# Impact of Multiple Restrikes at Vacuum Circuit Breakers on the EMC of Medium Voltage Switchgear

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*Abstract*— **Switching operations in the primary circuits of medium voltage switchgears are mostly attended by discharge processes in terms of pre- and restrikes between the switch contacts. Due to their high amplitudes as well as their steep wave fronts, such discharges are known to be very broad banded and severe sources of electromagnetic disturbance. This contribution deals with the origin and the consequences of repetitively occurring electromagnetic disturbance pulses due to multiple restrikes at vacuum circuit breakers.**

**On the basis of measurements at a special switchgear test setup, the impact of multiple restrikes at vacuum circuit breakers on the EMC of the switchgear installation is analyzed in time and frequency domain. Based on the results, the severity of multiple restrikes is estimated by comparing the disturbance values with conventional (well known) switching disturbances like during disconnector operations. Finally, some approaches for the handling of multiple restrikes at vacuum circuit breakers with respect to the EMC aspects are given in the summary.**

***Keywords-component; transients; medium voltage; switchgear; vacuum; circuit; breaker; multiple restrikes; reignition***

## I. Introduction

Multiple restrikes are defined as a series of ignitions between the switch contacts of a circuit breaker during opening operation.

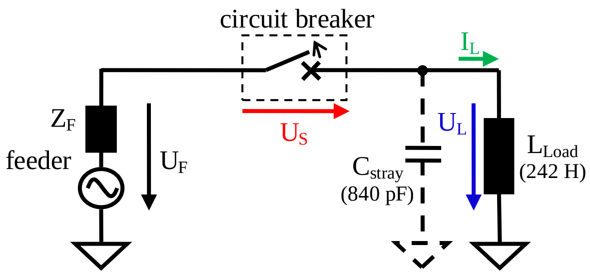


Figure 1. Equivalent circuit diagram of a typical restrike circuit

Such restrikes typically arise when breaking inductive loads (e.g. free-running transformers, induction motors or power compensation coils) using very fast electrically recreating switches like vacuum circuit breakers.

### A. *Process of origin*

The creation of multiple restrikes begins with the mechanical separation of the two switch contacts. At the first moment the electrical contact remains due to an instantly triggered electric arc. Once the arc current reaches the chopping value of the circuit breaker (shortly before its natural zero crossing), the arc ceases abruptly. The frequently used CuCr contacts cut off at values of 3 to 5 Amperes and within a time period of only a few nanoseconds.

When chopping the inductive load current, the energy

$$W = \tfrac{1}{2}\, L \cdot I^2$$

$$(\text{ here } = \tfrac{1}{2} \cdot 242\ \text{H} \cdot (0.31\ \text{A})^2 = 11.63\ \text{J})$$

remains in the coil of the disconnected circuit. This amount of energy starts oscillating between the inductive load (energy stored by the magnetic field) and the stray capacitance of the disconnected part of switchgear (energy storage by the electrical field). For the case that no restrikes occur, the resonant circuit oscillates until the complete energy is extracted by the ohmic damping of the primary parts as well as by the magnetization losses of the inductive load. The result is a damped oscillating voltage curve at the load side with a peak voltage value of (ideal value without losses)

$$U_{max} = \sqrt{2W / C}$$

$$(\text{ here } = \sqrt{2 \cdot 11.63\ \text{J} / 842\ \text{pF}} = 166\ \text{kV}).$$

The oscillation frequency has values from a few hundred Hertz up to some Kilohertz.

$$f_{res} = 1 / (2\pi \cdot \sqrt{L \cdot C}\,)$$

$$(\text{ here } = 1 / (2\pi \cdot \sqrt{242\ \text{H} \cdot 840\ \text{pF}} = 353\ \text{Hz})$$

The following graph (figure 2) shows a simulation of the voltage and current shapes for the case of an ideal circuit breaker without restrikes. The simulated curves were verified by a detailed comparison with real measurements. The contact distance was measured by a special sensor.

However, the subsequent graph shows the load voltage for the interesting time period of the real measurement. All following evaluations and calculations are based on this measurement.

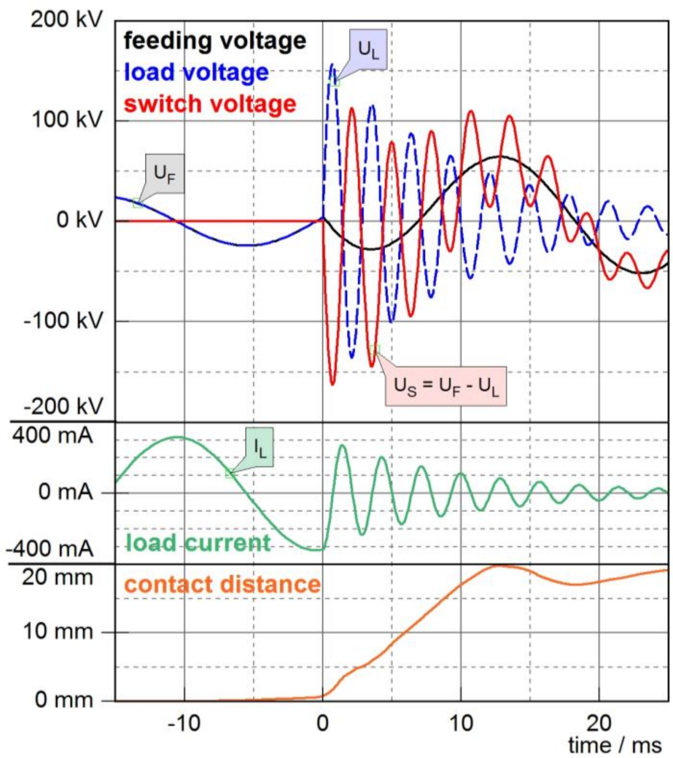


Figure 2. Simulated / measured curves of a inductive load breaking situation

The high resonance frequency causes the circuit voltage to rise quite faster than the dielectric recovery of the switch. As soon as the voltage in the resonant circuit reaches the actual breakdown value of the switch contacts (depending on the distance), a restrike causes a fast voltage breakdown between both contacts of the switch. The restrike arc typically lasts for some microseconds and extracts an amount of energy which is defined by the voltage step of the load side:

$$W = \tfrac{1}{2}\, C_{Stray} \cdot U^2_{Load}$$

e.g. for restrike "n": $= \tfrac{1}{2} \cdot 840\ \text{pF} \cdot (88\text{kV})^2 = 3.25\ \text{J}$

The remaining energy inside the coil starts oscillating anew and the voltage of the LC – circuit rises again.

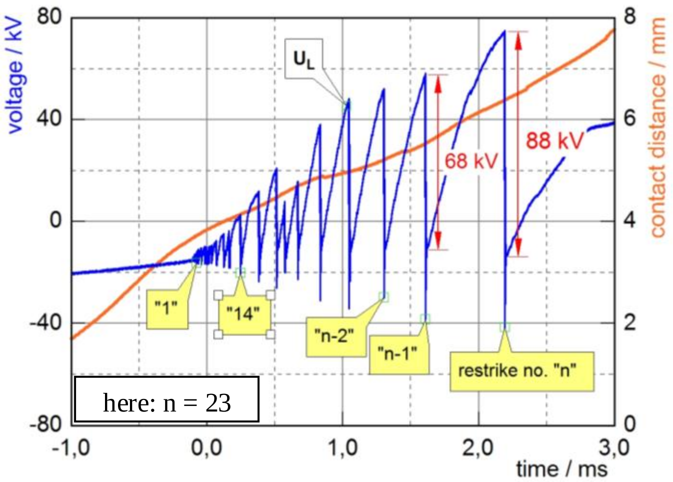


Figure 3. Simulated / measured curves of a inductive load breaking situation

If the required voltage for a new ignition is reached a second restrike occurs, and the ignition voltage is now higher due to the increased distance of the switch contacts. The restrikes proceed until the remaining energy in the coil is not sufficient any more to reach the required voltage level to trigger a further ignition of the circuit breaker contacts.

The basic calculation formulas can be roughly verified by a simple energy consideration applied on the recorded measurement curve of figure 3. The approach is to calculate the maximum voltage after the last restrike by, first, summing up the energy which is extracted from the LC circuit by the restrikes:

TABLE I. EVALUATION OF THE SUM OF EXTRACTED ENERGY

| restrike no. | ignition voltage | extracted energy | restrike no. | ignition voltage | extracted energy |
|---|---|---|---|---|---|
| 1 | 1.3 kV | 0.00071 J | 13 | 6.5 kV | 0.01775 J |
| 2 | 1.8 kV | 0.00136 J | 14 | 18.6 kV | 0.14530 J |
| 3 | 2.2 kV | 0.00203 J | 15 | 26.8 kV | 0.30166 J |
| 4 | 2.2 kV | 0.00203 J | 16 | 32.8 kV | 0.45185 J |
| 5 | 4.1 kV | 0.00706 J | 17 | 22.4 kV | 0.21074 J |
| 6 | 5.4 kV | 0.01225 J | 18 | 27.1 kV | 0.30845 J |
| 7 | 4.4 kV | 0.00813 J | 19 | 49 kV | 1.00842 J |
| 8 | 4.3 kV | 0.00777 J | 20 | 57.6 kV | 1.39346 J |
| 9 | 3.2 kV | 0.00430 J | 21 (n-2) | 61 kV | 1.56282 J |
| 10 | 6.1 kV | 0.01563 J | 22 (n-1) | 68 kV | 1.94208 J |
| 11 | 8.7 kV | 0.03179 J | 23 (n) | 88 kV | 3.25248 J |
| 12 | 11.1 kV | 0.05175 J | | **$W_{sum}$ =** | **10.74 J** |

Then, the extracted energy has to be substracted from the energy that was stored shortly before the first restrike occurred:

$$W_{osc} = \tfrac{1}{2} \cdot L \cdot I^2 - W_{sum} = 11.63\ \text{J} - 10.74\ \text{J} = 0.89\ \text{J}$$

Finally, the resulting amount of energy can be taken to calculate the peak value of the damped voltage oscillation after the restrikes:

$$U_{max,osc} = \sqrt{2 \cdot W_{osc} / C_{stray}} = \sqrt{2 \cdot 0.89\ \text{J} / 840\ \text{pF}} = 46\ \text{kV}$$

The calculated value of 46 kV is 6 kV under the real value of figure 3, but nevertheless, meets the measured value quite well. The reason for the small deviation is probably based on the limited scale-reading accuracy.

### *B. Electromagnetic impact of multiple restrikes*

Every transient voltage breakdown in terms of a restrike can be seen as a broadband disturbance pulse at the primary side of the switchgear. Propagating on many different coupling paths, the disturbance pulses can reach almost every electronic equipment inside the switchgear. Basically, some relationships can be noted:

- The more compact the switchgear is built up, the shorter gets the distance between the disturbance source and the susceptible device, and therefore the stronger is the coupling.
- Every switchgear installation has specific resonance frequencies which are pronounced more or less dominant, depending on the position of measurement.

## II. Reproduction in the Laboratory

### *A. Test setup*

For the reproduction of the multiple restrikes in the laboratory one phase of a 40 $kV_{L\text{-}L}$ medium voltage switchgear was used.

The inductive load was realized by a test transformer which was shortened at the low voltage side. Hence, only the leakage inductance of the high voltage winding was used. Some data of the test transformer are:

| | |
|---|---|
| Rated voltage | $U_n = 100$ kV |
| Rated power | $S_n = 10$ kVA |
| Related short circuit voltage | $u_k = 7.6$ % |

Using this data set, the leakage inductance of the high voltage winding can be calculated:

$$Z_n = (U_n)^2 / S_n$$

$$= (100\text{ kV})^2 / 10\text{ kVA} = 1\text{ M}\Omega$$

$$|Z_T| = u_k \cdot Z_n = |R_T + jX_T|$$

$$\approx X_T = \omega \cdot L_T \quad (jX_T >> R_T)$$

$$L_T = u_k \cdot Z_n / \omega$$

$$= 7.6\ \% \cdot 1\text{ M}\Omega / (2\pi \cdot 50\text{ Hz})$$

$$= 242\text{ H}$$

The stray capacitance of the switched high voltage circuit has a value of 840 pF and consists of a coil part (210 pF), a cable part (155) and a switchgear part (455 pF).

The feeding voltage was 17 $kV_{L\text{-}E}$, provided from an $SF_6$ insulated GIS transformer via 10 m of medium voltage power cable. For this feeding voltage the amplitude of the inductive load current was 224 $mA_{RMS}$. The following figure shows a simplified single line diagram of the test setup:

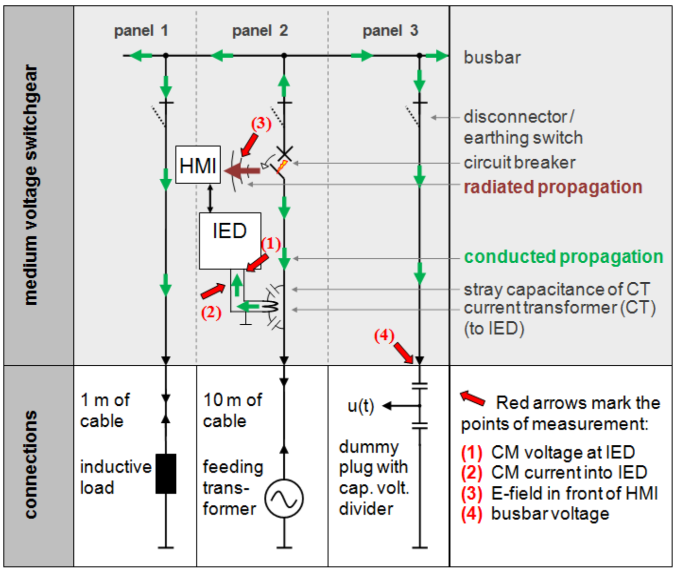


Figure 4. Single line diagram of the test setup (including propagation paths)

### *B. Coupling Paths within the Switchgear*

As shown in the single line diagram of the test setup (figure 4), there are two major propagation paths for the switching disturbance.

On the one hand the electronic components are exposed to radiated disturbances. Sources of the radiation are several primary parts. More precisely, either the ignitions themselves as well as the conductors, which are connected to the switch, emit electromagnetic waves. The strongly pronounced peaks in the frequency spectra of the disturbances are almost based on resonance frequencies of primary conductors or on cavity resonances of the high voltage compartments.

The second, but also very relevant propagation path concerns to all electronic devices which are capacitive coupled to the primary parts, for example capacitive voltage indication systems or instrument transformer circuits of protection units. The coupled transient overvoltages on the secondary wiring are responsible for the requested susceptibility levels of the interfaces of the devices, but they also generate a certain amount of radiated disturbance.

### *C. Choice of measurement values and equipment*

The following characteristic measurement values are chosen to have the ability to evaluate both, the galvanic and the radiated stress to secondary components due to switching operations in the primary circuits:

- The common mode disturbance voltage, measured at the current transformer input of the protection relay. (measurement (1) at figure 4)
- The common mode disturbance current into the protection relay, measured at the analog current transformer input of the IED. (2)
- The electrical field component of the radiated disturbance, measured directly in front of the Human Machine Interface of the protection relay. (3)

A commercial, broad band high voltage probe (type Tektronix P5100A) was used to measure the disturbance voltage at the protection device. The bandwidth of this probe is 500 MHz.

The common mode disturbance current was picked up by an RF current clamp (type FCC F-65) providing a bandwidth of 1 GHz.

The electrical field strength was monitored by a one dimensional field probe with a capacitive caption of the electric field values and an analog fiber optical signal transmission. The bandwidth (-3dB value) of the field probe is 400 MHz.

Further, the busbar voltage was measured by a broadband capacitive voltage divider (measurement 4 at figure 4). The divider is mounted in the power cable socket of the right panel in terms of a special dummy plug. This measurement helps to evaluate the ignition voltage by reading out the voltage steps like in figure 3. Alternatively, this measurement curve can be bandpass-filtered to see directly the breakdown values of the voltage (see figure 9).

### III. DISTURBANCE MEASUREMENTS

The following measurement curves were recorded during the opening operation of figure 3. The inductive load current was cut off nearly to its minimum value at about 310 mA.

Each curve consists of 10 Mio. of samples using a record length of 4 milliseconds (sample rate = 2.5 GS / s). Thus, afterwards every single restrike can be zoomed in and analyzed in more detail.

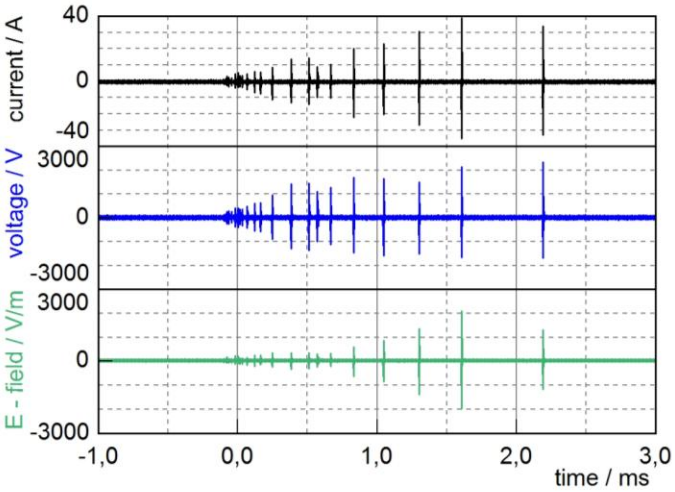


Figure 5. Measurement curves of the disturbance pulses

The measurement shows that every restrike produces a transient impulse at each of the three disturbance measurement curves. For the galvanic disturbance values it is observed that higher ignition voltages cause higher disturbance amplitudes. Regarding the disturbance current, the last restrike is an exception. The reason for the smaller value compared to the restrike before will be clarified later.

The following figures (6 and 7) show the zooms of the disturbance measurement curves during the last two restrikes (with the highest ignition voltages). Some characteristic values can be read out:

Restrike no.23 ("n"):

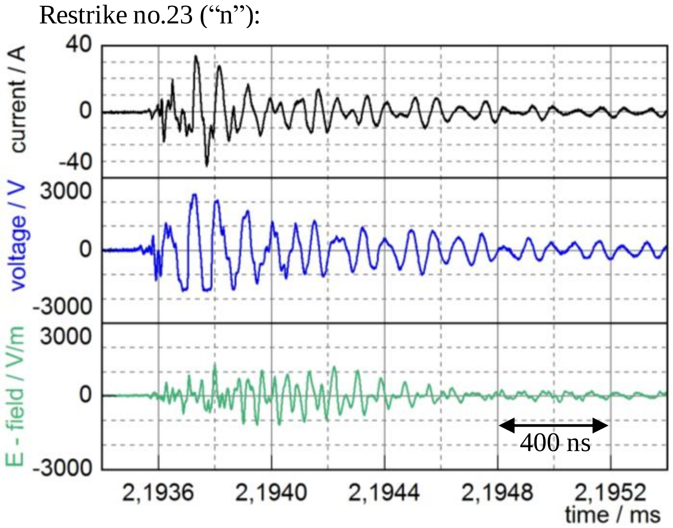


Figure 6. 2µs - zoom to the disturbance of the last restrike

Restrike no.22 ("n-1"):

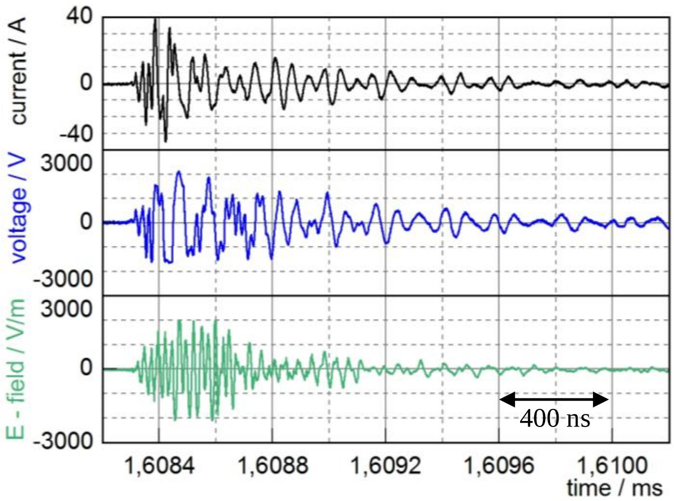


Figure 7. 2µs - zoom to the disturbance of the penultimate restrike

- The pulse duration is typically about 2 microseconds.
- The disturbance voltage at the CT port of the IED has a maximum value of about 2.3 kV (restrike no. "n").
- The maximum value of the common mode current into the IED is 39 A (restrike no. "n-1").
- The electrical field value within the low voltage compartment of the switchgear reaches values up to 2000 V / m (restrike no. "n-1").

By comparing both zooms, one will notice that restrike no. 22 ("n-1") has more high frequency parts in the early stages of the pulses. As higher frequencies on the wires can radiate better, also the electrical field value is much higher for restrike "n-1" compared to the last one (no. "n").

*Short discussion: Why does the last restrike produce less high frequency disturbances?*

*The only possible answer is given by the bandwidth of the stimulating pulse, i.e. by the breakdown process within the vacuum bottle itself. A smaller bandwidth implies that the breakdown time of the insulation was longer. A reason for the slower breakdown could be that the insulation environment within the vacuum bottle was cooler when the last restrike happened than at the one before. The lower temperature of the vacuum bottle could be traced back to the longer time period without a restrike before the last one occurred (see figure 3 or figure 5). So, the plasma channel of the previous restrike had more time too cool down before the last restrike occurred.*

*This thesis is pretty difficult to verify, even though the line of argument is conclusive. An alternative root for the variation of the high frequency contents could also be some other (unknown) statistical variation between the last two restrikes.*

To allow an analysis in the frequency domain, Fourier Transformations of the disturbance pulses of both zooms (figures 6 and 7) were carried out. The resulting amplitude density spectra are plotted in the following figure (8). The red dashed lines mark the noise levels due to the limited vertical resolution of the measurement devices.

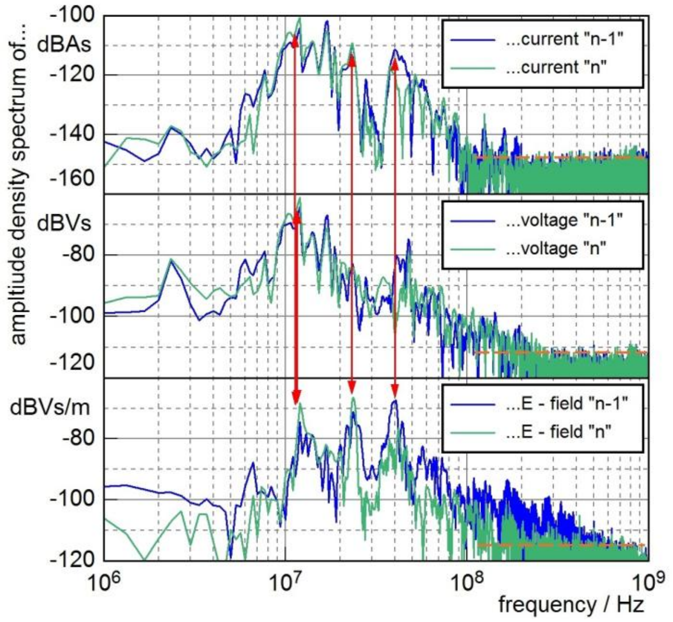


Figure 8. Fourier transformation of the zoomed disturbance curves

The spectra demonstrate that the galvanic coupled disturbances are limited regarding their bandwidths. The significant spectral contents are in the range up to about 200 MHz, whereas the radiated electrical field has a very broad banded spectrum with contents up to 750 MHz.

The comparison of the different types of disturbance shows that nearly every significant disturbance frequency of the current and voltage are also strongly represented in the electrical field. The red arrows mark some examples. The disturbance spectrum of the electrical field can be seen as a global indicator for the estimation of the bandwidth of the discharge in the vacuum bottle.

With regard to the discussion after the inspection of the time signals, their spectra confirm the statement that the disturbance of the last restrike has a smaller bandwidth. Especially the spectra of the radiated electrical field show significantly higher values in the upper frequency range for the penultimate restrike compared with the last one.

Also the current spectrum of the “n-1” restrike has stronger contents in the frequency range between 100 and 200 MHz. Thus, the higher frequency contents are probably responsible for the higher peak value in the time signal of the disturbance current.

## IV. Estimation of Severity

The estimation of the electromagnetic severity of multiple restrikes at vacuum circuit breakers is based on a comparison with the generated disturbance pulses due to disconnector switching operations. The measurement of figure 9 shows the galvanic coupled disturbance values at the IED as well as the corresponding ignition voltage during a complete opening operation of a disconnector. The test setup was almost equal to the restrike measurement setup, but the inductive load was disconnected. The disconnector of the middle panel was operated under a feeding voltage of 17 kV.

The measurement shows clearly that the galvanic coupled disturbance is linear proportional to the ignition voltage between the switch contacts. The highest disturbance is measured when the ignition voltage has the highest value, i.e. when the disconnector contacts form the widest possible spark gap. The maximum values (for an ignition voltage equal to the peak-to-peak value of the feeding voltage) are 27 A regarding the CM current and 1.7 kV for the disturbance voltage.

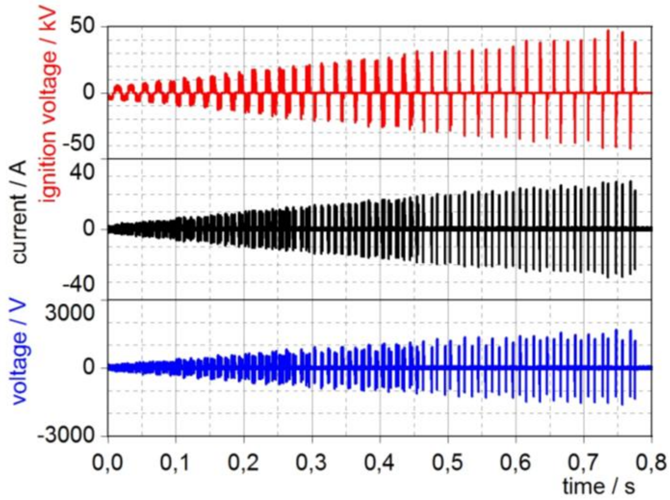


Figure 9. Disturbance measurement during disconnector opening operation

Thus, for the estimation of the circuit breaker severity the maximum possible ignition voltage at the circuit breaker contacts has to be determined:

The worst case is a reignition through the completely opened circuit breaker insulation. Then, the breakdown voltage is at least the peak value of the power frequency withstand voltage of the circuit breaker (here $\hat{U}d$ = 100 kV). Then the disturbance is at the maximal level, but basically it should be clarified if this special situation is realistic.

For the clarification, the same test setup for a higher feeding voltage of 23 kV (= the rated voltage of the switchgear) is considered. Then a cut off value of 428 mA inductive current is possible. This implies that about twice the energy feeds the resonant circuit and, thus, an ignition voltage of 100 kV (14 % more than in the case) seems to be very realistic even without calculations.

The obligatory proof by calculation can be done by first determining the oscillating energy for the new situation:

$$W_{new} = \tfrac{1}{2} \cdot 242\ \text{H} \cdot (0.428\ \text{mA})^2 = 22.17\ \text{J}$$

Then the amount of energy which was extracted by the first 23 restrikes in the test case above has to be substracted from the new energy value.

$W_{osc, new} \quad = 22.17\ J – 10.74\ J = 11.43\ J$

With the result, the new peak value of the oscillation after restrike no. 23 can be calculated:

$$U_{osc, new} = \sqrt{2 \cdot W_{osc,new} / C_{stray}}$$
$$= \sqrt{2 \cdot 11.43\ J / 840\ pF} = 165\ kV$$

*Remark:*

*The worst case would be reached, when the inductive load had a value of 24 H (instead of 242 H). Then the inductive load current would be sufficient to reach the cut-off value of the breaker (3 A), assuming once again a feeding voltage of 23 kV. The remaining energy in the switched LC circuit when chopping 3 A of inductive load current is*

$$W = ½\ L \cdot I^2 = ½ \cdot 24\ H \cdot (3\ A)^2 = 108\ J$$

*This amount of energy is 9.3 times higher than in the tested case and would be sufficient to reach a voltage (for the same value of stray capacitance) of*

$$U = \sqrt{2W / C} = 507\ kV.$$

So, the absolute minimum increase factor regarding the electromagnetic disturbance emission of circuit breaker restrikes compared to already known and therefore allowed disturbance due to disconnector operations can be calculated. It is given by the ratio of the peak value of the power frequency withstand voltage of the opened circuit breaker and the peak-to-peak value of the feeding voltage:

$$k_{min} = \hat{U}_d / U_{n,p\text{-}p} = U_d / 2 \cdot U_{n,L\text{-}E}$$

$$(\text{here } k_{min} = 70\ kV / (2 \cdot 23\ kV) = 1.5\ )$$

This minimum increase factor presumes that the highest ignition voltage limited to the peak value of the power frequency withstand voltage of the breaker. For the practical EMC planning of medium voltage switchgear where the occurrence of multiple restrikes is supposed, an increase factor for the immunity of 2 should be chosen. This allows also restrikes at 30% higher ignition voltages which seem to be realistic because an absolutely reliable breakdown of the circuit breaker insulation at exactly the peak value of the test voltage is very unlikely.

## V. Summary / Conclusion

Electromagnetic disturbance pulses due to multiple restrikes at vacuum circuit breakers are very broad banded because of the very fast breakdown of the insulation medium. Coupled through many different propagation paths, they are measurable at nearly every position in the switchgear. Regarding the galvanic disturbance at electronic equipment like IEDs, mainly resonance frequencies like line resonances in the primary and secondary circuits are strongly present. The higher frequency contents (>200 MHz) of the ignitions are almost completely damped by the skin effect of the connected wires and therefore less pronounced at the terminals of the IED. In terms of the radiated disturbance, restrikes emit broad banded disturbance signals with strong frequency contents up to 750 MHz.

The galvanic coupled disturbance at the IED is linear proportional to the breakdown (ignition) voltage at the switch contacts immediately before the restrike happens. The maximally arising voltage at the load side is determined by the resonance circuit’s inductance and capacitance values as well as by the actually stored energy when the inductive current gets cut off. Assuming that enough energy is stored in the LC circuit, the least disturbance levels can be estimated for an ignition voltage equal to the peak value of the power frequency withstand voltage of the opened circuit breaker. For the tested setup, the calculated values are 1.5 times higher than the disturbances during a disconnector operation.

The recommended calculation basis for EMC planning is a disturbance / susceptibility increase factor of 2. This factor is valid for nearly all types of medium voltage switchgear, because it is simply based on the ratio between the rated voltage of the switchgear and the peak value of the power frequency withstand voltage of the installed circuit breaker.

Finally, medium voltage switchgears with inductive loads connected by short power cables are very risky in terms of multiple restrikes at the circuit breaker. The expected disturbance has twice the value in comparison to disconnector disturbance or circuit breaker prestrikes.

Approaches to handle multiple restrikes at vacuum circuit breakers are either to increase the electromagnetic susceptibility of the installed electronic equipment also by a factor of 2 or to avoid such very high disturbance values. The very high disturbance values can be avoided by different ways, e.g.

- by increasing the length of the power cable between the load and the circuit breaker. Then, the value of the capacity in the resonant circuit is higher and the maximally possible voltage of the circuit decreases.
- By implementing surge arrestor at the load side. So, the maximum overvoltage in the switched LC circuit is limited to a fixed value.
- By installing a suitable RC-circuit (also called “snubber circuit”) in parallel to the circuit breaker contacts. This method slows down the voltage rise at the load side so that the circuit breakers insulating clearance has more time for the electrical recreation.

## VI. References


[1] ABB AG, Hennig Gremmel, Gerald Kopatsch, 2006, *Schaltanlagen Handbuch*, Cornelsen, Berlin, 233-252.

[2] Adolf J. Schwab, Wolfgang Kürner, 2007, *Elektromagnetische Verträglichkeit,* Springer, Berlin / Heidelberg, Germany, 88-91.

[3] Edgar Dullni, Wenkai Shang, Dietmar Gentsch, Ingmar Kleberg, Kaveh Niayesh, 2006, "*Switching of Capacitive Currents and the Correlation of Restrike and Pre-ignition Behavior*", IEEE Transactions on Dielectrics and Electrical Insulation vol. 13, 65-71.

[4] Dennis Burger, Stefan Tenbohlen, Wolfgang Köhler, Werner Ebbinghaus, 2011, “*Sources of transient electromagnetic disturbance in medium voltage switchgear*”, EMC Europe 2011, York, GB.