

# High resistance neutral earthing of MV networks with embedded generation

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Multiple, distant neutral earths on an electrical network may give rise to circulating zero sequence currents, and have implications for the earth fault level and associated protection. An embedded generator (EG) may be required to provide a point of neutral earthing in addition to an existing utility-network earth, and such cases present challenges which may overcome using modern protection relays.

Power systems are earthed to create a reference point for the system voltage, to facilitate the detection and discriminative isolation of faults involving earth, and to limit overvoltages under transient conditions (e.g. lightning, switching surges, earth faults etc.) [1]. Since the 1970s, Eskom has adopted a philosophy of resistive neutral earthing for its medium voltage (MV) distribution networks. As the HV/MV supply transformers feature delta-connected MV windings, the MV neutral point is derived using a neutral earthing compensator (NEC), with zig-zag connected windings, and with an internal neutral earthing resistor (NER). The value of the NER is chosen such as to limit the current under an earth fault condition to less than 360 A on rural overhead networks, and 800 A on urban cable networks [2]. In practice, it is common for a network to be supplied by two parallel transformers, providing a total fault current of 720 A (rural) or 1600 A (urban). Neutral earthing of the radially-fed MV networks is provided only at the source substation. The connection of one or more EGs to an MV distribution feeder brings with it the question of an MV neutral earthing philosophy at the generator or generator transformer. A typical single line diagram of such an application is shown in Fig. 1, with the distributor substation supplying two MV feeders: feeder A and feeder B. An EG is connected to feeder A. As is typical, the EG is connected via a generator transformer.

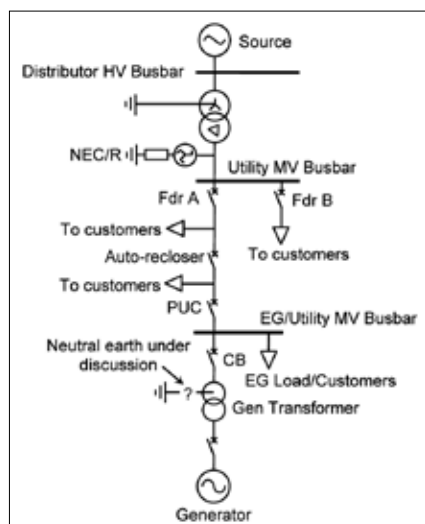


Fig. 1: Single line diagram of an MV network with embedded generation.

On Eskom's MV networks, it is preferred that the MV neutral of the generator transformer is not earthed [3], to avoid common problems resulting from the application of multiple, distant neutral earths [4]:

- The addition of a zero phase sequence (ZPS) current source/s on the network may necessitate that earth fault and sensitive earth fault (SEF) protection relays are made directional. In traditional passive networks, such protection is achieved using non-directional protection
- Despite an overall increase in earth fault current, current sharing between the sources of zero sequence current will render some relays less sensitive to the detection of earth faults
- Multiple points of neutral earthing provide a path for circulating zero sequence currents and/or triplet harmonics (i.e. 3rd, 6th, 9th etc.). Zero sequence (50 Hz) currents may circulate between the distant neutrals on account of mismatched phase impedances on the line. Circulating ZPS currents between distant earths may be problematic on MV networks as they may cause nuisance operation of SEF protection.

The absence of an MV neutral earth at the EG facility causes problems when the generator is required to "island" with the EG's in-house load, as that section of network would be left un-earthed. Referring to Fig. 1, this will occur when the EG is operated with the point of utility connection (PUC) circuit-breaker open. Earthing of the generator transformer's MV neutral will equally be required in the case when the EG is islanded with a portion of the distributor's network (e.g. should the grid supply be unavailable, and the Feeder A circuit-breaker or auto-recloser in Fig. 1 is opened).

The United Kingdoms Electricity Association [4] has a philosophy of switching the generator transformer's neutral earth for operation in islanded mode. This is an effective solution for providing a neutral earth for the island, yet avoiding the problems of multiple earths when operating in grid-connected mode. Being dependent on a mechanical switching device, this philosophy affects the reliability of the earth connection and introduces complexities to the islanding control logic.

For example, the neutral earth must be closed immediately prior to islanding, and opened immediately upon re-synchronisation of the island to the utility network. The control circuitry requires interlocks to prevent islanding should the earth switch fail to close, and to prevent long term parallel operation with the earth switch failing to open.

This paper describes the results of an investigation into provision of a permanent high resistance neutral earth connection at the EG facility, and considers the application of a NER to limit the earth fault current from the EG facility to the order of 36 A (i.e. 10% of the source-supplied fault current). Symmetrical component theory is used to determine the magnitude of zero sequence currents expected to circulate between the distant MV earths. Further, the paper examines the implications of the high resistance earthing practice on the provision of earth fault protection for the EG facility and for the distribution network.

## Limitation of circulating currents by high resistance earthing

The theory of symmetrical components may be used to study the current and voltage distributions on a three phase network subject to mismatch in series impedance of the phase conductors [5]. For simplicity, it is assumed that the impedance mismatch can be modelled as a lumped series impedance in one phase of an otherwise balanced three phase system.

A simplified single line diagram is presented as Fig. 2. "Z" represents the amount by which the series impedance of one phase conductor is higher than that of the adjacent phases. By inserting a negative value for Z, it is possible to model a line with one phase impedance lower than the other phases (e.g. the centre phase of an un-transposed line of vertical or horizontal phase configuration). The load is lumped at the EG installation's MV busbar. The EG is not modelled for the initial studies.

The sequence representation of the single line diagram of Fig. 2 is shown in Fig. 3. As per theory, the impedance "Z" is modelled as  $\frac{2}{3}$  in the positive phase sequence (PPS) network.

The sequence network of Fig. 3 indicates that mismatched series impedances of

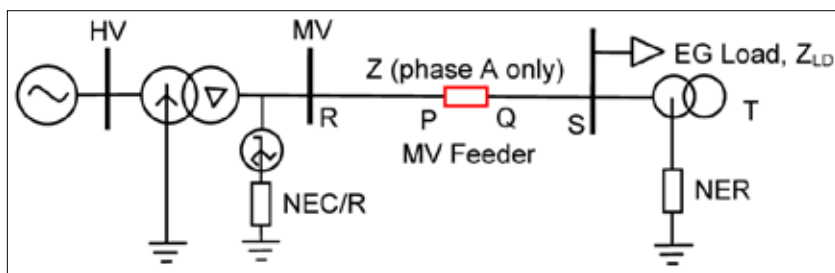


Fig. 2: Simplified network model used to study circulating currents due to mismatched phase impedances on an MV feeder.

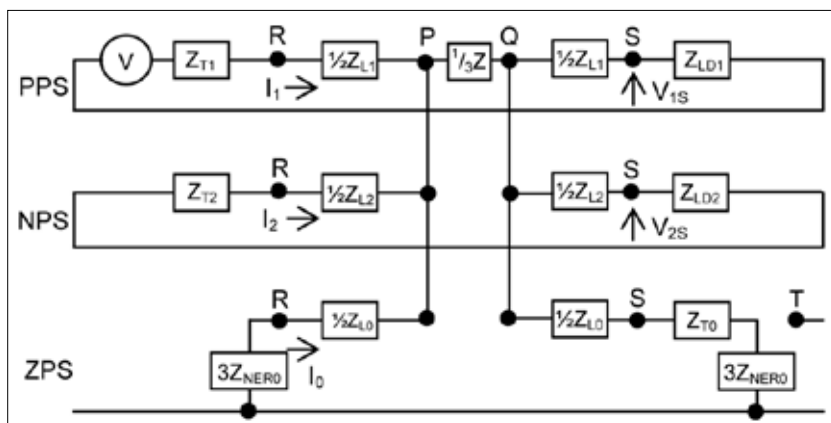


Fig. 3: Sequence representation of single line diagram.

Description	Symbol	22 kV	11 kV	Comment
Source	V	12,7 kV∠0°	6,35 kV∠0°	Phase-to-neutral voltages
Line impedance	$Z_{L1} = Z_{L2}$	0,5 Ω/km∠50°	0,5 Ω/km∠50°	ACSR Hare conductor
	$Z_{L0}$	1,6 Ω/km∠70°	1,6 Ω/km∠70°	
Source / Trfr	$Z_{T1} = Z_{T2}$	4,84 Ω∠90°	1,21 Ω∠90°	Assume 10 MVA, Z = 10%
EG transformer	$Z_{T1} = Z_{T2}$	7,26 Ω∠90°	1,82 Ω∠90°	Assume 5 MVA, Z = 7,5%
	$Z_{T0}$	6,53 Ω∠90°	1,63 Ω∠90°	Assume 90% of $Z_{T1}$
Source earthing impedance	$Z_{NER0}$	17,5 Ω∠0°	8,75 Ω∠0°	Assume two 360 A NEC/Rs in parallel.
EG earthing impedance	$Z_{NER0}$	35 Ω∠0°	17,5 Ω∠0°	Case 1: Standard 360 A NER
		350 Ω∠0°	175 Ω∠0°	Case 2: 36 A NER
Load impedance	$Z_{LD1} = Z_{LD2}^*$	96,8 Ω∠0°, 131 A	24,2 Ω∠0°, 262 A	5 MVA at unity power factor
		48,4 Ω∠0°, 262 A	N/A	10 MVA at unity power factor

\*Assume  $Z_{LD1} = Z_{LD2}$  for resistive loads. For motor loads  $Z_{LD1} < Z_{LD2}$

Table 1: Typical impedance values for the sequence network of Fig. 3.

the phase conductors on a feeder will give rise to negative phase sequence (NPS) (i.e. unbalanced) current. In the event that multiple, distant neutral earths are provided, a quantity of zero phase sequence (ZPS) current will flow. The magnitudes of this "circulating" zero sequence current can be ascertained by inserting typical impedance values for 11 kV and 22 kV networks into the model of Fig. 3. Such values are shown in Table 1. Calculations are performed for two cases:

- with a standard 360 A NER at the EG facility, and
- with a 36 A NER at the EG facility (i.e. high resistance earthed).

For simulation purposes, it is assumed that the source substation includes parallel supply transformers. The EG is installed 10 km from the source substation. The "unbalance" impedance Z is assumed to be  $1,5\Omega < 50^\circ$ . This corresponds to 30% of the total positive sequence impedance of the line which is considered to be a high value for illustration purposes. Quantities of interest from the simulations include:

- The zero sequence current,  $I_0$ . Earth fault protection relays operate based on  $3I_0$  current inputs.
- The percentage voltage unbalance seen at the load, Point S, in Figs. 2 and 3.

Evaluation of the percentage voltage unbalance seen by the load will give an indication of the maximum impedance mismatch of the phase conductors that can be tolerated before the 2% unbalance limit of NRS 048-2 [6] is exceeded.

Results for the solution of the network of Fig. 3 using impedance and voltage values from Table 1 are shown in Table 2.

The above results are considered to be for a worst case scenario on account of:

- Parallel transformers being assumed at the source: lowering  $Z_{NER0}$ , and increasing the amount of circulating  $I_0$  current
- The short line length. The zero sequence impedance of an overhead line is greater than its positive and negative sequence impedances, thus less  $I_0$  current will "circulate" on longer lines
- The EG was not modelled. The EG will reduce the amount of power being transferred from Busbars R to S, and will thus limit  $I_1$ , and consequently  $I_2$  and  $I_0$ .
- An extreme value of line impedance mismatch was chosen, accounting for large voltage unbalances at the load busbars. The 2% voltage unbalance limit of NRS 048-2 includes provision for unbalanced loading, not considered in the present study.

The simulation results presented in Table 2 suggest the following outcomes:

- The amount of circulating current that flows due to multiple MV earths is proportional to the degree of network loading.
- The maximum levels of circulating  $3I_0$  current with standard 360 A NERs will not, on their own, cause incorrect tripping of SEF protection (typical pick-up settings from 4 A to 8 A) or excessive heating of the NERs.
- For the same network load and line impedance mismatch, circulating  $3I_0$  currents are three times higher on an 11 kV network than on a 22 kV network.
- Application of a 36 A NER at the EG installation reduces the circulating current to approximately 15% of that when a standard 360 A NER was applied.
- The resistance of the NERs at the source substation and at the EG installation have a negligible effect on the percentage voltage unbalance ( $V_{2S}/V_{1S}$  in Fig. 3) seen at the load. This is because with both low and high resistance earthing, the zero sequence network impedance is significantly higher than that of Z and of the negative sequence impedance. The NER impedance is trebled in the zero sequence network.

Further simulations conducted by varying the size of the unbalance impedance Z indicate that both the amount of circulating  $3I_0$  current and the unbalanced voltage

Voltage level	Network load	360 A NER at EG facility		36 A NER at EG facility	
		$I_{l0}$ (A)	$V_{S2}/V_{S1}$ (%)	$I_{l0}$ (A)	$V_{S2}/V_{S1}$ (%)
22 kV	10 MVA	2,13	0,93	0,32	0,93
22 kV	5 MVA	1,14	0,49	0,17	0,49
11 kV	5 MVA	3,87	1,77	0,60	1,77

Table 2: Circulating 3I<sub>0</sub> current and voltage unbalance due to multiple MV neutral earths.

seen at the load vary in direct proportion to Z. Overall, the application of a high resistance NER at the EG installation effectively reduces the amount of circulating 3I<sub>0</sub> current that flows due to multiple neutral earthing.

### Implications for earth fault protection.

High resistance earthing at the EG facility has the following implications for earth fault protection, both at the facility and within the utility network:

#### Sensitivity

High resistance neutral earthing at the EG's facility requires that sensitive earth fault protection be applied whilst the facility is operating in the islanded mode. A common practice is to set the earth fault pick-up to between 10% and 20% of the maximum fault current (i.e. between 3.6 A and 7.2 A for 36 A earthing) to provide the maximum coverage of motor windings. Earth fault protection of such low pick-up values is best derived from core-balance current transformers (CTs) as the alternative residual connection of three phase CTs may cause mal-operation in the event of saturation of any of the phase CTs, which may occur during phase faults, transformer inrush, and motor starting conditions [7, 9]. The application of core balance CTs is generally not practical on overhead networks.

Sensitively-set earth fault protection using residually connected CTs may be stabilised by applying a burdening resistor in series with the numerical relay, by supervising the current-based protection using modern CT saturation detection algorithms, or by applying suitable time delays. With regard to the latter solution, Eskom Distribution has successfully used time-delayed SEF protection (typically 5 A, 5 s) on its MV feeders, mostly using residually connected CTs, specified to class X (knee point voltage: 0,4 V per turn, resistance 5 mΩ per turn), of ratios 200/1 or 400/1. The application of lower ratio CTs may be problematic owing to increased ratio and phase angle errors at lower ratios [8], and lower knee point voltages: increasing the likelihood of saturation.

Despite the limitation of fault current, the application of time delays (of the order of 5 s) may not be acceptable from a safety perspective in a factory environment as the raised voltages of the healthy phases increases the likelihood of a second, "cross country" earth fault occurring.

#### Fault level variation in islanded- and grid supply modes

The earth fault level within the EG facility

will vary between 400 A and 1600 A when supplied from the grid, and to below 40 A when supplied in islanded mode. The latter requires the application of sensitive earth fault protection, with attendant time delays. Time delayed sensitive earth fault protection may not be suitable for the higher fault levels of the grid supply, necessitating faster, less sensitive earth fault protection in addition to the SEF protection. The provision of different earth fault protection elements is readily possible using modern numerical protection relays, but adds to the complexity of setting and testing.

#### Requirements for directional protection

Reference [9] describes how SEF protection within radially-fed industrial cable networks is often required to be directional. A residual capacitive current, equal to three times the feeder's three phase charging current, is established on healthy feeders under an earth fault condition elsewhere on the network; often exceeding the SEF pick-up. Directional SEF protection requires that suitable voltage transformers, and directional protection relays are provided.

The choice to limit the EG's neutral earth to a 36 A fault current contribution was made, in part, to avoid the need for directional earth fault protection in the distribution network with distant, multiple MV earths. A 396 A fault on feeder B in Fig. 1 for example, will have a 36 A contribution from the EG's neutral earth (and 360A from the utility substation). Feeder B's earth fault protection will operate significantly faster than that of Feeder A (and the auto-recloser indicated) with the result that the Feeder A protection need not be directional.

A possible grading problem arises for low current faults on feeder B: a 60 A fault having a 5 A contribution from the EG facility. With a typical pick-up of 40 A, and time multiplier of 0,35, normal inverse curve, feeder B will trip on earth fault protection after 6 s. Feeder A and the auto-recloser may trip on SEF in a similar time. Such problems may, however, be overcome through the use of definite-time earth fault protection on the distribution network or by applying a maximum triptime (i.e. low-set definite-time element) in conjunction with an inverse characteristic.

### Conclusion

It is preferred that MV-connected embedded Generators do not provide a point of neutral earthing to the networks to which they connect. In cases where the EG facility requires an MV neutral earth, and where the EG facility is distant from the source substation, the problems associated with multiple neutral earthing can be overcome by switching the EG neutral earth when required.. This paper served to investigate aspects of an alternative neutral earthing option: that of applying a permanent high resistance earth at the EG facility. The high resistance earthing philosophy requires that sensitive earth fault protection be provided for times of islanded EG operation. This typically requires specialised, and sometimes directional, protection that is largely redundant during times when the facility operates in parallel with the grid. Equally, the advantages of high resistance earthing are not available during times of grid-connection. Overall, protection of the EG facility in islanded- and grid-supplied modes presents a number of challenges that may be overcome using modern protection relays, but which may be more complex and more costly than the alternative of switching the EG facility's neutral earth.

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