8 Insulation Resistance

The importance of insulation resistance in electrical systems, installations, devices and components was mentioned officially for the first time about one hundred years ago. Nowadays insulation resistance thresholds, their testing and monitoring, as well as indication and protective measures have become imperative. Residual current protective devices (RCDs), which trip at direct contact, applied in TT and TN systems are generally known. Less known however, is residual current monitoring as a measure for fault indication. In IT systems the absolute value of an installation is permanently monitored and an audible and/or visual warning signal initiated, if this value fall below a certain level.

The American NFPA (National Fire Protection Association) publishes statistics about fires and causes of fires in American households every year. Electrical distribution equipment fires ranked first in property damages in 1999 [8.1]. Electrical distribution equipment includes: fixed wiring; transformers or associated overcurrent or disconnect equipment; meters or meter boxes; power switch gear or overcurrent protection devices; switches, receptacles or outlets; light fixtures, lamp holders, light fixtures, signs, or ballasts; cords or plugs; and lamps or light bulbs.

In 1999, electrical distribution equipment in the home caused 40,100 structure fires, 226 civilian fire deaths, 1,166 civilian fire injuries, and $ 804.7 million in direct property damage.

During the five-year period from 1994 through 1998, electrical distribution equipment caused an annual average of 38,400 home structure fires, 352 civilian fire deaths, 1,343 civilian fire injuries, and $ 614.2 million in direct property damage.

Electrical distribution equipment fires ranked:

- fourth in number of home structure fires in 1999 and fifth during 1994-1998
- fifth in home fire deaths in 1999 and fourth during 1994-1998
- seventh in home fire injuries
- first in direct property damage in 1999 and second during 1994-1998

Electrical distribution equipment caused 11 – 13 % of the fires in one- and two-family dwellings or manufactured homes, but only 5 – 6 % of the fires in apartments. A study done by the U. S. Consumer Product Safety Commission in the mid 1980's examined detailed information about electrical equipment residential fires in specific cities. They found that improper alterations contributed to 37 % of the fires; improper initial installations factored in 20 % of the incidents; deterioration due to aging system components contributed to 17 % of the fires; improper use was a factor in 15 % of the incidents; inadequate electrical capacity contributed to another 15 %; faulty products were implicated in 11 %, and contributing factors were unknown in 6 % of the fires studied.

Other American safety research data (CFOI and SOII) shows that 2,287 U.S. workers died and 32.807 workers sustained days away from work due to electrical shock or electrical burn injuries between 1992 and 1998. The narrative, work activity, job title, source of injury, location and industry for each fatal electrical accident were examined. A primary causal factor was identified for each fatality. Electrical fatalities were categorized into five major groups. Overall, 44 % of electrical fatalities occurred in the construction industry. Contact with overhead power lines caused 41 % of all electrical fatalities. Electrical shock caused 99 % of fatal and 62 % of non-fatal electrical accidents. Comprising about 7 % of the U.S. workforce, construction workers sustain 44 % of electrical fatalities. Power line contact by mobile equipment occurs in many industries and should be the subject of focused research. Other problem areas are identified and opportunities for research are proposed. Improvements in electrical safety in one industry often have application in other industries. [8.2]

German research reports from 1990 on “causes of fatal accidents due to electric current in low voltage distribution systems” state that the cause was attributed to insulation faults, in numbers that are 26 out of 164 accidents in the group of operating errors [8.3]. In these cases the insulation had either been damaged or removed from devices by unskilled persons, or made ineffective through water.

Although these figures should not be overestimated, they do point out that preventive insulation measurements by TT and TN systems, as well as permanent insulation monitoring by IT systems is of great importance.

Let me quote at this point an abstract from the NFPA President & CEO, Mr Jim Shannon from the Spring 2003 edition of nfpa-journal in a comment he made on the deadly nightclub fires, two of which had occurred in Rhode Island and Chicago, which had tragically killed 118 young people and is titled: Nightclub tragedies underscore the need for safety improvements.

“Existing arrangements, retroactive application of code requirements, and inspections and permitting activities must also e critically examined.

NFPA has always rapidly incorporated lessons learned following significant fires throughout the last century. On countless occasions, our codes and standards have been the impetus for needed reforms nationally and worldwide.

The application and enforcement of those codes and standards have saved countless lives. But those responsible for updating codes and standards as well as the enforcement community must learn from and respond to these tragedies.” [8.4]

When the insulation resistance is being considered, there are two aspects clearly distinguishable:

- the insulation resistance of de-energized systems without connected consumers
- the insulation resistance of energized systems with connected consumers

The significant differences in the insulation values of the different types of systems shall be clarified here since differences are often unrecognised, confused or unknown.

The dangers of applying electrical energy is known since the pioneering days. For good reason insurance engineers of the Phoenix Fire Office in London had demanded special safety measures for installing electrical wires by insulating them with a non-flammable insulation material and a double protective layer made of a solid durable substance.

8.1 History on Safety Regulations in Germany (1883)

Numerous fires in several industrial branches caused by electric current prompted German Fire Insurances to publish their first safety regulations for electrical installations on 20th August **1883**, basically dealing with arc and filament lamps. The publication of the German translation of “Regulations of the Phoenix Fire Office” for electric lighting and power stations in **1891**, a significant work at the time, created an awareness in the German public. The value of this work at the time was shown in 16 re-prints in the first eight years. For the first time it contained values on the insulation resistance, which was made proportionally dependent on the type of system and number of consumers connected.

German experts believed that making the insulation resistance dependent on the number of light bulbs was too inaccurate. The Association of Electro-Technique in Berlin (ETV) therefore published “Safety regulations for electrical high voltage installations against fire hazards” in December **1894**. §5 was on the insulation resistance.

The first comprehensive safety standards for electrical installations in Germany were published in January **1896** by the “Verband Deutscher Elektrotechniker e. V. (VDE)” (German Electro-technical Association), which addressed the insulation resistance in a whole chapter [8.5].

The most important prerequisite for avoiding personal and material damage by electrical equipment is an adequate insulation resistance. For that reason it is advisable to place a much higher demand on it, than necessary for operational reasons. Testing the insulation resistance is crucial for the evaluation of the safety-aspects of the installation.

8.2 Insulation Resistance – a Complex Matter

The insulation resistance against earth, respectively against the live conductor, respectively against exposed conductive parts of the live conductors in electrical installations or equipment are a highly complex matter, as they not only consist of just the insulation of the conductors, but also have clearances or contaminated and damp creepage distances. The most common representation is an equivalent circuit as shown in **Figure 8.1**, where a) represents insulation resistance independent of the voltage level, being in combination with b) which includes a voltage-dependent resistance, which is commonly called the insulation resistance. Low electrical voltages are considered in d). The leakage capacitance in c) is a relatively constant quantity, which only varies if the system is extended (cable length or added consumers).

Insulation faults, that are short circuits and earth faults are primary reasons for the safety considerations in electrical installations. Their share lies at 80 % to 90 % of the total number of systems faults.

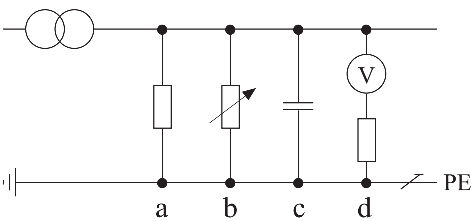

Figure 8.1 Equivalent diagram for insulation resistances
a, b, c constant and variable resistance and capacitive resistance
d voltage with series resistance

8.3 Definitions

The International Electrotechnical Vocabulary defines insulation fault as follows:

Insulation fault: “An insulation fault is a defect in the insulation of an equipment, which can result either in abnormal current through this insulation or in a disruptive discharge” [IEV 604-02-02].

The standard series of IEC 61557, “Electrical safety in low voltage distribution systems up to 1000 V a. c. and 1500 V d. c. – Equipment for testing, measuring or monitoring of protective measures” offer a number of definitions, just to mention a few:

Part 6, “Residual current devices (RCD) in TT, TN and IT systems”:

Fault current: “Current flowing to earth due to an insulation fault” [IEC 61557-6]

Part 8, “Insulation monitoring devices for IT systems”:

Insulation resistance: "Resistance in the system being monitored, including the resistance of all the connected appliances to earth" [IEC 61557-8]

8.4 Influence Quantities

Usually, if an electrical installation or electrical equipment is brand-new, it can be assumed that the insulation resistance is in a good state. Naturally manufacturers of wires, motors, etc. are constantly improving the insulation condition of their installation for the practical application in the industry. But a number of factors have a deteriorating influence on the insulation and cause resistance, for example: mechanical damage, vibrations, excessive temperatures, dirt, oil, corrosion, moisture from industrial processes or from environmental and climatic conditions.

Every system has a specific insulation resistance against earth. In new installations this resistance is within the MΩ range. However, installations are affected by various external influences:

- electrical effects through overvoltage, overcurrent, frequency, lightning as well as magnetic and inductive influences
- mechanical effects due to shock/impact, flaw/bend, vibration and penetration of foreign bodies, such as nails
- environmental effects due to temperature/moisture, light/ultraviolet rays, chemical influence, pollution, animals

Furthermore every electrical installation and hence the electrical insulation are subject to aging effects, which also gradually deteriorate the insulation values.

Despite the greatest of care by the manufacturers of electrical equipment on the selection as well on the erection of electrical installations, it cannot be guaranteed that sooner or later even the best insulation material will deteriorate and cannot meet the requirements regarding electrical and mechanical stress. Consequences from resulting insulation faults may be:

- short circuits
- short circuits to earth
- short-circuit to exposed-conductive parts

In the case of a short-circuit to exposed-conductive parts, the conductive parts, which are not included in the operating circuit (inactive parts), are conductively connected to energized parts (active parts) of the operating circuit. At this process faults occur, which result in touch voltages. Even low fault currents, starting as creeping contact resistances may develop into arcs, short-circuits or short-circuits to earth. They may become dangerous, if in close proximity to flammable or combustible agents. In TN or TT systems this fire risk already comes into existence with the first insulation fault at the unearthed conductor, if the loss of electric energy at the fault location is too high.

In IT systems an electric energy loss of this magnitude is only possible, if insulation faults occur at two different phase conductors at the same time.

8.5 Insulation Measurement and Monitoring

Beside permanent monitoring of the complete systems and installations, testing the insulation resistance in de-energized systems is one of the most important safety tests for electrical installations and equipment.

8.5.1 Measurements in De-Energized Systems

The insulation resistance of de-energized systems or parts of an installation is measured with devices in accordance with IEC 61557-2 (see Chapter 17). There are certain requirements, these measuring devices must meet, which are likewise regulated by IEC standards. In this way the construction and test-engineers of an electrical installation may be able to achieve and compare proper measuring results. All protective measures, with or without protective conductor, require insulation measurement. Attention should be paid to de-energizing all test-objects before applying the insulation measurement methods between:

- all phase conductors and protective conductors
- neutral and protective conductors
- phase conductors
- phase and neutral conductors

Tests may also be conducted with energized equipment. If the insulation resistance of these consumers is too low, the devices have to be disconnected and installation and devices be tested separately.

8.5.2 Residual Current Monitoring in TN and TT Systems

TN and TT systems are a well tried and often applied measure of protection against indirect contact by disconnection via a residual current protective device (RCD). The idea behind this measure is to lead all conductors, which shall be monitored, except for the protective conductor of course, through a current transformer. In a faultless system the sum of all currents equal zero, this means that no voltage is induced in the current transformer. If a fault current flows to earth, the sum of all currents is unequal zero. The voltage generated in the secondary winding of the current transformer releases a trigger to activate the protective device for disconnection of the installation.

A less known method for indicating a fault, is the method of residual (or fault) current monitoring. IEC 62020, 3.3.1 defines a residual current monitor (RCM) as a “device or association of devices which monitors the residual current in an electrical installation, and which activates an alarm when the residual current exceeds the operating value of the device”. RCMs are devices with an auxiliary source.

Although it is not an absolute measuring system, as is the case in IT systems, the RCMs are capable of detecting fault currents in TN and TT systems at an early stage. This allows appropriate steps to be taken without de-energizing the whole installation. A large setting range of the RCMs allows adaptation to special applications. However, insulation faults occurring symmetrically on all conductors against PE or earth are not detectable by residual current measurement.

8.5.3 Continuous Monitoring of the Absolute Insulation Value in IT Systems

The above description of the insulation resistance in principle applies to all types of distribution systems. The continuous monitoring of the absolute insulation value of the complete installation is only possible in IT systems with insulation monitoring. This means monitoring during operation and during the de-energized state of

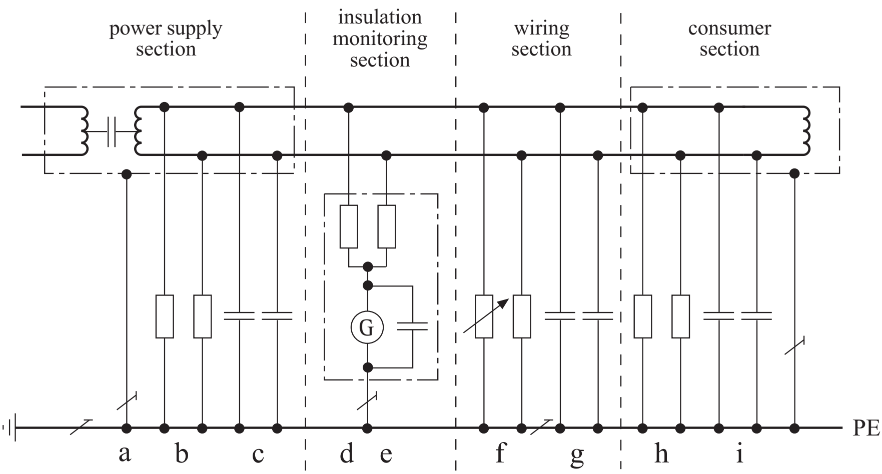

Figure 8.2 Equivalent circuit diagram for a.c. IT system

a, b, c transformer coupling capacitance, transformer leakage resistance, transformer leakage capacitance (capacitive resistance)

d, e internal d. c. resistance and a. c. impedance of the insulation monitoring device

f constant and varying insulation resistance

g leakage capacitance of the installation (capacitive resistance)

h, i insulation resistance and leakage capacitance (possibly also EMC filter capacitances) of connected current-using equipment the installation. Monitoring devices are positioned between the active, unearthed IT system and earth, respectively protective conductor, which are continuously measuring and signalling visually or audibly, as soon as minimum or maximum set response values are reached.

IT systems are being supplied by a transformer, a generator, an accumulator or another independent current source. The special feature of these a. c. or d. c. systems is, that no live conductor of the system is directly earthed. The advantage is that the first short-circuit to exposed-conductive parts or to earth does not interfere with the operation of the installation. An electrical installation designed as an IT system consists of the power source, a wiring system and the connected electrical equipment. **Figure 8.2** is an example of an a. c. IT system represented as an equivalent circuit diagram. The absolute insulation level of energized IT systems of course is lower than the insulation level of individual sections as seen in Figure 8.2. In addition, influence quantities as described before are to be considered.

8.6 Complete Monitoring in IT Systems

Protective measures against indirect contact according to IEC 60364-4-41 are dependent on the coordination of the type of distribution system and the protective device. In IT systems with supplementary protective equipotential bonding, the system usually is monitored for first insulation faults by means of an insulation monitoring device (IMD), which consists of an IMD according to IEC 61557-8 with an alarm and test combination connected to the IMD.

These standards apply to monitoring devices which continuously monitor the insulation resistance to earth of unearthed IT a. c. systems, respectively IT a. c. systems with galvanically connected d. c. circuits with nominal voltages up to 1000 V, as well as IT d. c. systems. Earth fault relays using the asymmetry voltage (voltage shift) as the only measurement criterion in the event of an earth fault are not insulation monitoring devices in the interpretation of IEC 60364-4-41 or IEC 61557-8.

As required by various standards, insulation monitoring devices signal a decrease in the insulation resistance to earth below a minimum value. Attention must be paid to the fact that the insulation resistance in the IT system is the resistance of the system being monitored, including the resistances of all the connected equipment to earth. The system leakage capacitances also have to be taken into consideration when selecting and setting insulation monitoring devices. The latest insulation monitoring devices designed in accordance to this standard are also capable of signalling the failure of connected wires to the monitored system or initiating an alarm, if the protective conductor is disconnected.

The response times of the insulation monitoring devices are subject to the system leakage capacitances. In pure a. c. systems the response times usually are below 1 s, with a negligible system leakage capacitance of up to 1 μF. However, response times of up to 10 s (IEC 61557-8) in a. c. systems and in a. c. systems with d. c. components, response times of up to 100 s are permitted.

Taking into consideration that an IT system with supplementary protective equipotential bonding in the event of the first can be likened to the design of a TN system, it becomes obvious that longer response times do not have adverse effects on insulation monitoring devices. Longer measurement periods are also required in systems with very high leakage capacitances or voltage fluctuations.

Literature

[8.1] Ahrens, M.: The U. S. Fire problem Overview Report. Quincy, Massachusetts/USA: NFPA Fire Analysis and Research, 2003, p. 70

[8.2] Cawley, J. C.; Homce, G. T.: Occupational electrical injuries in the United States, 1992 – 1998, and recommendations for safety research. Journal of safety research 34 (2003) no. 3, pp. 241 – 248

[8.3] Zürneck, H.: Ursachen tödlicher Stromunfälle bei Niederspannung. Schriftenreihe der Bundesanstalt für Arbeitsschutz und Arbeitsmedizin: Research Report, Fb 333. 3. Ed. Bremerhaven: Wirtschaftsverlag NW Verlag für neue Wissenschaft, 1990, p. 30

[8.4] Shannon, J.: Nightclub tragedies underscore the need for safety improvements. nfpa Journal 97 (2003) March/April, no. 2, editorial

[8.5] Rudolph, W.: Einführung in die DIN VDE 0100. VDE-Schriftenreihe 39. 2. Ed., Berlin · Offenbach: VDE VERLAG, 1999