Influence of distributed generation on the protection principles of a 70 kV/15 kV transformer in antenna: the zero-sequence over-voltage protection $U_{0>}$

*F. Debrue**, *C. Gonzalez†*, *T. Wijnhoven†*, *P. Goossens§*, *J. Driesen†*

**KU Leuven, Belgium,*

†*Electrical Department ESAT/Electa, EnergyVille, KU Leuven, Belgium, E-mail: carlos.gonzalezdemiguel@esat.kuleuven.be,*

§*Elia (TSO), Belgium*

Keywords: Power system protection, distributed generation

Abstract

Distributed Generation (DG) influences the traditional protection schemes. In this paper the influence of DG on the protections of the Belgian grid operator, Elia, is explained for a 70 kV/15 kV transformer in antenna. Based on the method of the symmetrical components, the detection of two different types of protections, zero-sequence overvoltage, $U_{0>}$, and negative-sequence overvoltage, $U_{2>}$, are analysed in case of a line-to-ground fault, a broken conductor without earth fault and a broken conductor with earth fault at the transformer side. The $U_{0>}$ relay is to be installed in the star point at the primary side of the transformer and measures the zero-sequence voltage. The $U_{2>}$ relay calculates the negative-sequence voltage at the secondary side of the transformer.

1 Introduction

Electric power systems were traditionally characterized by big centralized power plants connected to the transmission grid. The consumers are connected to the distribution system. The power flows are mainly unidirectional from HV to LV. This downstream approach made the protection of distribution systems relatively simple, where it was mainly based on selectivity of relatively cheap overcurrent protections. In the recent past, the amount of Distributed Generation (DG), connected at Medium Voltage (MV) level, has risen. This has a great impact on the protection principles of power systems. The single line equivalent of a transformer in antenna of the Belgina case study is shown in Fig. 1. In the past, the protection schemes were designed for a passive MV grid, where it was sufficient to open the HV circuit breaker D. In case the MV is active due to the presence of DG, there is a possibility that the fault is fed through the MV-side even after tripping D.

The paper describes the work done in [1], where the influence of DG on the protection principles of a 70kV/15kV transformer in antenna on a 70kV-connection is investigated for

three types of faults on the HV-cable: an earth fault, a broken cable without earth fault and a broken cable falling on the ground at the transformer side. The fault calculations are based on the method of the symmetrical components. As a solution for the non-detection of the faults by the classic protections, the zero-sequence overvoltage relay $U_{0>}$ is investigated. As in some cases this protection is expensive, the alternative of the negative-sequence overvoltage relay $U_{2>}$ in the MV-side is investigated. The paper is organised as follows: in section 2 the Elia protection scheme is explained. In section 3 the approach to the problem is explained. Section 4 contains the sequence schemes to calculate the different faults. The most important results are given to see which protection is adequate. Finally, all the conclusions are summarized.

Fig. 1: Single line equivalent scheme.

2 Elia protection principles

A distinction between the case with and without circuit breaker in front of the transformer has to be made. In the case of an underground cable, both cases are Elia standards. In case of an overhead line, only the case with circuit breaker in front of the transformer is an Elia standard. The protection scheme of a 70kV/15kV transformer in antenna on cable with a circuit breaker in front of the transformer is shown in Fig. 2 for new installations. There are two main protections in the source substation. They trip the HV circuit breaker D without any time delay. The first main protection is a distance protection with a teleprotection that trips D' and d. The reason is that the faulted portion can remain energized when the MV is active. The second main protection is a line differential protection. This protection is based on the comparison of the currents at both ends of the cable and requires, therefore, a communica-

tion path. The minimal threshold value is typically set to 30% of the nominal current.

Fig. 2: Elia protection scheme in new installations with a circuit breaker in front of the transformer.

The transformer is protected against faults by a differential protection and other internal protections, like the Buchholz relay. In case of absence of a circuit breakers D' in front of the transformer, these protections trips the HV circuit breaker D through a communication path. For security reasons, there are always two independent communication paths foreseen in this case (in case of a circuit breaker D' installed, there is only one). In absence of a voltage during 5s, a mechanism, called 'clearing', trips the circuit breakers D' and d .

At the MV, there is an overcurrent protection. Distributed Generation (DG) is always equipped with Loss of Main (LoM) protection to prevent unwanted islanding. The LoM-protection fails to trip if the production of the DG and the load are matched.

The zero-sequence overvoltage protection $U0>$ is installed in the star point at the primary side of the transformer. The primary function of this relay is to be a back-up protection in case of earth faults in active MV. In case that the communication paths are out of service, the main protections trip the HV circuit breaker D , but not D' and d . If the LoM-protection fails, the fault is fed through the MV. Because of the isolated star point of the transformer, the currents are very low and cannot be detected by the overcurrent protection at the MV. In new installations, providing $U0>$ is relatively cheap. This protection only requires one extra voltage transformer. The threshold value is typically 25% and the protection has a time delay of

3s to guaranty the selectivity of the other protections.

It has to be pointed out that in existing installations, especially at 70kV, sometimes no communication paths are provided. This is especially the case when there is a circuit breaker D' in front of the transformer, because in absence of D' the installation of communication path is justified for faults in the transformer, as said above. In this case, a differential protection is impossible. In the source substation there is one main protection and one back-up protection. In absence of communication paths these are usually a distance protection and an overcurrent protection. Also, installing $U0>$ is expensive. It requires civil engineering (fundaments, supports) and high voltage operations: installation and connection of the voltage transformer. For this reason the alternative $U2>$ protection is also investigated. It calculates the negative-sequence voltage at the secondary side of the transformer. This protection is cheap because the three necessary voltage transformers are always foreseen at the secondary side of the transformer. It has a typical threshold value of 15% and a time delay of 3s to guarantee the selectivity of other protections.

3 Approach overview

In [1], the following approach has been implemented:

1. Starting from the single line equivalent circuit (see Fig. 1) the sequence networks are built using the method of the symmetrical components ([2–7]) to calculate asymmetrical faults. The interconnection of the sequence networks depends of the type of the fault (see Fig. 3, Fig. 5, Fig. 6 and Fig. 9).
2. These models are used to calculate analytically the currents and voltages in the circuit. An extensive elaboration as well as the full results can be found in [1], but are not handled in the present paper.
3. These equations are implemented in Matlab and solved for several parameters: the length of the cable, the place of the fault and the fault resistance.
4. A model of the asymmetrical circuit has been built in the SimPowerSystem toolbox of Matlab in order to validate the results calculated analytically.
5. Based on the results, the effectiveness of the protections is investigated for the different type of faults.

The used data in the case study are given in Table 1.

4 Fault calculations

This section describes the three studied fault types: line-to-ground fault, single-line broken conductor without earth fault and single-line broken conductor with earth fault.

Element	Property	Value
System	Rated voltage (L-L)	70 kV
	$I_{short-circuit}$	20 kA
	Z_0/Z_1	2
Transformer	Rating	40 MVA
	Voltage ratio	70 kV / 15 kV
	Connection	Yd1 (isolated)
	Impedance voltage	11%
Load	Active power	40 MW
	Power factor	0,95 (lagging)
DG (Sync.)	$X_{short-circuit}$	50 %
Cable	R_1	0,056 Ω/km
	R_0	0,367 Ω/km
	X_1	0,133 Ω/km
	X_0	0,178 Ω/km
	C_1	0,3598 μ/km
	C_0 (assumption)	0,2159 μ/km
	Length	1 km to 10 km
	Length	1 km to 10 km
Line	R_1	0,0455 Ω/km
	R_0	0,2016 Ω/km
	X_1	0,1114 Ω/km
	X_0	0,1008 Ω/km
	C_1	0,1936 μ/km
	C_0 (assumption)	0,1161 μ/km
	Length	12,3 km
	Length	12,3 km

Table 1: Case study data

4.1 Line-to-ground fault

In case the MV is passive (0% DG), the $U_0>$ protection has no use, since the fault will be eliminated by the protections in the source substation as said above. If the MV is active due to DG, $U_0>$ is a back-up protection that only will trip if the communication path is out of service and the LOM fails to disconnect the DG. This last condition only happens when load and DG are perfectly matched, which has a low probability. In this case the elimination of the fault happens in two steps. First, the distance protection or differential/overcurrent protection will trip the circuit breaker D so the system becomes ungrounded. In a second phase the $U_0>$ will trip the circuit breakers D' and d at both transformer sides.

4.1.1 First phase:

The sequence networks are connected at the fault point in case of a line-to-ground fault as shown in Fig. 3. To calculate shunt faults, like the line-to-ground fault, the easiest method is the Thevenin equivalent method [8]. In this method only the currents due to the fault are calculated and to obtain the total current, the load current has to be included. The load current is obtained from the prefault state and is then summed with the fault current obtained from the Thevenin equivalent method.

The fault current for different scenarios, in Fig. 4, is very high due to the grounding of the grid. Even for a length of the cable of 10 km and a fault impedance of 5 Ω , the fault current is still

Fig. 3: Line-to-ground fault fed by grid and DG: the sequence network (phase 1).

more than 5 kA. The high fault currents will be detected without problem by the relays in the source substation (distance and differential/overcurrent protection). These will trip the circuit breaker D in base time, i.e. without time delay. Therefore, the circuit breaker will be opened very fast, i.e. in maximum 120ms. In some cases, for example when there is no fault resistance, the $U_0>$ protection will start detecting the fault, which has no consequences due to the time delay [1].

Fig. 4: Fault current.

4.1.2 Second phase:

The sequence network is shown in Fig. 5. Due to the isolated star point of the transformer and the disconnection of circuit breaker D, the system is not effectively grounded anymore. It can be seen in Fig. FIG5 that the zero-sequence capacitance is the determining factor in the scheme, since all the other se-

ries impedances are small compared to it. As explained in [9], the zero-sequence capacitances coincide with the capacitances between the phases and the earth. This is a determining factor that can also be seen from the three-phase system, where the capacitances are necessary to provide a return path for the fault current [1].

Fig. 5: Line-to-ground fault only fed by DG: the sequence network (phase 2).

In ungrounded systems the voltage over the healthy phases will rise approximately by a factor $\sqrt{3}$, i.e. 73%, to the line-to-line voltage, as explained in [8], [10]. This can cause a degradation of the isolation if the fault is not eliminated. The zero-sequence voltage which corresponds to the neutral shift, is approximately equal to the phase voltage as derived in [1], [8]. From the calculations in [1], it follows that for a cable of 1 km, the zero-sequence voltage is approximately 1,01pu and for a cable of 10km, this is 1,08pu. The magnitude of the fault currents are respectively 8 A and 89 A. A fault resistance of 0 Ω or 5 Ω has no influence, because it is negligible in comparison of the zero-sequence capacitance. As a result of the low currents, the overcurrent protections at MV will not detect the fault. It is also calculated that the negative-sequence overvoltage relay $U_{2>}$ is not suitable for the elimination of this type of faults.

4.2 Broken conductor without earth fault

A broken conductor only happens with overhead lines. This type of fault is less critical than the broken conductor falling on the ground because there is no immediate human safety hazard. Indeed the conductors are in principle not touchable, so there is only a unbalanced grid. The sequence network is shown in Fig. 6. The positive, negative and zero-sequence are connected at both sides of the opening. In the case without DG, the branch with U_{DG} is an open circuit. The circuit has to be calculated with the network reduction method. First, the voltage sources

are calculated from the pre-fault state. Then the circuit is calculated with the superposition method whereby each voltage source is short-circuited at a time. The current in the open phase is logically zero. The differential protection does not detect the fault, because it only measures the capacitive currents, causing a small difference in current between both ends of the conductor. The distance protection is also not suitable for the fault detection as the voltages in the source substation are balanced and do not differ significantly from their nominal values. Also the magnitude of the currents is not much different from their nominal value [1].

Fig. 6: Broken conductor: the sequence network.

As shown in Fig. 7, $U_{0>}$ and $U_{2>}$, both detect the fault in the case no DG is connected. As the amount of DG rises, the current through the HV-conductor will become lower and the sensitivity of those protections will be less (see Fig. 8). In case of a perfect match, there is no current flowing, and no detection at all. The amount of DG where the protections will not detect the fault is also shown. This point is of course dependent of the chosen threshold values. For a threshold of 25%, $U_{0>}$ will not detect when more than 35% of the load is fed by DG. For a threshold of 15%, $U_{2>}$ will not detect when more than 48% of the load is fed by DG.

4.3 Broken conductor with earth fault at the transformer side

As said in the previous section, there is a human safety hazard in this case because the fallen conductor is touchable. This means that the fault has to be eliminated automatically. A broken conductor fallen on the ground is a simultaneous fault including an open-phase series fault and a line-to-ground shunt fault. In case of simultaneous faults, ideal transformers are included to calculate the fault [4]. Because the faults are in the same phase, the transformer ratio is 1:1. The sequence network is shown in Fig. 9. The distance protection does not detect the fault because the voltages and currents in the substations are not different enough from their nominal values. The differential protection measures the fault current, shown in Fig. 10. It

Fig. 7: The zero-sequence voltage at the primary side and the negative-sequence voltage at the secondary side of the transformer for a open-phase fault in the middle of the conductor.

Fig. 8: The current in the HV-conductors for a open-phase fault in the middle of the conductor (threshold = 450 A).

can be seen that this is lower than the minimal threshold value of 450 A. The detection by $U0>$ and $U2>$ is shown in Fig. 11. Both protections are suitable for the elimination of the fault. The sensitivity of $U2>$ however will decrease as the amount of DG rises.

5 Discussion

The $U0>$ protection is easy to install in new installations. As said before, this is not the case in existing installations. In this paper it has been shown that $U2>$ can be used as a cheap alternative for detecting the cable break, but cannot be used for detecting the line-to-ground fault where the HV circuit breaker in the substation is tripped. To decide whether or not to install the protection a risk analysis must be done. The probability of the fault staying fed is dependent on the presence of communication paths to trip the circuit breaker at the other side of the fault by the classic protections. Another important factor is how the MV is made active. In this paper it was assumed that this is due to the presence of DG. In this case the fault can only be sustained if the LoM protection fails. The MV can also be active due to the presence of a parallel transformer in antenna.

Fig. 9: Broken conductor falling on the ground at the transformer side: the sequence network.

Fig. 10: The fault current for a broken conductor with a phase fault (HV/MV transformer side) in the middle of the conductor (threshold = 450 A).

Fig. 11: The zero-sequence voltage at the primary side and the negative voltage at the secondary side of the transformer for a fault in the middle of the conductor.

In this case the probability that the fault is not eliminated is much higher than in the case with DG.

6 Conclusions

This paper analyses the use of the zero-sequence overvoltage protection, installed in the star point of $Y - \Delta$ transformers, for detection of line-to-ground faults with active MV and cable breaks with and without falling on the ground. It is shown that for line-to-ground faults, $U_0 >$ is an adequate protection. Mostly it will be used as back-up protection in case the communication paths are out of service and the LoM protection fails to disconnect the DG. The $U_2 >$ protection is not suitable as back-up protection for this type of faults.

In case of a cable break with and without falling on the ground, $U_0 >$ or $U_2 >$ are the main protections to eliminate the fault. In case of passive MV both have approximately the same sensitivity. In case the amount of DG rises, the cable break without earth fault will be less and less detectable. However this is not critical as there is no immediate safety hazard. In the more critical case of a cable break with earth fault, both protections detect the fault independently of how big the amount of DG is. However the sensitivity of $U_2 >$ will decrease when the amount of DG rises. $U_0 >$ is more insensitive to the amount of DG. All the results are summarized in Table 2.

Fault type	$U_0 > (25\% U_n)$	$U_2 > (15\% U_n)$
Earth fault	Yes: $U_0 \approx U_n$	No
Cable break (no earth fault)	Yes (0% DG): $U_0 \approx 53\% U_n$ No (100% DG): $U_0 = 0\% U_n$	Yes (0% DG): $U_2 \approx 50\% U_n$ No (100% DG): $U_2 = 0\% U_n$
Cable break (earth fault)	Yes (0% DG): $U_0 \approx 35\% U_n$ Yes (100% DG): $U_0 \approx 35\% U_n$	Yes (0% DG): $U_2 \approx 33\% U_n$ Yes (100% DG): $U_2 \approx 25\% U_n$

Table 2: Summary of results

Acknowledgement

Thomas Wijnhoven has a PhD fellowship of the Research Foundation - Flanders (FWO).

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