditional system protection scheme used in transmission systems, which are from the beginning meshed and active and, therefore, bidirectional power flows are usual [14]. The main underlying idea is to define different protection zones considering the relative position of the DRES units. This is achieved by calculating the impedance at each relay as the ratio U_m/I_m, where U_m is the measured voltage and I_m is the measured current at the relay point. Under normal conditions, the measured impedance includes the load impedance hence, the value is high. But, in case of a fault in the line, the measured impedance will be equal to the line impedance alone, which is very low. Hence, by comparing the measured impedance with a set value, the occurrence of fault and whether it is within the particular protection zone is identified. The main disadvantage of this methodology is that the particular characteristics of distribution systems make its application extremely difficult, since they are composed by several sections with heterogeneous lengths and X/R ratios. Moreover, the impedance estimation of the distance relay depends on the power injected by the DRES.

Differential protection: The differential protection is based on the simultaneous measurement of the current at both ends of a feeder [15], [16]. In normal operating conditions, the current entering to a feeder should be equal to the current leaving from that feeder. However, this condition will not be satisfied during a fault on the feeder. Differential protection is capable of providing protection for a specified feeder effectively, while not responding to outside faults. However, it has to be considered that it is not an economic solution, since it requires a communication link between the extremes of the protection line to perform the current comparison.

Adaptive protection systems mainly rely on the use of adaptive relays, which can have their settings changed on the fly, in order to adapt to changes in the power grid. A communication network is usually used to transmit commands to the relevant relays. Adaptive systems are mainly proposed for microgrids, [17] – [23], in order to react to changes of grid topology (e.g. from grid-connected to islanded mode), but are also considered for conventional distribution grids by some authors [22], as they can also react to the intermittent nature of DRES. Like in the case of differential protection, the implementation cost might be high, since it requires extended communication infrastructure and a centralized controller that implements the decision-making algorithm for the relay settings.

Modifying DRES control: One promising solution is to properly modify the CI-DRES control during a fault, in order to control the injected fault currents. This method has many advantages, such as no cost for additional equipment, less need for modifying the relays settings and enhanced FRT for the CI-DRES, enabling higher CI-DRES integration. Currently, DRES are required to provide only grid voltage support during a fault, by injecting positive or negative sequence reactive power. Towards this purpose, several papers have been published, focusing on the converter control, in order to fulfil the grid code requirements [6] – [11]. However, there is limited research on the active participation of CI-DRES, in case of weak grids. In [24] and [25], distance-based control methods are presented for islanded microgrids, with looped topology. The magnitude of the injected fault current is a function of the relative distance to the fault. A similar fault distance-based DRES reaction method for islanded radial microgrids is proposed in [26].

Energy Storage Systems (ESS): ESS could provide sufficient amount of fault current into a grid with low short-circuit capacity or a microgrid operating in islanded mode. For fault clearing purposes, fast-acting with high power density ESS (e.g. ultracapacitors) are the most suitable [28]. Moreover, ESS prove to become a necessity, in order to increase the reliability of the protection system. A detailed review of possible communication failure impacts and the need for ESS is presented in [28].

2.3. Protection rules for MV distribution grids

Initially, in order to better understand the impact of the reduced short-circuit level on the protection system, the protection rules for the main feeder protection and the back-up protection have to be defined. An important aspect of the proposed methodology is the use of legacy overcurrent protection devices, without any need for upgrading the existing ones or modifying the utility infrastructure. Only the protection settings have to be redefined, according to the following grid parameters; *i)* upstream grid short-circuit level, *ii)* line/cable type and cross-section and *iii)* line length. The protection curves are designed, based on these parameters and common established protection practices [40], and they remain unchanged even if the CI-DRES penetration increases.

Each protection device has two protection elements: *i)* overload protection and *ii)* short-circuit protection. Overload protection (ANSI code 51) is implemented via an inverse time curve and the pick-up current is 1.1 – 1.2 times the rated current of the protected device (line or transformer). Regarding the short-circuit protection (ANSI code 50), it is implemented through a definite time curve. The settings for the feeder protection relays are defined in relation to the minimum expected short-circuit current, $I_{SC,min}$, which is the case of a 3-phase short circuit at the end of the feeder. The short-circuit setting IFSC (I>>, ANSI 50) is defined as $0.9 \cdot I_{SC,min}$, while it can vary between 1.5 and 3 times the rated thermal current of the feeder line I_{lth}. Therefore, the short-circuit setting for the feeder protection relay is defined by:

$$\mathrm{I_{FSC}} = \max\left[1.5 \cdot \mathrm{I_{lth}}, \min\left(0.9 \cdot \mathrm{I_{SC,min}}, 3.0 \cdot \mathrm{I_{lth}}\right)\right] \quad (1)$$

For the back-up protection the relay setting will be $0.9 \cdot I_{SC,\min\_all}$, where $I_{SC,\min\_all}$ is the minimum short-circuit current of all feeders, which belong to the transformer secondary network. For coordination reasons, minimum setting is 1.5 times the rated current of the transformer I_{tr}, and maximum setting is 3.0 times I_{tr}. So, the short-circuit relay setting (I_{TRSC}) is given by:

$$I_{TRSC} = max\left[1.5 \cdot I_{tr}, \min\left(0.9 \cdot I_{SC,\min\_all}, 3.0 \cdot I_{tr}\right)\right] \quad (2)$$

Back-up protection must be coordinated with the downstream protection devices and is, by definition, slower than the feeder/main protection. The protection curve is presented in Fig. 2. As it is obvious, protection settings are independent of the CI-DRES penetration level. These protection settings are constant for a given grid topology and upstream grid short-circuit capacity.

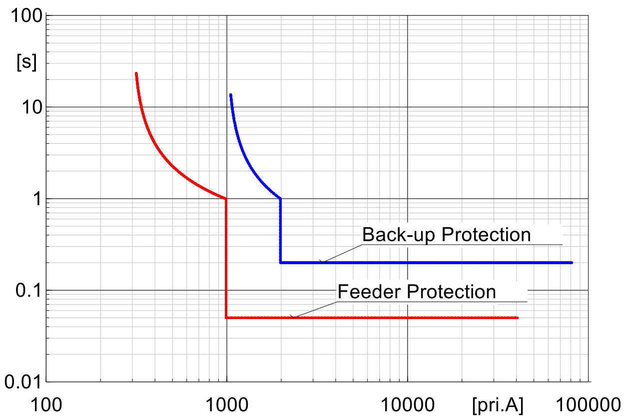


Fig. 2. *Protection curves for feeder and back-up protection*

2.4. *Definition of the limit between high and low short-circuit level*

Initially, the short-circuit level which is considered as "insufficient" has to be defined. This "marginal" short-circuit level is defined using the protection rules established in Section 2.3, and corresponds to the short-circuit level at which either back-up or feeder protection is ineffective. Since the tripping threshold of the back-up protection is higher than the respective threshold of the feeder protection, back-up protection is the first to fail. From (2) it is evident that in the case of a distribution grid of low short-circuit level, back-up protection becomes ineffective when the short-circuit capacity is 1.5 times the rated power of the transformer.

3. Proposed protection methodology

3.1. *Converter-interfaced DRES fault reaction*

In this study we consider that the grid is protected by conventional OC devices. The operation of these devices is based on the difference in the magnitude of fault currents, as compared to normal operation currents. However, for their smooth operation a minimum short-circuit capacity is required. Under increasing CI-DRES penetration levels and the respective decommissioning of conventional power plants, the CI-DRES should have an active role in the protection of distribution grids. This section aims at defining the way CI-DRES should react in the event of a grid fault, when the short-circuit capacity of the upstream grid is significantly low.

Under such conditions, the main idea is that all CI-DRES units should possess FRT capabilities and act in an

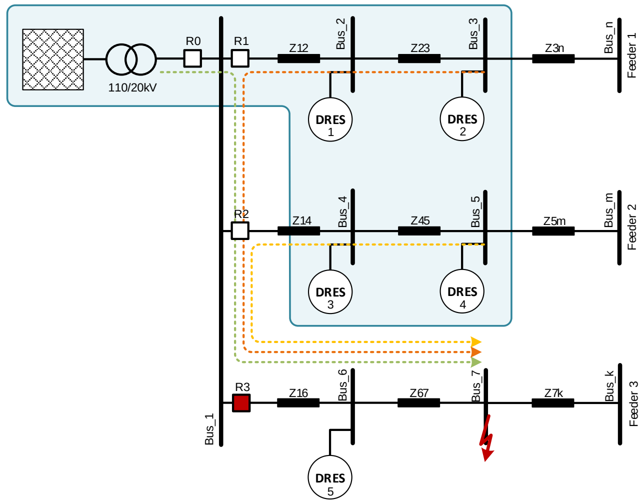


Fig. 3. *Protection philosophy for weak distribution grids with high share of CI-DRES*

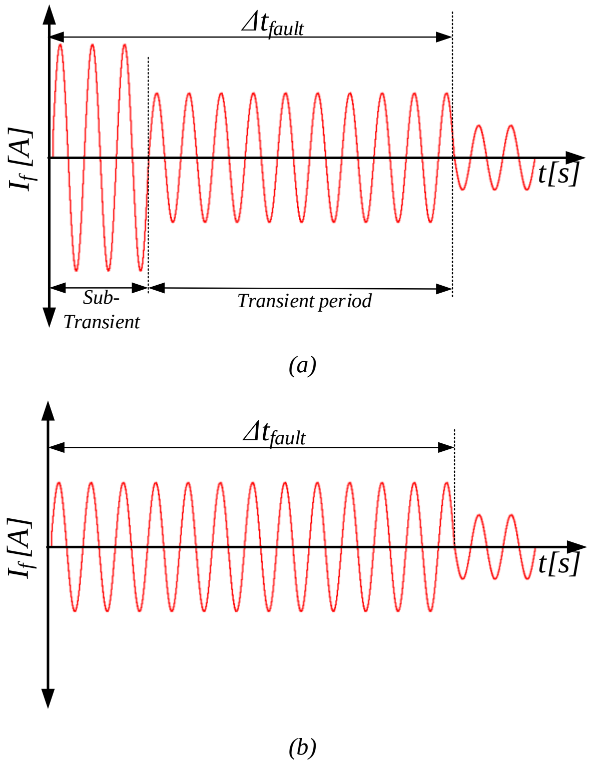


Fig. 4. *CI-DRES fault current: a) with sub-transient and transient part, b) with transient part only.*

aggregated way, actively supporting the upstream grid short-circuit capacity, during faults. The main concept is presented in Fig. 3. As shown, the upstream grid, together with the CI-DRES in all "healthy" feeders, form a new entity that will provide the required fault current. The aim is to activate the main feeder protection device (R3), isolating the faulty feeder.

Regarding the individual contribution of each CI-DRES, that is located in a "healthy" feeder, it is controlled to inject the maximum possible current, under the following constraints; *i*) the maximum converter current capability (today's commercially available converters can safely supply for short term a current 2-3 times their rated one [41]) and *ii*) avoid sympathetic tripping. Each CI-DRES will inject a current of pre-defined magnitude, based on the nominal CI-DRES power, ensuring that the aggregated fault current will not lead to sympathetic tripping. The fault current that will be injected, will have a profile similar to the one shown either in Fig. 4(a) or (b). According to Fig. 4(a), the fault-current contribution of a CI-DRES will have constant amplitudes during the sub-transient and transient periods, similar to the behaviour of a SG. By dividing the fault period, the CI-DRES can inject higher fault currents during the sub-transient period, leading to the faster activation of the respective protection device. However, the stress upon the power electronic switches of the interface converters will be higher during the sub-transient period, which should last only for a few periods of the fundamental frequency. In case the fault insists, the CI-DRES will inject a lower transient current for a longer period. The sub-transient/transient periods and the required maximum time duration for clearing a fault are defined by the operational characteristics of the power electronic switches. The aforementioned differentiation is important and effective in the case of protection devices with inverse-time protection curves, where a higher fault current will lead in shorter tripping time. However, in the case of definite time (DT) protection curves, the fault current profile of Fig. 4(b) is more suitable, since the tripping time is the same, as long as the fault current exceeds the relay instantaneous ($I_{>>}$) settings. Thus, an unnecessary high stress upon the power electronic switches of the converters can be avoided. Based on the protection curves shown in Fig. 2, this paper will adopt the current profile of Fig. 4(b), for the examined case studies.

Regardless of the type of fault current profile, the magnitude of the current that each CI-DRES will inject is limited by the aforementioned constraints to a value equal to I_{fkmax}. This value is shared among the various CI-DRES within the same feeder, in proportion to their rated power:

$$I_{fi} = I_{fkmax} \frac{S_{ni}}{\sum_{l=1}^{N} S_{nl}} \tag{3}$$

where, I_{fi} is the fault current injected by CI-DRES i, S_{ni} its nominal apparent power and N the number of CI-DRES in the feeder. In this way, each CI-DRES will be almost equally overloaded during a fault, meaning an equal requirement for stressing of the DRES converters.

As explained, in order to activate R3, CI-DRES in “healthy” feeders should inject a high current to support the fault clearing. On the other hand, CI-DRES that are located in the faulty feeder (fault is downstream of the DRES), should minimize their contribution to the fault (even zero if possible), in order to prevent blinding of the main feeder protection.

3.2. CI-DRES topology and Control

Although the converter configuration and control are of high importance for the implementation of the proposed protection strategy, it is out of the scope of this paper to get into much detail. Any CI-DRES that can provide controllable fault currents can contribute to the proposed protection philosophy. For our study, a three-leg four-wire DC/AC converter has been employed for interfacing with the distribution grid. A general overview of the CI-DRES topology is shown in Fig. 5.

Under steady-state, the converter is controlled to inject active and reactive power, according to specified *P-f* and *Q-V* droop curves. However, when a fault event is detected (by monitoring the voltage level), the converter is operated as a controllable current source, injecting currents of specific magnitude and PF. An important aspect of the control is that it can be applied both in the case of symmetrical and asymmetrical faults. The control of the interfacing converter is shown in Fig. 6. In the DC side, in parallel to the primary source, a FESS (e.g. ultracapacitor) is connected, in order to handle any power mismatch that might appear during the fault, providing FRT capability to the CI-DRES. The FESS is connected to the DC-link via a DC/DC converter.

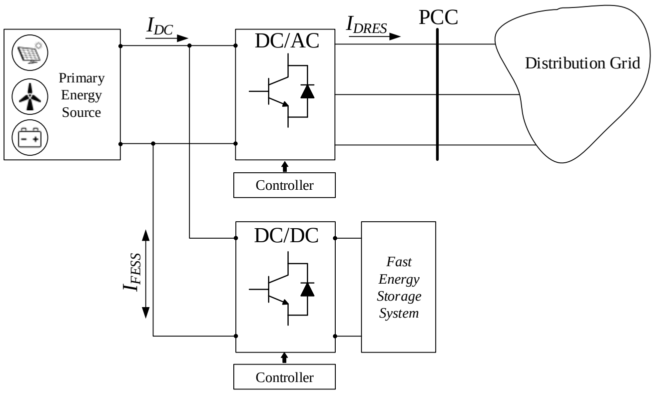


Fig. 5. *CI-DRES* Converter topology

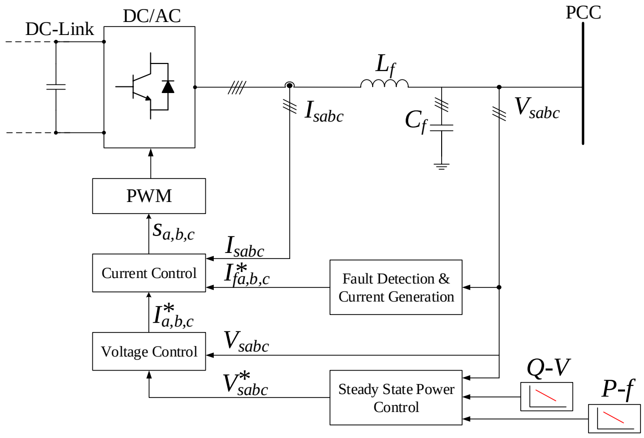


Fig. 6. *CI-DRES* Converter control

3.3. FESS and Control

The FESS is a vital component for the effective and reliable implementation of the proposed protection methodology. It provides the additional fault current or absorbs any surplus energy in order to fulfil the control objectives set in Section 3.2. Additionally, it ensures adequate fault current even in the case of primary source unavailability (e.g. during the night in the case of PV units). In this study a fast-acting storage device (e.g. ultracapacitor) is proposed. Ultracapacitors are storage devices that possess high charging/discharging rates and low maintenance requirements [42]. Nowadays, their capital cost per unit energy is estimated in the range of €15 – €25/Wh for such implementation, including the additional cost of the DC/DC converter [43], [44]. In order to implement the proposed fault clearing methodology, it is estimated that, in the case of a 10kVA CI-DRES, less than 20Wh FESS capacity is required. Thus, the additional cost of the FESS is 10 – 15% of the inverter cost, but less than 3% – 5% of the total installation (e.g. PV plant) cost. This additional cost can be easily justified by the enhanced CI-DRES performance and might also be paid off in a future ancillary services market [45].

Regarding the control of the FESS DC/DC converter, its main objective is to control the DC-link voltage magnitude (V_{DC}) at a constant reference level (V_{DC}^{*}). The control of the FESS is shown in Fig. 7. Regarding the size of the FESS, it should be adequate for maintaining the power balance in the DC-Link, providing FRT capability to the CI-DRES for a minimum time interval equal to the tripping time of the feeder protection device [46].

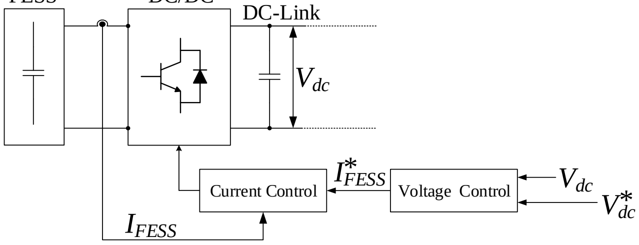


Fig. 7. FESS control

3.4. Detection of the fault direction

In order to determine the relative position of the fault and the CI-DRES, a fault-direction detection method is required. This information is critical for determining the CI-DRES behaviour during the fault, in those cases where the short-circuit power of the upstream grid is extremely low. In these cases, it is proposed that CI-DRES inject currents during the fault, enlarging the short-circuit current through the protection device, to assure an adequate fault detection. However, the effectiveness of the CI-DRES current injection depends on its relative position with respect to the fault. This can be explained using the simple grid shown in Fig. 3. A fault takes place at Bus_7 and is detected by all CI-DRES through the voltage variation. A current injection by a CI-DRES is not effective as far as it flows to the short-circuit, without passing through the protection at the feeder head, i.e. R3. This is the case for CI-DRES 5. In this case, a CI-DRES must ride through the short-circuit, connected to the grid, but with a null current injection, as this current would clearly contribute to the protection blinding, rather than to protection activation. Conversely, when a CI-DRES is connected upstream of the fault (DRES 1, 2, 3 and 4), current injection is welcome, because it adds to the short-circuit current from the upstream power system, flowing through the protection device. The detection of the fault current direction can be implemented through the simple control scheme shown in Fig. 8. It is based on determining the angle between the voltage at the CI-DRES point of common coupling (PCC) and the current in the feeder at the same node. For this reason, three current transformers (CTs) are required to be installed for each CI-DRES, measuring the current flowing in or out of the feeder. The angle of the feeder current and the voltage at the CI-DRES PCC is extracted using PLLs [47].

This method is fast, providing safe results regarding the position of the fault. The CI-DRES reaction based on the fault location is summarized through the following equations:

$$\cos\left(\theta_i - \theta_v\right) = \begin{cases} > 0 & I_{DRES} = 0 \\ < 0 & I_{DRES} = I_{fi} \end{cases} \quad (4)$$

where, θ_i is the angle of the current vector and θ_v the respective angle of the voltage.

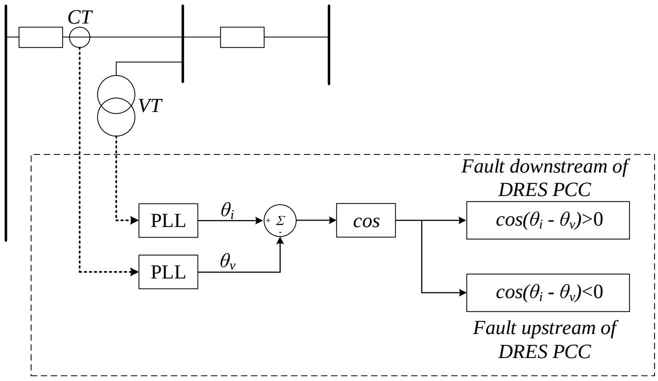


Fig. 8. Fault location detection

3.5. Relation between R/X and PF of injected fault current

In the previous section, we presented the way a CI-DRES should react during a fault, based on the fault location. Our analysis focused on the magnitude of the injected fault currents, neglecting the phase angle (i.e. PF). However, in order to maximize the impact of the proposed method, the PF of the injected power during a fault is of significant importance. PF is an important part of all fault reaction requirements, included in current Standards [31]. This section defines the relation between the injected fault currents (expressed through the PF), the line characteristics and the grid impedance. Our aim is to define the *PF* that maximizes the voltage within the distribution grid for a specific *R/X* ratio of its feeders and the upstream grid impedance. Maximizing the voltage during a fault has multiple benefits for the distribution grid:

- Higher voltage level will allow CI-DRES to ride through faults for longer time periods.
- Higher voltage will provoke higher fault currents in the faulty feeder.

Fig. 9 shows a simple equivalent circuit that is used for our mathematical analysis, supposing that there is only one equivalent CI-DRES in the grid.

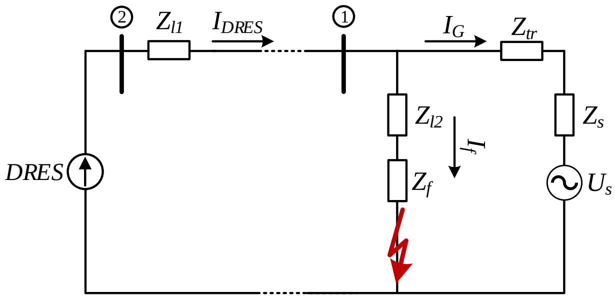


Fig. 9. *Equivalent circuit for voltage vs PF calculation*

The voltage at the CI-DRES PCC is V_2, while V_1 is voltage at Bus_1, which is the main bus of the distribution grid at the MV terminals of the HV/MV transformer (represented by Z_{tr}). The upstream transmission grid is represented by V_s in series with Z_s. The respective feeder impedances are represented by $Z_{l1}$and Z_{l2}, while the fault impedance by Z_f. I_{DRES} is the current injected by the equivalent CI-DRES.

$$\vec{V}_2 = \vec{V}_1 + \vec{I}_{DRES} \cdot \vec{Z}_{l1} \quad (5)$$

$$\vec{V}_1 = \frac{\vec{Z}_{l2}+\vec{Z}_f}{\vec{Z}_{l2}+\vec{Z}_f+\vec{Z}_s+\vec{Z}_{tr}} \cdot [\vec{V}_s + \vec{I}_{DRES} \cdot (\vec{Z}_s + \vec{Z}_{tr})] \quad (6)$$

V_1 is maximized when $\vec{I}_{DRES} \cdot (\vec{Z}_s + \vec{Z}_{tr})$ is maximized. This means that the PF of the injected current should be equal to:

$$pf\_1 = \cos\left[\arctan\left(\frac{X_s+X_{tr}}{R_s+R_{tr}}\right)\right] \quad (7)$$

where, X_s, X_{tr}, R_s, R_{tr} are the reactance and the resistance of the upstream grid and the transformer respectively. Hence, the voltage at the CI-DRES PCC, V_2 will be:

$$\vec{V}_2 = \frac{\vec{Z}_{l2}+\vec{Z}_f}{\vec{Z}_{l2}+\vec{Z}_f+\vec{Z}_s+\vec{Z}_{tr}} \cdot [\vec{V}_s + \vec{I}_{DRES} \cdot \vec{Z}_{tot}] \quad (8)$$

$$\text{Where: } \vec{Z}_{tot} = \left[(\vec{Z}_s + \vec{Z}_{tr}) + \frac{\vec{Z}_{l2}+\vec{Z}_f+\vec{Z}_s+\vec{Z}_{tr}}{\vec{Z}_{l2}+\vec{Z}_f} \cdot \vec{Z}_{l1}\right] \quad (9)$$

V_2 is maximized when the 2nd term in the bracket of (8) is maximized. This corresponds to a PF equal to:

$$pf\_2 = \cos\left[\arctan\left(\frac{X_{tot}}{R_{tot}}\right)\right] \quad (10)$$

where X_{tot} and R_{tot} are the reactance and resistance that correspond to Z_{tot}. The PF from (7) is constant and does not depend on the position of the CI-DRES, when estimating the PF for maximizing the voltage at the main Bus_1. However, from (8)-(10), it is obvious that the PF for maximizing the voltage at CI-DRES PCC, depends on the grid topology (i.e. fault location, fault impedance, grid and transformer impedance and CI-DRES position). While the upstream grid and transformer impedance are known when designing the protection system, the CI-DRES and fault location are arbitrary. Therefore, in order to define a suitable value for the PF, a parametric analysis is required, considering extreme cases for the CI-DRES position and the fault location.

3.6. CI-DRES FRT Capability

The entire analysis and protection philosophy presented in Section 3 is based on the assumption that the CI-DRES possess FRT capability and remain connected to the grid, throughout the fault duration. FRT is supported by the FESS, which is integrated in each CI-DRES in order to handle any power mismatch during a fault. Since the power injected can be either active or reactive, depending on the grid characteristics and voltage level at the CI-DRES PCC, the FESS might be required to charge or discharge during a fault, maintaining the power balance in the DC-link. In both cases, it is of crucial importance for the CI-DRES to remain operational during the fault in order to be able to provide active power after the fault clearance, preventing any system instability. Energy will be stored in the FESS in case the power that can be injected to the grid is less than the power of the primary source, or a high inductive current is required in order to support the voltage recovery (i.e. less active power should be injected). The same is valid also for a CI-DRES that is located in a "faulty" feeder, which should minimize the current injection. On the other hand, energy will be released in case active power is required to be injected during a fault. Employing a FESS, ensures also that the required current injection will be available even in the case of primary source unavailability. Since the FESS should have sufficient charging or discharging capacity, the state of charge should be properly controlled. A method for sizing and control of an ultracapacitor, for improving the FRT capability of a wind turbine, is presented in [44].

In addition to the CI-DRES FRT capability, the selected FRT curve [48] is also related to the effectiveness of the proposed method. The minimum FRT duration should be at least equal to the tripping time ($t_{I>>}$) of the main feeder instantaneous protection setting, (I>>). The DRES should ride through voltage sags down to zero for a time interval equal to $t_{I>>}$. Fig. 10, graphically illustrates the relation between FRT curve and the protection device tripping time.

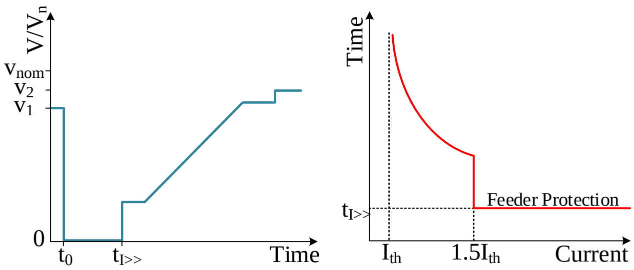


Fig. 10. *Relation of FRT curve with protection curve.*

4. Results

4.1. Benchmark grid description

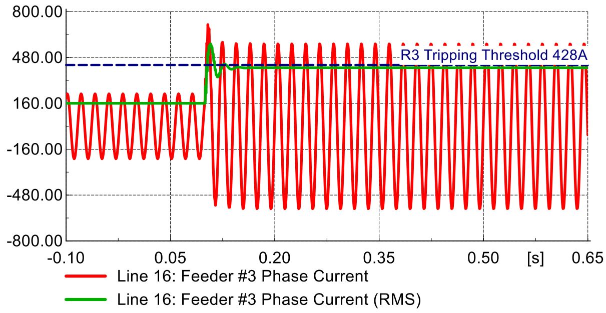
In this part, simulation results are presented for validating the proposed CI-DRES fault reaction methodology, when operating in distribution grids, connected to upstream transmission systems with very low short-circuit capacity. In the following figures, electromagnetic transient (EMT) and RMS simulation results are presented using DIgSILENT PowerFactory Software. The distribution grid examined is the simple three-feeder MV grid, shown in Fig. 3. The grid parameters are summarized in Table 1. The protection curve for the main feeder protection relay consists of two elements; the overload inverse-time and the instantaneous DT protection curve, with a pick up current of 1.5 times the rated cable ampacity (428A) at 300ms.

Table 1. Grid Parameters

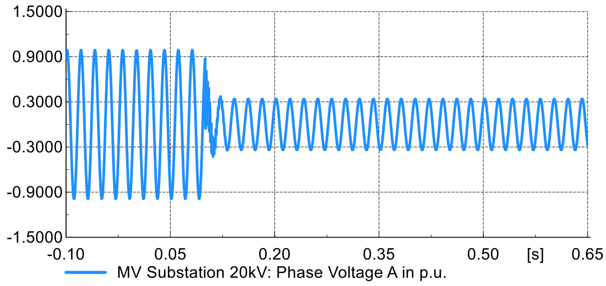
Parameter	Value
Upstream grid short-circuit level (MVA)	25
Upstream grid R/X ratio	0.1
Transformer ratio (kV)	110/20
Transformer power (MVA)	25
Transformer short-circuit voltage u_k	12%
Transformer cooper losses (kW)	25
Cable type	NA2XS2Y
Cable cross-section (mm^2)	120
Cable positive seq. resistance (Ω/km)	0.501
Cable positive seq. reactance (Ω/km)	0.716
Cable rated current (kA)	0.285
Bus_7 distance from Bus_1	10km
CI-DRES No 1 and 3 distance from Bus_1	5km
CI-DRES No 2 and 4 distance from Bus_1	10km
CI-DRES No 5 distance from Bus_1	5km

4.2. Case A: Nominal current injection

Initially, all CI-DRES are connected to the grid and they are controlled to inject their nominal current during the fault. A three-phase solid fault takes place at Bus_7. As shown in Fig. 11, because of the low short-circuit capacity of the main grid and the limited contribution by the CI-DRES, the total fault current is less than the instantaneous tripping threshold ($I_{>>}$=428A) of the main feeder protection R3 and the fault cannot be cleared by the instantaneous protection element. The fault will be eventually cleared by the overload inverse time curve, but with significant delay, which might cause damage to equipment and pose danger for personnel. It is clear from this case study that the CI-DRES should increase their fault contribution, in order to trigger the protection devices. This case resembles the use of FCL proposed by several studies, which clearly cannot by applied when the upstream grid short circuit capacity is significantly low.

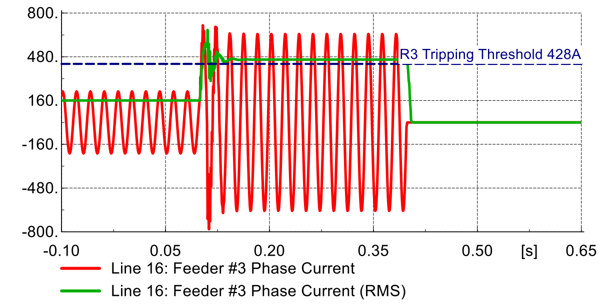


(a)

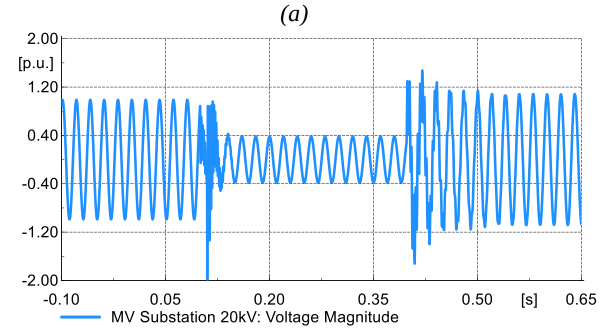


(b)

Fig. 11. *CI-DRES injecting nominal current, a) Fault current in feeder 3 and b) voltage of main Bus_1.*



(a)



(b)

Fig. 12. *Proposed CI-DRES reaction (PF =1), a) Fault current in feeder 3 and b) voltage of main Bus_1.*

Table 2. CI-DRES fault currents

Max. Fault Current	428 A				
DRES No	1	2	3	4	5
Rated Power [MVA]	5.0	3.0	6.0	4.0	5.0
Rated Current [A]	144.3	86.6	173.2	115.5	144.3
Pre-fault Current [A]	144.3	86.6	173.2	115.5	144.3
Fault Current [A]	267.5	160.5	256.8	171.2	0
Overload factor	1.85	1.85	1.48	1.48	0

4.3. Case B: Fault contribution by CI-DRES (PF=1)

Then, CI-DRES are connected in feeders 1, 2 and 3. According to the method proposed in Section 3.1, in order to avoid sympathetic tripping of the healthy feeders, the maximum total injected current must not exceed the instantaneous threshold (428A). This is the first constraint. The second constraint is the maximum current capability of the CI-DRES converters. Each CI-DRES that is located upstream of the fault injects a fault current proportional to its rated power. CI-DRES that are located in the faulty feeder 3 should inject no current. Table 2 summarizes the fault current injected by each CI-DRES, based on these two constraints. The form of the injected fault current is the one shown in Fig. 4(b). Before the fault, each DRES is injecting the rated current. An important feature of the proposed method is that all CI-DRES in the same feeder are equally overloaded. The overload factor given in Table 2, is defined as the ratio of the total current injected during the fault to the rated current. Fig. 12 presents the simulation results after connecting the CI-DRES in the grid. Initially, CI-DRES are controlled to inject currents at unity PF. Fig. 12(a) shows the fault current in the faulty feeder 3 and Fig. 12(b) the voltage of the main Bus_1. Fig. 13(a) and (b) presents the current injected by each CI-DRES in the healthy feeders 1 and 2, during the fault. CI-DRES 5 in the faulty feeder does not inject any current in order to prevent blinding of feeder protection, as shown in Fig. 13(c). This is achieved by the method proposed in Section 3. The fault causes a sudden voltage drop in the terminals of all CI-DRES. Fig. 14. shows the value of $cos(\theta_i - \theta_v)$ for the detection of the fault location, which is crucial for determining the CI-DRES reaction. For DRES_1 - DRES_4 this term is negative, while for DRES 5 (purple line) it becomes positive immediately after the fault occurrence, meaning that the fault is downstream of DRES_5. Thus, DRES_1 - DRES_4 are controlled to inject the pre-determined current mentioned above, while DRES_5 is controlled to fulfil the FRT requirement, with zero current injection. Through the contribution of CI-DRES to the fault, feeder 3 is isolated and the voltage is restored, while sympathetic tripping is prevented.

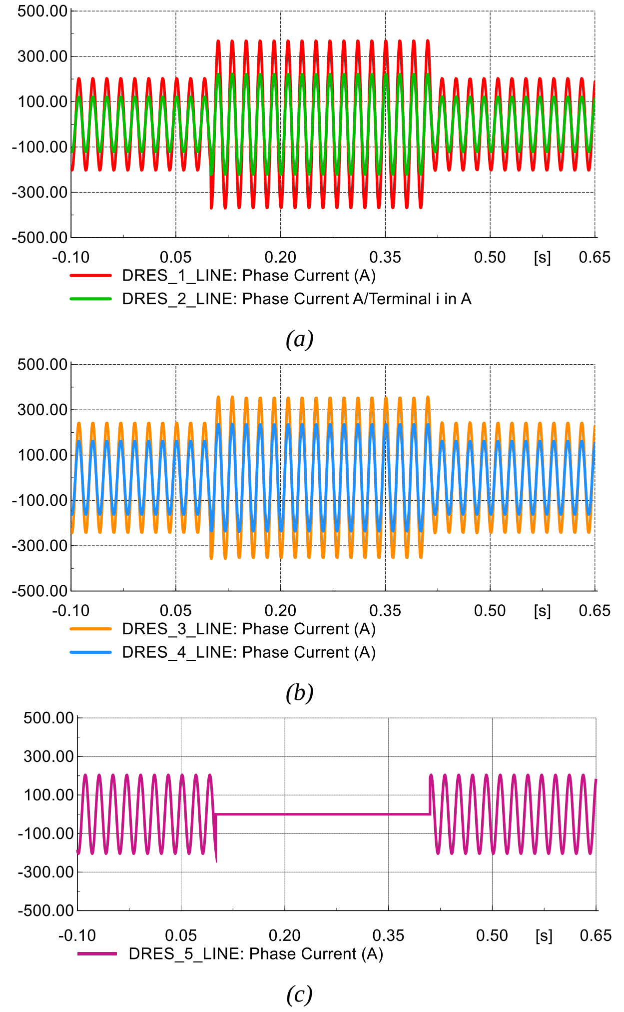


Fig. 13. *Fault current injected by each CI-DRES: a) in feeder 1 and b) in feeder 2 and c) in feeder 3.*

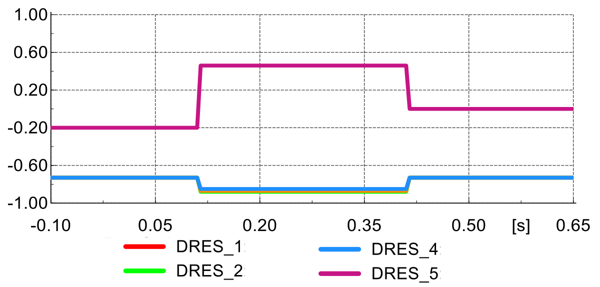


Fig. 14. *Value of cos(θ_i-θ_v) for fault position detection*

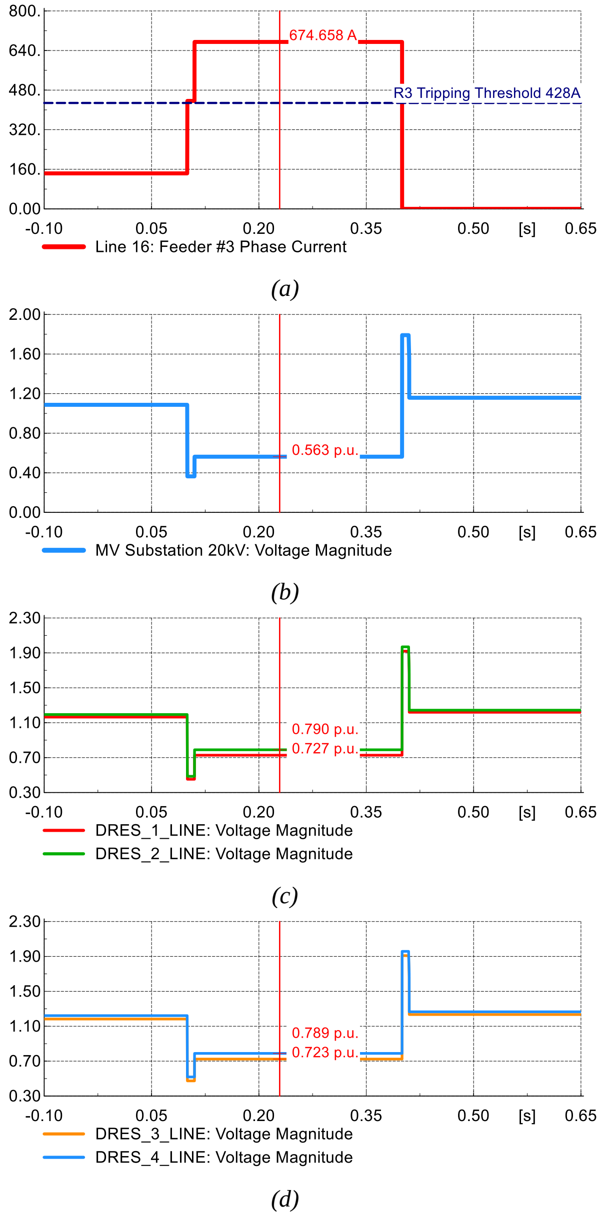


Fig. 15. *Proposed CI-DRES reaction (PF =0.1), a) Fault current in feeder 3, b) voltage of main Bus_1, c) voltage of DRES 1 and 2 PCC and d) voltage of DRES 3 and 4 PCC.*

4.4. Case C: Fault contribution by CI-DRES (PF=0.1)

In all previous cases, the fault current injected by each CI-DRES was at unity PF. However, as presented in Section 3.5, the impact of the proposed method on the protection system could be maximized by controlling, not only the magnitude of the injected currents, but the PF as well. From (6) and (7) the impact of different PF (PF_1) on the Bus_1 voltage (V_1) – and eventually on the fault current – can be calculated. It has already been mentioned in Section 3 that the PF for maximizing the voltage at Bus_1 does not depend on the DRES position, but only on the upstream grid and transformer parameters, which are constant. Using the parameters given in Table 1, the PF that maximizes the voltage of main Bus_1 is calculated equal to 0.1. Although the *R/X* of the lines is 0.7, a high inductive fault current is required to maximize grid voltage. This is because in the case of grids of low short-circuit level, the upstream grid reactance is significantly high.

Fig. 15 presents the simulation results in the case the CI-DRES inject fault currents of the same magnitude as in the previous section, but with a PF of 0.1 (inductive). RMS values of the currents and voltages are illustrated. As it is obvious, a significant increase in the fault current has been achieved. Table 4 summarizes the simulation results for different PFs, regarding the injected power from each CI-DRES. The PF is the same for all CI-DRES in each case. By injecting a mainly inductive fault current, an increase up to 47.0% (compared to the case of PF=1) in the main Bus_1 voltage is achieved. The respective increase of the voltage at the point of CI-DRES PCC is 31.9 – 37.2%. This leads to a significantly higher fault current in feeder 3 (47.0%).

However, comparing the cases of PF equal to 0.1 and 0.5, it can be noticed that the impact on the voltage is not very large, while the fault current in both cases is much higher than the tripping threshold of the protection device.

Table 4. Results for different PF

Element	PF = 0.1	PF = 0.5	PF = 0.7	PF = 1	[%]
Fault Current [A]	674.7	642.3	610.5	459.0	47.0
Bus 1 Voltage [pu]	0.563	0.536	0.509	0.383	47.0
DRES 1 Voltage [pu]	0.727	0.709	0.682	0.530	37.2
DRES 2 Voltage [pu]	0.790	0.773	0.747	0.589	34.1
DRES 3 Voltage [pu]	0.723	0.709	0.683	0.534	35.4
DRES 4 Voltage [pu]	0.789	0.778	0.753	0.598	31.9

4.5. Case D: Maximum fault contribution by CI-DRES – Sympathetic tripping

In this case study, it is supposed that the CI-DRES inject the maximum permissible current, in the event of a fault. This is equal to 2 times their rated current, at unity PF. As a result, a high current flows from the two healthy feeders to the faulty one, which might cause sympathetic tripping, i.e. tripping of the main protection device at the head of the healthy feeders. Depending on the relay settings, any of the healthy feeders might trip before the fault is cleared. Since in our case study all main feeder protection devices have the same settings, in term of tripping time, this will lead to the simultaneous disconnection of all feeders, including the faulty one. Fig. 16 depicts the currents sensed by each feeder main protection relay. This case denotes the need for a methodology to restrain the fault currents provided by the CI-DRES, in order to prevent sympathetic tripping.

4.6. Case E: Fault contribution by all CI-DRES, irrespective of the fault location

According to the methodology presented in Section 3.1, when a CI-DRES is located in a faulty feeder (the fault location is downstream of the CI-DRES), it should reduce the injected fault current, in order to avoid blinding of the main feeder protection. In this last case study, it is supposed that all CI-DRES, regardless if they are located in a healthy or a faulty feeder, react in the same way, injecting a relative high current, according to the two following constraints; *i)* respect the converter fault current capability, *ii)* avoid sympathetic tripping. This case study can be used for comparison with other protection methods [24], [25], which consider only the distance as a parameter, but not the relative location (downstream or upstream). The simulation results are presented in Fig. 17. As it is obvious, in the absence of the location-based reaction, the fault current in feeder 3 is less than the tripping threshold and the fault is not cleared by the instantaneous protection element. The results denote the need to consider the fault location as a parameter for the CI-DRES fault reaction.

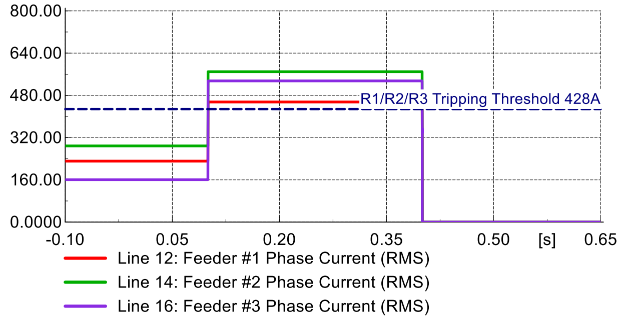


***Fig. 16.** Maximum fault contribution by CI-DRES. Fault currents in each feeder.*

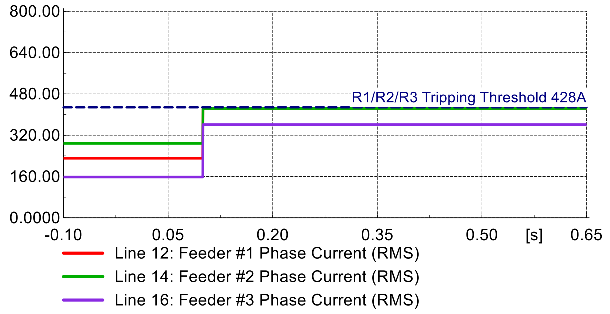


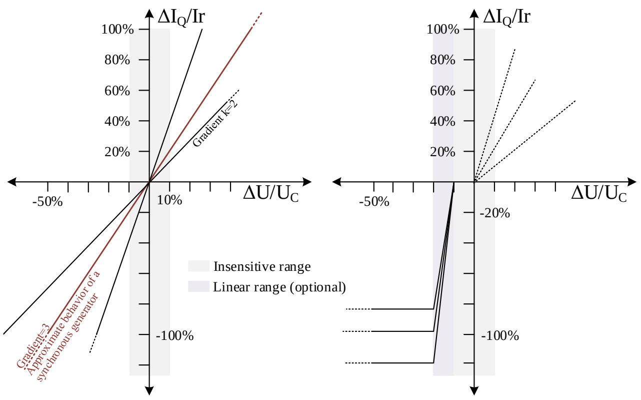
***Fig. 17.** CI-DRES fault conrtibution irrspective of the fault location. Fault currents in each feeder.*

5. Discussion

5.1. Comparison to the Standard EN50549:2019

In order to better evaluate the proposed protection method, it is important to compare our approach with protection practices/requirements included in the current Standards and grid codes for protection of distribution grids. Until recently, only TSOs (e.g. in Ireland and Germany) had specified requirements for the reactive current injection by DRES, in order to support the voltage recovery during a fault, while there are no Standards that explicitly refer to the protection of weak distribution grids. The Standard EN50549, issued in 2019 [31], has been recently published, and refers to typical (stiff) distribution grids. Although, it has not been yet adopted by many grid codes, it is a good basis for discussion and comparison with the methodology proposed in this paper. According to this Standard, generation units might be required to operate in three modes, regarding their reaction during faults, for providing voltage support; *i)* active power priority, *ii)* reactive current limitation and *iii)* zero current threshold. In the *active power priority* mode, the DRES units are required to deliver maximum available active power, limited only by the current limitation of the generation unit. In the *reactive power limitation* mode, each DRES injects additional reactive current (ΔI_q) that is a linear function of the voltage drop (ΔU), according to a specified gradient *k*. This mode is shown in Fig. 18(a). U_C is the declared supply voltage and I_r the rated current. The gradient *k* is defined by the DSO, based on the specific characteristics of the grid. In the *zero current threshold* mode, the DRES shall have the capability to reduce the injected current down to or below 10% of the rated value, in order not to interfere with the smooth operation of protection devices.

The *reactive power limitation* and the *zero current threshold* operation modes are also adopted in our study. In this paper, DRES located in the faulty feeder are required to limit their fault contribution, in order to prevent blinding of protection. This is similar to the *zero current threshold* mode included in the Standard EN50549:2019. Furthermore, in this study, CI-DRES in "healthy" feeders are required to inject high (reactive) fault currents, in order to trigger the protection device at the head of the faulty feeder, similar to the *reactive power limitation* mode proposed in the EN50549 Standard. In this mode, one major difference with respect to the Standard, is that the current injection, below a predefined voltage level, is not a function of the voltage drop. All the participating CI-DRES, in "healthy" feeders, are required to inject a constant fault current, at specific PF, irrespective of the voltage level. This increased fault current contribution is the result of the new enhanced (vital) role that the CI-DRES will have, when operating in a grid of low short-circuit level. The PF depends on the specific grid parameters and is defined using the methodology described in Section 3. As proved in Section 4, in a weak distribution grid, a mainly reactive fault current is required to support the voltage restoration. The fault current injection proposed in this study can be approximated by the curves in Fig. 18(b). In this figure, it is shown that when the voltage drop is up to 10%, the CI-DRES are operating in steady-state mode and no additional fault current is injected. The purple shaded area represents a linear increase of the fault current, when the voltage drop is in the range 10% - 20%. This area is optional and its voltage range can be defined according to the specific requirements posed by each DSO. It provides a smooth transition between the two operational modes, extending the insensitive voltage range.



(a) *(b)*

Fig. 18. *Reactive power injection during voltage sags according to: a) Standard 50549:2019 and b) proposed method.*

In conclusion, the proposed protection method shares the same principal requirements, in respect to the DRES fault reaction, properly modified in order to overcome the shortcomings of the reduced short-circuit level of the upstream grid. The main requirements that are fulfilled by the proposed method are summarized as follows:

- The method is compatible with conventional OC protection devices, without the need of any protection upgrade or investments for communication infrastructure.
- Different current profiles (constant or time-varying) can be selected based on the protection curve.
- Increased (reactive) current injection is provided in order to trigger the protection means, which is of high priority in the absence of a stiff grid.
- CI-DRES possess increased FRT capability by employing a FESS, in order to maintain the power balance during the fault. Using the FESS, fault clearing is ensured even in the case of primary source unavailability. Moreover, active power balance after the fault clearing is secured.
- The PF of the injected currents can be calculated in order to maximize the voltage at the main bus or at the DRES PCC during the fault. An increased voltage at the terminals of the DRES will lead to increased time they can stay connected for a given FRT curve.
- A grid-specific analysis is provided that allows the selection of a higher PF (compared to the optimal case). In this way adequate fault current is ensured and at the same time active current injection during the fault is provided.

5.2. Comparison to other fault protection methods

Section 2.2 presented an overview of the protection methods that are proposed in the technical literature, in order to overcome common protection problems and meet the requirements, posed by the latest grid codes. Most of these studies are dedicated to the current or near future requirements and standards regarding the CI-DRES operation in stiff distribution grids or microgrids. In the context of stiff grids, the use of FCL is widely proposed, as a means for limiting the DRES contribution to the fault and eventually, prevent protection problems, like blinding of protection and sympathetic tripping. In a weak grid, FCL could be used only to prevent sympathetic tripping. However, FCL present increased switching losses, long recovery times and increased cost. Instead, this paper proposes the fault current limitation to be performed through the control of the grid-interfacing converter, without any additional equipment. When a fault is detected, the CI-DRES converter is operated as a controllable current source, injecting the desired fault currents. The aggregated fault current provided by all the CI-DRES in the same feeder is controlled to be less than the tripping threshold of the main feeder protection devices, preventing sympathetic tripping. However, in the context of a weak grid, FCL could be used to limit the current provided by conventional directly-coupled SGs. Therefore, FCL could complement the methodology proposed in this study, in the case DRES based on SGs are also connected to the distribution grid.

During the last decade, there is a lot of ongoing research on the protection problems in microgrids. A microgrid operating in islanded mode, poses similar protection challenges with a very weak distribution grid, like the one examined in this paper. One of the methods proposed for microgrid protection is the differential protection. Differential protection is proved to be very effective in detecting and clearing a fault. However, it requires an extensive communication network, dedicated protection relays, current measurement infrastructure and a fast processing unit, in order collect and compare the currents entering and leaving the feeders. Another commonly proposed method is the adaptive protection. Through the adaptive protection the relay settings are changed on the fly, based the operation mode of the microgrid, or the DRES penetration level. The settings are transmitted through a communication network to the protection devices. However, in case the upstream grid short-circuit capacity is very low, adaptive protection might become ineffective, since the activation of the protection devices cannot rely on the upstream grid fault currents. Even if the protection settings would be changed on the fly, they should be selected close or even less than the rated feeder current, and protection coordination would be hard to be achieved. In terms of implementation cost, it might be very high, both for the differential and the adaptive protection, while the communication network needs to be expanded each time a new DRES is connected to the grid. Moreover, reliability is under question, due to the risk of communication failure. On the other hand, the protection method proposed in the current study is entirely based on local measurements, without any means of communication. The only additional cost is the one for the FESS, which is proved to be less than 5% of the total installation cost. The method presents low implementation cost and is reliable and effective even under primary source unavailability.

There are also a few studies that propose the modification of the CI-DRES control, in a similar manner to the one presented in this study. More specifically, in [24] and [25], CI-DRES are controlled to inject faults currents in order to activate the protection devices in a looped microgrid, while the magnitude of the injected current is proportional to the relative distance to the fault. Although these methods are also based only on local measurements and maintain the legacy protection devices, they are effective only in looped islanded grids, while all protection devices should have the same settings. Moreover, they cannot be applied in grid-connected mode, because coordination among the various protection devices cannot be achieved. If applied in a radial distribution grids, distance related current injection, might lead to sympathetic tripping, if additional constraints are not applied. Simulation results in Section 4.5 proved that if the fault currents are not limited according to the relay tripping threshold, it could indeed lead to sympathetic tripping. A similar distance-based CI-DRES fault reaction for radial microgrids grids is presented in [26]. However, this method considers only feeders with loads, while all CI-DRES are connected to the main bus. In contrary to these methods, the one proposed by the current study can be applied to any islanded grid or distribution system connected to a weak transmission system. Finally, an important aspect is that it does not pose any restriction regarding the location a CI-DRES can be installed. This is achieved by detecting the relative fault location. In the absence of such a control protection blinding is likely to appear, as shown in the results of Section 4.6.

6. Conclusions

This paper proposes a new protection philosophy for distribution grids with high share of CI-DRES. It refers to a future scenario, where the increasing CI-DRES penetration will lead to the decommissioning of conventional power plants, which in turn will result in distribution grids of significantly lower short-circuit level. A control strategy for CI-DRES was proposed for their active contribution to the fault clearing, considering conventional overcurrent protection devices. Aim of this method is to support the short-circuit level through the aggregated action of the CI-DRES. All CI-DRES that are located in a “healthy” feeder should participate in the fault clearing procedure by injecting a fault current limited by certain constaints, without the need for further external means or upgrade, avoiding additional investements as the CI-DRES penetration increases. It was shown that by injecting controllable fault currents, the total fault-current level is significantly increased, ensuring smooth operation of the existing protection devices. It was also shown that the proposed method is even more effective when the power injected during a fault is of specific PF. The PF that provokes maximum fault currents is correlated to the *R/X* ratio of the lines (and the upstream grid impedance), through analytical equations. Finally, it was shown that the proposed methodology is in line with recently issued Standards, however, it proposes a slight modification to address the cases of upstream transmission grids with low short-circuit capacity.

7. Acknowledgments

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