MICROELETTRICA SCIENTIFICA
M.S. RESISTANCES

GROUNDING SYSTEMS

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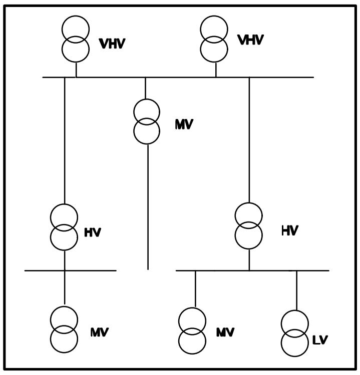
INTRODUCTION

NETWORKS

In the most industrial countries, the power generation stations are located far from cities and centres of consumption.
The generated energy must be transported from the power generation centre and distributed to the end users (industrial or public).

There are 4 types of networks

- Very High Voltage: VHV
- High Voltage: HV
- Medium Voltage: MV
- Low Voltage: LV



The networks are designed, properly operated, maintained and kept in repair to prevent and avoid failures due to:

- atmospheric: surge, storms
- mechanical
- insulation defect.

In three-phase networks, a distinction is made between the following kinds of faults .

Type of fault		Initial Symmetrical Short-Circuit Current
1	Three phase fault	I"k3p
2	Phase to Phase fault clear of earth	I"k2P
3	Two phase to earth fault	I"k2PE
4	Phase to earth fault	I"k1P

A 3-phase fault affects the three-phase network symmetrically, all three conductors are equally involved and carry the same rms short-circuit current .The faults must be detected, identified and eliminated
Short circuits are always caused by insulation defect and induce a short-circuit current, there are several types of short circuits:

Type	Cause
Permanent Short Circuit	Solid Insulation (Broken Ceramic, Glass Insulation)
Fugitive Short Circuit	Gas Insulation
Intermittent Short Circuit	Caused By Storm & Lines Undulation or Vibration

Short circuits have a disastrous effect on: networks, equipments, supplies, telecommunications networks & security.
They must be detected, eliminated or reduced:

- by an adequate protection material and components
- by an adequate earthing method.

✓ *Networks*
Near the power generation center, short circuits are able to reduce the resistant torque of generator and upsetting the balance.

✓ *Equipment*
The over current induced by short circuits can rise up to 20 to 30 times the value of nominal currents. The over current will create a thermal effect and a mechanical effect, which cause the destruction of equipments.

✓ *Supply*
Short circuits will cause micro disconnections, harmonic and voltage drop.

✓ *Interference with Telecommunication Networks*
The over current induced by short circuits leads to a longitudinal voltage on telecommunication lines. When these lines are in parallel with the power voltage it may go up to a dangerous level (for material and security).

SAFETY (FAULT DETECTION)

The protection apparatus and components control and measure the voltage frequency and the current.
The fluctuation of these characteristics depends on the load and must be kept into same value range.
Current between 0,9 and 1,3 In
Voltage between 0,7 and 1,1 Un.

If the controlled values (by protection components) are without this range, there is a fault somewhere in line.

SYSTEM EARTHING

DESIGN CONSIDERATIONS

The general purpose of earthing system is to protect life and property in the event of 50/60 Hz faults (short-circuit) and transient phenomena (lightning, switching operations).
The question of how a system shall be earthed is governed by the regulation.
The choice of earthing to one point on each system is designed to prevent the passage of current through the earth under normal conditions, and thus to avoid the accompanying risks of electrolysis and interference with communication circuits.

Earthing may not give protection against faults which are not essentially earth faults .
(i.e.: when a phase conductor on an overhead-line breaks.)

The earthing of an electrical system depends on several criteria:

- Location within power generation center
- Networks
- Regulations.

Several methods exist for system earthing which can be divided into:

- insulated
- solid earthing
- impedance earthing

The protection scheme depends on earthing methods.

CRITERIA TO CHOOSE THE EARTHING METHOD

VOLTAGE LEVEL:

The insulation level of material (transformer, generator, etc.) must be in accordance with the **induced over voltage at the time of short circuit.**

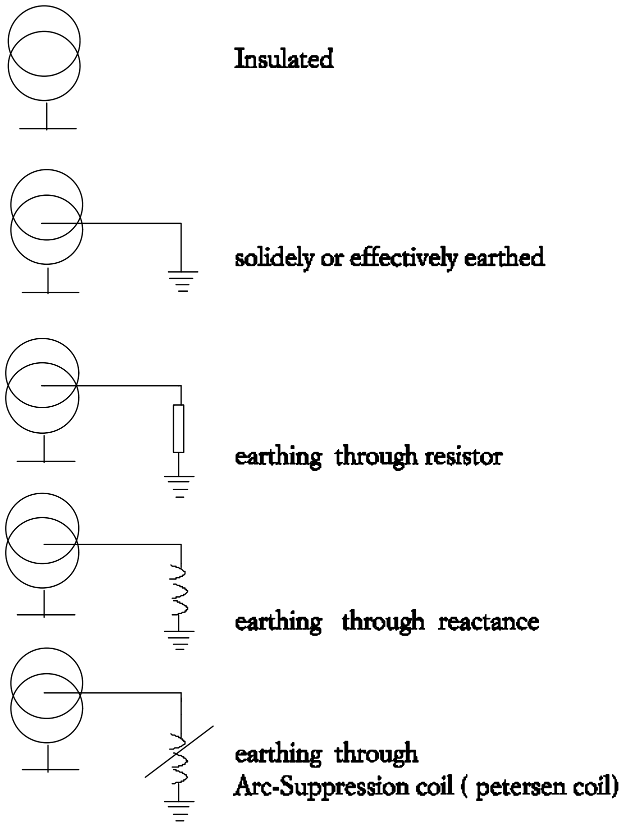
INSULATION COORDINATION:

The earth fault current will induce locally an over voltage which must be compatible with the insulation of low and medium voltage components, **to ensure the continuity of supply.**

LIMITATION OF FAULT CURRENT

To reduce the electrodynamics stresses on material, to limit the induced voltage on telecommunications lines and over-voltage on LV components.

METHODS OF NEUTRAL EARTHING



	Insulated	***Solidly Earthed***	***Low Resistance Grounding***	***High Resistance Grounding***	***Earthing Reactance***	***Arc Suppression Coil***
Fault Current	Few Amps 3cwv	20 To 30 Times The Value Of Nominal Current	From 100 To 3000A	Less Than 10A	At Least 25 To 60 % Three Phase Fault Current	0
Over voltage	Yes Line To Line Voltage	No Line To Ground Voltage	No Line To Ground Voltage	No Line To Ground Voltage	No Line To Ground Voltage	0
Double Earth Fault ***Earth Fault Arc***	Yes Self Quenching	No Sustained	Slight Partly Self Quenching Sustained	Slight Partly Self Quenching Sustained	Slight Partly Self Quenching Sustained	Yes Self Quenching
Interference With ***Telecommunication***	No	Overhead Line = Yes Cable = No	Overhead Line = Yes Cable = No	Overhead Line = Yes Cable = No	Overhead Line = Yes Cable = No	No
		X0/X1=Positive & < Than 3 R0/X1= Positive & <1	R0<Xc0 R0>2x0	R0<Xc0 R0>2x0	X0/X1<10	

X0: Zero-Sequence reactance of the system
R0: Per phase zero-sequence resistance of the system
V: Line to ground voltage
X1: Positive-Sequence reactance of the system
XC0: Distributed per phase capacitive of reactance to ground the system

INSULATED NEUTRAL SYSTEM (No Intentional Earthing)

The neutral is not earthed directly. In reality, the electrical system is earthed through the system capacity to earth.
The earth fault causes a few amperes fault current due to the cable capacitance current, and the voltage of healthy phases will not rise above the line to line voltage. So, the system can operate with present earth fault improving the system continuity and supply.

The detection of fault location is very difficult. The main detection components is a voltmeter. **This method is typically used for LV networks**

SOLIDLY EARTHED OR DIRECT EARTHING

The neutral of power transformers or generator is **directly connected to station ground.**
The Fault current = the three phase symmetrical short-circuit current and can rise from 20 to 30 times the nominal current.
The over-voltage in the healthy phase will not exceed the line to earth voltage.

No limitation of fault current when the system is solidly earthing.

IMPEDANCE EARTHING

The purpose of this method is **to limit the fault current for greater safety**.
There are three type of impedance earthing through resistor, reactance or Arc suppression coil (petersen coil).

EARTHING THROUGH RESISTOR

The neutral is connected to earth through one resistors. The fault current is limited to chosen value: $I_f = \frac{V}{R}$

R= resistance value of resistor (W)
V= line to earth voltage (kV)

A system properly earthed by resistor is not subject to destructive transient over voltages.

The reasons for limiting the current by resistor may be one or more of the following:
- to reduce burning and melting effects in faulted electric equipment,
- to reduce mechanical stresses in circuits and apparatus carrying fault currents,
- to reduce electric shocks hazards are blast to personnel caused by stray ground fault currents in the ground return path.

There are two classes, **High resistance** value or **low resistance** value, distinguished by the level of ground fault permitted to flow (No recognized standards for the level of earth fault current that defines these two classes).

- In practice there is a clear difference.
- High resistance value typically uses earth fault current levels of 10 A or less.
- Low resistance value typically uses ground fault current levels above 10 A and up to 3000 A .

Both classes are designed to limit the earth fault current and to keep the system free from transient over voltages (maintained to a safe level).

However, the high resistance method usually **does not require immediate clearing of a earth fault** since the fault current is limited to a very low level, the protective scheme associated with high resistance value is usually detection and alarm.
The low resistance method **has the advantage of immediate and selective clearing of the earthed circuit**, but requires that the minimum earth fault current be large enough to positively actuate the applied earth fault relay.

EARTHING THROUGH REACTANCE

The neutral is connected to earth through reactor .
The ground fault that may flow is a function of the neutral reactance, the level of the fault current is often used as a criteria for describing the degree of grounding.
In this method the ground fault current should be at least 60% of the three phase fault current to prevent serious transient over voltages. This is considerably higher than the level of fault current desirable in the system using resistor, and therefore **reactance grounding is usually not considered as an alternative to the system using resistor.**

This system is used when the system neutral transformer is not available (DELTA connected system) in such case the reactor is used as transformer grounding to obtain the neutral .

EARTHING THROUGH ARC-SUPPRESSION COIL (PETERSEN COIL)

An earthing reactor connected between the neutral of a system and earth and having a specially selected, relatively high value of reactance in such that the reactive current to earth under fault conditions balances the capacitance current to earth flowing from lines so that the earth current at the fault is limited to practically zero
If the ground fault is in air, such as an insulator flash-over, it may be self extinguishing. This method of grounding is used primarily on 110 kV systems, consisting largely of overhead transmission or distribution lines.

Since systems of such construction are rarely used in industrial or commercial power systems.

OBTAINING THE SYSTEM NEUTRAL

The best way to obtain **the system neutral for grounding purposes** in three phases systems is to use source transformers or generators with **Wye-connected windings**. The neutral is the readily available.

When the system neutral may not available, earthing transformer may be used to obtain the neutral.

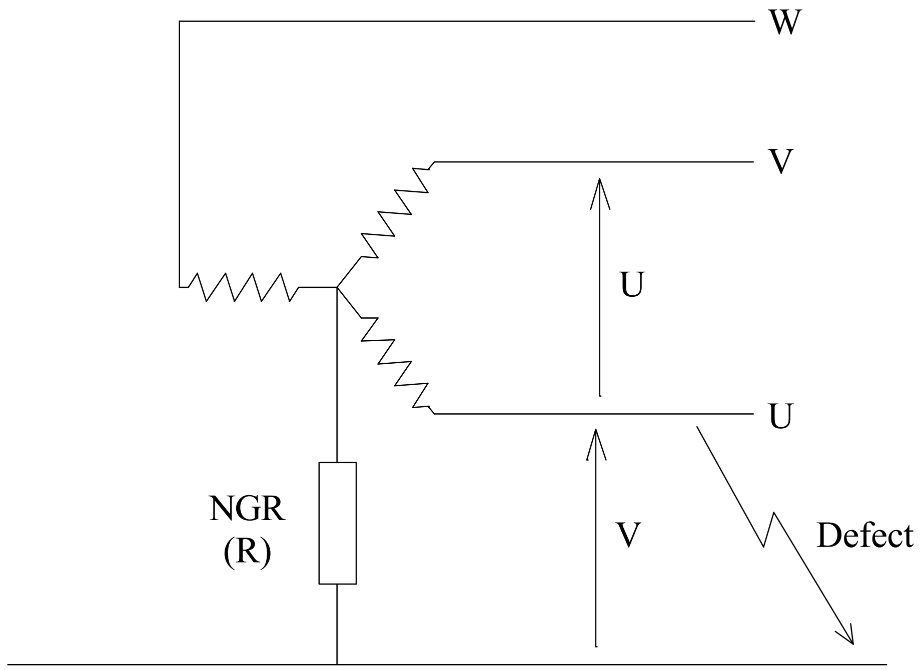
EARTHING THROUGH RESISTORS

This is the most common solution. It is used when **the neutral of the supply transformer is available (DELTA/WYE)** and its own impedance is **not enough to limit fault current.**
Experience has shown that this is the most efficient and economical solution. The advantage of this solution becomes even greater if Nickel Chrome stainless steel resistors are used instead of liquid resistors.

STANDARDS:

There is no specific IEC standards for neutral earthing resistors,

The IEC standards applicable on resistor concern, the insulation, lightning impulse withstand voltage IEC 60, or IEC standards concerning the protection degree.
The only existing standards specific for Neutral Earthing Resistor are the IEEE - 32 standards. For neutral earthing resistor made from stainless steel, the allowed temperature rise for 10,30 or 60 sec = 760°c, 610°c for extended time rating and 385 °C for continuous rating



THE TECHNICAL PARAMETERS FOR EARTHING RESISTOR:

- Rated voltage U Line to Line Voltage and V= line earth voltage
- Rated Fault current If, Effective value of current flowing through the resistor.
- Rated Time t
- Resistance value R = U/If at ambient temperature (20 or 25 °C).

INSULATION LEVEL OF EARTHING RESISTOR:

WHAT IS IT ?

This is the withstand voltage, which it is possible to apply between the active part of the resistor and the earth on a permanent basis. It must be at least equal or higher than line to earth voltage

CALCULATION OF RESISTOR

There are some basic formula used for the designing of high power or high voltage resistors .

- Ohm Law: Voltage = Current X Resistance **$U = R . I$**
  Power = (Current)² x Resistance **$P = R . I^2$**
  Power = Voltage x Current **$P = U . I$**
  Power = (Voltage)² / **$P = U^2/R$**
- Energy absorbed by resistor when carrying in the current
  $W = I^2 . R . t$
  $W = U . I. t$ (Constant Power)
- Temperature Coefficient (variation of resistivity of material used with temperature)
  a=f(Resistivity & Temperature)
- Calculation of Electrical Resistance at different temperatures
  $R_{q2} = R_{q1} . [1+ a . (q2 - q1)]$

ADIABATIC OR PRACTICALLY ADIABATIC HEATING:

When the flow of an electric current through a resistor is relatively short, dissipation is negligible and the heating temperature of that resistor depends on its capacity to store the electric energy (i.e. its heat value itself) in proportion to the mass and specific heat of the material used.
The rise in the resistor's temperature will be provided by the relation:

$$\Delta\theta = \int_0^T RI^2 dt/mc \quad \text{or} \quad \Delta\theta = \int_0^T U^2 dt/Rmc$$

- U = Line / Neutral Voltage
- Δθ corresponds to the temperature rise of the resistor; Δθ = θ2-θ2 (°K)
- θ2 = Temperature of resistor after rated time (°C)
- θ1= ambient temperature (°C)
- C, the specific heat of the material (joule/kg/°C)
- I, the effective current in amperes (A)
- R a mean value of the resistance (Ω) for an intermediate temperature between cold an hot.
- T= rated time

The real ohmic value of the resistor is taken into account, because it varies with the temperature which itself depends on the current flow time.
With that method of calculation we can determine the exact dimensions of the resistor to be built.

For resistors adiabatic heating, masses as high as possible are therefore required.

CALCULATION OF HOT RESISTANCE VALUE (RESISTANCE VALUE AFTER RATED TIME):

The resistance of resistor element changes to extent with temperature after rated time
The change may be calculated from the temperature coefficient of resistivity .

$$\mathbf{R_2 = R_1 x(1+aDq)}$$

- R_2: Hot resistance value (Ω)
- R_1: Resistance value at ambient temperature (Ω)
- α: Temperature coefficient of resistivity of the used resistance material
- Δθ: Temperature Rise °K

DETERMINATION OF FAULT CURRENT:

The fault current must be specified in accordance with the protection scheme and in accordance with nominal current of equipment (generator or transformer) .

RESISTANCE MATERIAL SELECTION

To build High power resistor, manufacturers use different kind of alloys, alloys are selected to meet the electrical & mechanical requirements and characteristics

Neutral Grounding Resistor is used to keep the voltage constant and limit the fault current and reduce it

$$\mathbf{V = I_f \times R}$$

After rated time:

- V must be kept constant
- I_f must be reduced as low as possible
- R must be increased as high as possible

To respect the above formula, R_2/R_1 **= 1+aDq** must be as high as possible

Example:
- Rated time: 10 Sec
- Voltage rise: 20% max
- R1: 8 Ω at ambient temperature
- If : 1000 A, max fault current allowed
- Δθ: 760°C as per IEEE-32

Case 1: Resistance Material is Nickel Chrome AISI 304 with α = 0.001/°C
Case 2: Resistance material is Ohmalloy (Aluminium Chrome & Steel) with α = 0,00012/°C

- Voltage Value $I \times R_1 = 8kV + 20\% = 9.6kV$
- After rated time R_2 (AISI 304) = 8 x (1 + 0.001 x 760) = 14.08 Ω
  R_2 (Ohmalloy) = 8 x (1 + 0.00012 x 760) = 8.7 Ω
  I_f (AISI 304) = $9600/14.08$ = 682A
  I_f (Ohmalloy) = $9600/8.7$ = 1103A

To reduce the fault current and keep the voltage constant, the resistance material must have a temperature coefficient as high as possible

Currently alloys used .

Nickel Chromium Stainless steel (Ni Cr)

These alloys are available with varying contents of Chromium and Nickel, they present an excellent resistance to oxidation and corrosion, the temperature coefficient is depending of the amount of Chromium & Nickel contents, from 0,0009/°C to 0,00001/°C .
Ni Cr alloy are not magnetic, and have very low inductance.

Aluminium Chromium alloy 1JR: or Aluchrom or Ohmalloy (Al Cr steel)

1JR is an oxidation resistant steel which offers good electrical resistance as well as resistance to scale . Because its high specific electrical resistance and very low temperature coefficient of resistance . It is used as resistance or as a magnetic core material
because its high specific inductance

Cast Iron

This material is not used anymore to build resistor, it has been replaced by NiCr Stainless steel or AlCr Steel.

KONSTANTAN .

It used when electrical resistance must be stable, it is available with varying contents of copper and Nickel .

Which Alloy I Have To Use To Built My Resistor?

The selection of alloy is depending on the electrical & mechanical requirement.
NGR Is used to maintain voltage constant (avoid induced voltage to rise) and limit the fault current during fault (few seconds)and limit interference with telecommunication lines .
The electrical resistance must rise as high as possible when fault is occurs .
The material to be used must has low resistance to scale and an high temperature coefficient, it must be No magnetic to limit creation of electromagnetic field and vibration due to the fault current

RESISTANCE ELEMENTS (TECHNOLOGIES)

Different Resistance elements are used to build resistor, elements are connected together in bank, connection is made in serial or in parallel to obtain the electrical resistance value .
The most known elements are

- Grid type or flat obtained by punching, expanding or cutting
- Edgewound coil type: obtained by wounding or wire .
- Mats type: obtained by woven the metallic wire and glass wire
- Liquid type: this technology is not used anymore for NGR, it is only used for some application as soft starter for starting of slip ring asynchronous motors.
  After Rated time , the temperature of resistors rises up to 760°C (in case of stainless steel resistance material) , the resistance value will increase to reduce the fault current and keep the voltage constant.
  The liquid Neutral Grounding Resistors require a monthly maintenance to avoid evaporation or freezing of liquid and add liquid to keep the resistance value unchanged . The cooling time is too low (few degree per hour) and the liquid grounding resistors can not withstand more than one fault per hour .

	Liquid Resistor	***Stainless Steel Resistor***
Limitation of fault current	No fault current increases	Yes fault current decreases
More than one fault per hour	No	Yes
Exploding risks	Yes	No
Evaporating or freezing	Yes	No
During fault rated time	R↓ , If↑	If↓ , R↑
Maintenance	Monthly	yearly
Lifetime	-	More than 20 years

CONNECTION OF RESISTANCE ELEMENTS WITH EACH OTHERS

Hot spot welding is recommended to:

- Ensure a good continuity of current
- Avoid current concentration and hot point

TIG or electrode welding: Deterioration of resistance elements by melting of welding due to Current concentration and hot point (high temperature)

INSULATING MATERIAL

- Ceramic & steatite rings are recommended for NGR's to avoid insulation failure due to the high temperature & humidity
- Mica & Mica washers are not recommended to be used when NGR's are installed in tropical area

INDOORS INSULATORS & BUSHINGS

After fault rated time the temperature of air into NGR's cubicle rise up to 150 ° C

- Ceramic indoor insulators sealed by high temperature cement & ceramic Bushings have a good voltage withstanding at high temperature, no melting
- Melting point of epoxy Insulators & Bushings is between 85 to 100°C, they are recommended to be used in low temperature environment less than 50°C

CONSTRUCTION OF RESISTORS

Different kind of construction:

Air cool Resistor

1.1 Natural ventilation

Most common arrangement, 90% of resistor are build to be cooled by natural air circulation,
The size of resistor is depending of the total energy to be dissipated by the resistance elements
Maintenance of resistor is easy the maintenance frequency is depending on the pollution in the area where resistor is installed .

1.2: Forced ventilated air .

Is used when the energy to be dissipated by resistance elements are important and the available space reserved for resistor is reduced .
This kind of arrangement requires air blower and ventilator .
Is generally used for Railway transit resistor(Dynamic braking resistor) or load bank
This kind of arrangement requires good maintenance.

Oil Cool Resistor .

Is used when the energy to be dissipated by resistance elements are important and the available space reserved for resistor is reduced, it is generally used for high voltage resistor ;Oil tank and oil cooling circuit are required

Water cool Resistor .

Is used when the energy to be dissipated by resistance elements are important and the available space is reduced, it is generally used in ship, submarine .
water tank is required, maintenance must taking into account of freezing or evaporation of water .

Gas cool resistor (SF6)

Is used when the energy to be dissipated by resistance elements are important and the available space reserved for resistor is reduced, it is currently used for high voltage NGR .

PROTECTION DEGREE AND HOUSING FINISHING

NGR is subject to thermal stresses:

- Current + Resistance = Energy to dissipate
- Energy = Temperature rise (as per IEEE-32); the max. temp. to be less or equal to 760°C.

Commonly NGR is self cooled by air circulation into housing. The natural air circulation accelerates the cooling of live parts, of resistance.
There are different kind of protection degree for resistors as per IEC 529 standard.
Please see Comparison Table below.

Protection degree	***Protection***		***Comments***
IP00	No protection	for indoor installation into fenced off area only	
IP23	Protected against solid objects greater than 12 mm and against spraying water.	for Indoor & Outdoor installation	Suitable and recommended for indoor & outdoor installation
IP43	Protected against solid objects greater than 1 mm and against spaying water.	for outdoor installation	Suitable for outdoor installation. The maximum temperature rise of resistance must be reduced to low value.
IP54	Dust protection and water splashing	for outdoor installation	Not recommended Exploding risk if no safety protection against pressure rise The hot spot temperature must be reduced to very low value. A space heater must be installed which required an AC (380, 220 or 115) or DC supply.

HOUSING FINISHING:

The Hot Dip Galvanizing finishing of housing is the best protection against corrosion or aggressive environment such as acid pollution.
For installation near the sea, the housing can be made from Nickel chrome stainless steel sheets AISI 316.
The Nickel Chromium stainless steel must be AISI 316 at least
We do not recommend painting housing.

Finishing	***Use & Protection***
Hot dip Galvanizing	Very good corrosion resistance, Very good acid pollution resistance, Recommended for indoor & outdoor, Recommended for installation near the sea.
Nickel Chrome stainless steel AISI 304	Not recommended for installation near the sea (salt and humidity).
Nickel Chrome stainless steel AISI 316	Recommended for installation near the sea.
Mill Galvanizing	Not recommended due to corrosion risk.
Paint	Not recommended because of painting destruction due to the elevation of temperature of housing and corrosion risk.
Mill Galvanizing & Paint	Better than paint only.

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COMPARISON

(In Quality Of Raw Materials, Components, And Technologies Used To Build High Voltage Neutral Grounding Resistors & Associated Equipments For Long Life Working Time).

ITEM	TO BE USED	NOT TO BE USED
	N.E.R.	
Resistance Material (Alloy)	Non-magnetic & non-inductive High Temperature Coefficient Nickel-Chromium Stainless Steel	Magnetic & Inductive High Temperature Coefficient Corrosive Alloy
Connection between Resistance Elements	Spot Welding / Bolts & Nuts Stainless Steel or Raw Copper	TIG or Electrode Welding Plated Copper
Insulating Material	Ceramic (Steatite…)	Mica
Insulators & Bushings	Ceramic & Mica glass	Epoxy
Housing Finish	Mild or Hot Dip Galvanizing	Painting, Stainless Steel & Aluminium
Protection Degree	IP23	IP54 or more
Terminals	Outdoor Bushing & Insulator Supported Internal Busbar	
Bolts & Nuts	Stainless Steel	Brass…
	Accessories	
Isolator	Silver Plated Blade Finish	Raw Copper Blade Finish

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NEUTRAL EARTHING RESISTORS DATA SHEET

	Value	
ELECTRICAL DATA		
Rated voltage U (lime to line Voltage kV)		**KV**
Rated Fault Current If (A)		**A**
Rated Resistances value at ambient temperature		**W**
Rated time		**Sec**
Permissible continuous current		**A or %**
Temporarily fault current		**A/sec**
INSULATION		
Insulation Level		**KV**
Power Frequency Withstand Voltage during 1 min 50 HZ		**KV**
Lightning impulse withstand voltage (peak value)		**KV**
ACCESSORIES		
Current Transformer characteristics (ratio/accuracy/class) LV or HV side		
Isolators (on load or Off load)		
Maximum current/time/Insulation		
ARRANGEMENT		
Outdoor or Indoor use		
Housing Finishing (Galvanizing/painted color/Stainless steel)		
Protection degree (IP)		
CONNECTIONS		
IN by bushing/direct on element in the bottom		
ENVIRONMENT		
Seismic requirement acceleration (vertical/horizontal)		
Pollution level		
Altitude		
Dimensions restrictions if any		

Table 6
Limiting Temperature Rises Above 30°C Ambient for Current Carrying Parts—Neutral Devices*†

Column 1	Column 2	Column 3		Column 4		Column 5		Column 6		Column 7	
		55°C Oil-Immersed		55°C Dry-Type		80°C Dry-Type		150°C Dry-Type		Resistors	
										Temperature Rise, °C	
		Temperature Rise °C	Time Factor‡ seconds	Temperature Rise °C	Time Factor‡ seconds	Temperature Rise °C	Time Factor‡ seconds	Temperature Rise °C	Time Factor‡ seconds	Stainless Steel #	Cast Grid #
Steady State for Continuous Current Ratings	Steady State (Hot-Spot) Section 4.2	65		65		110		180		385	385
	Steady State (Average) Section 4.2	55		55		80		150		—	—
Rated Time for Thermal Current Ratings (rated voltage for certain resistors)	Extended-Time (Average) Section 4.3.3	75		75		110		200		610	385
	Ten-Minute (Average) Section 4.3.2	125		125		185		275		610	460
	Less than 10 Minutes (Average) Section 4.3.1	120	22 500	120	103 000	160	143 000	250	98 400	760	510
		125	15 000	130	53 300	170	86 700	260	63 000		
		130	9 000	140	30 000	180	53 700	270	41 000		
		135	6 700	150	16 700	190	33 300	280	26 600		
		140	4 300	160	9 330	200	21 000	290	18 000		
		145	3 000	170	5 330	210	13 700	300	12 000		
		150	2 100	180	3 330	220	9 170	310	8 340		
		155	1 500	190	2 000	230	6 170	320	5 670		
		160	1 030	200	1 270	240	4 170	330	4 000		
		165	733	210	767	250	2 830	340	2 800		
		170	517	220	500	260	1 970	350	1 968		
		180	270	230	333	280	967	360	1 434		
		190	143	240	257	300	500	380	750		
		200	77	250	150	320	277	400	406		
		210	40	260	103	340	157	420	243		
		220	25	270	73	360	94	440	140		
		230	15	280	50	380	61	460	84		
		240	8.8	300	26	400	34	480	51		
		250	5.3	320	14	420	22	500	32.4		
		260	3.3	340	7.7	440	14	520	20.5		

Notes to Table 6:

*The values in this table are based on the thermal aging characteristics of the insulation. Devices built to these thermal limits will have normal insulation life.

Other factors may limit temperature rises in specific designs. For example:

(1) The reduction in the mechanical strength and increase in elongation of copper at temperatures above 300°C and aluminum above 350°C.

(2) Gas evolution from insulation and oil adjacent to hot conductors.

(3) Auto-ignition of insulation or oil.

†No limits have been established for capacitors.

‡The time factor of a device for use in determining the limit of temperature rise shall be calculated as follows:

$$f = \frac{C\theta_1 M \text{ seconds}}{P}$$

$$\begin{aligned} \theta_1 &= 1.182\,\theta_2 - \theta_3 && \text{for 55°C oil-immersed devices} \\ &= 1.182\,\theta_2 && \text{for 55°C dry-type devices} \\ &= 1.373\,\theta_2 && \text{for 80°C dry-type devices} \\ &= 1.200\,\theta_2 && \text{for 150°C dry-type devices} \end{aligned}$$

where

θ_1 = Steady-state hot-spot temperature rise at continuous current rating either above top oil temperature for oil-immersed equipment or above the ambient air temperature for dry-type equipment.

θ_2 = Average winding rise over ambient for rated continuous current under standard operating conditions

θ_3 = Top oil rise over ambient for rated continuous current under standard operating conditions

P = Specific power (watts per unit mass of conductor material)

C = Specific thermal capacitance (joules per degree Celsius unit mass) of conductor material and its associated insulation, as calculated in Eqs 13 and 14

M = Multiplier from Table 7.

NOTE: The values of both C and P shall be taken at the temperature corresponding to θ_1 and standard ambient conditions.

#The temperature rise limits for extended time, ten-minute or less rated resistors are hot-spot values.

The rated voltage of a grounding transformer is the maximum line-to-line voltage at which it is designed to operate continuously.

10. Resistors

10.1 Resistor Element. A resistor element is the conducting unit which functions to limit the current flow to a predetermined value.

The element material shall possess a balanced combination of properties, uniformity of resistance, and mechanical stability over the intended operating temperature range, without any injurious effects to the elements and its associated insulation.

10.1.1 *Rated Voltage* (see definition in Section 13). Since the active material used in resistors has an appreciable temperature coefficient, the resistance is materially changed during the time of operation causing the voltage to increase or the current to decrease. When the product of the fault current and resistance at 25° C exceeds 80 percent of the line-to-neutral voltage of the circuit, the resistor shall be rated for constant voltage and the rated voltage shall be taken equal to the line-to-neutral voltage.

10.1.2 *Temperature Coefficient of Resistance.*

(1) The conductor element resistance changes to some extent with temperature. The change may be calculated from the temperature coefficient of resistivity.

$$a = \frac{R_2 - R_1}{R_1\,(\theta_2 - \theta_1)} \qquad \text{(Eq 2)}$$

$$R_2 = R_1\,[1 + a\,(\theta_2 - \theta_1)] \qquad \text{(Eq 3)}$$

R_1 and R_2 are resistances in ohms at temperatures θ_1 and θ_2 in degrees Celsius, respectively, and a is the temperature coefficient of resistance.

(2) Where special temperature coefficient is required, such data are to be brought to the attention of those responsible for the design of an unusual service condition.

10.1.3 *Conductor Connections.* All conductor terminations shall be bolted, welded, or brazed. Low-melting alloys used to join connectors which would be adversely affected by the resistor operating temperatures shall not be used. All conductor terminations must be mechanically secure to provide continuous electrical continuity.

10.1.4 *Resistance Test.* Overall resistance shall be measured to determine that the resistance is within the design value. Unless the application requires close resistance tolerance, the dc resistance shall not vary more than ± 10 percent from the guaranteed value.

10.2 Insulation Levels. The line end and ground end insulation levels shall be selected from Table 4 on the basis of fault voltage criteria, Columns 3 and 4.

10.3 Dielectric Tests. Dielectric test withstand levels shall be those listed in Table 5, Column 6.

10.3.1 *Impulse Tests.* Impulse tests are not required for resistors.

10.3.2 *Applied-Potential Tests.* Applied-potential tests are required. They shall be made by applying between terminals and ground for the complete device, or between terminals of each unit and its own individual frame, the specified voltage from a suitable external source. When specifications do not require that such a resistor be completely assembled at the factory, it shall be permissible for the manufacturer to waive the applied voltage test of the complete device, substituting the applied-potential test of each section, supplemented by insulation data which will show that the complete resistor will meet the insulation requirements of service and would pass the applied-potential test when assembled.

In many cases resistors are made in sections insulated from each other and from ground by standard apparatus insulators whose insulation value has been established. Each section may consist of one or more frames or unit assemblies of resistance material supported on a suitable framework. In such cases each frame or unit assembly shall receive an applied-potential test. The voltage applied from the terminals of each assembly to its own frame shall be twice the rated voltage of the section of which the frame is a part plus 1000 V when rated 600 V or less, or 2.25 times the rated value plus 2000 V when rated over 600 V.

Table 10
Respective Metric and English System Nomenclature for Eqs 15 and 16

Symbol and Identity		Metric	English
θ	Final temperature rise	$^\circ C$	$^\circ F$
θ_1	Initial temperature rise	$^\circ C$	$^\circ F$
θ_0	Initial temperature	$^\circ C = \theta_1 + 30$	$^\circ F = \theta_1 + 86$
a_0	Temperature coefficient of resistance, change in resistance per degree, at initial temperature,	$^\circ C$	$^\circ F$
δ	Density of material	$\frac{g}{cm^3}$	$\frac{lb}{in^3}$
$*C$	Effective integrated specific heat	$\frac{Cal}{g \cdot {}^\circ C}$	$\frac{Btu}{lb \cdot {}^\circ F}$
J_0	Initial current density	$\frac{A}{cm^2}$	$\frac{A}{in^2}$
r_0	Resistivity at initial temperature	$\frac{\Omega}{cm^3}$	$\frac{\Omega}{in^3}$
t	Time	s	s

$\log_{10}{}^{-1} = \text{antilog}_{10}\, x = 10^x$

*For cast iron, over the range of temperature covered by this standard, C shall be taken as 0.130.

14.5.2 *Thermal Capability Calculation for Neutral Resistors*

14.5.2.1 *Respective Metric and English System Equations for Temperature Rise and Current Density, When Current is Constant.* The eddy-current loss may usually be ignored due to the high-resistance materials used in neutral resistors.

The temperature rise when the current is held constant, and all heat is assumed to be stored in the active material, shall be computed by the following equations, where all quantities have been defined in Table 10.

Metric

$$\theta = \frac{1}{a_0}\left[\log_{10}^{-1}\left(\frac{0.104\, a_0\, r_0\, t\, J_0^2}{C\delta}\right) - 1\right] + \theta_1$$

(Eq 15)

English

$$\theta = \frac{1}{a_0}\left[\log_{10}^{-1}\left(\frac{a_0\, r_0\, t\, J_0^2}{2430C\delta}\right) - 1\right] + \theta_1$$

For design purposes, it is more convenient to insert the desired temperature rise and derive the current density which will produce the desired temperature rise. Thus

Metric

$$J_0 = \sqrt{\frac{9.62C\delta \log_{10}\,[1 + a_0\,(\theta - \theta_1)]}{a_0 r_0 t}}$$

English (Eq 16)

$$J_0 = \sqrt{\frac{2430C\delta \log_{10}\,[1 + a_0\,(\theta - \theta_1)]}{a_0 r_0 t}}$$

NOTE: Equations 15 and 16 apply only when the temperature coefficient of resistance a_0 is substantially constant over the temperature range used, and must not be used for materials for which the coefficient varies greatly.

14.5.2.2 *Respective Metric and English System Equations for Temperature Rise and Current Density, When Voltage is Constant.* For some resistors (see 10.1.1) temperature rise is computed on the basis that constant voltage is maintained between the terminals, the current being allowed to decrease as the resistance increases with temperature. The temperature rise, with all heat stored in the active material and with constant voltage,