Modal Analysis of a Typical Power over Ethernet Configuration

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***Abstract*—In this work, a transmission-line model of a typical Power over Ethernet configuration, where data and power share the same transmission medium, is investigated by resorting to modal decomposition. It is shown that in the ideal case in which all circuit components behave ideally, data and power propagate through different paths without interference. The obtained modal circuits are then used as starting point to investigate the detrimental effects on signal transmission introduced by possible imbalance (i.e., asymmetry with respect to ground) affecting the involved circuit components.**

***Keywords*—Conducted Emissions, Modal Analysis, Power over Ethernet (PoE), Transmission Lines.**

I. INTRODUCTION

Power over Ethernet (PoE) is a technology that enables power transmission through data communication networks, i.e., twisted pair Ethernet cables. It was initially developed for Voice over Internet Protocol (VoIP) when the communication switched from classical copper wires to Local Area Network (LAN) Ethernet cables, and then standardized since 2003 by IEEE 802.3. During the years, both data rate and allowed power were increased, and several configurations were developed to meet different demands. The main advantages are in terms of reduction of space and costs thanks to the possibility to eliminate power supply wiring, as well as in terms of increased scalability and flexibility of network elements. Consequently, such a technology nowadays is applied in different frameworks spanning from Internet of Things, Building Automation, Industrial Lighting to the Automotive and Aerospace sectors [6].

Limiting our perspective to automotive applications, the common transmission medium (also considered in this work) is represented by Category 5 (CAT 5) cables, although a few of standards are still including Category 3 (CAT 3) cables and lower. It consists of eight conductors grouped into four twisted-wire pairs (TWPs), among which two are used for signal transmission in a typical communication scenario (with speed in the order of 10-100 Mbps). As far as network topology is concerned, the IEEE 802.3af standard and its successive versions defined two possible configurations, i.e., *Alternative A* and *Alternative B* [5], for PoE implementation [4]. In *Alternative A*, the power is transmitted in the cable conductors of two signal pairs by applying a common-mode voltage to each pair (see Fig. 1). This configuration does not interfere with the data transmission due to the Ethernet differential signaling, besides it effectively leaves two TWPs free. In the second configuration, i.e., *Alternative B*, power is transmitted through the two unused TWPs of the Ethernet cable.

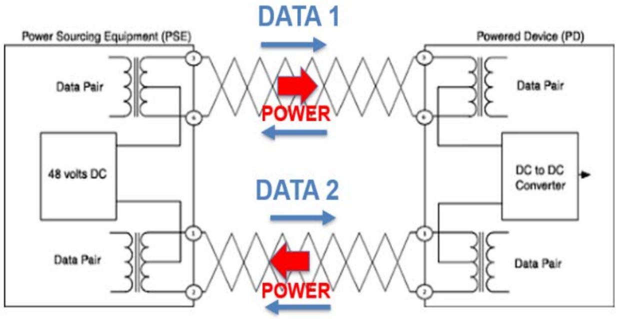

Fig. 1. Principle diagram of the *Alternative A* PoE transmission scheme.

Two types of PoE devices, i.e., the so-called Power Sourcing Equipment (PSE) and Powered Device (PD), are introduced by the IEEE 802.3af standard. As shown in Fig. 1, the *Alternative A* PoE topology includes a PSE on the left side, and PD(s) on the right side, and two TWPs as data and power transmission medium. The PSE is fed from the power supply (here a 48 V DC battery), and transmits the power through the signal TWPs. Both power and data are received by the PD through a RJ45 connector.

In this paper, *Alternative A* scheme is studied since it allows the use of less conductors and is more challenging. The aim is to study the electromagnetic compatibility (EMC) behavior of the chosen PoE configuration via circuit analysis, by introducing suitable modal transformations and deducing the pertinent modal circuits. The analysis will first encompass the study of this PoE topology in the theoretical case in which all circuit components behave ideally with the objective to outline the ideally-uncoupled paths for data and power propagation. Then, the detrimental effects introduced by non-ideal symmetries with respect to ground (imbalance) affecting system components are investigated, by resorting to circuit interpretation of imbalance in terms of controlled voltage sources coupling the modal circuits.

II. MODAL TRANSFORMATION & CIRCUIT CONFIGURATION

A. Description of the Structure under Analysis

As shown in Fig. 2, the studied configuration consists of four center-tapped transformers (baluns) to couple the transmitted power and communication signal with the TWPs. For each TWP, the first balun is connected at the output of the transmitting module, while the second one is connected at the input of the receiving module. In the source (left) end, a common voltage is provided by a 48-V DC battery connected between the center-taps of the two baluns. A CAT 5 cable interconnects the PSE and the PD, which contains a DC/DC converter that interfaces the load.

It is worth mentioning, that the configuration can be duplicated by using the other two TWPs not shown in Fig. 2. However, owing to the symmetry of the system architecture modelling just a pair of TWPs as shown in Fig. 2 is enough to understand and model the paths of propagation of signals and power on the PoE topology under analysis.

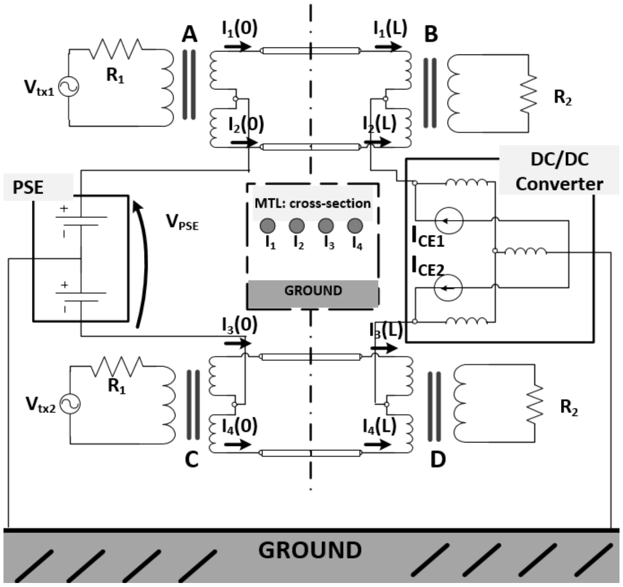

Fig. 2. Circuit diagram of the *Alternative A* PoE network topology, where only two of the four TWPs in the CAT 5 cable are represented.

B. Modal Transformation

For simulation of the network in Fig. 2, the two TWPs interconnecting the PSE and the PD are modelled as four-conductor transmission lines (TLs) running above ground (i.e., the car chassis). According to TL theory and modal analysis, for this structure four propagation modes can be defined as follows. First, since differential signaling is exploited for data transmission, two *transmission modes*, representative for the differential data paths between the two wires in each TWP, are introduced as:

$$v_{tx1} = v_1 - v_2 \qquad v_{tx2} = v_3 - v_4 \tag{1}$$

where subscripts 1, 2 denote the two wires in the upper TWP in Fig. 2, while 3, 4 identify the two wires in the bottom one. Since the power is transmitted through the center-taps of the four baluns, a *power mode* representative for the power transmission path from the DC source towards the DC-DC converter is introduced, as the difference between the common mode of the first pair and the common mode of the second pair as:

$$v_{pw} = \frac{v_1 + v_2}{2} - \frac{v_3 + v_4}{2} \tag{2}$$

Eventually, a *common mode* path accounting for the undesired current following through the ground plane is defined as:

$$v_{cm} = \frac{v_1 + v_2 + v_3 + v_4}{4} \tag{3}$$

It is worth noticing here that such a common mode should be theoretical null, since neither signals nor power should theoretically flow through this path as long as the structure under analysis behaves ideally. However, as it will be shown in the following, in practical realizations a non-null common mode current can flow through this path, giving rise to undesired effects, such as radiated emission.

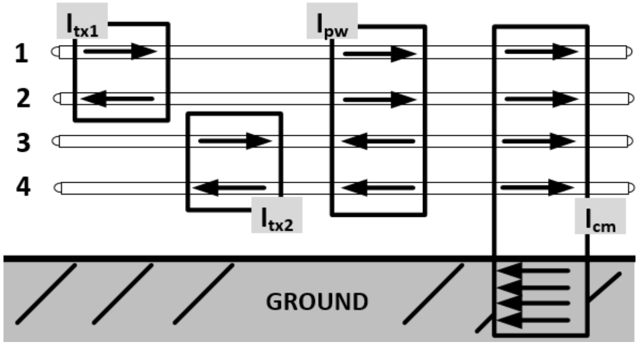

Fig. 3. Graphical representation of four modes over the studied PoE architecture.

In line with aforesaid mode definitions, the similarity transformation matrix **T**

$$\boldsymbol{T} = \begin{bmatrix} 1 & -1 & 0 & 0 \\ 0 & 0 & 1 & -1 \\ \frac{1}{2} & \frac{1}{2} & -\frac{1}{2} & -\frac{1}{2} \\ \frac{1}{4} & \frac{1}{4} & \frac{1}{4} & \frac{1}{4} \end{bmatrix}^{-1} \tag{4}$$

is introduced to transform the vector of physical voltages/currents $\boldsymbol{x}$ into the corresponding vector of modal voltages/currents $\boldsymbol{x}^M$ as $\boldsymbol{x}^M = \boldsymbol{T}^{-1}\boldsymbol{x}$, (where superscript M is used to denote modal quantities).

A graphical representation of such a mode definition is provided in Fig. 3, where the propagation paths of the corresponding modal currents are outlined.

Before applying the modal transformation to various circuit components, some simplifying hypotheses are made. Firstly, the p.u.l. inductance matrix of the MTL is supposed to exhibit the form:

$$\mathbf{L} = \begin{bmatrix} l & l_\mu & l_m & l_m \\ l_\mu & l & l_m & l_m \\ l_m & l_m & l & l_\mu \\ l_m & l_m & l_\mu & l \end{bmatrix} \tag{5}$$

where the peculiar matrix symmetry is a consequence of ideal wires twisting. Under the hypothesis of thick insulation [3], it is possible to prove that also the p.u.l. capacitance matrix exhibits similar symmetries.

By applying the modal transformation in (4) to the aforesaid p.u.l. matrices, the obtained modal inductance and capacitance matrices result to be diagonal. For instance, the modal p.u.l. inductance matrix takes the form:

$$\begin{aligned} \mathbf{L}^M &= \mathbf{T}^{-1}\mathbf{L}\mathbf{T} \\ &= \mathrm{diag}\left\{ l - l_\mu ; l - l_\mu ; l + l_\mu - 2l_m ; l + l_\mu + 2l_m \right\} \end{aligned} \tag{6}$$

This result indicates that the four modes previously introduced propagate separately along the wiring structure with characteristic impedance and propagation velocity for the *k*-th mode evaluated starting from the k-th diagonal elements of the inductance and capacitance modal matrices in (6) as:

$$Z_c^k = \sqrt{l^k / c^k}, \ k = 1, \ldots, 4 \tag{7}$$

$$v^k = \frac{1}{\sqrt{l_k c_k}} \ , \ k = 1, \ldots, 4 \tag{8}$$

Let us first consider the ideal scenario where all components are perfectly balanced with respect to ground, that is the center-tap of each balun transformer is perfectly centered, and the dc/dc converter structure is ideally symmetric, i.e., its passive part can be represented by an impedance matrix with the form [3]

$$Z_{dcdc} = \begin{bmatrix} z_{cn} & z_m \\ z_m & z_{cn} \end{bmatrix}. \tag{9}$$

Under these ideal conditions, it can be proven that the equivalent circuits associated with each of the above-introduced modes (see Fig. 4) are completely uncoupled. Hence, data and power propagate separately without the risk of interference even if they share the same transmission medium. Moreover, no common mode current in the external loop involving the ground plane is expected.

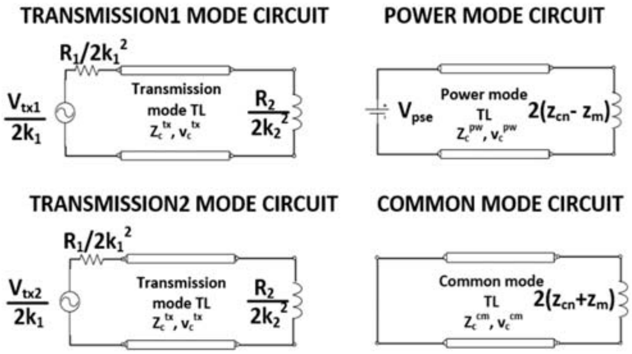

Fig. 4. Equivalent modal circuits under ideal conditions.

III. IMBALANCE MODELING

In practical implementations, the non-ideal behavior of the involved components compromises the assumption of perfect balancing, with consequent degradation of transmission properties. From the modelling viewpoint, such a lack of symmetry/balance with respect to ground reflects in the presence of non-null off-diagonal elements in the modal matrices, which couples the modal circuits [1]. Such undesired behavior may cause errors in signal transmission and be responsible for radiation and susceptibility issues. Hence, it has to be carefully accounted for by the designer in order to design proper countermeasures.

Among the possible reasons of imbalance, here the imperfect centering of the balun center-tap is modeled and analyzed [1]. For simplicity, only an unbalance affecting the balun transformer labelled as "balun *A"* in Fig. 2 is hereinafter considered, however the effect of multiple baluns unbalance can be readily superimposed owing to system linearity. To this end, a parameter δ is introduced to model the unbalance affecting the balun as

$$\delta = (N_{m1} - N_{m2})/N_2 \tag{10}$$

where N_{m1}, N_{m2}, N_2 represent the number of turns of the secondary winding as clarified in Fig. 5.

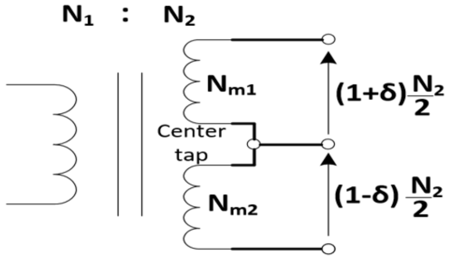

Fig. 5. Illustration of center-tap unbalance for balun transformer *A*.

By applying the modal transformation in (4), it is possible to highlight the effect of δ on modal voltages as:

$$\mathbf{V}^M(0)=\mathbf{V}_{\mathrm{id}}(0)^M+\delta\frac{V_{tx1}}{2k}\begin{bmatrix}0\\0\\1\\\frac{1}{2}\end{bmatrix}-\delta\frac{R_1}{8k^2}\begin{bmatrix}0&0&4&8\\0&0&0&0\\2&0&0&0\\1&0&0&0\end{bmatrix}\mathbf{I}(0)^M+\mathbf{o}\left(\delta^2\right)\tag{11}$$

where $v_{id}(0)^M$ denotes the vector of ideal modal voltages in the absence of unbalance and k is the transformer ratio.

As can be seen from (11), off-diagonal elements in the impedance matrix are responsible for undesired mutual coupling between modal circuits. This effect is included in the modal circuits by the use of controlled voltage sources, as shown in Fig 6. Note that the second *transmission mode 2* is still uncoupled, as long as the unbalance only affects the baluns belonging to the first TWP.

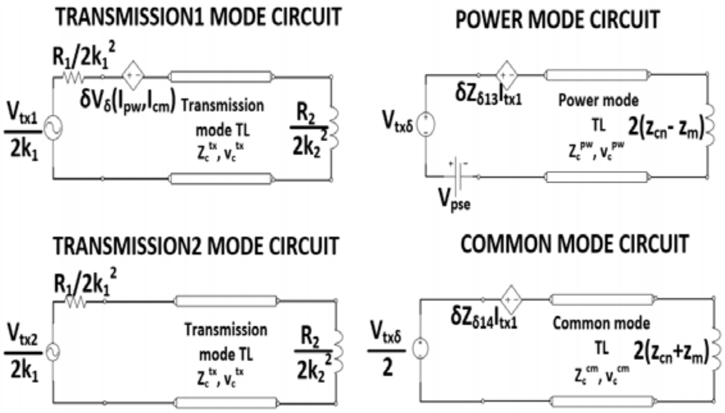

Fig. 6. Equivalent modal circuits under non-ideal conditions.

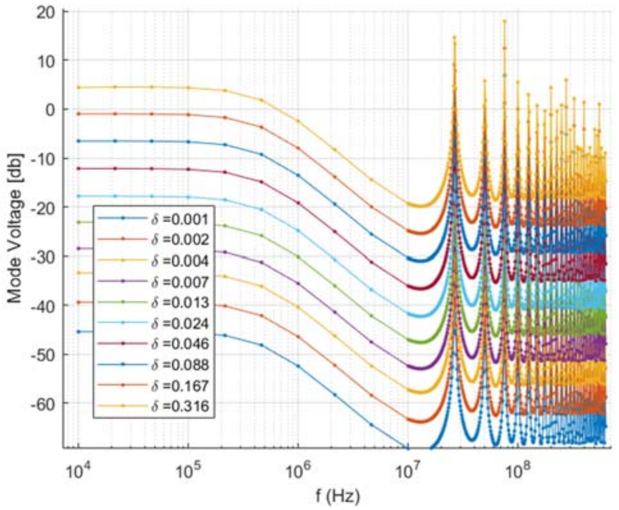

Fig. 6. Sensitivity to δ of the undesired voltage induced at the input of the first receiver (i.e., the receiver connected to the first TWP) by a (unitary) current flowing through the *power-mode* circuit.

The most critical effect of δ is to couple the *transmission modes* with the *common* and *power mode circuits*. As a matter of fact, this undesired coupling makes the transmission modes susceptible to the high-frequency noise generated by the DC-DC converter, thus posing possible issues in terms of integrity of the transmitted signal. Under ideal conditions, such a high-frequency noise is expected to propagate through the *power mode* path only, but in the presence of imbalance (i.e., in this case, for $\delta\neq 0$) the conducted emissions generated by the converter can also leak onto the data paths due to undesired mode conversion.

As an example, Fig 7 shows the sensitivity to δ of the undesired voltage induced at the input of the first receiver (i.e., the receiver connected to the first TWP) by a unitary-valued current flowing through the *power-mode* circuit. The plot highlights the detrimental effect played by undesired imbalances on the performance of the transmission system, which should be theoretically immune from interference from the power circuit under ideal conditions.

IV. CONCLUSION

In this paper, a suitable modal decomposition has been introduced and exploited to investigate data and power transmission paths on a typical PoE configuration, where two of the four TWPs in a CAT5 cable are exploited to simultaneously transmit signals and power. With the final objective to provide a useful tool for the designer, equivalent modal circuits are derived which allow to highlight the role that each of the involved circuit component plays on the signal and power paths. It is shown that under ideal conditions (i.e., in the absence of asymmetries with respect to ground), the four propagation paths are separate, hence no interference is expected between data and power. Moreover, no current is expected to flow through the common mode path (involving the ground plane), thus minimizing radiation and susceptibility to external fields. Eventually, the detrimental effects on signal transmission of asymmetries (i.e., imbalance) in the balun secondary windings were investigated, by introducing suitable (controlled) voltage sources into the modal circuits to represent undesired coupling resulting from mode conversion. Further investigations are currently on-going, including the development of a suitable test setup to experimentally validate the theoretical results and to improve the accuracy of components modelling.

REFERENCES

[1] T. Monopoli, “Analysis of a Typical PoE Configuration with Coupled Transmission Lines”, Master Thesis, Politecnico di Milano, 2020.

[2] G. Spadacini, F. Grassi, D. Bellan, S. A. Pignari, and F. Marliani, “Prediction of conducted emissions in satellite power buses,” *International Journal of Aerospace Engineering*, Vol. 2015, Article ID 601426, pp. 1-10.

[3] G. Spadacini, F. Grassi, F. Marliani and S. A. Pignari, "Transmission-Line Model for Field-to-Wire Coupling in Bundles of Twisted-Wire Pairs Above Ground," *IEEE Trans. Electromagn. Compat.*, vol. 56, no. 6, pp. 1682-1690, Dec. 2014.

[4] IEEE Standard for Information Technology 2012 — Local and metropolitan area networks — Speci_c requirements — Part 3: CSMA/CD Access Method and Physical Layer Specifications Amendment 3: Data Terminal Equipment (DTE) Power via the Media Dependent Interface (MDI) Enhancements". In: *IEEE Std 802.3at-2009* (Amendment to IEEE Std 802.3-2008) (2009), pp. 1.

[5] IEEE Standard for Ethernet Amendment 2: Physical Layer and Management Parameters for Power over Ethernet over 4 pairs, " in *IEEE Std 802.3bt-2018* (Amendment to IEEE Std 802.3-2018 as amended by IEEE Std 802.3cb-2018) , pp.1-291, 31 Jan. 2019

[6] K. Matheus and T. Königseder, *Automotive Ethernet*. Cambridge, U.K.: Cambridge Univ. Press, 2017.