On the modelling of multi-windings traction transformers

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Abstract: - In order to predict the behaviour of traction drives, the modelling of the supplying multi-windings transformer is of great importance. This paper aims to present the actual mostly used models of such transformers as well as new models under study, in the frame of a long term agreement of our universities with some of the known specialized industries. Two AC models are presented based on two different philosophies, and a third one describing the transformer used as inductance in DC mode is explained. Concrete cases are taken as examples to illustrate the application domain of these transformers.

Key-Words: - Traction, transformer, polygonal scheme, multi-windings, railways, locomotive, drives

1 Introduction

The way a multi-windings traction transformer is used to supply Railways' three-phase drives is shown in Fig. 1. This converts a single phase catenaries' voltage into four independent low voltage sources, which feed different rectifiers (AC/DC). The four three-phase induction motors are driven by frequency converters, assuring so the velocity control of the locomotive.

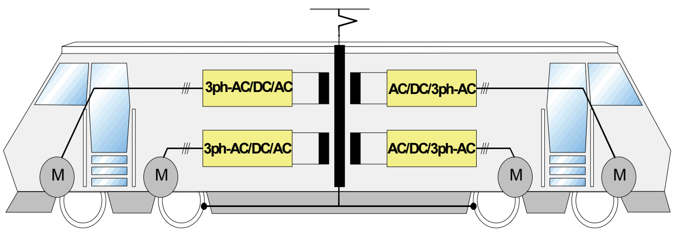


Fig.1

Depending on the geographical region that the locomotive crosses, the traction transformer is supplied by a given voltage at a certain industrial frequency. The actual trend -especially in Europe where there is a plenty of supply characteristics- is to build multi-systems locomotives that can roll across countries' borders without stopping despite the supply switching. This leads to design traction transformers that can be operated under various frequencies.

Requirements on maximum harmonics content in the network current, lead system designers to use elements models, which give a good approximation of the drives behaviour in a reasonable way; this means that one should consider the right model that is enough accurate while consuming the shortest simulation time. This paper deals with the modelling of one element of three-phase drives, namely the traction transformer.

2 Using appropriate transformer models

According to how the transformer is going to be used, one among several schemes can be chosen.

At industrial frequencies, the very popular model is the short-circuit impedance between two terminals of a two-winding transformer [1]. As soon as the magnetic effect has to be taken into account, the magnetizing branches are added to the simplified model [2]. When a multi-system locomotive leaves an AC supply line to enter a DC distribution one, the transformer is no more useful as an AC device; it will be then operated as a smoothing reactor [3].

2.1 Polygonal equivalent scheme

This kind of scheme has been developed in order to include all transformer windings in one electrical circuit (Fig. 2).

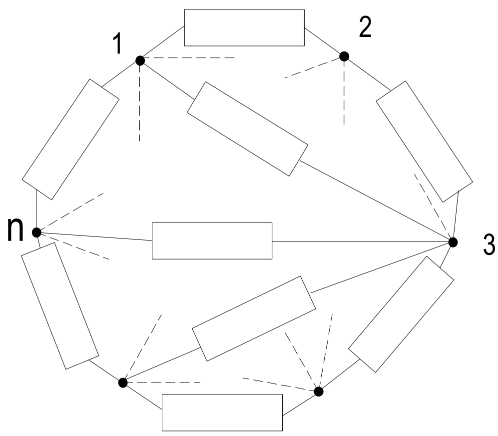


Fig.2

Each impedance between a pair of terminals (Z_{ij}) is composed of a resistive and an inductive part; its determination is based on the short-circuit tests between all pairs of windings. Equations (1) to (5) give the relations that allow deducing the scheme impedances [1], where Zcc_{ij} is the short-circuit impedance between windings i and j.

$$\begin{cases} Z_{ij} = -\dfrac{1}{b_{ij}} \quad for \quad i \neq j \neq 1 \\ \\ Z_{1i} = \dfrac{1}{b_{ii} + \sum\limits_{j(\neq i \neq 1)} b_{ij}} \end{cases} \tag{1}$$

$$Y = \frac{1}{Z} = \begin{pmatrix} b_{22} & \cdots & \cdots & b_{2n} \\ \vdots & \ddots & & \vdots \\ \vdots & & \ddots & \vdots \\ b_{n2} & \cdots & \cdots & b_{nn} \end{pmatrix} \tag{2}$$

$$Z = \begin{pmatrix} a_{22} & a_{23} & \cdots & a_{2n} \\ a_{23} & \ddots & & a_{3n} \\ \vdots & & \ddots & \vdots \\ a_{2n} & a_{3n} & \cdots & a_{nn} \end{pmatrix} \tag{3}$$

$$a_{ii} = Z_{cc1i} \tag{4}$$

$$a_{ij} = \frac{\left(Z_{cc1i} + Z_{cc1j} - Z_{ccij}\right)}{2} \tag{5}$$

2.1.1 Limits of the polygonal scheme

Using an electrical scheme for a non-ideal electromagnetic device does not represent the reality in all load cases [4], man should then consider some typical operation modes and match a simplified scheme for each case.

2.2 Scheme including magnetic effect

By no-load cases as well as for predicting inrush currents, the polygonal scheme is no more suitable. A new model including magnetizing branches has been developed [2, 5]; its principle is represented on Fig. 3 in case of a four-winding transformer. Its validity is proven through Matlab/Simpowersys simulations.

Fig. 4 shows this model for a five-winding transformer (nodes 1 to 5), in which the horizontal elements –i.e. windings resistances and equivalent stray inductances- are described under Fig.5. The magnetizing branches (i.e. vertical ones) are visible in Fig.4 and represented by subsystems L_1 to L_5.

Each of these blocks encloses a measurement of the voltage as in Fig.6, which is transmitted into a model's deeper part shown in Fig.7. The magnetizing current 'Im' that has been calculated in the 'add' block of Fig.4 is also another input.

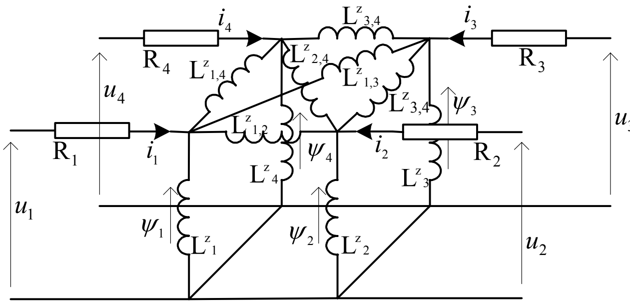


Fig.3

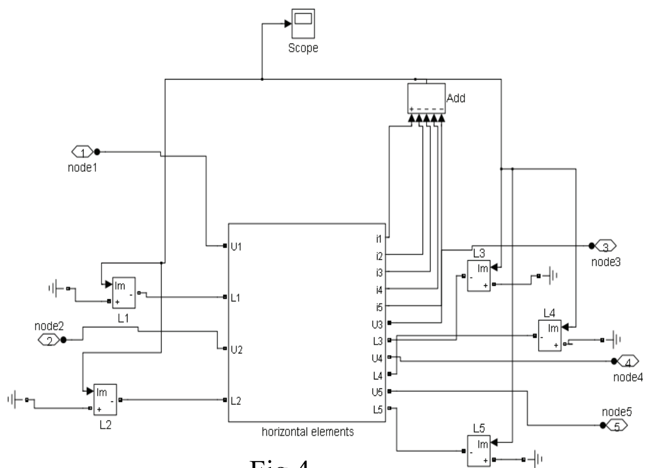


Fig.4

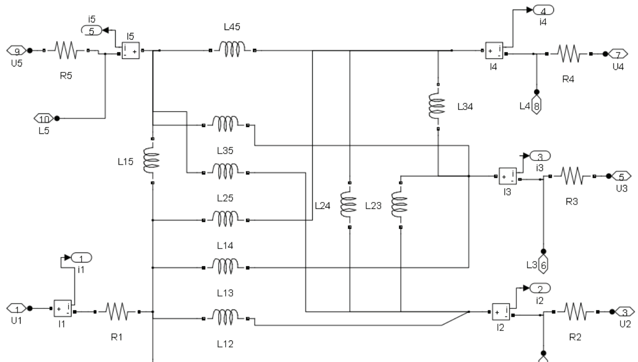


Fig.5

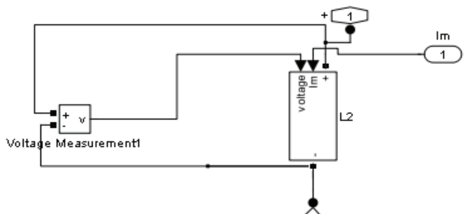


Fig.6

At the end, the voltage between the vertical branch terminals, as well as the magnetizing current are the input quantities allowing producing the steering current source that represents the dynamic inductances L_1 to L_5 respectively. The shunt resistor in this model has a very high value; its use is necessary to allow connecting two current sources together.

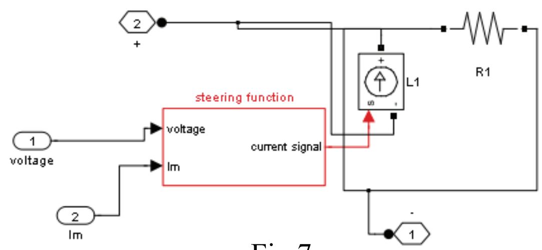


Fig.7

The steering function of Fig.7 is detailed in Fig.8. It represents the deepest part of the dynamic inductance model.

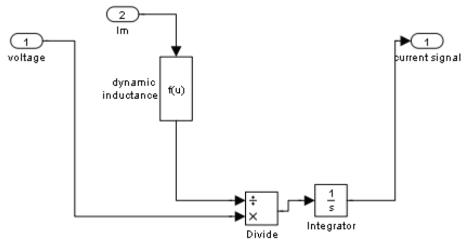


Fig.8

The function f(u) is described in Fig.9 and corresponds to equation (7). It has been deduced as a derivative of the measured Flux-current curve, approximated by equation (6) and illustrated in Fig.10.

$$\Psi = a \cdot a\sinh(b \cdot I) \quad (6)$$

$$L_{dyn} = \frac{a \cdot b}{\sqrt{b^2 \cdot I^2 + 1}} \quad (7)$$

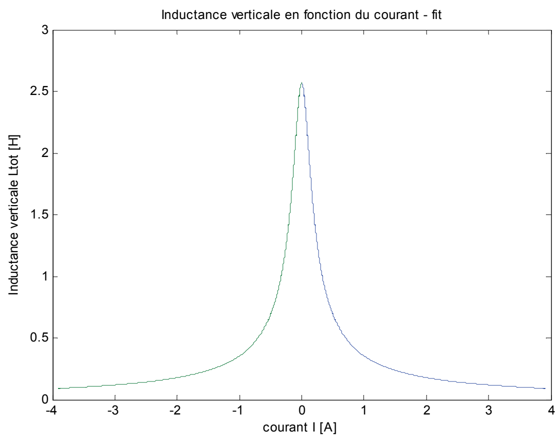


Fig.9

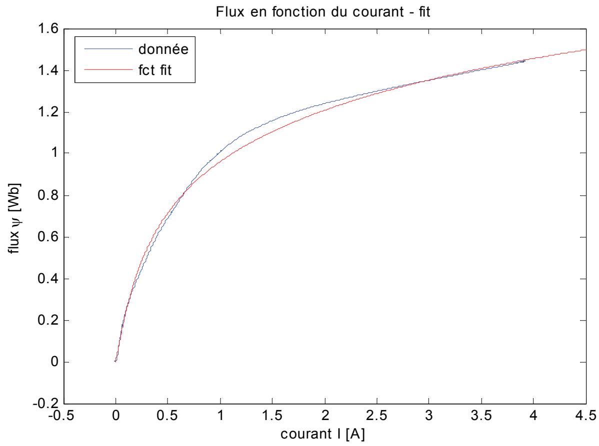


Fig.10

2.3 DC model of the transformer

This model is detailed in [3]. Its principle is the use of some transformer windings in DC mode. The serial connection of the four low voltage traction windings (2Ui-2Vi) of Fig.11 leads to the input smoothing reactor of the DC supply. The inductance value is properly determined during the design phase of the transformer.

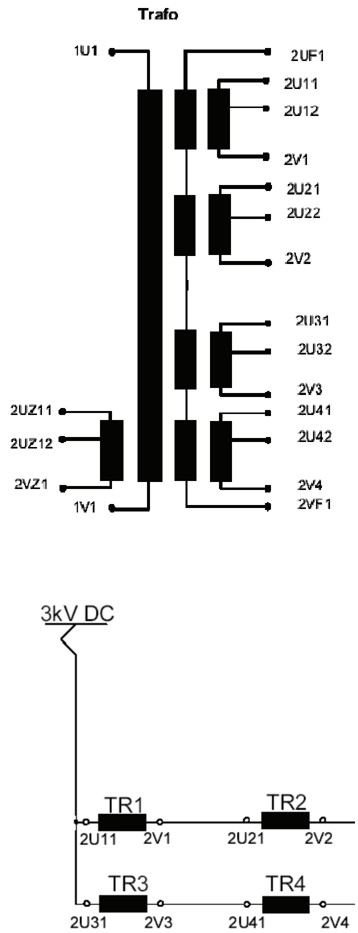


Fig.11

3 Investigation of typical load cases

The above presented models have been used to deal with some typical load cases. This section shows the best use for each model, depending on the load case.

3.1 Steady-state short-circuit current

3.1.1 Polygonal scheme

In short-circuit case, it is enough to use the polygonal scheme as shown in Fig.12 for a six-winding transformer. This figure represents an operation with four Traction windings in short-circuit to ground in AC mode. The uniqueness of the equivalent scheme used is discussed in [4], and the results are adequately commented.

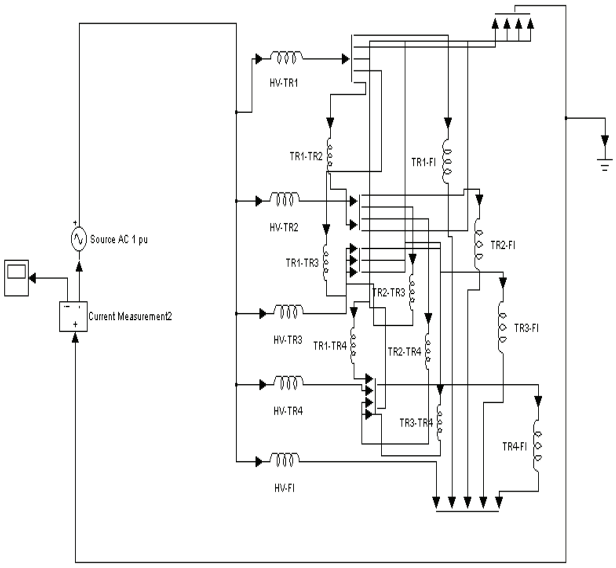


Fig.12

3.1.2 Scheme with magnetic effect

The same test on a five-winding transformer is also made by using the scheme including magnetic effect (Fig. 13). Voltage and currents are visible in Fig.14 and correspond to real measurements on such a transformer.

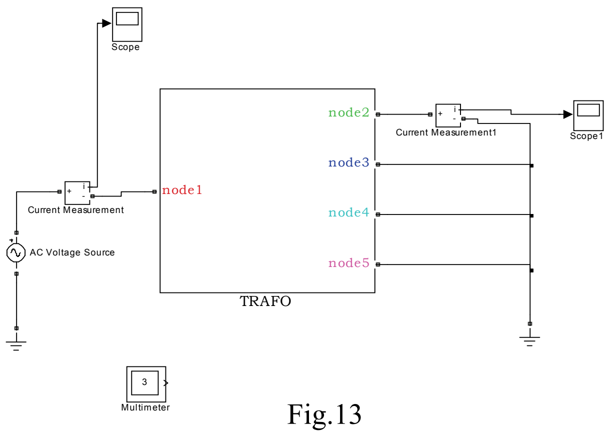


Fig.13

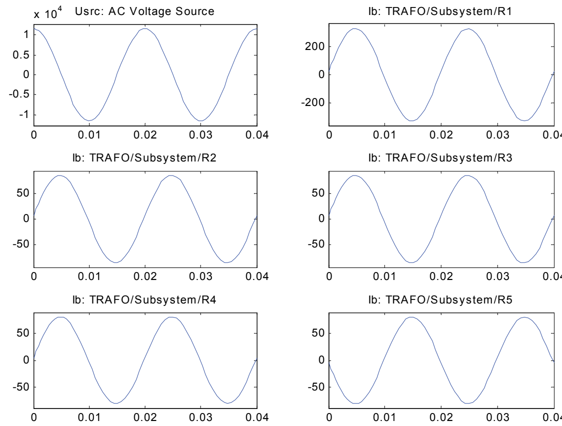


Fig.14

3.2 Steady-state no-load current

We considered a five-winding transformer. The primary winding has been supplied at the rated voltage. Terminals of Traction side (nodes 2 to 5) have been disconnected (Fig.15). Multimeter block and scope block show the resulting voltage and current in Fig.16.

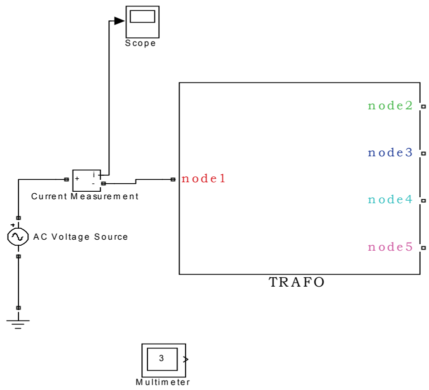


Fig.15

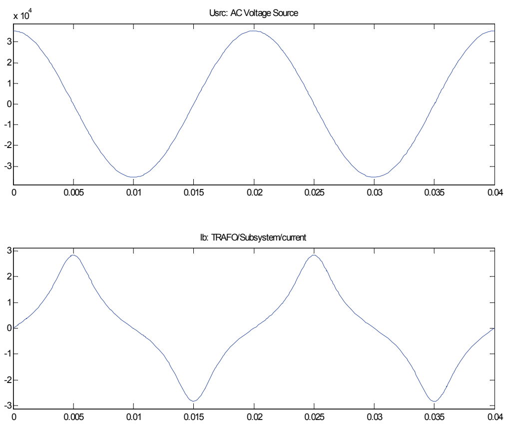


Fig.16

The no-load current shown in Fig.16 is typical for locomotive transformers. This denotes the saturation of iron core at rated voltage and frequency (25 kV / 50 Hz).

3.3 Transformer no-load inrush current

The inrush current of this transformer is simulated for two different switching instants. Fig.17 shows the layout principle of this test. Fig.18 gives the output current by a maximum voltage crossing, while in Fig.19 the voltage was on a negative slope.

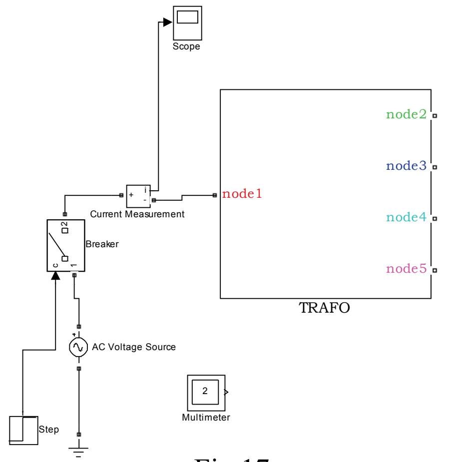


Fig.17

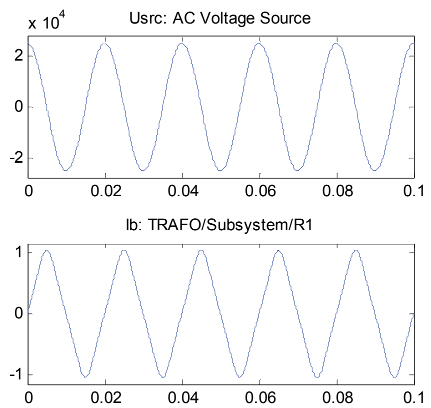


Fig.18

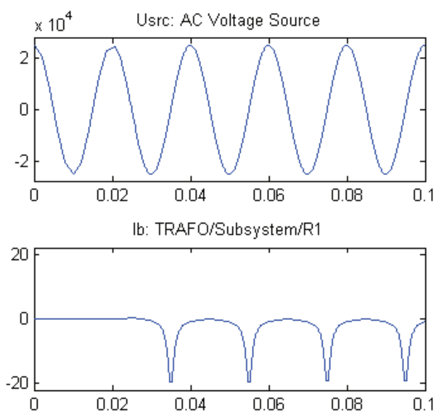


Fig.19

3.4 Dynamic short-circuit current

The complete model has also been used to investigate the sudden short-circuit of the above transformer, according to Fig.20. Results are shown in Fig.21, where one distinguishes the supply voltage, the primary current as well as the secondary current related to the primary side. The effect of the magnetic branches is virtually insignificant.

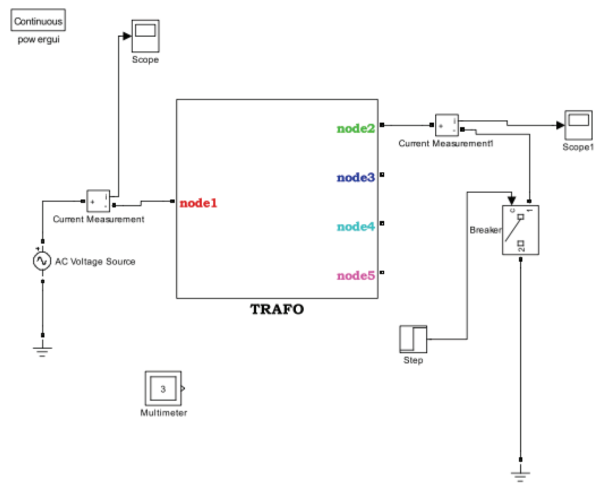


Fig.20

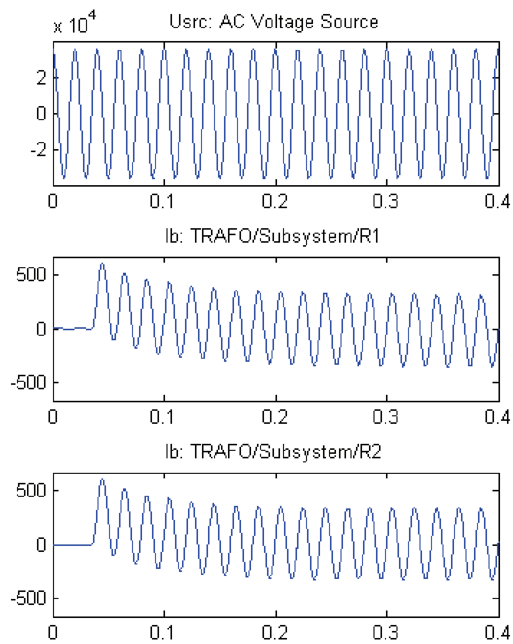
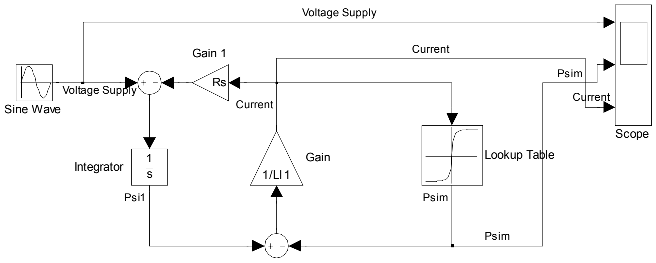


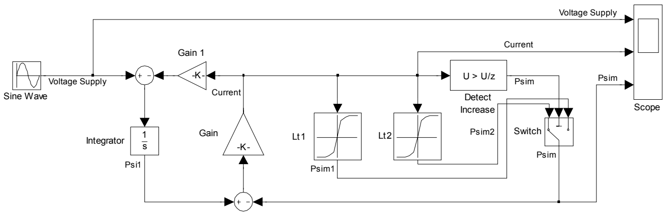
Fig.21

3.5 DC operation (Ripple effect)

The Matlab-Simulink model of the transformer used as an inductance in DC mode is illustrated in Fig.22. Magnetizing curve accounting for the saturation effect is modeled by one (a) or two (b) lookup-tables, which describes each a mathematical function (Arc-tangent). This model is fully parameterized and adaptable to any transformer characteristics.



(a)



(b)

Fig.22

Simulation results of this latter model are visible in Fig.23. The current shape reflects the saturation of the transformer in this operation mode.

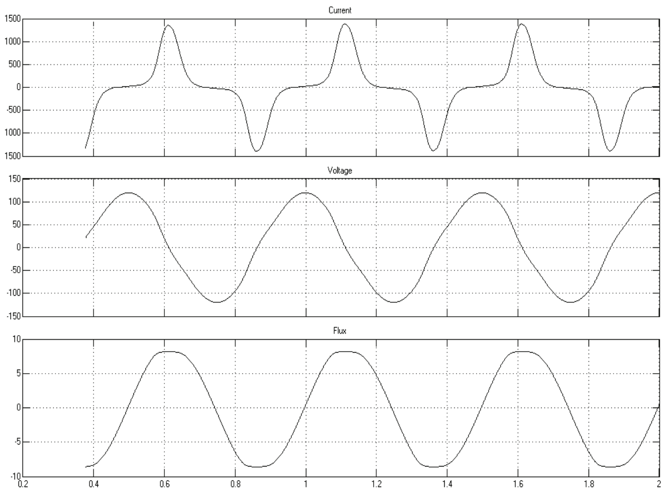


Fig.23

4 Conclusion

Modelling Traction transformers depends always on the manner they are going to be used. A complete model is generally mandatory in the no-load operation of the locomotives.

For short-circuit or load cases an adequate scheme without magnetic branches is generally sufficient.

In any case, special care has to be taken when determining the elements of the equivalent scheme.

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