Sources of transient electromagnetic disturbance in medium voltage switchgear

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Abstract— **Over the last decades, the worldwide market for medium voltage switchgear has shown a strong tendency to integrate power, control, protection and communication functions into a common panel. Today, this market demand is met by user-specific switchboards, consisting of modular composed switchgear panels with intelligent electronic devices (IEDs) for customized protection and control functionalities. Since switching operations inside a medium voltage switchgear are known to be serious sources of electromagnetic disturbance, the combination of the high voltage switching disturbance and strong coupling paths (due to the compact design) requires a carefully planning of electromagnetic compatibility.**

On the basis of practical measurements at a three panel switchgear installation, the paper will compare the interference behavior of different switching devices like air insulated disconnector, SF_6 insulated disconnector and vacuum circuit breaker. The comparison will include the different disturbance levels of these sources in time and frequency domain and will also have a look on their most important propagation paths.

Keywords- sources; transients; medium voltage; switchgear; EMC; disconnector; circuit breaker

I. INTRODUCTION

Medium voltage switchgear is built for the controlled connection and disconnection of electrical energy consumers or feeders to the medium voltage level of power distribution grids. The connection or disconnection of MV equipment to the switchgear's busbar is typically carried out by three different types of switches: disconnectors, load-break switches and circuit breakers. From the electromagnetic point of view, every operation of a switch can go along with an arcing process that generates very fast transients (VFTs). Inevitably, the transient signals propagate in some degree into the whole substation by conducted coupling and by field (EM) coupling. Especially the applied EM stress to intelligent electronic devices (IEDs) plays an important role for the EMC of the whole switchgear installation. This investigation will clarify some characteristics of the different disturbances produced by air insulated disconnector, SF_6-insulated disconnector and vacuum circuit breaker.

II. THE SWITCHGEAR TEST SETUP

The tested switchgear was specially built for this test and consists of three single panels with a common busbar. Figure 1 shows the single line diagram of the switchgear in its upper part and in the lower part the connected equipment is figured. Panel 1 is not that important for the measurements, but it helps to intensify the discharge effects due to its stray capacitance (total stray capacitance ≈ 900 pF). The disconnector of panel 1 is closed and the MV cable socket is terminated by a dummy plug. At panel 3 there are almost the same conditions, but the dummy plug is equipped with a capacitive voltage divider (bandwidth 300 MHz).

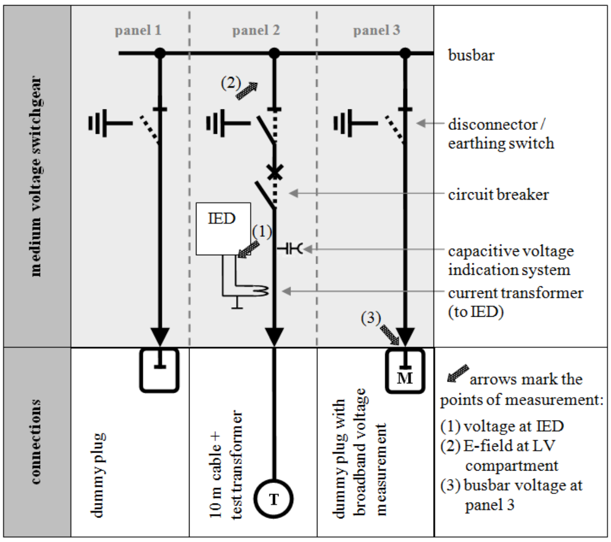

Figure 1. Switchgear test setup.

At panel 2, the test transformer feeds the nominal voltage (23 kV_{L-E}) to one phase of the switchgear. This panel is, in contrast to the other ones, equipped with an IED for control and protection. In addition to the disconnector, this panel contains also a vacuum circuit breaker. These two switches inside the mid panel are used for the test to generate the switching disturbances. For this purpose, the disconnectors' encapsulation is either filled with SF_6 or with air.

III. THE DIFFERENT ARCING PROCESSES

The arcing process varies due to the functional principle of each switch, but basically a switch can have prestrikes and restrikes. Prestrikes occur in the case of making operations, restrikes normally belong to breaking operations.

A. Disconnector arcing

Both, SF_6- and air- insulated disconnectors, have the same background for the arcing process from the physical point of view. The principle of the arcing process can be explained by the simple example of a galvanic disconnection of an unloaded part of busbar (just like in this test):

The simplified electrical situation for a disconnector operation is described by the equivalent circuit diagram of Figure 2. It includes the feeding transformer (with its source impedance Z_{series}), the strew capacitance of the arrangement at the feeding side, and the strew capacitance of the switched part of busbar.

Immediately after the electrical disconnection of the switch contacts, the disconnected part of busbar stores the actually present charge Q in its stray capacitance and remains at the related (constant) voltage level

$$V = Q / C_{stray} \qquad \text{Equation 1.}$$

This is called the *trapped charge effect*.

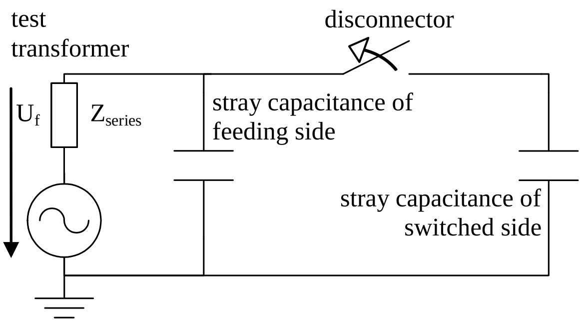

Figure 2. Equivalent circuit diagram for disconnector arcing.

Upon, the potential of the opposite contact changes due to the sinusoidal AC voltage of the feeding side. The increasing potential difference causes a rising electric field between the disconnector contacts. Finally, the breakdown field strength of the insulating medium (air or SF_6) is reached and an ignition leads to the sudden reloading of the switched part of busbar. Following, the photograph of Figure 3. will give an impression of the sudden reloading by an ignition between the disconnector contacts.

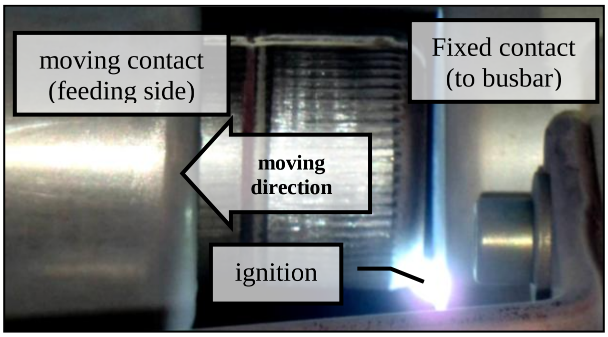

Figure 3. Ignition at the disconnector under test.

Once the charge transfer is completed, the arc ceases. This ignition process repeats several times per half cycle and creates a stepped voltage curve at the disconnected part of busbar, see Figure 4.

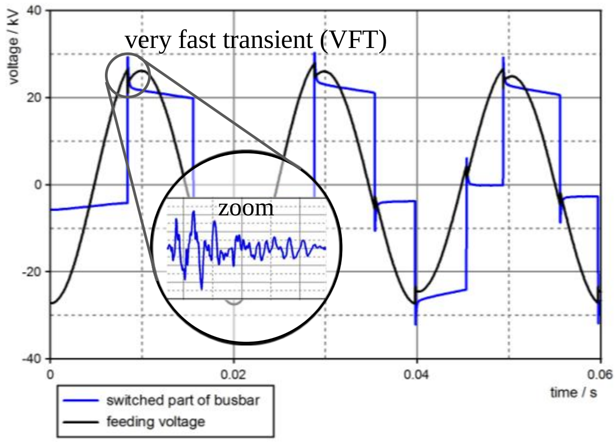

Figure 4. Voltage measurement at busbars.

The ignitions occur until the disconnector contacts have reached a sufficient distance not to exceed the breakdown field strength of the insulation medium any more. Increasing the distance of the disconnector contacts also increases the amplitude of the transient disturbance but decreases the number of ignitions per half cycle.

For disconnector making operations, the arcing process happens in the same manner, but in the reverse order. The ignitions start taking place when the electrical field between the contacts reaches the breakdown field strength of the insulation medium. The reduction of the contact distance enlarges on the one hand the number of ignitions but also decreases the amplitude of the produced transients. Finally, the galvanic connection brings the arcing process to an end.

Remark: The feeding voltage curve in Figure 4 shows also some small steps. This is due to the change of the voltage drop at the source impedance when the capacitive load increases by the strew capacitance of the switched part.

B. *Vacuum circuit breaker arcing*

At vacuum circuit breakers, there is no long-lasting arcing process between the breaker contacts. The disturbance generation due to switching operations is limited to only a few pre- or restrikes.

The prestrike generation while closing the vacuum circuit breaker is comparable to the disconnector arcing process, because it is simply based on the potential difference between the switch contacts. As a result of the fast contact movement, mostly only one single prestrike occurs.

For the breaking operation of vacuum circuit breaker it is a completely different situation. The occurrence of restrikes is strongly dependent from the type of load. Typically, inductive loads (e.g. transformers or induction motors) connected by short medium voltage cables built resonant circuits and lead to multiple restrikes across the opening breaker contacts. The amplitude of transients is significantly higher for restrikes than for prestrikes (up to a factor of 2.5). For more information about multiple restrikes, see the references [3], [4].

IV. DISTURBANCE MEASUREMENTS

Two of the most usual ways of disturbance propagation are the electromagnetic radiation and the conducted propagation of travelling waves along the busbar. The radiated disturbance can affect directly the electronic equipment within the switchgear environment. Travelling waves on the busbar can couple, e.g. through the stray capacitance of instrument transformers, to the cabling of the IED. In respect to the described propagation paths, the following points for disturbance measurement were chosen:

- Voltage at CT ports of the IED
- Electrical field at the low voltage compartment
- Voltage at the busbar of panel 3

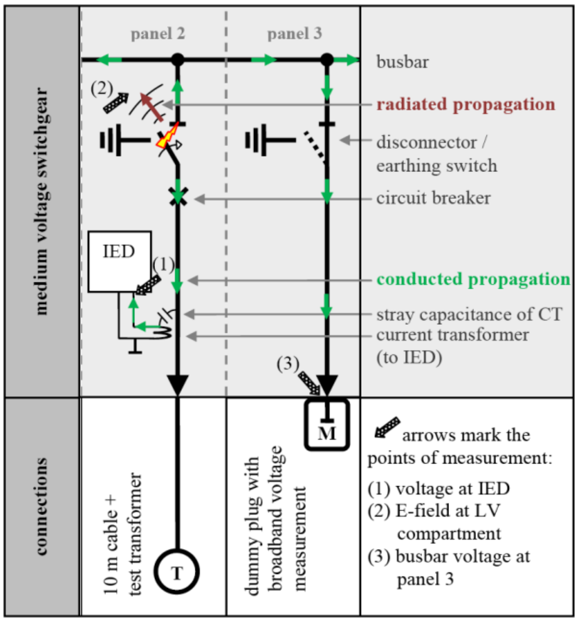

Figure 5. Test setup and measurement points.

A. *Disturbance voltage at the IED*

The conducted disturbance voltage (common mode) at the current transformer ports of the IED was measured by a LeCroy high voltage probe (type: PPE20KV).

Figure 6. High voltage probe, type LeCroy PPE20KV. The bandwidth of the high voltage probe is 100 MHz (-3 dB point). The attenuation factor is 1000.

The measurement of the common mode (CM) disturbance voltage at the current transformer (CT) ports of the IED is used to evaluate for each type of switch

- the overall number of ignitions
- the total duration of the complete arcing process
- the maximum disturbance voltage at the IED

Therefore, each switch's arcing process is observed during the total making operation (Figure 7.).

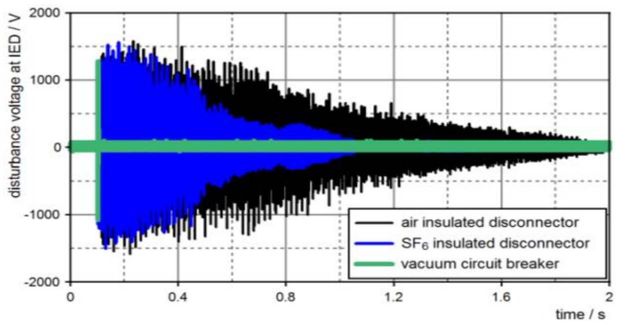

Figure 7. CM disturbance voltage at the IED's CT ports.

The following values have been evaluated from a couple of measurements, in which the variations were in the range of a few percent. So they can be seen as validated average values, which are very typical for the used switch types.

TABLE I. TYPICAL VALUES OF THE TOTAL ARCING PROCESS

Switch	Total # of ignitions	Total arcing time	Max. dist. voltage
Air ins. Disconnector	≈ 1000	1.9 s	1580 V
SF_6 ins. disconnector	≈ 500	0.95 s	1560 V
Vacuum circuit breaker	1	2 µs	1280 V

B. *Electrical field strength*

A 1-dimensional (transient) electrical field probe with fiber optical signal transmission was used to measure the transient electric field signal which occurs in the low voltage compartment of the switchgear.

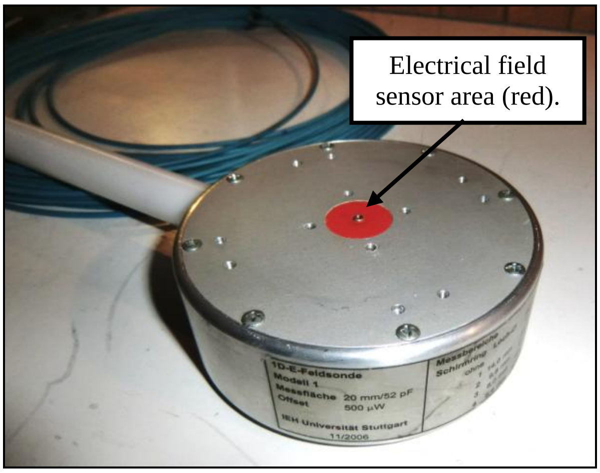

Figure 8. 1-D Electrical field probe. The bandwidth of the electric field probe is 400 MHz (-3 dB point). It was developed and assembled (2006) at the University of Stuttgart, Institute of Power Transmission and High Voltage Technology (IEH).

The electrical field signal provides the desired information to compare the spectral contents of single pulses, their amplitudes, as well as their temporal durations. It was chosen for the spectral analysis because it is more or less a global indicator for the frequency spectrum of the disturbance sources. Disturbance voltage measurement at special locations is much more selective and is related to special coupling phenomena, i.e. resonances of cables. The following graph (Figure 9.) shows the radiated electrical field, measured for the different types of switch:

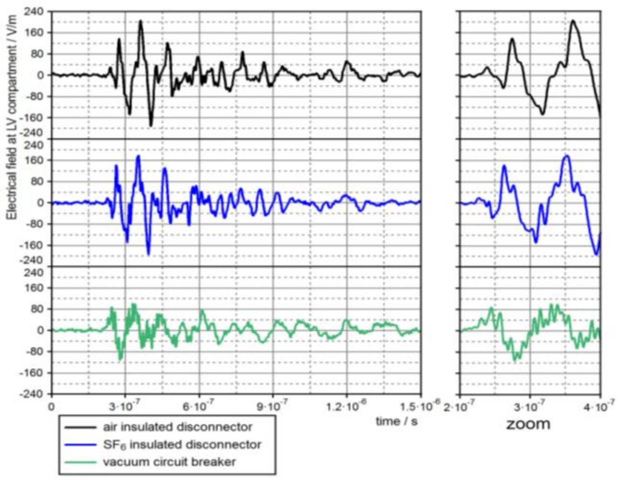

Figure 9. Electrical field measurement.

Findings:

- All pulses have nearly the same duration of about 1.5 microseconds.
- The maximum amplitude of the radiated field is the same for both disconnectors (200 V / m). For the vacuum circuit breaker, the maximum amplitude was 120 V / m.
- The zoom on the first 200 nanoseconds shows that the air insulated disconnector disturbance has the smallest frequency spectrum and the vacuum circuit breaker disturbance has the widest one.

For a further comparison of the frequency spectrum, the three traces of Figure 9. were Fourier-transformed. Further, the frequency spectra were normalized, to eliminate any absolute effects, and thus, to make the curves more comparable in respect to their relative spectral contents.

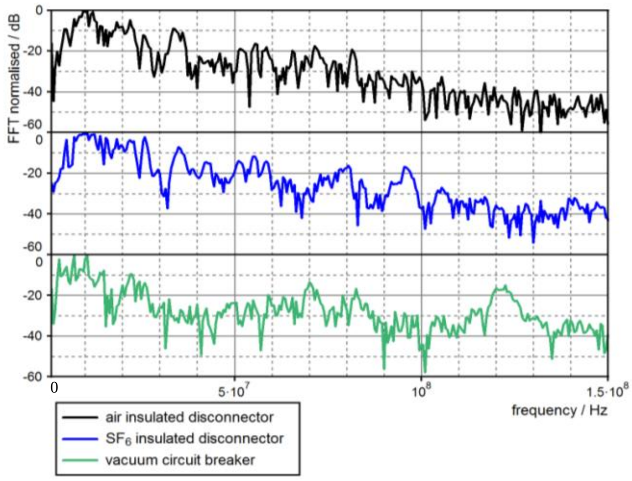

Figure 10. Normalized FFT of electrical field measurement.

For the interpretation of the 3 Fast-Fourier-Transformation (FFT) shapes of Figure 10. , the spectral contents clearly larger than 10% (-20dB) of the peak value should be taken into account. The following properties can be found:

- The disturbance of the air insulated disconnector has its main frequency contents in the range of 3 MHz up to 37 MHz.
- The frequency spectrum of disturbance produced by SF_6 insulated disconnector is quite wider with significantly higher values in the mid range (50 - 80 MHz) and an additional peak at 95 MHz.
- Vacuum circuit breakers produce the disturbance with the widest spectrum. The main frequency content lies between 3 MHz and 27 MHz, but there are also significant contents at 70 MHz and 120 MHz.

C. *Busbar voltage*

The measurement of the conducted disturbance at the busbar was realized by a special measurement plug, working as a broad band capacitive voltage divider (Figure 11.) inside a “size 2” medium voltage cable socket.

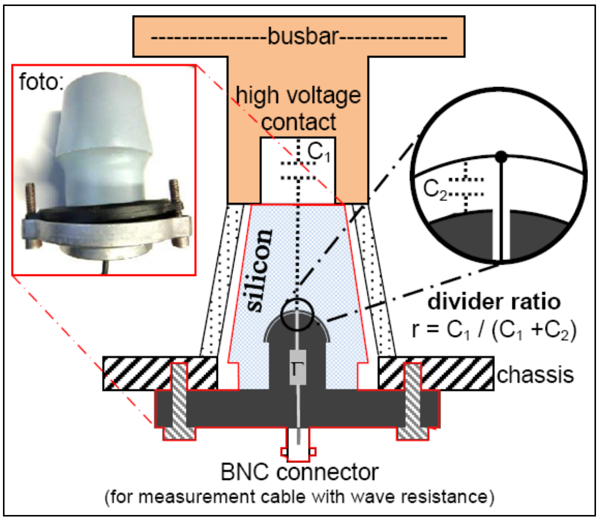

Figure 11. Capacitive voltage divider in a dummy plug. The bandwidth of the voltage sensor is 350 MHz, verified by the measurement of a 4 kV square voltage signal with a rise time of $t_{rise} \approx 1$ ns.

Measuring the busbar voltage by the broadband capacitive voltage divider provides information about the wave propagation characteristic of the switchgear’s primary parts. The following figure (Figure 12.) shows for each switch the sudden recharging process of the switched part of busbar (i.e. one single voltage step in Figure 4.)

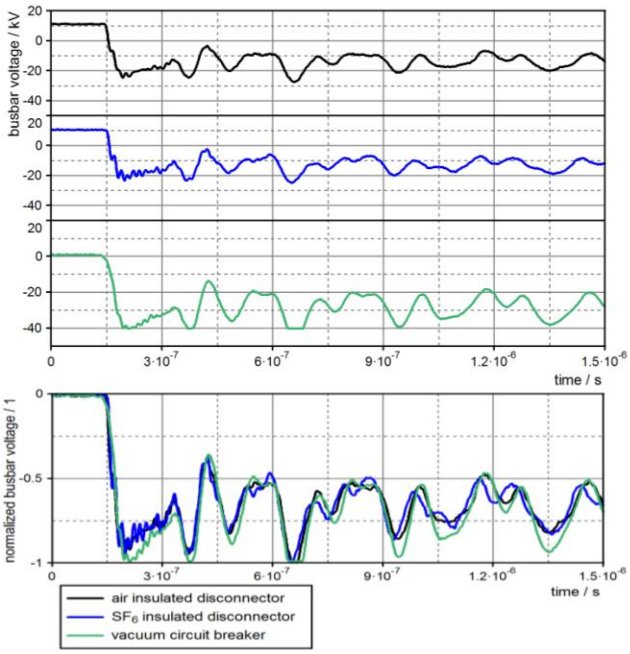

Figure 12. Voltage at the switched part of busbar.

The waveforms look very similar, because of the range of frequencies that can propagate from one panel to the next is obviously limited. The stimulation of the propagable frequencies is different for each kind of switch. Therefore, the SF_6 insulated disconnector trace seems to have the highest spectral amplitudes regarding higher frequencies while the vacuum circuit breaker stimulates only lower frequencies as well as very high ones that cannot propagate. A look at the frequency spectra of the busbar voltage curves (Figure 13.) confirms that spectral contents higher than 65 MHz get almost completely damped in this setup.

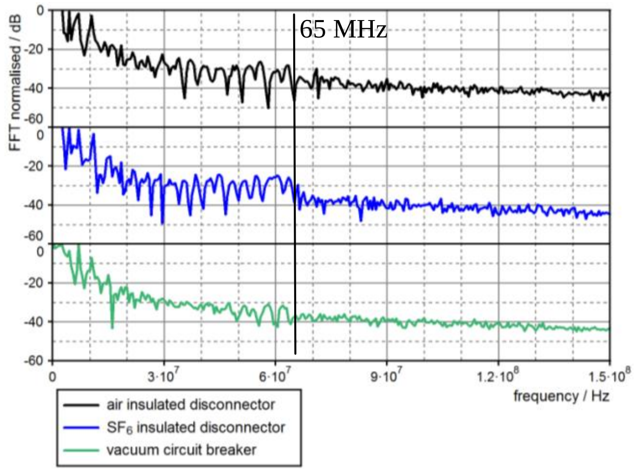

Figure 13. FFTs of the busbar voltage curves.

V. Summary / Conclusions

Based on the different propagation paths, the summary shall give a final classification of the switching devices.

In case of radiated disturbance coupling to the electronic equipment in the low voltage compartment, the vacuum circuit breaker plays the most decisive role. Its severity is due to the wide bandwidth of the generated disturbance. Though, the maximum amplitude of the investigated prestrike disturbance is smaller than for disconnectors, but for (multiple) restrikes the expected amplitude is more than twice the value while the relative frequency spectrum stays constant. The least critical radiated disturbance is generated by the air insulated disconnector because, in fact, it reaches the same amplitude like SF_6 insulated disconnectors, but the stimulated frequency range is clearly smaller.

Regarding the conducted disturbance occurring at the IED’s measurement ports, generally, the disconnectors are more severe than the vacuum circuit breaker. The reason for the higher interference potential of the disconnectors is the quite long duration of their switching operations. In contrast to the vacuum circuit breakers’, the arcing process of disconnectors is significantly longer lasting than the starting time values of usual protection functions (typically 20 milliseconds up to a few hundred milliseconds). Thus, disconnector arcing can possibly stimulate the protection mechanisms and, in the worst case, initiate IED misoperation. A deeper comparison of the two types of disconnectors shows that the SF_6 insulated one produces the disturbance with the wider frequency spectrum while the maximum amplitude of the disturbance is equal for both ones. Hence, the probability for electromagnetic impact on IEDs is the highest for the SF_6 insulated disconnector, but also air insulated disconnectors are more severe than vacuum circuit breakers.

Last but not least it should be noted, that also the coupling to nearby switchgear panels is more severe for the disconnectors, because of the very high frequency content of the circuit breaker disturbance spectrum is almost completely damped.

For the future, there could be a chance for an intentional use of this low pass characteristic of the switchgear. It may be possible to reach switchgear designs with lower cut-off frequencies for the conducted electromagnetic coupling between the panels, and in this way, to significantly reduce the propagation radius of the switching disturbances.

VI. References

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