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Multiport Converters for Fast Chargers of Electrical Vehicles -- Focus on High-Frequency Coaxial Transformers

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***Abstract*—A bi-directional multi-port converter can accommodate various energy storages and sources. Therefore, a multiport converter will be a good candidate for application as a future universal converter for (hybrid) electrical vehicles or local distribution systems. For the multiport converter proposed in this paper, the main design challenge is the design of its three-phase symmetrical transformer. In this converter, symmetry of the leakage inductances is essential to ensure balanced three-phase currents (transferred power). These currents are interconnected by three single-phase high-frequency link transformers. To realize the equality of the leakage inductances a specific transformer design is necessary. Since conventionally wound three-phase transformer core shapes suitable for high-frequency are expensive and difficult to build, a coaxially wound transformer will be designed in this paper.**

***Index Terms*-- Coaxial transformers, electrical vehicle, fast charger, multi-port.**

I. INTRODUCTION

As a possible alternative to internal combustion engine vehicles, research, development and investments on electric vehicles (EVs) is increasing and a few EVs can be found in the market nowadays. The power train in a full electric vehicle is mainly composed of an electric motor, a battery, and a converter to control the power flow between motor and battery and charge the battery.

The vehicle battery can be fast or slow charged [1]. If the battery is slow charged the converter to manage the power flow is inside the vehicle and it is usually called an EV on-board charger, where the vehicle can be direct charged from a utility grid. It can take between 6 to 8 hours to charge the battery. On the other hand, a fast charger can charge a vehicle battery in only 15 minutes. It is called EV off-board charger because the charger converter is outside of the vehicle. In this case, the vehicle battery is directly charged using direct voltage.

Fast chargers require high current in a short time and thus the converter which manages the power flow between grid and vehicle battery has to be able to control the power flow and supply high currents. However, most of the plugs, connectors and the utility grid itself are not designed to supply high current peaks. This means an extra power source for shaving peak power will be necessary. As an alternative, battery storage could be connected to the off-board charger and be used as an extra source. In the future grid network system the vehicle battery and the storage battery could be connected to the utility grid, becoming part of the system. These batteries will be used to store and supply energy when necessary, enhancing the performance of the utility grid.

A similar idea was proposed by [2] where a storage battery is used to supply extra power in a fast charger system network. In [2], only one stationary battery storage is connected to a dc bus in parallel with many off-board charger converters. Because the dc bus voltage is obtained by rectifying the grid voltage, bidirectional power flow is not possible. Thus the energy storage in the stationary battery cannot supply the grid, this being a drawback of such a configuration.

A converter to connect these three ports - the off-board charger, the grid and the battery storage - is proposed in this paper, as shown in Fig. 1.

The interconnection of the three-port converter as proposed is achieved through a high frequency transformer, which uses three separate windings as shown in Fig. 1. The main design challenge of the proposed high-power three-phase three-port converter is the realization of this transformer, where low and symmetric leakage inductances are essential to ensure balanced three-phase currents (transferred power).

Transformers that can provide low valued natural symmetric leakage are either conventionally or coaxially wound. Since conventionally wound high-frequency three-phase transformer core shapes are expensive and difficult to manufacture, a coaxially wound transformer is proposed and investigated in this paper.

To check the theoretical and simulation results, a simple one turn and two-winding coaxial transformer prototype was constructed. Two prototypes were made, one using a tube of 28.6 cm long and another using two tubes, each with a length of 14.3 cm. Both prototypes use toroidal ferrite cores, with a relative permeability (μ_{fe}) of 700.

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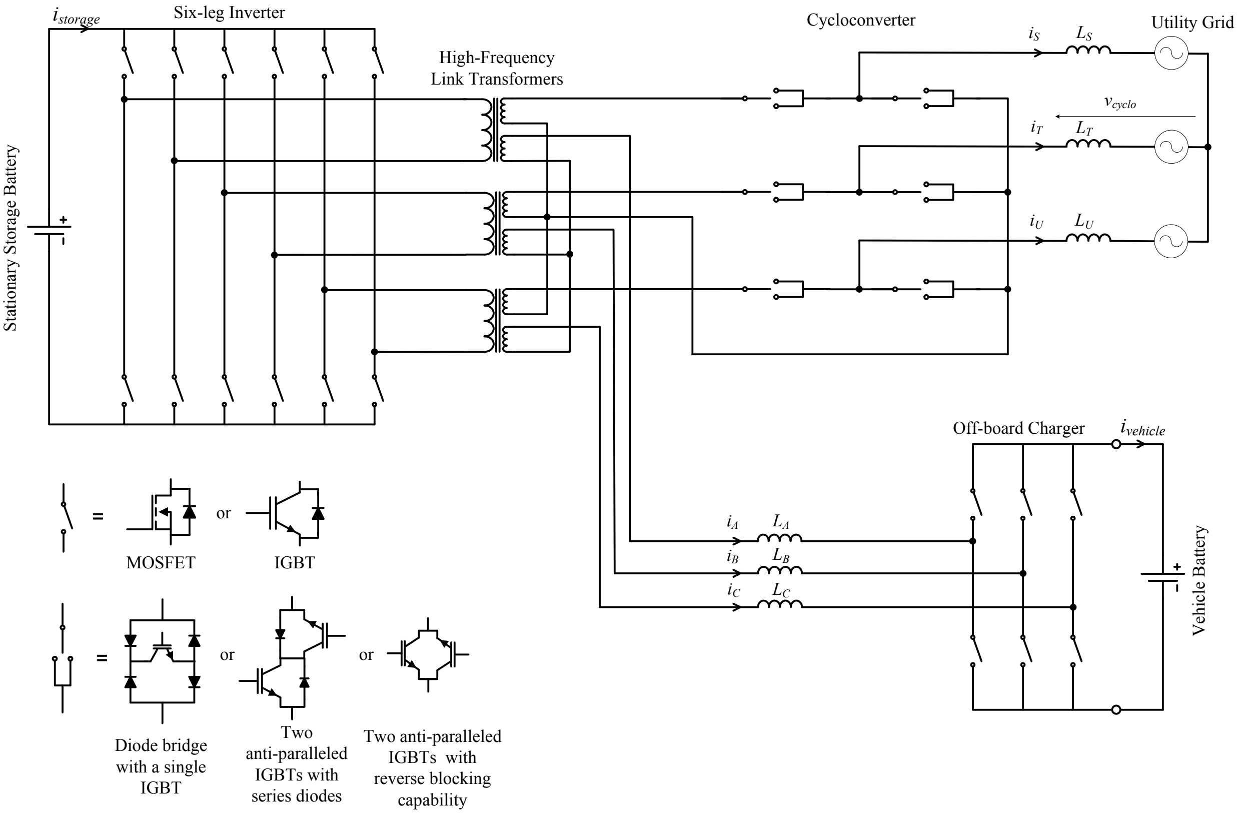


Fig. 1. Proposed bi-directional high-power three-phase three-port converter.

Results obtained from experimental measurements using an impedance analyzer were compared with theoretical and simulation results, showing good equivalence.

II. BI-DIRECTIONAL HIGH-POWER THREE-PHASE THREE-PORT CONVERTER PROPOSAL

The proposed converter is composed of three ports: the vehicle battery, the utility grid and the stationary storage battery.

The storage battery port is implemented with a six-leg inverter to have the possibility to use soft switching techniques between the stationary storage and off-board charger port without necessity of resonant circuits. Thus, it is possible to avoid extra passive components (inductors and capacitors) and also to increase the power delivered by this port. The method used to obtain soft switching is presented in [3]. The power flow through these two ports is controlled by means of the phase-shift between the two ports [4][5].

The port connected to the grid is implemented by a cycloconverter [6], due to the necessity of alternating current in this port. A cycloconverter was used to avoid using a back-to-back converter with its big bank of electrolytic capacitors and inductors. In the cycloconverter it is possible to use three different switch configurations - a diode bridge with a single IGBT, two anti-paralleled IGBTs with series diodes or two anti-paralleled IGBTs with reverse blocking capability - as represented in Fig. 1. The power flow between the storage and grid port is again obtained through phase-shift voltage between the ports.

In the topology of Fig. 1 all the ports are bi-directional, giving the possibility be use the vehicle or storage battery to supply the utility grid when it is necessary.

In Fig. 2 the current and voltage in the vehicle battery are presented for a power level of 40 kW and a switching frequency of 20 kHz. The bus voltage is 400V and the average current inject in the vehicle battery is 100A.

Fig. 3 shows the waveforms of the current drained from the grid using a phase shift of 5 degrees between the fundamental voltage in the output of the cicloconverter and the utility grid, again for a power level of 40kW.

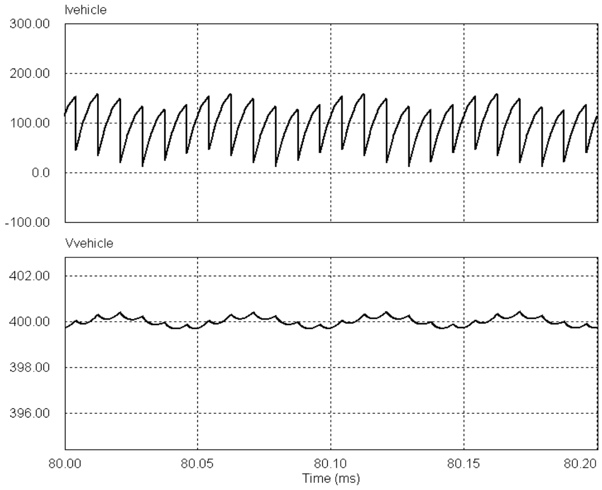


Fig. 2. Vehicle battery current and voltage for 40kW and 400V.

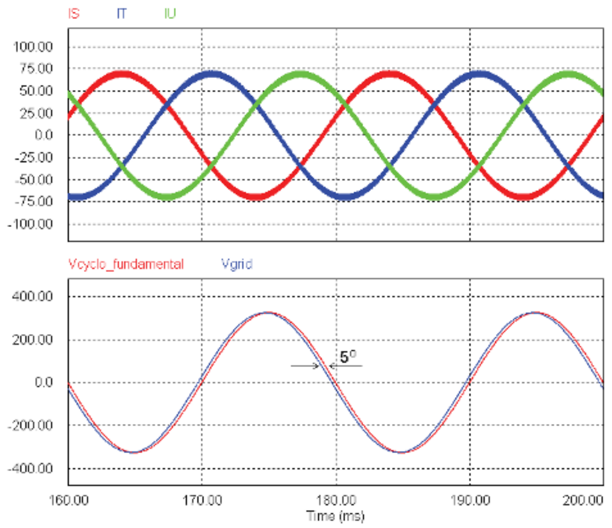


Fig. 3. Three-phase current drained from the grid when a phase shifted of 5 degree is applied between the fundamental voltage in the output of the cicloconverter and grid.

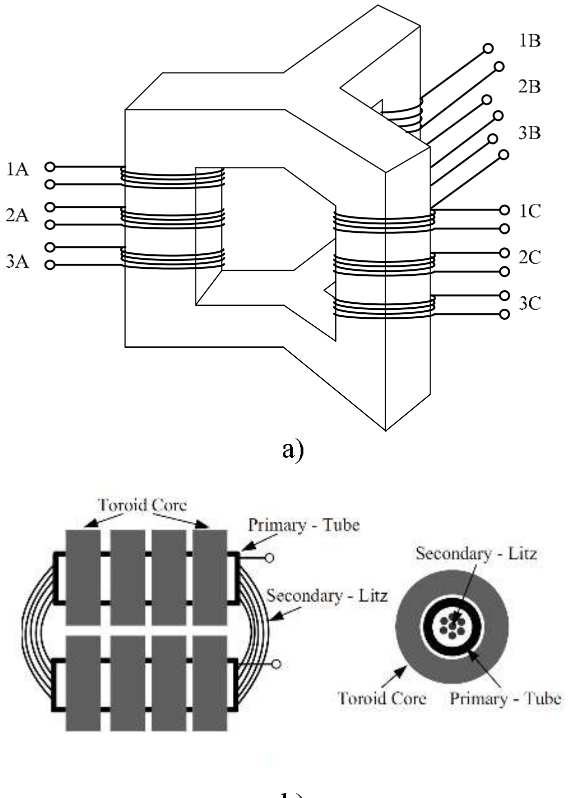
III. COAXIALLY WOUND TRANSFORMER

Transformers that can provide natural leakage symmetry are either conventionally [4] or coaxially [8] wound, as shown in Fig. 4. Since conventionally wound high-frequency three-phase transformer core shapes are expensive and difficult to build, a coaxially wound transformer is proposed in this paper. Coaxial winding techniques are commonly used in radio-frequency transformers, offering a feasible solution to confine the leakage flux within the inter-winding space. This prevents the core from being saturated locally [8]. As a result, the core and copper losses are lower, and local heating is avoided. Furthermore, from a mechanical point of view, this technique results in reduced forces within the transformer and a robust construction. In [8], it has been demonstrated that coaxial windings can lead to low loss and low leakage inductance power transformers in high-frequency soft-switched dc-dc and resonant converters. Some of the important loss aspects such as the influence of skin effect on winding resistance, the variation of core loss caused by non-uniform core flux density, and the choice of the dimensions and aspect ratios for maximum efficiency were examined in [9]. Coaxial winding techniques therefore provide a viable method for the construction of the converter transformer in Fig. 1.

As demonstrated in Fig. 1, a multi-port three-phase transformer can be thought of as three separate phases for analysis purposes. Thus, the study of only one single-phase transformer is enough in the following.

A Two windings coaxially wound transformer

To start with, the calculation of leakage inductances is considered only for two windings: the primary winding as an outer tube and an inner tube as the secondary, as shown in Fig. 5. To make the calculations easier, the secondary is considered as a solid tube.



a)

b)

Fig. 4. Two different techniques to build multi-port transformers: a) conventionally and b) coaxially wound transformer.

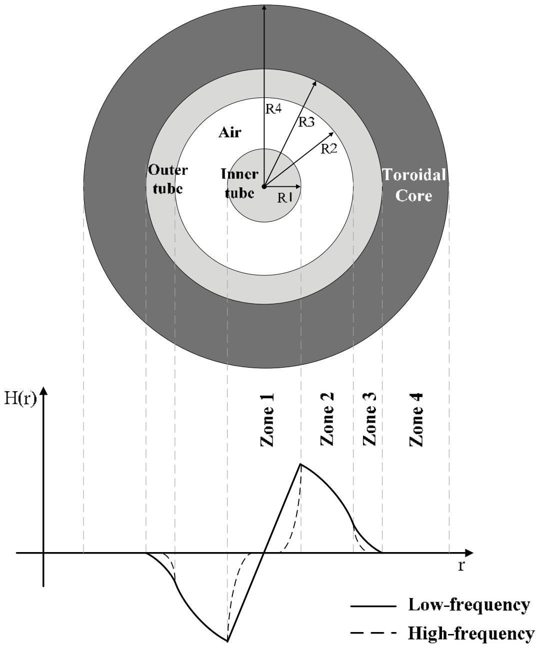


Fig. 5. Coaxial cable view with magnetic field profile, considering direct current circulating in the primary winding and this same current returning from the secondary winding.

The methodology presented in [10] was used to calculate the leakage inductance in the coaxial transformer. In Fig. 5, a view of the coaxial cable with the magnetic field profile is shown.

To determine the total leakage inductance in Fig. 5 the calculation of the magnetic field in zones 1 to 4 is necessary. Because the cable is coaxial, in zone 4 the magnetic field is zero. By means of the magnetic field values it is possible to calculate the total energy in Fig. 5 using

$$W = \frac{1}{2}\int_{vol} \vec{B}\vec{H} d_{vol} = \frac{1}{2} L_{leak} i^2 . \tag{1}$$

After some mathematical manipulations the total leakage inductance per meter is found to be

$$L_{Leak} = \frac{\mu_o N^2}{2\pi}\left(\left(\frac{1}{4} + \ln\left(\frac{R_2}{R_1}\right)\right) + \left(\frac{{R_3}^4}{\left({R_3}^2 - {R_2}^2\right)^2}\ln\left(\frac{R_3}{R_2}\right) + \frac{\left({R_2}^2 - 3{R_3}^2\right)}{4\left({R_3}^2 - {R_2}^2\right)}\right)\right) \tag{2}$$

where μ_o is the permeability of free space, which is equal to 4π x 10^{-7} A/m, and N is the number of turns (made equal to 1 in Fig. 5). Equation (2) was developed considering direct current circulating in the primary winding and this same current returning from the secondary winding.

A 2D numerical model of the coaxial transformer in Fig. 5 was developed with Maxwell software, to calculate the energy in the four zones of the transformer. When a current with the same value in the outer tube and inner tube is imposed with opposite direction, the energy will be concentrated in the zones 1 to 3, as shown in Fig. 6. The numerical calculations confirm that the result found in (2) is correct.

If high-frequency current is used, skin effects should be considered. The magnetic field profile will change, but it can be estimated as illustrated by the dotted line in Fig. 5. Thus, to calculate the leakage inductance at high frequency, radii R1 and R3 must be recalculated by subtracting the skin depth as defined by

$$\delta = \sqrt{\frac{2}{\omega\, \sigma\, \mu_o\, \mu_{cu}}} , \tag{3}$$

where the terms ω, σ and μ_{cu} are, respectively, the angular frequency, which is equal to $2\pi f$, the conductor's conductivity, in Siemens/meter, and the relative permeability of copper.

The magnetizing inductance

$$L_{mag} = \frac{\mu_o\, \mu_{fe}\, N^2}{2\pi}\ln\left(\frac{R_4}{R_3}\right), \tag{4}$$

where, μ_{fe} is the relative permeability of the ferrite, can be calculated considering current only in the primary (outer tube) or secondary (inner tube) winding. Therefore, all energy will be concentrated in the toroidal core, as demonstrated in Fig. 7, and only a small amount of energy will concentrated in zones 1 to 3. However, to keep (4) simple, only the core was considered.

Using the same procedure, as before, the magnetizing inductance observed from the secondary side was calculated, leading to the same result. Once the magnetizing and leakage inductances are known, it is possible to determine the 2 by 2 inductance matrix of this transformer.

A 3D model (Fig. 8) was also made to evaluate the fringing flux from the external cables. In the next sections an experimental set up will be build and the fringing flux will be compared with this model.

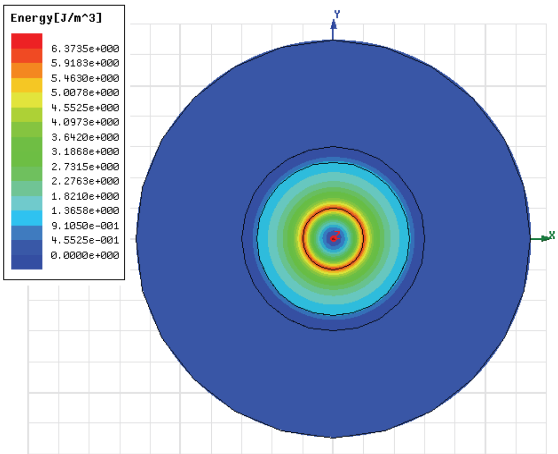


Fig. 6. 2D model, developed with Maxwell software, assuming the current in the outer and inner tubes to have the same value and opposite directions.

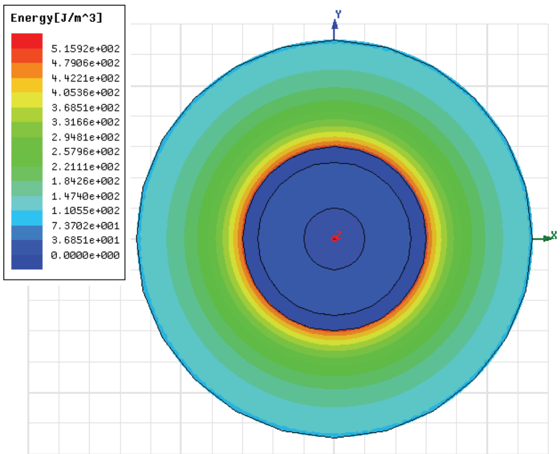


Fig. 7. 2D model, developed at Maxwell software, considering current only in the outer tube or inner tube.

B Three windings coaxial wound transformer

The procedure explained in subsection *A* was repeated here, however, using three windings instead of two.

A 3 by 3 inductance matrix can be calculated. However, to obtain this matrix it is necessary to find six parameters, i.e., the magnetizing and leakage inductances observed from each side, as discussed in the next section.

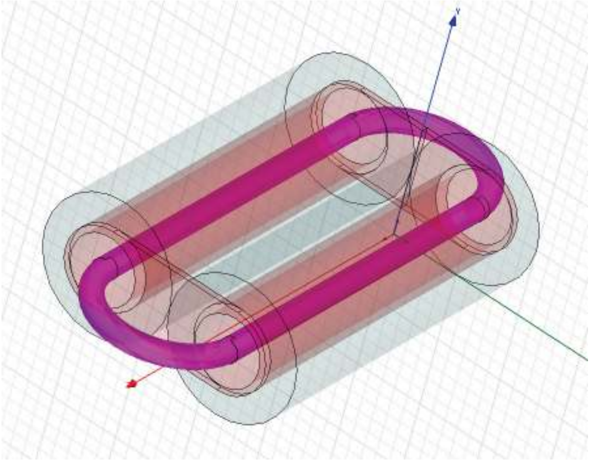


Fig. 8. 3D model from Maxwell software.

IV. INDUCTANCE MATRIX

Now we have a method to calculate leakage and magnetizing inductances of a multi-port coaxial transformer, the related inductance matrix can be defined.

Based on Faraday's Law, the voltage across the terminal of a winding composed of several turns, considering the magnetic flux equal in all turns, is defined as

$$u = \sum_j \frac{d}{dt}\Phi_j \, . \tag{5}$$

Assuming it is composed of several windings, the voltage across a terminal winding i is described by

$$u_i = \sum_{j=1}^{N_i} \frac{d}{dt}\left[\Phi_{ji,1} + \Phi_{ji,2} + \ldots\right], \tag{6}$$

where i is the number of the windings and j is the number of turns. Thus, Φ_{ji} denotes the flux through the turn j of the winding number i. The secondary index is referring to the different currents through winding 1,2,3,…

The flux Φ_{ji} is caused by the current i through the winding j, and is proportional to this current. Thus, it is possible to write a matrix, normalizing the flux to the current, as

$$\begin{bmatrix} u_1 \\ u_2 \\ \ldots \end{bmatrix} = \begin{bmatrix} \sum_{j=1}^{N_1} \frac{\Phi_{j1,1}}{i_1} & \sum_{j=1}^{N_1} \frac{\Phi_{j1,2}}{i_2} & \ldots \\ \sum_{j=1}^{N_1} \frac{\Phi_{j2,1}}{i_1} & \sum_{j=1}^{N_1} \frac{\Phi_{j2,2}}{i_2} & \ldots \\ \ldots & \ldots & \ldots \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_1 \\ i_2 \\ \ldots \end{bmatrix}, \tag{7}$$

where the terms in the diagonal are known as measurable inductances and will be designed as L_{ij}. The others terms are mutual inductances and will be addressed as M_{ij}. Thus, the matrix can now be represented by

$$\begin{bmatrix} u_1 \\ u_2 \\ \ldots \end{bmatrix} = \begin{bmatrix} L_{11} & M_{12} & \ldots \\ M_{21} & L_{22} & \ldots \\ \ldots & \ldots & \ldots \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_1 \\ i_2 \\ \ldots \end{bmatrix}. \tag{8}$$

It is useful to define coupling coefficients as

$$k_{ij} = \frac{M_{ij}}{\sqrt{L_{ii} \, L_{jj}}} \, . \tag{9}$$

A Inductance matrix for two-windings transformer

Using the inductance matrix (8) it is possible to determine the terms of a π-model transformer with i windings. The inductance matrix

$$\begin{bmatrix} u_1 \\ u_2 \end{bmatrix} = \begin{bmatrix} L_1 & M \\ M & L_2 \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_1 \\ i_2 \end{bmatrix} \tag{10}$$

represents the π-equivalent circuit diagram shown in Fig. 9. In this figure we assume $M_{12}=M_{21}=M$.

The primary and secondary leakage inductance equations are defined in accordance with

$$L_{lp} = L_1 - NM \tag{11}$$

$$L_{ls} = L_2 - \frac{M}{N} \tag{12}$$

respectively, based on Fig. 9.

Because the model has 4 parameters and (10) only 3, this model is underdetermined. Some designers use this fact set the primary and secondary leakage inductance equal.

To measure the 3 parameters in (11) and (12) for a real transformer, three steps are carried out: measure the magnetizing inductance in the primary side, leaving the secondary open, short-circuit the secondary or primary side and measure the leakage from both sides and measure the magnetizing from secondary side with the primary open. Using these three steps is possible to define the components in Fig. 9.

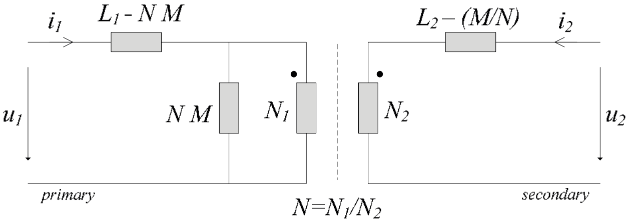


Fig. 9. Circuit diagram of π-model for a 2 winding transformer.

B. Inductance matrix for a three-windings transformer

For a three-winding transformer the inductance matrix is defined as

$$\begin{bmatrix} u_1 \\ u_2 \\ u_3 \end{bmatrix} = \begin{bmatrix} L_1 & M_{12} & M_{13} \\ M_{21} & L_2 & M_{23} \\ M_{31} & M_{32} & L_3 \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_1 \\ i_2 \\ i_3 \end{bmatrix}. \tag{13}$$

The circuit diagram for the π-model using three-winding is shown in Fig. 10.

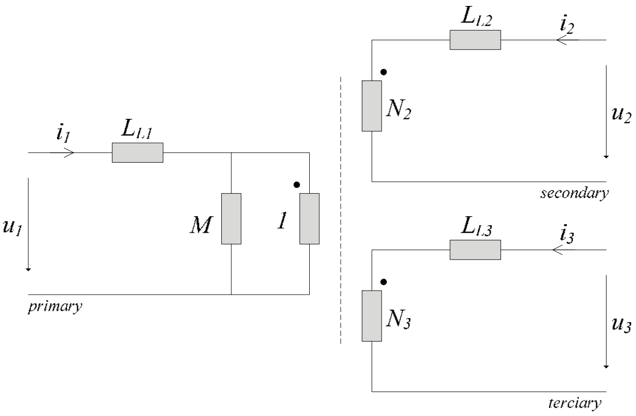


Fig. 10. Circuit diagram of the π-model for a 3 winding transformer.

Because the inductance matrix and circuit diagram both have 6 parameters, this system is therefore uniquely determined. The 6 parameters from Fig. 10 are found to be

$$\begin{aligned} L_{L1} &= L_1 - \frac{M_{12}M_{13}}{M_{23}} & M &= \frac{M_{12}M_{13}}{M_{23}} \\ L_{L2} &= L_2 - \frac{M_{12}M_{23}}{M_{13}} & N_2 &= \frac{M_{23}}{M_{13}} \quad . \\ L_{L3} &= L_3 - \frac{M_{13}M_{23}}{M_{12}} & N_3 &= \frac{M_{23}}{M_{12}} \end{aligned} \qquad (14)$$

To calculate these 6 parameters in a real transformer, 6 steps must be carried out: measure 3 reflected magnetizing inductances on each side, considering the other 2 windings open, then short-circuit two windings and measure the remaining two leakage inductances for all windings.

For transformers with more than 3 windings a π-model is overdetermined. The inductance matrix can, of course, always be calculated using (8).

V. EXPERIMENTAL RESULTS

To check the theoretical and simulation results a simple one turn and two windings coaxial transformer prototype was constructed. Two prototypes were made: one using a tube 28.6 cm long (Fig. 11a) and another using two tubes, each with a length of 14.3 cm (Fig. 11b). Both prototypes used toroidal ferrite cores, with a relative permeability (μ_{fe}) of 700.

Results obtained from experimental measurements using an impedance analyzer are summarized in Table 1. A 3D Maxwell model was only developed for two tubes because most of leakage inductance is concentrated inside of the core, when one tube prototype is used. Thus, the fringing flux of the prototype from Fig. 11a was neglected.

TABLE 1
EXPERIMENTAL RESULTS FOR TWO-WINDING COAXIAL TRANSFORMER PROTOTYPES

	Leakage inductance (*n*H)	Magnetizing inductance (μH)
Theoretical (1 tube)	65.13	28.22
Theoretical (2 tubes) disregarding external cables	65.13	28.22
3D Maxell software (1 tubes)	---	---
3D Maxell software (2 tubes)	66.4 (internal leakage) + 31.21 (external leakage) = 96.61	28.34
Experimental (1 tube)	68.54	27.75
Experimental (2 tubes)	92.99	27.61

Theoretical, simulation and experimental results were obtained at 10 kHz. Theory and simulation considered the skin effect.

Table 2 shows the theoretical, simulation and experimental inductance matrix of the configuration described in Fig. 11a.

TABLE 2
MATRIX INDUCTANCES FOR TWO AND THREE-WINDING TRANSFORMERS.

Two-winding transformers		
Theoretical (μH)	Simulation (μH)	Experimental (μH)
$\begin{bmatrix} 28.22 & 28.23 \\ 28.23 & 28.30 \end{bmatrix}$	$\begin{bmatrix} 28.22 & 28.22 \\ 28.22 & 28.29 \end{bmatrix}$	$\begin{bmatrix} 27.46 & 27.57 \\ 27.57 & 27.75 \end{bmatrix}$
Three-winding transformers		
Theoretical (μH/m)	Simulation (μH/m)	
$\begin{bmatrix} 104.51 & 104.51 & 104.51 \\ 104.51 & 104.83 & 104.61 \\ 104.51 & 104.61 & 104.83 \end{bmatrix}$		

Because a prototype of a coaxial transformer using three windings was not yet build, Table 2 only shows theoretical and simulation results. Since the theoretical and simulation values were very close to each other, only one 3 by 3 matrix is shown.

a)

b)

Fig. 11. Prototype coaxial transformers using: a) one tube and b) two tubes.

VI. CONCLUSIONS

Theoretical and simulation results were obtained for a single phase coaxial transformer which will be used on each phase of a multi-port converter proposed. Experimental results are given for one turn and two windings. The measured magnetizing and leakage inductances compare quite well with the theoretical and simulated values.

Once the dimensions of the coaxial transformer and some of its desired characteristics, e.g., number of turns and relative permeability of ferrite, are defined the leakage and magnetizing inductance can be accurately calculated.

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