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Modelling of the Harmonic Penetration of High Power Electric Traction

Doctoral thesis booklet

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Introduction

The main parameters of the Hungarian high power electric traction system are: 25 kV, 50 Hz, single phase. The transformers are connected direct to the high voltage supply network at 120 kV line-to-line voltage. After the spreading of locomotives equipped with DC traction motors and rectifier units the disturbance originating from the railway traction systems has increased. Harmonic filters are used to limit the harmonic currents flowing into the upstream network. My research is dealing with the modelling of network current resonance and the harmonic voltage distortion caused by the high power electric traction.

There are plenty of research groups working on topics related to power quality and harmonic penetration, however only a few of them are dealing with AC railway networks. That is why the structure of the traction supply networks is not uniform. The first country over the world was Hungary where the 50 Hz electrification system was introduced, followed the first tests made in 1923 by Kálmán Kandó. The first railway line where this system was applied is between Budapest and Hegyeshalom. The project was finished in 1934; the first section had been opened on 12th September 1932 between Budapest and Komárom. In spite of more and more countries recognised the advantage of the 50 Hz electric traction systems, a lot of countries have been investigated in different systems till the 1930's. Because of the extremely high costs of the system conversions they remained by their original system, so in the western part of Europe the DC traction is characteristic on different voltage levels. The only exception is the triangle of Switzerland, Germany and Austria completed with the two Scandinavian countries, Norway and Sweden, where the supply system is AC, but the frequency is 16 $^2/_3$ Hz (in Austria, Germany and Switzerland it has been rounded to 16,7 Hz in 1995). Switzerland is a good example why these systems have not been converted: 60% of the Swiss railway lines had been electrified until 1934 (and in 1960 they reached the 99.6% rate). The system of Kálmán Kandó looks conquering the world. Nowadays this system is used by new electrification projects. The main reason is that there is a speed limit by the DC systems because of the high currents, thus the high speed lines are built with 50 Hz system in the traditional DC system operator countries, too. The present situation is still very colourful. Usually we find the system borders at the frontiers. [1]

After studying the proceedings of the specific IEEE conferences, which are dedicated to the topic of power quality (ICHQP, former ICHPS series) I needed to conclude that there are just limited number of papers dealing with the harmonic penetration of electric railways. The current amplification and its resultant penetration, which is close to the central topic of my dissertation is the speciality of AC traction systems. Those countries, being the most active on IEEE conferences have not got 50 Hz railway system: in the United States the railway has not got big percentage (and importance) in transportation, in the western European countries and in Japan the system frequency is basically not the same than that of the communal networks. Studying the conferences of the last 20…30 years most of the papers were made by Hungarian, Italian and British authors.

In the first four chapters of the dissertation the detailed introduction of the problem of harmonic penetration and the applied models are presented, while in the 5th, 6th and 7th chapter my novel results and the corresponding theses are reported. Below my theses are summarized:

The Double Domain Simulation and its application

To determine the harmonic penetration of the high power railway networks, it is possible to investigate more kind of models:

- The easiest way is *modelling in the frequency domain*. It's obvious to use it because the parameters of the network elements are known in the frequency domain. In this case it is necessary to determine the locomotive current spectrum in advance by site measurements or other calculations.
- It is possible to compose a sophisticated *model working in the time domain*. The parameters of the locomotive can be calculated without any difficulties in the time domain, but the network impedance in function of frequency is known in the frequency domain as results of site measurements. The main problem is with the upstream network impedance. Its driving point impedance curve is frequency dependent and the conversion into time domain could results in a very difficult transfer function with at least 5-5 poles and zeros.
- My goal is the combination of the two domains, performing the so called *double domain simulation* method: the time domain calculations will be reduced to the locomotive, and the impedance of the whole network is calculated in the frequency domain.

The results can be calculated with an iteration algorithm, which was developed to convert the variables between the time and frequency domain vice and verse. The double domain simulation is suggested to apply especially around the network resonance frequencies, where the amplification of the harmonic currents causes high harmonic voltage distortions. The resultant currents and voltages are much more accurate when modelling the system in the double domain compared to the results of the simple frequency domain simulation where the locomotive is represented with a previously measured harmonic current spectrum. With the double domain procedure 1…2% accuracy can be reached with 3…5 iteration steps. Using the double domain simulation it is possible to take account, that the current spectrum of a nonlinear load (e.g. locomotive) supplied from a frequency dependent network impedance (e.g. the driving point impedance as seen from the pantograph of the locomotive) depends on this impedance.

The double domain simulation is discussed in the Chapter 5. First a brief overview can be studied on the theoretical modelling possibilities and the results of other research groups (Chapter 5.1), later the detailed introduction of double domain simulation is reported with some application examples and calculation results (Chapters 5.2&5.3).

The novelty of the procedure is based on four aspects:

1. The double domain simulation is an innovative algorithm, can be adjusted by a lot of parameters. The harmonic penetration of the high power electric traction can be calculated by arbitrary loco configuration.
2. With this procedure it is possible to take account all kind of nonlinear loads include current source rectifiers and have any kind of supply voltage dependency of their current shape. It means that its current and voltage shapes are in interaction.
3. The double domain simulation method is suitable for determining psophometric currents which can be used for calculating the caused psophometric disturbance in the surrounding telecommunication lines related to electromagnetic compatibility (EMC).
4. This method has better accuracy than that of the previous models, because all the network elements are calculated in the right environment and domain, without any simplification. The measured parameters can be used directly in the model.

The double domain simulation is an iterative procedure where the traction system and the supply network impedance is calculated in the frequency domain and the locomotive in the time domain. The calculations results can be compared with the measurements and it can be concluded that the accuracy is better than the calculations only in the frequency domain or only in the time domain.

In the previous paragraphs of the thesis booklet the double domain simulation method has been introduced. It's simple calculation and perspicuity has been demonstrated in the dissertation and some calculation results has been analysed.

Regarding the double domain method the following thesis can be drawn:

1st thesis:

The double domain simulation method is suitable for calculating the harmonic penetration of the high power electric traction with the strictest frequency dependent representation of the network elements. As a result, the accurate voltage and current time functions and their spectra will be calculated.

1st thesis, 1st sub thesis:

Besides the harmonic components the fundamental frequency component of time variant nonlinear loads, equipped with rectifiers (e.g. AC locomotives with DC motors), depends on the contact voltage vice and verse. The current of these consumers can be determined by the double domain simulation with arbitrary accuracy.

The application possibilities of the 1st thesis

The results can be used not only under Hungarian circumstances, but in every railway company where the 50 Hz system is used (and the public electric network has got the same frequency). During the last decade more and more countries decide applying the 50 Hz system because the DC traction system would check the growth of the speed, which is against the goal of having a quick and easy usable high speed electric railway network. It is possible to notice that those countries where the electric traction has traditionally DC system, they are developing 50 Hz railway traction systems with 25 kV overhead line voltage for the new high speed tracks between bigger cities, and the transit between the different systems are solved by special locomotives are equipped to handle multiple voltages and frequencies. The double domain simulation method will be applicable in more and more countries in the forthcoming years. The accurate simulation results are very important during the optimization of harmonic filtering and determining the optimal wiring structure.

The results of the thesis are published in the following papers: [S1]-[S11], [S17]

The analytical approximation of the upstream network

A lot of papers are focused on network modelling, but few of them are dealing with the details of the upstream network representation. In most of the cases the frequency dependency can be neglected. For fundamental frequency load flow calculations it is enough to represent the upstream network with the driving point impedance can be calculated from its shortcut power. This technology is widely used, the calculation method is well known, and the network can be represented by a Thèvenin model.

However if the goal of the calculation is determining the harmonic penetration caused by nonlinear loads, it is not enough to represent the driving point impedance with the 50 Hz equivalent value, in this case the so called harmonic driving point impedance curve should be determined. [3]

The conclusion of Chapter 6 is that in case of harmonic penetration calculations, when the goal is studying the network resonance effect, the accuracy of the THD calculations can be better with 2…3% if the frequency dependency of the upstream network is not neglected. The different representation methods are summarized in Chapter 6.1. The developed polynomial-trigonometrical approximation method (Chapter 6.2) has reliable accuracy even so the density of the known points is not enough high or the increment of the function is not smooth, what would degrade the accuracy of the simple polynomial approximation. The other big advantage is that the calculation time is much less than by the quadratic interpolation, what is used by the authors of reference [28]. The calculations of the novel approximation method is based on two compound equations (R and L), which can be calculated with previously determined parameters. In this case the same equations can be applied in the whole frequency range. In case of quadratic interpolation it would be necessary to write a quadratic function for each 3-3 consecutive points, and the function should be calculated with complex numbers.

After the paragraphs of Chapter 6 the following thesis can be drawn:

2nd thesis:

The accuracy of the polynomial representation of the impedance of the frequency dependent upstream network can be increased with additional trigonometrical functions.

2nd thesis, 1st sub thesis:

In case of nonlinear loads, which are supported by rectifier and have not got constant current, the fundamental frequency *component of the consumed current is depending on the harmonic driving point impedance curve of the upstream network.*

2nd thesis, 2nd sub thesis:

In case of the harmonic penetration calculated with the double domain simulation method, the accuracy of the calculation is depending on the accuracy of the approximation method used for representing the upstream network.

The application possibilities of the 2nd thesis

With this model the main goal was the better accuracy on the results of double domain simulation method, however, the application range is much wider. The main advantage is that empiric curves, which would be hardly represented by simple polynomial equation, can be approximated with the combination of polynomial and trigonometrical functions. This combination can be inserted to an arbitrary mathematical model. The application is practical in the following cases:

- in case of the increment of the function is not smooth, and/or
- Few points are known along the function we would like to represent.

There are a lot of cases where the calculations should be done in the frequency domain and the upstream network should be represented. The polynomial-trigonometrical interpolation can be applied also in three phase networks, and – counter to the introduced model of the double domain simulation method – it is a mathematical formula, which does not need any specific engineering software.

The results of the thesis are published in the following papers: [S15], [S16], [S19]

The applicable filtering methods

In Chapter 7 the harmonic elimination of the traction system is introduced based on harmonic filtering. The topicality is based on the electric power law and accounting regulation from 1999, which holds out a promise to the Hungarian State Railways Co. of fining in case of too much reactive power consumption or capacitive generation. The tariff regulation estimates that the inductive and capacitive reactive energy should be measured and fined separately. [9]

The studying of harmonic production and penetration is in the research program of Hungarian State Railways Co. for more decades. In a lot of cases the R&D partner was the Department of

Power Systems, what is the predecessor of my working place, the Department of Electric Power Engineering at the Budapest University of Technology and Economics. [9] My goal was developing a modelling method, which is suitable for modelling the different harmonic filtering methods, and the effect of the devices can be represented by calculations.

- The frequency dependent part of the double domain simulation method, which is suitable for harmonic penetration calculations, can be completed to model passive harmonic filtering. (Chapter 7.1)
- Developing the double domain simulation method it is possible to integrate the active harmonic filtering. The active filter model should be calculated in the time domain like the locomotive model. (Chapter 7.2)
- After the two previous chapters it is possible to compose the so called hybrid harmonic filter. The hybrid filtering method can also be used by traction systems. (Chapter 7.3)

It was not my goal to plan new harmonic filters. In Chapter 7 I would like to demonstrate, that the double domain simulation method is suitable for modelling reactive power compensation and harmonic filtering. It can be a useful and cost saving tool during filter planning tasks. The following thesis can be drawn:

3rd thesis:

The double domain simulation method can be completed for modelling the effect of passive, active and hybrid filtering method.

- *The passive harmonic filter can be inserted directly to the frequency dependent traction supply system model.*
- *The active harmonic filter is a microprocessor controlled current injecting device, which can be calculated advantageously in the time domain similar to the locomotive model. The active filter can be integrated to the iterative procedure of the double domain simulation; the resultant method is the so called double cycled double domain simulation method, which is suitable for simulation of active filters.*

- *Hybrid harmonic filtering is the combination of passive and active filtering. The double cycled double domain simulation can be completed with passive filter, thus the effect of hybrid harmonic filtering can be analysed and both filters are simulated.*

The application possibilities of the 3rd thesis

The double domain simulation is suitable not only for modelling the harmonic penetration of the electric traction, but also for modelling the different harmonic filtering strategies. The accuracy depends on the accuracy of the network element representation.

- In case of passive filters the R, L and C values should be known (including the loss resistance of the reactor and capacitor).
- In case of active filtering the first version is representing with harmonic current generator, but it is possible to prepare the model of a PWM controlled device, too. In case of the parameters and the control loop is known, it is possible to compose the controlling algorithm for the IGBTs. In this case the real operation during harmonic filtering can be represented.
- The hybrid filtering is in experimental stage, but applying the previous two points together would let us model it.

The goal of this modelling is representing the different filtering possibilities on the planner desk, backing up the connecting researches. The double domain simulation method will help to select the most advantageous solution, regarding the composition of reactive power compensation and harmonic filtering. It was not a goal to analyse the economical side of harmonic filtering investments. With the help of it the technical details can be studied with previously defined traction supply system parameters and locomotive configuration.

The results of the thesis are published in the following papers: [S10]-[S14], [S18]

Publications

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