Impedance Analysis of an RMU for On-line PD Measurement

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Abstract
A new system to monitor partial discharges (PD) on-line in medium-voltage power cables is being developed. On-line measurement implies that the equipment can be applied when the cable is in operation, i.e. without disrupting service. A PD gives a high frequency pulse, propagating through the MV power cable. At the termination cable, the PD pulses partially reflect and partially propagate into the connected Ring Main Unit (RMU) due to the impedance transition. For correct interpretation of PD signals from the cable under test, it is essential to know the involved impedances up to several megahertz. An analysis of the impedances of the RMU elements is performed. A theoretical analysis based on lumped impedances is verified using various measurements. The measurements have been carried out on a test-grid consisting of two RMUs and several cables and show good agreement with predictions. This method of analysis will be used in the on-line PD monitoring system.

1. Introduction

The distribution grid is a fine-meshed network, operating between 1 kV and 36 kV. This type of network can be operated either using medium voltage (MV) cables or overhead lines. In The Netherlands, virtually 100% is realised through cables. Most of the outages, experienced by the end users are a result of disturbances in the distribution grid. For assessment of the reliability and the condition of the distribution network, the condition of the cables is a key issue. The two most commonly used cables in the Dutch distribution grid are the paper insulated lead cover (PILC) cable and the cross-linked polyethylene (XLPE) cable. The PILC cables are generally the oldest. Knowledge of aging of this cable is important for determining the rest-life and failure probability of cable connections. Partial discharges in the cable are an indication for the aging of the PILC cable.

A new method is being developed to measure PD activity in power cables, while the cable is in operation i.e. on-line. Partial discharges occur during normal operational conditions and signals from these discharges can be picked up by inductive sensors without direct contact to the cable. The installation point for such a sensor can only be at RMUs the cable interconnects. The electrical characteristics of the RMU, in terms of impedance, are essential for the correct interpretation of measured signals from the power cable. The aim of this paper is to analyse and characterise the impedance of an RMU.

2. RMU model

An MV power cable interconnects either two RMUs or a substation with an RMU. When the system remains in operation, the only suitable place for installation is the RMU [1]. A PD originating from the cable, propagates through the cable as a TEM wave (Fig. 1). At the interface of the cable and the RMU, the pulse partially reflects from and partially transmits into the RMU. For the interpretation of the measured signal, the impedance of both the cable and the RMU have to be known. Since the characteristic dimension of an RMU is lower than the quarter wavelength for frequencies relevant for PD detection, a lumped impedance approximation can be used to model an RMU.

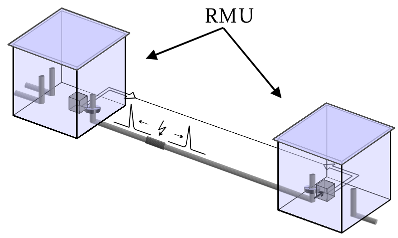

Fig. 1 - PD pulse propagation

A PD signal propagates via different modes over commonly applied belted cables. As we aim for detection at conductors on earth potential, the mode of interest is the propagation mode between the three conductors together with respect to the earth screen, which is referred to as the Shield to Phase (SP) mode.

2.1. Components in an RMU
RMUs are constructed in various ways and therefore a general matching model of an RMU does not exist. The hardware components in an RMU have to be identified first. For the analysis, the simplest configuration is chosen. This is an RMU with one incoming MV cable and one connected transformer to the low voltage network (Fig. 2). This type of RMU can be found in a grid opening of a ring structure or at the end of a radian line. RMUs with more than one incoming cable are more common and they can be modelled similarly. In a single cable RMU, the *MV cable* is installed on a *circuit breaker*, which connects the cables to a common rail. Via a fuse the rail is connected to *transformer connecting cables* (TCC), which connect the rail to a *transformer*. These four elements are examined in more detail.

Power cable - The considered power belted cable in the distribution network is a three-phase cable. For the SP channel, the three phases are modelled as a single conductor. Cables are usually sufficient long to be considered as a long transmission line. In good approximation, the cable can be modelled by its characteristic wave impedance Z_0 which is given by:

$$Z_0 = \frac{1}{2\pi}\sqrt{\frac{\mu_0\mu_r}{\varepsilon_0\varepsilon_r}}\ln\left(\frac{R}{r}\right) ,$$

where *R* is the outer radius of the coaxial structure and *r* of the effective conductor radius. Values for power cables are in the range of 10 Ω to 50 Ω.

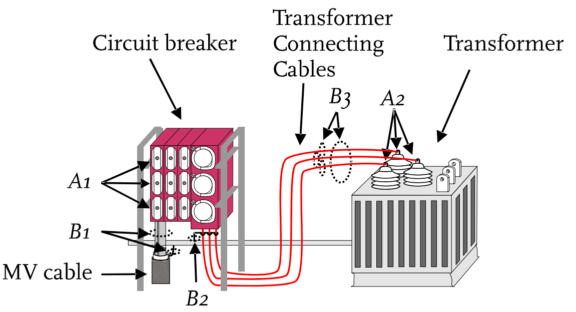

Fig. 2 - Ring Main Unit

Circuit breaker - The cable is mounted on a circuit breaker which connects the cable to the grid. A commonly used circuit breaker is an epoxy insulated type (Magnefix). The end of the cable is brought into an (oil) insulated socket where the three phases are separated and brought to the circuit breaker. The concentric earth screen of the power cable is connected to the earth of the switchgear. From this point, the cable cannot be modelled with its characteristic wave impedance. The breaker connects the cable to the common rail of the circuit breaker. Via another circuit breaker and fuses, the rail is connected to the transformer by means of TCCs. Concerning the earth connections, the shield of the incoming cable and the shield of the TCCs are connected to a common earth. Considering the SP channel, the circuit breaker is a good conductor for low frequency. In the frequency range of interest however, the self-inductance of the breaker through the earth connections, becomes significant. In the range of 1-10 MHz, the self-inductance impedance ranges from 3 Ω to 30 Ω, which is in the same order of magnitude as the characteristic impedance of the power cable. The capacitances between the conductors and the earth can be neglected due to the large spacing.

Transformer connecting cables - The circuit breaker is connected to the transformer via one TCC for each phase. The earth shield is connected to the RMU common earth at the circuit breaker. A typical length of such a cable is 5 metres and it can be modelled by its capacitance between the phases and earth, and a self-inductance due to the TCC-earth to the transformer-earth connection. The per-metre capacitance of a single conductor with a concentric earth screen is given by:

$$C' = \frac{2\pi\varepsilon_0\varepsilon_r}{\ln\left(R/r\right)} .$$

For the SP analysis the three TCC capacitances are taken in parallel.

Transformer - The transformer connects the RMU to the low-voltage grid. For the impedance modelling at high frequencies, capacitive coupling parameters are dominant in a transformer [2]. In reference [3] a model is presented that can be used in the MHz range. This model omits interwinding capacitances, proximity effect, skin effect and hysteresis, because these effects contribute little to the overall high-frequency behaviour Each transformer phase can be modelled by a direct capacitance to ground in parallel to a path via the transformer windings to ground, also including its resistance. A simplified electrical model for the transformer is depicted in Fig. 3.

2.2. Lumped impedance model

For the modelling of an RMU with lumped impedances, two circuit paths can be identified. The first path is a loop containing the MV cable (Z_0). The connection has a resistance R_{conn} that cannot be neglected, e.g. due to the skin effect. Via the circuit breaker and the earth of the TCC's the loop is closed. This loop has a self-inductance $L_{self,1}$. In addition, the long connection acts as an antenna that radiates EM energy and is modelled by a frequency dependent radiation resistance as described in reference [4]. This impedances is included via $R_{rad,1}$. The TCC forms a capacitive connection to earth (C_{TCC}). Parasitic effects are incorporated by a capacitance parallel to the self-inductance of the loop ($C_{par,1}$).
For the second path, the capacitance of the TCC (C_{TCC}) is connected to the inductance of the loop, which is modelled by $L_{self,2}$. The losses are given by R_{diss} and radiation resistance is also included in $R_{rad,2}$. The loop is closed by the HV side of the transformer (Z_{trans}). $C_{par,2}$ models parasitic effects for high frequencies.

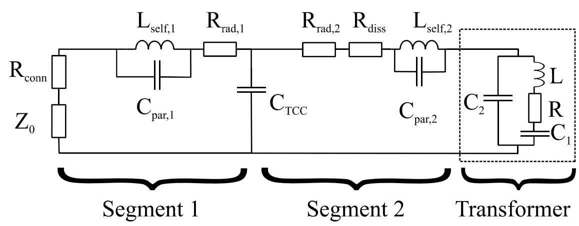

Fig. 3 - RMU lumped impedances model.

3. Experimental arrangement

Information on the substation impedance is obtained by inductive signal injection and simultaneous detection at appropriate sites within the RMU. In Section 3.1, the measurement system is described and in Section 3.2 the available test-grid is presented.

3.1. Measurement system

For inductive measurement there is no galvanic connection between the measurement system and the MV conductors. Two types of inductive sensors are used for measuring the impedance of the RMU: a Rogowski coil for injection and a Current Transformer (CT) for detection. The “core” of a Rogowski coil is formed by the air it encloses, which ensures that a Rogowski coil does not saturate. This makes an air coil suitable for injection. For sensitive measurement a ferromagnetic core with high μ_r is used. The sensor must be constructed such, that the magnetic flux density induced by current from the power system at 50 or 60 Hz does not saturate the core. The applied Fischer Current Coil (FCC-70) meets this requirement. This coil is not suitable for injection, since the core may saturate due to the high power pulse excitation. For impedance determination, it is necessary to obtain both the voltage over the impedance and current through the impedance. The voltage is the induced voltage by the Rogowski coil. The resulting current is measured by the current transformer. In Fig. 4 the equivalent circuit for inductive coupling is depicted. The induced voltage U_{obj} can be related to the injected current I_{inj} according to reference [5]:

$$\frac{U_{obj}}{I_{inj}} = Z_t = \frac{j\omega M Z_{obj}}{Z_{obj} + j\omega L_2}.$$

For the two previously described coils, two operation conditions can be defined:

- for an air coil in combination with a large Z_{obj}, $\omega L_2 << Z_{obj}$. The transfer impedance can be approximated by $Z_t \approx j\omega M$,
- for a current transformer, μ_r is very high and thus $\omega L_2 >> Z_{obj}$. The transfer impedance can be approximated by $Z_t \approx M \cdot Z_{obj} / L_2$.

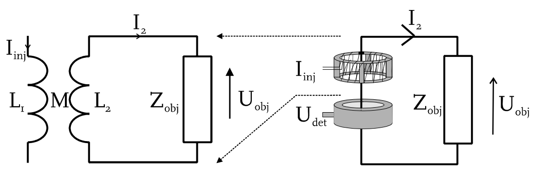

Fig. 4 - Injection and detection coils.

3.2. Experimental test setup

For verification of the model a test-grid, with two RMUs and a connecting cable with one joint, is available (Fig. 1). This test-grid is not part of an overall grid and switching has no consequences for power delivery. In the RMU, galvanic connections to the MV cable and to the circuit breaker rail are possible at the circuit breaker (Fig. 2, A1). At the transformer HV side connection can be made as well if the grid is not powered (Fig. 2, A2).

The RMU is equipped with a Magnefix switching device and the earth shield of the incoming cable is connected to the common earth of the RMU and not to the housing of the switching equipment. Injection and detection can take place between the three phases and earth screen (Fig. 2, B1). This site is referred to as Past Last Earth Connection (PLEC). Generally, there is sufficient space to install two coils (Fig. 4). Another site where inductive measurement can be performed is the earth of the TCC (Fig. 2, B2), although this can involve complications, see [1]. The third site where coils can be installed is at any of the TCC cables (Fig. 2, B3).

4. Results

In the RMU model, two segments were defined (Fig. 2). In the test-setup, these two loops can be split, either by disconnecting the TCC at the transformer or by disconnecting the transformer at the circuit breaker. The two segments have one common element, the TCC capacitance. The impedances are measured and fitted to the model of Fig. 2. The results for Segment 1 are given in Fig. 5.

In the frequency range between 500 kHz and 9 MHz model and measurement agree. Above this range, the injected power becomes low and the high circuit impedance causes reduced measurement accuracy. The impedance value for the cable Z_0, and the connection resistance R_{conn} correspond to estimated values. The magnitude of the radiation resistance $R_{rad,1}$ is frequency dependent and corresponds to an antenna with an effective length of 5 metre. The radiation resistance is an effective value made up by all conductors in the segment. Under the assumption that all contribution can be added, 5 m is indeed in the order of the size of the system. The self-inductance of the first segment $L_{self,1}$ can be approximated by a s square loop of 1 m by 50 cm, and an effective conductor radius of 13 cm. The simplified model does not take the complex structure of the total self-inductance of the three conductors into account, but still gives a good indication. The capacitance of the TCC agrees with the values found in the cable data sheet. The parasitic capacitance has a typical value that is expected for a section of this size.

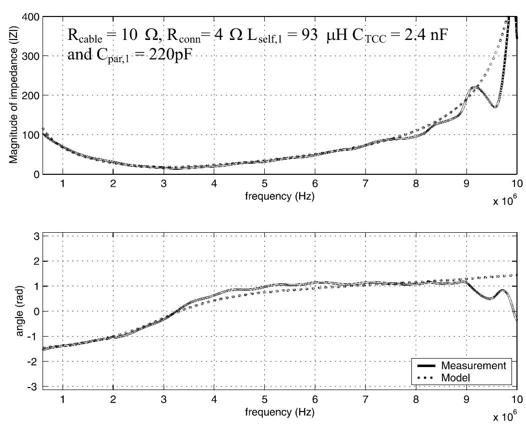

Fig. 5 - Segment 1, model and measurement results.

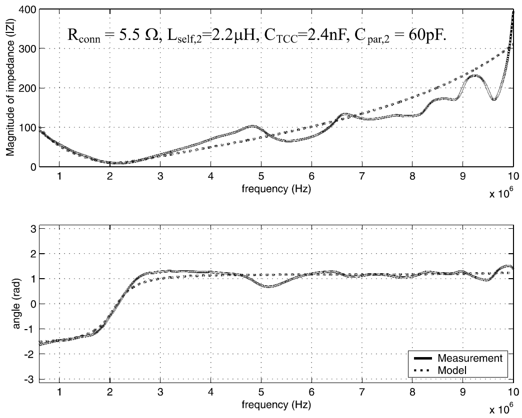

Fig. 6 - Segment 2, model and measurement results.

The results of the measurement and modelling of Segment 2 are given in Fig. 6. The transformer is short-circuited and not part of this segment. Measurement and model coincide up to a few MHz. Segment 2 is larger than Segment 1, and parasitic effects are more pronounced especially at higher frequencies. Model extension with additional components to account for these effects would make the model unnecessary complex and is not performed. Above 9 MHz the measurement becomes less accurate, again due to the low power of the injected signal.

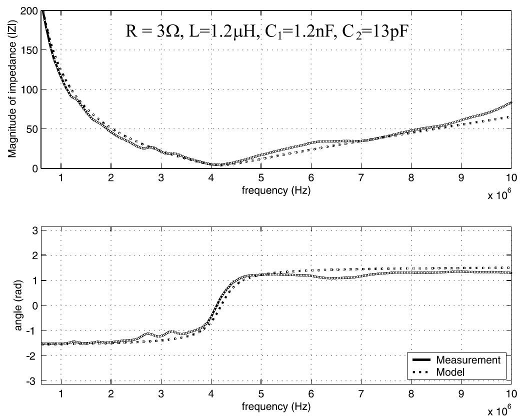

Fig. 7 - Transformer measurement and model.

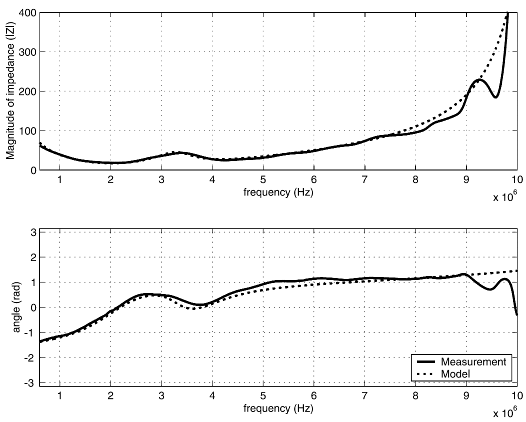

Fig. 8 - PLEC impedance; measured and modelled.

The transformer is analysed separately. In Fig. 3 the SP model for a transformer is given. The comparison between the measurement of the transformer impedance and the model of the transformer are presented in Fig. 7. These results are in agreement with earlier determined values [6].

Finally, the RMU was measured at PLEC and compared with the model of Fig. 2. The result, presented in Fig. 8, shows good agreement for frequencies up to 9 MHz.

5. Discussion and conclusions

An accurate lumped element model of an RMU can be derived in the range of 1 and 10 MHz. The magnitude of the lumped impedances can be traced back by analysis of the RMU. The model was verified with measurements, and generally good agreement was found. With this approach, other RMUs can be investigated and the model can be fitted to the results.

The presented model is valid for an RMU with one incoming cable. The model can be extended to RMUs with several incoming cables as long as the size of the RMU remains smaller than a quarter of a wavelength in the frequency range of interest.

In general, an MV grid is coupled to the transmission grid in a substation. The substation is constructed differently from an RMU. Generally, the switching equipment is shielded by a metal enclosure. The earth screen of the PILC cable is electrically connected to the enclosure, which makes impedance measurement hard. In addition, the size of a substation makes the lumped impedance approximation less applicable and transmission line effects may become notable. More research is needed to extend the model to large substations.

6. Reference

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