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USING FERRITE TO IMPROVE DIRECTIONAL SENSING FOR PULSE TRAVELLING IN MV POWER CABLES WITH TWO INDUCTIVE SENSORS

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Abstract: Inductive sensors are widely used for detection of high frequency signal, e.g. from partial discharge (PD) activity. A single inductive sensor, installed in a ring main unit (RMU) in a medium-voltage (MV) system, is not able to judge the direction of the signal origin. A method to determine its origin with two inductive sensors, proposed in earlier literature, employs a second sensor in the same RMU to determine signal propagation direction. This method can be extended for a recorded pattern, including reflections coming from both directions. This paper discusses a method to discriminate structures in a complete recorded pattern, originating from different sides. The method is tested on a 420m laboratory scale test set-up with two RMUs upon injected pulses. The main difficulty to extract the injected pulse from the recorded pattern, due to resonances caused by the RMU-components, could be relaxed by the use of ferrite material.

1 INTRODUCTION

A RMU in a MV system mainly consists of a MV to low-voltage (LV) transformer and connected MV cables. A single inductive sensor around one of the MV cables is not able to determine whether a PD pulse originates from the cable with the installed sensor or from any other connected cable. A number of methods have been proposed to design sensors suitable for directional sensing [1-2]. However, they often require special manipulated components. A method to determine the origin of a detected pulse with an additional inductive sensor was proposed in [3]. One sensor is clamped around the cable under test at its end in the RMU. The other sensor is installed around the cable that is connected to the MV/LV transformer, either around these (shielded) cables or around their earth connections.

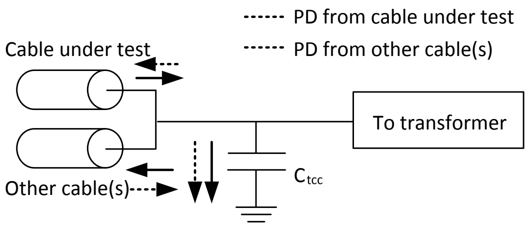


Figure 1: Illustration of PD propagation direction

In Figure 1 the cable which connects the transformer is depicted with its capacitance C_{tcc}. The relative polarity of the current along the cable under test and through C_{tcc} uniquely depends on the propagation direction. By utilizing this feature, a transfer function can be constructed which either keeps or removes a detected pulse from the recorded signal depending on its propagation direction.

The proposed transfer function method is not limited to a single pulse but can also be applied to a series of pulses having different arrival times. They form a pattern covering structures from multiple reflection points in a cable connection. Such a pattern arises in cable diagnostics, especially for online techniques where the cable is part of the grid. Pulses either from PDs, from external origin coupling to the cable, or deliberately injected to analyse the cable's characteristics, propagate in all available channels (in case of 3-phase cables). They reflect back to the sensor from all channels where the pulse experiences a change in impedance along the propagation path.

In the present work the interest concerns reflection patterns upon injected pulses to investigate the cable characteristics and changes over time e.g. due to degrading components. A recorded pattern in a power cable includes the original pulse and the reflections coming from both directions. Based on the proposed method in [3], this paper aims to improve the results by utilizing ferrite material to help get rid of reflections not originating from the cable under test. This proposed method is applied in a laboratory scale experiment on a 420m cable section: with 120m cable on one side and 300m on the other side of an RMU.

In section 2, this paper recapitulates the construction of filters to separate signal structures coming from either cable side. Practical implication is hampered by difficulties to extract the injected pulse from the complete pattern. Section 3 discusses the use of ferrite on appropriate locations in the RMU to reduce oscillations due to injection and to decrease the overlap with early reflections. Actual measurements with the test set-up are presented in Section 4.

2 THEORY REVIEW

In this section, the directional sensing filter for single pulse based on [3] will be reviewed.

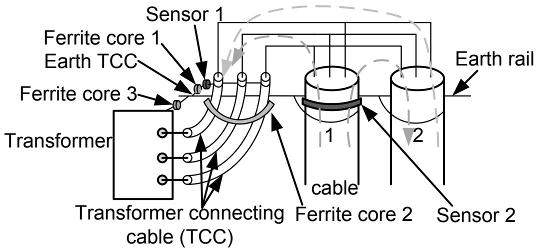


Figure 2: Illustration Schematic drawing of RMU with two sensors; sensor 2 can be at the cable under test being either cable 1 or 2; in this figure it is shown around cable 1

The schematic drawing of RMU with two sensors is shown in Figure 2 [3]. One sensor is located at the earth TCC while the other is around cable 1 (note that in order to record any signal, it must be placed at the cable end past any earth connection). Any pulse arriving at the RMU either from cable 1 or 2 will be detected by the two sensors. Calibration transfer functions are constructed for pulse from cable 1 and 2 separately [3].

$$H_1 = \frac{I_1}{I_{1tcc}}; \quad H_2 = \frac{I_2}{I_{2tcc}} \qquad (1)$$

where $I_{1(2)}$ is the pulse from cable 1(2) detected by sensor 2; $I_{1tcc(2tcc)}$ is the pulse from cable 1(2) detected by sensor 1, all transformed to frequency domain. This concept applies also for later equations. In order to retain the pulse from cable 1 and remove pulse from cable 2, a filter can be constructed as:

$$I_{1r} = H_{f1}(I - H_2 I_{tcc}) = \begin{cases} I_1 & if\ I = I_1\ and\ I_{tcc} = I_{1tcc} \\ 0 & if\ I = I_2\ and\ I_{tcc} = I_{2tcc} \end{cases} \qquad (2)$$
$$H_{f1} = \frac{H_1}{H_1 - H_2}$$

where H_{f1} is the correction transfer function; I is pulse from either cable 1 or cable 2; if I is I_1, I_{tcc} is I_{1tcc} and if I is I_2, I_{tcc} is I_{2tcc}; I_{1r} is the remaining signal after filtering. It can be seen from (2) that I_{1r} is zero for pulse from cable 2 and it is I_1 for pulse from cable 1. A similar procedure for keeping pulse from cable 2 while filtering pulse from cable 1 results in:

$$I_{2r} = H_{f2}(I - H_1 I_{tcc}) = \begin{cases} I_2 & if\ I = I_2\ and\ I_{tcc} = I_{2tcc} \\ 0 & if\ I = I_1\ and\ I_{tcc} = I_{1tcc} \end{cases} \qquad (3)$$
$$H_{f2} = \frac{H_2}{H_2 - H_1}$$

Thus by applying (2) and (3) it is possible to selectively filter a signal.

However, this technique not only applies to single pulses from a single direction. Because the system is linear it equally applies to a sum of multiple signals from multiple directions. When a pulse is injected locally at the RMU in Figure 2, as being applied in [4], the injected pulse will propagate along cable 1 and cable 2. The pulse will be reflected when there are impedance impurities like cable joints. The injected pulse, together with all reflections, will be recorded at sensor 1 and sensor 2, forming a reflection pattern. The directional sensing method described in section 2 for single pulse can also be applied to a complete reflection pattern. Assume that

$$I^P = \sum_{n=1}^{k} I_{1n} + \sum_{n=1}^{l} I_{2n}$$
$$I^P{}_{tcc} = \sum_{n=1}^{k} I_{1ntcc} + \sum_{n=1}^{l} I_{2ntcc} \qquad (4)$$

where I^P is the reflection pattern recorded in sensor 2 and $I^P{}_{tcc}$ is the reflection pattern in sensor 1; I_{1n} ($1 \le n \le k$) are the pulses in sensor 2 from cable 1 including the injection and reflections; I_{2n} ($1 \le n \le l$) are the pulses in sensor 2 from cable 2; $I_{1ntcc(2ntcc)}$ are the pulses in sensor 1 from cable 1 (2); k and l are used to indicate the reflection number.

Applying the direction sensing filters with (2) and (3) to the pattern in (4) gives:

$$I_{1nr} = H_{f1}(I^P - H_2 I^P{}_{tcc}) = \sum I_{1n}$$
$$I_{2nr} = H_{f2}(I^P - H_1 I^P{}_{tcc}) = \sum I_{2n} \qquad (5)$$

It can be seen from (5) that with the directional sensing method for a single pulse, the reflection pattern can be treated in such a way that also all reflections from one direction remain present while reflections from the other direction are removed.

3 PRACTICAL CONSIDERATION

Two calibration pulses are applied to obtain the transfer functions H_1 and H_2 needed for directional sensing [3]. Resonance can be caused by transformer and its connection. Ferrite cores can be used to damp the resonance. This section discusses practical considerations for the calibrations.

3.1 Resonance

A lumped component model was proposed in [5] for partial discharge propagation in RMU, which is shown in Figure 3. L_c is the inductance of the loop from connected component (either cable or transformer) to bus bar; L_{bb} is the inductance of the loop between bus bar and earth; capacitance C_{tr}, inductance L_{tr} and resistance R_{tr} are used to model the transformer while C_{tcc} L_{tcc} R_{tcc} are used to model the transformer connecting cable (TCC). $Z_{c,1}$ and $Z_{c,2}$ are the characteristic impedances of two connected cables. When a pulse is injected in the RMU, transformer and TCC with their connections to the busbar will cause resonances that disturb the injected signal because of the involved inductances and capacitances. Measurements in [5] show that the resonance frequency range starts from 1-2 MHz. For studying PDs in MV cable connections, frequencies exceeding 10 MHz usually are of minor importance due to strong signal attenuation. The resonances will extend the duration of the injected pulse and it may merge with the reflections shortly thereafter. The resonances make it hard to select the injected and reflected pulses that are needed for calibration of the transfer function.

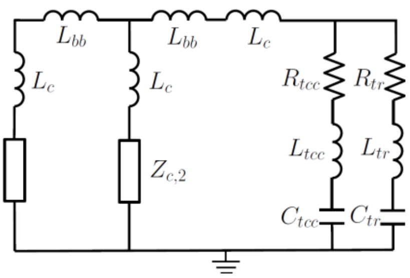


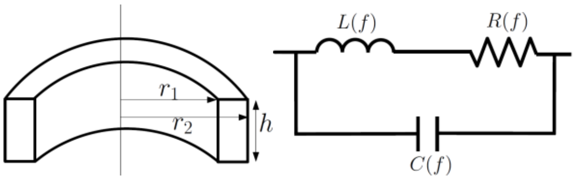
Figure 3: Lumped components model for RMU

3.2 Ferrite cores

A ferrite core adds impedance to the applied circuit to damp the resonance(s). Several factors are considered for the ferrite application including location, dimension and impedance.

Ferrite location: Since resonance is mainly caused by the transformer and the TCC, ferrite impedance insertion should be added in these branches. To add more impedance to the TCC circuit, ferrite can be place around the earth wire of the TCC, as the indicated ferrite core 1 in Figure 2. The use of ferrite around each individual phase of the TCC is not an option due to core saturation by the power frequency phase current. For the transformer circuit, possible locations are around the three TCC's together (indicated as ferrite core 2) or around the earth wire of transformer (indicated as ferrite core 3) in Figure 2. However in practice, it is inconvenient to access the earth wire of the transformer. Thus, for the transformer, the ferrite core is clamped around the three TCCs together.

Ferrite dimension: Ferrite's dimensions are limited by lack of space, RMU configuration and the sizes available in market. Ferrite core 1 with dimension 74/39/13 mm ($r_2/r_1/h$) and ferrite core 2 with dimension 140/106/25 mm ($r_2/r_1/h$) are chosen which corresponds to the positions indicated in Figure 2, where r_1, r_2 and h are indicated in Figure 4(a).



(a) (b)

Figure 4: (a) Dimension of ferrite core; (b) Equivalent lumped-element circuit for a ferrite core

Ferrite impedance: A ferrite core can be modelled by a lumped-element circuit [6]. The impedance is dependent on the complex permeability. The *RLC* parameters correlate with the geometry and material parameters of the ferrite core and the geometry of the cable structure around which the ferrite is clamped. The *R*, *L*, and *C* parameters are frequency dependent due to the frequency dispersion of the ferrite [6]. To reduce the resonance effect of a RMU, ferrite can be used to add extra impedance to the circuit in the frequency range from 1 MHz to 10 MHz. For this, resistive impedance is the main design criterion rather than inductance and capacitance. Resistance can damp the resonance, while inductance and capacitance mainly change the resonance frequency. Suitable material is chosen and a reference impedance measurement was performed. The measurement circuit is shown in Figure 5. The circuit impedance was measured by a network analyzer and the impedance difference with and without ferrite core is taken as the reference impedance of the ferrite core.

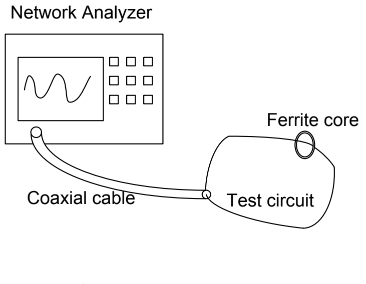


Figure 5: Reference impedance measurement circuit for ferrite core

The impedance from 300 kHz up to 10 MHz is shown in Figure 6. The resistance reaches 52 Ω for core 1 (74/39/13) around 0.9 MHz and 34 Ω for core 2 (140/106/25) around 0.7 MHz. They drop to a few Ohm above 2 MHz. The imaginary parts of the impedance are mainly inductive below 1 MHz and they become capacitive above it. It can be expected that with the insertion of the ferrite core in the RMU, the resonance caused by transformer and TCC will change. It should be noted that the impedance observed in Figure 6 is not exactly the same as the impedance addition to be expected when the ferrite is applied in a RMU since the test circuit is not identical to a particular RMU circuit.

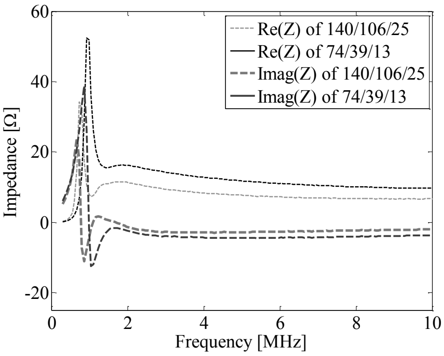


Figure 6: Measured reference impedance of ferrite cores

3.3 Ferrite core in RMU

A full scale test set-up is designed and constructed with typical Dutch RMUs and MV cables at the DNV KEMA premises in Arnhem, the Netherlands. The ferrite cores (74/39/13 and 140/106/25) are applied in the RMU with a 380 V/10 kV 1000 kVA transformer and two MV cables. Ferrite 1 (74/39/13) is applied around the earth wire of the TCCs and Ferrite 2 (140/106/25) is clamped around the three TCCs as shown in Figure 2. A pulse signal is injected at the position of sensor 2 and sensor 2 is used to record the signal. The effect of the two ferrite cores to the resonance is shown in Figure 7. It can be observed that ferrite 1, around the earth wire of the TCCs reduces the resonance more than ferrite 2. The FFT of the patterns are shown in Figure 8. Ferrite 1 blocks more components around 4 MHz than the ferrite 2 around the TCCs, while the ferrite 2 reduces the signal around 2 MHz. This observation matches the two resonance frequencies caused by transformer and TCC separately [5]. Note that the pulse around 1.2 µs (indicated with dashed block) is the reflection from the cable impedance impurity which will be explained later.

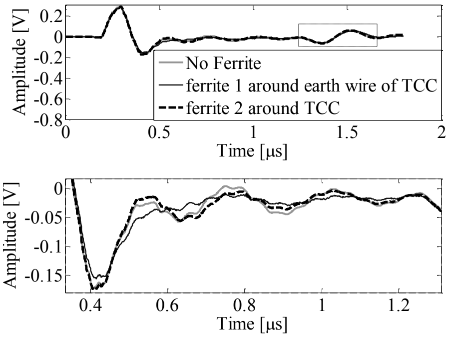


Figure 7: Effect of ferrite to block resonance in time domain; the bottom figure zooms in over a limited duration where the main effect by ferrites can be observed.

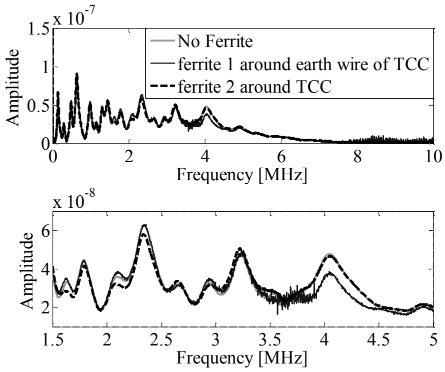


Figure 8: Ferrite effect to block resonance in frequency domain; bottom figure zooms in on a limited frequency range

4 DIRECTIONAL SENSING MEASUREMENTS

4.1 Test circuit

A 420 m long laboratory scale test circuit with the RMU in 0, MV cables and joints is used for testing the proposed directional sensing principle. The circuit is shown in Figure 9. Pulse signal and detection is performed in the RMU1 at the transformer side.

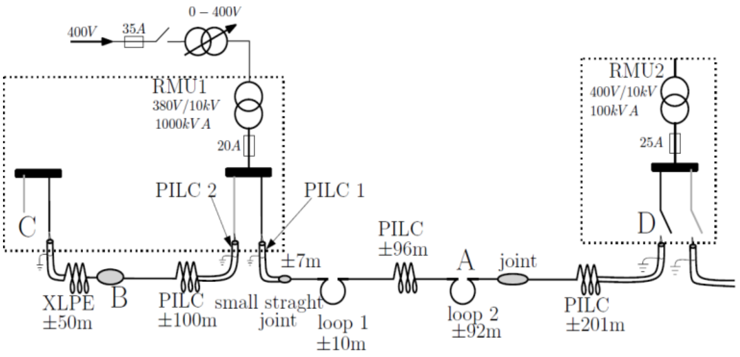


Figure 9: Test circuit for directional sensing experiments

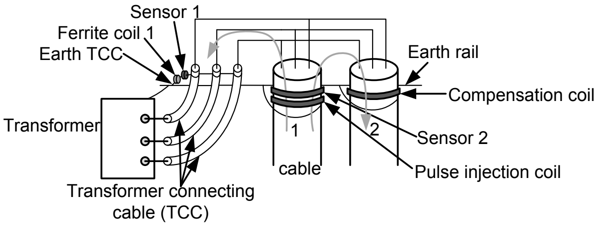


Figure 10: Test configuration for pulse injected in cable 1 at the transformer side in RMU1

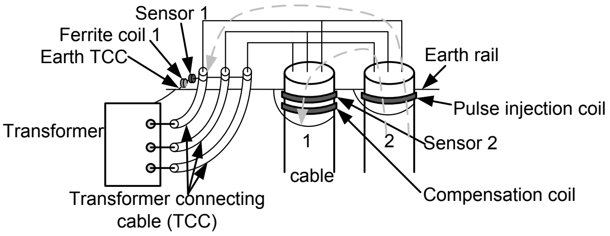


Figure 11: Test configuration for pulse injected in cable 2 at the transformer side in RMU1

The signals from different directions are arranged by placing the injection probe at two different places. The test for signal from cable 1 is done as shown in Figure 10. The test for signal from cable 2 is done as in Figure 11. The ferrite core is only used in the earth wires of the TCCs (ferrite 1) since it has better resonance damping effect for the signal recorded in sensor 2 and it can also reduce the resonance phenomenon for the TCC circuit recorded in sensor 1. Note that a compensation probe is used to keep the two circuits identical to each other, since the injection core also adds impedance to the circuit.

4.2 Ferrite effect

Pulse injection is performed both at cable 1 and cable 2. Injection and reflections are recorded for both sensor 1 and sensor 2. For the signal injected at cable 1, the result is shown in Figure 12 and for the signal injected at cable 2, it is shown in Figure 13. The clear reflection around 2.3 *μs* is from point A in Figure 9. Signals preceding this point are mainly determined by the oscillation following the injection. It can be observed that the ferrite core can clearly damp the resonance, especially for the signal recorded with the sensor 1. The damping of resonance facilitates selection of pulses used for transfer function calculation.

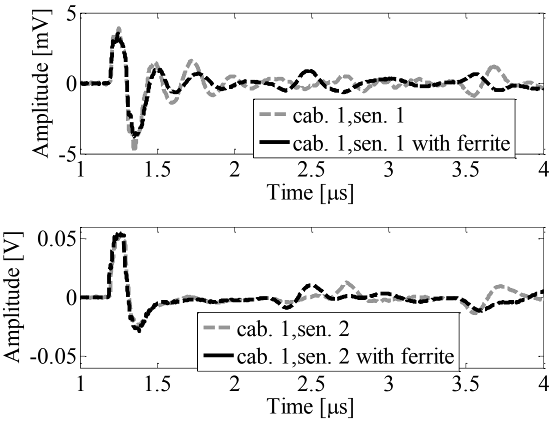


Figure 12: Patterns recoded with both sensor 1 and sensor 2 for pulse from cable 1

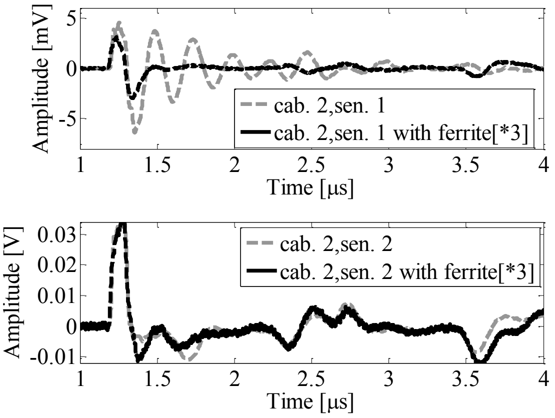


Figure 13: Patterns recoded in both sensor 1 and sensor 2 for pulse from cable 2, [*3] means signal recorded with ferrite is enlarged for 3 times

4.3 Filter for directional sensing

In order to get the transfer functions in (1), (2) and (3), injected pulses need to be selected from the patterns recorded as shown in Figure 12 and Figure 13. The resonance hampers the pulse selection. With the help of a ferrite core, it is possible to select the suitable duration of the signal for transfer function derivation. The pulse selection is shown in Figure 14. The area indicated with the dashed block is used for transfer function calculation. The selection excludes the reflection from point A in Figure 9. Though there are reflections prior to A, those reflections are damped by the ferrite core and they hardly affect the transfer function derivation. The directional sensing result with the derived transfer functions is shown in Figure 15. Points A, B, C, D are the clear reflection points corresponding to the positions indicated in Figure 9. It can be seen that A and D are almost fully reflections from the right side of RMU while B and C are reflections from the left side. In the top figure of Figure 15, the reflection A and D are eliminated from the pattern while B and

C remain after the filtering. It means that only the reflections from left side of RMU are present in the pattern. In the bottom figure in Figure 15, contrary to the top figure, reflection B and C disappear almost fully in the pattern, while A and D remain. This means that only the reflections from the right side of the RMU are detected. Directional sensing is thus achieved by this filtering technique and now further enabled with the help of ferrite material. It should be noted that due to the effect of ferrite, the reflections prior to point A, such as the 7 m straight joint and the 10 m loop 1 on the right side of RMU, are damped and they are selected as part of the transfer function calculation. Thus it is not possible to distinguish these reflection points. Furthermore, if one reflection is overlapping from two directions, it cannot be filtered out completely by this approach, such as the reflection around 6.6 μs in Figure 15.

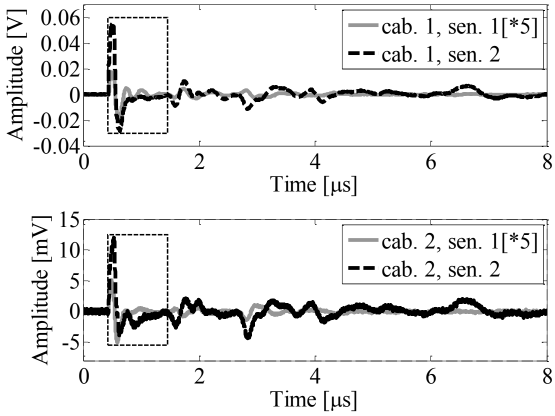


Figure 14: Selection of injected pulse from complete record for transfer function derivation

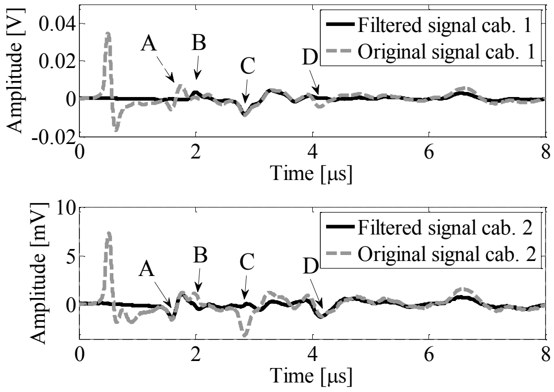


Figure 15: Directional sensing result; points A, B, C and D refer to reflection locations in Figure 9

5 CONCLUSION

A method for directional sensing with the help of ferrite core is presented. It is shown that with the suitable choice of ferrite material and applying it on the correct location, the resonances caused by transformer and TCC can be suppressed. This method can therefore enable pulse selection to calculate the required transfer functions. With the derived transfer functions, the pulse injection and reflections from one cable direction can be discriminated.

6 ACKNOWLEDGMENTS

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