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6. СОВЕТУВАЊЕ

Охрид, 4 - 6 октомври 2009

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DIRECTIONAL RELAY COORDINATION IN UNGROUNDED MV RADIAL DISTRIBUTION NETWORKS USING A REAL-TIME DIGITAL SIMULATOR

ABSTRACT

In this paper, the results of a relay co-ordination study of an existing ungrounded medium voltage (MV) network are presented. For this study, a Real Time Digital Simulator (RTDS) has been used, which was a part of a closed-loop relay test system. The relay is a Siemens electronic directional overcurrent relay with an earth-fault element. Amplifiers were applied in order to supply the relay with its nominal secondary current and voltage. Furthermore, sequence-components were used for the calculation of the protection blinding zone inside the feeder cable during single phase-to-ground faults. As a result, a maximum allowable network capacitance to ground is calculated for which all ground faults can be detected and interrupted**.**

Keywords: Ungrounded networks, ground faults, RTDS, blinding of protection

1 INTRODUCTION

Currently more than ever, electricity companies tend to optimize their asset management strategy. A clear power system protection concept plays a key role within this strategy. Medium voltage (MV) distribution networks were initially left ungrounded because the need for higher basic insulation coordination was inferior to the advantage of continuous circuit operation during single phase-to-ground faults [1]. Distribution networks continue to expand however and so do zero-sequence fault-currents. Moreover, temporary overvoltages (up to 3.5 p.u.) can be present during single phase-to-ground faults [2]. However, it is very expensive to invest in better neutral-grounding methods and therefore, much effort has been made to optimize existing relaying methods. RTDS technology originated in the mid 1990's as there was a growing need for fast power system simulation studies [3][4]. RTDS is extensively used nowadays in closed-loop protective relay testing and system studies for which real-time operation is required [5]-[8].

This paper presents a relay coordination method for the protection against single phase-to-ground faults of 2 parallel feeder cables in a MV ungrounded distribution network. The protection method relies on overcurrent and directional protection by making use of the zero-sequence quantities of the voltages and currents. Boundary conditions are presented by generalizing the fault current calculation for several values of the MV network cable capacitances.

Section 2 describes a simplified network model simulated in both MATLAB and RTDS. The applied fault calculation method is described briefly. In section 3, the basic operation of unidirectional and directional relays as it is used in practice in closed-loop operation is discussed. Minimum relay settings are determined and a current margin factor α is introduced. Simulation results for both RTDS and MATLAB are presented in Section 4. The presence of a death-zone (DZ) is calculated and discussed. The work is outlined by a practical example.

2 NETWORK DESCRIPTION

The analyzed network is shown in Fig. 1a, which is a simplification of a typical ungrounded 10 kV network which is extensively utilized in the Netherlands.

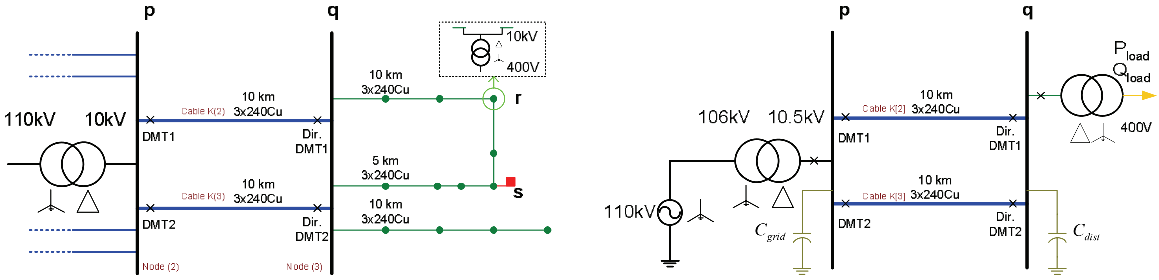


Fig. 1: a) Typical ungrounded MV network with two feeder cables. b) Ungrounded MV network with aggregated load and cable capacitances.

The coordination study focuses on single phase-to-ground faults inside the two parallel feeder cables. The MV network is connected to the high voltage (HV) network at the HV/MV substation (p). From here, feeder cables (between p and q) supply MV distribution substations (q), from where the power is transported further to the low voltage (LV) side by distribution cables (right to q) and distribution transformers (r). Some distribution cables lie in a circular way in order to be manually interconnected in case of an emergency (s). Definite minimum-time relays (DMT1 & DMT2) are positioned at the substation side of cable K(2) and cable K(3). Directional relays (Dir. DMT1 & Dir. DMT2) are placed at the end of the feeder cables. The network of Fig. 1a is further simplified by aggregating the distributed capacitances of the cables to one lumped capacitance, as shown in Fig. 1b. Distribution cables between q and s are represented by their capacitance to ground at node q by

$$C_{dist,0} = \sum_{n=q}^{\text{distribution cable}} C_{g,n} \tag{1}$$

where $C_{g,n}$ is the capacitance to ground for the nth cable section of the distribution cable on the right-hand side of q. Cables located left from node p are represented by their aggregated capacitance to ground at node p by

$$C_{grid,0} = \sum_{n=p}^{\text{MV grid}} C_{g,n} \tag{2}$$

Similar equations hold for the positive-sequence capacitance

$$\begin{cases} C_{dist,1} = \sum_{n=q}^{\text{distribution cable}} C_{g,n} + 3C_{k,n} \\ C_{grid,1} = \sum_{n=p}^{\text{MV grid}} C_{g,n} + 3C_{k,n} \end{cases} \tag{3}$$

where $C_{k,n}$ is the phase-to-phase capacitance for each cable section of the distribution cables (right to node q) and the rest of the MV cables (left to node p) respectively. This is allowed because

- the fault current is produced by the charging currents of the cables' distributed capacitances only;
- Relay operation is based on RMS-value measurements and thus, for the sake of simplicity, lumped capacitances have been used instead of distributed parameters, and
- The error introduced by using lumped capacitances instead of distributed parameters is very small for ground faults in ungrounded networks.

For other types of short circuits however, a π-equivalent circuit is more suitable as the fault current is dependent on the short-circuit ratio of the MV network. Feeder cables are modeled by π-equivalents. The load right to node q has negligible influence on the zero-sequence fault current and hence it is aggregated to one load directly connected to node q. The load on the left to node p is neglected since it has little influence on the fault current amplitude and phase angle at node q. Transformers are modeled by their leakage impedances; the load is modeled by a lumped element. The sequence networks and the network parameters that are used during the study are given in appendix A.

3 RELAY OPERATION

3.1 Directional relay ground-fault element operation

For ungrounded systems, it is not convenient to detect single phase-to-ground faults by using phase currents only. During ground faults, the combination of load current and capacitive fault current is measured. The direction of ground faults should therefore be determined by an earth-fault element, which uses zero-sequence components $\underline{U}_0$ and $\underline{I}_{e,relay}=-3\underline{I}_0$ as phasor quantities [9]. $\underline{U}_0$ will be used as a reference phasor that is rotated by an angle RCA_0 to make a distinction between forward and backward faults as depicted in Fig. 2.

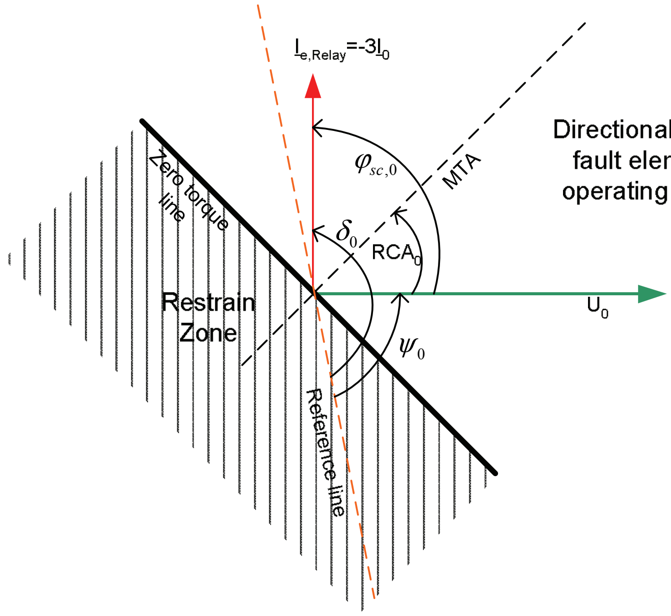


Fig. 2: Operating and restrain zone for a typical directional earth-fault element.

For the measured zero-sequence power holds, to detect a forward ground-fault:

$$P_0 = \Re\left(\underline{U}_0 e^{jRCA_0} \underline{I}_{e,relay}^{*}\right) = \Re\left(U_0 e^{j\psi_0} e^{jRCA_0} I_{e,relay} e^{-j\delta_0}\right) = U_0 I_{e,relay} \cos\left(\varphi_{sc,0} - RCA_0\right) > 0 \tag{4}$$

where $\varphi_{sc,0}$ the angle between $\underline{U}_0$ and $\underline{I}_{e,relay}$ during unbalanced conditions, RCA_0 the zero sequence relay characteristic angle, ψ_0 the phase angle of $\underline{U}_0$ and δ_0 the phase angle of $\underline{I}_{e,relay}$. The currents that flow *into* the cable are measured, which results in a zero sequence current $\underline{I}_0$ *lagging* $\underline{U}_0$ by 90°. Two conditions should be fulfilled to trigger the pick-up/drop-off timer of the directional earth-fault element. First, the RMS-value of $\underline{I}_{e,relay}$ must be higher than the pick-up value and second, a forward direction must be detected.

3.2 Relay Settings

The earth-fault element minimum relay settings are determined by the charging current of the distribution cables (right to node q in Fig. 1b). A ground fault in cable K(3) should cause DMT2 *or* Dir. DMT2 to trip. Thereafter, the capacitive fault current flows partly through the healthy feeder cable towards the faulted cable, causing the other relay to trip. Now, the ground fault is isolated and the faulted cable is selectively interrupted. During this period, the healthy cable carries the full distribution cable capacitive charging current $I_{e,dist}$ (in case Dir. DMT2 trips) or the remaining MV-network capacitive charging current $I_{e,grid}$ (in case DMT2 trips). Moreover, DMT2 and the unidirectional element of Dir. DMT2 also measures the charging current of cable K(2), $I_{e,cable}$. The cable protection must not respond to these currents. Table 1 shows the minimum earth-fault element settings for both DMT and Dir. DMT relays. For $I_{e,dist}$ holds

$$I_{e,dist} \approx 3U_{q,0}\omega C_{dist,0} \tag{5}$$

where $U_{q,0}$ is the zero-sequence voltage during a single phase-to-ground fault, ω the radial frequency and $C_{dist,0}$ the distribution cable aggregated capacitance [10]. Consequently holds for $I_{e,cable}$

$$I_{e,cable} \approx 3U_{p,0}\omega C_{cable,0} \tag{6}$$

with $U_{p,0}$ the zero-sequence voltage at node p. The settings shown in Table 1 are the minimum relay pick-up settings. Every network topology change would make adjustment of the relay settings necessary. Therefore, a margin factor α is introduced to prevent undesirable, uncoordinated circuit interruptions. Applying a too high margin can result in a death-zone (DZ) area within the cable, an area in which ground-faults will not be detected. Table 2 shows the minimum earth-fault settings including the proposed margin factor α.

Table 1. Earth-fault element minimum pick-up settings

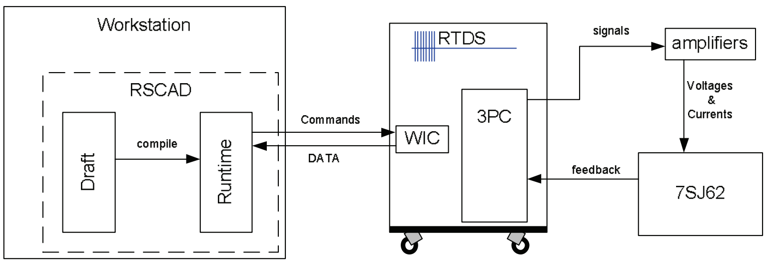
Current setting	Application	Pick-up value
Dir. DMT $+I_{e>}, +t_{e>}$	Dir. DMT earth-fault element pick-up current and time	$I_{e,dist}, 0.3s$
DMT $I_{e>}, t_{e>}$	DMT earth-fault element pick-up current and time	$I_{e,dist} + I_{e,cable}, 0.9s$

Table 2. Earth-fault element minimum pick-up settings including α

Current setting	Pick-up value
Dir. DMT $+I_{e>}, +t_{e>}$	$\left(1+\frac{\alpha}{100}\right)\cdot I_{e,dist}, 0.3s$
DMT $I_{e>}, t_{e>}$	$\left(1+\frac{\alpha}{100}\right)\cdot I_{e,dist} + I_{e,cable}, 0.9s$

3.3 Closed-loop operation

The implementation of an external relay is done according to Fig. 3a. The connected 7SJ62 directional relay replaces Dir. DMT2 of Fig. 1b during real-time operation. At the workstation, a short-circuit current can be ignited by the runtime environment. The relay trip contact is connected to the digital input of the RTDS which establishes a closed-loop system. The voltage and current signals, which are created at the analogue output of the RTDS, must be amplified to rated secondary voltages and currents in order to let the relay work properly. The applied amplifiers are Quad 50E audio amplifiers, which are connected in wye to simulate the secondary circuit as realistic as possible. Toroidal transformers have been connected in series to the current amplifiers to produce correct rated secondary currents. The trip contact of the relay was connected to the RTDS in which a virtual switch was triggered during the simulation. The operation of the amplifier has been verified at KEMA T&D, Arnhem, the Netherlands. Fig. 3b shows the verification of the zero-sequence current amplification as measured by the relay for both Quad 50E amplifiers and KEMA amplifiers. Although some differences can be observed, the Quad 50E amplifiers provide correct relay operation: The fault direction and the RMS-value are determined properly.



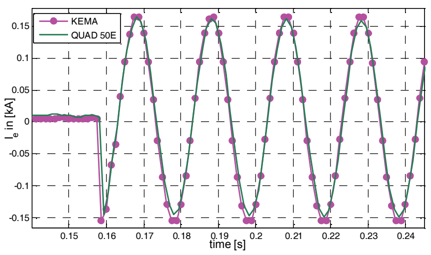


Fig. 3: a) Closed-loop operation of a 7SJ62 directional relay. b) Earth return path current as measured by the directional relay for both the Quad 50E amplifiers and the sophisticated amplifiers of KEMA T&D.

4 SIMULATION RESULTS

4.1 Correct cable interruption

Correct relay coordination is satisfied simply and solely if

$$I_{e,Dir\,DMT} > +I_{e>} \quad \cup \quad I_{e,DMT} > I_{e>} \quad \forall \quad k \in \{0..1\} \tag{7}$$

where $I_{e,Dir\,DMT}$ the earth-fault current measured by the directional overcurrent relay, $I_{e,DMT}$ is the earth-fault current measured by the overcurrent relay and k the fault location in per-unit cable-length. This means that at least one relay that protects the feeder cable should pick up during a single phase-to-ground fault inside the feeder cable. Fig. 4 shows the waveforms of a single phase-to-ground fault being interrupted correctly by the 7SJ62 and the RTDS.

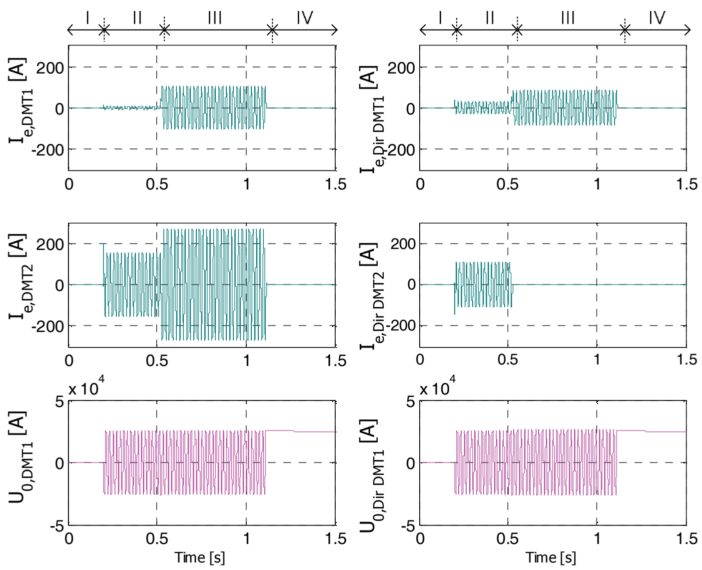


Fig 4: Correct circuit interruption after a single phase-to-ground fault. Upper left and right graphs represent earth-fault current measured by the relays protecting cable K[2]; Centre left and right graphs represent earth-fault currents as measured by the relays protecting cable K[3]. Bottom graphs show the zero-sequence voltage at node p and q during a single phase-to-ground fault.

Only zero-sequence quantities are shown as the phase elements of all four relays do not respond to the small fault current. Basically, the fault interruption can be divided into four steps:

I *pre-fault voltages and currents*: The system is in steady state as a balanced set of voltages and currents are present. Therefore, no zero-sequence quantities occur.

II *fault ignition*: A single phase-to-ground fault is initiated in the centre (k=0.5 per unit) of cable K[3] at t=0.20 s. Zero-sequence currents are measured by the relays as the system is unbalanced. Both DMT2 and Dir. DMT2 pick-up by the measured earth-fault current flowing towards the fault. The directional relay needs one period for the direction determination and it will eventually trip at t=0.52 s, interrupting the cable at one side. Dir. DMT2 is part of the closed-loop system, hence a small trip delay was expected, which is common in practical situations as well.

III *MT2 interruption*: During this period, cable K[3] is connected to the grid by node p only, making it evident that the earth-fault current can flow from one side only. The earth-fault element of DMT2 had already been triggered in period II and trips after another 0.6 s. at t=1.12 s. During this period, $I_{e,dist}$ flows through cable K[2] and both relays may not pick up on this current.

IV *Post-fault situation*: at t=1.12 s the faulty cable is interrupted and the system restored from unbalanced operation. At the fault clearing time instant, this yields that the charging current of the cleared phase recovers while the capacitances of the healthy phases are fully charged and the charge is trapped inside the cable. This leads to a symmetrical three-phase voltage system with a direct voltage component of $\sqrt{2}U_{phase}$ which gradually increases or decreases, seriously stressing the cable isolation [10]. This residual voltage can be observed as a DC-component in the zero-sequence waveforms.

4.2 Death-zone calculation

When no relay picks-up at all during a single phase-to-ground fault, a DZ is present. To determine whether a DZ is present in a cable or not, $C_{dist,0}$ was varied and $C_{grid,0}$ was held fixed as single phase-to-ground faults were simulated at equally distributed locations in cable K[3]. Fig. 5a shows the occurrence of a DZ while varying $C_{dist,0}$ and hence $\mu = {C_{dist,0}}/{C_{grid,0}}$ for fault location intervals of 100 m. (0.02 pu). Since the relay settings change during variation of $C_{dist,0}$ as well, both DMT and Dir. DMT settings are spanning 2 parallel planes. When for a particular value of μ and k (7) does not hold, a DZ is present. Only the lowest value of μ, μ_{lim}, is important for correct relay co-ordination while this value corresponds to the maximum allowable cable capacitance (and hence cable length) installed right to node q.

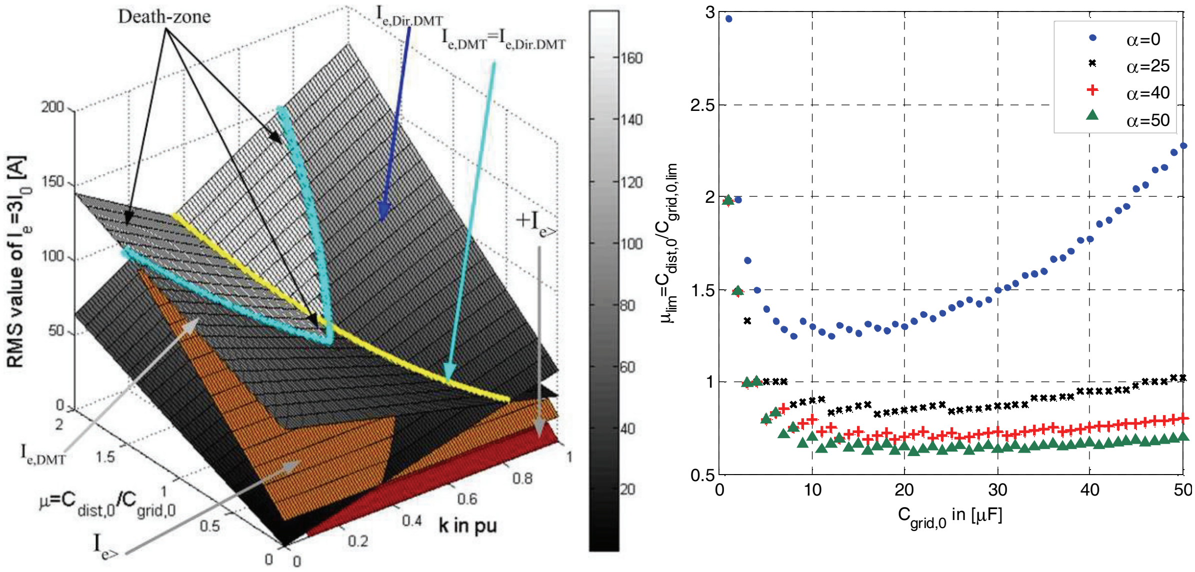


Fig. 5: a) Presence of a death-zone during a single phase-to-ground-fault in cable K[3] as the fault location k (in pu) and the network capacitance factor μ are varied. Earth-fault currents measured at both cable ends are depicted as two planes crossing each other at the indicated line. $I_{e>}$ and $+I_{e>}$ settings vary with μ, spanning two parallel planes. b) μ_{lim} as a function of $C_{grid,0}$ for α=0, α=25, α=40 and α=50. $C_{grid,0}$ was varied with steps of 1 μF during the simulation.

The DZ calculation shown in Fig. 5a is valid for the given network only. No conclusions can be drawn about the maximum allowable capacitance $C_{dist,0,lim}$ for other values of $C_{grid,0}$. Therefore, the calculations are generalized by taking the variation of $C_{grid,0}$ into account as well. Fig. 5b shows the values of μ_{lim} as a function of $C_{grid,0}$ for α=0, α=25, α=40 and α=50. It can be observed that, for approximately 5 μF≤$C_{Grid,0}$≤35 μF, μ_{lim} is constant and hence invariant of $C_{grid,0}$. The average value of μ_{lim} for α=25 at the interval 5 μF≤$C_{Grid,0}$≤35 μF is μ_{lim}=0.86. Calculations are performed by varying $C_{dist,0}$ and $C_{grid,0}$ whilst the feeder cable length is kept fixed. It turned out that the variation of the cable length results in small variations of the average values of μ_{lim}.

5 CONCLUSIONS

This contribution presented a detailed relay coordination study. Single phase-to-ground faults have extensively been studied and a protection method for single phase-to-ground-faults in ungrounded cable networks has been proposed. The method can be used generally for radial cable networks. For the discussed network, the following can be concluded:

- For a limited range of network capacitance, μ_{lim} is equal to 0.86;
- The method has only been applied for two parallel cables. More parallel cables should lead to less critical protection coordination;
- All phase-to-ground faults in the MV network should be interrupted selectively;
- For the given network, a maximum $C_{dist,0}$ of 17 μF can be applied for correct relay coordination

The study presented here shows that the RTDS can be used with full success for protection studies because relays can interact with the circuit as they do in practice as well. Amplifiers are needed for correct amplification of voltage and current signals. It can be questioned whether a DZ situation would occur in practice or not: the sum of the distribution cables on the right from node q is as long as the sum of the cables on the left from node p. Moreover, extensive distribution networks are meshed in practice which makes a sophisticated protection strategy necessary.

6 LITERATURE

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7 APPENDIX A

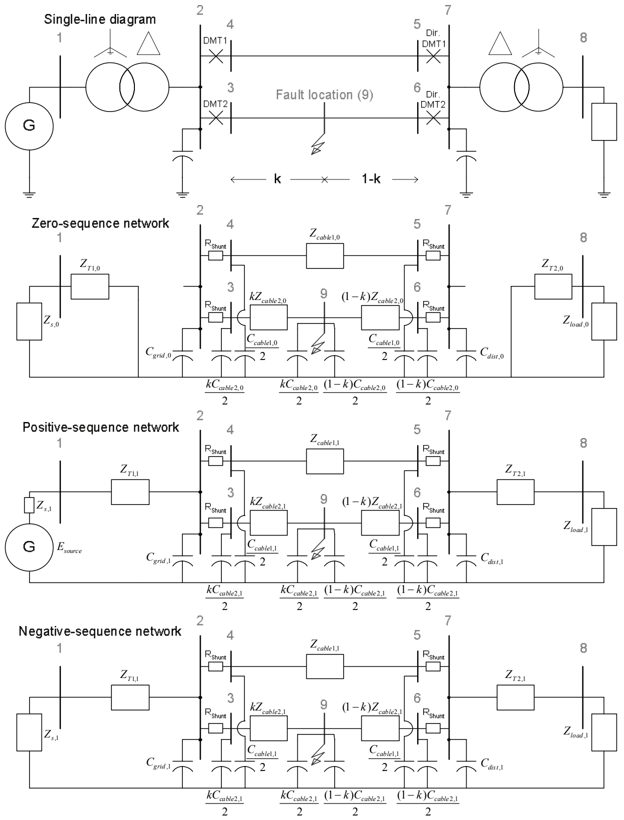

Fig. 6: Sequence networks of the aggregated network shown in Fig 1b.

Table 3. Network parameters as referred to the MV side

Parameter	Value
$\underline{E}_{source}$	6.29 kV
$Z_{s,0}$;$Z_{s,1}$;$Z_{load,0}$;$Z_{T2,0}$;R_{shunt}	1e-6 Ω
$Z_{T1,0}$	2.7+j33.4 Ω
$Z_{T1,1}$	1.348+j40.87 Ω
$C_{grid,0}$	20-6 F
$C_{grid,1}$	36.4e-6 F
$C_{dist,0}$	10e-6 F
$C_{dist,1}$	18.21e-6 F
$C_{cable1,0}$;$C_{cable2,0}$	2.8e-6 F
$C_{cable1,1}$;$C_{cable2,1}$	5.1e-6 F
$Z_{cable1,0}$;$Z_{cable2,0}$	10.97+j1.1 Ω
$Z_{cable1,1}$;$Z_{cable2,1}$	0.79+j0.76 Ω
$Z_{load,1}$	5.833+j12.04 Ω
$Z_{T2,1}$	0.2205+j1.9845 Ω