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Influence of Ring-Main-Units and Substations on the Propagation of PD Pulses

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Abstract—**Partial discharge (PD) location in online diagnostics on medium voltage cables is achieved using a sensor at each cable end. Monitoring consecutive cables with a single monitoring system would, however, be more efficient. Moreover, substations and ring main units (RMU) along a cable connection without possibilities for sensor installation can be circumvented by installing the sensor at the next RMU. This paper studies the influence of RMUs and substations along the cable under test on online PD monitoring, including their influence on detection sensitivity, location accuracy and charge estimate accuracy. Models for RMUs and substation are proposed and verified by measurements. The performance of online PD monitoring is studied for a number of network configurations.**

Index terms*—*defect location, partial discharges, power cables, ring-main-units, substations.

I. INTRODUCTION

Recently, there is an increasing interest in online monitoring systems that detect and locate partial discharges (PDs) in medium-voltage (MV) cables. These PD monitoring systems can be installed on a single cable between two ring-main-units (RMUs) [1]-[3]. It saves costs and effort to monitor two or more consecutive cables using a single monitoring system. Moreover, practical experience with the PD-OL system, with inductive sensors, shows that for a number of large substations, with many parallel MV cables, and RMUs installing is hampered or even impossible. A solution would be to monitor two consecutive cables with the problematic RMU/substation in between as shown in Fig. 1. In this paper the influence of RMUs and substations along the cable under test on the PD detection sensitivity and location accuracy is investigated.

An RMU or substation is a combination of the complex impedances of the switchgear, transformer, MV cables, and other components. Therefore, the load impedance as seen by a PD pulse arriving from a cable is not matched to the cable's characteristic impedance. When a PD pulse that propagates through the cable under test arrives at an RMU or substation a part of the pulse will reflect and a part will transfer to continuing MV cable(s). The result is a change in pulse shape and amplitude. This change has an influence on the sensitivity and accuracy of the PD detection. The influence of different RMU and substation configurations is analyzed in this paper. Investigated variables include: switchgear dimensions, number of connected cables, number of RMUs/substations along the cable under test, and the total cable length.

II. RMU AND SUBSTATION MODEL

RMUs and substations basically have a similar topology. One or more incoming MV cables are connected to a common busbar via switchgears. In addition, one or several transformers can be connected to the busbar. A modular installation consists of a series of compartments. Each compartment connects a single component, cable or transformer, to the busbar. The main difference, relevant to the proposed model, between an RMU and a substation are the number of connected cables and the dimensions of each compartment. A typical RMU has 1–5 connected cables, while a substation can include up to 30 cables. Each compartment in an RMU is typically 10–40 cm wide, while in a substation the width is 40–150 cm. The model depicted in Fig. 2, based on [2], involves only components affecting the system behavior from 500 kHz to 5 MHz, relevant for PD cable diagnostics with remote sensors.

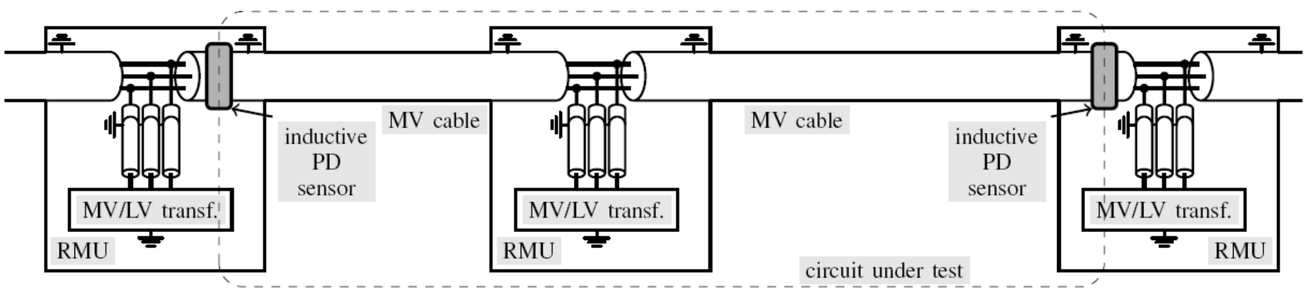

Figure 1. Monitoring two consecutive MV cables with one RMU along the cable under test. RMUs consist of a medium-voltage (MV) to low-voltage (LV) transformer which is connected by three single-phase transformer connecting cables (TCC) to the busbar.

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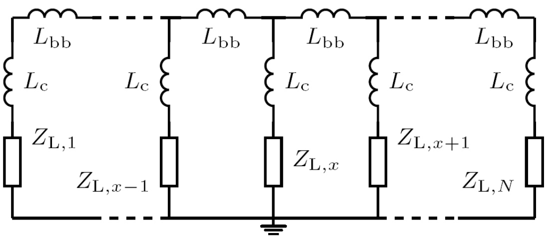

Figure 2. Equivalent circuit of RMU or substation with *N* components

Each compartment has a load impedance Z_L in series with inductance L_c. The impedance Z_L represents the component that is connected to that compartment, usually an MV power cable or a transformer. The inductance L_c covers the inductance of the loop from the connected component to the busbar. The inductance L_{bb} is the inductance of the loop between busbar and earth over the distance of the width of one compartment. The MV cables are represented as a characteristic impedance Z_c. In the frequency range of interest a power transformer can be modeled by a series connection of the capacitance C_{tr} between transformer windings and grounded core and casing, inductance L_{tr} of the loop inside the transformer, and resistance R_{tr} representing losses in the transformer. The cables that connect the transformer to the busbar (TCC) are modeled by the capacitance C_{tcc} from cable conductor to earth screen, inductance L_{tcc} of the connecting loop and earth connection, and resistance R_{tcc} representing conductor and insulation losses in those cables [4].

III. RMUs and Substations along Cable under Test

The load impedance $Z_{load}(\omega)$ for PD pulse arriving from a cable usually differs from the cable's characteristic impedance Z_c. The pulse will therefore partly reflect and partly transfer to other connected MV cables, resulting in a pulse distortion. The effect of an RMU (or substation) can be expressed in the total transfer function $H_{rmu}(\omega)$. It is a combination of the current transmission coefficient $\tau_c(\omega)$ from the cable under test to the load impedance $Z_{load}(\omega)$ and transfer function $H_{cn}(\omega)$ that describes the distribution of the current (inside the RMU) from the incoming cable to the other connected components:

$$H_{rmu} = \tau_c \cdot H_{cn} = \frac{2Z_c}{Z_c + Z_{load}} \cdot H_{cn} \tag{1}$$

Both the transfer function $H_{cn}(\omega)$ and the load impedance $Z_{load}(\omega)$ can be derived from the RMU/substation model.

A. RMUs with Two Connected Cables

Most RMUs in a distribution grid with a ring structure have two connected MV cables. The total transfer function $H_{rmu}(\omega)$ is calculated applying the model together with (1) for a typical compact RMU with two connected MV cables and an MV/LV transformer. The total transfer function $H_{rmu}(\omega)$ is plotted in Fig. 3. If there are L identical RMUs along the cable under test, the combined transfer function $H_{tot}(\omega)$ is given by:

$$H_{tot} = (H_{rmu})^L \tag{2}$$

The total transfer functions $H_{tot}(\omega)$ for three and nine RMUs with parameter values taken equal to what is actually measured in real RMUs [4] are plotted in Fig. 3.

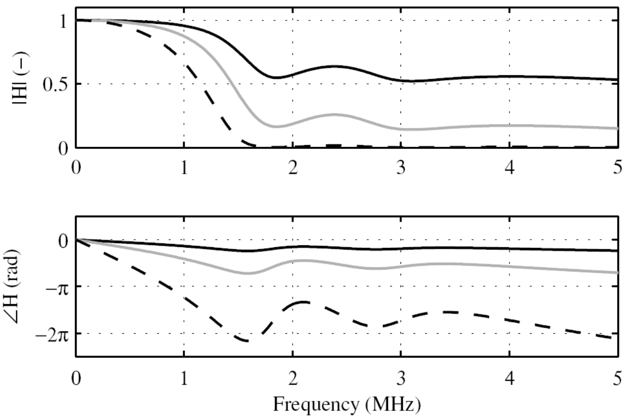

Figure 3. Total transfer function $H_{tot}(\omega)$ of a typical RMU (solid black line). The combined transfer functions of three (gray line) and nine (dashed black line) consecutive RMUs are also plotted.

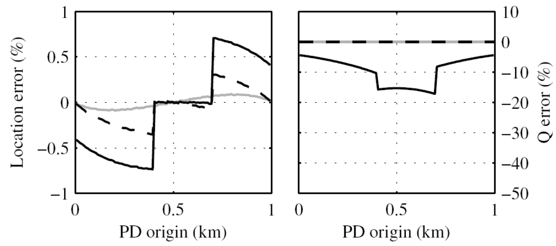

Figure 4. PD location and amplitude error for different PD origins. The cable is a 1 km long PILC cable with a typical RMU at 400 m and at 700 m. The RMUs at the beginning and end of the cable are matched to the characteristic cable impedance. Black solid line: matched filter that does not take into account RMUs along the cable, black dashed line: adaptive matched filter, and gray solid line: reference without RMUs.

Each RMU adds a phase shift to the signal. Since a linear phase shift corresponds to a time delay, location errors may arise when this phase shift is not anticipated for. Depending on the algorithm to establish pulse arrival times [5], the change in pulse shape may also introduce location errors. The location error is estimated on basis of simulated PDs arising from different origins. The location accuracy and charge estimation accuracy is determined for each PD origin. Three different simulations are performed:

1) Reference simulation. The circuit does not include the RMUs along the cable under test. The arrival time is estimated by the energy criterion (EC) [5] and the charge Q is estimated by integrating the current over time.
2) Matched filters based on cable system model that does not take into account the RMUs along the cable under test, while for the simulation the RMU(s) are present. The arrival time and amplitude of the PDs are determined using matched filtering technique [3].
3) Adaptive matched filters. Matched filters are based on detected PD pulses, as described in [6]. These filters do take into account the RMUs. The arrival time is estimated by the energy criterion (EC) [5] and the charge Q is estimated by integrating the current over time.

In Fig. 4 the simulation results are plotted for a 1 km PILC cable with two RMUs. The maximum location error increases from 0.1% of the total cable length to 0.7% for the filters that do not take into account the RMUs, and to 0.3% for adapted filters that do take into account the RMUs. For PDs arising between the RMUs the phase shifts at both ends cancel and no additional error is introduced. RMUs along the cable under test not only increase the PD location error, they also introduce a charge Q estimation error. For the second simulation (original matched filters) the maximum charge estimation error is 15%. This simulation demonstrates that one or more RMUs with two connected MV cables along the cable is acceptable for most practical situations. Only in case of relatively short cables with several (three or more) RMUs the maximum location error will be above 1%. However, for short cables location accuracy just above 1% is not a real problem, because the absolute error is still limited to only a few meters.

B. RMUs / Substations with over Two Connected Cables

A (PD) pulse arriving at a substation or RMU with more than two connected MV cables distributes its energy over multiple outgoing cables. This results in a significant signal loss and therefore a lower PD detection sensitivity. In this section the influence of a substation and RMUs with more than two connected MV cables is analyzed. The substation model is used to study the distribution of an incoming pulse over multiple outgoing cables in a large substation. A substation with fifteen connected MV cables is modeled (details in [7]). A pulse arrives from the cable connected in compartment 5 and distributes over the other cables. The total transfer functions from cable 5 to four outgoing cables are plotted in Fig. 5.

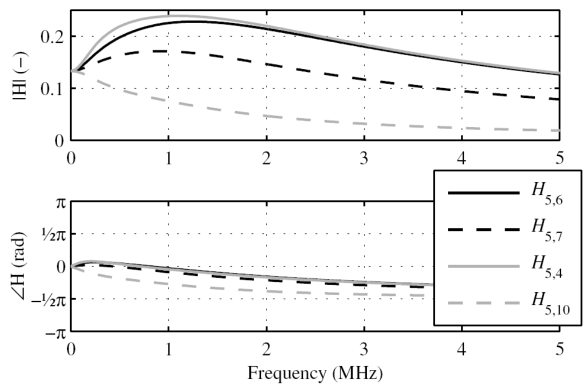

Figure 5. Total transfer function for a pulse arriving at the substation from the cable in compartment 5 to other cables. The substation has 15 connected MV cables. $H_{m,n}(\omega)$ denotes the total transfer function $H_{rmu}(\omega)$ for a pulse arriving from cable m and going to cable n.

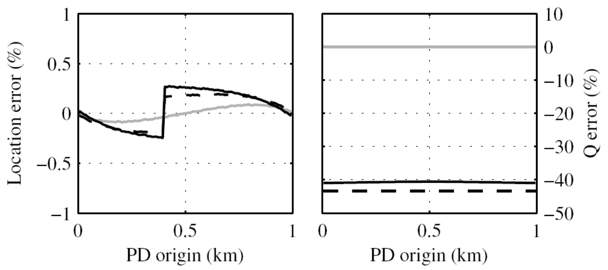

Figure 6. PD location and amplitude error for different PD origins. The cable is a 1 km long PILC cable with a substation with 15 connected MV cables at 400 m. The RMUs at the beginning and end of the cable are matched to the characteristic cable impedance. Black solid line: matched filter that does not take into account RMUs, black dashed line: adaptive matched filter, and gray solid line: reference without RMU.

For low frequencies the transfer function to all cables is close to 2/15, the ratio to be expected from (1) if the influence of the transformer and inductances can be neglected. For higher frequencies the effect of the inductances becomes significant, resulting in a decrease of the transfer function for cables further away and an increase for the cables close to the cable from which the pulse arrives. Depending on distance (within substation) between cables, the total cable length and the noise spectrum a substation with fifteen connected cables will result in a deterioration of the detection sensitivity by a factor 5–15.

The influence of this particular substation along the cable under test on the PD location accuracy and charge estimation accuracy is analyzed using the same simulation method as in Section III-A. The results are plotted in Fig. 6. The cables being monitored are connected to compartments 5 and 6 in the substation. See $H_{5,6}(\omega)$ in Fig. 5 for the total substation transfer function for this configuration. The maximum location error is within 0.3%. The charge estimation error is 40–45% due to the large signal loss at the substation.

IV. Experiments

A. Compact RMU along Cable under Test

To verify the feasibility of monitoring multiple consecutive cables with RMUs along a cable connection, a PD-OL partial discharge monitoring system is installed on such a circuit. The PD-OL system [1] is installed on a circuit consisting of four consecutive XLPE cables with a total length 5661 m and three RMUs along the connection at 4694 m, 5033 m and 5106 m. The PD density monitored over a period of 11 days is plotted in Fig. 7. On July 31 PD activity started on one location. Over a couple of days the discharge activity intensified. The utility replaced the joint at the location of the discharge activity. Investigation of the joint showed that it was partially burned due to excessive heating caused by a bad crimp connector. After repair the discharge activity had disappeared. According to the circuit data from the utility the joint is at 3526 m, while the PD-OL system located the PDs at 3520 m. This corresponds to a deviation of 0.1% of the cable length.

The PD-OL system is also successfully installed on several other circuits with one or more RMUs along the cable. These circuits include cable circuits with PILC cable and circuits with XLPE cable. The number of RMUs in these circuits varies

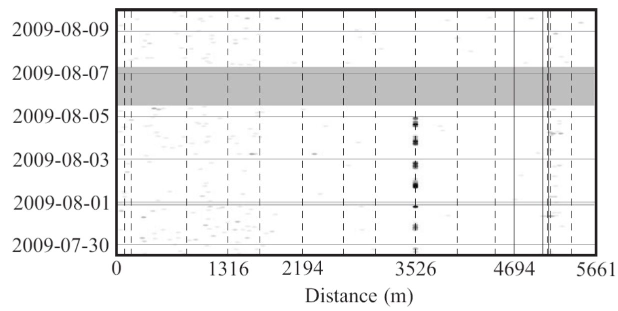

Figure 7. Detected PD density (darker means higher density). The circuit consists of four consecutive XLPE cables with a total length of 5661 m and RMUs at 4694 m, 5033 m and 5106 m. Dashed vertical lines indicate joint locations. Solid vertical lines indicate RMU locations. The solid gray areas indicate periods during which there was no PD measurement, e.g. during the period that the joint was being replaced.

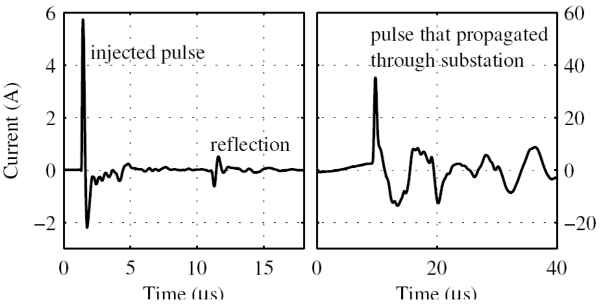

Figure 8. Measured signal after pulse injection in the first RMU of a cable connected in a large substation (left). The injected pulse is detected in the first RMU of another cable connected to the same substation (right). Note that the horizontal and vertical scaling is different for both figures and the zero time points are uncorrelated (no synchronization).

from one to five. It must be noted that due to imprecise cable information provided by some utilities, or to mixed cable segments with different propagation velocities, sometimes larger deviations occur.

B. Large Substation along Cable under Test

The propagation through and reflection on a large substation is tested on a substation with 22 connected MV cables and two HV/MV transformers. A pulse is injected in the first RMU of the 7th MV cable. The cable circuit between this RMU and the substation consists of single-core XLPE cables with a length of approximately 800 m. The injected pulse is detected in the first RMU of the 12th MV cable. The length of the cable between this RMU and the substation is approximately 700 m. The injected and detected pulses are plotted in Fig. 8. The pulse that is transmitted through the substation and detected in the first RMU of the 12th cable is approximately 200 times smaller than the injected pulse; much smaller than what could be expected from propagating through a length of 1500m XLPE cable. This indicates that most signal content is lost due to the substation. Because the propagation coefficient of this particular cable is as expected unknown, it is not directly possible to determine the transfer function of the substation from this measurement. An indication of the pulse transfer through the substation can be obtained from the comparison of transmitted and reflected signal amplitudes. The signal of the injected pulse also shows the reflection of the injected pulse on the substation. This reflection is about 12 times larger than the pulse that propagated through the substation. The distance that both pulses propagated through a cable is similar; the main difference is reflection on and propagation through the substation. Neglecting the influence of transformers (low-frequency approximation) the substation model predicts a reflection coefficient of Γ_{rmu}=-0.9 and a total transfer function of H_{rmu}=0.09. The expected factor of 10 corresponds closely to the measured ratio of 12.

V. Conclusion

An RMU along the cable under test introduces a signal loss and a PD location error. The influence of a compact RMU with two connected cables is neglectable if the total cable length is longer than approximately 1 km. The longer the total cable length is, the smaller the relative influence of an RMU along the cable. For a 4 km PILC cable the signal loss caused by nine RMUs (all with two connected cables) is neglectable and the location accuracy is well within 1% of the cable length. If the RMU(s) along the cable connection have more than two connected cables a significant part of the signal is lost, decreasing the detection sensitivity significantly. In case of PD signal detection based on adaptive filtering, the influence of an RMU along the cable on the charge estimation and location accuracy can be reduced by creating new adaptive templates based on measured PD signals.

A large substation along the cable connection introduces a large signal loss, which may be unacceptable in some situations with a two-sided measurement system. However, a major part of an incoming pulse reflects on a large substation with many connected cables. The guaranteed reflection on such substation opens the possibility for a single-sided PD measurement from the other cable end. The PD origin can be determined using TDR with the reflection on the substation at the far cable end (see e.g. [8]-[10]). A single-sided measurement has the disadvantage that the maximum cable length that can be monitored is halved with respect to two-sided detection, that it is sensitive to reflections on joints in the tested cable and other connected cables, and that it is more difficult to discriminate between PDs and disturbing signals.

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