INVESTIGATING ADAPTATION OF LINE PROTECTION MEANS TO LOW-VOLTAGE-RIDE-THROUGH REQUIREMENTS IN LOW-VOLTAGE DISTRIBUTION FEEDERS WITH PHOTOVOLTAIC GENERATORS

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ABSTRACT

As the adoption of low-voltage-ride-through requirements for low-voltage distribution systems with distributed generators is under consideration, the fulfilment of these requirements should be examined not only as for the proper response of the generating units, but also regarding the selective operation of line protection means (fuses). Within this context, this paper demonstrates the problem of improper (early) fuse operation, with regard to the low-voltage-ride-through requirements, through simulations in a test distribution feeder with photovoltaic generators. A preliminary solution to this problem is examined, based on proper short-circuit current limitation. Two different approaches of this solution are described and compared. Potential techniques for the detailed implementation of the proposed concept are finally discussed.

INTRODUCTION

The integration of distributed generation (DG) into distribution systems has necessitated the adoption of low-voltage-ride-through (LVRT) requirements by relevant grid codes over the last years [1]. LVRT regards the capability of DG units to remain connected to the network during faults, providing voltage support, for a time duration which depends on the voltage drop at the point of common coupling (PCC).

Many countries around the world have started standardizing LVRT requirements for medium-voltage (MV) distribution systems (e.g. [2]), although a global standard has not been adopted. Despite the fact that these requirements have not been widely applied to low-voltage (LV) distribution systems yet, their extension to include these systems has been under consideration [3].

Within this context, a significant issue to be examined regards the proper response of DG units to fault situations. In this direction, LVRT-oriented inverter-design concepts have been proposed for LV distribution systems [3, 4], since inverter-interfaced DG (IIDG) units are expected to dominate these systems in the near future.

In terms of distribution system protection, the traditional practice for DG units recommends rapid disconnection during faults [5], limiting their influence on protective relay operation. However, considering the new requirements, the contribution of DG units during faults should be taken into account [6]. Special attention should be paid to avoid any conflict between the protection scheme of a distribution line and the LVRT requirements of DG units. In [7], the overcurrent reclosers protecting a MV distribution feeder with DG are suitably re-set (delayed), so as to allow the DG units to remain connected to the examined feeder during faults, meeting the LVRT requirements.

Given that the latter issue might become more challenging in LV distribution networks, which are typically protected by non-settable fuses, the purpose of this work is, primarily, to demonstrate the conflict between the operation of LV line protection means and the LVRT requirements of the downstream photovoltaic (PV) units, and, secondarily, to investigate a solution to deal with this conflict.

OPERATION OF LV LINE PROTECTION MEANS VS. LVRT REQUIREMENTS

In LV distribution feeders with DG units (usually PV units), a major challenge to meet LVRT requirements regards not only the response of these units during faults, but also their coordination with the feeder protection means. Typically, LV distribution feeders are protected by a fuse installed at their departure, which, in fact, operates on the basis of a non-settable time-overcurrent characteristic curve, unlike overcurrent relays (OCR) applied in MV networks. As such, the fuse cannot be reconfigured after its installation, failing to meet line protection and DG LVRT requirements at the same time.

This issue is further described with the aid of Fig. 1, which depicts a generic radial LV distribution feeder (protected by a fuse installed at its departure) and a PV unit which is connected to the feeder. In case of a fault occurring anywhere in the feeder (e.g. at point F), the PV unit should remain connected according to the adopted LVRT characteristic, providing voltage support to the grid. Nevertheless, no matter whether the PV unit can respond well to this requirement, the fuse melting is solely upon its time-overcurrent characteristic and the magnitude of the short-circuit current I_A (see Fig. 1) flowing through it. Hence, there is a chance that the fuse will melt (thus disconnecting the feeder from the grid) sooner than the disconnection time imposed by the adopted LVRT characteristic. In such a case, LVRT requirements will be

violated. This situation is more likely to occur in short feeders, where current I_A is high even for faults at the remotest point of the feeder (thus leading to a faster fuse melting).
In order to better demonstrate the above-described problem, fault-simulations are performed next, considering a LV distribution feeder with two PV units.

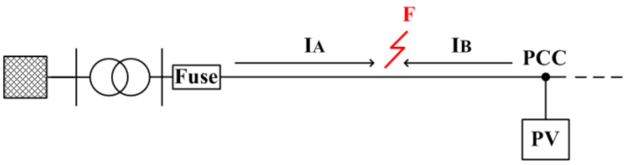

Fig. 1. Generic LV distribution feeder.

Test distribution feeder description

For the simulation study, the 50 Hz, 0.4 kV, LV distribution feeder of Fig. 2 is considered and modelled with DIgSILENT PowerFactory, based on typical data of LV distribution systems (e.g. data regarding distribution transformer, protection means, distribution line etc.). Specifically, all the segments of this feeder consist of 150-mm^2 NAYY cable. Segments L_{01} and L_{12} are 25-m long, whereas segments L_{23} and L_{34} are 20-m long. Note that a relatively short feeder is assumed, since the problem of early fuse melting is more intense in this case, as explained previously. The external grid is represented by an equivalent source with a maximum short-circuit power of 200 MVA at 20 kV. The feeder is supplied from the external grid through a 20/0.4 kV transformer. The total system load is 140 kVA (133 kW).
Two 20 kW PV units are also considered connected to points PCC_1 and PCC_2 (PV_1 and PV_2, respectively). The maximum steady-state short-circuit contribution of each PV unit is limited to its nominal load current. Note that, in case of a fault, we assume that PV_1 and PV_2 can remain connected for as long as it is imposed by the LVRT characteristic of [2] for type-2 generators (including IIDG) connected to MV distribution networks, which in the current analysis is extended to LV networks as well. This LVRT characteristic is shown in Fig. 3. Moreover, PV_1 and PV_2 are suitably set for reactive voltage support.
As regards the feeder protection, a 250 A gL fuse (F_{LV} in Fig. 2) is installed at its departure. This is a fuse type commonly used in LV distribution systems. The current-rating of the fuse is selected considering the maximum possible load current in the examined feeder. Fig. 4 illustrates both the minimum-melting (MM) and the total-clearing (TC) time-overcurrent characteristic of fuse F_{LV}.

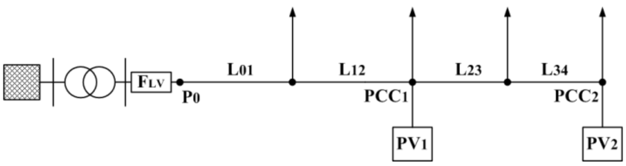

Fig. 2. Test distribution feeder.

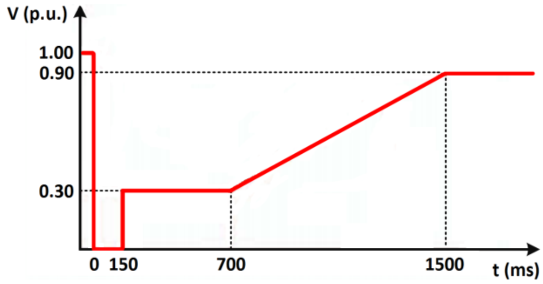

Fig. 3. Adopted LVRT characteristic.

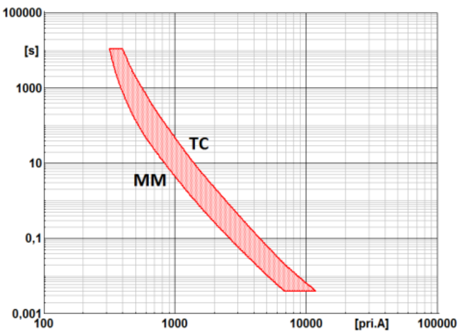

Fig. 4. Time-overcurrent characteristic of fuse F_{LV}.

Problem demonstration

To demonstrate the problem of LVRT violation due to the fast melting of the fuse protecting a LV feeder, faults are simulated in the feeder of Fig. 2 at points P_0 (i.e. in front of F_{LV}), PCC_1 (i.e. at the PCC of PV_1) and PCC_2 (i.e. at the PCC of PV_2). All common types of fault are simulated: line-line-line (LLL), double-line (LL), double-line-ground (LLG), and single-line-ground (SLG).
Table 1 shows the lowest per unit (p.u.) line-line voltage (as this is of interest according to [2]) measured at PCC_1 and PCC_2, during LLL, LL, LLG and SLG faults, occurring consecutively at P_0, PCC_1 and PCC_2. As expected due to the short length of the feeder and the fault severity, a very intense voltage drop is observed at PCC_1 and PCC_2 during LLL, LL and LLG faults. A less intense voltage drop is observed during SLG faults.
Following, Table 2 summarizes the minimum-melting and total-clearing time (t_{MM} and t_{TC}, respectively) of fuse F_{LV} for each one of the examined fault-cases, whereas Table 3 gives the duration for which PV units should normally remain connected (according to Fig. 3) in each fault-case. The key point of our analysis is found upon the conflict between the clearing time of F_{LV} (Table 2) and the duration of PV-connection imposed by the adopted LVRT characteristic (Table 3).
Comparing the time values of Table 2 and Table 3, in all the examined fault-cases, LVRT requirements are violated, since fuse F_{LV} melts (or even starts melting) before the required time duration of PV-connection expires. The presented simulation results (though indicative) support well our argument and highlight the potential conflict of line protection (fuse) and LVRT requirements in LV networks.

Table 1. Lowest line-line voltage (in p.u.) at PCC_1 and PCC_2 in each fault-case.

Fault position		P_0		PCC_1		PCC_2	
Measurement point		**PCC_1**	**PCC_2**	**PCC_1**	**PCC_2**	**PCC_1**	**PCC_2**
Fault type	**LLL**	0.00	0.00	0.00	0.00	0.16	0.00
	LL	0.00	0.00	0.00	0.00	0.16	0.00
	LLG	0.00	0.00	0.00	0.00	0.16	0.00
	SLG	0.56	0.56	0.57	0.57	0.62	0.59

Table 2. t_{MM}/t_{TC} (in ms) of F_{LV} in each fault-case.

Fault position		P_0	PCC_1	PCC_2
Fault type	**LLL**	7/41	13/79	21/133
	LL	11/65	20/128	32/216
	LLG	7/40	12/76	21/138
	SLG	7/40	22/144	50/357

Table 3. Required time duration (in ms) of PV-connection in each fault-case, according to Fig. 3.

Fault position		P_0		PCC_1		PCC_2	
PV unit		**PV_1**	**PV_2**	**PV_1**	**PV_2**	**PV_1**	**PV_2**
Fault type	**LLL**	150	150	150	150	150	150
	LL	150	150	150	150	150	150
	LLG	150	150	150	150	150	150
	SLG	991	991	1006	1006	1081	1036

Examined solution

An obvious solution to the above-described problem would be to replace the fuse protecting the LV feeder with an OCR, so as for the latter to be set according to the LVRT requirements for the PV units. However, this solution would not be practical. This is because the fuse protecting a LV feeder has been chosen so that it coordinates with its upstream protection means in the LV or in the MV side (commonly non-settable fuse), which in turn coordinates with its own upstream protection means. Hence, if the fuse were replaced by an OCR with a different time-overcurrent characteristic, the upstream protection scheme should be also replaced/re-set accordingly.

In order to avoid the mass protection reconsideration in both the LV and the MV distribution system, a potential solution could be the proper limitation of the short-circuit current flowing through the LV fuse, so as for the latter to be suitably delayed, allowing the PV units to stay connected for as long as LVRT requirements impose. The current limitation could be performed by a current-limiting device (CLD) installed at the departure of the LV feeder (i.e. at the fuse location).

This concept is explained with the help of Fig. 5, which illustrates a generic MM characteristic, corresponding to the fuse of Fig. 1. Let us consider the fault of Fig. 1 again, where t_A (see Fig. 5) is the t_{MM} of the fuse, resulting from its MM characteristic and short-circuit current I_A, and t_{thr} is the minimum required time duration of PV-connection that is imposed by the adopted LVRT characteristic and the voltage drop at PCC. As it has been previously explained, since $t_A < t_{thr}$, the fuse starts melting before PV-disconnection, so LVRT is violated. By applying a CLD at the fuse location, I_A can be limited to a lower value I_{thr}, so as for the t_{MM} of the fuse to become equal to t_{thr}. In this way, the fuse operation is suitably delayed, according to the LVRT requirements. Note that, for the CLD design, we consider the t_{MM} of the fuse instead of its t_{TC}. Although conservative, this is a safety measure that we take in order to render the above process more reliable, ensuring that LVRT requirements will be always satisfied.

What has to be further examined is how to determine the value of I_{thr} so as to ensure that LVRT requirements are satisfied in any possible fault-case. In the following, two different approaches are proposed for this purpose.

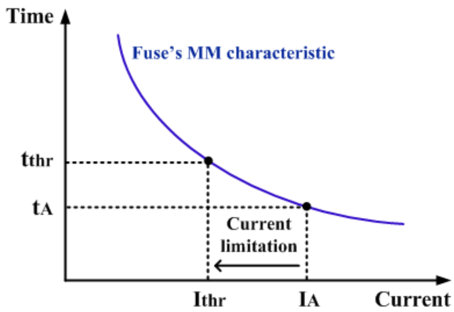

Fig. 5. Proposed current-limitation concept.

1st approach: Fixed I_{thr} setting

In the first approach, CLD operates based on a fixed I_{thr} setting, suitable for all the possible fault-cases. For determining this I_{thr} setting, the next steps are followed:

1) A fault-simulation study is performed in advance to determine the voltage range appearing at the PCC of the PV units connected to the feeder. Specifically, all types of fault are simulated at both the departure and the remotest endpoint(s) of the feeder, as well as at the PCC of each PV unit. Note that these are the marginal (critical) fault positions for determining the voltage range appearing at each PCC during faults.
2) From all the outcome voltage values during the previous step, the maximum one (i.e. corresponding to the minimum voltage drop) is determined.
3) Based on the maximum voltage value extracted in the previous step, the required time duration of PV-connection (t_{thr}), indicated by the adopted LVRT characteristic, is determined. It is noted that the calculation of t_{thr} is based on the minimum voltage drop appearing at any PCC of the examined feeder during all the simulated faults. As such, its value will be greater than or equal to all the t_{thr} values that can be imposed by the adopted LVRT characteristic in the examined system.
4) Based on the MM characteristic of the fuse protecting the examined feeder, we determine the current that results to $t_{TC} = t_{thr}$. This is set as I_{thr}.

In the following, an attempt is made to demonstrate the first approach by calculating some key parameter values throughout step-1 to step-4. To begin with, in step-1, a fault-simulation study should be performed in advance to determine the voltage range appearing at each PCC. For this purpose, we can consider the simulations conducted previously. Next, the maximum PCC voltage (step-2) is calculated considering Table 1, and equals 0.62 p.u. This value is used in step-3 to calculate t_{thr}, which, according to Table 3, equals 1081 ms. Finally, I_{thr} is found to be 1398 A, using the MM characteristic of F_{LV} and the calculated t_{thr} value (step-4).

2nd approach: Adaptive I_{thr} setting

Unlike the first approach, in the second one, I_{thr} is adaptively set. This approach is less conservative, increasing so the protection speed. Specifically, a dedicated I_{thr} setting is calculated in each fault-case, based upon the minimum line-line voltage at the CLD location, which is the substantial difference from the previous approach. t_{thr} is then calculated considering the same LVRT characteristic. Finally, I_{thr} is calculated based on the MM characteristic of the fuse protecting the examined feeder.

It is a fact that the voltage measured at CLD location, which is used to calculate I_{thr}, might differ from that appearing at the downstream PCC. However, given the short length of LV distribution feeders, the low short-circuit contribution of PV units connected to such networks and the, much stronger, external grid source feeding the CLD-bus, the voltage measured at CLD is expected to be greater than or equal to the voltage at each PCC. Hence, the calculated t_{thr} and I_{thr} will satisfy LVRT requirements.

Although not so likely, in the case where the above assumption is not always valid for the examined feeder, a safety margin can be considered for the calculated t_{thr}. The use of communication links between the CLD and each PCC, so as for the former to receive the actual voltage measurements from the latter, would render the present approach even more accurate. However, such a practice would increase the implementation cost.

In the following, the second I_{thr}-setting approach is applied to the feeder of Fig. 2. Table 4 presents the voltage measured at the CLD location for the fault-cases of the previous subsection. Tables 5 and 6 give the corresponding t_{thr} and I_{thr} values, respectively (separately calculated for each fault-case). In almost all cases, F_{LV} clears the fault faster when the second approach is applied (compared to the fixed-I_{thr}-setting approach), whereas it always meets LVRT requirements.

POTENTIAL CLD DESIGN TECHNIQUES

The previous description constitutes just a preliminary outline of the proposed solution, whereas the conducted simulations are indicative. However, for the detailed design of CLD, which will be addressed by the authors in the future, both software (control) and hardware parts should be properly considered. In this section, we briefly discuss the basic principles of these parts.

Control principles of CLD

Referring to the feeder of Fig. 2, the generic control diagram of CLD is presented in Fig. 6, considering the above-described I_{thr}-setting approaches (fixed or adaptive). $i_A(t)$ and $v_{P0}(t)$ represent the instant values of current and voltage, respectively, at P_0 (fuse location). As discussed previously, the main goal of CLD is to limit I_A to I_{thr}. As such, CLD is an ac-chopper which handles the fundamental current component. CLD can be principally seen as an impedance, placed in series with the fuse.

An important issue to consider concerns the fact that the RMS voltage calculation might introduce a delay in the response of CLD, which, in some cases, may fail to timely limit I_A and prevent an early fuse melting. A possible solution to this problem could be the incorporation of a default first-level current limiter in $i_A(t)$, so as to prevent the fuse from melting before the response time of CLD. The control-scheme of Fig. 6 can then be applied in a second level, supplementary to the default current limiter (according to the approach chosen, as it has been described previously). The first-level current limiter is expected to have a fast response, as it will be dictated only by the switching frequency of CLD, being decoupled from voltage calculation. Hence, we expect that LVRT will be met even for high $i_A(t)$ and relatively slow RMS calculators. The detailed investigation of this solution (first-level current limiter) and its influence on the application of the two I_{thr}-setting approaches will be addressed by the authors as part of future work.

Table 4. Lowest line-line voltage (in p.u.) at CLD location.

Fault position		P_0	PCC_1	PCC_2
Fault type	LLL	0.00	0.23	0.36
	LL	0.00	0.23	0.35
	LLG	0.00	0.23	0.35
	SLG	0.57	0.60	0.67

Table 5. t_{thr} (in ms) in each fault-case.

Fault position		P_0	PCC_1	PCC_2
Fault type	LLL	150	150	691
	LL	150	150	677
	LLG	150	150	677
	SLG	1006	1051	1156

Table 6. I_{thr} (in A) in each fault-case.

Fault position		P_0	PCC_1	PCC_2
Fault type	LLL	2337	2337	1563
	LL	2337	2337	1571
	LLG	2337	2337	1571
	SLG	1423	1408	1376

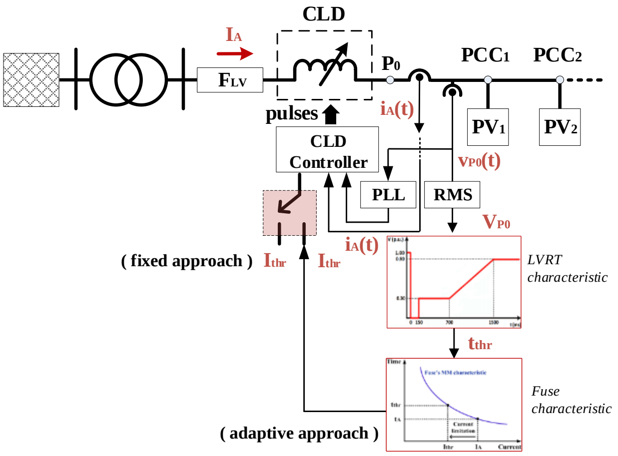

Fig. 6. Generic control scheme of CLD.

Hardware design principles of CLD

Many topologies can be utilized to implement the ac-chopper. A particularly appealing topology though is the one proposed in [8] for a three-phase induction machine inrush current limiter. Nevertheless, the topology design should meet the following two requirements:

a) Efficiency of device should be as high as 98%.

b) Power density of device should match current density of power grid-tied inverters (> 5 kW/kg).

Wind band gap semiconductors (such as Silicon Carbide-SiC and Gallium Nitride-GaN) constitute an excellent solution to meet above requirements. For example, in [9], an efficiency of > 98% and a 6.49 kW/ kg power density are achieved, considering three-phase inverters for aircraft applications.

CONCLUSION

This paper demonstrates the problem concerning the early operation of a fuse protecting a LV distribution feeder, with regard to the LVRT requirements of the PV units connected to the feeder. The simulation study performed shows that this problem can be quite intense in short feeders, which are commonly found in LV distribution systems. A potential current-limitation-based solution is investigated, including two different approaches. The second (adaptive) approach can lead to faster fault clearance compared to the first (non-adaptive) approach, as the I_{thr}-setting of CLD is more "well-suited" to the voltage appearing at each downstream PCC. On the other hand, the first approach has a quite straightforward logic which is secure against fault situations characterized by ascending PCC-voltages along the feeder. However, since such situations are not so likely in common LV distribution feeders with PV units, the adaptive approach can be considered a good compromise between protection speed and LVRT requirements. Finally, control and hardware principles concerning the future detailed implementation of CLD are briefly discussed.

ACKNOWLEDGMENTS

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