Frequency-dependent Multi-Conductor Transmission Line Model for Shielded Power Cables Considering Geometrical Dissymmetry

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In this paper, a broad-band frequency-dependent multi-conductor transmission line (MTL) model for multi-core shielded power cables considering geometrical dissymmetry is presented. The Finite Element Method (FEM) is employed to obtain the frequency-dependent per-unit-length (PUL) resistances and inductances and the self- and mutual-capacitances of the power cable. The stable high-order rational approximation for the frequency-dependent parameters is applied by using the Modified Vector Fitting Method (MVFM) and circuit synthesis theory is employed to compute the equivalent macro-circuit models. Meanwhile, the Fast Residue Perturbation Method (FRPM) and an optimization method are applied to accomplish their port and component passivity, respectively. The simulated frequency responses well agree with the results by using FEM.

***Index Terms*—Multi-conductor transmission line, shielded power cable, vector fitting, circuit synthesis theory.**

I. Introduction

THE ACCURACY of a power cable model is relevant to accurately quantify the conducted electromagnetic interference (EMI) (150 kHz~30 MHz) in speed drive systems. The studied power cable is used to drive a variable frequency permanent magnet synchronous motor of a high precision grinding machine. It is long enough to regard it as an electrically large structure compared to the minimum wavelength so that a distributed parameter model must be applied.

In [1] VFM is also used, but both the port passivity and the component passivity are not guaranteed. The circuit with an active port may bring an unstable network when it connects with passive loads. Besides, negative components may be introduced just using the VFM. Therefore, a stable and passive frequency-dependent MTL model for shielded cables is obtained in this paper by using MVFM, circuit synthesis theory, FRPM and an optimization method.

II. Model Description

A. Geometry of the Power Cable

The geometry and dimensions of the under study power cable are shown in Fig. 1 and Table I, respectively. The entire cable and the phase conductors are coated with PUR sheath and TPE mixture, respectively.

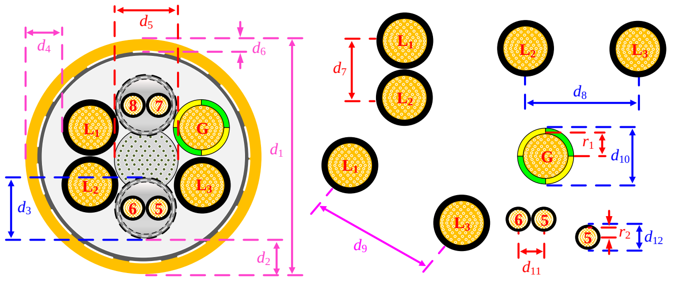

Fig. 1. Geometry of the power cable.

TABLE I
DIMENSIONS OF THE POWER CABLE

Item	Value	Unit	Item	Value	Unit
r_1	1.382	mm	d_6	1.60	mm
r_2	0.691	mm	d_7	4.60	mm
d_1	19.50	mm	d_8	8.00	mm
d_2	3.92	mm	d_9	9.23	mm
d_3	3.66	mm	d_{10}	4.56	mm
d_4	3.46	mm	d_{11}	1.68	mm
d_5	4.60	mm	d_{12}	1.58	mm

B. Model Description

One cell of the cable model is illustrated in Fig. 2. The PUL resistance $R_0(f)$ and inductance $L_0(f)$ depend on frequency are obtained by using FEM, considering skin- and proximity effect.

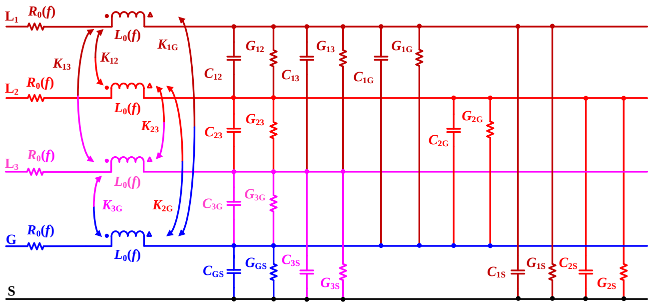

Fig. 2. Frequency-dependent MTL model for the shielded power cable.

C. Circuit Implementation of Frequency-dependent Parameter

The equivalent macrocircuit implementation procedure for the frequency-dependent $R_0(f)$ and $L_0(f)$ is illustrated in Fig. 3.

The Foster-type equivalent circuit can be obtained after the steps of applying MVFM, FRPM and optimization method.

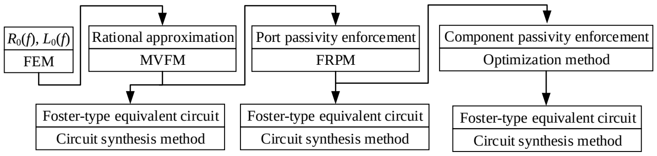

Fig. 3. Equivalent circuit implementation procedure for $R_0(f)$ and $L_0(f)$.

The frequency-dependent (100 kHz~40 MHz) $R_0(f)$ and $L_0(f)$ are computed by means of a FEM commercial software and are represented in Fig. 4 [2].

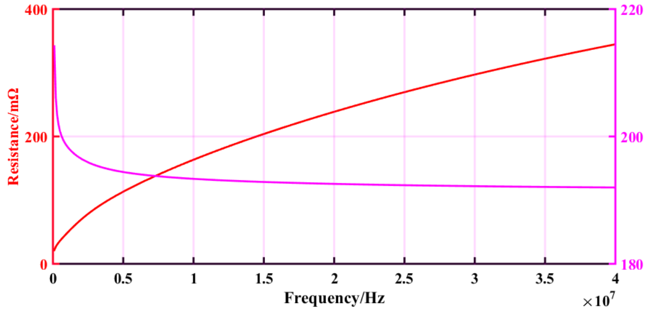

Fig. 4. Frequency-dependent $R_0(f)$ and $L_0(f)$.

In order to obtain the equivalent macro-circuit models for $R_0(f)$ and $L_0(f)$, the stable high order rational approximation for an admittance function $Y(s)$ by means of MVFM is applied [3]:

$$Y(s) \cong \sum_{p=1}^{P} \frac{c_p}{s-a_p} + d + sh. \tag{1}$$

where P is the number of real poles; a_p and c_p are the real poles and real residues, respectively; d and h are constant and proportional terms, respectively.

Noting that the poles in (1) are all real poles as the consequence of there are no resonance points both for $R_0(f)$ and $L_0(f)$ in the frequencies of interest.

Then, we apply FRPM to fulfil the port passivity of (1) considering the following requirements [4]:

$$d > 0, \quad h > 0, \quad eig(\operatorname{Re}\{Y(s)\}) > 0. \tag{2}$$

Finally, the equivalent macro-circuit is obtained by using the circuit synthesis theory, as presented in Fig. 5.

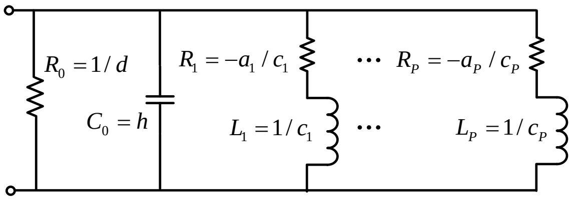

Fig. 5. Equivalent macro-circuit model for rational function in (1).

The component passivity is enforced with the help of the sequential quadratic programming optimization.

TABLE II

POLES AND RESIDUES FOR $R_0(f)$ BY USING MVFM, FRPM AND OPTIMIZATION

Pole (MVFM)	Residue (MVFM)	Residue (FRPM)	Residue (Optimization)
-1.0754×10^8	4.8951×10^8	4.7061×10^8	4.7061×10^8
-3.2448×10^7	-7.9348×10^7	-5.0372×10^7	0.9900
-7.4046×10^6	8.3735×10^7	5.3945×10^7	5.3945×10^7
-2.3716×10^6	-4.9582×10^7	-2.9875×10^7	0.9900

Table II presents the poles and residues for $R_0(f)$ at the stages of MVFM, FRPM and optimization method, respectively. The real parts of these poles indicate that the macro-model is stable. The port passivity for the macro-model based on the criterions presented in (2) is achieved. Thus, a stable network is guaranteed when the macro-model connectes with passive load.

The component values of the equivalent circuit model for $R_0(f)$ are shown in Table III. The optional fitting order is 4. Corresponding results for $L_0(f)$ will be given in the full paper.

TABLE III

PARAMETER VALUES FOR THE EQUIVALENT CIRCUIT OF $R_0(f)$

R_0 (Ω)	C_0 (F)	R_1 (Ω)	L_1 (H)
0.5045	9.0720×10^{-9}	0.2646	1.9844×10^{-9}
		2.7726×10^7	1.0101
		0.2610	3.0984×10^{-8}
		1.6587×10^6	1.0101

Fig. 6 shows the simulation results of the equivalent circuit of $R_0(f)$ compared with the FEM result.

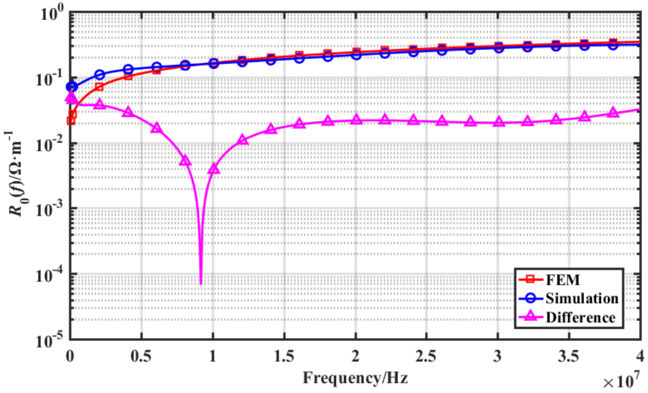

Fig. 6. Comparison of $R_0(f)$ for FEM and simulation.

In the full paper, the effect caused by the number of cells on the simulation accuracy will be discussed. Furthermore, the measured impedance according to the schematic in Fig. 7 will be compared with the simulation. Additionally, typical transient overvoltages wil be computed applying the proposed model.

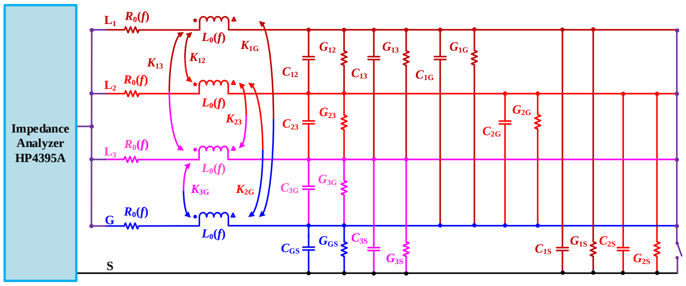

Fig. 7. Schematic diagram for the impedance measurement.

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