

**GUIDELINES FOR GRID
INTERCONNECTION OF SMALL POWER
PROJECTS IN TANZANIA**

**PART C:
APPENDIX**

**STUDIES TO BE CONDUCTED,
ISLANDING AND PROTECTION**

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GLOSSARY, DEFINITIONS AND ABBREVIATIONS

AVC: Automatic Voltage Controller

AVR: Automatic Voltage Regulator

Captive Generation: Generating plant available at customer facilities, but not connected in parallel with the distribution network.

Captive Line Load: Load, up to the 1st point of automatic isolation, which is (or may be) supplied by an Embedded Generator, excluding Captive Local Load.

Captive Local Load: Load within the Embedded Generator premises including generator auxiliaries

Captive Load: The sum of Captive Line Load and Captive Local Load

Combined Heat and Power (CHP): A plant that generates electricity and supplies thermal energy, typically steam, to an industrial or other heating or cooling requirement.

Distribution Network: A public electricity supply network operating at or below 33 kV, connected to Tanzania's main grid or operating as an isolated mini-grid

DNO: Distribution Network Operator: Licensee responsible for the operation of a distribution network in Tanzania.

EF: Earth Fault (protection)

EG: Embedded Generator

Embedded Generator: A single generator, or a group of generators, connected to the DNO's distribution network, of capacity range and interconnection voltages stated in Section A2 of the guidelines.

Export of Electrical Energy: Supply of Electrical Energy by a Generator to a Distribution Network.

Generating Company: A company, a group or an individual who plans to connect or has already connected an Embedded Generator to a Distribution Network.

Grid Interconnection: A link between a Distribution Network and the Embedded Generator's electricity system, made for the purpose of Exporting or Importing Electrical Energy.

Grid Substation: A substation in the main grid where electrical energy at 220 kV, 132 kV or 66kV is transformed into 33 kV or 11 kV.

Highest (Lowest) Voltage of a System: The highest (lowest) value of operating voltage which occurs under normal operating conditions at any time and at any point in the system.

HV: High voltage, exceeding 1000 V between conductors and 600 V between conductors and earth.

Import of Electrical Energy: Receipt of Electrical Energy by the Embedded Generator from a Distribution Network.

Interconnection Certificate: A Certificate issued by a Distribution Network Operator to an Embedded Generator, after testing the Grid Interconnection.

Interconnection Voltage: The nominal voltage at which the grid interconnection is made.

Islanding: The process whereby a power system is separated into two or more parts, with generators supplying loads connected to some of the separated systems.

Islanded Operation: The situation that arises when a part of the Distribution Network is disconnected from the grid and is energised by one or more generators connected to it.

LOI: Letter of Intent: Issued by a Distribution Network Operator to a Generating Company to signify the intent to purchase power from a Generating Company at a particular location.

LOM: Loss of Mains (protection)

LV: Low voltage, not exceeding 1000 V between conductors and 600 V between conductors and earth.

Mini-grid: An isolated power system not connected to the Tanzania national grid, and operated under the regulatory supervision of Energy and Water Utilities Regulatory Authority.

Neutral Point Displacement Voltage: The voltage between the real or virtual neutral point and the earth.

NVD: Neutral Voltage Displacement: A technique to measure the displacement of the neutral voltage with respect to earth.

Nominal Voltage: A suitable approximate value of voltage used to designate or identify a System.

OC: Over-current (protection)

OF: Over-frequency (protection)

Operating Voltage: The value of the voltage under normal conditions at a given instant and at a given point in the system.

OV: Over-voltage (protection)

Point of Common Coupling (PCC): The location of the connection between a Distribution Network and the Embedded Generator, beyond which other customer loads may be connected. The PCC may be separate from the Point of Supply where a line is dedicated to the connection of an Embedded Generator.

Point of Supply (POS): The location of the connection between a Distribution Network and an Embedded Generator.

Power Purchase Agreement (PPA): An agreement between the Distribution Network Operator and the Generating Company for the purchase of electricity.

ROCOF: Rate-of-change of Frequency (protection)

RP: Reverse Power (protection)

SBEF: Standby Earth Fault (protection)

Spinning Reserve: The difference between the total available capacity of all generating sets already coupled to a power system and their total actual loading.

Step Voltage: The difference in surface potential experienced by a person bridging a distance of 1 m with his feet without contacting any other grounded structure.

Touch Voltage: The potential difference between the ground potential rise (GPR) and the surface potential at the point where a person is standing, where at the same time having his hands in contact with a grounded structure. GPR is defined as the maximum voltage

that a station grounding grid may attain relative to a distant grounding point assumed to be at the potential of remote earth. The touch voltage could be from hand to hand as well.

Transferred Voltage: This is a special case of the touch voltage where the voltage is transferred into or out of the station by a conductor grounded at a remote point or at the station ground, respectively.

TNS: Terra Neutral Separate (system of earthing): In this earthing (grounding) system, the DNO provides separate neutral and protective conductors throughout the system. The protective conductor is connected to the neutral of the source. All exposed conductive parts of a consumer's installation are connected to the protective conductor provided by the DNO via the main earthing terminal of the consumer's installation.

TNO: Transmission Network Operator

TT: Tera Tera (system of earthing): An earthing (grounding) system where all exposed conductive parts of an installation are connected to an earth electrode provided by the consumer which is electrically independent of the source earth.

UV: Under-voltage (protection)

UF: Under-frequency (protection)

Voltage Level: One of the Nominal Voltage values used in a given system.

VS: Vector Shift (protection)

C1 STUDIES AND INFORMATION TO BE EXCHANGED

DNO may conduct the studies listed in the following subsections before authorising the interconnection of an Embedded Generator. These studies will be conducted within the period of validity of the LOI, after the Generating Company provides information shown in Annex A1 of these guidelines, and when the DNO is satisfied that the detailed designs for the Embedded Generator are in progress.

C1.1 Stability

DNO may analyse the effect of implementing the additional generation on the stability of its distribution system as well as the source systems. Information on the EG required for a stability study should be submitted by the Generating Company, irrespective of the generator capacity.

This may be waived by the DNO for small Embedded Generators, typically less than 1 MW. However, DNO reserves the right to request this information at a later date.

The Generating Company shall provide a model of the Automatic Voltage Regulator (AVR) of the EG, when the proposed capacity is over 5 MW. The Form of the AVR Model is shown in Figure C3.

The Generating Company shall provide a model of the speed Governor of the EG, when the proposed capacity is over 5 MW. Important information such as the inertia constant and governor characteristics shall also be provided.

C1.2 Load Flow

DNO may carry out load flow studies to determine the current flows in each branch of the network, voltage levels at each node and losses etc. when the proposed EG is added to its network.

Objectives of this study are to ensure that thermal ratings of the equipment would not be exceeded; unacceptable voltage rises would not occur, economic operation of the distribution system is guaranteed and DNO to become aware of the extent of reverse power flows.

Depending on the extent of reverse power flows back into the transmission system, the Transmission System Operator (TNO) may carry out appropriate studies to assess the effects of adding EGs to distribution networks.

C1.3 Fault Levels

The Generating Company shall provide to the DNO, information related to fault levels as shown in Annex A1 of Part A of these guidelines.

However, in the case of generators proposed to be connected to 66 kV systems, the Generating Company will be required to provide information to the DNO to enable the TNO to assess the asymmetrical fault currents as well.

The DNO will carry out a fault study with the proposed generator included in the network model. This will enable the DNO to determine the fault level at each node, total fault current at the faulted node and the fault current distribution.

The study may lead to the requirement for more detailed information from the Generating Company for detailed analysis.

C1.4 Protection

On the one hand it is the responsibility of the DNO to ensure that the connection of an EG will not adversely affect its system or the consumers, and also will protect the public from dangers arising out of the EG being connected to its distribution system. On the other hand, it is also the DNO's responsibility to ensure that its distribution system will facilitate the EG to export the energy as laid down in the PPA, without hindrance.

For this reason, the DNO will be required to carryout a protection study to ascertain that the protection system agreed upon will fulfil the requirements identified above. Minimum protective system requirements for the EGs are given in the ensuing sections of the guidelines.

C1.5 Voltage Levels

C1.5.1 Interconnection Voltage

The Generating Company should choose the interconnection voltage in consultation with the DNO. Table A1 of Part A of the guidelines shows the guidelines for the selection of interconnection voltage.

Network availability, its reliability/capacity, proximity of the EG from the distribution network, investments on connecting lines, switchgear and protection systems are the main factors that influence the decision of the POS and the interconnection voltage.

Development plans published by the DNO will provide details of the distribution systems in the area in which the Generating Company plans its project. With this information, the Generating Company should enter into a dialogue with the DNO to decide on the suitable

voltage and the Point of Supply. Based on these discussions, the DNO shall define the Point of Supply and its nominal voltage, at the time of issuing the LOI.

Once the POS is decided, DNO may carry out all the necessary studies and shall provide the Generating Company with the applicable normal operating voltage, maximum normal voltage, maximum permitted voltage and information on the power factor limits at the POS.

C1.5.2 Voltage Flicker

Synchronous generators do not normally cause voltage flicker, but wind turbine driven induction generators connected to weak systems (low fault levels) could give rise to undesirable voltage flicker situations.

The generator should not cause voltage flicker at the POS which exceeds the limits defined in *Engineering Recommendation P28*, "Planning limits for voltage fluctuations caused by industrial, commercial and domestic equipment in the UK".

C1.5.3 Voltage Rise

The voltage rise at the POS due to the generation must be within operational limits. The target bandwidth for voltage on the 33 kV busbar of a grid sub-station is $\pm 5\%$. The target voltage on the 33 kV busbar of the grid sub-station is 33 kV.

C1.5.4 Studies on Voltage Flicker and Voltage Rise

A two-stage approach will be required in conducting these studies:

Stage I: Exclude load connections to distribution lines and grid transformers

Stage II: Include load connections to distribution lines and grid transformers

The Stage II study will be required when the Stage I study indicates a potential problem.

C1.6 Earthing

The Generating Company shall provide information about the proposed earthing arrangement to the DNO. Guidance on the earthing system is given in Sections A4 (in Part A) and Section C5.

C2 FAULT LEVELS

C2.1 General

Fault levels in a distribution network must be maintained within design limits. Ratings of switchgear shall be in accordance with the declared design fault level to ensure healthy system performance.

The connection of a generator to a distribution system will increase the fault level on the network when both the generator and grid are connected, and the effect of this change should be considered.

Fault levels in rural distribution networks tend to be relatively low and the contribution of smaller embedded generators are not normally a problem.

C2.2 Fault Level Information

The DNO shall provide the design fault levels at the POS to the Generating Company.

The Generating Company shall provide fault level contribution of generator(s) at the POS. The Generating Company shall provide tolerances on the fault level data provided.

The information requirements are specified in Annex A1 in Part A of these guidelines.

C2.3 Asynchronous (Induction) Generators

For induction machines, the data set is not standard and, therefore, data requirements for asynchronous generators should be agreed between the DNO and the Generation Company.

C2.4 Fault Level Calculation

The DNO shall be responsible for monitoring fault levels on the distribution network and performing detailed assessments as appropriate, to ensure that fault limits are not exceeded.

Fault calculations shall be based on methods defined in IEC 60909, Short Circuit Current in AC Systems. The make and break fault levels are described below in order to provide an outline, and a common understanding of the principle quantities.

C2.4.1 Make Fault Level

This is the peak symmetrical fault current after the initial fault. The following parameters determine this fault level: system voltage, rotating machine sub-transient reactance and

time constant, grid transformer source impedance, network impedance and overall X/R ratio. The calculation is based on the most onerous source impedance and network configuration to derive a maximum value. In networks with high X/R ratio, it is typically about $1.8 \times \sqrt{2}$ times the initial symmetrical fault level and is often the main limiting factor.

C2.4.2 Break Fault Level

This is the total fault current at the instant of circuit breaker fault interruption. The elapsed time from the initial fault is dependent on the speed of relay and breaker operations, and is typically in the range of 4 to 8 cycles. The following parameters determine this fault level: system voltage, rotating machine transient reactance and time constant, grid transformer source impedance and network impedance. The calculation is based on the most onerous source impedance and network configuration to derive a maximum value. The decrement of generator fault contribution, particularly for asynchronous machines, is typically very significant during this period, and should be taken into account for detailed fault level assessments.

C2.4.3 Steady-state Fault Contribution

This is the symmetrical fault current at a time after the complete decay of sub-transient and transient fault contribution from rotating machines. The steady-state contribution of synchronous machines is influenced by the AVR characteristic. However, for most purposes, this quantity would be used for minimum fault level only and, in this case, it would be normal to neglect all EG contribution, and use the most onerous source and network conditions to derive a minimum value.

C2.4.4 Asymmetrical Fault Level

It is the normal practice to earth 11 kV and 33 kV systems only at the source. However, in the case of 66 kV systems, the neutral is multiple earthed. This may cause the single phase-earth fault currents to be higher than the symmetrical fault currents. Hence in determining the make fault levels of circuit breakers associated with 66 kV systems, the asymmetrical fault currents should be considered.

C2.5 Fault Level Reduction and Management

Connection of an additional generation will always lead to an increase in the fault level. Where it has been identified that the resulting fault level would exceed the design fault level, following are the possible options to address this problem:

C2.5.1 Replacement of Switchgear and Components

Fault level capabilities of the network could be increased by replacement of the switchgear with equipment with a higher design rating. This is the obvious and traditional solution, but will be expensive.

C2.5.2 Network Splitting/Changing System Feeding Arrangements

By splitting the network or at times by changing the system feeding arrangements, it is possible to achieve lower faults levels. This is a low cost solution and should be considered only if it does not lower the system reliability/stability/power quality below the desired levels.

C2.5.3 Increasing the Impedance

This may take the form of an isolating transformer, a current limiting reactor or additional length of circuits. A current limiting reactor could give rise to voltage problems and also increase system losses.

C2.5.4 Short Circuit Current Limiters

Described above are some methods of permanently reducing the fault levels of the network. Fault levels do not remain constant and depends on network configuration, type of fault, etc. Hence the fault levels of a system will not remain constant but vary between certain definite maximum and minimum levels.

This situation has given rise to the introduction of new devices which come into action when the fault level increases to a pre determined value. Short circuit current (I_S) limiters, superconducting fault level limiters, solid state fault current limiting circuit breakers are a few examples and of these, I_S limiters have found wide application.

An I_S limiter comprises a fuse and a switching device which comes into action only when the fault current exceeds a pre-determined level. Hence under normal operating conditions, the question of lowering of system reliability/power quality does not arise. The fuse needs to be replaced after an operation and the average rate of operation is around once in four years. In the circumstances, the I_S limiter can be considered as a good option.

All other devices may be expensive and mostly not commercially available.

C3 VOLTAGE REGULATION

C3.1 General

Control of voltage on the distribution system is affected by the connection of embedded generation. The power being fed into the grid from the EG will raise the voltage at the POS. This may be an acceptable support to local network voltage or it may cause the operational or statutory voltage limits of the local distribution system to be exceeded.

The rise in voltage will mainly depend on the level of embedded generation compared with the demand, reduction of voltage drops in the network due to the lower current flows as a result of the export of power from the EG, and the import and export of reactive power by the EG.

Induction generators import reactive power whereas synchronous generators can operate in both modes either importing or exporting reactive power. Voltage at the POS will rise if the EG exports reactive power and will decrease if it imports reactive power.

The effectiveness of the generator operating in the “reactive power import” mode to mitigate voltage rise depends on the X/R ratio of the distribution system. For example, a cable feeder with a low X/R ratio would require a large proportion of imported reactive power to have a significant mitigating effect on the voltage rise at the POS.

The import of reactive power increases the current flow in the distribution network, leading to additional network losses and use of capacity.

The consumption of reactive power by a generator may reduce the capacity and efficiency of generating plant due to the resulting higher currents flowing in the generator stator windings.

The voltage rise at the POS may also be mitigated by a reduction in the upper limit of voltage at the grid substation. This can be achieved by reducing the bandwidth and/or the target voltage of the substation AVC. However, both options would require careful consideration: Reducing the AVC bandwidth would potentially increase the tap change operation frequency of the grid substation transformers, and would also potentially cause remote customers to experience voltage levels below statutory limits. DNO will give careful consideration to the optimisation of network voltage control, possibly using AVC with line drop compounding settings for voltage boost and power factor droop, to encourage the connection of embedded generation without compromising statutory obligations to existing customers.

C3.2 Step Voltage Changes

Discussed above is the steady state voltage rise in the network due to the introduction of the EG. However, the network can be subjected to step voltage changes when an induction generator is connected to the network. Energisation of an EG transformer from the network or sudden tripping of an EG could also give rise to the step voltage changes. Maximum step voltage changes are defined in the Engineering recommendations G75/1 and P 28¹ and these are $\pm 3\%$ for planned switching and $\leq 6\%$ for unplanned outages.

¹ <http://www.ena-eng.org/ENA-Docs/>

C3.3 Voltage Limits

Having determined an optimum target voltage and limits for voltage at the grid substation, these limits shall be declared and be available to all prospective Generating Companies. See Annex A1 of Part A on information to be provided by the DNO

Voltage at the Point of Common Coupling should be in accordance with the statutory limits.

Non-statutory limits may be agreed between DNO and the generating company if no other customers are affected. An example is, where the PCC is remote from the POS with a long line that only serves the generating site or with no direct connection of customers at the line voltage.

DNO reserves the right to review and revise any such non-statutory limits. The Generating Company shall bear the costs resulting from any such revisions.

C3.4 Power Factor Requirements

The PPA shall specify a power factor for the EG – this will be typically unity but may be lagging (exporting reactive power), depending on voltage regulation issues. It should be noted that this specified value will be subject to the tolerance of the generator power factor control unit.

Payments for reactive power may be considered in the future, and are not covered in these guidelines. This will require consideration of loss adjustments for reactive power export.

It may be desirable to operate generators in a voltage control mode to limit voltage rise on distribution circuits, with a likelihood of consequent reactive power imports. In this situation, the interaction of the generator voltage control systems will need to be considered when there is more than one generator connected to a distribution line.

Similarly, generator power output can be constrained to limit voltage rise under conditions of low feeder load. Again, the interaction of power or voltage constraint control systems where there is more than one generator needs careful consideration.

It should be noted that the main objective of encouraging embedded generation is to maximise the use of natural resources to produce electrical energy, which otherwise would have to be generated by burning fossil fuels. Exploitation of these resources would be maximised when EGs are operated as close as possible to unity power factor.

C4 REVERSE POWER FLOWS

When the power generated by EG exceed the demand of the of the distribution system, surplus power will flow to the higher voltage system from the lower voltage network. It could be through the distribution transformer or even through the grid substation transformer. This is just the opposite of what the power utilities are accustomed to and in fact such considerations may have not been foreseen by distribution system designers. Hence such operations would naturally give rise to various difficulties and problematic situations.

C4.1 On Load Tap Changer Operations

One of the problems distribution systems will encounter when EG generation exceeds the distribution system load is voltage regulation. Capacities of transformers with single-resistor on load tap changers may not permit the reverse power operation or will have to be operated at reduced capacities. However, most tap changers are of two-resistor type and these will not have problems under reverse power conditions.

C4.2 Line Drop Compensation

Another facility commonly used in the AVC is the line drop compensation. Under reverse power flow conditions, compensation reduces the secondary voltage of the transformer according to the line drop, instead of raising it.

C4.3 Fixed Tap Transformers

It is customary for utilities to set the taps of distribution transformers at optimum taps to ensure that electricity supply of all consumers are within the statutory limits, presuming that voltage at the substation (or grid substation) would be higher than that at the feeder end. However this voltage distribution could reverse with EG reverse power flows and hence the electricity supply provided to the consumers could be outside the statutory limits.

C4.4 Embedded Generator Operation

Under reverse power flow conditions, it may be necessary for the EGs to operate at power factors away from unity to meet the system reactive power requirements as the grid substation transformers maintain a constant voltage at the bus bars.

However, if external means are used to meet the reactive power requirements, this situation will not arise.

C4.5 Losses

When EG output is lower or equal to the distribution system loads, losses incurred in transmission and distribution system will decrease, as the active and reactive power requirements of the loads need not be transported through the transmission and distribution system all the way from distantly located large generators.

However, under reverse power flows depending on the extent of EG generation and its location, system losses could increase and will result in higher system operational costs.

C4.6 Protection

It is the standard practice to protect the GSS transformers with directional overcurrent relays and obviously the relay is set at a value lower than the transformer rated current. Hence, if the reverse power flows exceed the limit on the setting of the relay, then transformers will get disconnected from the system thus creating an unwarranted outage.

C5 EARTHING OF ELECTRICITY NETWORKS AND EMBEDDED GENERATORS

C5.1 General

Public electricity transmission and distribution networks are connected or referenced to earth as close to their energy source as possible. This is done by connecting the neutral point of the transformer or the generator winding to the ground directly or through an impedance. In addition, all non-current carrying metalwork of plant and equipment of the stations are also grounded. The main objectives of such grounding are to control the voltage of the systems and metal work within predictable limits and providing a pre-determined path for the flow of fault currents with which detection of undesired connections between system conductors and ground become possible. This facilitates operation of protective devices in the event of a single earth fault thereby preventing electric shock hazards and reducing the damage due to possible over voltages, mechanical stresses, etc

The Generating Company may use either separate earth electrodes for HV and LV systems or a single common electrode for both systems. The second method is cost effective, but then the design, installation and operation of the earthing systems shall ensure that there should be no undesirable rise in voltages of the low voltage system in the event of an earth fault or surge discharge in the high voltage network. Hence, earthing systems for substations and plant in electrical networks have to be designed giving due consideration to the type of network, its protection policies and system parameters such as earth fault current magnitudes, resulting voltages appearing in earth systems and speed of protection.

Note that the term HV is used for all voltages above 1000 V, to be consistent with the other sections of the guidelines.

C5.2 DNO Electricity Supply Networks

DNO electricity supply networks in Tanzania are connected to earth at a single point or at two or more points. Multiple network earthing may exist at a single substation location or at different points in the network to facilitate interconnections and operational changes.

The methods used to earth the electricity networks in Tanzania are as follows:

- Solid earthing of neutral points of all transformer windings connected to networks having an operating voltage of 66 kV or higher.
- Impedance or solid earthing of transformer secondary windings supplying networks having an operating voltage of 33 kV
- Impedance or solid earthing of transformer secondary windings providing customer 11 kV supplies or supplying the DNO network with an operating voltage of 11 kV.
- Solid earthing of transformer secondary windings providing customer low voltage supplies or supplying LV networks.

C5.3 Compatibility of Network and Generator Earthing

Arrangements should be agreed to earth the Embedded Generator's system in a manner compatible with the DNO supplies. To accept additional points of network earthing such as generator parallel earthing, DNO will consider the following technical issues:

- Controlling magnitude of earth fault current
- Maintaining a predetermined path for earth fault current
- Adequacy of the existing earth fault detection systems in the DNO networks
- Limiting circulating currents at fundamental and harmonic frequencies
- Avoiding interference to communication systems
- When appropriate, maintaining the effectiveness of network earthing

Any system earths provided by the EG should be closed only when DG fed systems operate isolated from the DNO network or only if studies carried out show that it is safe to operate in the parallel mode.

Furthermore, appropriate protection will be required at the EG to maintain safe conditions in the DNO network, should its normal earth point become isolated or disconnected.

C5.4 Generator Parallel Earthing

It is the normal practice to generate electricity at or around 11 kV or at lower voltages. When generation is at a lower voltage than the DNO network voltage, a step up transformer is used to connect the generator to the DNO network. If the generation voltage is the same as that of the DNO network, then direct connection could be allowed giving due consideration to earthing aspects.

11 kV Generators

Large generators, (larger than 1 MW) may be earthed when operating in parallel with 11 kV or 33 kV networks. This will normally require a neutral earthing impedance of value to be agreed. Typically, this may be of value adequate to limit the fault current to a maximum of 1 pu to ensure an adequate protection performance and minimise damage at fault conditions.

A major issue arises when an impedance-earthed EG is directly connected to a DNO network, which is designed as an effectively earthed system. If such a system is allowed to operate islanded, then under earth fault conditions, voltages may rise above the design levels. Subject to the criteria for parallel earthing being satisfied, impedance earthed 11 kV generators may be allowed to operate directly connected to the DNO network.

LV Generators

Where a generator is connected to the DNO supply networks and at risk of being islanded, the preferred method for safe operating conditions is for the generator to be earthed at the PCC to the DNO supplies.

Parallel earthing when operating in parallel with the DNO electricity supply network will generally provide safer generator connections. To allow this, DNO will consider the technical issues listed above.

The decision regarding earthing of small generators when operating in parallel with public electricity networks should take into account the overall cost of providing the earthing facility due to the large number of small generators which may be connected in parallel.

Use of a suitable transformer winding or the interlocking of switches and automatic earthing of the generator neutral (when the incoming mains are disconnected) may be required to avoid parallel generator earthing. Where a generator is required to operate independent of the DNO supplies, it must have an earth electrode system, which should be bonded to the DNO earthing system or terminal, wherever this is available and practical, provided the DNO's earth system will not transfer dangerous voltages to the generator earthing system. Alternatively where permitted, a generator may use a shared earth system.

The agreed method of earthing a generator should achieve minimum risk to generator plant, the supply network it is connected to and operating personnel.

The DNO may decide that a generator must not have parallel neutral point earthing when operating in parallel with the DNO supplies. In this case, appropriate protection must ensure that an islanded generator is automatically disconnected.

An islanded generator may continue to operate and supply Local Captive Loads and some Line Captive Loads, subject to the fulfilment of any one of the following conditions.

- The generator/network connection point may be appropriately parallel-earthed while the generator operates.
- The network at the PCC may be automatically earthed if islanded.
- Appropriate devices such as Neutral Voltage Displacement protection may be provided to ensure safe conditions, and disconnect the generator if an earth fault occurs in the DNO system or the generator system.

Where a generator is connected to the DNO LV supply network away from a substation, the preferred method to ensure safe operating conditions and remove risk of damage if neutral conductors become open circuit, is for the generator to operate without a parallel neutral earth connection.

Protective devices must disconnect an islanded generator under this condition.

Where the DNO gives a written approval for a parallel connection of earthing systems, the following conditions apply:

- Consumer's supply must be Protective Multiple Earthed
- Generator star point must be connected to the DG's earth electrode and to the DNO earthing terminal/neutral. If the DNO earth electrode is at the POS, then the EG need not provide an independent earth electrode subject to agreement with the DNO.
- Generating unit must not produce harmonic distortion greater than that allowed in G5/4-1

If the DNO supply is direct from a HV/LV substation situated in the EG's premises with the generating plant adjacent to the POS, the requirement for the EG to provide an earth electrode can be waived off and the neutral connected solidly to the DNO neutral earthing system.

The arrangement must ensure that the connection of the generator neutral point to the generator's earth system and the distribution network earth system/terminal is substantial, solid, direct and clearly identified.

Regular checks on the earthing system must be conducted by the Generating Company.

C5.5 Interconnection of DNO and Generator Earth Systems

Earthing an electricity supply network and a generator system requires the DNO and generator plant and electrical equipment to be connected to an earth system with appropriate earth electrodes.

Wherever networks operating with different voltages are in close proximity and resistance areas of their earth systems overlap, the overlapping earth systems should be interconnected and the resistance of the overall earth system should be reduced to a safe value considering the maximum prospective earth fault currents at the site.

HV metered supplies to generator premises require a combined HV earth system. The DG's HV earth terminal will include an earth connection to a DNO earth electrode system and possibly provide a metallic path to the point where the DNO HV network neutral point is earthed.

The generator will have to consider the possible effects of connecting the generator system HV and LV earth systems and ensure safe operating conditions.

LV supplies to generator premises from a dedicated, local DNO HV/LV transformer will normally have independent HV and LV earth systems. If combined, the rise of voltage and the transferred voltage to the LV neutral shall be within acceptable limits. If independently earthed, the DNO LV earth terminal should preferably be connected to the EG's earth system. This will minimise the risk of damage to plant in the EG's system.

The insulation of the supply transformer LV winding and terminals must be adequate to prevent danger from the rise of voltage on the HV earth system for an earth fault in the supplying substation.

The separation of the DNO HV and LV earth system and the generator earth system must be adequate to ensure that any overlap of the resistance areas of the two earth systems does not cause danger.

Where the DNO LV earth terminal/system may not be made available to the generator (TT system) a metallic path to the DNO LV network neutral from the EG's earth system will not be available.

In such a case, DNO and EG's earth systems should have an appropriate earth loop resistance to ensure operation of over-current protective devices such as fuses and MCCBs.

If the earth fault loop resistance is high, then earth leakage relays should be installed by the EG. For discrimination between earth leakage relays, time delayed earth leakage relays should be installed along with instantaneous relays.

The design of all earth systems must ensure that all touch and step voltages are within acceptable limits. Transferred voltages to EG's plant must not create unacceptable touch and step voltages. Precautions must be taken to prevent damage and remove danger arising from transferred voltages to and from external metallic services and metallic paths.

For descriptions, drawings and limitations of various low voltage earthing systems, refer the latest revision of BS 7671 or its equivalent, and Electricity Supply Regulation 1988 (as amended) or its equivalent. Low voltage earthing systems should satisfy the above standards and regulations.

C5.6 Design of Earth Systems

Connection to the general mass of earth must be made using an earth system and ground electrodes of adequate thermal and current carrying capacity, and dimensioned to provide and maintain reasonably constant earth loop impedance, appropriate to the sensitivity of the installed protection devices. Connection of all plant to the earth system should ensure appropriate bonding and should also maintain touch and step voltages between and around the earthed plant, inside and outside of buildings, within acceptable limits.

A DNO's HV earth facility may not be effectively connected to local ground and may be subject to significant voltage rise above the potential of the general mass of earth. This may occur when earth fault current flows for a local earth fault or a fault elsewhere in the supply network.

Wherever an earth terminal is available from the DNO, this should be connected to the generator earth system to ensure the lowest possible impedance return path for earth fault currents to the point the supply network is earthed.

This will minimise voltage rise, reduce stress on insulation and normally will be adequate to operate the EG's protective devices.

Control of resulting transferred voltages to generator premises will be achieved by the design of the EG earthing system and bonding of exposed metalwork on plant and equipment.

In certain cases, DNO may require the location to be classified appropriately for insertion of barrier facilities and safe isolation facilities in external metallic services, such as telecommunications with metallic wires.

Safety requires compliance with earthing standards, and prompt detection and isolation of earth fault currents. The design of an earth system must ensure that touch and step voltages do not exceed voltage limits in the relevant DNO's documents or standards appropriate to the disconnection times.

C5.7 Generator Circulating Currents in Earth Connections

Where two or more generators operate in parallel with their star points/neutrals connected to a common neutral conductor or an earthing busbar, harmonic currents may circulate between machines. For harmonic currents to circulate, differences in harmonic voltages must exist between the machines and this may influence their possible operation with parallel neutral and earth connections.

The voltage waveform produced by the synchronous generator is primarily determined by the flux density distribution round the air-gap. In a salient pole synchronous machine, pole faces may be chamfered to reduce harmonic content of the voltage waveform. Also, in a cylindrical rotor machine, the way the rotor winding is distributed can achieve similar improvements. A perfectly sinusoidal voltage is rarely obtained and some harmonic voltages will invariably be present in the generator output voltage. Typically low order harmonics such as 3rd and 5th are dominant.

Typical effects of harmonic current flowing in earth connections are telephone interference, heating of a neutral earthing resistor and the requirement to derate a generator.

Harmonic currents must also be considered in determining the sensitivity for earth fault protection or alarm devices. Earth fault protection is usually provided by a CT and relay in the generator neutral/earth connection. This will respond to system earth faults in addition to those on the generator winding. If this is too sensitive it may be subject to operation due to out of balance and harmonic currents in the generator neutral

Parallel earthing of a generator and the utility network neutral earth system will form an external zero sequence loop. Triple harmonic voltages (3rd and multiples) because of their relative and additive phase displacements may produce significant circulating currents between the generator neutral and the external earth connections.

Other harmonics such as the fifth and seventh harmonics form a balanced set of voltages and minimal circulating current.

C6 SYNCHRONISATION OF GENERATORS

C6.1 General

Synchronisation means the minimisation of the difference in magnitude, frequency and phase angle between the corresponding phases of the generator output and the grid supply prior to the connection of the two supplies.

Synchronisation can be achieved either manually or automatically, the latter being preferable. It is very unlikely that new installations will include only manual synchronisation. If manual synchronisation is suggested for a particular reason, its safe and reliable operation should be seriously considered and implemented carefully.

C6.2 Voltage Fluctuation

During synchronisation of a single generator, the induced voltage fluctuation on the grid should not normally exceed 3% at the PCC, and should also meet the requirements of voltage step and flicker.

C6.3 Synchronous Generators

Before a synchronous generator can be connected to the grid, the generator must be run up unconnected and its speed adjusted to synchronise the generator output with the grid supply.

The voltage difference between the generator output and the grid supply should also be minimised. It is usual for the unconnected generator voltage to be set a few volts above the typical grid voltage.

Automatic synchronisation is usually achieved using a control system that incorporates control of the generating unit field and a governor or an electronic load control system.

C6.4 Asynchronous Generators

Asynchronous generators normally require special measures to minimise the inrush current taken by the generator from the grid at the time of connection in order to meet the voltage fluctuation requirements of Section B3 in Part B of these guidelines.

Suitable equipment and procedures may include:

- Electronic soft-start equipment
- Resistance starter
- Mechanically driving the generator up to near synchronous speed prior to connection.

C6.5 Other Types of Generators

Other types of generators, which will include static inverters will need to have their output synchronised with the grid before or during grid connection. The transient characteristics of the connection shall be submitted to DNO.

C6.6 Synchronising Check Relay

A synchronising check relay must be used to inhibit the operation of a synchronous generator connection breaker or contactor when the two supplies are outside pre-set limits. (induction generators do not require synchronisation check relays.) This can be achieved using an electrical interlock.

Typical relay settings will be:

- $\pm 20^\circ$ of phase angle
- maximum difference in voltage of supplies of 7% of the same nominal voltage
- maximum slip frequency 0.11%

A time delay, typically 2 seconds, on the operation of the relay is commonly used to ensure that the slip frequency is within limits.

Synchronising check relays may operate on a single or all three phases of the supplies. A single phase relay will not be able to check for phase rotation of the two supplies. If a single phase relay is used, then the phase rotation of the two supplies must be checked prior to first connection and following any maintenance operations that involved disconnection of any power cabling in the system.

C7 ISLANDED OPERATION

C7.1 General

In the context of embedded generation, an islanded network will typically comprise:

- i) A single feeder or feeder section following a trip of the source circuit breaker or auto recloser.
- ii) A primary network or bus-section following a trip of the incoming circuit breaker(s).

It has been established that unplanned islanding is not acceptable, and hence protection is required to detect the condition and trip the generation within an acceptable time-frame.

In general, in an islanded group, there will not be a stable balance between load and generation resource. However, it is possible, in a few situations, that the generator, prime mover controls and other rotating machinery in the system can establish a new equilibrium between generator(s) and load in an islanded group.

The sequence of conditions prior to and during islanding are:

Pre-islanded condition

The active and reactive power outputs of the generator are exported to the grid. The grid voltage and frequency are controlled by the grid and therefore stable conditions of voltage and frequency are achieved.

Initiating cause of islanding

There are many possible causes of islanding but they fall into two categories: fault or operational.

At the instant of islanding

At the instant that islanding occurs, there is an instantaneous change in the power flows of the islanding circuit and outputs of generators connected.

Island operation

For steady-state conditions to continue, the islanded electrical generation must equal the electrical load. Since the probability of pre-islanded generation and load being equal is extremely unlikely, the power imbalance must cause an acceleration or deceleration of the rotating plant in the islanded network and a resulting drift in frequency which will be detected by OF/UF or ROCOF or vector shift relays, disconnecting the islanded generator.

C7.2 Hazards of Islanding

The potential hazards presented by operating a generator in an islanded situation are:

- Unearthed operation of the distribution system
- Lower fault levels
- Out of synchronisation reclosure
- Voltage levels
- Quality of supply
- Risk to maintenance personnel

C7.2.1 Unearthed Operation of the Distribution System

It is usual for distribution lines to be earthed at the grid substation only, with an HV delta unearthed arrangement at the EG connection. This will always be the case where multiple earthing is not allowed, as is the case in Tanzania at the time of writing.

When part of a distribution network is disconnected from the grid substation earth point, the unearthed system will be energised by embedded generators unless the generators are disconnected by islanding protection. The line to earth voltages of the three phases may then drift, or in the case of a line to earth fault, will be forced to shift. One phase will be referenced to earth causing the other phases to have a phase to earth voltage equal to

the nominal phase to phase voltage. In this case, the normal design voltage limits for insulation and other equipment may be exceeded. This situation can be detected using a Neutral Voltage Displacement relay.

C7.2.2 Lower Fault Levels

If the islanding takes place due to the distribution feeder tripping on a phase fault, then the islanded system is very likely to have low fault levels, possibly even lower than the minimum fault level of the grid substation during normal operation.

Under these conditions, EG relays might not be able to clear the faults and will result in sustained arcing causing damage to equipment and exposing the public to danger.

C7.2.3 Out of Synchronisation Reclosure

In the period following the initiation of islanding, a phase difference could develop between the grid and islanded side of the isolating circuit breaker or recloser, and then the grid and islanded network are said to be 'out of synchronism'. If the circuit breaker or recloser recloses before the EG is disconnected and the difference in voltage vectors of the two systems are far apart, then large currents will flow between the grid and the EG subjecting the EG and its prime mover to severe mechanical shocks. It may even cause damage to other equipment connected to the system

With the use of dead line check, synch check or voltage check relays for the grid substation breakers, it is possible to block reclosing into live islands. In most applications, the dead line check or voltage check relays may be adequate, since the probability of prolonged islanded operation is extremely small. When automatic reclosing is used, then the dead time should be suitably adjusted to coordinate with the anti-islanding protection of EGs.

Pole mounted reclosers should be equipped with a voltage check on the load side to prevent reclosing onto a line energised from an islanded EG, if and when its anti islanding protection has failed/delayed to operate.

C7.2.4 Voltage Levels

The operation of a generator supplying a distribution feeder in an islanded situation may cause the system voltage levels to be outside normal operating or statutory limits.

The voltage will be determined by the output of the embedded generators, which are primarily designed for connection to the grid and may be operating in power factor control mode with little control of output voltage.

These could cause insulation failure in electrical equipment causing flashovers and damages to rotating equipment.

The generator voltage protection limits of nominal $\pm 10\%$ may not protect consumers from voltage excursions substantially outside statutory limits but will limit the duration for compliance with BS EN 50160.

C7.2.5 Quality of Supply

The islanded network will have a significantly lower fault level. This is likely to increase the harmonic levels and voltage fluctuations. Frequency deviations are possible and would cause damage to motors and also would lead to equipment mal-operation.

C7.2.6 Risk to Maintenance Personnel

The connection of a generator to a distribution line that has been disconnected from the grid for the purposes of maintenance or repair may cause harm to personnel if the line that is expected to be dead remains energised.

All lines must be considered as possibly energised from remote sources and a distribution line that has been disconnected for maintenance or repair should be undertaken as detailed in the DNO's safety and operations manuals.

C7.2.7 Embedded Generator Tripping due to Abnormal Conditions in the Network

C7.3 Extraneous Faults

Certain faults occurring elsewhere in the power system could cause tripping of embedded generators. For example, a transient fault on a transmission line such as a lightning stroke could cause a depression in voltage of an extensive area and this could initiate tripping of embedded generators.

C7.4 Under Frequency Load Shedding Relays

Distribution feeders to which EGs are connected will trip on the activation of under frequency load shedding relays due to generation shortfalls.

Hence under frequency load shedding relays on feeders with an average net export capability shall be rendered inoperative. The cumulative generation capability of a feeder shall be updated and compared with metered loads.

Excessive and unwanted tripping will affect the life time of the switchgear and also will cause financial losses to the EG, though the effect to the DNO is insignificant.

C7.5 Distribution Feeder Faults

EGs could trip on downstream feeder faults feeding through a recloser or even for faults on other distribution feeder faults fed from the same grid substation if EG relays are not properly graded.

It is advised that EG should ensure that all its protection relays are coordinated properly with DNO's protection relays.

C7.6 Restoration

In the event of an EG getting disconnected from the DNO system due to a DNO supply failure, EG shall ensure that reconnection of its generators are possible only after a minimum time delay of 1 minute after the restoration of the electricity supply by the DNO. .

C8 PROTECTION METHODS AND RELAY SETTINGS

C8.1 General

The generating company is required to design its protection system to reliably detect faults or abnormal conditions and provide an appropriate means of automatically isolating the faulty equipment or systems selectively, and as fast as possible.

Following are the possible abnormal condition that could arise:

- (a) Over current
- (b) Earth fault
- (c) Under frequency
- (d) Over frequency
- (e) Under voltage
- (f) Over voltage
- (g) Loss of mains
- (h) Neutral voltage displacement
- (i) Reverse power

C8.1.1 Over current and earth fault

Over current, preferably voltage controlled or voltage restrained over-current and earth fault protection, must be installed on the generator to detect the faults within the generator and the network, and should be coordinated properly.

C8.1.2 Over and Under Frequency

The frequency of the system is monitored and any excursions outside preset limits will cause the relay to operate. Settings will be dependent on the generator characteristics, network connection arrangement and operating requirements. Protection settings need to be coordinated with the load shedding schemes of the DNO's system.

C8.1.3 Under and Over Voltage

Under and over voltage protection should be provided for the installation to monitor the voltages of all three phases.

Settings will be dependent on the generator characteristics, network connection arrangement and operating requirements. Protection settings can be determined at the design stage in consultation with the DNO.

C8.1.4 Loss of Mains

The purpose of loss of mains protection is to detect an islanded situation and disconnect the EG from the network. When islanding takes place the disturbance in the distribution system may take the form of,

- a change in voltage or frequency or
- a single shift in the voltage vector or
- a change in reactive power flow.

The stand-alone detection of an islanded situation is based upon the detection of this electrical disturbance.

The magnitude and type of disturbance will depend on the type and capacity of the generating plant, the distribution line and transformer characteristics, and the nature of the connected loads.

If at the time of disconnection,

- the remaining connected load and generated power are in balance **and**
- the feeder reactive power demand and generated reactive power are in balance **and**
- the feeder line to earth capacitance are equal for all phases,

then there will be no disturbance on the line. System fault level will be the only system characteristic that will change, but it cannot be monitored or measured to detect an islanded situation. This balanced embedded generation and load situation is extremely unlikely to occur.

Hence, in the unlikely event of loads closely matching the EG loads at the time of distribution circuit breaker gets opened from the GS, this condition will not surface and the relays will fail to detect the islanded situation. This cannot be avoided.

C8.2 Rate of Change of Frequency (ROCOF) and Vector Shift

The most common and widely used methods used to detect loss of mains are Rate of Change of Frequency (ROCOF) and Vector shift, and it is now common to use a relay based on both these principles. The settings of relays should be decided in consultation with the DNO.

Rate of Change of Frequency (ROCOF)

Rate of Change of Frequency relays are widely used for islanding detection and its design is either based on zero crossing counting or Discrete Fourier transform technique.

The relay based on zero crossing counting method will detect zero crossings of the generator voltage, measure the time between the zero crossings and calculates a new frequency after each zero crossing. In case the frequency changes exceeds the pre-determined setting levels since the last zero crossing, the relay will recognize it as a ROCOF condition. As is well known, the accuracy of the zero-crossing method is influenced by harmonics, dc offset and noise.

The other relay uses Discrete Fourier Transform (DFT) to convert sampled data from current and voltage phasors into a representation of the fundamental frequency phasor. Depending on the sampling frequency and anti-aliasing filters, unwanted frequencies could be eliminated and hence accurate frequency estimation could be done.

Relays based on DFT are not affected by harmonics, noise or dc offset and are superior to the other, but research is continuing to improve the performance of the relays using the zero counting technique.

Typically, a 10% load imbalance will lead to a ROCOF of 2 Hz/s although this is dependent on the type and inertia of the machines connected to the islanded network.

ROCOF could be successfully used in islanding detection if the frequency changes in the DNO's grid are not very sensitive to the load imbalances as the frequency changes become indistinguishable from a grid disturbance from an islanding situation.

The Generating Company should carefully analyze the stability studies carried out by the DNO to ascertain whether ROCOF could be used in islanding detection.

Advantages:

Cheap and quite fast acting for large imbalance.

Disadvantages:

Unable to distinguish national grid and local islanding events. An acceptable setting to avoid a detrimental effect on the grid leads to less sensitive islanding protection.

Vector Shift Relay

Vector shift relays were initially used to disconnect generators during local disturbances and have successfully been used to detect islanding disturbances. They operate by measuring half cycle voltage periods (time between zero crossings) and detecting a step change exceeding an equivalent vector shift setting (typically between 6° and 12° in a half cycle). It detects a voltage vector shift arising when there is a step change in the current through the generator internal impedance. Such a condition will be caused by a fault or the onset of islanding. If there is no preceding fault then the sensitivity to islanding is low (6° is equivalent to about 1.67 Hz/s or about 10-20% load imbalance).

The magnitude of vector shift progressively diminishes from the point of circuit fault towards the primary bus bars and through the infeeding transformer/s. Transformer impedance is significant and the vector shift imposed at the bus bar is transferred to all the un-faulted feeders on the local network. For this reason, there will inevitably be line faults that can cause all vector shift relays on the local distribution network to operate simultaneously. It is for this reason that the total capacity of generation with vector shift protection must be limited as defined in the guidelines.

Key features:

Voltage Vector Shift is inherently susceptible to spurious tripping during faults because it detects voltage angle disturbance rather than the characteristic of the islanded condition.

All relays connected to a medium voltage network, sourced from a primary bus will probably be activated by a single fault close to the bus.

If the islanded condition is not preceded by a fault (i.e. by underfrequency or manual tripping of feeder breaker), then the relay is unlikely to operate where load and generation are closely matched and voltages are substantially normal.

The ability to discriminate between islanding and other faults is improved when faults occur at electrically distant points.

Three-phase detection, requiring vector shift on any phase, increases dependability of islanding protection, but may also increase the number of spurious trips.

Three-phase detection, requiring simultaneous vector shift of the same direction on all phases, would reduce the number of spurious trips but may also reduce the dependability of islanding protection since most onset fault conditions are excluded.

Advantages:

Cheap and fast acting.

Disadvantages:

Inherently liable to tripping for local distribution faults and possibly nearby 132 kV faults. Insensitive to the onset of islanding.

C8.3 Intertripping

The most reliable method of preventing an islanded situation is by inter-tripping the generator breaker with the opening of the DNO's circuit breaker at the grid substation or the recloser.

C8.3.1 Operation

Intertripping is a direct means of islanding protection. It operates by sending a trip signal from the circuit breaker or recloser responsible for the islanding to all the generators which use this method as the loss of mains protection. It should be noted that there may be more than one trip source because there may be more than one level of islanding possible.

Intertripping must be initiated from all points on a circuit, downstream of which the minimum load may not overload a generator or operate its loss of mains protection.

Intertripping may be used to disconnect a single generator and ensure multiple smaller generators are mismatched by trapped load.

The reliability of intertripping is dependent on the security of the transmission method. Dedicated pilot wires, public telephone or satellite communications are possible but the reliability should be assessed on an individual basis.

This will typically be an expensive method of protection and will usually be considered for larger generators close to the primary substation.

C8.3.2 Application

An inter trip may be implemented using a secure communication channel between the sub station and the generator. A secure communication channel will consist of a fixed wire or a fibre optic link. Radio or cellular phone communications are not presently considered to be reliable for inter trip purposes. It should be implemented in a fail safe manner, such that if there is a failure in the communication channel, the generator will disconnect from the grid.

An intertripping system is typically unqualified and trips the generator upon opening of the source circuit breaker without further checks. It is made more complex where there is more than one breaker that can initiate islanding. For example, a generator remote from the primary may be islanded by a field auto recloser, the feeder breaker and/or the primary substation breakers. The risk of islanding at each level would need to be assessed before establishing the scope of the intertripping scheme.

Key features:

The principle cost is for a reliable means of communication for the trip signal from the initiating breaker(s) to the generation site. The options are: buried or overhead (underslung or wrapped) pilot cable or wires (fibre optic or metallic conductor), power line carrier signals, rented channels via public telecom or, radio signals. Each method should be assessed for dependability of operation and susceptibility to spurious trips. A less dependable method may be acceptable when used in conjunction with another loss of mains device.

Advantages:

Generally dependable.
Generally immune to spurious tripping.
Fast operation.

Disadvantages:

High cost of installation of private communications.
Metallic paths may transfer high damaging or touch voltages between locations.

C8.4 Fault Thrower

This is a special application of a fault thrower. It is a form of intertripping using the phase conductors as the medium for communication. The fault thrower would be installed at the source substation and would be operated following opening of the circuit breaker. The device would either put a short circuit on the islanded feeder creating detectable over current or undervoltage and causing operation of generator protection or it could put an earth fault on one phase, causing the operation of the NVD protection.

Key features:

Operation would be delayed to allow generator relays to operate if sufficient load imbalance exists. It would only be effective for generators connected between source breaker and first auto recloser. Beyond the recloser, other means such as vector shift would be more appropriate.

Advantages:

With moderate prospective fault currents, it is simple, dependable, reliable and much cheaper than intertripping.

Disadvantages:

More expensive than vector shift and RoCoF.

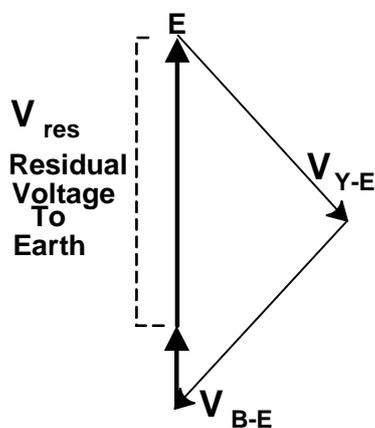
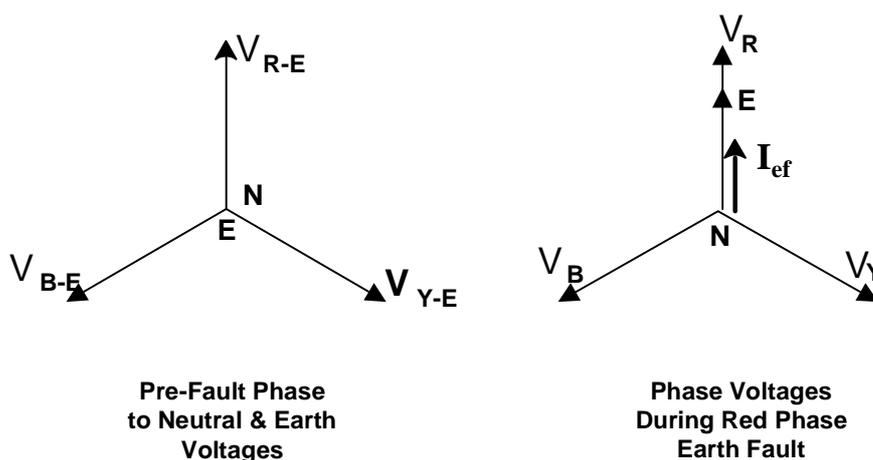
Introduces operational risks when closing split points.

C8.5 Neutral Voltage Displacement (NVD) Protection

C8.5.1 General

An NVD scheme measures the displacement of the neutral on the HV side of the generator transformer and operates with delay when the displacement exceeds the trip setting. This device does not detect islanding because an islanding condition can exist without neutral displacement. Its purpose is to detect an earth fault causing an unsafe islanding condition. Under balanced conditions, the neutral of a 3 phase electrical system is held at the earth potential. This is held by the balanced phase to earth capacitance of the three phase system and the method of earthing of the neutral.

Figure C 1- Network Voltages During an Earth Fault

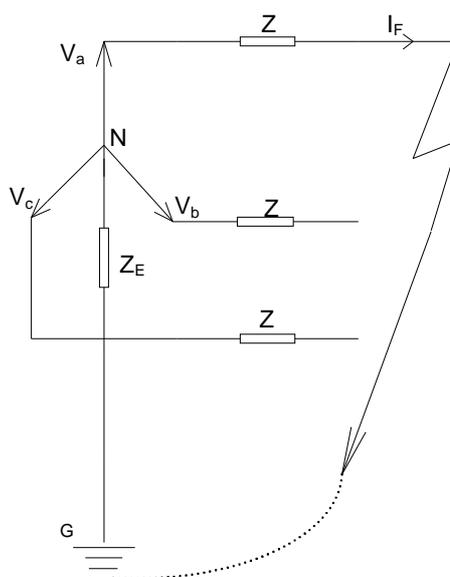


NOTE
 Vectors shown are for an earth fault assuming a system with a solid arthed neutral and significant earth electrode resistance or assuming an earth fault in system with a resistance in the neutral to earth connection and a smaller resistive earth impedance. This is a typical condition.

Under earth fault conditions in an unearthed or ineffective earthed network, voltage difference is produced between the system neutral and earth. This displacement of the neutral voltage from the earth voltage is called Neutral Voltage Displacement (NVD).

C8.5.2 Derivation of NVD

Consider the general case shown below:



$$V_{NG} = -I_F Z_E = -V_{aN} \times \frac{Z_E}{Z_E + Z}$$

$$V_{aG} = V_{aN} + V_{NG}$$

$$V_{bG} = V_{bN} + V_{NG}$$

$$V_{cG} = V_{cN} + V_{NG}$$

$$\therefore V_{aG} + V_{bG} + V_{cG} = 3 V_{NG} \quad \text{as} \quad V_{aN} + V_{bN} + V_{cN} = 0$$

$$V_{NG} = \frac{V_{aG} + V_{bG} + V_{cG}}{3} = \frac{3V_0}{3} = V_0$$

V_0 = Zero sequence voltage

$V_{aG} + V_{bG} + V_{cG} =$ Sum of the phase to ground voltages and is called the residual voltage

$$V_{RES} = 3V_0 = 3V_{NG} = 3 \times \text{Neutral Voltage Displacement}$$

C8.6 Measurement of NVD

NVD is implemented by using three voltage transformers (VTs) on the HV side of the connection transformer. The VTs are connected phase to ground.

Figure C2 illustrates the connection and operation of NVD protection.

The VTs' secondary windings are connected in "broken delta" or "open delta" with an over voltage detection relay connected across the open corner of the delta. This detection relay will then measure the sum of the phase to earth voltages. The VTs must be capable of measuring voltages up to 1.9 pu without the output collapsing.

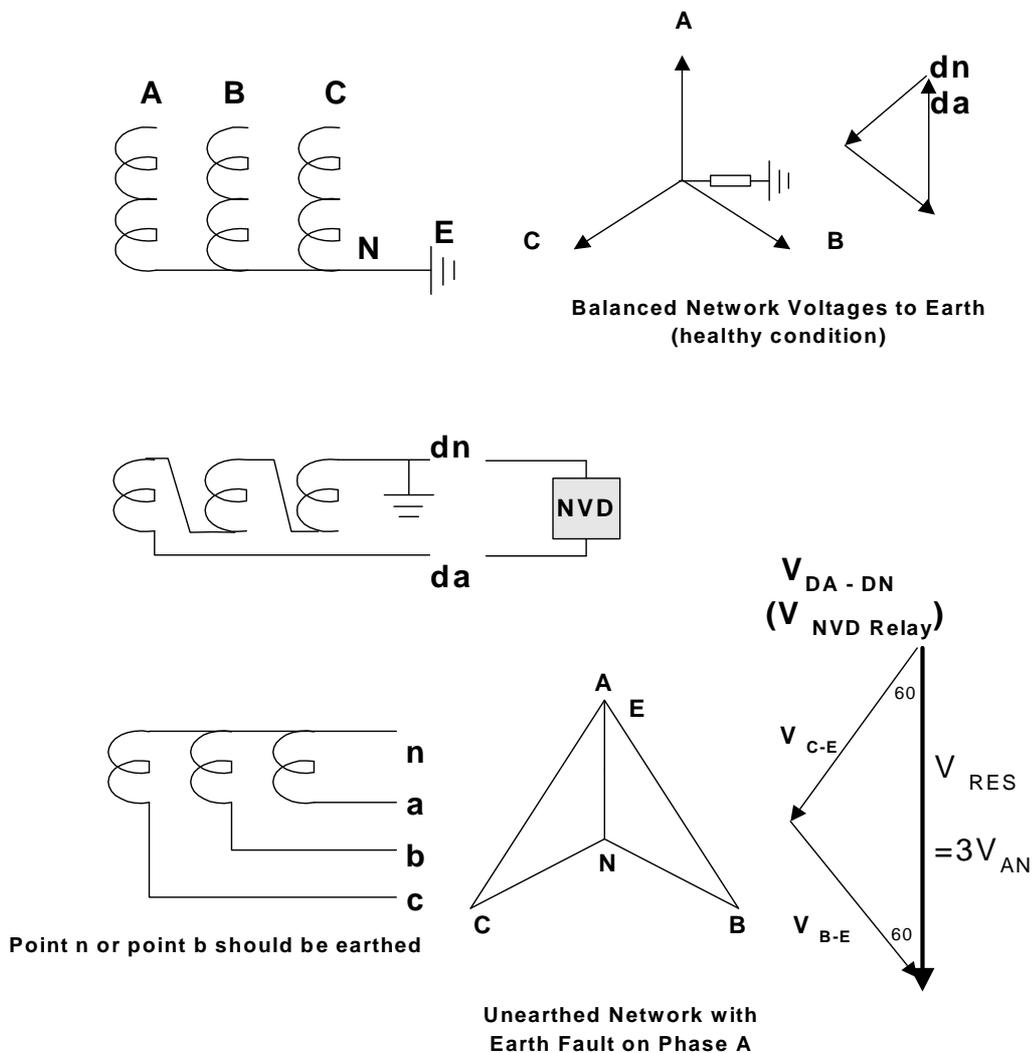
The NVD could be measured by means of a 3-phase VT with five limbs. The two extra limbs are required to provide return paths for the zero sequence fluxes of the three phases. The primary of the VT is connected in star with the neutral solidly earthed. The secondary windings are connected in series with the two outer terminals brought together, but kept open (open delta). The residual voltage appears across the open delta terminals.

If three single phase VTs are used, then extra limbs are not required as each VT has a closed path for all its sequence magnetic fluxes. The NVD could also be obtained by measuring the voltage difference between neutral point of a power transformer winding and earth by means of a single phase VT.

Figure C 2- Neutral Voltage Displacement Protection using a Three-phase 5 Limb Voltage Transformer with an Open Delta Winding

NOTE

Vectors are shown for an earth fault in a system with an impedance in the neutral to earth connection that is large compared to the source impedance. This is a typical condition.



C8.7 Effects of the Method of Neutral Earthing on NVD

It can be shown by the method of symmetrical components that V_{RES} during an earth fault mainly depends on the ratio of $\frac{Z_0}{Z_1}$ (K_0) where Z_0 is the zero sequence impedance in the fault path and Z_1 is the positive sequence impedance. For high impedance earthed or isolated neutrals, K_0 is very high and V_{RES} will approach 3 times the phase to neutral

voltage. For solidly earthed systems, K_0 could be small resulting in an insufficient displacement of the neutral voltage.

Under normal operating conditions, the sum of the phase to neutral voltages will be near zero. When there is a ground fault on one of the HV lines, there will be a substantial voltage across the detection relay.

The detection relay will then be used to trip either an HV or LV breaker to disconnect the generator from the line.

Key features:

Requires a 5 limb or 3 single phase transformers with open delta connected secondary winding and an earth electrode. HV metering voltage transformers may be utilised to reduce the incremental cost. The voltage transformers must then meet the requirements of metering as well as NVD.

The time delay should be coordinated with the source earth fault protection.

Special consideration is required where arc suppression coils are used.

Advantages:

NVD is a dependable means of satisfying safety requirements and mitigating the risk of islanding when generators operate without parallel earthing.

Disadvantages:

NVD does not replace loss of mains and therefore it is an additional cost. It is very expensive if no suitable HV metering voltage transformer is available (i.e. when the point of supply is at LV and HV protection is pole mounted fuses).

The NVD protection should grade with the earth fault protection at the grid or primary substation, so that feeder earth faults are cleared at the DNO's substation before NVD protection in other feeders operate.

C8.7.1 Reverse Power

When a grid connected synchronous generator loses its driving force from the prime mover, it will continue to run as a synchronous motor drawing power from the grid. This is an undesirable condition and should be prevented. A true wattmetric relay should be used to detect this condition and the settings should be decided according to manufacturer's recommendations.

Typical settings

3-25% of rated power

C8.7.2 Protection Relays, Current and Voltage Transformers

Protection relays shall be of suitable quality to provide reliable and consistent operation. The performance levels of the relays shall be declared by the manufacturer.

It is preferable to use proven protection equipment supplied by a reputable manufacturer with a track record in this type of application. The performance of all protection relays shall be within the scope of the relevant IEC standards. Particular consideration should be made of the requirements for current transformers to sustain operation when fault currents occur. Current and voltage transformers should be appropriately selected and comply with the appropriate IEC standards.

Secondary injection test points should be provided where practical to facilitate commissioning and later testing of relay settings and operation.

C9 SURGE PROTECTION

C9.1 General

Equipment associated with an embedded generator requires to be protected from hazardous effects of transient over-voltages.

Occurrence of transient over voltages can be due to external as well as internal causes. Lightning is the most common source for transient over-voltages. However, damaging transients could originate from within the grid system itself, due to switching operations, ferro resonance, etc.

Adequate measures should be taken to protect the insulation and equipment from being damaged due to the above conditions.

An LV/HV transformer usually connects the embedded generator to the grid system of the DNO. It is essential that the HV side of the transformer be protected from transient over voltages by installing gapless metal oxide surge arresters with polymer housings.

The connections to earth electrodes and the design of the earth system should be appropriate for the surge protection function.

C9.2 Location of the Arrester

Location of the arrester is a critical factor. In order to maximise the arrester effectiveness, all lead lengths should be made as short as possible.

Arresters require connection to the system phase conductor and earth. Inherent inductance in the leads produces a voltage build up during impulse discharges. It is usual to assume a value of 1.3 to 1.5 kV/m for the lead voltage build up.

During surge conditions, the net residual voltage that will appear across the transformer will be equal to the sum of the arrester residual voltage and the voltage drops across the leads. The ability of the surge arrester to protect the transformer can be assessed by comparing the net residual voltage with the withstand voltage of the equipment.

C9.3 Earthing

The current practice in Tanzania is to provide a separate earth for the transformer LV neutral and to link the lightning arrester earth with the transformer tank earth. When this method is adopted, under surge conditions, a potential stress could develop across the two windings. Also due to capacitive effects, transient voltages can be transferred to the LV side. Hence providing arresters on the LV side will ensure better protection for the equipment.

However, in multiple earth systems, it is advantageous to interconnect the arrester ground terminal and transformer tank earth with the secondary neutral earth. With this connection, possibility of a voltage stress developing between the two windings is minimised.

It is recommended that the embedded generator shall follow the standard practice adopted by the DNO.

C9.4 Selection of the Lightning Arrester

Higher rated voltages or higher maximum continuous operating voltages and the best surge protection of the equipment are contradictory requirements. Many other system and equipment parameters have to be considered and an optimisation process has to be followed to select the basic characteristics of the arrester which will provide the best protection to the equipment to be protected. It is recommended that the procedure given in IEC 99-5 should be followed for the selection of the arresters.

Due consideration should also be given to the following aspects when selecting the arrester.

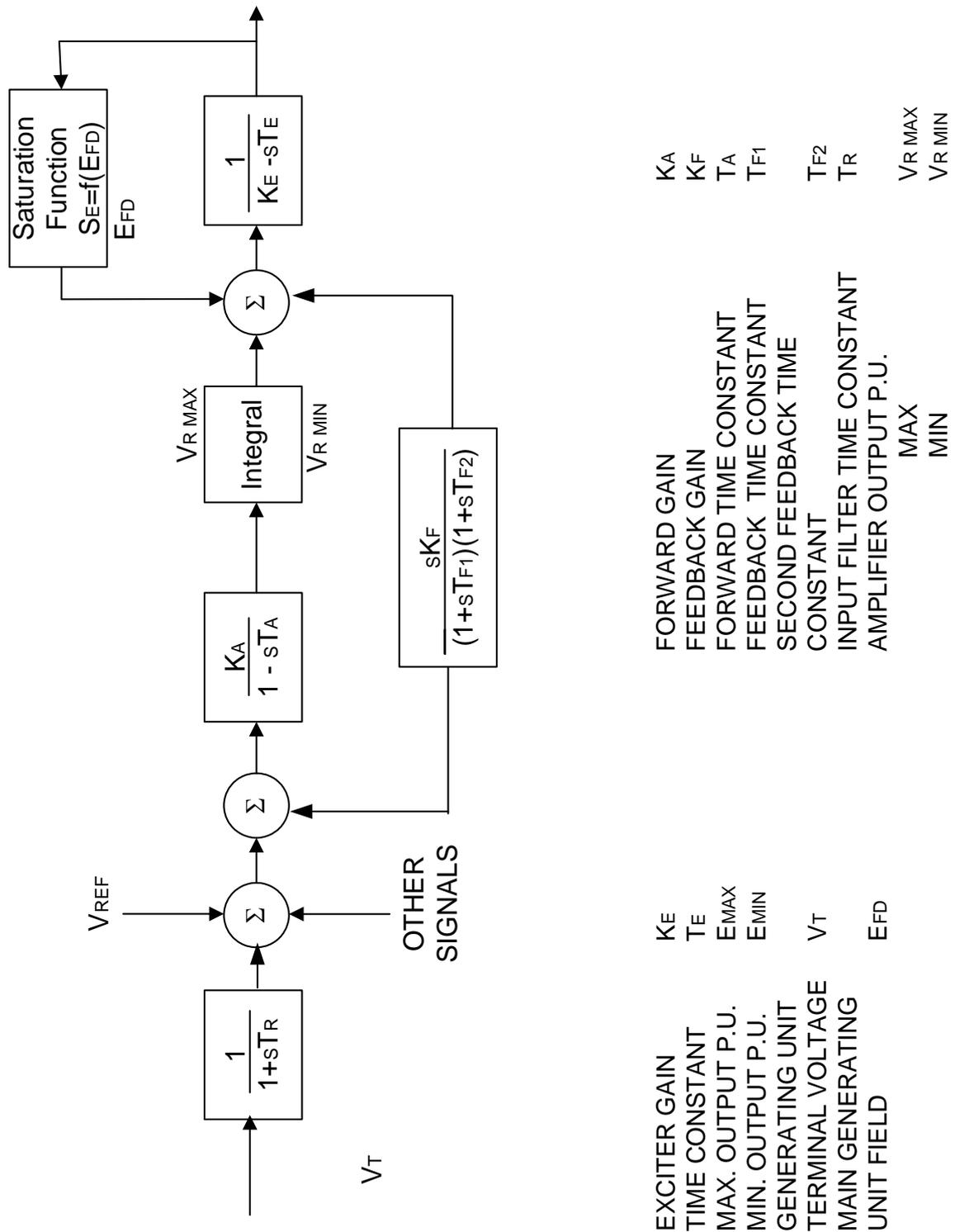
- Service life
- Environmental aspects
- Polymer characteristics
- Energy handling capacity

Arresters chosen shall comply with the standards adopted by the DNO.

C9.5 Generators Directly Connected to LV Overhead Lines

Small generators directly connected to the distribution LV overhead lines could also be subjected to transient overvoltages. It is recommended that surge arresters chosen according to the guidelines laid down in IEC 99-5. Protection performance could be improved by installing a second set of arresters on the overhead line.

Figure C 3- Typical AVR Modelling Information



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