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Leakage Currents in Power Line Filters

Basics about leakage currents including calculation and measurements

1. Abstract

During normal operation of electrical equipment some current is flowing along the protective earth conductor towards earth. These currents, called leakage currents, pose a potential safety risk to the user and are therefore limited by most current product safety standards. Residual current devices or leakage current breakers are found more and more in order to interrupt the supply if high leakage current is detected.

Power line filters, or EMC filters, contribute to the overall leakage current of equipment with their capacitors against earth. Today's technologies make the use of noise suppression filters almost mandatory and thus increase the importance of leakage currents for the end user. Customers are often confused with the ratings of leakage currents, because filter manufacturers do not use harmonized methods for the calculation. As a result the leakage currents of filters with identical circuits, but from different manufacturers cannot be compared directly. This article explains the basics about leakage currents and shows methods for calculation and measurements.

2. Requirements in the standards

The protective earth connector protects the user from dangerous touch voltages in case of malfunctions or short circuits in electrical equipment. In order to guarantee this basic function, the current on the protective earth line must be limited, which is why most product safety standards include provisions for measuring and limiting leakage currents. This shall be illustrated on the basis of EN 60950-1, the product safety standard for office equipment and information technology equipment.

While leakage current is used as the common description, the standard actually differs between touch current and protective conductor current. Touch current is all current flowing through the human body, when he touches the electrical installation or equipment. The protective earth current on the other hand is the current flowing through the protective earth conductor in normal operation of the equipment or installation. It is this current that is also referred to as leakage current.

All electrical equipment must be constructed to not allow dangerous touch and protective earth currents, which could endanger the user. In general the touch current should never exceed 3.5mA, which is confirmed with a measurement as described later in this article.

The limit of 3.5mA is not realistic for all kind of equipment and therefore there is an additional provision in the standard for equipment with an industrial-type power connector (pluggable equipment type B) and protective earth connector. The touch current can be above 3.5mA, if the protective earth current does not exceed 5% of the input current. In addition the minimum cross-section of the equipotential bonding conductor must be in compliance with EN 60950-1. Last not least the manufacturer has to attach one of the following warning labels to his electrical equipment.

“Warning!
High touch current. Connect to earth first.“

“Warning!
High leakage current. Connect to earth first.“

Besides the common product safety standards there are also safety standards for passive EMI filters. For Europe is this EN 60939; VDE 106 part 102. The VDE consults at the moment on improved information regarding the leakage current data by EMI filters, calculation procedure and measuring procedure are discussed to the information of the leakage current.

However, this standard does not contain any additional requirements regarding the tolerable high of leakage currents for filters. The situation is different though for the American standard for EMI filters, the UL 1283. Not only are all the usual safety tests required, but also the confirmation of the leakage current of the filter. By default this leakage current is not allowed to exceed 0.5mA for a cord-connected or direct-plug-in filter otherwise not more than 3.5mA. It if does, the filter must be marked with a safety warning stating that the filter is not intended for use in residential areas. An earthing connector for electric shock protection must exist and the filter must be connected to an earthed power outlet or connection.

3. Calculation of leakage currents

This chapter will explain the possibilities of calculating leakage currents. The results will not necessarily correspond to the measurement results, because the tolerances of components and the unbalance of the supply network (in case of 3-phase networks) can only be assumed for the calculation. Also of the mains voltage (50Hz/60Hz) overlaid harmonics can lead to higher leakage currents.

EMI filter manufactures provide often the calculated value for leakage currents at nominal voltage with an unsymmetrical of 3% and a capacitor tolerance of +/- 20%. The parasitic components of the magnetic components will be neglected for all calculations as well as the impedance of the protective earth connector. The calculation only takes into account the tolerances of the filter capacitors. In typical EMI filters capacitors are used to suppress differential- mode and common-mode interference. In the first case so called X-capacitors are connected between the phases respectively between phase and neutral conductor. For common-mode suppression Y-capacitors are used between phase and earth.

Frequency- and voltage-dependency of the capacitors will also not be taken into account. This would be important for ceramic capacitors, where the value changes significantly with voltage and frequency. As a consequence the leakage currents of filters with ceramic capacitors can also be higher than the result of the calculation.

3.1 Leakage currents in 3-phase supply networks

In order to calculate the leakage current in 3-phase supply networks it is necessary to determine the voltage between the supply star point M_Q and the load star point M_L. On the supply side are the three phase voltages $\underline{U}_{L1}$, $\underline{U}_{L2}$ and $\underline{U}_{L3}$, which are connected in the star point M_Q. On the load side are the three impedances $\underline{Z}_1$, $\underline{Z}_2$ and $\underline{Z}_3$, which are also connected to a star. The two star points M_Q and M_L are linked over the impedance $\underline{Z}_{QL}$, where the voltage drop $\underline{U}_{QL}$ occurs.

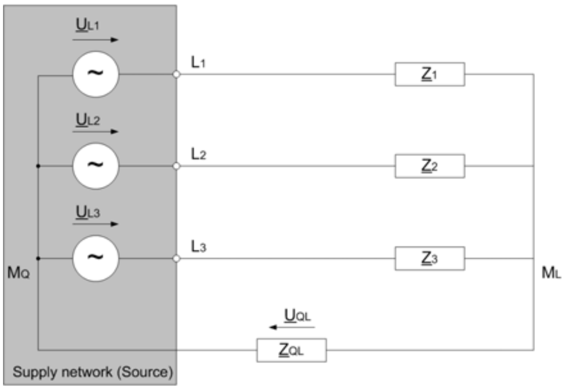

Figure 1: Star connection of supply and load

The actual voltage U_{QL} across the impedance Z_{QL} can be calculated with the following equation:

$$\underline{U}_{QL} = \frac{\frac{\underline{U}_{L1}}{\underline{Z}_1} + \frac{\underline{U}_{L2}}{\underline{Z}_2} + \frac{\underline{U}_{L3}}{\underline{Z}_3}}{\frac{1}{\underline{Z}_1} + \frac{1}{\underline{Z}_2} + \frac{1}{\underline{Z}_3} + \frac{1}{\underline{Z}_{QL}}} \qquad (1)$$

One of the common configurations for passive 3-phase filters is the star point connection of three X-capacitors, which are then connected to the earth potential or housing of the filter via on Y-capacitor. In case of a balanced capacitor network the leakage currents will be negligible, because the summery of all currents in a three phase system is = 0. On the other hand the leakage currents will reach the maximum value at the highest unbalance between the phases. Causes for the unbalance are the tolerances of the capacitor values as well as the voltage unbalance in the supply network.

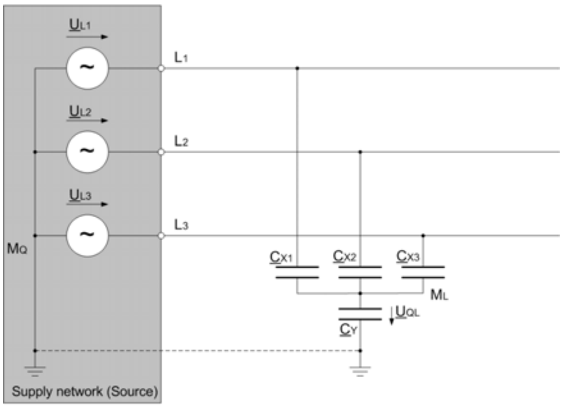

Figure 2: Typical capacitor configuration in 3-phase filters

It follows that the critical factor for the leakage current is the voltage $\underline{U}_{QL}$ resulting from the unbalance of the capacitors $\underline{C}_{X1}$, $\underline{C}_{X2}$ and $\underline{C}_{X3}$. In most filters the rated values are identical, but are also subject to manufacturing tolerances. The resulting leakage current $\underline{I}_{leak, max}$ from the voltage drop $\underline{U}_{QL}$ at the capacitor C_Y can be determined as:

$$\underline{I}_{leak,\max} = \underline{U}_{QL} \cdot j\omega C_{Y,\max}$$

with $\omega = 2 \cdot \pi \cdot f$ (2)

Most capacitors in passive filters are rated by the manufacturers with a tolerance of ±20%. The highest voltage drop at C_Y occurs when two of the X-capacitors show the lowest tolerance values and one shows the highest. In addition C_Y is assumed at its highest tolerance value. If these assumptions are put into equations (1) and (2), the resulting leakage current is

$$\left|I_{leak,\max}\right| = \omega C_{Y,\max} \frac{U_{\max} C_{X,\max} - U_{\min} C_{X,\min}}{C_{X,\max} + 2C_{X,\min} + C_{Y,\max}} \qquad (3)$$

To put a good picture to the theory an example calculation can be performed with a 480V 3-phase filter. The capacitor values are given with C_X=4.4µF and C_Y=1.8µF; the tolerances for all capacitors are ±20% according to the manufacturer. Not considering the supply voltage unbalance the leakage current is calculated as approximately 23mA.

Practical experience shows that the tolerances of capacitors are never that wide spread. More realistic seems an assumed tolerance range from -20% to 0%. Using this assumption in the calculation above the result for the leakage current is only about 10mA. It should be pointed out though, that there is no agreement between filter manufacturers regarding the calculation method for leakage currents in filters. It is therefore perfectly possible to have differing leakage currents of two filters, even though the circuit diagrams and component values are identical.

Up to this point the voltage unbalance of the supply network was not taken into account for the calculation. In practical application supply networks do have a certain unbalance. To include this into the calculation, the supply network standard EN 50160 is used, which defines the conditions in public power supply networks. According to this standard, the voltage unbalance for regional networks can be up to

3%. Using this in the previous calculation the leakage current now adds up to 26mA for a capacitor tolerance of ±20% and 13mA for +0/-20%.

3.2 Leakage currents in single-phase networks

Compared to 3-phase networks, the calculation of leakage currents in single-phase networks is significantly easier. With given supply voltage and frequency the leakage current depends solely on the total capacitance. Figure 3 shows the typical capacitor circuit for single-phase filters.

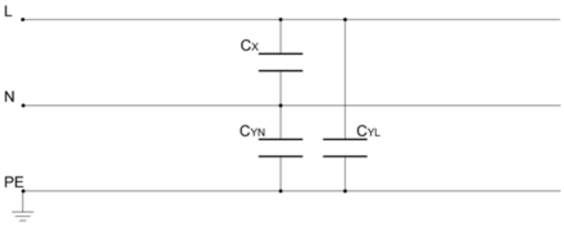

Figure 3: Typical capacitor configuration for single-phase filters

For normal operation the leakage current is determined by the capacitors C_{YL} respectively C_{YN}. The total amount is given by the equation

$$I_{leak} = \omega C_{Y,\max} \cdot U \qquad (4)$$

For a filter with C_X=100nF and C_Y=2.2nF and a given tolerance of ±20% the leakage currents results in 190µA. The worst case scenario is given if the neutral conductor is interrupted. The total capacitance then consists of two parallel capacitors: C_{YL} on the one hand and the series connection of C_X and C_{YN} on the other. Figure 4 shows the equivalent circuit.

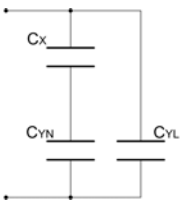

Figure 4: Total capacitance with interruption of neutral

The following equation is used to calculate the total capacitance.

$$C_{ges} = C_{YL} + \frac{1}{\frac{1}{C_{YN}} + \frac{1}{C_X}} \qquad (5)$$

For fault conditions the maximum leakage current can be as high as 377µA.

4. Measurement of leakage currents

Calculating the leakage current is one way, performing measurements is the other. The necessary measurement methods are described in safety standards like EN 60990 / VDE106 part 102 "Methods of measurement of touch current and protective conductor current".

4.1 Measurement according to EN 60950 linked to EN 60990

As mentioned in the chapter "Requirements in the standards" EN 60950 uses the terms "touch current" and "protective earth current" rather than "leakage current". The measured current is always the touch current. Since the methods for single-phase and 3-phase networks are fairly similar, only the method for single-phase equipment is described.

The basic setup for the measurement is shown in figure 5. Output B of the measurement equipment is connected with the earthed neutral conductor of the system. Output A is connected to the earth terminal of the equipment via switch S_{TEST}. The switch S_{PE} is open.

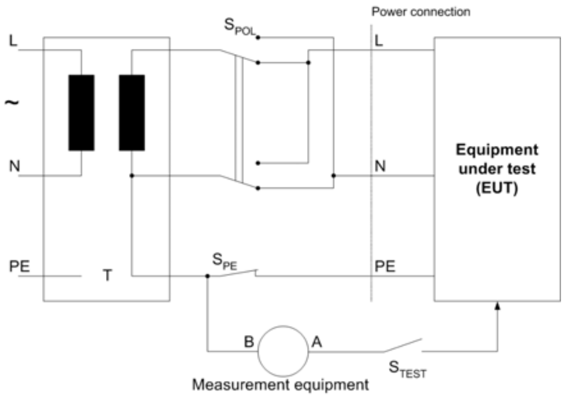

Figure 5: Measurement setup for touch currents

The measurement also has to be done with reverse polarity. For this purpose switch S_{POL} is used. The permissible leakage current depends then on the type of equipment and is defined in the standard.

The touch current for accessible parts of the equipment is also measured independent from the type of equipment. At this point, however, the measurement is not described in more detail since it does not relate to the leakage current itself.

The measurement equipment indicated in figure 5 can be used in two versions. The first possibility is the use of a voltage measurement circuit as shown below.

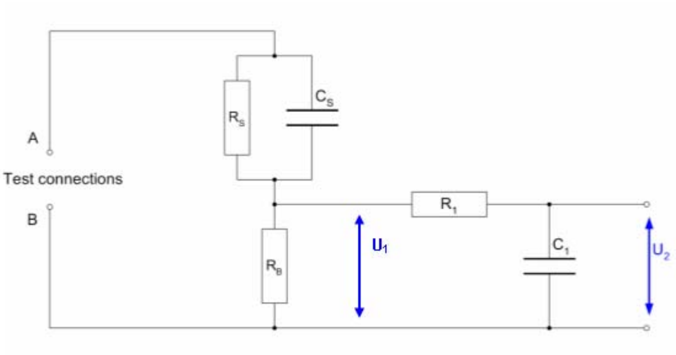

Figure 6: Measurement equipment for voltage measurement

R_S	1500Ω
R_B	500Ω
R_1	10kΩ
C_S	0.22µF
C_1	0.022µF

The required input impedance for measuring the voltage U_1 and U_2 must be >1MΩ, the input capacitance must be <200pF. The frequency range needs to be 15Hz to 1MHz.

The conversion formula for the valued touch current (for perceptibility or reaction) from U_2 to I_{leak} is:

$$I[A] = \frac{U_2}{500\Omega}$$

For the unvalued touch current the value of the voltage U_1 is used instead of U_2.

Alternatively to the voltage measurement according to figure 6 a current measurement with the circuit according to figure 7 can be performed.

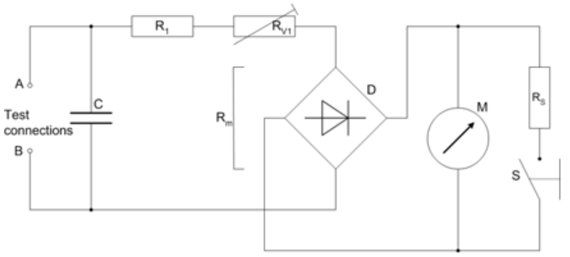

Figure 7: Measurement equipment for current measurements

M moving coil meter

R_1+ R_{V1}+ Rm 1500Ω±1% with C=150nF±1% or
2000Ω±1% with C=112nF±1%
at 0.5mA dc

D measurement rectifier

R_S non-inductive resistor for range X 10

S range selector

For non-sinusoidal waveforms and frequencies above 100Hz, voltage measurements according to figure 6 deliver more precise results.

5. Influence of the supply network topology on leakage currents

In the chapter “Measurement of leakage currents” it was already mentioned that the leakage current is lowest when the supply network and the capacitor network are balanced. Every unbalance increases the leakage current.

With this in mind it becomes also obvious that the supply network topology must have a significant influence on the amount of leakage current from equipment. For some networks it might even be necessary to design special filters in order to reduce the leakage current. This is especially true for the use of European filters in Japanese power networks.

The specialty of the Japanese supply network is the fact, that one of the phases is directly earthed, normally delta grounded. This is principle shown in figure 8.

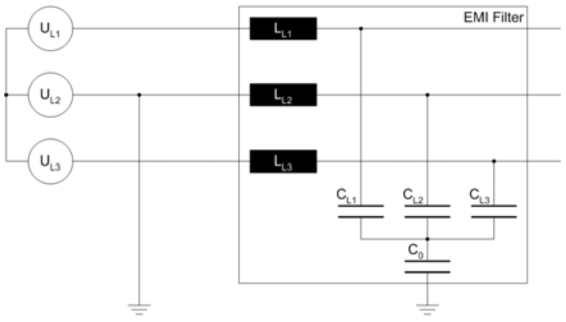

Figure 8: Principle of a Japanese supply network

This type of setup results in a parallel connection of L_{L2} in one branch and C_{L2} and C_0 in the other. The equivalent circuit is shown in figure 9.

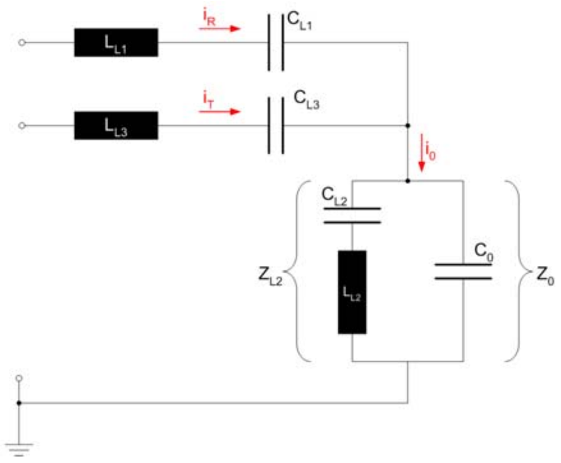

Figure 9: Equivalent circuit for figure 8

With this arrangement the impedance towards earth is completely changed resulting in different voltage drop and leakage current. The outcome of this is that the leakage current ratings for European filters cannot automatically be used for a Japanese network.

One possible solution could be to change the impedance of the earthed phase in the filter and thus create an unbalanced filter. Alternatively one could increase the impedance in all phases and thus reduce the total capacitance against earth (Y-capacitance) in the filter in order to maintain the symmetric setup of the filter without increasing the leakage current significantly.

6. Summary

Due to safety considerations the effects of leakage currents need to be taken into account when using passive EMI filters. Most manufacturers typically define the leakage current per phase for normal operation.

Usually the rating of the leakage current is not the result of a measurement, but rather of a calculation. The preconditions for the calculation was up to now not standardized, but rather defined by the manufacturer. These preconditions include the tolerances of the components, the supply voltage unbalance and the operation mode (normal operation, fault condition). Due to this two filters with identical component ratings and circuit diagrams, but from different manufacturers can differ significantly in leakage current.

The measurement of leakage currents is well defined in the respective product safety standards and therefore easy to reproduce. It is, however, not feasible to perform the measurement as a 100% production test. The measurement is only done for type testing during the certification process.

Harmonics with the higher frequency which of the mains voltage are overlaid raise the leakage currents considerably.

Last not least the leakage current also depends largely on the supply network. A filter with low leakage current in European networks can show significant leakage current in Japanese networks. It can therefore easily trip an existing leakage current breaker.

Conscientious manufacturers will always be aware of a realistic calculation for the values of leakage currents and indicate in their specifications also the terms for the calculation. Otherwise it will be very difficult for the end user to reliably calculate the total leakage current of his equipment or installation.

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