Core asymmetry influence on transmission line parameters of three-core power cables

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Abstract  
Time-domain reflectometry applied for power cable diagnostics employs transmission line parameters to determine signal shape and delay. This paper proposes to utilize pulse reflection measurement to evaluate the symmetry of a three-core power cable as part of production quality assessment. For a rotation-symmetric three-core power cable, transmission line parameters can be obtained analytically, and with modal analysis propagation channels can be decoupled. Asymmetry caused by inaccurate core positioning complicates the decoupling process. This paper utilizes the “field-circuit” approach for the analysis. The finite element method is used to obtain the electromagnetic field distribution for two types of asymmetry introduced in a cable design. Modal analysis results are validated by considering asymmetry as a perturbation of the symmetric cable design. The influence of asymmetry on the time-domain pulse response is simulated. Deviation from a symmetric configuration is observable, in particular in terms of propagation velocity, which can be employed to assess cable manufacturing accuracy.

INTRODUCTION

Transmission line analysis is essential to interpret wave propagation along power cables, for example arising from transient overvoltage and partial discharge events [1, 2]. Transmission line modelling is employed for interpretation of time domain reflectometry (TDR) measurement, where the time delay and amplitude of the reflected pulse is used for example fault location, water ingress detection [3, 4]. For three-core power cables, asymmetry in the position of the cores affects the transmission line parameters, resulting in pulse response distortion. As the core symmetry is a key parameter for quality control of three-core cable manufacture and there is need for a method to check the cable symmetry after sample production, it is proposed to utilize TDR as a non-destructive evaluation method. For this purpose, the sensitivity of transmission line parameters to asymmetry needs to be investigated.

An analytical approach was established for symmetric cables to calculate the per-unit-length series impedance and shunt capacitance in [5, 6]. The method has been developed by later researchers in different aspects, for example incorporating semi-conductive layer [7, 8] and improving the ground return impedance calculation [9, 10]. In [11], Patel pointed out that formulas based on [5] and [6] include skin effect but neglect proximity effect, which underestimates cable losses at the operating frequency and affects the transient waveforms for closely packed cables. The method of moments with surface admittance operator (MoM-SO) approach was proposed to overcome the limitations [12, 13]. The referred analyses dealt with cables having rotation symmetric geometry, while asymmetry is not considered.

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Numerical methods are used to handle a complex or asymmetric cable structure. The finite-element method (FEM) is able to take into account an uneven current distribution over conductor areas and to handle non-coaxial electric field distributions [14]. Yin implemented FEM to calculate frequency dependent impedance for power cables up to 1 MHz [15]. Salles calculated the terminal voltage of umbilical cable in the frequency range of 30–80 Hz with FEM [16]. Gustavsen used FEM to derive electrical parameters of umbilical cables up to 100 kHz [17]. Patel used FEM as reference to evaluate MoM-SO method [12]. Since FEM has the advantage to treat cables with irregular shapes, it will be adopted to obtain transmission line parameters of asymmetric three-core power cables in this paper.

Modal analysis is used to interpret the propagation characteristics of high frequency signals within symmetric cables. A symmetric three-core power cable with common earth screen has one shield-to-phase (SP) propagation mode and two identical phase-to-phase (PP) modes. Each mode has its own characteristic impedance and propagation coefficient. These parameters can be verified by pulse response measurement [18].

Symmetric multi-core cables have degenerate modes, which become nondegenerate in the presence of asymmetry. Modes with originally equal propagation velocities will become distinct, which can be observed as different delays in pulse reflection measurements. The present work validates the modal analysis with perturbation theory for two asymmetric cable geometries. The analyses are performed up to 10 MHz, which includes the relevant frequency components for power cable diagnostics [19].

This paper is organized as follows. Section 2 describes the symmetric three-core cable and briefly reviews the transmission line analysis in frequency domain. Section 3 gives the result of SP and PP mode transmission line parameters for the symmetric cable by means of FEM and modal analysis. This method is validated with perturbation theory in Section 4 and the core asymmetry influence on the reflectometry is discussed for two given asymmetric cables. Discussion and conclusions are provided in Sections 5 and 6.

2 THREE-CORE CABLE AND TRANSMISSION LINE THEORY

Three-core cables of different designs are widely used in medium voltage system [20]. An example examined for this paper is a 10 kV cross-linked polyethylene (XLPE) cable with a single metallic earth screen around the assembly. The cable cross-section is shown in Figure 1. The cable dimensions and typical material properties are summarized in Table 1 [21].

The common earth screen serves as the reference conductor for the multi-conductor transmission line analysis [22]. The voltage \( V \) and current \( I \) waves along the conductors at position \( z \) are calculated from the telegraph equations in frequency domain [1]:

\[
\frac{\partial V(z)}{\partial z} = -ZI(z)
\]

\[
\frac{\partial I(z)}{\partial z} = -YV(z)
\]

(1)

\( V \) and \( I \) are defined as

\[
V = (V_1, V_2, V_3)^T
\]

\[
I = (I_1, I_2, I_3)^T
\]

(2)

where \( V_i \) is the voltage on conductor \( i \) with respect to the earth.
Impedance for SP and PP mode

PULSE RESPONSE MEASUREMENT SETUP

The setup for pulse injection measurement is shown in Figure 2. A pulse (115 ns duration and 3 V amplitude) is injected by means of a signal generator with the oscilloscope connected via a short cable (less than 50 cm) and a T connector, as shown in Figure 2. In this way, the 1 MΩ oscilloscope impedance can be regarded as “open” in parallel to the 50 Ω generator input and distortion from reflections between them are negligible for frequencies below 10 MHz. The injection pulse parameters are chosen such as to have sufficient signal energy, but at the same time the pulse duration should be short enough to prevent overlap with reflections. Therefore, the optimal pulse parameters depend on the signal transit time and signal attenuation for the cable under test. Signals are recorded with a 12 bit, 60 MS/s digitizer (Spectrum ML3033). To increase the signal-to-noise ratio each measurement is averaged 1000 times. The injected signal reflects at the adaptor between the 50 Ω coaxial cable (50 m long) and the power cable under test. Later reflections arise at the far end of the power cable. Part of the signal transmits into the measurement cable and is recorded, and part of it reflects back into the power cable. Therefore, multiple reflections arise in the measurements. The exact reflection pattern depends on the excited modes upon signal injection. For the simulated waveforms, the injected pulse is first converted to frequency domain. Next, its transfer is determined based on the measurement configuration of Figure 2 and the propagation characteristics of the cable from the FEM analysis. Then, the signal arriving back at the oscilloscope is restored by means of the inverse Fourier transform. More details can be found in [18].

4 | TRANSMISSION LINE PARAMETERS DERIVATION WITH FEM

This section summarizes the FEM approach applied to calculate the impedance and admittance matrices. The SP and PP mode parameters are derived for the symmetric three-core power cable described in Section 2 and the obtained transmission line parameters are compared with measurement.

4.1 | Impedance for SP and PP mode

The per-unit-length voltage drop along a set of parallel conductors depends on the specific current excitation. The series impedance can be derived from the voltage induced by the current. The electric circuit is coupled with FEM analysis to provide the currents. As shown in Figure 3(a), the current is injected into the three cores of the cable. The voltage response is determined by the SP mode impedance. Similarly, when the current is admitted between two cores as in Figure 3(b), the circuit voltage depends on the PP mode impedance. It should be noted that
for direct measurement of the PP mode, a symmetric (double) output function generator would be needed.

The equation governing the 2-D domain problem is [17, 23]

\[ \nabla \cdot \left( \frac{1}{\mu} \nabla A \right) - j \omega \sigma A + j_s = 0 \]  

(5)

where \( \mu \) is the permeability, \( \sigma \) is the conductivity of the medium, \( \omega \) is the angular frequency, \( j_s \) is the current density and \( A \) is the axial component of the magnetic vector potential \( A \), which is defined by (\( B \) is the magnetic flux density):

\[ B = \nabla \times A \]  

(6)

Solving Equation (5) leads to a system of linear algebraic equations with its size determined by the number of nodes in the discretization mesh. COMSOL Multiphysics [24] is used to implement FEM over the specified frequency range. Since the cable under study has a symmetric geometry, one SP mode impedance \( Z_{\text{sp}} \) and one PP mode impedance \( Z_{\text{pp}} \) are derived at each specified frequency.

### 4.2 Admittance for SP and PP mode

To obtain the SP mode admittance, a voltage source is applied between three cores of the cable and earth screen in Figure 4(a). The current from the energized conductor to the earth screen is determined by the SP mode admittance. The PP mode admittance determines the current through two cores while voltage is on the conductors, as in Figure 4(b).

The values of self- and mutual-admittances (both per unit length) are obtained by numerical integration of Laplace equation of Equation (7) over all the nonconductive regions [25]:

\[ \nabla \cdot (\varepsilon E) = 0 \]  

(7)

where \( \varepsilon \) is the permittivity of the medium and \( E \) is the electric field strength. The capacitance is derived from electric field energy \( W' \) based on the field solution for the electric field strength distribution over the solution region calculated.

\[ W' = \frac{1}{2} C \int V'^2 = \frac{1}{2} \int \varepsilon |E|^2 dS \]  

(8)

### 4.3 Validation with measurement

Based on the cable geometry and material properties, the impedance and admittance matrices can be estimated analytically [26, 27]. Measured results for the attenuation, propagation velocity and characteristic impedance are compared with the calculated ones by analytical estimation and FEM, as shown in Figure 5. In general, the FEM result matches the measurement better than analytical estimation. The attenuation found with FEM is significantly closer compared with the analytical estimation, presumably because of the fact that the analytical estimation ignores the proximity effect [11]. The remaining
deviation in the attenuation may be caused by uncertainty in the material properties, in particular for the semiconductive layers which significantly contribute to the attenuation [28]. The discrepancies in propagation velocities are within 5%. For example (at 7 MHz), the SP FEM velocity is about 105 m/μs and the measured result is about 110 m/μs; the PP FEM velocity is about 135 m/μs and the measured result is 140 m/μs. The characteristic impedance between FEM and measured result is also within 5% for the PP mode: 36.9 and 35.8 Ω respectively. The SP impedance deviates about 8%: 7.9 Ω versus 7.3 Ω. The uncertainty in the cable material properties influences the modelled modal propagation characteristics. However, irrespective of the parameter values involved, for a perfect symmetric cable the responses upon injection should be exactly the same for any conductor. By probing and comparing the distortion of the responses (a relative change), one measures directly the deviation from symmetry.

Some material properties in Table 1 are typical values for similar cable designs. The uncertainty in semi-conductive layer thickness is in the order of 10% and the dielectric properties are not precisely known. Further, the imaginary part of permittivity for XLPE is assumed constant, but it may increase with frequency in the megahertz range [26]. The oscillation near 8 MHz in Figure 5 relates to the width of the injected signal (115 ns) in the pulse reflection measurements, which causes oscillations in its frequency spectrum. Beyond this frequency the signal is less accurate due to significant attenuation.

5 | CORE ASYMMETRY

Due to manufacturing tolerances, the intended three-fold core symmetry can be broken. Asymmetric geometry affects the transmission line parameters. The SP and PP modes as defined with Equation (4) are no longer the precise eigenmodes. In addition, the vector components of the eigenmodes may become orthogonal and normalized set of eigenvectors.

Asymmetry hampers interpretation in terms of simple modes, but for small asymmetry one can express the distorted mode in terms of the original ones by means of perturbation analysis.

Perturbation analysis is most conveniently applied to an orthogonal and normalized set of eigenvectors $x_{0,v}$ for the unperturbed matrix $K_0$. In addition, the corresponding
transformation matrices to modal voltages $\mathbf{T}_v$ and currents $\mathbf{T}_i$ become the same. The eigenvectors for either voltage or current can be represented by:

$$
\begin{align*}
\mathbf{x}_{0,1} &= \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & 1 & -1 \end{pmatrix}^T \\
\mathbf{x}_{0,2} &= \frac{1}{\sqrt{6}} \begin{pmatrix} 2 & -1 & -1 \end{pmatrix}^T \\
\mathbf{x}_{0,3} &= \frac{1}{\sqrt{3}} \begin{pmatrix} 1 & 1 & 1 \end{pmatrix}^T
\end{align*}
$$

The choice for $\mathbf{x}_{0,1}$ relates directly to the second PP mode in Equation (4), but $\mathbf{x}_{0,2}$ is a linear combination of the PP modes to ensure orthogonality. Vector $\mathbf{x}_{0,3}$ refers to the original (non-degenerate) SP mode.

Substituting the set of relations at the right in Equation (10) into the eigenvalue equation on the left, and equating the first order terms in $\delta$, results in:

$$
(\mathbf{K}_0 - \lambda_0) \delta \mathbf{x}_i = (\delta \mathbf{\lambda}_x - \delta \mathbf{K}) \left( c_{x,1} \mathbf{x}_{0,1} + c_{x,2} \mathbf{x}_{0,2} \right)
$$

Next, successively left multiply Equation (12) with the transposition of $\mathbf{x}_{0,1}$ and $\mathbf{x}_{0,2}$ to obtain (left hand side is zero because the eigenvectors are orthogonal):

$$
\begin{pmatrix}
\mathbf{x}_{0,1}^T & \mathbf{x}_{0,2}^T
\end{pmatrix}
\begin{pmatrix}
\delta \mathbf{K}_{x,1,1} & \delta \mathbf{K}_{x,1,2} \\
\delta \mathbf{K}_{x,2,1} & \delta \mathbf{K}_{x,2,2}
\end{pmatrix}
\begin{pmatrix}
c_{x,1} \\
c_{x,2}
\end{pmatrix} = \delta \mathbf{\lambda}_x
$$

The matrix elements of Equation (13) can be calculated from the difference of the product of simulated impedance and admittance matrices between asymmetric and symmetric case employing the known eigenvectors for the symmetric cable. The eigenvectors in Equation (13) provide the proper linear combinations of the unperturbed eigenvectors and the eigenvalues provide the (first order) correction of the eigenvalues from which the propagation velocity and attenuation correction can be calculated. Agreement with the actual modes is considered as an indication whether the original modes for the symmetric cable are a good approximation for interpretation of the asymmetric cable propagation channels.

### 5.2 Case I: rotated conductor

Conductor 1 including the surrounding semi-conductive layer is rotated over 5°. Employing the simulation procedure described in Section 3, the per-unit-length series impedance and shunt admittance are derived by means of FEM analysis applied on the cable geometry. Figure 7 depicts the signal attenuation and propagation velocity of the three modes for cable with a rotated conductor.

The sensitivity of the velocity separation is studied as function of the degree of asymmetry. Figure 8 shows the result for a rotation from -5° to +5° of one conductor. The solid lines are result from direct calculation. The dashed lines are the first order approximation from perturbation analysis. The horizontal dotted line serves as reference, indicating the value for the symmetric cable. In the frequency range of 100 kHz to 10 MHz the propagation velocity is rather constant. Therefore, a frequency of 1 MHz is taken as being representative, since frequencies exceeding 10 MHz attenuate strongly during propagation and frequencies beneath 100 kHz may be filtered out due to the response of high-frequency current transformers used to detect the signals.

It is observed, that one mode (red curve) experiences a significant shift whereas the other (blue curve) varies considerably less. A rotation of 5° results in about 3% difference in velocity. Its detectability is verified with simulation of the time-domain response on consecutive signal injections in the three phase conductors with respect to the earth screen, as shown in Figure 9. Figure 9(a) depicts an experimental result from [18] obtained by pulse injection measurements at a 350 m cable segment. The injected signal is indicated as $i'$. The peak near 2.2 μs is the reflection at the transition from measurement cable to the cable under study, labelled as $i''$. The encircled reflections labelled as
FIGURE 9 Time domain response for symmetric and asymmetric cable with rotated conductor 1; (a) pulse response measurement for symmetric cable; (b) pulse response simulation for asymmetric cable; (c) zoomed waveform of (b) around the arrival of the first reflection from the far end of the power cable ($v^2$)

$v^2$ are from the power cable far end, which is not terminated. Later reflections are shown inside the dashed rectangle. The measurement configuration is simulated for a cable with core asymmetry ($5^\circ$ rotation). The analysis is based on the frequency dependent cable characteristics simulated with FEM using the model parameters from Table 1. The simulated pulse response patterns upon injection in different phase conductors shown in Figure 9(b) are close to the measured result. The measured attenuation and dispersion is larger compared to the simulation, which is consistent with the results shown in Figure 5.

Due to slight differences in transmission line parameters upon asymmetry, the pulse responses obtained from the injections in the three cores are different. The second reflection $v^2$ is zoomed in Figure 9(c). The peak around 9.2 $\mu$s arises from the SP mode. The relative time delays between the original degenerate modes near 7.5 $\mu$s agree with the velocity separation shown in Figures 7 and 8. A pulse injected at core 1, however, does not show up as distinct peaks near 7.5 $\mu$s. This is because hardly any signal energy enters the differential mode $x_{0,1}$ between the adjacent phases of the phase where the signal is injected and recorded. For the other injection, due to the velocity difference, the original degenerate modes split into two partly overlapping reflection peaks, corresponding to modes 1 and 2.

5.3 Case II: displaced conductor

The centre of one core is shifted outward over a distance of 2 mm. Following the simulation procedure in Section 3, the series impedance and shunt admittance are derived. The transmission line parameters are compared in Figure 10. The green curves represent the SP mode, the blue and red curves the separated degenerate modes. The dashed lines are the first order approximation from perturbation analysis. The main effect is in the propagation velocity of one of the original degenerate modes, whereas the other remains relatively constant. The latter (blue curve) is the mode between the two conductors with fixed positions. As the reflection symmetry is maintained, the $x_{0,1}$ mode as defined in (11) is exact. The other mode (red curve) can be approximately associated with $x_{0,2}$ in (11).

For a frequency of 1 MHz the variation in propagation velocity is shown in Figure 11. The solid lines represent result from direct calculation. The dashed lines are the first order approximation from perturbation analysis. The horizontal dotted line serves as reference, indicating the value for the symmetric cable.
The conductor centre position is varied over a range between -2 and +2 mm. Also here, a clear difference emerges, which corresponds to the velocity difference in Figure 10. The deviations (3% maximum) of the first order perturbation approximation are related to the relatively large maximum displacement with respect to the insulation layer thickness (3.4 mm). The pulse response simulation is shown in Figure 12 for a power cable with 2 mm core displacement. The reflections from the cable far open end (encircled) show that they are significantly different between injection at core 1 (the displaced conductor) and injection at the other two cores. The zoomed in waveform in Figure 12(b) shows a single reflection around 7.7 μs for core 1 injection and two reflections for signal injections in conductors 2 and 3. An applied pulse to either conductor 2 or 3 with unit height, can be decomposed in terms of the modes defined in Equation (11). After propagation, these modes can be combined to find the phase voltages again. This ratio approximately agrees with the observed peak magnitudes resulting from the pulse reflection simulation, see Table 2. Since cores 2 and 3 are symmetric with respect to core 1, injection in core 1 does not excite the $a_{0,1}$ mode.

6 | DISCUSSION

The investigated rotation symmetry distortions involve a rotation and a displacement of one of the conductors. The analysed asymmetrical cases with their pulse injection locations and excited modes are summarized in Table 2. Their mode parameter differences lead to final reflection pattern variations.

Injecting a pulse signal between a single core and the earth screen leads to responses that depend on the selected conductors. More specifically, reflectometry when injecting at the conductor with modified position does not lead to a visible separation of the originally degenerate mode. However, reflectometry upon injecting in one of the others shows separation. From perturbation analysis, it can be decided whether the asymmetry can be considered small in the sense that the original symmetric modes can still be used as sufficient accurate representation of the real modes.

The deviation in signal delay and amplitude when injecting in the three cores separately is a measure for the core asymmetry. An improvement in sensitivity for detecting asymmetry can be obtained by evaluating the difference in signal responses upon the injections at different cores. The difference from injection at a displaced/rotated conductor and a correctly placed one would show up as a signal with two equal peaks having opposite polarities. If the delay in between would be small compared to the signal broadening from dispersion, resulting in overlapping peaks, a difference signal can still be recognized.

7 | CONCLUSION

The transmission line parameters of an asymmetric three-core power cables are extracted with FEM analysis. Two cases are analysed when introducing a small asymmetry in the configuration by displacing/rotating conductors over a small distance with respect to perfect rotational symmetry. It is validated by first order perturbation analysis that such asymmetry results in modifications of the signal propagation parameters, in particular concerning propagation velocities. These changes are observable in pulse reflection measurements. The sensitivity of propagation velocity to asymmetric core positioning can be employed to assess manufacturing deviations when producing symmetric cables. The method can be applied to buried cables, cables still on cable reels and even during cable production. The challenge for the online application is integration in the manufacturing process and pulse optimization for the TDR measurement.

The advantage of waveform analysis is that it cannot only assess the cable symmetry, but also able to evaluate the transmission line characteristics, which is crucial for high frequency phenomenon, e.g. partial discharge and overvoltage. The methodology proposed in this paper can be used to analyse

| TABLE 2 | Mode contribution for different asymmetrical geometry |
|---------|------------------------------------------------------|
| Unit pulse injection | Excited modes contribution |
| Core 1 | 2/3 mode 2 + 1/3 mode 3 |
| Core 2 | 1/2 mode 1 + 1/6 mode 2 + 1/3 mode 3 |
| Core 3 | 1/2 mode 1 + 1/6 mode 2 + 1/3 mode 3 |
other asymmetrical cable's transmission line characteristics as well with multiple modes, for example umbilical cables.

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