Monitoring of High Voltage Metal Oxide Surge Arresters

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ABSTRACT
High voltage metal oxide surge arresters have proven to be extremely reliable devices within the electrical transmission and distribution systems. Since they are comparatively unexpensive, a continuous or regular monitoring easily might exceed the value of the arresters, particularly for system voltages of 245 kV and below, and should be well-considered. Harmonic leakage current analysis, a very commonly used monitoring method, bears a high risk of measuring errors and often gives rise to misinterpretations. This paper roughly explains some of the reasons. It is recommended to renounce on leakage current monitoring provided that long term stability has been a main concern of the manufacturer's MO resistor development and that this performance is permanently verified during production. However, monitoring of impulse energy stresses is strongly recommended. This can very effectively be realized by control spark gaps, which are unjustly not very popular so far and in many cases even unknown to the users. Control spark gaps are unexpensive, compact, are based on a passive working principle without the need for a power source, have a proven long-term performance and give extensive information about energy stresses applied to the arrester. A wider application of control spark gaps for arrester monitoring would be reasonable and useful.

INTRODUCTION
MO arresters have been used now for more than 15 years, and most of them have shown excellent long time performance. There are mainly two conceivable risks which may shorten the lifetime of an arrester: moisture ingress into the housing and electrical aging of the MO resistors.

Reliable sealing against moisture ingress in fact is a demanding challenge for the arrester manufacturer. But evidently technically accurate solutions of sealing systems are possible, which have proven good performance for over 20 years so far.

The possibility of electrical aging of the non-linear MO resistors is imaginable. They are permanently connected to the line voltage, and the requirements on long time stability for tens of years under continuous operating conditions on the one hand and on energy absorption capability in combination with the capability of thermal recovery in case of overvoltage conditions on the other hand are extreme. It should be appreciated, however, that arrester designs are on the market, which have not shown any problems of electrical aging for 15 years now. For these arresters MO resistors have been used, which from the beginning were optimized in terms of long time stability not only in air but also in different surrounding atmospheres. In addition the arrester design has been optimized in order to minimize those effects possibly enforcing electrical aging, such as internal partial discharges.

Continuous arrester monitoring, if correctly performed, may require expensive equipment. Especially for system voltages of 245 kV and below, the expenses for monitoring easily exceed the value of the arresters, since these are comparatively low-priced devices within the transmission and distribution system. Furthermore, the risk of measuring errors and misinterpretations of the measurements is high and might lead to unnecessary arrester exchanges, which again produce additional expenses in equipment and working time. Therefore, far more than for expensive equipment as transformers or circuit breakers, the necessity of arrester monitoring should be well-considered. If MO resistors are used, which are developed particularly with regard to long-term stability, if this is verified by adequate verification procedures both during development and the running production, and if the arresters are designed to avoid excessive stresses for the resistors like internal partial discharges, there is no need to invest in costly on-line monitoring systems.

This contribution reflects some of the problems of a continuous or regular arrester monitoring and shows inexpensive alternatives which may be used instead.
MONITORING BY LEAKAGE CURRENT ANALYSIS

The leakage current through a MO resistor (and arrester respectively) is mainly capacitive, with only a small non-linear resistive component. Figure 1 shows the oscillogram of a measurement performed on a single MO resistor under laboratory conditions. In this example, where continuous operating voltage is applied, the total current peak value through the MO resistor is 1.4 mA. The peak value of the resistive component, which is the instantaneous current value at voltage peak, is only 230 µA.

![Oscillogram of a measurement performed on a single MO resistor under laboratory conditions.](image)

**Figure 1:** Current through a MO resistor under applied continuous operating voltage

Electrical aging will result only in increase of the resistive component of the total leakage current, and in consequence of the power losses, but not of the capacitive component. The peak value of the total current is virtually not affected. This is demonstrated by Figure 2, showing the result of a computer simulation. For this simulation, the voltage-current-characteristic of a MO resistor was changed as expected due to aging, while the applied voltage (continuous operating voltage) and the capacitance of the resistor were kept constant. It can be seen, for example, that an increase of the resistive component by a factor of two starting from the new condition will lead to an increase of the total leakage current amplitude of only about 6%. A leakage current meter, which measures the peak value - and this is similar for the
arithmetic mean and the r.m.s. value - is therefore not suited as an indicator for electrical aging (it may give some worthwhile information, however, in case of moisture ingress into the arrester, which will affect the peak value of the total current).

Thus, in order to detect possible electrical aging from a leakage current measurement, the resistive component or the power losses have to be measured. Both alternatives require a phase-correct voltage signal or very sophisticated compensation circuits in addition, which in most cases rules this solution out for practical reasons (voltage signal not available) and makes it very costly, respectively (the document /1/, recently prepared by Working Group 10 of IEC TC 37, gives an overview about the actually applied methods and their related problems).

The need for an additional voltage signal or for compensation circuits can be overcome by using the third order harmonic in the leakage current as an indirect measure of the resistive component. In principle a harmonic analysis of the leakage current does not require any measuring signal apart from the current itself. At a first glance, realization of this method seems to be easy and allows to use comparatively simple equipment. Therefore, it is one of the most commonly applied methods for leakage current analysis on the occasion of inspections. There are, however, some restrictions, which will be discussed in the following.

![Figure 3: Voltage-current-characteristic of a MO resistor, given for the total current, the resistive component and the third order harmonic](image)

Figure 3 gives an explanation why the third order harmonic of the leakage current can be used: it has a voltage dependence very similar to the resistive component of the current. However, the current amplitudes to be measured are extremely low. While the leakage current at continuous operating voltage has a peak value of 1,4 mA and the resistive component 230 µA (see also Figure 1), the third order harmonic peak value is below 50 µA. This is just about 3,5 % of the total current and difficult to measure in a substation with its normally severely disturbed electromagnetical environment.

For a correct interpretation of the measured results the temperature and voltage dependence of the absolute value of the resistive component as well as of the ratio between the resistive component and the third order harmonic must be taken into account. These dependencies are shown in Figures 4 and 5.

Even if the arrester did not absorb energy shortly before the leakage current measurement, the actual temperature of the MO resistors is unknown. It can only insufficiently be derived from the ambient temperature. The normal continuous operating temperature of the resistors is higher than ambient temperature, just some degrees Celsius due to the power losses, but considerably more due to solar
radiation or discharge activities on the insulator surface under polluted conditions (the operating duty test of IEC 99-4 therefore starts with a temperature of 60 °C, which shall take these possible influences into account). As it can be seen from Figure 4, a temperature increase from 20 °C to 60 °C will rise the resistive component of the leakage current by about 70% and the third order harmonic by about 50%. So the absolute values as well as the ratio between them change with temperature. This leads to intrinsic uncertainties for the third order harmonic analysis, where the real MO resistor temperature is unknown.

Figure 4: Temperature dependence of the resistive component and the third order harmonic in the leakage current

Figure 5: Voltage dependence of the resistive component and the third order harmonic in the leakage current

Another, perhaps the major problem of the harmonic analysis is the third order harmonic content of the voltage, which is also unknown during the measurement, and which is the reason for the highest measurement uncertainties. A rough estimation gives an idea about the problem: a third order harmonic content of 1% in the voltage will cause 3% of third order harmonics in the linear capacitive component of the leakage current. Using the example of Figure 1, where the capacitive component (which is nearly identical with the total leakage current peak value) is 1.4 mA, the third order harmonic caused by the harmonics in the voltage has a peak value of 42 µA. This nearly equals the third order harmonic caused by the non-linear resistance, which for this example is a little bit less than 50 µA. Since the phase angle of the
harmonics in the voltage is accidental, the value of 42 µA may be fully subtracted or added to the 50-µA-
fraction. The measurement cannot differentiate between these two components. So the possible error is in
the range of about -80% to +80%.

Figure 6 shows the result of a systematical investigation performed by a computer simulation. Third order harmonic contents up to 3% with phase angles from 0° to 360° were superimposed to the
voltage applied to a MO resistor with the same electrical characteristic as for that used for the
measurement of Figure 1, and a Fourier analysis of the total leakage current was performed. The extremes
of the error in total current third order harmonic were found for phase angles of 120° and 270°.

While for example in a 420-kV-system the third order harmonic content of the voltage is usually
below 1%, for the lower system voltages with often higher harmonic contents momentous
misinterpretations may result if the influence of the harmonics in the voltage is not compensated. This is
possible /2/, but may lead to expensive solutions.

![Graph showing possible error range of a harmonic analysis of the leakage current for different contents and
phase angles of third order harmonic in the voltage.]

As a further consequence of the sensitivity of the harmonic analysis to harmonics in the voltage, it is
not easy to get reliable information from the manufacturer about the ratio between the resistive component
and the third order harmonic of the leakage current. In many laboratories the test voltage is not free of
harmonics, thus making it nearly impossible to get the necessary information compensated for the influence
of the harmonics.

Summarized, there are a couple of sources of potential measuring uncertainties when performing
harmonic leakage current analysis for surge arrester monitoring. While some of them can be eliminated,
e.g. the influence of the third harmonic in the voltage, others, such as the unknown arrester temperature,
remain problematic. Anyway, if the leakage current monitoring shall remain unexpensive, the risk of wrong
conclusions due to measuring errors is high and by this makes its application doubtful in many cases.

ALTERNATIVE APPROACH TO THE LEAKAGE CURRENT MONITORING

As explained so far, a harmonic analysis of the leakage current may be problematical for several
reasons, and this is similar for other methods based on leakage current measurement. Avoiding the
necessity of leakage current monitoring would be the better alternative. This can be recommended on two
conditions:
1) Electrical aging under continuous operating conditions can surely be excluded by adequate long time stability tests during development and particularly in the running production of the MO resistors.

2) The arrester is checked for possible excessive impulse stresses, which may lead to impulse degradation.

Verification of the long-term stability of the MO resistors during development and production

The so-called accelerated aging test is part of the operating duty test of IEC 99-4 (paragraph 7.5.2) and by this part of the type test. The MO resistors are operated in an oven under applied continuous operating voltage and with a resistor temperature of 115 °C for 1000 hours. This test is considered to simulate a real lifetime of more than 100 years under normal operating conditions. During the test the power losses are measured and recorded as shown in Figure 7. Preferably, the power losses should permanently decrease, but IEC 99-4 also allows an increase (in this case, as the only consequence, the voltages applied to the test samples in the operating duty tests have to be corrected).

![Figure 7: Results of an accelerated aging test acc. to IEC 99-4](image)

The accelerated aging test can be used to ensure a maximum of confidence in long term stability if following modifications are introduced:

a) An increase of the power losses should not be accepted. Today decreasing power losses are state of the art. Only resistors showing this characteristic should be used for production. (Note: MO resistors, which are optimized for long term stability, may show comparatively high power losses at ambient temperature, since there is a certain interdependence between aging performance and power losses. This, however, does not negatively affect the arrester service if at the same time the temperature coefficient of the power losses is small. Power losses are only decisive after energy absorption, when the arrester is heated up to a temperature near the thermal stability limit. Therefore, not the power losses at ambient temperature but for instance at 150 °C are of real interest. Besides, a benefit of higher power losses at ambient temperature is for instance a more even voltage distribution along the arrester, thus allowing smaller dimensions of the grading rings.)

b) IEC 99-4 requires that the test has to be run in the actual surrounding medium. It is also mentioned that this might be "subject to a modification during the normal life of the arrester". Electrical aging - if it happens - is strongly enforced by an oxygen-free atmosphere surrounding the MO resistors. The electrical characteristic of the ZnO material vitally depends on the oxygen in the material, and an oxygen-free atmosphere may cause oxygen depletion in the resistor surface areas if its passivation is imperfect. Even if an arrester was filled with air during production the oxygen contained therein may be consumed by internal partial discharges, thus possibly leading to an unintentional oxygen-free atmosphere in the arrester. Therefore, accelerated aging tests - at least the design and development tests - should generally not be run in open air but in gases such as N₂, CO₂ or SF₆.
c) The accelerated aging test should not just be performed during design and development of the MO resistors, but also as a sample test of each batch during running production.

If long-term stability of the MO resistors is verified as described before, there is only a negligible risk of electrical aging under continuous operating conditions. Investigations - some results are given in Figures 8 and 9 - have shown that even those resistors of an arrester, which are stressed by higher voltages and temperatures due to an uneven voltage distribution along the arrester, are not endangered. Both elevated temperatures and elevated operating voltages will cause an acceleration in the change of the electrical characteristic in the leakage current region. Performance improvement as well as degradation effects will be enforced. If the power losses tend to decrease under "normal" operating conditions they will do in the same way but much faster under higher temperatures and/or operating voltages (vice versa, resistors with increasing power losses would show the same behaviour but much more intensified).

![Figure 8: Accelerated aging test with $U = U_c$ at different temperatures](image)

![Figure 9: Accelerated aging test with $\vartheta = 115 \, ^{\circ}\text{C}$ and different voltages](image)

**Surge counters and monitoring spark gaps**

It was shown what can be done by the manufacturer to exclude electrical aging of the MO resistors. If these points are followed there is no reason for a continuous or regular leakage current monitoring in service. It will be very useful and important, however, to get information about the impulse energy stresses applied to the arrester. In case of an obvious energy overstress (which is a very unlikely event) the manufacturer should be contacted. It may then be recommended to check the arrester off-line, for
example by recording the complete voltage-current-characteristic, which will give a clear indication if the arrester definitely has to be exchanged or not.

Though information about energy stresses cannot be given by surge counters, some words about these devices shall be spent in this place. Surge counters are extensively used, since they are unexpensive, easy to install and easy to use. The value of their information, however, is limited, since surge counters just indicate if something "happened" or not. No further conclusion can be drawn about the severeness of the events. High readings might cause more irritation than real information about arrester stresses. In order to avoid unnessecary worries, the sensitivity of counters should be chosen to reasonable values. There is no need to count currents far below 100 A. Reasonable values (i.e. such values, which represent the lower limits of noticeable arrester stresses) are for instance 1 kA for lightning impulse currents 8/20 µs, 200 A for switching impulse currents 30/60 µs and 100 A for long duration impulse currents.

State-of-the-art counters use current transformers, as it is shown in Figure 10. This allows a very compact design, and the counter can be combined with other monitoring devices simply by series connection, since it does not produce any voltage drop. Furthermore, overloading of the counter is impossible. No care has to be taken if the arrester in series is for example a small light duty or a heavy duty multi-column type - there is no limitation for the counter in terms of current amplitudes or energy stresses. Finally this type of counter is intrinsically resistant to short circuit currents in case of an arrester failure.

![Figure 10: Circuit diagram of a modern surge counter](image)

1 - Primary conductor, 2 - Toroidal core, 3 - Secondary winding, 4 - Evaluation electronics, 5 - register

As just mentioned, surge counters do not give any information about energy stresses. There have been approaches in developing very sophisticated electronic devices for this purpose. But in fact with the control spark gap a very simple solution is available, which is not new, but offers benefits, which are not self-evident for quite a few other alternatives: it is unexpensive, compact, is based on a passive working principle without the need for a power source, has a proven long-term performance, and it gives very useful and extensive information about energy stresses. In some countries (e.g. in Germany) control spark gaps are standard equipment of station arresters, but worldwide their use is actually limited. One reason might be that potential users fear difficulties with the interpretation of the electrode current marks. Indeed, some experience is helpful (as for all monitoring techniques), which however does not rule out that even unskilled persons from the beginning will be able to derive the elementary information contained in the marks.

Figures 11 and 12 show circuit diagram and cross section of a control spark gap, which in this or similar constructions has successfully been applied for tens of years mainly in Germany.

The operating principle is simple: the two pairs of electrodes are bypassed by a resistor, which allows the leakage current to flow to ground. Once the arrester operates, the voltage drop caused by the discharge current will cause a sparkover of the gaps. The resistor is released, and the full discharge current passes through the gaps, leaving clearly visible marks on the copper electrodes. It should be pointed out that the sparkover voltage of the gaps, which is in the range of 10 kV, does not add to the residual voltage of the arrester. It just forms a very short peak in the beginning of the residual voltage impulse appearing at the arrester terminals and has gone to zero long before the residual voltage peak value is reached.
The control spark gap of Figure 12 includes two pairs of electrodes. The upper one, fixed in the cover, is permanently kept in the housing and by this records the full lifetime of the arrester in terms of energy stresses. The lower pair can easily be accessed and is replaced with new electrodes on the occasion of inspections if current marks are visible. In this way number and severity of events can be better assigned to certain time periods.

Figure 18 shows a collection of control electrode pairs with current marks produced in the laboratory. This can be taken as a reference supporting the evaluation of the electrodes. Depending on the kind of discharge current there are two characteristic kinds of current marks:

a) Lightning impulse currents of some tens of microseconds time duration result in roughening and discolouration of the electrode surfaces within circular areas of relatively large diameters. The discolouration is connected to the polarity: marks of positive polarity tend to be blue. The mark diameter roughly follows the dependence \(d_{[\text{mm}]} = \sqrt{\left( i_{[\text{kA}]} \right)}\), see Figure 13.

b) Surge currents caused by internal overvoltages of some milliseconds time duration produce beads of melted metal on the electrode surfaces. An evaluation of Figures 18 g) to k) shows that the appearance of the marks (diameter and deepness of the erosion) is roughly proportional to the current-time-product of the discharge current and, since the voltage variation in the kA-range is small, proportional to the energy absorbed by the arrester: Figure 18 k) (1900 A / 2 ms) is very similar to 18 i) (1000 A / 4 ms), while 18 h) (1000 A / 2 ms) is about one half of the first two examples. The marks of 18 g) (500 A / 1 ms) represent a quarter of 18 h) in good approximation.
Figure 13: Diameter range of current marks for lightning impulse currents

In the following, three examples of control electrodes taken from real service are presented:

Figure 14: Electrodes of an arrester for the protection of the transformer neutral in a resonant earthed 123-kV-system. About 25 current marks of max. 100 A can be detected, which are caused by the transient oscillations during an intermittent earth fault. The arrester stress was negligible, hence there is no reason for a further check of the arrester performance.

Figure 15: Example of control electrodes from service (back-to-back station; negligible stress)
Figure 15: Electrodes of a valve protection arrester in a back-to-back converter station. These electrodes show about 15 marks of switching impulse currents in the range 100...200 A / 1 ms. Though the stresses for the arrester are negligible, this result may give reason for further investigations about possible abnormal operating conditions of the valves. This is also an example for a very simple solution of a serious problem: valve protection arresters are operated at high potential making galvanic connections to earth impossible. Monitoring of arresters by electronic devices can lead to very expensive solutions.

Figure 16: Electrodes of an arrester in a 245-kV-system with mainly one strongly melted mark of about 7...9 mm in diameter. Such severe marks are very seldom. Though this arrester did not fail, it is recommended to check its integrity in a laboratory or to take it out of service preventively.

Summarized, these examples give an idea about the possibilities of this simple monitoring method. The number of impulse stresses can be determined. It can be distinguished between external and internal overvoltages. In most cases also the polarity of the impulse currents can be recognized. And even in cases where a final statement on the exact current amplitudes is difficult - which sometimes happens - it can be decided anyway if the arrester stress was negligible (which is the usual situation) or not. Only for these unlikely cases further off-line investigations on the arrester performance should be performed.

Figure 17: Surge monitor including control spark gap, surge counter and mA-meter
Figure 18: Examples of current marks on control electrodes
In order to combine the control spark gap with the often required surge counter and mA-meter, newer very compact devices, including all these components in one housing, have been developed. An example is shown in Figure 17. It is part of a modular system, which brings together the benefits of control electrodes with the actual demands of users for low cost, easy-to-use monitoring devices.

**CONCLUSION**

Though most MO surge arresters have shown excellent long time performance for more than 15 years, monitoring is often required in order to detect possible electrical aging. Third order harmonic analysis of the leakage current, which is a common practice, bears a high risk of measuring errors and often gives rise to misinterpretations.

If, however, MO resistors are used, which are developed particularly with regard to long-term stability, if this is verified by adequate verification procedures both during development and the running production, and if the arresters are designed to avoid excessive stresses for the resistors like internal partial discharges, there is no need to invest in costly on-line monitoring systems.

Nevertheless, it is very important to get information about the impulse energy stresses applied to the arrester. In case of an obvious energy overstress the manufacturer should be contacted. It may then be recommended to check the arrester off-line, for example by recording the complete voltage-current-characteristic, which will give a clear indication if the arrester definitely has to be exchanged or not.

Monitoring of impulse energy stresses can very effectively be realized by control spark gaps, which are unjustly not very popular so far. Control spark gaps are unexpensive, compact, are based on a passive working principle without the need for a power source, have a proven long-term performance and give extensive information about energy stresses applied to the arrester. A wider application of control spark gaps for arrester monitoring would be reasonable and useful.

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