# Permanent Insulation Monitoring & Insulation Test in LV Marine Power Systems

by Christian Collombet and Jean-Paul Sorrel

## Executive summary

Permanent insulation monitoring is mandatory for LV marine power system using isolated neutral. Insulation tests are required as well at construction of the installation. This paper provides guidance for the settings of Insulation Monitoring Devices according to safety rules. Recommendations are given about IMD injection method according to the type of loads, mainly while power conversion systems are used.

# Introduction

According to marine standards IEC 60092-201, neutral earthing method shall be selected based on technical and operational factors among:

- TN system (without hull return),
- IT system impedance earthed,
- IT system isolated.

Isolated neutral (IT) is commonly used in LV whereas there is no need to supply loads with phase to neutral connections.
In addition, IT system:

- is mandatory to supply emergency power system,
- prevents from black-out under first fault condition,
- reduces the risk of fire due to leakage currents,
- avoids damages on rotating machines windings and magnetic steel parts.

## Isolated neutral and insulation resistance

Permanent insulation monitoring is mandatory with isolated neutral system and the Insulation Monitoring Device (IMD) shall comply with IEC 61557-8. IMD allows permanent insulation resistance ($R_F$) measurement during operation, with energized systems. IMDs are installed to monitor every sub-network galvanically insulated. Whereas a neutral point is not available, the injection is made through one phase. Setting a consistent value for the threshold alarm is key to ensure a proper detection of a hazardous low insulation and to prevent nuisance alarm.
Rotating machines, transformers, switchgear and controlgear assemblies, cables, loads, etc. are subject to individual insulation resistance tests during manufacturing, installation commissioning and periodic maintenance. Despite those tests make it possible to give a feeling on the operational quality of a product or a sub-assembly they do not make it possible to conclude on the operational quality of an entire power system.
As insulation tests and permanent insulation monitoring are performed according to different service conditions, their measurements are not directly comparable or equivalent.

## Impact of marine regulations

Along with marine regulations evolution and fuel consumption reductions, ships power systems are evolving, embedding new systems which may have a direct impact on insulation resistance.
As regulations apply to existing fleets, ship power systems are subject to significant evolution during its life cycle: addition of scrubber systems, ballast water treatment, variable speed drive for engine room cooling fans and pumps, etc.
Therefore, selection and setting of IMDs must be consistent with these new applications.

# Marine LV Power systems Characteristics

Figure 1 shows a typical LV power system single line diagram.
Main loads and propulsion are supplied from 690V generators through the main switchboard. Auxiliary loads are supplied at 440V and 230 V.
Emergency switchboard is used at both 440V and 230V.

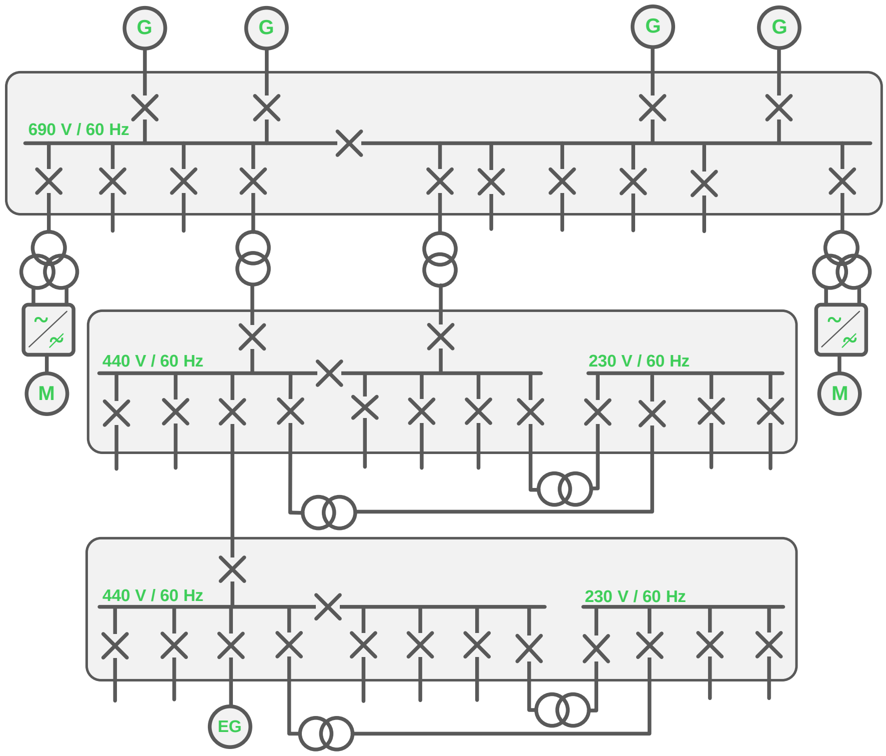



**Figure 1**

*Typical LV single line diagram*

## General considerations

Insulation of LV power systems can be characterized by:

- A leakage resistance between phases to ground,
- A leakage capacitance between each phase and the ground.

Leakage resistances and capacitances value depend on cables, frequency converters EMC filters, rotating machines, transformers, etc.
For a network properly insulated, we agree to have balanced insulation resistance and balanced leakage capacitance between phases and ground (R1=R2=R3=Ri, C1=C2=C3=C).

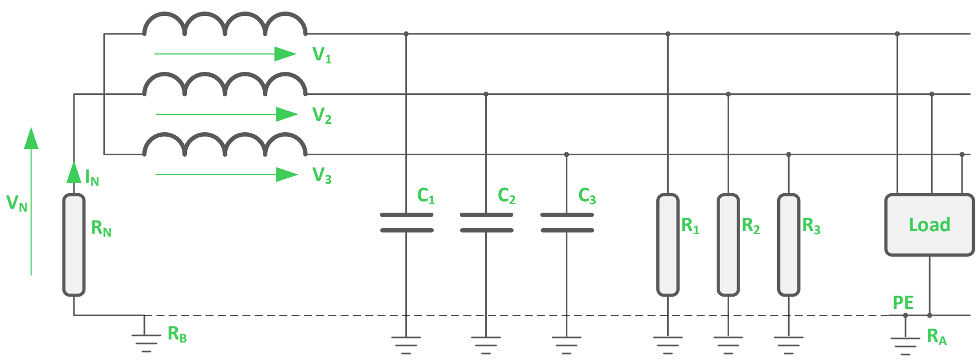



**Figure 2**

*Equivalent diagram of LV power system with IT neutral earthing in normal operation*

- In normal situation (no earth fault, **Figure 2**), currents through insulation resistances and capacitances are balanced thus $\sum I_{ci} = \sum I_{Ri} = I_N = 0$ and there no hazardous voltage between load case and earth (Uc = 0 V).

- In case of low insulation (**Figure 3**) on one phase then currents through resistance and/or capacitance are unbalanced $\sum I_{ci} = \sum I_{Ri} = I_N \geq 0$ .

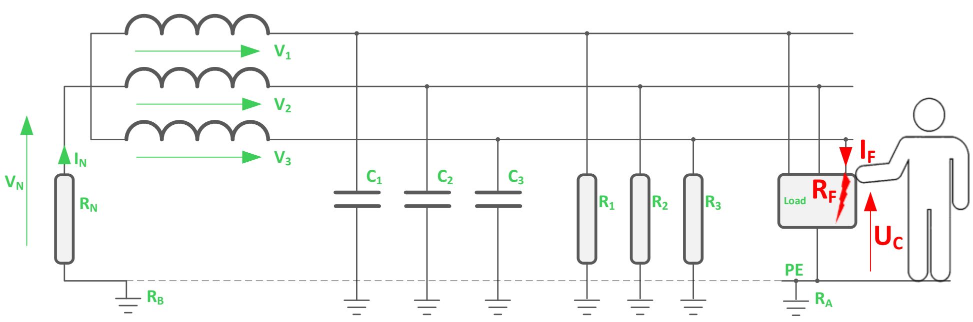



**Figure 3**

*Equivalent diagram of LV IT power system with low insulation between phase 3 and earth*

Due to their high value compared to capacitance at 50 or 60 Hz, the leakage resistances impact on the fault current $I_F$ can be neglected.
Thus, the fault current $I_F$ and touch voltage $U_C$ can be obtained from the following formulas:

- $I_F = U_0 \frac{(1+3jC\omega R_N)}{R_F+R_N+3jC\omega R_N R_F}$ , **Equ. 1**
- $U_c = R_A I_F$. **Equ. 2,** where $R_A$ is the hull resistance.

If the PE conductor is wired, then the touch voltage is calculated considering $R_A$ in parallel with $R_B$ plus the PE resistance.

## Typical characteristics

Considering typical characteristics for the power system as illustrated on **Figure 1**, a pure isolated neutral with $R_N = \infty$ (ie ≥ 1 MΩ, unearthed system), touch voltage and fault current can be drawn as functions of insulation resistance values.
For the calculation of the touch voltage the hull resistance $R_A$ is estimated to 2 Ω max.
The power system capacitance depends on the connected circuits thus depends on the operating conditions of the vessel. **Table 1** gives the considered variation of the leakage capacitance for each voltage levels of the considered power system.

**Table 1**

*Typical leakage capacity for according to voltage level*

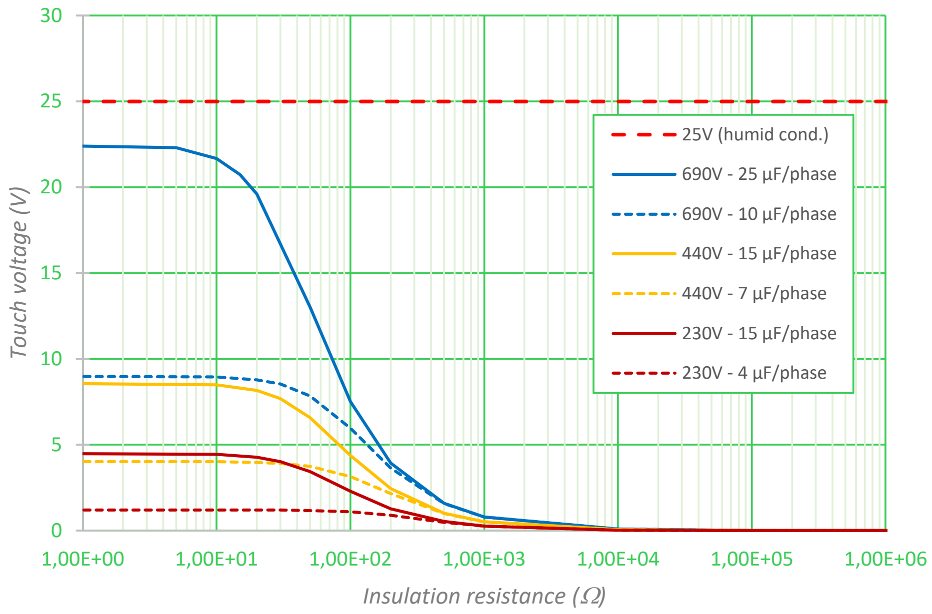
| Voltage level | Typical range for leakage capacity per phase (µF) | |
|---|---|---|
| | Max | Min |
| 690 V | 25 | 10 |
| 440 V | 15 | 7 |
| 230 V | 15 | 4 |

## Touch voltage during insulation fault

As expected, the touch voltage for the 3 voltage levels is maintained lower than the safety voltage in dry and humid conditions, for the whole range of leakage capacity and even while the insulation resistance is lowering towards a bolted short-circuit.
**Figure 4** shows the impact of leakage capacity on the touch voltage for 690V, 440V and 230V distributions.

**Figure 4**

*Touch voltage as a function of the insulation resistance*



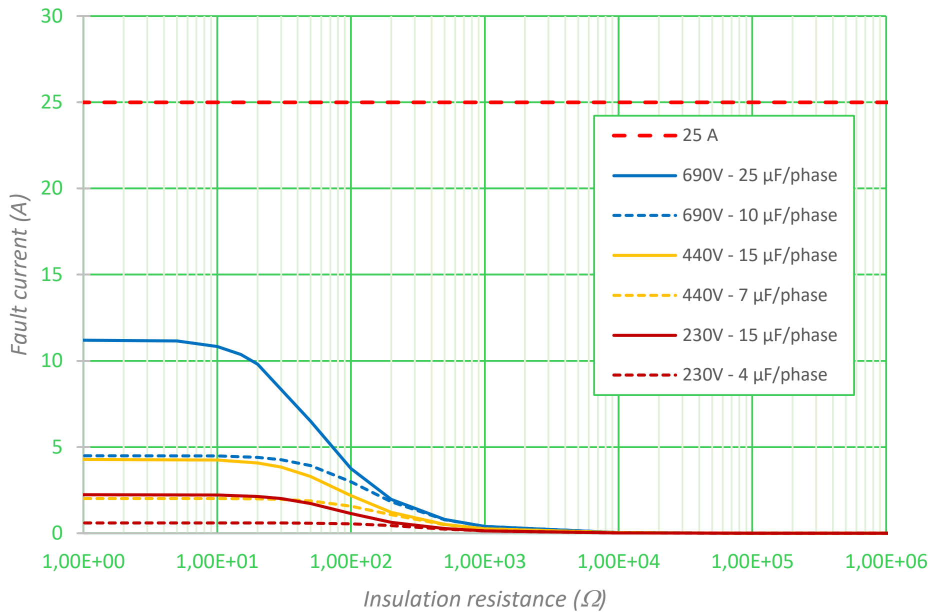

## Fault current

To prevent damage in magnetic circuits of transformers and rotating machines, to reduce the risk of abnormal temperature rise, the fault current shall stay under 25 A.

With $R_N = \infty$ (ie ≥ 1 MΩ, unearthed system), **Figure 5** shows the fault current kept under 5 A as long as the insulation resistance is greater than 100 Ω.

**Figure 5**

*Fault current as a function of the insulation resistance*




# Permanent insulation monitoring

## Settings of IMD and IEC standards recommendations

For unearthed systems used for continuity of supply IEC60364-5-53 specifies from a note in §537.2.3 the set points of Insulation Monitoring Devices (IMD):

- 100 Ω per volt as typical setting,
- 300 Ω per volt for pre-alarming.

To prevent excessive over-heating, IEC60364-5-53 §532.2.3.4 recommends setting IMD alarm to a value not lower than 100 Ω / volts as well.

**Table 2** gives the recommended settings as per IEC60364-5-53 applied to the typical 690V, 440V and 230V distribution. Such settings ensure a fault current below 10 mA for any voltage as illustrated on **Figure 6**.

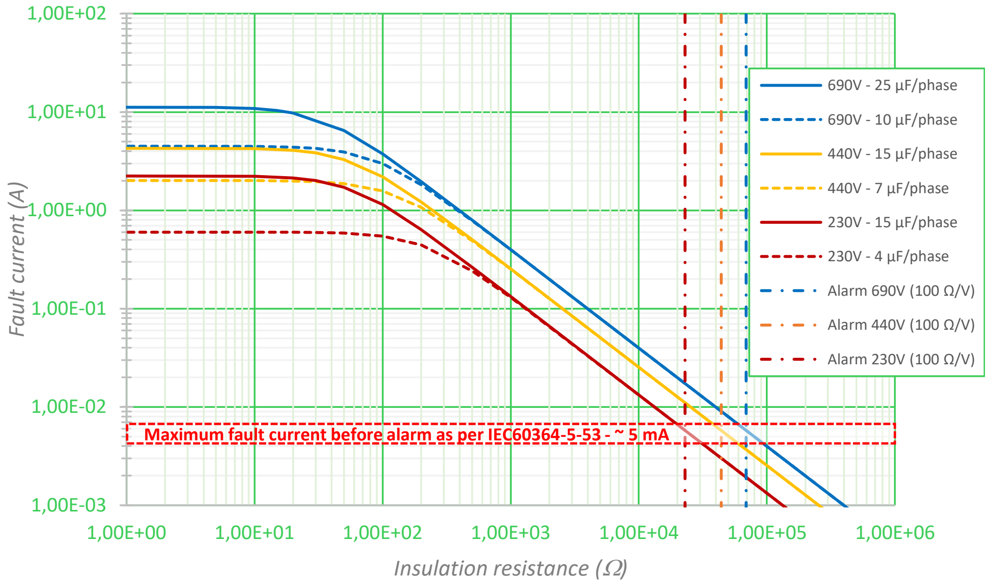
**Table 2**

*Recommended settings and IEC60364 threshold calculation*

| Voltage level | Pre-alarm (300 Ω/V) | Pre-alarm Recommended | Alarm (100 Ω/V) | Alarm Recommended |
|---|---|---|---|---|
| 690 V | 207 kΩ | 200 kΩ | 69 kΩ | 70 |
| 440 V | 132 kΩ | 130 kΩ | 44 kΩ | 50 |
| 230 V | 69 kΩ | 70 | 23 kΩ | 25 |

**Figure 6**

*IMDs alarms as per IEC60364-5-53 and resulting maximum fault current before alarming for the considered range of voltage*



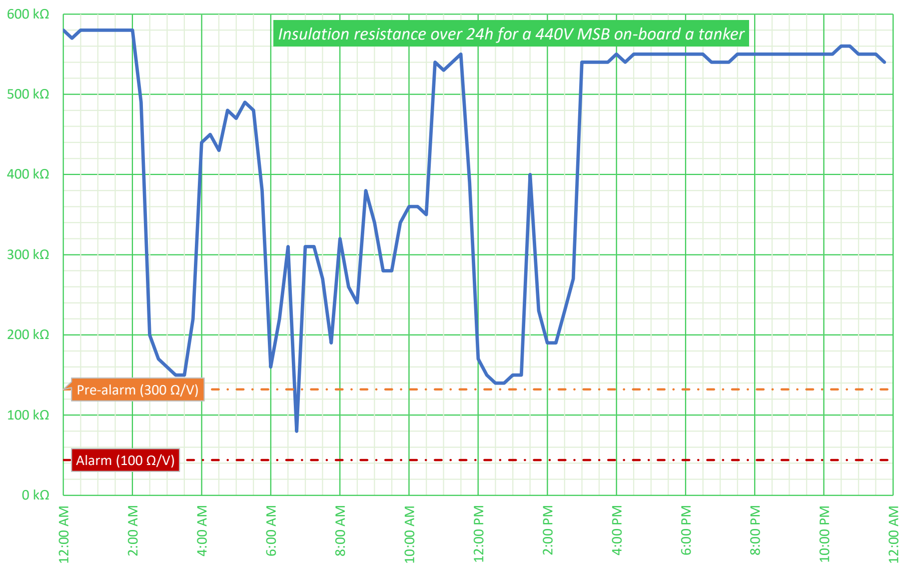

Even under humid conditions, **Figure 4** demonstrates that low insulation doesn't create dangerous touch voltages considering typical leakage capacity values as per **Table 1**.
Therefore, IMD alarm shall be set to ensure detection in case of actual insulation fault and prevent nuisance alarm.
Some applications may create cycling drop of insulation resistance not related to actual faults:

- a low insulation resistance may be consecutive to the presence of humidity due to a prolongated shutdown, off-line insulation monitoring may be help-ful to evaluate the state of health before energization and powering on the installation allow the insulation to be raised to a greater value,
- specific cycling processes like de-icing resistances of reefers may also cause temporary low insulation.

**Figure 7** is a recording of the insulation resistance from a 440V main switchboard of a tanker over 24 hours while the vessel is at sea. During half of the day, the insulation resistance is quite stable between 550 kΩ and 600 kΩ. Over the second half of the day, the insulation resistance varies in a wider range and drops down to 80 kΩ for a short period reaching temporarily the pre-alarm setting.

**Figure 7**

*Recording over 24 hours of the insulation resistance measured at a 440V main switch-board on-board a*




The IMD has recorded the leakage capacity as well over the same period, and its variation is between 6.9 µF and 7.6 µF. Considering greatest leakage capacity and assuming hull resistance of 2 Ω, **Figure 8** and **Figure 9** illustrate the fault current and touch voltage as a function of recorded insulation resistance.

**Figure 8**

*Fault current as a function of recorded insulation resistance at 440V main switchboard on-board a tanker*

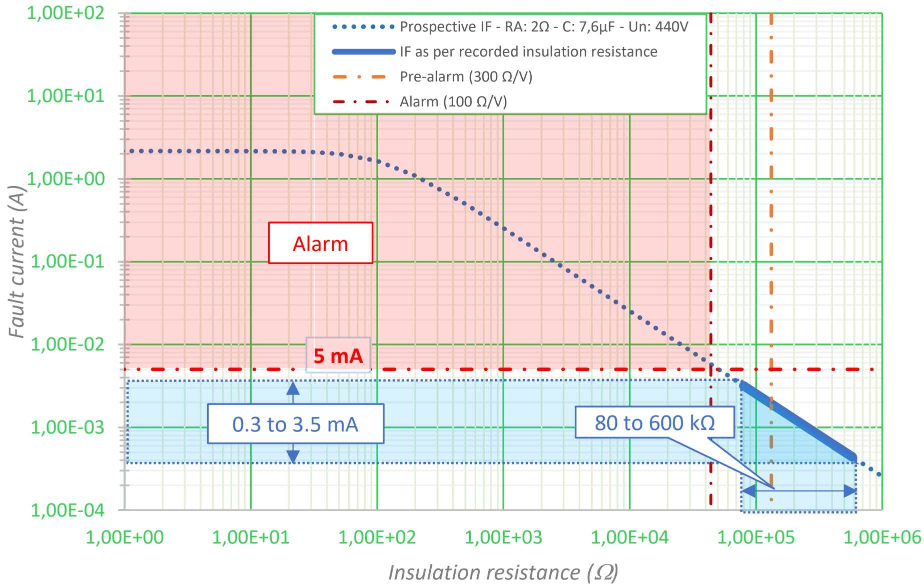
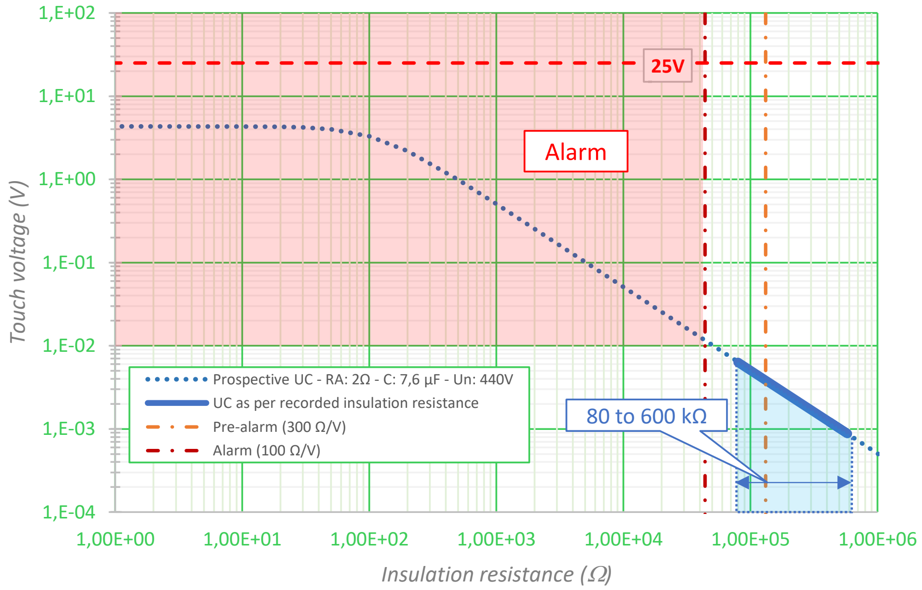


**Figure 9**

*Touch voltage as a function of recorded insulation resistance at 440V main switchboard on-board a tanker*

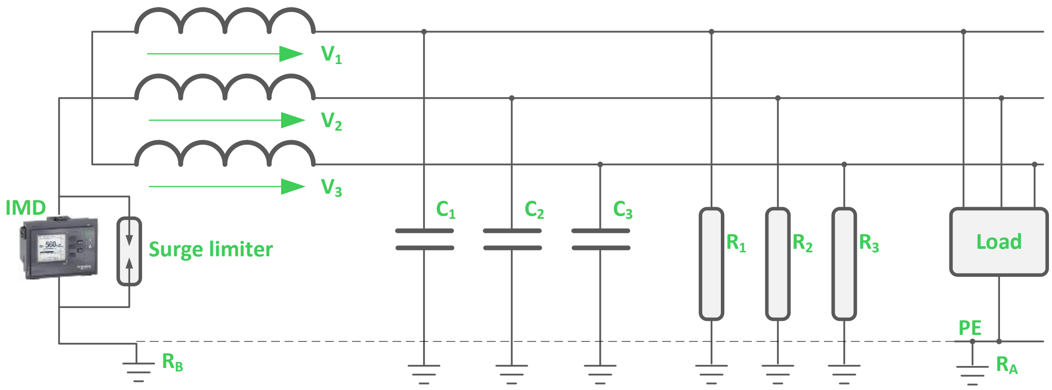



## IMD types and measurement method

Insulation Monitoring Device (IMD) shall comply with IEC61557-8 requirements and shall be placed to monitor every sub-network galvanically insulated.

**Figure 10**

*IMD connected at neutral*




The surge limiter (**Figure 10**) prevents against damages caused by over-voltages due to internal disruptive breakdown between the MV/LV windings of the transformers or in case of lightning overvoltage.
The principle of an IMD is to inject a measurement voltage $U_m$ between the neutral point (or any phase if the neutral point is not accessible) and the earth of the power system to monitor. When an insulation fault occurs, a current $I_m$ corresponding to the measurement voltage and the fault impedance is circulating. This current is detected and used to evaluate the insulation compared to the alarm and pre-alarm thresholds.
According to IEC61557-8 IMDs are classified in 3 types:

- Type AC IMD for pure AC IT systems,
- Types AC/DC IMD for IT systems with directly connected (*) rectifiers and for pure DC IT systems with directly connected (*) AC inverters,
- Type DC IMD only for pure DC IT systems.

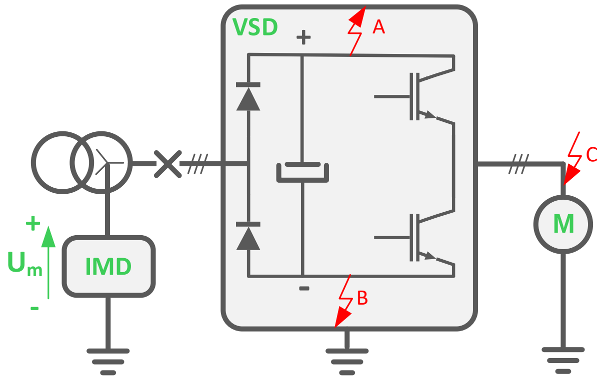
(*) Directly connected without galvanic insulation.

The type of IMD depends directly on the measurement method. Basic IMDs are commonly using DC voltage as measurement method.
DC injection IMDs measure only the insulation resistance and their use shall be restricted to purely AC power systems without DC component.
An IMD using DC injection can be misled by DC leakage currents. DC leakage currents occur where static converters experience insulation fault on the DC

bus: depending on the current circulation and the polarity contributing to the fault (A or B on **Figure 11**), the DC leakage current may over-estimate the measured insulation resistance instead of detecting a low insulation, thus hiding the insulation fault.

**Figure 11**

*Impact of a DC leakage current on a basic IMD using DC injection*




Advanced IMDs are using AC measurement voltage, either low frequency or multi frequency voltage and are compliant with DC power systems and AC/DC power systems.
Therefore, when variable speed drives, static converters or any nonlinear loads are used an AC injection IMD classified type AC/DC by IEC61557-8 shall be used. Therefore, the fault detection covers the entire installation including VSD and downstream cable and motor (fault C on **Figure 11**).

**Figure 12**

*IMD IM400*
*Type AC/DC and type DC according to IEC61557-8*


It is relevant to use an IMD like IM400 (**Figure 12**) designed for AC or DC networks and able to measure the leakage capacity (C) in addition to the insulation resistance ($R_F$).
According to IEC61557-8 IMDs shall measure the insulation resistance with a relevant accuracy up to a value of leakage capacitance for which it has been designed. A leakage capacitance above the designed value can introduce an error on measured insulation resistance.
As illustrated by **Figure 4** and **Figure 5**, the higher the leakage capacity, the higher the touch voltage $U_C$ and fault current $I_F$.
A specific attention shall be carried out to EMC filter (capacitors) of static converters while connected to the earth as they will contribute to the leakage capacitance.
These capacitors are responsible for residual differential currents at power on, as well as in normal operation.
Preferably, EMC filters shall be not earthed to avoid excessive capacitance and leakage currents (ie a balanced 3 phases insulated filters shall be used).

## Insulation fault localization

Once a low insulation is detected by the IMD, it is mandatory to look for the place of the fault and identify the faulty feeder.
The fault localization can be made:

- Manually by sequential opening of feeder circuit-breakers,
- Manually with a mobile fault locating kit,
- Automatically with fault localizer installed at least on most critical switchboard feeders.

Using modern fault localizers enables insulation fault resistance and leakage capacitance measurement per feeder. It is recommended to use such devices to ease and fasten the fault localization at least for critical circuits. Mobile localization kits can be used to complete the localization on terminal circuits (**Figure 13**).

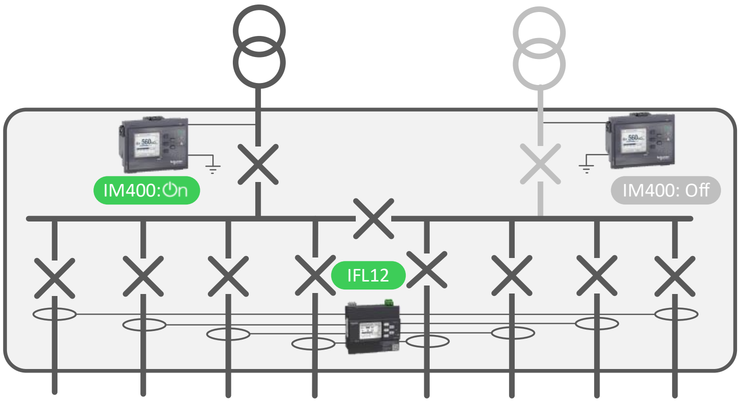



**Figure 13**

*IMDs & IFL fault localizers to identify automatically faulty feeders*

# Insulation resistance test

## Standards requirements

Installation standards and classification society rules (some are listed below) are providing guidance for insulation resistance tests or measurements for equipment and components to be performed at commissioning. The purpose of these tests is to ensure the good insulation of each part of the installation.
The instrument intended to measure insulation resistance is an insulation resistance meter or ohmmeter. This device is connected to the section to be tested.
IEC 60364-6:2016 §6.4.3.3 requires insulation resistance measurement during initial verification of equipment between live conductors and live conductors and the earth.
The insulation shall be measured while the installation is not energized and considering:

- the test voltages indicated in **Table 3**,
- main switchboard and each distribution circuit tested separately,
- loads disconnected, IMD and fault localizers disconnected.

**Table 3**

*Minimum values of insulation resistance as per IEC60364-6:2016 Table 6.1*

| Rated circuit Voltage | Test voltage | Minimum insulation resistance |
|---|---|---|
| ≤ 500 V | 500 V DC | 1 MΩ |
| > 500 V | 1000 V DC | 1 MΩ |

Similar test voltages are required in marine standard IEC60092-401 ED4, table 7.
IEC60092-401 is specifying the testing instruments as well as the test conditions and minimum expected insulation resistance for the different elements of the installation.
A measurement of insulation resistance is valid for a given ambient temperature and humidity level. For motors and generators, it is recommended to record the test conditions and to perform it in warm condition Immediately after running with normal load.
For switchboard IEC69092-401 specifies to perform the test between busbars and busbars and earth with all circuit-breakers and switches open. The ex-pected minimum insulation values are given in **Table 4**.

**Table 4**

*Minimum values of insulation resistance for average climatic conditions as per IEC60092-401 ED4*

| Minimum expected Insulation resistance | | | |
|---|---|---|---|
| Rated Voltage | Power cables | Motors, generators | Switchboards |
| ≤ 50 V | 0.3 MΩ | None | 1 MΩ |
| ≤ 400 V | 1 MΩ | None | 1 MΩ |
| > 400 V | $\frac{Un}{1000}$+1 MΩ | None | 1 MΩ |

For power cables and switchboard, it is recommended to subdivide the installation and disconnect appliances if tests do not comply with above table values.

## Classification societies requirements

Classification Societies require insulation resistances test consistent with IEC60364-6.
DNV in its rules for classification of ships in Part 4 Chapter 8 §4.3.3 requires to perform insulation resistance testing for all outgoing power circuits from switchboards (independently) according to **Table 5**.

**Table 5**

*Test voltages and minimum insulation resistance as per DNV-RU-SHIP Pt.4 Ch.8.*

| Rated circuit Voltage | Test voltage | Minimum insulation resistance for a single consumer |
|---|---|---|
| Un ≤ 250 V | 2 x Un DC | 1 MΩ |
| 250 < Un ≤ 1000 V | 500 V DC | 1 MΩ |

DNV mentions as well that no minimum value for insulation resistance of a distribution system (ie sub-network) is given. However, DNV mentions that it is expected to be about 0.5 kΩ per volt, it corresponds to:

- 345 kΩ for 690V distribution system,
- 220 kΩ for 440V distribution system,
- 115 kΩ for 230V distribution system.

ABS rules for building and classing steel vessels in chapter 8 section 4 § 29.13 requires insulation resistance measurement of power and lighting cables. ABS rules requires that each circuit insulation resistance between conductors and between conductors and the earth is higher than the values stated in **Table 6**.

**Table 6**

*Insulation resistance of power and lighting cables as per ABS Pt.4 Ch.8. Sect.4*

| Load demand | Expected insulation resistance |
|---|---|
| ≤ 5 A | > 2 MΩ |
| ≤ 10 A | > 1 MΩ |
| ≤ 25 A | > 0.4 MΩ |
| ≤ 50 A | > 0.25 MΩ |
| ≤ 100 A | > 0.10 MΩ |
| ≤ 200 A | > 0.05 MΩ |
| > 200 A | > 0.025 MΩ |

## Conclusion

Isolated neutral is widely used in LV marine mower systems as it enables to keep circuits energized while a first fault to earth occurs. This is possible due to very low leakage current and safe touch voltage as long as the installation has been designed according to rules and standard. A specific attention must be paid to the resistance of equipotential bounding to earth that has to be as low as possible and practically not exceeding 5 Ω to maintain a safe touch voltage.
Leakage capacitance impacts the value of the earth fault current and may be monitored in case of wide installation or in case of installation using numerous static converters.
Insulation Monitoring Device (IMD) selection and settings have a major contribution:

- to keep the installation safe,
- not to generate nuisance alarming,
- not to be misled by insulation fault on DC bus of static converters.

Settings of alarming and pre-alarming threshold must consider actual fault and not temporary or transient low insulations due to specific processes operation.
In installation where static converters (Variable speed drives, UPS) are used it is recommended to install IMD using AC injection and measuring leakage capacitance like IM 400 from Schneider Electric.

To remain on the advantage of isolated neutral, the first fault must be eliminated within the shortest practical delay which requires the intervention of maintenance crew. Automatic fault localizer such as the IFL12 from Schneider Electric makes it possible to shorten the detection of the faulty circuit.

## About the authors

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# Glossary

| | |
|---|---|
| **ABS** | American Bureau of Shipping |
| **AC** | Alternative Current |
| **C** | Leakage capacitance |
| **DC** | Direct Current |
| **DNV** | Det Norske Veritas |
| **EMC** | Electro-Magnetic Compatibility |
| **f** | Frequency in Hz |
| **IEC** | International Electrotechnical Commission |
| **IEV** | International Electrotechnical Vocabulary |
| $I_F$ | Fault current in A as per IEV 826-11-11 |
| **IMD** | Insulation Monitoring Device |
| **LV** | Low Voltage (Un ≤ 1 kV in AC) |
| **PE** | Protective Earth |
| $R_A$ | Resistance of equipotential bounding to earth, ie hull resistance |
| $R_B$ | Resistance of the neutral connection to earth |
| $R_F$ | Insulation resistance in Ω as per IEV 151-15-43 |
| $R_N$ | Resistance between neutral and earth in Ω |
| $U_C$ | Touch voltage in V as per IEV 195-05-11 |
| $U_0$ | Phase to neutral voltage in V |
| $U_n$ | Phase to phase voltage in V |
| **VSD** | Variable Speed Drive |
| $\omega$ | Angular frequency in rad/s as per IEV 103-07-03 ($\omega = 2\Pi f$) |

# Resources

[Electrical Installation Guide Schneider Electrics](#)
**Chapter F: Protection against electric shock - Implementation of the IT system**

Cahier Technique N° 178 Schneider Electric

Cahier Technique N°204 Schneider Electric

Vigilohm Insulation Monitoring Devices

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