Propagation of PD pulses through ring-main-units and substations

Citation for published version (APA):

Wagenaars, P., Wouters, P. A. A. F., Wielen, van der, P. C. J. M., & Steennis, F. (2009). Propagation of PD pulses through ring-main-units and substations. In *Proceedings of the 9th International Conference on Properties and Applications of Dielectric Materials (ICPADM) 5-9 August 2009, Harbin, China* (pp. 441-444). Institute of Electrical and Electronics Engineers. <https://doi.org/10.1109/ICPADM.2009.5252394>

DOI:

[10.1109/ICPADM.2009.5252394](https://doi.org/10.1109/ICPADM.2009.5252394)

Document status and date:

Published: 01/01/2009

Document Version:

Publisher's PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

- A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
- The final author version and the galley proof are versions of the publication after peer review.
- The final published version features the final layout of the paper including the volume, issue and page numbers.

[Link to publication](#)

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the "Taverne" license above, please follow below link for the End User Agreement:

www.tue.nl/taverne

Take down policy

If you believe that this document breaches copyright please contact us at:

openaccess@tue.nl

providing details and we will investigate your claim.

Propagation of PD Pulses Through Ring-Main-Units and Substations

Paul Wagenaars^{1*}, Peter A.A.F. Wouters¹, Peter C.J.M. van der Wielen², E.Fred Steennis^{1,2}
1 Eindhoven University of Technology, P.O. Box 513, 5600 MB Eindhoven, The Netherlands
2 KEMA, P.O. Box 9035, 6800 ET Arnhem, The Netherlands

* E-mail: p.wagenaars@tue.nl

Abstract: Online partial discharge (PD) monitoring systems are traditionally installed at a single medium-voltage (MV) cable connection between two ring-main-units (RMUs). It is more efficient to monitor two or more consecutive cables using a single monitoring system. Moreover, practical experience with the PD-OL system [1], shows that for substations, with many parallel MV cables, and RMUs installing the inductive sensor may be hampered or even impossible. In this paper the influence of RMUs and substations on the propagation of PDs is studied. An RMU or substation can be modeled as a combination of complex impedances representing switchgear, transformer and MV cables. A PD pulse from a cable encounters a load impedance that does not match the cable's characteristic impedance, resulting in partial reflection and partial transmission to other cables. Models for RMUs and substations are proposed and verified by measurements. Feasible options for online PD monitoring through RMUs or substations are determined.

Keywords: partial discharges; power cables; diagnostics; ring-main-units; substations; modeling

INTRODUCTION

In recent years, there is an increasing interest in online monitoring systems that detect and locate PDs in MV cables. These systems are usually installed on a single cable section between two RMUs. Location of the PD origin can be achieved by installing a PD measurement unit at both cable ends and by evaluating the difference in arrival time of the PD pulse at both units. It would save money and effort to monitor two or more consecutive cables, with one or more RMUs along the cable connection, using only a single monitoring system (consisting of two measurement units), see Fig. 1. Moreover, practical experience with the PD-OL system [1] with inductive sensors, showed that for large substations comprising many components, and sometimes also for RMUs, installation is hampered or even impossible. Some installations, for example, do not provide sufficient space for installing the measurement unit at the desired location at the cable. Monitoring two consecutive cables, at both sides of the RMU/substation, solves this problem.

An RMU or substation along the cable connection that is being monitored affects PD pulses propagating through it. An RMU or substation acts as a complex impedance combining the influence of switchgear, trans-

former, MV cables, and other components such as line reactors. Therefore, the load impedance as seen by a PD pulse arriving from a cable is not matched to the cable's characteristic impedance. The pulse will partly reflect and partly transfer to outgoing MV cables, resulting in a distortion of the pulse shape and amplitude. The significance on the performance of the PD monitoring system is investigated in this paper.

First, models for typical RMUs and substations are developed. Next, the models are verified by field measurements. Finally, simulations using these models are performed to investigate the influence of RMUs and substations on propagating PD pulses and the resulting influence on the performance of the PD monitoring system.

RMU AND SUBSTATION MODEL

RMUs and substations basically have a similar topology. There are one or more incoming MV cables that are connected to a common busbar via a switchgear. In addition, one or more transformers can be connected to the busbar. A modular installation consists of a series of compartments. Each compartment connects a single circuit or transformer to the busbar. The main differences between an RMU and a substation are the number of connected cables and the dimensions of each compartment. A typical RMU applied in the Dutch grid has 1–5 connected cables, while a substation has 5–30 cables. The width of each compartment in an RMU is typically in the range of 10–40 cm, while in a substation the width ranges from 40–150 cm.

The model presented in this section is based on a more detailed model presented in [2] and is adjusted so that it can be applied to both RMUs and substations. Also some elements of the original model that have hardly influence in the frequency range 100 kHz–5 MHz are removed. Two or more consecutive cables, as considered here, usually have a total length exceeding a few hundred meters. PD signals after having traveled this distance will hardly have energy above 5 MHz.

In Fig. 2 the equivalent circuit of an RMU/substation is depicted. Each compartment has a load impedance Z_L in series with inductance L_s . The impedance Z_L represents the component that is connected to that compartment, usually an MV power cable or a transformer. The inductance L_s is the inductance of the loop from the connected component to the busbar. The inductance L_{bb} is the inductance between busbar and earth over the distance of the width of one compartment.

Fig. 1: Setup monitoring two consecutive cables with one RMU along the cable under test.

Fig. 2: Equivalent circuit of RMU or substation with N compartments

Fig. 3: Equivalent of RMU with two MV cables and MV/LV transformer

In Fig. 3 the load impedance Z_L in each compartment is replaced by equivalent circuits of the connected components for an RMU with three compartments (two MV cables and an MV/LV transformer). The MV cables are represented by their characteristic impedance Z_c . The transformer is modeled by the capacitance C_{tr} between transformer windings and grounded core and casing, inductance L_{tr} of the windings and the loop of the connecting cables, and resistance R_{tr} representing losses in the transformer. The transformer connection cables (TCC) that connect the transformer to the busbar are modeled by the capacitance C_{tcc} from cable conductor to earth screen, inductance L_{tcc} of loop and earth connection, and resistance R_{tcc} representing losses.

MEASUREMENTS

The proposed model is verified by measurements on an RMU and a substation. The RMU involves three compartments, two cable and a transformer. The substation

contains 2 transformers and five cable connections.

Ring-main-unit measurements

To be able to study the effect of an RMU or substation on the propagation of PD pulses typical values for the components in the presented model must be known. The model parameters were determined using measurements for several RMUs. A pulse is injected inductively at one cable end. In the RMU at the far end the resulting waveform is measured at three locations: around the incoming and outgoing cables (PLEC1 and PLEC2), and around the common earth connection of the transformer connecting cables (earth TCC). These location are indicated in Fig. 3. Two transfer functions are calculated:

$$H_{c2}(\omega) = \frac{I_{c2}(\omega)}{I_{c1}(\omega)} \quad \text{and} \quad H_{tcc}(\omega) = \frac{I_{tcc}(\omega)}{I_{c1}(\omega)} \quad (1)$$

where I_{c1} is the current measured at PLEC1 (incoming cable), I_{c2} the current measured at PLEC2 (outgoing cable), I_{tcc} the current at earth TCC. H_{c2} is the transfer function from the incoming to the outgoing cable, and H_{tcc} the transfer function from the incoming cable to the earth of the transformer connecting cables. An example of the measured H_{c2} and H_{tcc} for one RMU is plotted in Fig. 4.

The transfer functions H_{c2} and H_{tcc} can be expressed in terms of the model parameters in Fig. 3. The parameter values for the model are found by a fitting procedure that minimizes the mean absolute relative error between the measured transfer functions and the modeled transfer functions. The model has nine parameters and therefore also local minima may exist. In order to converge to the global minimum the starting values must be chosen accurately. Often, one or two resonances can be observed, as is the case in Fig. 4 near 2 MHz and 3 MHz. The products $L_{tr}C_{tr}$ and $L_{tcc}C_{tcc}$ are chosen such that they match these frequencies. The capacitance of the transformer connection cables can be estimated by multiplying the length with the capacitance value taken from the cable datasheet (≈ 140 nF/m). Earlier impedance measurements [2] showed that the typical characteristic impedance (Z_c) of a three-core 10 kV PILC cable is approximately 10Ω and that the total inductance of the loop between two installed MV cables is approximately 800 nH. The total inductance of the loop between the two MV cables in the model in Fig. 3 is $2L_s + L_{bb}$. Because

Fig. 4: Measured (solid) and modeled (dotted) RMU transfer functions H_{c2} (black) and H_{icc} (grey).

the field measurements are performed on similar PILC cables and the same type of installation the constraints $2L_s + L_{bb} = 800\text{ nH}$ and $Z_c = 10\Omega$ are kept fixed in the fitting procedure. The modeled transfer functions after the fitting procedure are included in Fig. 4. The model parameters for this RMU are: $L_{tr} = 3.2\mu\text{H}$, $C_{tr} = 1.6\text{ nF}$, $R_{tr} = 5.6\Omega$, $L_{icc} = 0.74\mu\text{H}$, $C_{icc} = 2.3\text{ nF}$, $R_{icc} = 2.4\Omega$, $L_s = 345\text{ nH}$ and $L_{bb} = 110\text{ nH}$.

Substation measurement

A measurement has been performed to verify the model of Fig. 2. The measurement was performed in a compact substation with five connected MV cables and two transformers. Each compartment is $42 \times 120 \times 70\text{ cm}$ (W×H×D). The transformers are connected to compartments 1 and 2, and the cables to compartments 3–7. For the measurement a pulse was injected inductively around the leftmost MV cable (in compartment 3). The injected current distributes over the other compartments. The injected current and the currents (I_4 to I_6) through the cables in compartment 4–6 are measured and the current transfer functions are calculated. For instance, in Fig. 5 the ratio $H_{46} = I_4/I_6$ is plotted. Additionally, at each cable an impedance measurement is performed to determine the impedance of that compartment ($j\omega L_s + Z_c$) in series with the rest of the substation. The model parameters are fitted by minimizing the mean absolute relative error between model and measurement: $L_s = 520\text{ nH}$, $L_{bb} = 140\text{ nH}$ and $Z_c = 8\Omega$.

At low frequencies the influence of the inductances are negligible and the ratio H_{46} is determined by the characteristic cable impedances. Because Z_c is equal for all the connected cables the ratio H_{46} plotted in Fig. 5 starts at 1. This means that the current injected around the cable in compartment 3 distributes equally over the other four cables. At higher frequencies the current distribution is mainly determined by the ratio of L_s and L_{bb} .

Fig. 5: Measured and modeled ratio of currents measured in compartment 4 and 6.

EFFECT ON PD MONITORING

The proposed models for RMUs and substations allow us to predict their effect on the PD waveform. The signal distortion and the effect on location accuracy is studied.

Effect of ring-main-unit

The effect of an RMU can be expressed in the total transfer function H_{rmu} . This transfer function is a combination of the transmission coefficient T_{c1} from cable 1 to the RMU, and the transfer function H_{c2} :

$$H_{rmu} = T_{c1} \cdot H_{c2} = \frac{2Z_c}{Z_c + Z_{load}} \cdot H_{c2} \quad (2)$$

where Z_{load} is the RMU impedance as seen by a pulse arriving from cable 1.

H_{rmu} is plotted for a typical RMU in Fig. 6. The parameter values for this simulated RMU were obtained by averaging the fitted parameters of measurements in five RMUs: $L_s = 340\text{ nH}$, $L_{bb} = 120\text{ nH}$, $L_{tr} = 2.6\mu\text{H}$, $C_{tr} = 2.5\text{ nF}$, $R_{tr} = 12\Omega$, $L_{icc} = 1.2\mu\text{H}$, $C_{icc} = 1.9\text{ nF}$, $R_{icc} = 8.6\Omega$, $Z_c = 10\Omega$. The figure shows that for frequencies up to 1.5 MHz PDs pass through the RMU almost unaffected. Because higher frequencies attenuate stronger than lower frequencies the effect of an RMU in the cable under test is larger for shorter cables than for longer cables.

In order to determine the effect of an RMU on the location accuracy a simulation has been performed with a circuit with a total length of 1 km and an RMUs at 400 m and at 900 m. The RMUs along the cable have a total transfer function H_{rmu} as depicted with the solid black line in Fig. 6. At its origin a PD pulse is simulated by a delta pulse. The propagation coefficient taken to simulate the PD propagation through the cable has been measured on PILC cable sample. The location accuracy is investigated by simulating PD measurements, as described in [3]. This simulation consists of a propagation time measurement followed by PD measurements for several loca-

Fig. 6: Total transmission coefficient of RMU (black) and substation (grey) and reflection coefficient of substation (dashed grey)

tions along the cable. The precise value of the arrival time of (PD) pulses is ambiguous and depends on the pulse detection algorithm. A robust method, based on the signal energy criterion [3], is employed here. The "measured" PD location is compared to the actual PD location.

In Fig. 7 the simulated location accuracy is plotted. As a reference simulation results of the location accuracy for the same circuit without RMUs along the cable under test is included. The introduction of the RMUs along the cable under test clearly introduces a location error. The maximum error is approximately 0.4% of the total cable length. For shorter cables this relative error will increase while for longer cables it will decrease.

Effect of substation

The model has also been applied to simulate the effect of a substation on PD pulse propagation. A substation with 15 connected MV cables has been modeled using $L_s = 1 \mu\text{H}$, $L_{bb} = 300 \text{ nH}$ and $Z_c = 8 \Omega$. These values are larger than found for the measurement in the previous section because the average substation installation has larger dimensions than the installation of the measurement. A pulse from cable 5 is transmitted to cable 6. The total transfer function to the neighboring cable $H_{\text{sub},56}$ is plotted in Fig. 6. The substation transfer function is smaller than H_{rmu} over the full frequency range. The transfer functions to cables at larger distance from cable 5 (not shown) are even smaller. A substation along the cable connection results in a large decrease in detection sensitivity. For a substation with many connected cables an alternative option for PD location can be considered. A single-sided measurement, based on time-domain reflectometry, with the substation at the far cable end is feasible. The load impedance of the substation is much lower than Z_c of the cable for frequencies up to roughly 1 MHz due to the many parallel cables. For higher frequency the load impedance is much higher due to the relatively large

Fig. 7: PD location error for different PD origins with two RMUs along the cable under test.

inductances L_s and L_{bb} . Because of this clear mismatch PD pulse reflection is guaranteed. This is illustrated by the reflection coefficient $R_{\text{sub},5}$ depicted in Fig. 6. $R_{\text{sub},5}$ is even larger than the RMU transfer function for almost the complete frequency range.

CONCLUSIONS

Monitoring several consecutive cables with a single PD system is feasible, provided that there are only RMUs along the cable under test. An RMU along the cable under test does introduce a location error, but for most cable connections this error is within a usually accepted range of 1% for PD location in power cables. Only for short cables the error will be beyond this limit. A substation along the cable under test results in a large decrease in sensitivity and is therefore not recommended. An alternative is to perform single-sided PD measurements, using time-domain reflectometry for location, with the substation situated at the far end of the cable under test.

The RMU and substation models can be used to further study their effect on PD diagnostics when placed along the cable under test or at the far end. Future research will be directed to the effect of RMUs and substations on parameters important for PD diagnostics, such as the detection sensitivity and the charge estimation.

REFERENCES

- [1] P. C. J. M. van der Wielen and E. F. Steennis. Experiences with continuous condition monitoring of in-service mv cable connections. In *Proc. Power Engineering Society (PES) Power Systems Conf. & Exp. (PSCE)*, Seattle, WA, USA, Mar. 2009.
- [2] P.C.J.M. van der Wielen. *On-line Detection and Location of Partial Discharges in Medium-Voltage Power Cables*. PhD thesis, Eindhoven University of Technology, Eindhoven, The Netherlands, 2005.
- [3] P. Wagenaars, P.A.A.F. Wouters, P.C.J.M. van der Wielen, and E.F. Steennis. Accurate estimation of the time-of-arrival of partial discharge pulses in cable systems in service. *IEEE Trans. Dielectr. Electr. Insul.*, 15(4):1190–1199, Aug. 2008.