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SCHOOL OF TECHNOLOGY
LUT ENERGY
ELECTRICAL ENGINEERING

MASTER'S THESIS

**ELECTRICAL SAFETY OF ISLAND OPERATED LOW VOLTAGE DC
NETWORK**

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Abstract

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Electrical Safety of Island Operated Low Voltage DC Network

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Today, renewable energy technologies and modern power electronics have made it feasible to implement low voltage direct current (LVDC) microgrids (MGs) capable to island operation. Such LVDC networks are particularly useful in remote areas. However, there are still pending issues in island operated LVDC MGs like electrical safety and controlled operation, which should be addressed before wide-scale implementation. This thesis is focused on the overall protection of an island operated LVDC network concept, including protection against electrical shocks, mains equipment protection and protection of photovoltaic (PV) power sources and battery energy storage systems (BESSs). The topic is approached through examination of the safety hazards and the appropriate methods to protect against them, comprising considerations for earthing system selection and realisation of the protection system.

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Abbreviations and symbols

A	Ampere
AC	Alternating Current
DC	Direct Current
DG	Distributed Generation
EMS	Energy Management System
HS-RCD	High Speed Residual Current Device
HVDC	High Voltage Direct Current
I>>	Over current Relay
ICT	Information Communication Technology
IEC	International Electrotechnical Commission
IED	Intelligent Electronic Devices
IM	Insulation Monitoring Device
LVAC	Low Voltage Alternating Current
LVDC	Low Voltage Direct Current
MCB	Miniature Circuit Breaker
MCCB	Molded Case Circuit Breaker
MG	Microgrid
MGCC	Microgrid Control Center
MPPT	Maximum Power Point Tracking
MV	Medium Voltage
PCC	Point of Common Coupling
PEI	Power Electronic Interface
PELV	Protected Extra Low Voltage
PV	Photovoltaic
RES	Renewable Energy Source
SOC	State of Charge
SELV	Separated or Safety Extra Low Voltage
SPD	Surge Protection Device

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1 Introduction

Protection of electrical installations is critical from the usability viewpoint. Both humans and equipment must be protected against dangerous effects of faults, without causing wide-ranging and long-term interruptions of power supply.

Modern power consumption clearly includes increasing use of DC in the end user equipment's. Microgrids (MGs) are also under brisk discussions, one of the main drivers being the strive for better reliability and power quality. MGs are usually mainly based on renewable sources i.e. wind or PV. Recent trends indicate increasing interest towards the use of PV, producing a DC power directly without conversion into AC. This is expected to result in high energy efficiency due to low conversion losses and is hence seen as one of the main drivers behind the DC MGs concept. DC distribution system allows consideration of direct connection of batteries to provide back-up energy supply during generation black-outs and also increasing the security of supply in case of outages in other equipment. LVDC is emerged from DC MGs concept and is commercializing in today's world. LVDC is also an economical solution for electricity distribution due to its higher transmission capacity and control opportunities provided by the converters in the system. LVDC can be implemented with two structural topologies i.e. unipolar max. 1500 VDC and bipolar max. ± 750 VDC. LVDC can be used as an appropriate option for managing our future load demands (Kakigano 2007).

LVDC MGs may be a feasible choice for areas which are far away from the main grid, where realisation of electricity supply is an issue. Such LVDC MGs are also known as Island operated LVDC MGs and can be one of reliable source of providing power. However, there are a lot of pending issues in island operated micro grids which should be resolved prior to implementation. One such issue is about protection of the whole network.

Electrical safety is one of the most important operational requirements. Furthermore, the fault characteristics are different in LVDC MGs compared to traditional interconnected AC networks. Differences are for instance caused by the wide-

ranging utilization of power electronic conversion and related limited supply capacity of fault currents, characteristics of DC in general and naturally intentional island operation based on dispersed located power sources. A protection system is needed which can deal with all abnormal situations within the limitations of the system characteristics of the LVDC network and that is fast, reliable and sensitive only to faults.

1.1 Thesis objective

The objectives of the thesis is to analyse the electrical safety risks of an LVDC microgrid in island operation and establish a protection system scheme for protecting against the adverse effects of the faults causing the electrical safety risks. The thesis focuses on PV powered LVDC microgrids with stationary battery energy storages and household loads. The research tasks in the thesis work are as follows:

- I. Literature review of DC MGs.
- II. Giving an insight of fault current effects on human body and equipment's.
- III. Pointing out different kinds of faults in the LVDC network. The sections which are taken into consideration are: PV panels, DC mains, Batteries and customer AC side network.
- IV. Describing different protection methods and earthing system.
- V. Designing protection system for the studied network.
- VI. Calculations of different fault currents.

1.2 Thesis Outlines

Chapter 2 gives idea of LVDC system in general and description of the studied system i-e network structure & topology , customer connection, power demand, energy sources and storage.

Chapter 3 is about the island network and electrical safety, focuses on MGs concept (AC, DC), the electrical fault situation in the MGs and the effect of those faults. This chapter also covers general overview for protection against faults.

Chapter 4 is about the electrical safety of the MGs i-e faults in different parts of the network i-e PV, DC mains, batteries & customer AC network and what will be the effect of these faults on equipment's. It further describes earthing system for different main components in the network in more detail.

Chapter 5 describes the protection methodology for the studied system i-e protection of PV panels, protection of batteries and protection of dc mains. Furthermore ICT differential protection and backup protection is also covered in this chapter.

Chapter 6 gives fault calculation of the studied system i-e line-to-line faults, line-to-middle faults and line-to-earth faults (single and double).

Chapter 7 gives details about relays settings.

Chapter 8 is about the conclusion of the thesis.

2 Description of the studied system

The studied system is island operated low voltage DC network. The main parts of the network are PV generator, LVDC mains, batteries and customer-end low voltage AC network. The island network covers the area, diameter of which is approximately 6 kilometres. Such regional grid is divided to several sections which may be equipped with their own generator and battery units. In ideal case the regional grid is formed by connecting several local smallish microgrids, capable to independent operation, together. Hence the entire setup resembles large power systems formed by interconnected regional or national grids. The presented studies focus on analysing the electrical safety of a section of the system, however, whilst taking into account the interconnection with neighbouring sections. Simplified representation of the section, presented in Fig. 2.1, is used in the analysis.

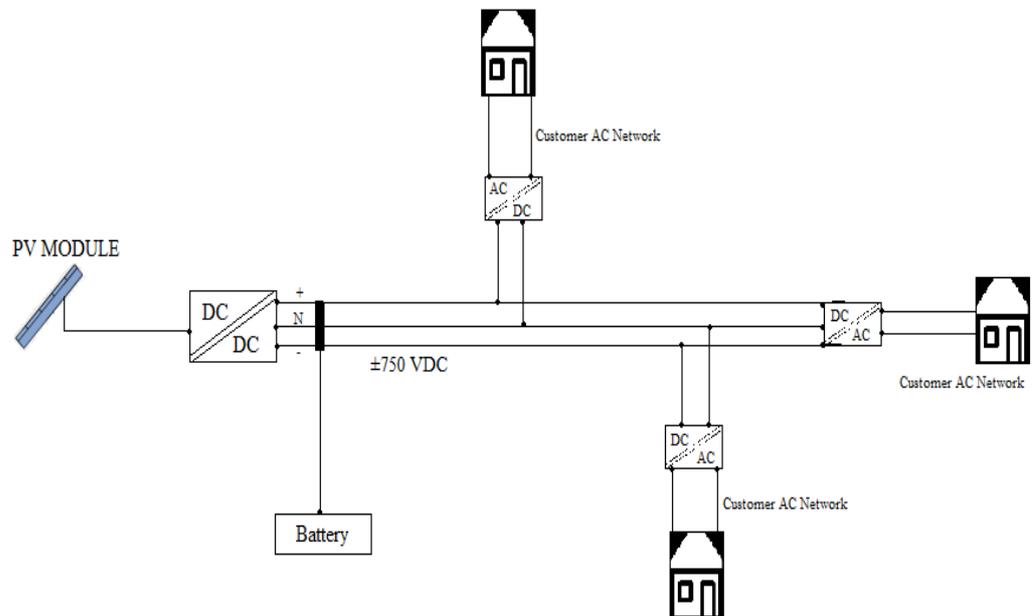


Fig. 2.1 Principled diagram of the studied LVDC system.

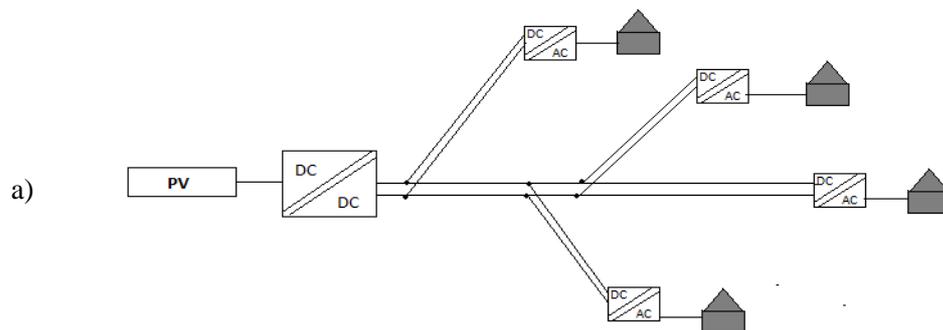
2.1 LVDC system in general

DC distribution is becoming more popular and an alternative way in future to supply power to all electrical equipment's connected by a bus system and controlled

by EMS (Jackson John Justo 2013). As an example PV system (DC based generation unit) which produces DC power, can be easily connected to the DC bus system or LVDC network via converters.

LVDC is emerging technology in the field of electricity distribution. The demand for distribution generation is growing as today's world is mostly relying on electrical power. Furthermore due the growing demand, electrical losses and outages cost also increases by network disturbances. LVDC technology plays a vital role to overcome these challenges (Jackson John Justo 2013).

LVDC system is based on power electronic converter and DC links between those converters and can be implemented of unipolar or bipolar structures .In unipolar system there is only one voltage level through which all the customers are connected. In the bipolar system two unipolar systems are connected in series. In the bipolar system customers can be connected between voltage levels with multiple ways. The connection alternatives are 1) between a positive pole, 2) between a negative pole, 3) between positive and negative poles and 4) between positive and negative poles with neutral connection (Pasi Salonen 2008). The following figure 2.2 shows DC unipolar and bipolar structures:



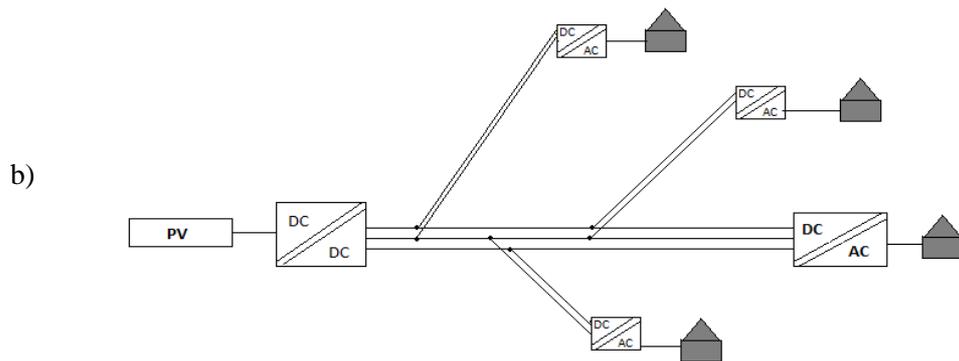


Fig. 2.2 LVDC unipolar structure a) and bipolar structure b) adopted from (Pasi Salonen 2008)

2.2 Stand-alone LVDC MG

A standalone LVDC MG is an off-the-grid system for location that is far from the main grid or not fitted with an electricity distribution system (Gulin 2009). Typical stand-alone LVDC system consist of generation sources, energy storage system and power electronic interfaces for grid control. The energy sources can be PV or Wind turbines or both, and for energy storage system batteries can be used. Power electronic converters are used for providing required voltage transformations and to control the system in electrical sense. By taking the example of the studied system where power sources are PVs, stand-alone LVDC system can be of two types:

a) Directly coupled system without batteries:

In directly coupled system energy sources i-e PVs are directly connected to DC loads. Energy is not stored in this system because batteries are not used and hence it's capable to give power to small appliances in the day time. MPPTs (maximum power point trackings) are used to efficiently utilize the sun energy.

b) Stand-alone system with batteries:

In standalone LVDC system, batteries are attached for energy storing. When power from the PV generator is not equal to the load demand by reasons like non-coincidence of production and demand, sunlight deficiency or fault conditions, then energy is charged or taken from the batteries to fulfil the needed power balance. The primary function of energy storage in standalone LVDC system is:

- I. To store the excessive energy and provide it when require.

- II. Eradicating transients to provide stable current and voltage.
- III. To provide surge currents to loads, when they are required.

2.2.1 Network structure and topology

The physical network topology can be radial or meshed (looped) or contain partially both, but the system is considered to be mainly operated in radial manner. The system is considered to be constructed as hybrid structure which means bipolar network with unipolar branches. The voltage levels in bipolar network are ± 750 VDC.

2.2.2 Customer connection and power demand

The estimated number of customers connected to the network is around 200 and at least 10-15 customers connection are required in order to build the island network.

Typical average peak power of the single customer connection is approximately 200 W in the beginning. However it is assumed to grow rapidly to figures around 800 W within few years. Therefore, the peak power handling capability of the total network can be estimated to be round 160 kW in a 200 customer network, without taking into account the crossing due to the probable non-coincidence of the peak loads at every customer.

2.2.3 Energy sources

Energy sources in a grid are of great importance because the feeding capacity of the whole grid depends on it. In case of the studied network the energy source are PVs (photovoltaic).

2.2.4 Energy storage

In island operated grid energy storage is one of the important component. This can feed the network in case when the main power sources goes down. In the studied network the batteries are used as energy storage, which will be connected to the DC mains directly or via converter.

2.2.5 Control and ICT

One of the important aspects of LVDC system is that it measures and controls the usage of energy which is important for supply and demand of the network. PEIs (power electronic interfaces) are used to communicate between various components of the network such as renewable energy sources, energy storage devices and load circuits for all technical issues such as power quality and power balance.

Due to PEIs MG can be operated into grid connected mode and islanded mode while providing high quality of power with minimum equipment costs.

According to (Jackson John Justo 2013), PEIs are required to fulfil these conditions.

- I. To provide the fixed cost and local voltage regulation
- II. To facilitate the DG unit to fast track the load demand using the energy storage devices.
- III. To incorporate the control methods for load sharing between the DG units.
- IV. To integrate the various key technologies for successful modern or future smart distribution systems.

According to studies (Jackson John Justo 2013), DC microgrids doesn't have issues of synchronization of frequencies and difficulties in voltage control during islanded mode but these issues can be found in AC micro grids. More specifically the DC micro grids are easy to operate because frequency or phase control structure is not taken in to account as compared to AC micro grids.

ICT is also playing a vital role in DC microgrid protection because traditional protection methods are difficult to use when there are DC/DC converter. So ICT provides better, fast and reliable protection by taking measurements from all point of the network and then compared it with the reference value. When the reference value is not equal to the specified value. It means there is fault and protection devices get activated (Fumio Kawano 2011).

3 Island network and electrical safety

Island network can be defined as a system consist of one or more power sources and loads operated autonomously and separated from the rest of the electric system. As island network is separated from the rest of the system so it tends to be weaker than the same network in the interconnected operation. It means that island network is more prone to faults and voltage fluctuations (Sulla 2008).

The three most important aspects of distribution system design are safety, reliability and economy. The safety is of highest priority, followed by reliability and economy. Power system safety mainly concerns current exposure. Current exposure can cause serious harm to the human body and even prove fatal. The consequences of current exposure depend on current amplitude as well as current duration. To ensure safety, the power systems include protection that limits the duration of faults (Geidl 2005).

A basic protection for electrical power system must fulfil the following 3s:

- I. **Sensitivity.** An abnormal condition should be identified before it exceeds the normal threshold value.
- II. **Selectivity.** In order for reliable power supply protection system should disconnect only faulty point from the rest of the healthy network in order to minimize fault consequences and improve the overall performance of the network..
- III. **Speed.** For avoiding damage to equipment and maintain stability in the network, protective relay should operate in the least possible time.

The 3s can be further extended by:

- I. **Dependability.** Protection system should operate in right situation i-e in order for best performance; it should detect and disconnect all faults from the network within the protection zone. There is also a need for backup protection for maximum possible protection measures for a system.
- II. **Security.** Protection system should design in a way that it avoids miss operation and rejects all events in a system that is not faults.

- III. **Redundancy.** In order to improve reliability in a network, protection system has to take care of the redundant functions of relays. It is also known as backup protection and can be obtained by combining different protection scheme.
- IV. **Cost.** Network designer put great effort to achieve maximum reliable protection with lowest cost possible while designing network parameters.

The following figure shows a flowchart of protection requirements:

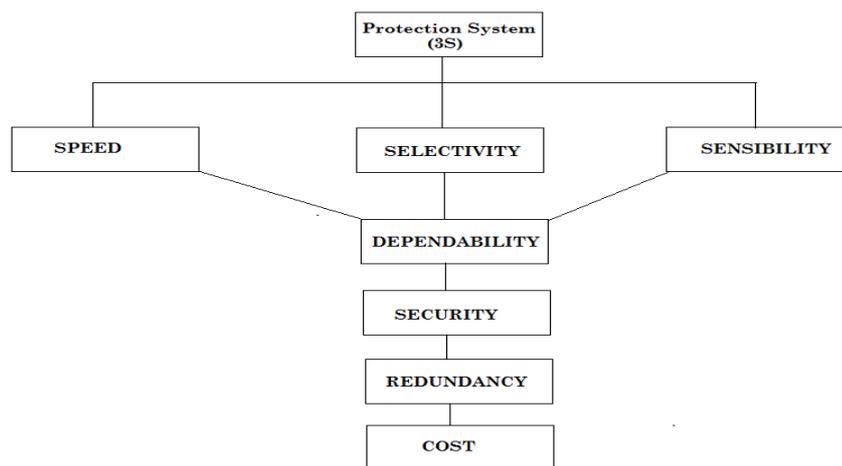


Fig 3.1. Flow chart for protection requirements

3.1 Definition of MGs

“A microgrid is a discrete energy system consisting of distributed energy sources (e.g. renewables, conventional, storage) and loads capable of operating in parallel with, or independently from, the main grid. The primary purpose is to ensure reliable, affordable energy security for commercial, industrial and federal government consumers”(Dohn 2011). The distributed energy sources operating together in a coordinated manner with controlled power electronic devices (active and reactive power flow controllers, frequency and voltage regulators) which are integrated with protective devices. They can be operated based on the principles of the AC power system (i.e AC MGs) or DC power systems (i.e DC MGs)” (Jackson John Justo 2013).

3.1.1 AC MGs

In AC MGs the main power source can be AC or DC. The DG units and ESS (energy storage system) is connected at different points within the distribution grid. More specifically a network consists with DG units and loads can form small isolated AC electric system or AC MGs. In most case, AC MGs adopts the voltage and frequency standards applied in most conventional distribution system. The following figure shows a typical AC MGs connected with MV system at PCC (point of common coupling). During normal operating conditions, the two networks are inter connected at the PCC while the loads are supplied from the local sources (e.g. The RES (renewable energy sources) based DG units) and if necessary from the utility (Jackson John Justo 2013).

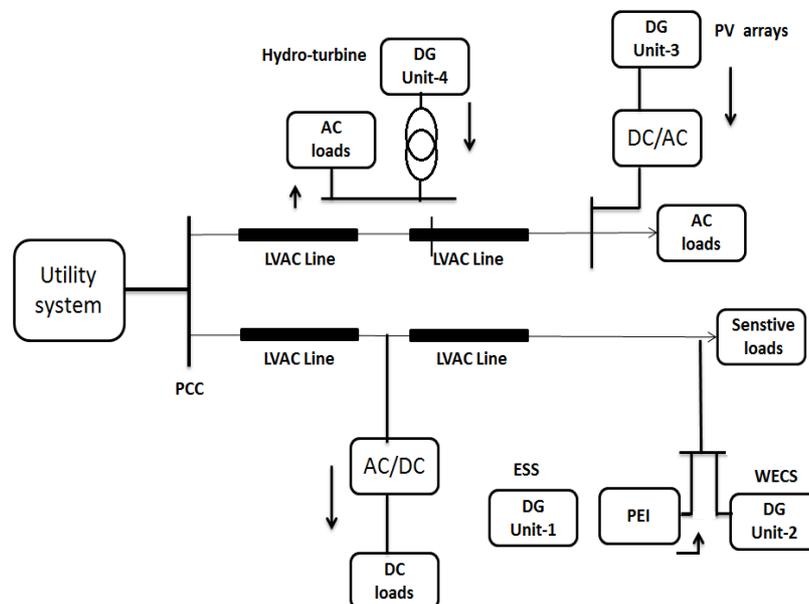


Fig 3.2. Structure of traditional AC MGs (Jackson John Justo 2013)

3.1.2 DC MGs

Alternating current is mainly carried out from power generation station via high-voltage transmission lines and by the use of distribution grids, it's become lowered down for the use of households and industry. DC is needed for power electronic devices, so further conversion of AC to DC is needed via rectifiers. DC power is

produced nowadays by renewable generation such as solar panel but it's again converted to ac power, sends via transmission lines and then converted back to DC for many end users. These conversion leads to energy losses due to the use of inefficient rectifiers. To minimize these conversion losses, DC MGs are the most efficient way. According to (A Seenuvasan 2013), on average this system reduces AC to DC conversion losses from an average loss of about 10% to 32%. The American Energy Independence and Security Act of 2007, Title XIII, identifies the elements that characterize the “Smart Grid” policy goals (Paul Savage 2010). In summary, these are:

- I. Reliability, security, storage and distribution generation
- II. Energy efficiency, sustainability and renewable inputs.
- III. IT/communications leverage/full cyber-security
- IV. Load awareness, demand side management and plug in vehicles
- V. Lowering unnecessary barriers to achieving the above.

DC MGs is the technology on which each of the above goals can be achieved with lower cost and higher efficiency than AC grids. Also on other hand due to renewable technologies in the market such a photovoltaic are become more widely accepting by households, so DC MGs will the most efficient solution.

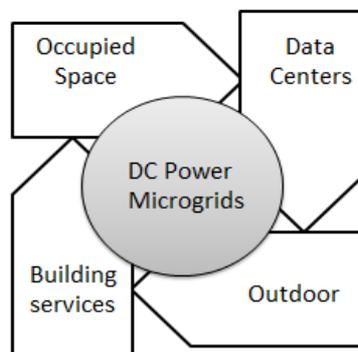


Fig 3.3. Implementation of DC MGs (Alliance 2011)

“The figure 3.4 shows the typical DC MG systems interconnected with the main systems at PCC which can be MV (medium voltage) AC network from conventional power plants or an HVDC (high voltage direct current) transmission line connecting an offshore wind farm”(Jackson John Justo 2013).

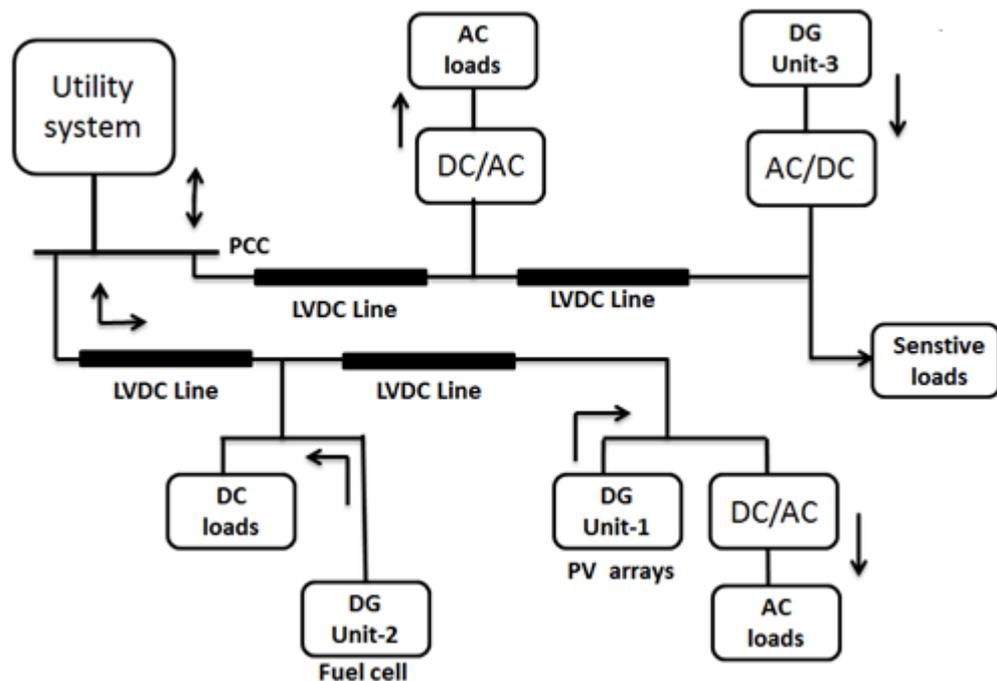


Fig 3.4. Structure of traditional DC MG (Jackson John Justo 2013)

3.2 Electrical safety challenges

Electrical safety of a DC MGs is the most important operational requirement and it's earthing and protection are critical. DC MGs is subjected to more critical safety requirements than a conventional utility power system because of the use of power electronics, which can create voltage dips in faults situations (Pasi Salonen 2009). Protection strategies should be proposed to achieve a safer and a reliable operation of DC MGs grid by minimizing the identified fault scenarios and should detect the faults situation, which can results in abnormal operation. Protection system should be also capable of allowing the DC MGs to operate either in grid connected or islanded modes of operation providing appropriate safety to customers and equipment's (Won-Seok Lee 2011).

3.2.1 Harmful impacts of electrical shock to humans

IEC 62368 Address the following Hazards (Helmut 2005):

- I. Fire hazard
- II. Burn hazard
- III. Radiation hazard

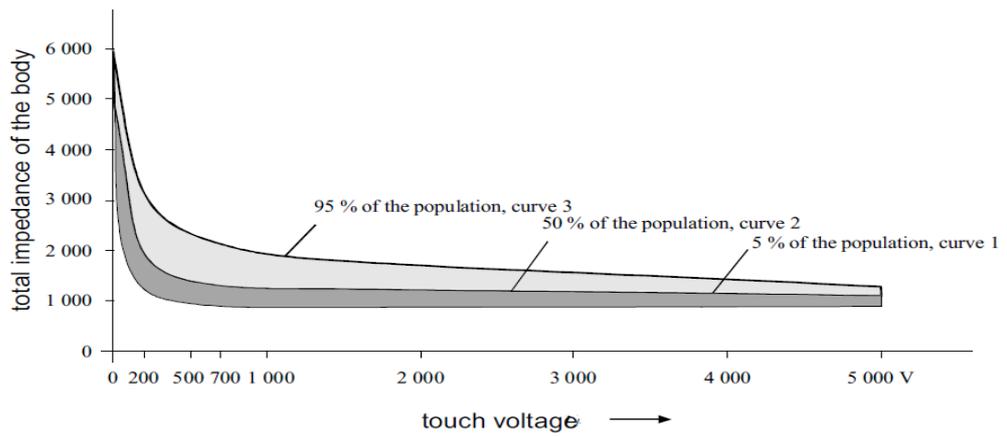
When voltage is applied across the human body, it will create a current. The current is limited by the magnitude of the voltage and the body impedance (Zipse 1999):

$$I_{body} = \frac{U_{body}}{Z_{body}} \quad (3.1)$$

There is nonlinear relation between body impedance and applied voltage. Body impedance depends upon on various factor, among these are location where the person stands i-e dry or humid, body mass, and gender. According to IEC standards the approximate body resistance is between 575 (5 % of the population) and 1050 Ω (95 % of the population) assuming large contact areas and an applied voltage that exceeds 1000 V. An applied voltage of 100 V will result in a body resistance between 990 (5 %) and 3125 ohm (95 %). The electric shock on the human body also depends on the amplitude, duration and path of the current through human body. Respiratory problems, loss of muscular control and ventricular fibrillation can be the results on human body when exposed to current (Guldbrand 2009).

Resistance plays an important role at the amount of energy when passes through the body. Human body has its own resistance to electric current, 99% of this resistance is at the skin. Dry and wet skin have different resistance values. Skin act like capacitor and more current flows it the voltage changes rapidly. Effects on human body in case of AC largely depends on frequency. Low frequency are more dangerous than high frequency. Low frequency in case of AC can provoke muscle contraction which can induce “cannot let go” effect by freezing the muscles of the hand (Peter E Sutherland 2005).

IEC publication 479 gives the human body impedance values in relation to the touch voltage to which it is subject.



5 % of the population means that 5 % of people have an impedance below curve 1.
 50 % of the population means that 50 % of people have an impedance below curve 2.
 95 % of the population means that 95 % of people have an impedance below curve 3.

Fig 3.5. Statistical values of the total impedance of the human body for a hand-to-hand or hand-to-foot current trajectory (AC) [IEC 497]

In a more broad perspective if we think what will happened when a person get an electric shock? The study reveals (Lee 2003), that there are two main ways electricity will hurt people.

- I. Normal functions of nerve cells can be blocked which can cause mild tingle up to a heart fibrillation.
- II. Electrical arcs can electrical burn which is essentially treated like other burn.

Standards and regulations distinguish two kinds of dangerous contacts i.e direct contact and indirect contact.

The nature electric shock also depends upon the nature of current i.e. AC or DC, which defines it's intensity of danger for a human life. The current effect on the human body depends also upon the magnitude and path of the current flow through human body. IEC publication 60479-1 updated in 2005 defines four zones of current-magnitude/time-duration, in each of which the path physiological effects are described. The figure 3.6 described electrical curves for AC when it passes through human body from hand to feet. Curve C1 shows that when a current greater than 30 mA passes the person is likely is likely to be killed, unless the current is interrupted in a relatively short time. The point 500 ms/100 mA close to

the curve C1 corresponds to a probability of heart fibrillation of the order of 0.14%.

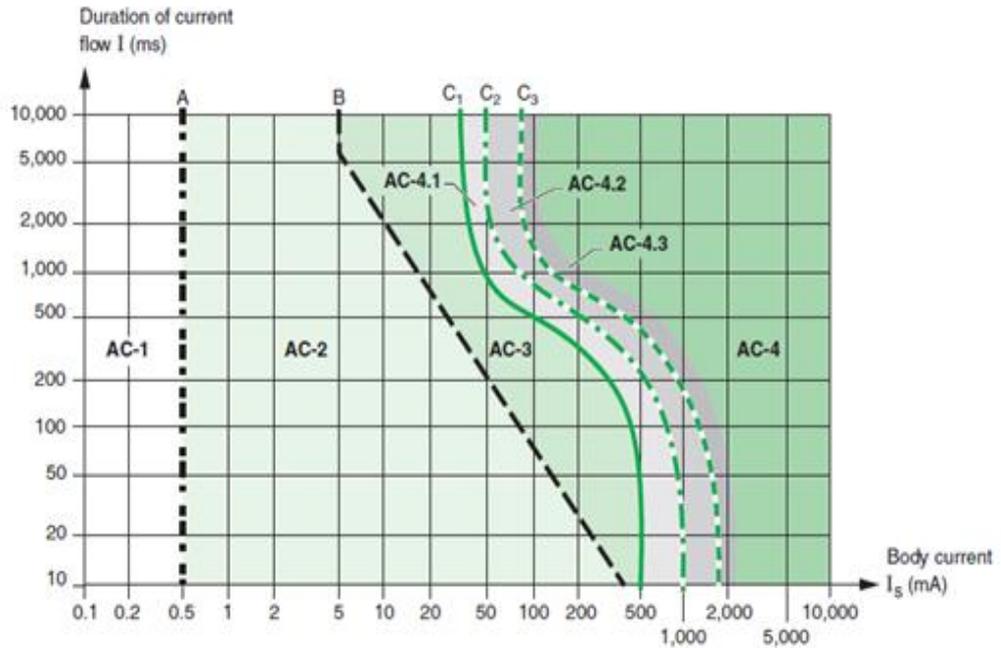


Fig 3.6. AC Curves [IEC 60479]

Table: 3.1. Effect of AC on body through different current zones

Zones	Effects
AC-1	Imperceptible
AC-2	Perceptible
AC-3	Reversible effects: muscular contraction
AC-4	Possibility of irreversible effects
AC-4-1	Up to 5% probability of heart fibrillation
AC-4-2	Up to 50 % probability of heart fibrillation
AC-4-3	More than 50% probability of heart fibrillation

The following figure 3.7 show curve for DC. By analysing the curve, one can see that if the human body comes in contact with current greater than 30 mA do not have the same effect on the person as in AC. By comparing the figures 3.6 and 3.7 Ac and DC current of 30 mA do not have the same effect. The B-limit for AC is considerably lower, ending to 5 mA current at 10 s point, while in the case of DC it is the B-limit that ends to about 30 mA at 10 s point. The C-limit, e.g. the limit

for lethal current is considerably higher with DC than with AC. The low frequency (like 50 and 60 Hz) AC currents easily cause ventricular fibrillation already with small currents (e.g. the 30 mA), but DC does not, unless the first impulse does not hit you exactly on the right time. There are smaller risk of death with DC. However, DC causes serious burn damages when the current rises high enough and lethal internal burns when the current is above 75 mA.

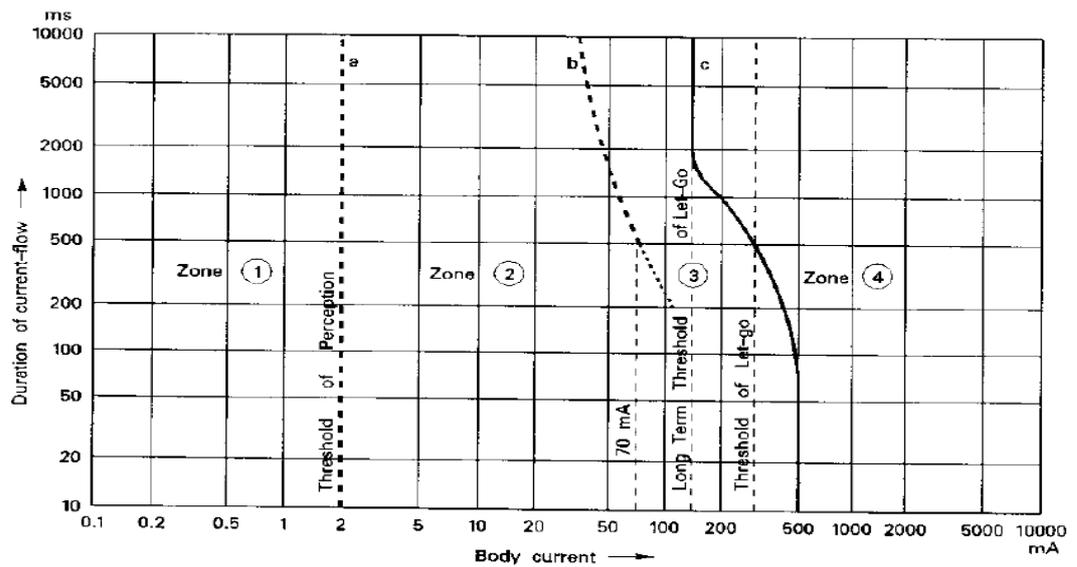


Fig 3.7. DC Curves [IEC 60479]

Table 3.2. Effect of DC on human body through different current zones

Zones	Effects
1	Usually no reaction
2	Usually no harmful physiological effects
3	Usually no organic damage can be expected, increasing with current magnitude and time, reversible disturbances in the heart or likely
4	Ventricular fibrillation likely, increasing with current magnitude and time other path physiological effects, For example: heavy burns are to be expected in addition to zone

DC is more likely to cause muscle tetanus than AC, making DC more likely to "freeze" a victim in a shock scenario. However, AC is more likely to cause a victim's heart to fibrillate, which is a more dangerous condition for the victim after the shocking current has been halted.

As high touch voltages leads into high currents flowing through the human body they cause humans tissue destruction. That is why it's generally known that the detrimental effects of electric shocks are due to the current flowing through the body, not the voltage itself. According to *Ohm's law* ($I=E/R$), it is difficult to correlate voltage with damage to the body because of the large variations in contact resistance usually present in accidents (Dalziel 1956). However, it is safe to assume the worst probable conditions to be present while analysing the risks due to touch voltages. This means that the contact resistance is for instance neglected or given some typical average value.

3.2.2 Voltage Transients

Voltage transients, sometime referred as "surges" or "spikes", are momentary changes in voltage or current that occurs over short period of time. Transients can be generated internally or from external sources.

External sources:

Lighting is the most common external source for voltage transients. Also short-circuit between two crossing systems, other with higher voltage level, causes voltage rise with transient inrush to the lower voltage system, until the protection operates.

Internal sources:

The main source of internal transients are device switching, static discharges and arcing. Transients can be generated from arcing via a number of sources like faulty contacts in breakers, switches and contactors. Other transients in power line can be normal utility operation such as opening and closing of disconnection switch

on energized lines. In distribution system poor or loose connection can also generate transients. Depending from the earthing system and overall system structure, earth faults and short circuits can also cause transient overvoltage.

Effects of voltage transients

- I. Electronics devices may operate at decreased efficiencies. Damage is not readily seen and can result in early failure of affected device.
- II. Integrated circuits (electronics chips) may fail immediately or fail permanently.
- III. Transients can interrupt the normal timing of motors and produce motor vibration, noise and excessive heat.
- IV. Transient may result in failure of all type of lights.
- V. In electricity distribution system transients degrade the contacting surface switches, disconnects and circuit breakers. Excess of transient voltage “nuisance tripping” of breakers and “fooling” it into reacting to a non-existent current demand.

3.3 Fault incidences and protection challenges

For reliable power supply, it's important to protect the grid in both islanded and grid-connected mode. The major issues raised from the protection point of view in the islanded mode are when power sources are attached through converter to the grid. The fault current supply capacity of converters is limited, so the overall magnitude of the fault current is typically not adequate for ensuring functioning of traditional over-current protection techniques. It is important to design a protection system which do not rely on high fault currents, but still enables reliable detection, identification and disconnection of faults. Development of a protection scheme for an island grid requires consideration of a combination of traditional protection devices, novel detection methods and proper protection design. The protection against the impacts of short-circuit currents and earth faults are naturally in the focus.

Fault can be simplified defined as an abnormal incidence in the network, that causes abnormal currents and voltages. Faults can be divided into two main types; active faults and passive fault. In active fault an actual current flows from one conductor to another conductor (line to line, line to neutral) or from conductor to earth (line to earth). It is recommended to clear these kind of fault as soon as possible because it very dangerous for the equipment and humans possibly somehow connected to the fault circuit. Passive faults are not real faults but it's the conditions which stress the network beyond its design capacity and will ultimately result in active faults. Example of such faults are overloading, overvoltage, under frequency.

3.3.1 Basic protection

IEC 61140 gives two possible ways as basic protection against electrical shocks

- I. Live conductors (energized parts) must not be accessible
- II. The touchable conductive part (metal enclosure of equipment's or metal pipes) must not be hazardous (live)

These two conditions must achieved both in normal conditions (no faults on the electrical system) and under fault conditions (such as fault from live conductor to a material casing)

Protection against fault conditions is achieved by basic protection, formerly known as protection against direct contact. Direct contact happens when a person comes in contact with live conductor (phase or neutral) or conductive element energised due to a fault. The most common basic protection method is placing the live parts 1) inside an enclosure or a casing made from insulation material, or 2) inside a conductive casing with protective earthing connection. Furthermore, the casings have to fulfil certain requirements concerning the size of an object that can be stuck in and their waterproofness. If the risk for contact voltages is greater the most common solution is utilisation of SELV (extra low voltage systems) or PELV (protected extra low voltage). Protection can also consist of placing live parts out of reach or insulating them by means of insulators, enclosure or barriers .

As an additional basic protection method, one of the most used method is to use High Sensitivity Residual Current Devices (HS-RCDs). However, the protection can never be based only on them.

Designing of protection system is completely independent from the earthing system however it is necessary in all supply circuits where earthing system is not mastered. IEC standard 61140 is used for protection against direct contacts (Electric 2008)

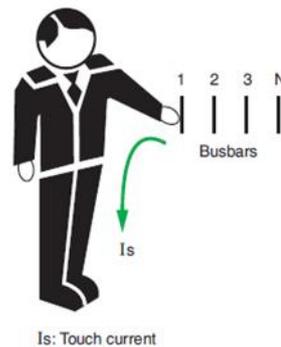


Fig 3.8. Direct Contact (Electric 2008)

IEC 61140 has also established protection classes for plugs and sockets used in electrical circuits. These classes are as follows (Excelsys 2006):

- I. Class 0 is based only on basic insulation protection and there is no earthing arrangements. These protection classes are intended to be used in dry areas.
- II. In Class I, the protection is provided by combination of basic insulation and use of electrical earth.
- III. Class II, are also known as double insulated and do not require an earth connection. the user is protected by at least two layers of insulation i-e, basic insulation and supplementary insulation between the current carrying parts and any metal assessable to the user.
- IV. Class III are designed to ensure protection from SELV power sources. The supply voltage of SELV is low enough that a person can safely come into contact without risk of electrical shock.

To define protection against the ingress of solid foreign objects and water with harmful effects, IP (ingress protection) codes are used. Annex B of the IEC standard gives instruction to technical committees for applying IP codes to the electrical equipment's.

The protection against the ingress of solid foreign objects is also used as a means of specifying protection against accidental contact with live parts. The IP code defined in the second edition of "IEC60529 Degrees of protection provided by enclosures (IP code)" consists of 2 numerals and 2 optional extra letters. The first numeral 0, 1,...6, or X defines the protection against ingress of solid foreign objects and against access to hazardous parts. The second numeral 0, 1,...8, or X defines the protection against the ingress of water. The higher the number the more stringent the protection requirement (529©IEC , Holland 2004).

3.3.2 Fault protection

Fault protection can be defined as “protection against electric shock during fault condition”. It means protection of persons or livestock possibly coming into contact with the exposed conductive parts which have become live due to fault condition. IEC 61140 standard has renamed “protection against indirect contact” with the term “fault protection”. The former name is at least kept for information.

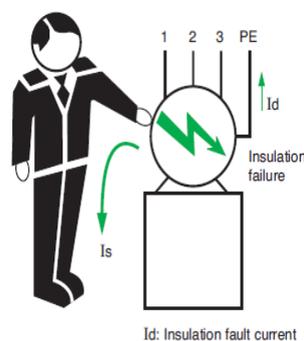


Fig 3.9. Indirect contact (Electric 2008)

Indirect contact happens when a person have contact with metal frame, accidentally energized due to an insulation failure. As such metal frames are normally connected to the protective earth system, a fault-current dependent potential rise between the frame and earth will appear. This is the touch voltage, discussed in an

earlier paragraph. If the fault current or the impedance of the equipotential bonding and earthing systems is high, the touch voltage increases and may become dangerous.

The fault protection can be referred as protection against indirect contact. Three basic principles can be distinguished, partly affecting also to the design of the fault protection system (ABB 2013):

- I. Implementing such earthing scheme that prevents an insulation fault representing a risks equivalent to direct contact.
- II. Equipotential bonding of frames helps to reduce contact voltage. Protective conductor (PE) is used which connects the frames of electrical equipment's of the entire network.
- III. The electrical hazards are measured for prevention of contacts in the network. For example measuring of insulation before energizing a device or prediction of faults based on monitoring system in unearthed installation (IT system).

All dangerous fault voltages in a network due to insulation fault, should be eliminated automatically by disconnecting the faulted part from the healthy part of the network. The disconnection methodology mainly depends on system earthing.

IEC 603641-4 states that the protective devices must coordinate with the earthing arrangement in the electrical installation in order to disconnect the supply if the touch voltages become dangerous for human body. There are two types of circuit described in IEC standard 603641-4. That is:

Final Circuit: It is the circuit which usually supplies equipment.

Distribution circuit: It is the circuit which supplies a distribution board to which other final circuits are connected.

Requirement for disconnection time in different earthing system are as follows:

- a) *TT earthing system*

For protection against indirect contacts by means of residual current devices the following condition should be fulfilled (ABB 2008).

$$R_A \cdot I_{\Delta n} \leq 50V \text{ then: } R_A \leq \frac{50v}{I_{\Delta n}} \quad (3.2)$$

Where:

R_A is the total resistance (in ohms) of the earth electrode and of the protective conductor of the exposed-conductive-parts,

$I_{\Delta n}$ is the rated residual operating current of the residual current-circuit breaker. In the following table U_o is the nominal AC or DC line to earth voltage.

Table 3.3. Maximum disconnection times for final circuits not exceeding 32A

System	$50v < U_o$		$130v < U_o$		$230v < U_o$		$U_o > 400v$	
	AC	DC	AC	DC	AC	DC	AC	DC
TT	0.3s	*	0.2s	0.4s	0.07s	0.2s	0.04s	0.1s

*disconnection may require for reasons other than protection against electric shock

b) TN System

According to IEC 60364-4-41. the following condition should be fulfilled in order to provide protection against indirect contact in a TN system for automatic disconnection of the circuit (ABB 2008).

$$Z_s \cdot I_a \leq U_o \quad (3.3)$$

Where:

Z_s is the impedance of the fault loop comprising the source.

I_a is the disconnection current in amperes of the protective device within the times defined in table as a function of the rated voltage U_o for final circuits with the currents not exceeding 32A.

Table 3.4. Maximum disconnection times for final circuits not exceeding 32A

System	$50v < U_o$ $> 120v$		$130v < U_o$ $> 230v$		$230v < U_o$ $> 400v$		$U_o > 400v$	
	AC	DC	AC	DC	AC	DC	AC	DC
TT	0.8s	*	0.4s	5s	0.2s	0.4s	0.1s	0.1s

*disconnection may be required for reasons other than protection against electric network

It is necessary to realize a supplementary equipotential bonding connected to the earth, when automatic disconnection cannot be provided in the compliance with the time of the table or within conventional time. However, the use of supplementary bonding does not exclude the need to disconnect the supply for other reasons, for example protection against fire, thermal stresses in equipment, etc.

c) IT system

According to IEC 60364-4 in IT system, the automatic disconnection of the circuit in case of a single earth fault is not necessary, provided the following condition is fulfilled (ABB 2008):

$$R_A \cdot I_d \leq 50 \text{ Va. c.} \quad (3.4)$$

$$R_A \cdot I_d \leq 120 \text{ Vd. c.} \quad (3.5)$$

Where:

R_A is the sum of the resistance, in ohms, of the earth electrode and protective conductor for exposed-conductive-parts;

I_d is the fault current, in amperes, of the first fault of negligible impedance between a line conductor and an exposed-conductive-part; such value takes account of the leakage currents and of the total earthing impedance of the electrical installation.

Insulation monitoring device should be installed in IT system which provide information about first fault condition in the network. According to IEC standard

61557-8 an insulation monitoring is a device which constantly monitor the insulation of an electrical device. The first fault situation should be cleared within 2 hours before the second fault take place otherwise it will lead in to dangerous situation.

3.3.3 Earthing system

Earthing is used in electrical networks to set up earth connection, to drain off the flow of electricity in the event of a short circuit, an earth fault or power surge for safety measures. The choice of earthing system can affect the safety and electromagnetic compatibility of the power supply, and regulations can vary considerably among countries.

An effective earthing system has the following objectives (Don Jacob 2008):

- I. The first key objective of earthing is to ensure human safety, if a person working or walking in an earthed network environment shouldn't be exposed to critical danger voltages. The touch and step voltage produced in a fault condition should be limited to safe value i.e. the current flowing through human body is limited to safe level.
- II. Earthing system should provide path to carry and dissipate electric current in to earth under fault condition which will help in to equipment safety and continuity of services.
- III. In case of lighting impulses or surges, earthing system should be provided in a facility in order to reduce damages to the equipment's and cables.
- IV. Protective equipment performance, particularly at minimum fault can improved by providing low resistance for the protective relays to see and clear earth faults.

There are two types of earthing system design: protective earthing and functional earthing. In protective earthing the system provides an earth wire between all the conductor surfaces and earth or earth wire of the conductor. Due to this the electrical potential of these surfaces are matched to that of the earth. The protective earthing can be single or multipoint.(Heimbürger 2005, IEEE 2012)

Functional earthing are also known as equipotential bonding and used for protection of electrical components from sudden power surges. It takes the direct power surge and route it safely to the earth. This protection scheme is commonly used in surge protection devices to protect electrical equipment's.

Due to the low resistance of protective earthing, a short burst of high current is produce to activate circuit protection device and shut off power to the circuit. However in case of functional earthing the circuit protection may not triggered. To avoid this problem, a residual current is installed to sense leakage current to the earth. When leaked current is detected, the device shuts the circuit down.

3.3.4 Overcurrent protection

Overcurrent is a situation in which larger currents than the intended ones exists in the conductor. These excess currents can lead to danger risks such as heating of conductor, fire and damages to the equipment's. Overcurrent in the electrical network can be taken place because of short circuits, excessive loads and incorrect design of the network. Over current protection devices such as circuit breaker and fuses are used to protect the network by opening the protection devices in case of excessive currents or dangerous temperature rise. Reliable overcurrent protection devices responds both in short circuit, ground faults and overloading in the network. Overcurrent risks can be overcome by using of fuses, circuit breakers, temperature sensors and current limiters. IEC 60364-4-43 give details on overcurrent protection.

Overcurrent protection must react fast and be selective and reliable in faulty network condition. It is also one of the basic protective relaying principles and with respect to distance and differential protection systems, overcurrent protection is more economical and, therefore, favored on a distribution level (Timo Keil 2008).

Different types of overcurrent protection area as follows (Alstom 2011) :

a) Discrimination by time:

In this type of protection scheme, each relay is given an appropriate time setting to control the circuit breakers in the network to ensure the circuit breaker nearest to the faulty zone opens first.

b) Discrimination by current:

In this method the fault current varies with the position of the fault because of the difference between the source and fault. Hence, the relays controlling the various circuit breakers are set to operate at suitably tapered values of current such that only the relay nearest to the fault trips its circuit breaker.

c) Discrimination by both time and current:

The methods described above has fundamental disadvantages. The disadvantage in case of discrimination by time alone is due the fact, that more severe faults are cleared in the longest operating time. In case of discrimination by current the disadvantage is that, it can be applied only where there is appreciable impedance between the two circuit breaker concerned. The inverse time overcurrent relay characteristic has evolved because of the limitation imposed by the independent use of either time or current co-ordination. With this characteristic, the time of operation is inversely proportional to the fault current level and the actual characteristic is a function of both ‘time’ and ‘current’ settings. When there is variation in fault currents between the two end of the feeder, faster operating times can be achieved by the relays nearest the source, where the fault level is the highest. The disadvantages of grading by time or current alone are overcome. *“The selection of the overcurrent relay characteristics generally starts with selection of the correct characteristic to be used for each relay, followed by the choice of the relay current settings. Finally the grading margins and hence time required to resolve conflicts, may involve use of non-optimal characteristics, current or time grading settings”*(Alstom 2011).

The current/time tripping characteristics of IDMT (inverse definite minimum time) relays may need to be varied according to the tripping time required and the characteristics of other protection devices used in the network. For these purposes, IEC 60255 defines a number of standard characteristics as follows:

- I. Standard Inverse (SI)
- II. Very Inverse (VI)
- III. Extremely Inverse (EI)

IV. Definite Time (DT)

Table 3.5. Relay characteristics to IEC 60255

Relay Characteristic	Equation (IEC 60255)
Standard Inverse (SI)	$t = TMS * \frac{0.14}{I_r^{0.02} - 1}$
Very Inverse (VI)	$t = TMS * \frac{13.5}{I_r - 1}$
Extremely Inverse (EI)	$t = TMS * \frac{80}{I_r^2 - 1}$
Long time standard earth fault	$t = TMS * \frac{120}{I_r - 1}$
$I_r = \frac{I}{I_s}, \text{ where } I_s = \text{relay setting current}$	
$TMS = \text{Time multiplier setting}$	

3.3.5 Under voltage protection

Voltage decrease to 90% of its nominal value for more than one minute is called under voltage. This is also sometime called “brownout” which is not officially used term for under voltage. Brownout is a phenomenon in which the utility intentionally reduces the voltage in order to accommodate high demand or other problems.

The customers end voltage are kept at $\pm 5\%$ of the nominal voltage value in the electrical network. Too much load on the utility system or the loss of major transmission line serving the a region can lead into under voltage scenarios. sometimes the utility deliberately cause under voltage to reduce the loads during the heavy load conditions. Under voltage leads into malfunction of the equipment and can cause excess wear on the devices as they will tend to run overly hot (Kennedy 2000).

Under voltage situation is also dependent on distribution system characteristics. For example, line losses can result in voltage drop, which can affect the end users, regardless utility voltage variations. The under voltage protection can be implemented in the electric network by under voltage relays.

3.3.6 *overvoltage protection*

Voltages that exceeds the normal values are known as overvoltage. The normal values are mainly defined by the ratings of used insulations, which are tested by taking into account appropriate regulations. Overvoltage condition are often caused, for instance, by lightning strikes on electrical network. Overvoltage protection doesn't consist of one element but rather several functional elements in one system. Just like in the case of voltage transients, also other phenomena, like internal faults may cause overvoltage, as well as the switching incidences.

For the purpose of overvoltage protection surge protection devices (SPDs) are used. According to IEC 61643, SPDs are classified into three types. These are as follows:

a) Coarse protection (SPD type I):

SPDs that are designed to withstand a strike of lightning and have largest impulse current discharge capacity are SPD type I. In this case the light strikes directly the conducting parts of the electric network

b) Medium protection (SPD type II):

SPDs that are designed to protect from indirect effects of lightning and have a lower impulse current discharge capacity are SDD type II. In this case strong electromagnetic field can be developed by light strike in vicinity and can results in high voltages in electric network.

c) Fine protection (SPD type III):

SPDs which are used to protect sensitive electronic devices from the impact of lightning strikes far away and have lowest current discharge capacity are known as SPD type III. "For reliable protection against surges, it's better to use SPD type

with SPD type II connected downstream if fractions of lightning currents are anticipated” (SMA 2011).

3.4 Special electrical safety characteristics of MGs

One of the major challenges in realisation of MGs is to design protection system capable to respond to the both modes of operation. The components of the protection system must be designed to operate in both the grid interconnected mode and the islanded mode. The fault currents and voltages in grid-connected and islanded MG are usually significantly different.

There are several methods proposed for protection of AC MGs. The wide variety of equipment's that are used in AC MG protection are the one which is used also for protecting the conventional AC distribution networks. These devices are mainly over current relays, reclosers, sectionalizers, MCBs and fuses.

Utilisation of fuses and automatic relays, operation of which is based on fault current measurement, is challenging in MG environment. These traditional protection devices are difficult to use with the power electronic converters, because converters are not able to supply high enough short circuit current for long time enough, as required by the traditional protection devices. Because of these challenges, novel protection system designs are needed with different fault detection methods. Furthermore, the earthing arrangements need to be reconsidered to enable person safety, even though the primary protection system would fail from some reason.

The low voltage distribution scheme vary among different utilities, such as fuse saving schemes, (*“This approach makes the attempt to minimize customer interruption time by attempting to open the breaker or recloser faster than it takes to melt the fuse. This saves the fuse and allows a simple momentary interruption—a blink. For most systems, this works pretty well. In high short-circuit areas, it may not be possible to make this approach work”*), fuse blowing scheme (*“The approach here is to eliminate the fast trip of the breaker or recloser and have the fuse operate for all permanent and temporary faults. The purpose of this scheme is solely and entirely to minimize momentary interruptions. This scheme is very*

successful in high short-circuit areas where a fuse save approach does not work anyway) (CRAIG A O MEALLY 2010), instantaneous reclose and delayed reclose delays. One of the method used for AC MG protection is to protect each DG unit with its own relay and operate in decentralized mode. This method is suitable for line-line and line to ground faults but however it's become less reliable in case of high impedance faults.

Another method used for AC MGs are centralized voltage protection. While using this method the phase voltages are transformed into d-q-0 axes and then it's compared with the reference voltage via MGCC (microgrid control centre) equipped with central protection unit. When the change in the measure voltage is different from the reference voltage, the tripping device become activated and isolate that part from the AC MG. In this case *“applications of high speed protection devices such as the standards IEC61850- based communication for fast response, selective and reliable operating scheme ,are mandatory”* (MESMAEKER 2005).

As DC MGs are emerging technology and still there are a lot of research going on to make them more reliable and efficient for commercial use, one of the main challenges that researchers are facing regard the protection of the grid. The main challenges are the protection system of the customer-end network, faults including inverter switching transients, and double-fault situations between AC and DC networks. Otherwise, the protection system in DC MGs mainly consists of current interrupting devices, protective relays, measuring equipment's and earthing systems.

Most of the faults in the DC MGs can be covered with combined over-current and short-circuit protection together with over current protection. If required by the earthing system, also earth leakage monitoring or respective isolation (or insulation) monitoring devices can be needed. Nowadays DC circuit breakers are also available in the market which can be used for short circuit protection more reliably than fuses.

For larger LV DC system such as traction power system, high speed DC circuit breaker are available. These circuit breakers are designed to fully handle rated

voltage and current and starts to interrupt the fault current within 0.01s. However, there may be problems at low currents which can cause circuit breaker contacts to weld together (SALOMONSSON 2008).

4 Electrical safety of studied DC micro grid

The safety issues are the most important in the whole network. The power quality can be sacrificed, if there could otherwise be a safety risk due to the securing power quality. At different points of the network i.e. at PV modules, DC mains, batteries, customer AC network and power electronic converters, there are risks of different fault scenarios.

Possible earthing arrangements assumed to be used for the system are TN-S at PV generator side and on customer AC network side and IT system for DC mains. One reason for the use of IT system for the DC mains is due to the continuity of power supply to customer-end network. The use of IT system in DC mains ensures low touch voltages during earth fault of a DC pole (Pasi Salonen 2009). IMD is used to detect the first fault situation in the DC mains and will not affect the power supply until second fault happens in DC mains.

4.1 Possible fault situations

As the LVDC network is composed of PV generator, DC mains, batteries and customer end network. The possible fault situation in each of these areas are discussed in the following paragraphs.

4.1.1 Possible faults in the PV Generator

To protect the PV generator from damages and to overcome the risks of safety hazards, a proper fault analysis should be taken into account while designing a PV power plant. Fault analysis in PV generator has a fundamental impact on the overall efficiency, reliability and safety of the system.

If the faults situation in a PV generator is not properly analysed, it will result in DC arcs and fire risks leading into damaging the PV cells. In addition, it may also cause energy losses in the PV generator. For instance, in UK domestic PV systems, the annual energy loss due to faults in PV systems is estimated to be up to 18.9%. Fault location, fault impedance and irradiance level, and use of blocking diodes has also a strong impact on the fault behaviour of the PV array (Ye Zhao 2013).

Table 4.1. PV Generator faults and their effects

Faults		Effects on Equipment's	
I.	Line-to-line Faults	I.	DC Arcs
II.	Line-to-Ground Faults	II.	Damage to Insulation
III.	Over current	III.	Fire
IV.	Reverse current		
V.	Over Voltage		

4.1.2 Possible faults in the DC Network

The DC mains are the main supply links to the customers and there should be taken care of the fault situation in order to have a reliable supply. According to studies (Pasi Salonen 2009) the possible faults situations in a dc network are:

Table 4.2. Dc main faults and their effects

Faults		Effects on Equipment's	
I.	short circuit in a positive pole	I.	Conductor break
II.	short circuit in a negative pole	II.	DC Arcs
III.	short circuit between positive and negative pole without neutral connection	III.	Welding of conductor
IV.	short circuit between positive and negative pole with neutral connection	IV.	Loosing transmission capability of the grid.
V.	short circuit through earth	V.	Degradation of conductor /changing characteristics of power transmissions
VI.	earth fault in positive conductor	VI.	Damage to insulation
VII.	earth fault in neutral conductor	VII.	Disturbance in control and monitoring
VIII.	earth fault in negative conductor		
IX.	Short Circuit fault through earth		

4.1.3 Possible faults in Customer AC Network

In LVDC System the customer AC network has the same fault scenarios as a traditional AC network. The possible faults are as follows:

Table 4.3. AC network faults and there effects

Faults		Effects on Equipment's	
I.	Phase-to-earth fault	I.	Damage to insulation
II.	Phase-to-phase fault	II.	Welding of conductors
III.	Phase-to-phase-to-earth fault	III.	Fire
IV.	Three phase fault	IV.	Dynamic instability
V.	Three phase-to-earth fault		

4.1.4 Possible faults in the Batteries

The possible faults in the batteries are as follows:

Table 4.4. Batteries faults and their effects

Faults		Effects	
I.	External Faults (physical damage)	I.	Temperature rise
II.	Over charging	II.	Explosions
III.	Short circuits	III.	Cell leakage
IV.	Ground faults	IV.	Internal grid and plate corrosion
V.	Under charging	V.	Loose inter cell connections
		VI.	Gassing
		VII.	Terminal corrosion

4.2 Earthing system selection

The purpose of earthing is to provide safety and protects personnel, equipment's and facilities against electrical hazards. Both earthing and overcurrent protection is necessary in a network and how they relate to provide a reliable means of protection.

As speed and sensibility is a key feature in a protection system which means the system should work accurately and quickly to diagnose the faulty point to minimize the damage, so for this proper earthing system plays an important role.

According to IEC 60364, there are three types of earthing system:

TT: Transformer neutral earthed, and frame earthed

TN: Transformer neutral earthed, frame connected to neutral

IT: Unearthed transformer neutral, earthed frame

The TN system, as in IEC 60364, includes several sub-systems:

TN-C: if the N and PE neutral conductors are one and the same (PEN)

TN-S: if the N and PE neutral conductors are separate

Each earthing system can be applied to an entire LV electrical installation; however several earthing systems may be included in the same installation. The purpose of these three earthing systems is identical as regards protection of persons

and property. They are considered to be equivalent with respect to safety of persons against indirect contacts.

According to studies (Bernard Lacroix 1995) the earthing system can be categorized as presented in the table 4.5 according to their performance.

Table 4.5. Evaluation of earthing system according to their performance

	TT	TN-C	TN-S	IT
Safety of persons (perfect installations)	GOOD	GOOD	GOOD	GOOD
Safety of equipment:				
✓ against fire hazard	GOOD	POOR	AVERAGE	GOOD
✓ in insulation faults	GOOD	POOR	POOR	GOOD
Availability of electrical power	AVERAGE	AVERAGE	AVERAGE	EXCELLENT
Electromagnetic compatibility	AVERAGE	POOR	AVERAGE	AVERAGE
Installations and maintenance:				
✓ Skills	AVERAGE	EXCELLENT	EXCELLENT	GOOD
✓ Availability of personnell	POOR	AVERAGE	AVERAGE	GOOD

4.2.1 PV Earthing

PV systems vary in ranges i-e from 12-volts system to hundreds of watts of systems. System and earthing practice varies between different countries. PV code and PV system earthing requirements has to follow in order for safe operation of PV generator. IEC has the following standards for PV system installation which also cover the earthing practice. These are as follows:

- I. IEC 60364-7-712: 2002-05: Electrical installations of buildings, Part 7-712: Requirements for special installations or locations and Solar photovoltaic (PV) power supply systems
- II. Technical specifications IEC TS 62257-7-1: 2006-12 Recommendations for small renewable energy and hybrid systems for rural electrification, Part 7-1: Generators Photovoltaic arrays

4.2.1

4.2.1

- III. Technical specifications IEC 62257-5: 2005-07: Recommendations for small renewable energy and hybrid systems for rural electrification, Part 5: Protection against electrical hazards
- IV. International standard for PV inverters, IEC 62109-1: Safety of power converters for use in photovoltaic power systems, Part 1: General requirements
- V. IEC 62109-2, Safety of power converters for use in photovoltaic power systems, Part 2: Particular requirements for inverters.

The PV systems can be unearthed or earthed depending on the used panel type and grid interconnection converter design.

Unearthed

In unearthed system the first fault will not cause any fault current but the second earth fault in the conductor with different voltage will allow fault current which will circulate through the circuit. Significant shock hazard can result in the form of a capacitive discharge on under grounded system because of the PV array modules and conductor capacitance to ground. In order to eliminate charges on these distributed capacitances resistance grounding can be used (Bower W.I 1994).

Earthed

In earthed system, the first ground fault will cause the current flow and the protection device i-e over current devices near the location will operate at instance to interrupt the fault current. Distributed capacitances are a lesser problem because they are already ground referenced and act in the same manner as the other grounded current sources (Bower W.I 1994).

Both unearthed and earthed PV system has it's on advantages and disadvantages.

In unearthed system there is less risk of fire hazard because multiple faults are needed in a PV array which results in fire scenarios. The best solution for human safety against electric shocks can be possible if there is reliable sensitive earth fault detection and no leakage. Due to well defined voltages to earth the personnel safety against the electric shock is reliable in earthed PV system. Personnel, equipment and fire safety can be achieved in both systems if they are designed

properly. Different earthing schemes of PV panels are show in the following figures.

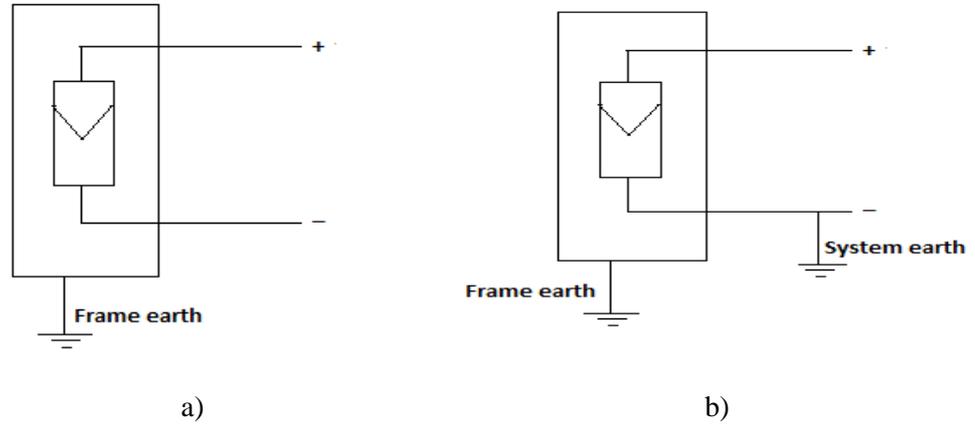


Fig 4.1 PV panel a) functionally unearthed (but protectively earthed), b) functionally earthed.

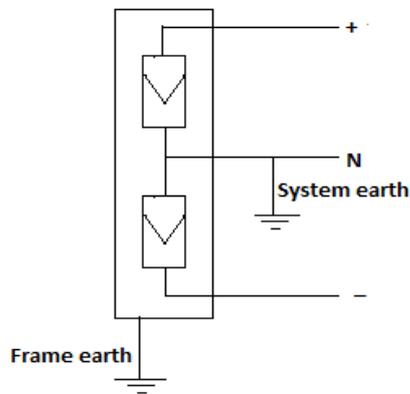


Fig 4.3. PV panel with centre taped functional earthing

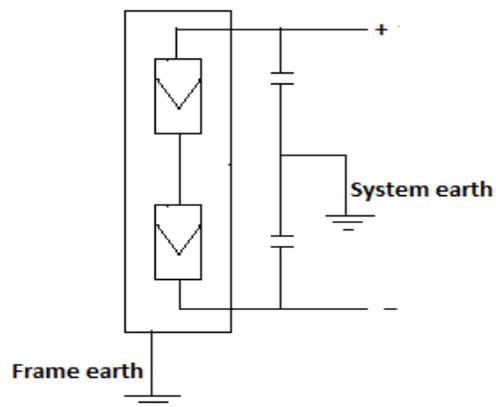


Fig 4.4. Capacitively coupled center taped earthing

4.2.2 Earthing of DC mains

The DC distribution system can be made with unearthed IT system or earthed TN system. The earthing arrangements in case of bipolar DC system are shown in fig 4.5 (Pasi Salonen 2009).

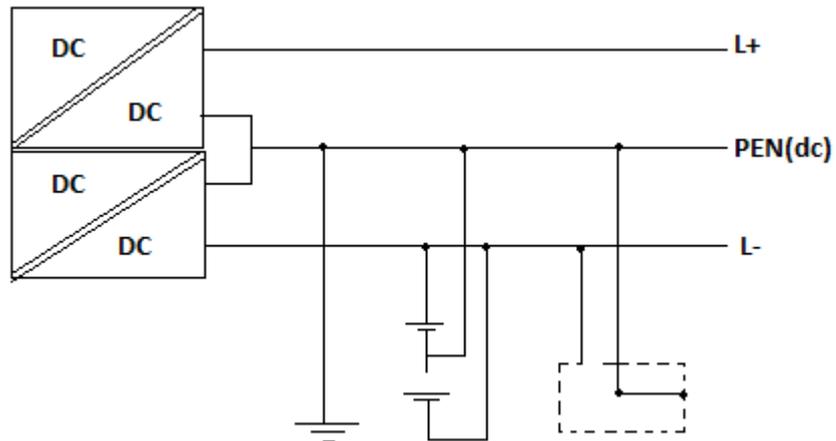


Fig 4.5. Earthing arrangements in case of earthed system Bipolar LVDC system adopted (Pasi Salonen 2009)

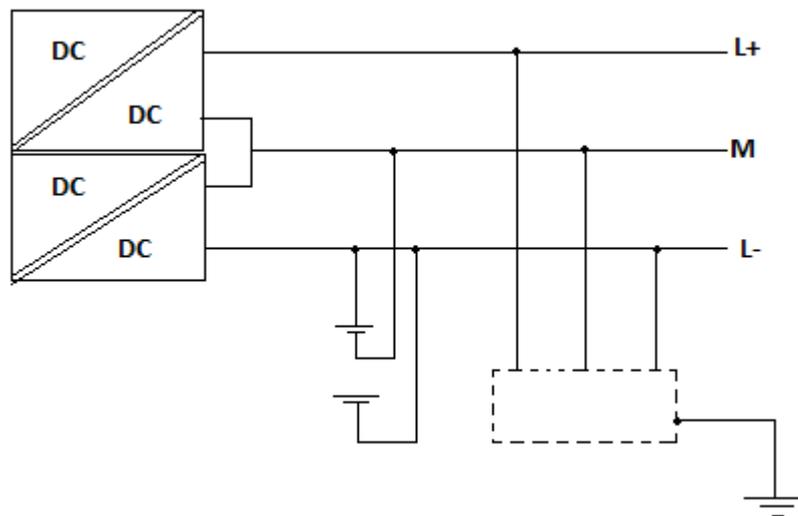


Fig 4.6. Earthing arrangements in case of unearthed system Bipolar LVDC system adopted from (Pasi Salonen 2009)

System maximum voltages are influenced by system earthing arrangements. The European Union directive 2006/95/EC defines DC voltage between 75 – 1500 VDC and AC voltage between 50 – 1000 VAC . Maximum allowable voltages

defined by LV standardization in different earthing arrangements are shown in the following table (Pasi Salonen 2009).

Table 4.6. Maximum voltages for grounded and ungrounded systems

Grounding Arrangement	Voltage against earth [VDC]	Voltage between conductors [VDC]
Earthed TN system	900	1500
Unearthed IT system	-	1500

LV transformer neutral point cannot be earthed like in traditional 20/0.4 kV AC system in both grounding arrangements. According to the table Evaluation of earthing system according to their performance the IT earthing is best option because it will no effect the continuity of power to the customer ends in first fault condition.

4.2.3 Earthing of AC network

TN-S system will be used for earthing in customer premises. This earthing system is compulsory for cross-sectional areas below 10 mm² for copper or 16 mm² for aluminium . On the other hand TN-C system must not to be used for cross-sectional areas below 10 mm² for copper or 16 mm² for aluminium (Electric 2007).

A TN-S system has the supply source directly connected to earth, the installation metalwork connected to the neutral of the supply source via the lead sheath of the supply cable, and the neutral and protective conductors throughout the whole system performing separate functions.

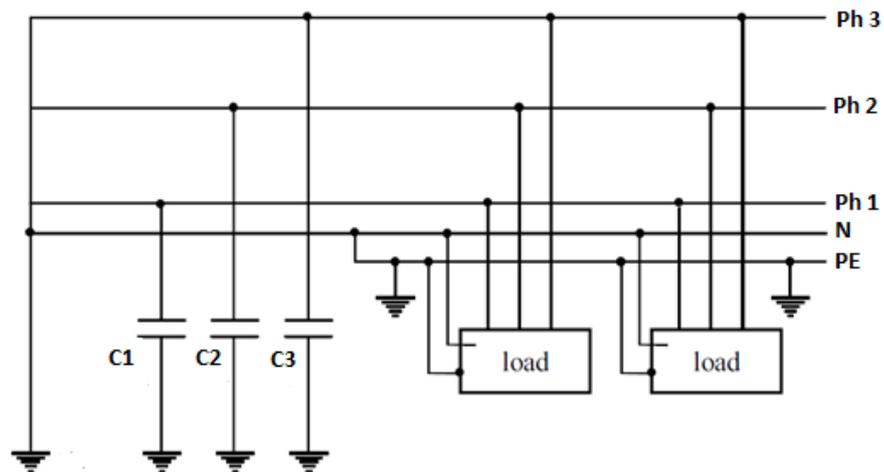


Fig 4.7. TN-S Earthing System (Electric 2007)

Fault connection and leakages occurs in TN-S system due to the network itself or defective devices. Energy supply is not affected by these faults but it causes some other disturbing influences such as fire risks, electromagnetic disturbances and possibility for the high frequency disturbance voltages in the neutral conductor to penetrate in to the protective earthing.

If the TN-S system is continuously supervised by monitoring devices the above mentioned disturbances can be eliminated and faulty connection and faulty devices can be located easily. There are several devices which is use for continuous supervision of TN-S network.

5 System protection overview

The safety issues are the most important in the whole network. The power quality can be sacrificed in a case where there could otherwise be a safety risk due to the securing power quality. At different point of the network i-e PV modules, DC mains, batteries, customer AC network and power electronic converters, there are risks of different fault scenarios. For protection against short circuit currents relays, circuit breakers and fuses are used depends on the short circuit current magnitude. Possible earthing arrangements used for the system is TN-S at PV generator side and on customer AC network side and IT system for DC mains. One such reason for the use of IT system for a DC mains are because, the continuity of power supply to customer end network. An insulation monitoring device is used to detect the first fault situation in the DC mains and will not affect the power supply until second fault happens in DC mains. The following figure 5.1 shows implementation of protection devices in one section of the network.

From the figure we can see protection devices are installed at different location of the network section. IM (insulation monitoring) devices are installed to detected earth faults and over current relays are installed to protect DC/DC converters and batteries in case of short circuits. Protection relays are active by ICT (information communication technology) differential protection system. At each section of the network ICT slave are installed to take measurements and give those measurement to the master ICT to control the protection system of the whole section. ICT are explained further in detail. The earthing system for PV panels and AC costumer network are TN-S, while for DC mains are IT earthing system. Both earthing system shares the same equipotential bonding. Furthermore each part of the section i-e PV generator, DC mains and Costumer AC network are galvanically isolated.

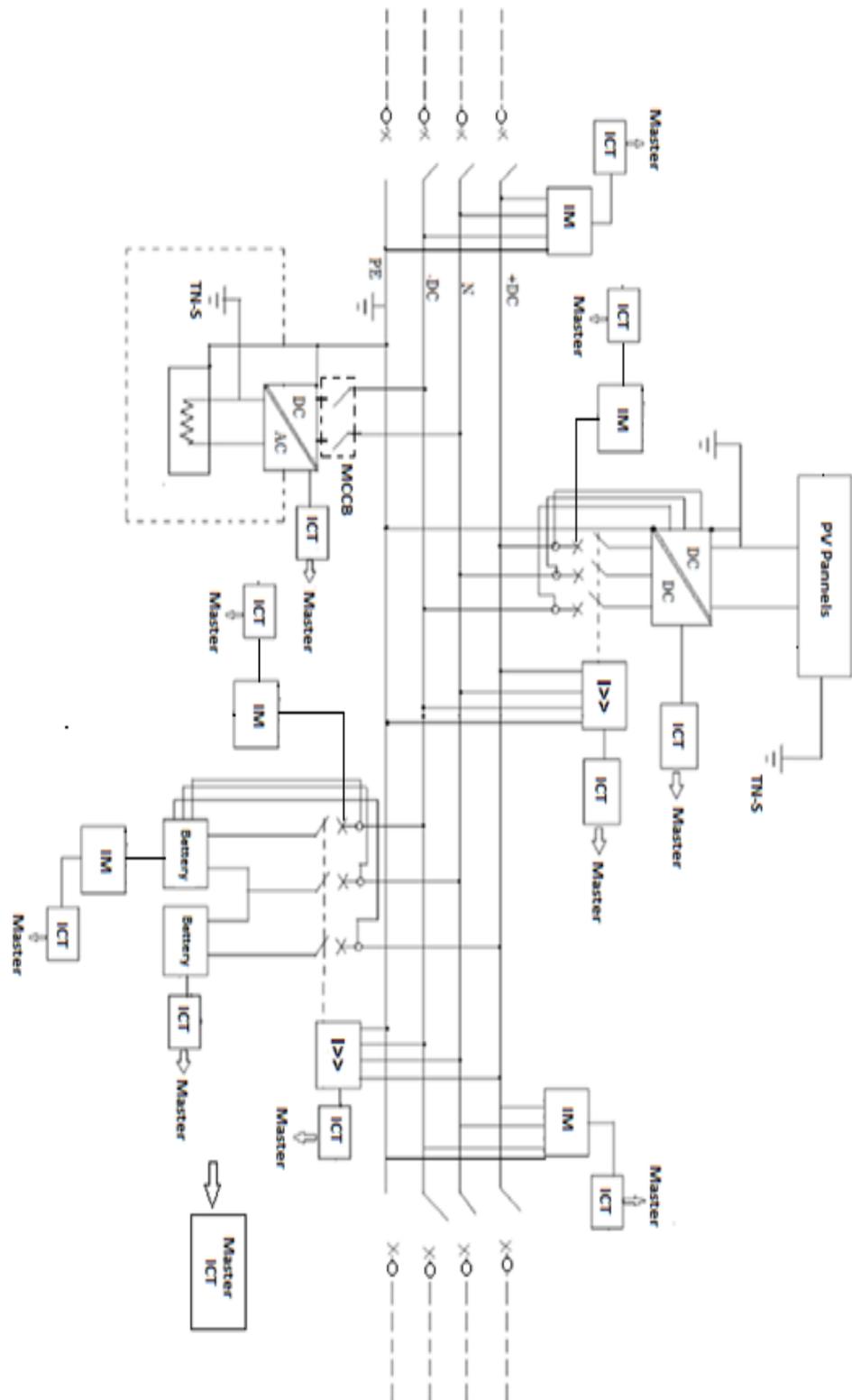


Fig 5.1. Protection system of the network

5.1 Possible risks from fault situations

The most possible fault situations are line faults, line-line faults and line-to-earth-faults. In case of DC mains as the earthing system is IT and will not affect the power continuity in first fault situation, but if second fault occurs the IT system will be changed into TN system and will affect the power continuity to the end users as well as risks for humans become increased. The double faults probability can be reduced by using insulation monitoring device which will detect first fault in the system. The other risk which should be taken into consideration is that the system shares same equipotential bonding, so if the short circuit currents flow from different points of the network there will be risk on humans and also chances of fire hazards. But this risk can be minimized by the use of galvanic isolation. As the PV generator, DC mains and Customer end network are galvanically isolated, so there is almost no risk of faults in one section will affect the other section.

5.2 Earth fault protection (DC mains)

In functional earthed TN system earth faults are always short circuited, so there is no need for separate protection devices against earth faults. Used protection devices can be overcurrent relays and fuses. As the DC mains in the Network is unearthed (IT) system, so it means that the earth faults are not short circuited and we can't detect the earth faults by traditional methods. So for this purpose insulation monitoring device is used to detect the first earth fault in the DC mains. LV standardization also demands insulation monitoring devices to be used in unearthed IT systems.

In a broader picture there is no single pole short circuit through earth in the IT system because of lack of current return path. Because of this quality traditional protection devices such as fuses cannot be used for protection in unearthed system. In case of double earth fault the IT system is converted into TN system which is more dangerous for equipment's and humans. For detection of first earth fault the LV standardization demands to use insulation monitoring devices in unearthed system and maximum earth fault clearance time is 2 hours. But it's also important the protection engineers clear the first earth fault situation in the network before the

second fault happens which can cause high earth voltage over allowed earth voltage limit (Pasi Salonen 2009).

5.3 Circuit Breakers

The circuit breaker operation depends on Relays which are further dependent on ICT system. The ICT in the system will give the trip instruction in case of fault situation. In real life situation the selection of circuit breaker is dependent upon short circuit currents which is based on the cable sizing, cable parameters and length of the cable. AC circuit breakers can be used for DC application but currently in the market there are also circuit breakers available which are purely designed for DC application. As the clearance time for DC fault is 0.5 sec, so B-type circuit breaker can be used (Pasi Salonen 2009).

5.4 PV System protection

There are two important characteristics of PV systems.

- I. AS long as the PV module is exposed to the sun the DC voltage level cannot be shut off.
- II. Short circuit current generated in PV modules are very low and therefore special measure should be done in order for the correct operation of the protection devices.

5.4.1 Protection against electric shocks

According to IEC 60364-712, if maximum open circuit voltage U_{ocMAX} of PV system is higher than 120 VDC a double or reinforced insulation should be used as protection against electric shock. In PV system fuses or circuit breakers cannot ensure safety against electric shocks because of the continuous DC current which cannot be cut-off as long as the PV panels are under the sunlight.

5.4.2 Protection against thermal effects

Thermal effects lead in to risks of fire. There are three conditions which can create abnormally high currents and can create such scenarios. These are as follows:

- I. Insulation fault
- II. Reverse current
- III. Overloading of cables or equipment's.

5.4.3 *Insulation fault detection*

For insulation fault double or reinforced insulation is the main solution but it cannot ensure electrical safety. Because of this reason insulation monitoring device should be used if the PV panel technology requires one of the conductors to be grounded. An Insulation monitoring device able to handle capacitance up to 500 μF is suitable for PV system.

5.4.4 *Protection against reverse current*

Reverse current in the PV module can be introduced by faulty wiring, short circuit or other related faults. In this case the open circuit voltage of one string is completely different from the other open voltage of the string which is connected in parallel to the same converter. Instead of the current flow from the healthy string to converter, it flow to the fault string and reverse currents take place which can lead to dangerous temperature rises and fires in PV modules.

In order to ensure safety against reverse current, the PV module withstand capability should be tested in accordance with IEC 61730-2 standard and the PV module manufacturer shall provide the maximum reverse current value (I_{RM}).

Reverse current in the faulty string is normally equal to the total current of the remaining strings. Overcurrent protection for a string should be taken in to account if the total number of strings that could feed one faulty string is high enough to supply a dangerous reverse current:

$$1.35 I_{RM} < (N_s - 1) I_{SC\ MAX} \quad (5.1)$$

where: I_{RM} is the maximum reverse current characteristic of PV cells defined in IEC 61730, N_s is the total number of strings, and $I_{SC\ MAX}$ is the maximum short-circuit current of PV string.

If there is only one string attached to the converter then there is no risk of reverse current or when the same number of PV modules connected in parallel made of two strings, the reverse current will be always less than the maximum reverse current capability of the PV modules. In case where PV generator is made of two strings, there is no need of reverse current protection.

Blocking diodes

Blocking diodes are mainly used in series with PV modules to prevent the system from reverse currents. The main reason for reverse currents is mainly because of batteries in night. Reverse current can also take place if one string becomes severely shaded, or if there is a short circuit in one of the modules, so to prevent other strings for losing current backward in both cases blocking diodes are used. In this scenario the shaded or damaged string is isolated from other string for protection point of view which may not results in dangerous situations. While taking this configuration into account, the blocking diodes are sometimes called “isolation diodes”.

As protection engineers doesn't consider it suitable for protecting the strings, since it's inadvisable to be used in PV generators. According to IEC 62257-7-1 blocking diodes are not suitable for over current protection as the blocking diode may not function correctly and could be short circuited. Blocking diodes can also leads to power loss owing to the effect of voltage drop on junction. This loss can be reduced to 0.4 v drop by using a schottky diodes instead of using a conventional diodes which results in 0.7 v drop.

“If reverse cut-off diodes are chosen, their maximum reverse voltage (according to IEC 60364-7-72 standards) must be at least twice the open circuit U_{OC} string voltage in STC (standard test conditions). The direct over current must be higher than the short-circuit current I_{SC} of the individual modules, with 1.25 I_{SC} minimum value” (ABB 2010).

5.4.5 *Protection against overcurrent*

Thermal effects can be caused by overcurrent which is dangerous for electrical installation. Short circuits in PV module depend upon solar irradiance but it's also important that maximum trip current should be significantly lower than $I_{STC_{MAX}}$. For over current protection fuses and circuit breakers are used and rating of string overprotection devices should be greater than 1.25 the array short circuit current $I_{SC_{STC_ARRAY}}$.

For array protection nominal related trip current (I_{TRIP}) of overcurrent protection devices for PV arrays (fuses or circuit Breaker) shall be greater than 1.25 times the array short-circuit current $I_{SC_{STC_ARRAY}}$.

While choosing protection device for overcurrent safety, the rating should be selected in order to avoid unexpected trip in normal operation taking into account temperature. A protection rating higher than 1.4 times the protected string or array short-circuits current $I_{SC_{STC}}$ is usually recommended.

According to IEC 712.433.1, an overload protection may not take into account for PV strings and PV array when the continuous-current capacity of the cable is equal to or greater than 1.25 times I_{sc_stc} at any location.

Another recommendation stated by IEC 712.433.2 is that overload protection may not be considered for PV main cables if the continuous current-carrying capacity is equal to or greater than 1.25 times $I_{SC_{STC}}$ of the PV generator.

5.4.6 *Protection against overvoltage (Surge protection)*

PV modules are exposed to lightning strikes which can cause over voltage in the system. There are two main methods for surge protection in PV systems.

Protection by equipotential bonding

Equipotential is necessary to create equal potential at all points in the installed system. For this purpose metal conductor that ensures equipotential bonding should be put between all live parts of a PV installation to bond all the earthed conductors and metal parts.

Protection by surge protection devices

For protection of sensitive electrical equipment's surge protection devices are of great importance. In order to use the SPD's for ensuring protection against surges, critical length L_{crit} and it's comparison with L the cumulative length of the D.C lines should be taken in to consideration. In case $L \geq L_{crit}$ SPD protection is necessary. L_{crit} can be calculated from the following table and depends upon PV installation type.

L is the sum of:

- I. Distances between the junction boxes and converters.
- II. Distances between the junction box and the connection points of the photovoltaic modules forming the string.

In both cases it should be taken into account that the lengths of the cable located in the same conduit are counted only once.

SPD can be installed at different locations on DC side depending on the number of converters and the length between the converter and PV panels. The SPD should be installed near converter if the length between the converter and PV panel is less than 10 meters. If the cable length exceeds than 10 m between solar panel and converter a second SPD should be installed near PV panel. *“To be efficient, SPD connection cable's to the L+/L- network and between the SPD's earth terminal block and ground must be as short as possible- less than 2.5 meters”* (Electric 2012).

5.4.7 Earth Faults in PV panels

PV panels are varying in design for example frameless PV panels PV panels with frames. In both design there must be earth faults which lead to current leakage to the earth. It is important to clear the faults by leakage current otherwise dangerous situation can arise which can results in fire risks. Earth faults are even possible if we use double or reinforced insulation. This situation can be more dangerous in case of double earth faults. An insulation monitoring device should be used which

can detect first fault and the fault should be cleared by the concerned safety person before second fault arises.

The double earth fault should be completely avoided because of the following reasons.

- I. In case of double earth faults or low short circuit capability of PV module under weak sun light, the fault magnitude will be low than the tripping value of overprotection devices. After a passage of time if the fault doesn't trip the protection device because of low fault current magnitude, will generate DC arcs which can lead in serious hazards like fire on PV panels.
- II. For PV systems circuit breakers and switches are usually designed in a way to break the rated current or fault current with all poles at open circuit maximum voltage (U_{OC_MAX}). Four poles in series (two pole in series for each polarity) are required to break the current when U_{OC_MAX} is equal to 1000V. When a double earth fault situation arises in PV system, the protection devices must break the current at full voltage with only two poles in series. Such switchgear is not designed for that purpose and could sustain irreparable damage if used to break the current in a double earth fault situation (Electric 2012).

As for prevention of double earth faults insulation monitoring devices is used which detect the first fault but it also stops the converters function, the first fault is still present and should be diagnosed by the staff before the second fault happens. PV system with high generation capacity in which each array is protected by circuit breakers, each array should be disconnected when first fault happens and didn't diagnosed with in the next few hours.

5.4.8 Selection of fuses for PV modules

PV generator can be made by several strings attached in parallel for achieving high current and power depends upon desired load capacity. For safety of PV panels, protection devices should be installed in every string. But it should also be kept in

mind if the PV generator is made of less than three strings will not generate enough fault current to damage the conductor, equipment's or modules. But when the PV generator are made from more than three string then a fuse link should be installed on each string to protect it from over current faults and isolate the faulty array in case of fault from the healthy arrays, which will help in continuity of power generation from the healthy strings. One thing should be taken in consideration that PV generating output is temperature dependent i.e. the exposure of the sun or irradiance level incline as well as shading effect. In operation fuse links, as thermal devices are influenced by ambient temperature.

Selection of Fuse Links for String Protection

For selecting fuse link the parameters given by the manufacturer should be studied and taken into account but the following factors should be used: 1.56 for current and 1.2 for voltage when selecting the fuse link which covers most variation due to installation (Bussmann 2012).

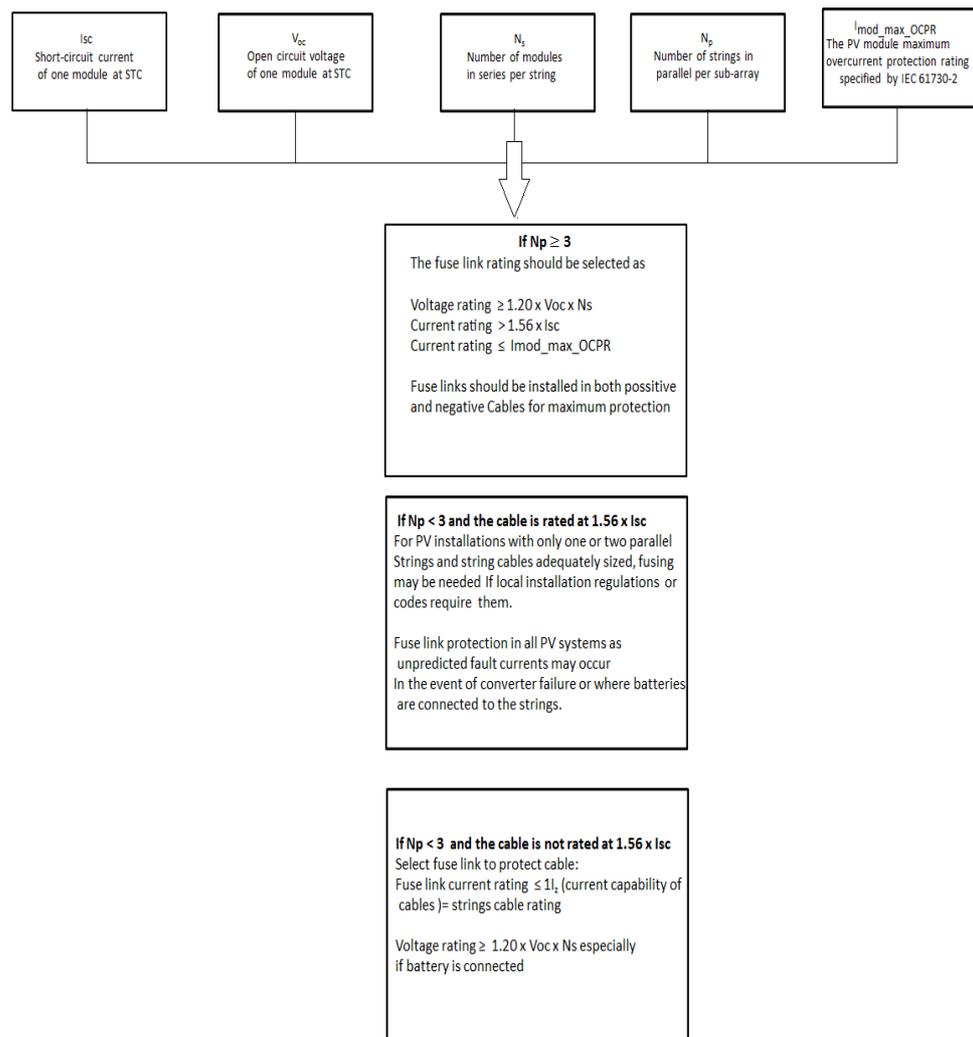


Fig 5.2. Flow Chart for fuse selection(string protection) adopted from (Bussmann 2012)

Selection of Fuse Links for Array Protection:

For selecting fuse link the parameters given by the manufacturer should be studied and taken into account but the following factors should be used: 1.56 for current and 1.2 for voltage when selecting the fuse link which covers most variation due to installation (Bussmann 2012).

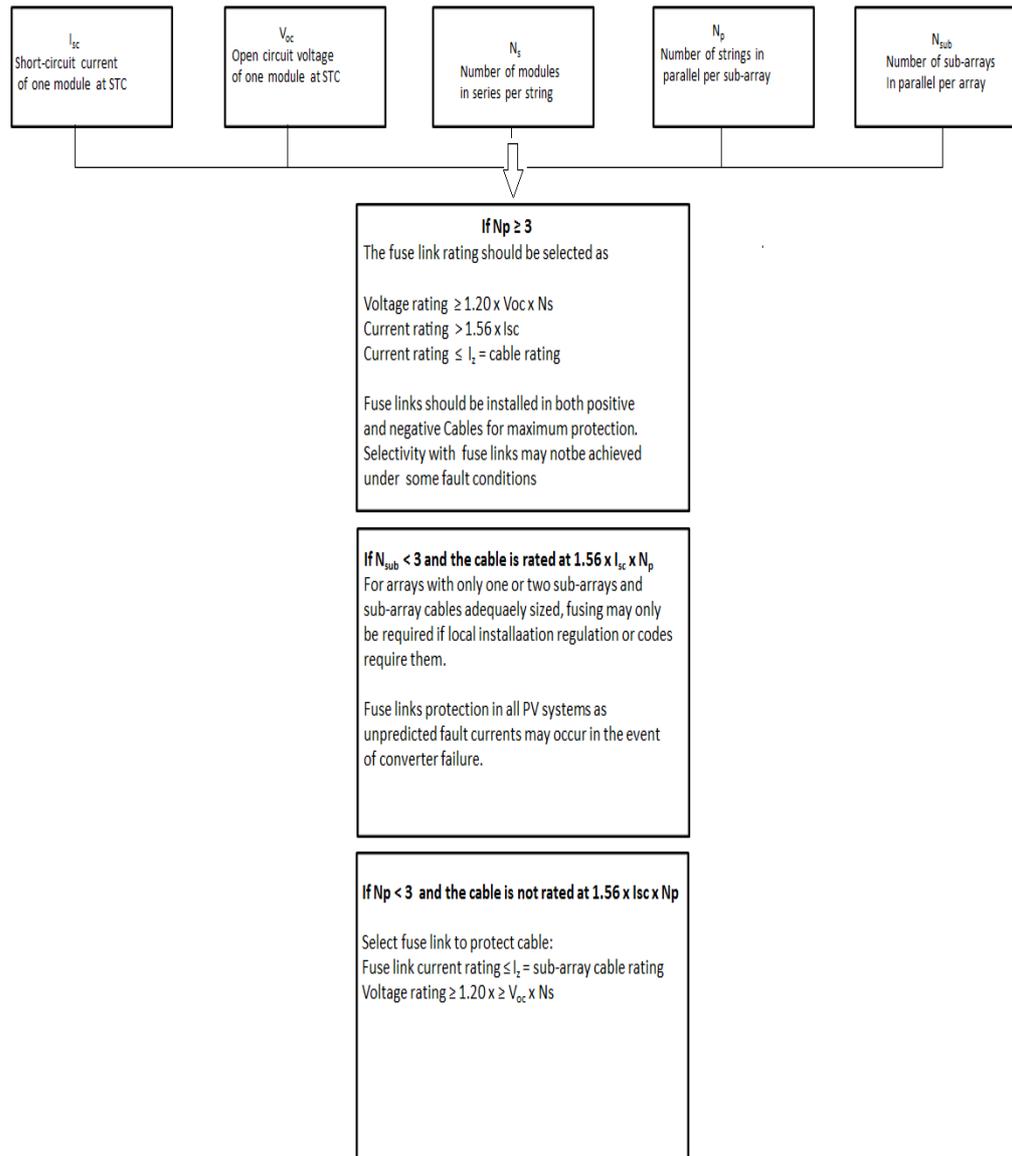


Fig 5.3. Flow chart for fuse selection (Array Protection) adopted from (Bussmann 2012)

5.5 Battery protection

The protection of batteries can be designed in different ways depending on the service requirements. Protection devices like fuses, circuit breaker, can be used for its protection. Overvoltage and under voltage protection should be also taken into consideration (IEEE 2002).

The things which should be taken into battery protection design are as follows:

- I. Risk of equipment damage should be minimized to greater possible extent during faulted conditions.

- II. Number and duration of the battery system service should be limited in fault conditions.

5.5.1 Overvoltage and undervoltage protection

Batteries can withstand moderate under voltage and over voltage for short period of time. As example if under voltage occurs in lead acid battery for long time, then there were be sulfation on plates inside the battery which may difficult to reverse and as result battery capacity will be lost. If over voltage happens in a battery for long time, it will increase the aging process and possible damage to the battery. In under voltage and over voltage conditions alarms are used to give identification of the situation. For this purpose voltage sensing devices are installed at the battery charger.

5.5.2 Batteries protection with fuses

Overload and short circuit protection can be provided by installing fuses in between the dc main and batteries as shown in the figure. Both positive and negative poles in unearthed system should contain fuses and in earthed dc system only the unearthed pole has to contain a fuses.

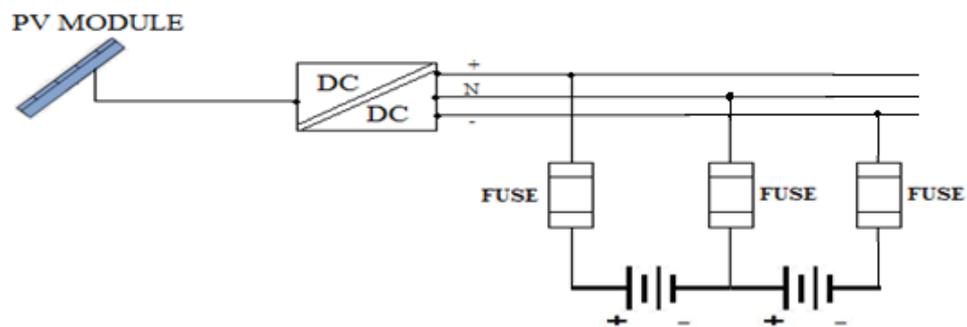


Fig 5.4. Battery protection with fuses adopted from (IEEE 2002)

When selecting fuses it should be taken in to consideration that partial melt of fuse element should be avoided during fault condition by coordinating the protective devices used on the load side of the battery fuse.

The fuses can be installed in a disconnect type holder. The disconnect type holder cannot be opened under significant load unless it's a load break switch. For manual current interruption in the fuse protection circuit a switching device can be used. Fuses do not usually require periodic maintenance or testing because their characteristics are stable and depend on the circuit they are used for. Fuses should be changed according to the circuit as there is no adjustable time-current characteristic for it.

The following considerations should be taken into account while selecting the fuse for battery protection.

- I. Voltage rating for the fuses should be greater than the battery system equalizing voltage.
- II. The fuse rating current should be at least 125% of the sum of the calculated continuous current and 100% of the momentary loads from the battery load profile. Calculated and anticipated high current should then be compared during the battery charging and discharging cycle.
- III. Interrupting rating should be kept up to a certain value which is sufficient to interrupt the maximum calculated short circuit current.
- IV. For batteries DC fuses are recommended but in case if AC fuses are used they should be properly re-rated for DC application.
- V. In case of a fuse blown, an alarm should be provided.

5.5.3 Protection by circuit breaker

Installation of a circuit breaker as the main battery protection can be provided as both overload and short-circuit protection or short-circuit protection only. Both positive and negative poles in an ungrounded system should contain circuit breakers and in a grounded DC system only the ungrounded pole has to contain a circuit breaker.

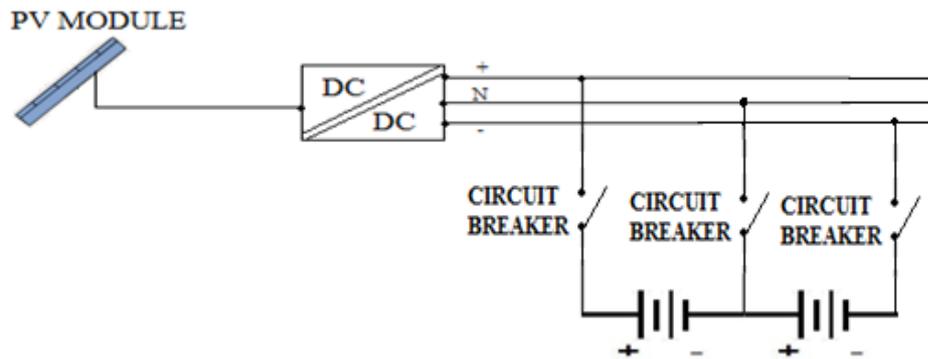


Fig 5.5. Battery protection with circuit breakers adopted from (IEEE 2002)

The following consideration should be taken into account while selecting the breaker for battery protection. The following consideration should be taken into account while selecting the fuse for battery protection.

- I. Voltage rating for the fuses should be greater than the battery system equalizing voltage.
- II. The fuse rating current should be at least 125% of the sum of the calculated continuous current and 100% of the momentary loads from the battery load profile. Calculated and anticipated high current should then be compared during the battery charging and discharging cycle.
- III. Interrupting rating should be kept up to a certain value which is sufficient to interrupt the maximum calculated short circuit current.
- IV. For batteries DC fuses are recommended but in case if AC fuses are used they should be properly re-rated for DC application.

5.5.4 Mid span protection

Installation on one or more protection devices i.e. fuse or circuit breakers in the middle of a battery string is known as mid span protection.

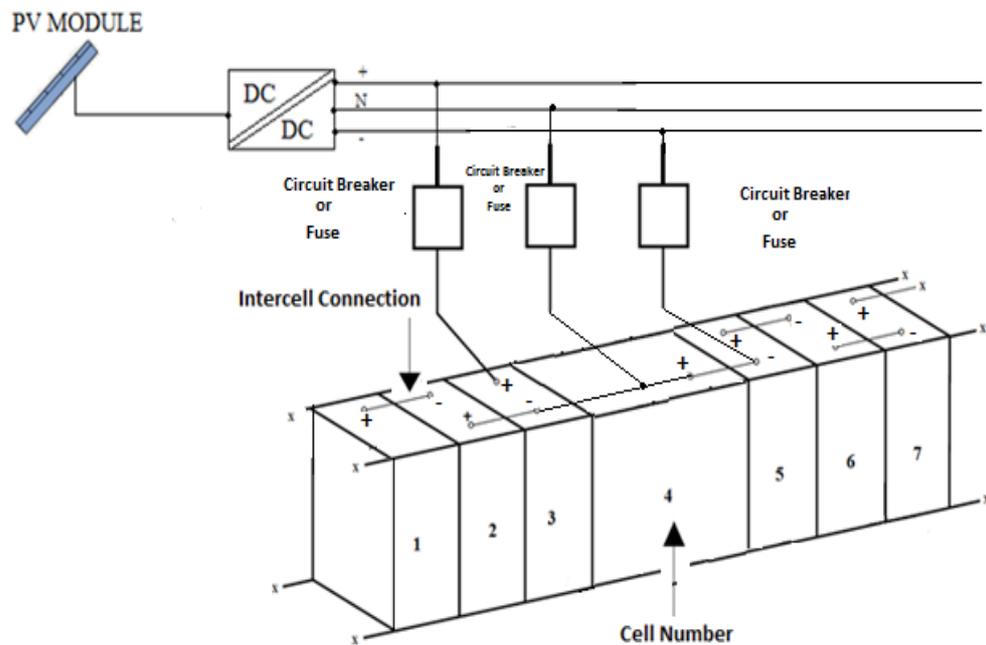


Fig 5.6. Mid span battery protection adopted from (IEEE 2002)

Mid span protection minimize damage or failure by limiting the short-circuit current through the battery. It opens the battery circuit for external faults and in some cases for internal faults which may involve only a portion of the battery.

Advantages:

- I. Only single pole protection device is required. The added circuit resistance from devices connections and contact can be minimized and failure to the battery system can be overcome by reducing the number devices that can be subjected to failure of the battery.
- II. Internal and external faults can be completely protected or minimized. Furthermore it can limit the number of cells that could be involved in faults. This advantage should be considered in cases where batteries are grounded or when batteries are connected in groups such as multi-cabinet or multi-rack installation, especially when connected in series. Available fault energy is reduced by up to one-half for certain types of faults.

A drawback to mid-span protection is that opening of the mid-span doesn't isolate the battery from the rest of the circuit. Single pole protection devices are generally located at the mid-point of the battery string. Multiple locations are used between racks or groups of batteries.

5.5.5 BMS on Battery Protection

A BMS monitors different operation state in the batteries. BMS is also know as high level PCM, which is safety control and management system to monitor battery status in order to make battery better working and lengthen battery life time objectively. BMS have the functions of (Chatzakis J 2003, Rahimi-Eichi H 2013).

- I. advanced integration of management
- II. protection
- III. communication
- IV. self-diagnose
- V. cell balancing

A BMS can provide the following protection functions (Garche J 2000).

- I. Overcharge protection
- II. Over discharge protection
- III. Overcurrent protection
- IV. Overheat protection
- V. Short circuit protection
- VI. Temperature sensing
- VII. Power gauge

To prevent under-charging, over charging and maximizing battery capacity the BMS may actively ensure that all the cells that compose the battery are kept at the same SOC through balancing.

It should also be noted that ICT system will be used to operate the circuit breakers via relays. While using ICT protection system it is impossible to use the fuses because it cannot control the fuse operation. One other question is about when batteries are connected via converter. Also in this case the protection system will

be based on circuit breakers, which will be based on relays, operated through ICT. But while designing the backup protection it will create problems because one dominant power source is needed to operate the network protection system in back up mode. So converter will limit the possibility of batteries as dominant source.

5.6 ICT based differential protection

As concerned to selectivity, sensitivity and speed of operation, differential protection is considered to be superior on other protection schemes. In differential protection scheme the differential function responds to sum of all currents of it's zone of protection which is zero or very close to zero, except in fault situations.

5.6.1 Implementing differential protection

The ICT system can be implemented in way that there should ICT slave in different parts of the network. Each ICT slave should be attached to relay, which is responsible for tripping the circuit breaker in fault situation. Each ICT slave is then connected via communication layer to master ICT, which take the current measurements from all the section of the network and do summation process. If the sum current is equal to zero, it means there is no fault and vice versa. The master ICT will give command to the slave ICT to activate the relay for tripping the circuit breaker.

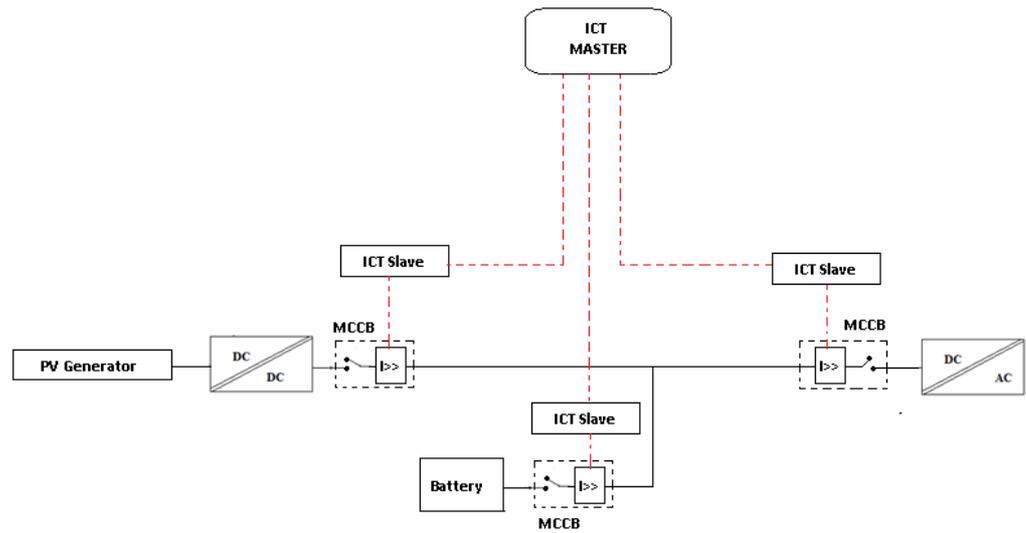


Fig 5.6. ICT Modules at different location of the network

5.6.2 Relays function with ICT in the network

Multiple relays will be installed into the network with ICT slave, which will operate independently by digital communication links. The main function of the multiple relays in the network is that it should depend on each other in order to provide the line current differential protection but are located at different sections and operate autonomously in terms of sampling, transmission and reception of data, filtering and protection of calculation. ICT modules are used for the purpose to sample digital data (i_D) from analog input (i_A) and then give to relay to operate in case of faults. The sampling rate depends on the design which can vary from few kilohertz to less than 20 samples cycle depending on the design. The same digital data feed the current differential subsystem of the relay as well as other local functions like metering, fault recording and protection (backup, breaker failure, and overcurrent). Because of these functions the sampling rate is high, even though the line current differential function may utilize these data as lower sampling rates.

To perform the current differential protection in the network the local current data must be communicated to remote terminal unit ($i_{TX} \rightarrow i_{RX}$). Each relay that receives a full set of data from its remote peers can align the data, runs in so-called master mode. Each relay that only serves the data but doesn't receive all the

remote data because of a permanent lack of communication (channel not installed) or temporary loss of communication is referred to as working in the slave mode. Direct transfer tripping (DTT) from masters allow the slave relays to issue the trip command to their breakers.

Channels traditionally used for line current differential protection are limited in the bandwidth (64 Kbps is a typical value) and therefore only limited amount of data can be exchanged between the relays at differ line terminals. In this respect, various line current differential designs differ considerably.

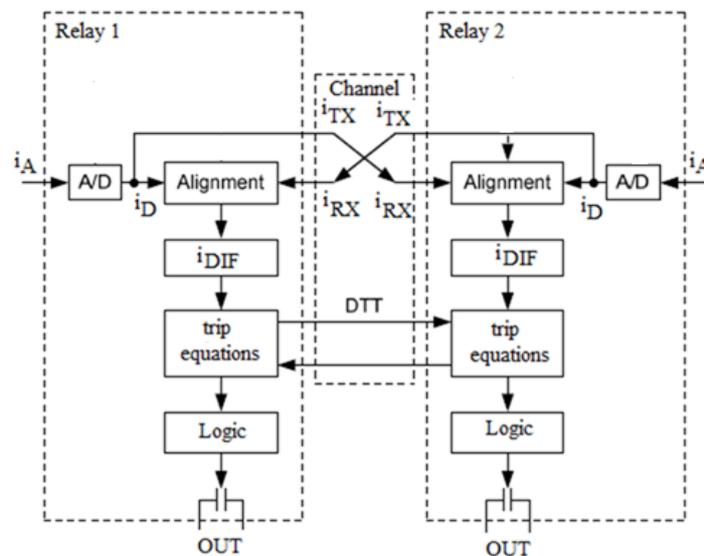


Fig 5.7. Relays function in case of ICT adopted from (Hank Miller 2010)

5.6.3 ICT control of the network for protection purpose

The Slave ICT in the network can be controlled by multilevel communication which can further control the relays, and operate in case of fault and trip the circuit breaker. In multilevel communication the data traffic of every intelligent electronic device (IED), which can be measurement device, protection device or any device generating information required by the network) is not broadcasted to every point of the network, but rather processed locally by a data concentrator or local control. This is also beneficial in case when different sections are attached and the data are then transfer to a Master control, which can do the protection calculation and give trip command to a section where fault take place.

To be able to implement this scheme, control needs to be designed so a certain amount of functions can be performed independently by the sector control, (preferably most of them), and only some functions require involvement of the master control. Besides the lower bandwidth requirements, other advantages like lower response time and independent operation in case of fault are achieved. Also, data measurements can be polled at higher frequencies, a higher sample definition.

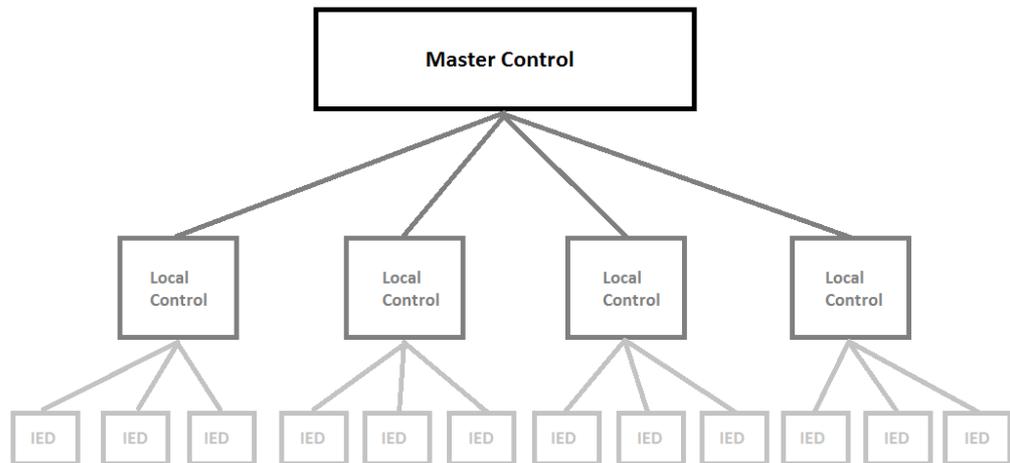


Fig 5.8. ICT control topology for protection in the network

The differential protection can be applicable in a network, when the relays are located at the terminal of the protection devices to monitor the electrical quantities with help of ICT modules required for the trip decision of the protection. The data of the network must be transferred from the remote terminals to the local and then compared with data at the local terminal. As previously mentioned that this function requires communication system for data transfer. Usually the communication system can PLC, optical fibers or wireless depends on the location and design of the network.

Measurements errors and shunt elements in the network may create an unauthentic differential signal, calling for adequate countermeasures. “These countermeasures became more sophisticated with advancements in the field of differential protection and progressed from adding an intentional time delay, percentage restraint, and harmonic restraint and blocking to sophisticated external fault detection algorithms and adaptive restraining techniques” (Hank Miller 2010).

Microprocessor integrated protection devices, like circuit breakers and relays, are capable of monitoring and taking measurements, and compilation of such information in real time by a monitoring station can detect even very small faults or building up faults. Specific sample times and delay requirements for implementation of such depend strongly in distances within the network, and therefore cannot be defined yet before the final deployment location is decided, so then a specific requirement for communication can be set, and have a strong effect in the decision of what technique or technology for communication will be used.

Delays between transmit and receive paths can be one of the challenge in ICT based protection. Traditional current differential relay requires a delay variation of less than 0.25ms for protection with high sensitivity characteristics. IEC 60834-1 recommends propagation delay of less than 5ms for current differential protection schemes (Anthony S Rajamanickam 2006) .

5.7 Selection of fuses

For fuse selection the following parameters can be taken in to consideration (OptiFuse 2010):

- I. Normal operating current
- II. Ambient temperature
- III. Overload current and length of time in which the fuse must open.
- IV. Maximum available fault current
- V. Pulses, Surge Currents, Inrush Currents, and Transients
- VI. Physical size limitations, such as length, diameter, or height
- VII. Considerations: mounting type/form factor, ease of removal, axial leads, visual indication, etc.
- VIII. Fuse holder features: clips, mounting block, panel mount, p.c. board mount, R.F.I. shielded, etc.

For selection of right ampere fuses for the network, we first have to know the full-load steady state current of the network at an ambient temperature of 25° C (68° F). After determining the current value, then the fuse rating should be selected as to be 135% of this value. As an example if the normal steady state current of the

network is 35 amps, then a 50 amps fuse rating should be selected [$35 \text{ amps} \times 135\% = 47.25 \text{ amps}$, the next larger standard size is 50A.

If the fuse is intended to be used in an environment with possibly high or lower ambient temperature, then the nominal fuse current would need to be sized significantly higher or lower. The voltage rating of the fuse must always higher than the voltage rating of the circuit that it is protecting.

5.7.1 Available short-circuit current

The available short circuit is delivered by source in the network when a short circuit takes place. Information about available short circuit current can be determined by calculation and is extremely important to be known for the proper operation of over current protection devices to open in case of short circuit takes place in the network.

The available short circuit current calculations are based on the following factors.

- I. How much short-circuit current is available from the utility?
- II. What is the resistance of the wiring from the utility to the piece of equipment where the fuse is installed?
- III. What is the internal resistance of the piece of equipment where the fuse is Installed

The selection of the fuse should make in a way that it's rating is greater than short circuit current available in the network during fault otherwise the fuse can explode and become harmful to the peoples and equipment's.

Currents oscillate back and forth in AC power which helps the fuse to clear the fault quickly. Dc power doesn't have this quality, so the fuse must find another way to clear the fault. Because of this main difference certain fuses are designed specifically for DC application but also some AC rated fuses can also be used in DC networks, however there may be a voltage de-rating in these cases.

Installation of fuses in the network depends upon the sizing of DC mains, the length of the dc mains and the load attached to the dc mains. The size of the DC

fuse also changes after the changing the size of the DC mains depending on different circumstances through distance. “Fuses used in the industry or traction system can be used in the DC distribution system. As there are negative voltages after fault situations, so it can be protected with reverse connected diodes in front of customer-end inverters. Negative voltage also affects the energy storages attached to the DC link”.

It should be taken into account that while using ICT protection, it's impossible to use fuses, because fuses cannot be controlled by ICT.

5.8 Back up protection

Backup protection for the network is important in case when the main protection system fails. The backup should be designed for earth faults and overcurrent protection.

5.8.1 Backup protection for over currents

The backup protection for over currents is in the following figure. As from the figure it is shown that it can be divided into two stages.

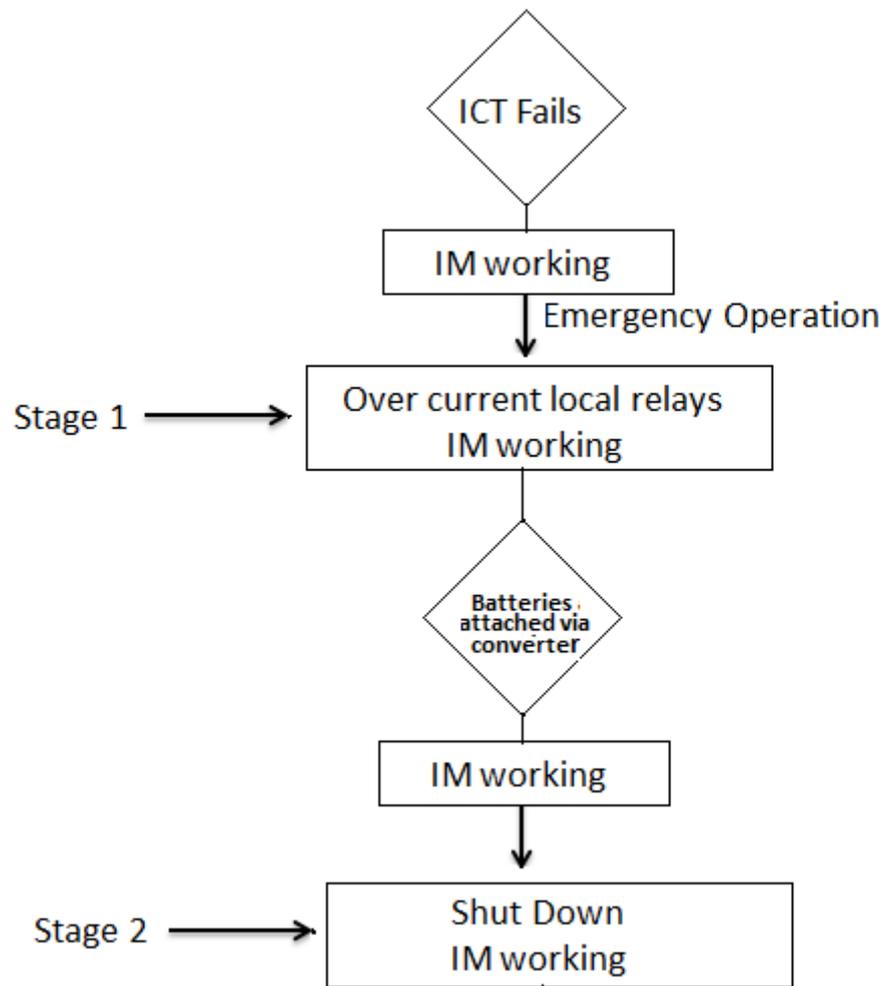


Fig 5.9. Figure showing backup protection stages for over currents

Stage 1

When ICT fails, the system goes to emergency condition. In this scenario one source should be dominant in order to feed enough short circuit current to activate the local relay. It is important that battery is attached directly to the DC mains to be dominant over PV panels. Because PV panel is feeding the network via converters and produce nominal current which is not enough to activate the local relay.

Stage 2

Batteries are no more dominant in the network because of the attachment via converters to the DC mains or the SOC (state of charge) is low to activate the local relay. In this case the system should be shutdown.

5.8.2 Backup protection for Earth Faults

From the figure backup protection for earth faults are shown. It can be divided in to two stages.

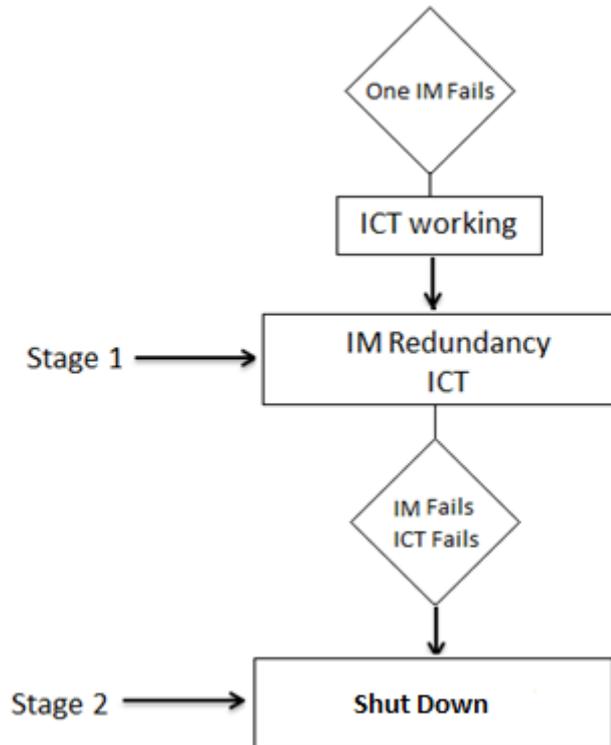


Fig 5.10. Figure showing backup protection stages for over currents

Stage 1

As one section consist of many insulation monitoring devices, In case when one insulation monitoring device fails and ICT is working the network will be shifted to stage 1. In this scenario the IM device will work in redundant mode i-e the ICT will give remote signal to other IM devices working in the network to detect the ground fault.

Stage 2

When ICT and IM both stops working the system will be sifted in to stage should be shutdown.

6 Faults current calculations

For the fault calculations we use thevenin theorem (Iftakhar 2008), considering DC as ideal source. While calculating short circuit currents are very high by using ideal dc source, but in real life it's small because the dc source is not ideal. In case of wind power it's 1.2 times less than the short circuit current calculated with ideal sources. Furthermore it also depends upon the converters topology which can be limited by a certain value, after that value the converter doesn't give more current and will stop.

6.1 Thevenin circuit model

Thevenin equivalent circuit model can be used for short circuit calculation. The following figure 6.1 shows an example of a Thevenin circuit model for simple DC system.

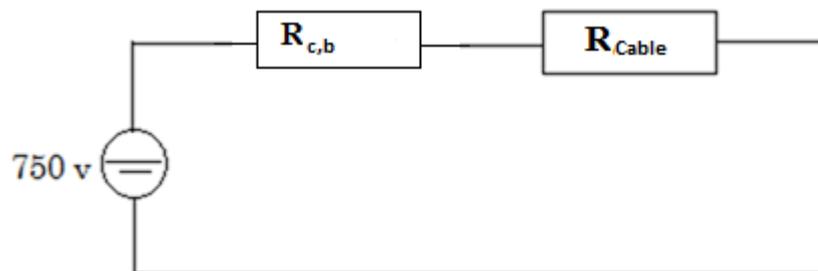


Fig 6.1. Thevenin equivalent circuit model

In real life short circuit current depends upon the cable length, sizing of the cable and it's parameter i.e. resistance, capacitance and inductance of the cable. When planning a network different size of cables are used in the same vicinity so it has also have a great impact on short circuit currents and then selection of protection devices based on them. Furthermore internal resistance of converters and batteries attached to the network should also be taken into account while calculating the short-circuit currents.

The following parameters are used for calculating the short-circuit current in case of ideal DC mains.

$R_{c,b}$ = internal resistance of the converter and battery (ohms)

R_{cable} = cable resistance depends on the length (ohms/meters)

R_c = Converter resistance = 0.0012 ohm

R_b = Battery resistance = 0.023 ohm

$R_{c,b}$ = 0.00114 ohms (converter and battery are in parallel)

Cable model 4 x 16 mm² cable are taken in to account for short circuit calculation. It should also be noted that the calculations are based on assumptions.

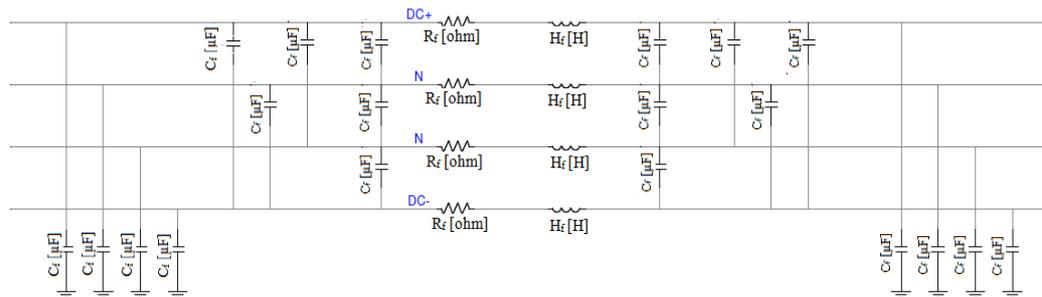


Fig 6.2. Cable model (Lana 2010)

The capacitances of the cable are not taken into consideration in the case example calculation of ideal DC, because it doesn't have a great effect on the steady state short circuit currents in real life.

The total resistance value of the used cable for short-circuit calculation is 1.91 ohms per kilometre in the 4 x 16 mm² example cable. According to this value, the single-conductor resistance will be as follow during different distances:

$$100\text{m} = 0.191 \text{ ohms}$$

$$200\text{m} = 0.382 \text{ ohms}$$

$$300\text{m} = 0.573 \text{ ohms}$$

$$400\text{m} = 0.764 \text{ ohms}$$

$$500\text{m} = 0.955 \text{ ohms}$$

As the cable contains of four conductors, so the middle two can be short and used as a neutral. So the total resistance of the cable per kilometre can be calculated by calculating the parallel resistance in both neutral lines and the with the positive and negative pole respectively, depending on short circuit current calculations in different poles.

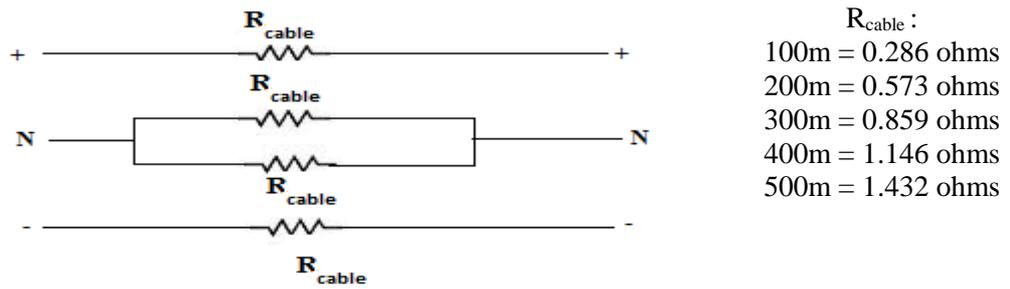


Fig 6.3. simplification of cable resistances for short- circuit calculation.

General formula used for short circuit calculation

$$I_{DC} = \frac{U_{DC}}{R_{tot}} \quad (6.1)$$

Where I_{DC} is fault current, U_{DC} is DC voltage over fault current, R_{tot} is total resistance of the fault circuit

6.2 Calculation of pole to middle faults

The following calculations represents short-circuit current in one pole at different locations , i-e 100,200,300,400,500 meters by taking into account DC/DC converter and battery in parallel. The battery is attached near the converter zone feeding the same fault point.

It should be noted that the converter has a current limiting functionality, which means that it cannot produce a current more than a certain limit during short circuit condition.

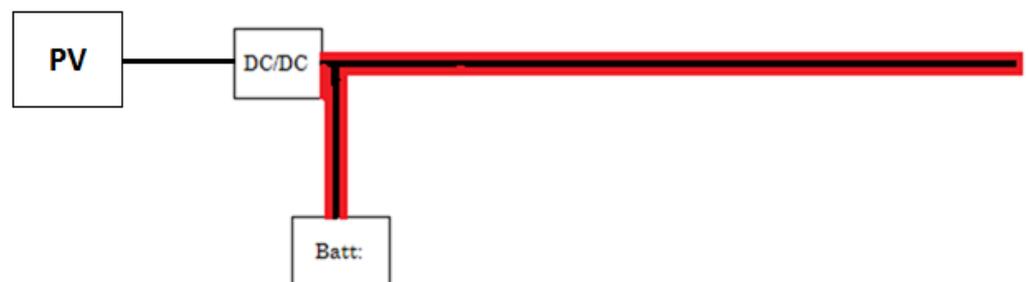


Fig 6.4. Path of short circuit current (single line faults)

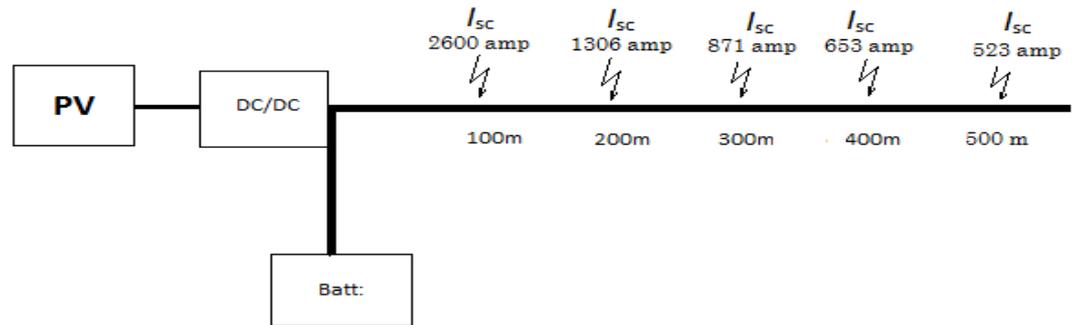


Fig 6.5. Short circuit currents at different locations (single to line faults)

The next calculations shows line faults, but in this case we change the battery locations through different parts of the network. From thevenin circuit model we can see that by changing the battery location we have to voltage sources feeding the same fault point from different distances.

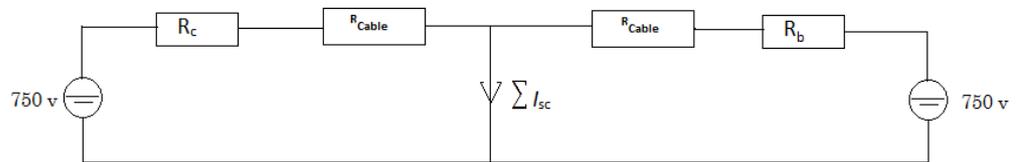


Fig 6.6. circuit model

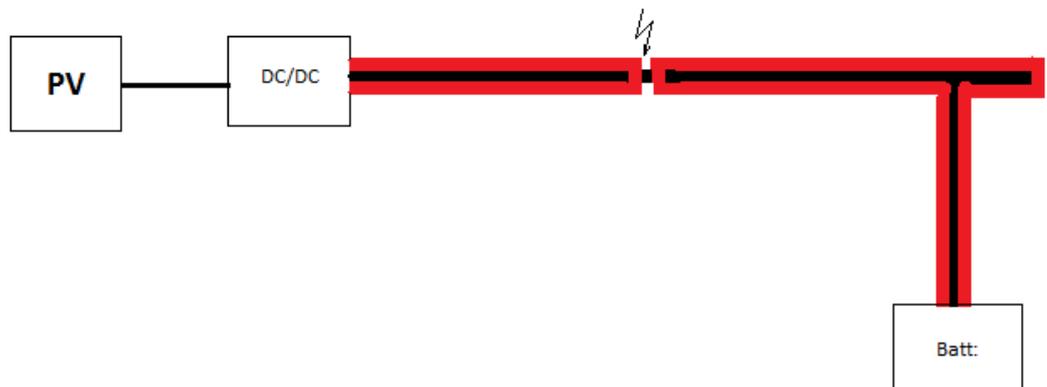


Fig 6.7. Path of short circuit current (battery location changing)

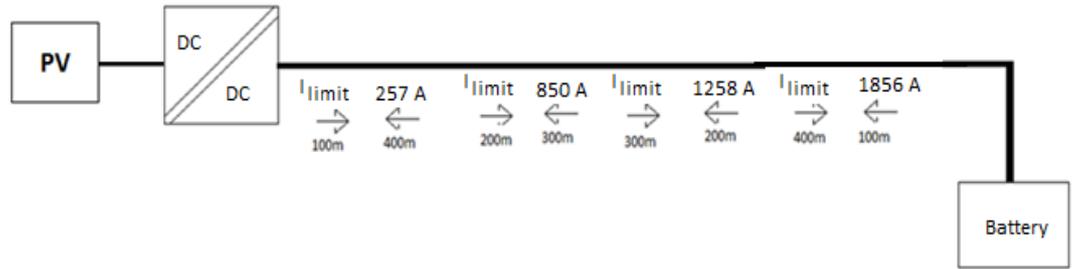


Fig 6.8. short-circuit currents feeding the same point from converter and battery

6.3 Calculation of pole to pole faults

The pole-to-pole faults can be calculated by applying faults on both conductors.

The following figure shows equivalent circuit for calculating line-to-line fault.

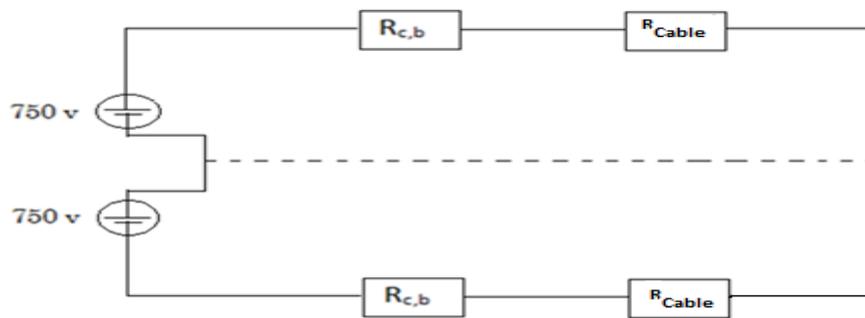


Fig 6.9. Circuit for calculating pole-to-pole fault

Table 6.1: Short-circuit calculation values

Distance	Fault Current
100m	3915.43 Amps
200m	1960.53 Amps
300m	1307.76 Amps
400m	981.03 Amps
500m	784.92 Amps

6.4 Calculation of pole to earth single fault

Line to earth fault can be calculated by taking the following circuit into account. The following figure shows equivalent circuit for calculating single line-to-ground fault.

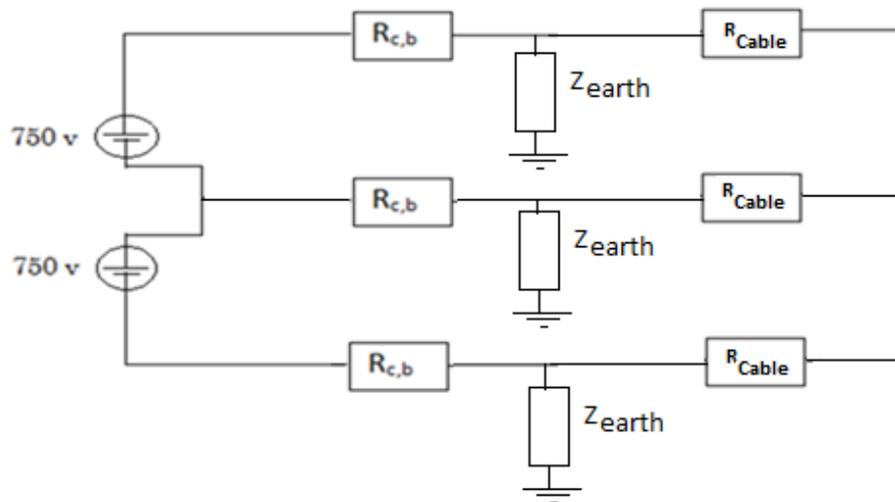


Fig 6.10. Circuit for calculating line-to-ground single faults

The calculations are done by taking into account different earth resistance i-e ,20, 30, 40, 50, 60, 70,80, 90, 100 ohms through 100 to 500 meters distance. It should be also taken into consideration that these calculation are purely on assumption basis and in real system the leakage resistance to earth in IT system cannot be under 1 M Ω in total.

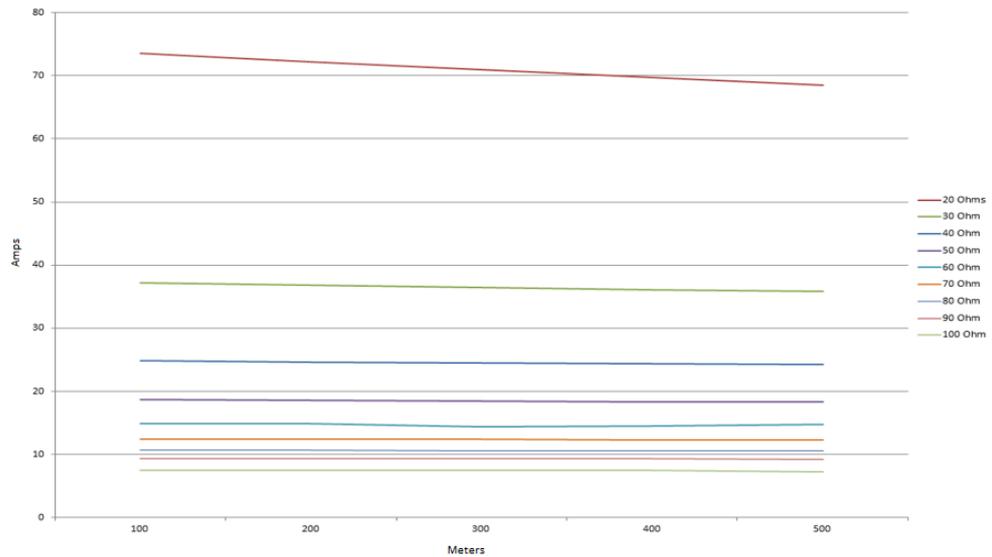


Fig 6.11. Graph for line-to-ground (single fault) calculation

The figure shows single line-to-ground single faults. As we can see there are straight lines in the graph, means not a lot of variations in the short circuit current through different distances while taking into account the same earth resistance, for example 20 ohm resistance for 100,200,300,400, and 500 meters respectively . As the earth resistance increases the short current decreases. The x-axis in graph represents distance in meters and y-axis represents short circuit current in amperes.

6.5 Calculation of pole to earth double faults

In double earth fault situation the earth resistance connects parallel with network resulting in high currents (Pasi Salonen 2009). The following circuit model is used for line-to-ground (double faults) calculation.

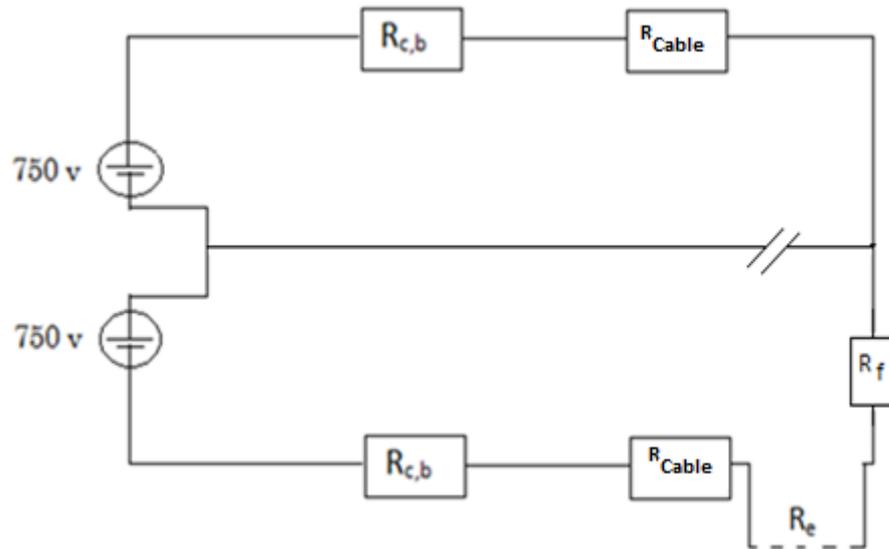


Fig 6.12. Circuit for calculating pole to earth double faults

The calculations are done by taking into account different earth resistance i-e 10, 20, 30, 40, 50, 60, 70,80, 90, 100 ohms through 100 to 500 meter distance.

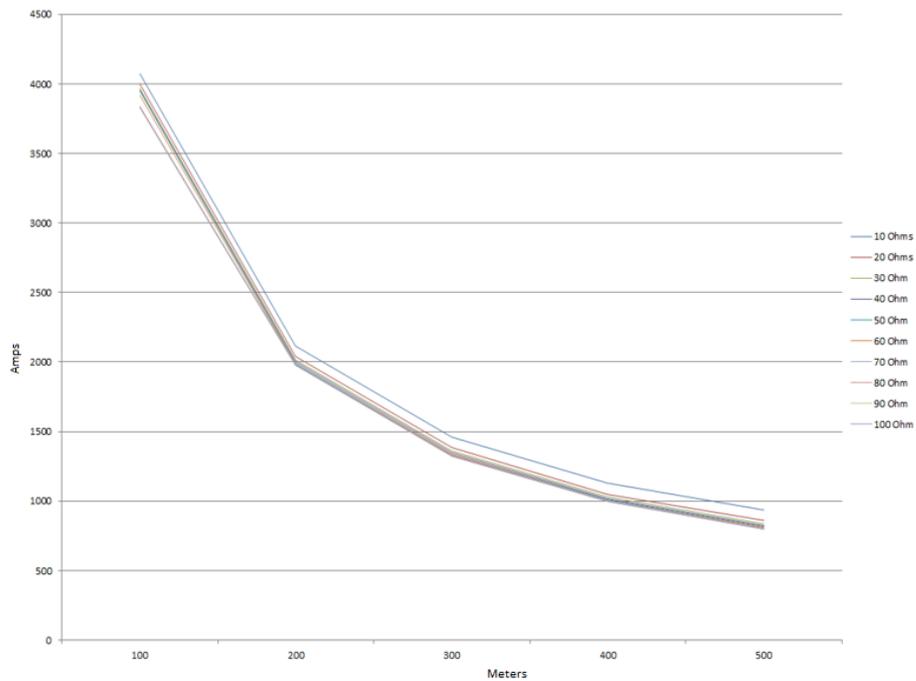


Fig 6.13. Graph for line-to-ground calculation (double faults)

The graph shows that in case of double line-to earth faults high short circuit currents are produced. There are also a lot of variations in the short circuit current through different distance while taking into account the same earth resistance for

example 20 ohm resistance for 100,200,300,400, and 500 meters respectively. It can be seen from the curves in the graph. As the earth resistance is increasing the short circuit current is decreasing. The x-axis in graph represents distance in meters and y-axis represents short circuit current in amperes.

Double fault is the only dangerous situation in IT earthed DC network, when the touch voltages in indirect contact are considered.

7 Determining relays settings

“According to the standards, the relay should start once the energizing current exceeds 1.3 times the set start current. when the normal, very or extremely inverse time characteristic is used. When the long-time inverse characteristic is used the relay should start when the energizing current exceeds 1.1 times the set start current”.

Selectivity diagrams are used to plan and manage the time-selective protection. Selectivity diagram mainly consist of specific time/current curves which shows the operating characteristics of the relays.

The following points should be taken into consideration for relay time setting:

- I. The relay operating time should not be unnecessarily prolonged in heavy fault conditions and a satisfactory margin must be maintained to secure the selectivity.
- II. Generally longer grading time must be used, when inverse time relay is used instead of definite time relays because the effect of the inaccuracy of the current measurement on the operating time must be observed.

As the protection system is mainly based on ICT differential methodology, so there should be also taken care of measurement errors caused by the sensors in Analog to Digital conversions of the converters and the time shifts in the ICT systems. Measurement errors can be acknowledged by taking into account the specification of the sensors but for the time shift in the ICT system, the following points should be taken into consideration.

- I. What amount of data is generated?
- II. How often it is generated?
- III. To where this data is send?

Furthermore it also depends on the geographical location where the grid will be situated.

Fault protection:

The insulation Resistance R_{Im} has to be higher or equal to $1\text{ M}\Omega$ ($R_{IM} \geq 1\text{ M}\Omega$). The protection should be selective i-e first it disconnects the faulty location in order to achieve the selectivity criteria in 3s for implementation of protection. It means that we have to put time setting for relays to activate the breaker near the fault location and trip it first. Normally the time setting is put on the basis that what is touchable voltage and for how long it's allowed to have that kind of touchable voltage in the system. According to low voltage standardization 75v is allowed for 10s in AC system.

For selectivity it is important the faulted location should be separated as soon as possible, which means that the tripping setting will be instant (trip as fast as possible). How fast actually it can be trip? depends upon the device and manufacturer. For example in case of bender relay the fastest time to send a trip signal is approximately 5s. So it means that 5s is needed to detect the actual fault and it also takes some time to open the breaker, but that is in milliseconds. Because of this the whole procedure can consider to be 5-6 seconds.

As the faulted location should be trip as fast as possible in order to make it separated from other location so in other part of the section we still have $1\text{ M}\Omega$ Insulation resistance and if we consider the selectivity, the time setting for other location on the section to trip the breaker must be slower than 5 sec. As we already have the method to calculate the steady state fault current for the system and after 5 sec the fault current will be in steady state. The time of the spike is 5-15 μsec , so it's too low and we have plenty of time for selective touch voltage protection by putting 15-30 sec tripping time for other breakers far from the faulty location in the section. So it will trip after other breaker near the faulty location trips.

So if the insulation resistance goes below $1\text{ M}\Omega$, all of the insulation monitoring relays will detect the fault and then check where the fault is located and trip the breakers accordingly. This is also called constant time or constant value tripping and can be applied for all the sections in the network.

Actual over current protection or stray current protection:

As the protection system is mainly based on differential protection system so it will measure the current at different location of the section. Current measurement devices are installed at all the sources and connection points, by which we can measure the current. By calculating the current we will find what will be the setting values. If the current measured value $\Delta \sum I$ goes over some limit then we have trip the breaker. The value can be achieved by the available stray current caused by the high impedance short circuit current in the system. When we have an ideal system there is no stray current (all the measurements are ideal), which means that tripping current value is anything other than zero. But in real system we have to take into account the normal state leakage resistance, because the system leaks every time. when we consider 750v and 1.5kv or 1 M Ω , there is very small current, so that's probably not the problem.

But the problem here arises due to digital measurement as each of it has their own processors. so the issue is, are the processor coherent in time so that each clock ticking at the same time? There might be some kind of difference between processors times for example two measurement devices measured data at the same time in the day i-e 1:00 pm but the processor clocks has a difference of half second in-between them. so there will be current measurement error. This problem can be solved by network administrator which should make sure that the clocks are synchronized and normally in networks the clocks are mostly synchronized, so it might not affect the measurements. The other error which should also be taken into account is sampling error. As concerned to sampling errors it depends on the accuracy of Analog to digital converters of the devices which samples the data i.e 12 bits, 16 bits, 32 bits or 64 bits. If we take 64 bits resolution for the range of 0-1500 v, then the sampling error is $8 * 10^{-17} v$ so it's too less and again it might not be a problem in our network.

Latency of data transmission are also very important to take into account for relay settings in case of differential protection. when the data is transmitted to two different location from the master unit i-e near and far location, there will be different

time delays in transmission. In this case there is again time differences for the measured values of current which will cause again error to the calculation. These time delays mainly depends upon grid architecture but in case of our grid it will be not an issue because we have divided the whole network in to small sections. According to (Davide Della Giustina 2013) the maximum time is 0.2 seconds, to detect the whole measurements from different parts of the section in case of power line and broadband communication. The other way to overcome this problem, we have to wait longer to get the data but then it will take more time to detect the fault which will have impact on ΔI protection. If we put long time, it means that we can wait longer for many of these current measurement signals from different locations of the section coming to the master unit and then calculate the average time, but to detect the actual fault then it will take more time.

The standardization suggest the tripping time value between 5-15 seconds. The tripping time value also depends on touch voltage protection, which comes from neutral earthed system but in this case we are taking measures for equipment protection, so it shouldn't be taken into account. So for equipment protection we have to set the time till how much the equipment can tolerate the short circuit current. For example, in case of cables which can tolerate quite high short circuit currents, which actually doesn't exist in our system. If we have 1 KA of short circuit current, the cable can actually tolerate for several minutes. But the problem arises with other devices, like batteries, measurement devices, PV panels. The maximum short circuit capability of these equipment can be known by the data sheets of the actual device from the manufacturer.

It should be also taken into consideration that if short circuit current occurs in the DC mains, PV might not be affected by this short circuit current because of the converters, which has the capability to shut down, if the short circuit current increase from a certain value and which are also galvanically isolated. If the short circuit occurs somewhere near the PV panel, there will be a voltage dip for some time but again it will not affect the PV panel because of the converters. In PV converters there is a limit, when the voltage drop from that limit it will shut down

by itself. In our system it will trip by itself (batteries will contribute for most of the time).

There is also an option to drive batteries by converter. There will some limit for the converter and after that, it will trip in case of short circuit current, it means there will be no more short circuit in the section. But then the problem arises that our system doesn't have enough time to detect the fault, which will leave the circuit breaker closed, because of this the short circuit fault will feed the other section and trip the batteries and PV panels. It is necessary the time for fault detection should be too short, that it operates before the local protection of batteries and PV panels. so that first we can disconnect the faulty section and then handle the situation to other sections that distribution can continue.

7.1 Trip time delays of IMDs:

For trip time delays setting of IMDs, the trip of the IMDs at the PV and battery connection can be delayed by 5 seconds compared to the trip time of the IMDs at the sectionalizing breakers. This is possible because of minimum chances of electric shocks due to earth fault current in IT earthed system. Such delay is however required to ensure the selectivity of the protection system so that only the IMDs at the faulted section will give trip signals to the breakers.

For example: after detection of insulation failure, sectionalize the network. In healthy section the IMDs notice that the fault has been cleared and discard the trip, but in faulty section the IMDs of the PV and Battery notice, that the fault is still on and trip (shut down) the faulty section.

8 Conclusions

DC MGs has becoming more popular in the recent years and plays important role in electricity distribution. Furthermore it's also possible to operate the DC MGs in both grid-interconnected mode and islanded mode. DC distribution systems are becoming an alternative way for power supply to the electrical equipment's connected by bus system and optimally controlled by EMS. As this technology is more reliable and efficient to use but still there are a lot research questions which should be solved in order to make it implemented all over the world. One such big question is about fault protection in DC MGs and in LVDC.

In this thesis the protection of a studied island operated low voltage DC MGs is studied, which main parts consist of PV panel, DC mains and batteries. From the studies it's evaluated that traditional protection system for PV and batteries can be used but DC mains encounter different kind of challenges with respect to protection. Different earthing systems are also evaluated and it is found that for DC mains IT earthing system will be the best option. As continuous power flow will provide efficient electricity supply to the customer end network, that's reason IT system is selected for DC mains. It will not interrupt the power supply in first fault situation but it's should be also taken into account that the first fault should be cleared as soon as possible when detected by insulation monitoring device. If second fault occur in the DC mains it will be more dangerous and proves fatal for humans as well as equipment's. Each part of the network is also galvanically isolated from each other, which help to protect each section of the network from another in case of fault. i.e. if fault occurs in PV generator, will not affect the DC main because of galvanically isolated converters.

Fuses and automatic relays are also difficult to use with power electronics converters. This is due to the fact that power converters do not produce enough short-circuit currents as long as the fuses want to react (blow). Therefore, different fault detection methods are used. In that case, the protection system consists of the current interrupting devices, protective relays, measuring equipment's and grounding systems. Both earthing and overcurrent protection is necessary in a network and

how they relate to provide a reliable means of protection. Protection devices which are commercially available for LVDC networks are fuses, molded-case circuit breakers, power circuit breakers, static switches and isolated-case circuit breakers. However the converter short circuit current capability needs to fulfill the used circuit breaker or other protection requirements.

For PV generators protection i-e over current, over voltage and reverse currents protection, the methods are already well known and large variety of protection devices are available in the market. The same goes for battery protection system. ICT differential protection is proposed for more reliable and fast protection of the network because it's difficult to use the traditional relay protection system as the fault current are low and limited by the converters to activate in the proper time.

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