

Impact of the modelling of transmission network components on the emission limits for distorting loads in HV system

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Abstract

The paper targets two major issues related to the allocation of harmonic voltage emission limits: modelling of the network components and methodology used for calculation of the voltage emission limits.

Paper consist of five sections, first section gives the background of the problem, second section represents modelling approaches used for modelling of the critical network components, third section describes the methodology used for calculation of the harmonic emission limits, forth section provide description of the developed PowerFactory and Matlab scripts. Two examples of calculated emission limits have been presented in this section as well. The fifth section summarises the presented work and gives conclusions.

Introduction

From the time IEC 61000-3-6 has been written, the characteristics of the power semiconductor switching technology has improved substantially. Power electronic systems have penetrated into almost every branch of the power industry. The growth of the market has pushed the price of semiconductors down, further supporting implementation of power electronics into many new fields.

Today, it is very hard to find any branch of the power industry which is not a potential source of distorting power. Consequently, one of the foundations of the IEC 61000-3-6, that there is some “potentially distorting power” as the component of “the total supply capability” of the network need to be more realistically understood.

The number and strength of the harmonic sources grow every day, further reducing the absorption capability of the network. At the same time, renewable sources do not increase absorption capability of the network when compared to synchronous generators. In addition, renewable sources are themselves additional sources of harmonic currents.

Consequently, the actual absorption capability of the network has to be estimated based on the actual network characteristics, and must be divided among all customers connected to the transmission network.

To utilise the absorption capability of the HV network in the best way, the calculation of the emission limits for distorting loads in HV system has become more complex and demanding. More often than not, the simplified assessment is no longer adequate, taking into account that almost all industrial installations are “important distorting installations”.

To improve the allocation methodology on individual emission limits for distorting load, we have developed a tool based on two software packages: PowerFactory and Matlab.

The tool calculates emission limits according to the methodology presented in the Appendix E of the IEC 61000-3-6 Standard.

The total potential distorting power is thus a function of the frequency as well as the influence coefficients. The effects of resonance phenomena at some frequencies can be analysed and their impact on the emission allocation can be evaluated taking into account the existing background harmonics, coincidence factor and summation law exponent for different harmonics.

The methodology has been applied at two connection points, one weak and the other strong. The results have been presented and analysed. Furthermore the network components such as transmission lines, transformers, and shunt elements have been modelled with different levels of complexity as part of the sensitivity analysis. The emission limits for distorting loads allocated based on the different network models have been presented and analysed.

Frequency scan analysis

Frequency scan analysis is commonly used in filter design. Analysis involves the derivation of the frequency response of a network looking from individual bus.

The nodal admittance of the network at frequency f has the form:

$$[Y_f] = \begin{bmatrix} Y_{11} & \cdots & Y_{1n} \\ \vdots & \ddots & \vdots \\ Y_{n1} & \cdots & Y_{nn} \end{bmatrix}$$

where Y_{ki} is the mutual admittance between busbars k and i at frequency f , and Y_{ii} is the self admittance of busbar i at frequency f . For each frequency of interest a separate system admittance matrix must be generated.

The impedance matrix may be obtained by matrix inversion.

PowerFactory calculates frequency dependent impedances for a given frequency range using *ComFswEEP*. Frequency Sweep has been used for computation of self- and mutual- network impedances as the part of the software packages presented in this paper.

An important aspect of applying frequency scan analysis is to determine which model best represents the various system components at the required frequency and obtain appropriate parameters for them.

We noticed that the biggest impact on the self and mutual impedance of the busbar is the model of the transmission lines. There is a substantial difference between self impedance of the busbars if the transmission lines have been modelled as lumped parameters (Pi model) or if the line has been modelled as the distributed parameters model. The modelling of the skin effect of the transmission line also has noticeable impact on the self and mutual impedances of the busbar.

The modelling of the skin effect of the transformers and reactors did not have significant impact on the self and mutual impedance of the busbar.

For the randomly chosen busbar, the self impedance and network impedance angle have been calculated and presented in the paper; see Figure 1 and Figure 2. However, conclusions have been made on broader analysis. Both busbar characteristics have been calculated for two instances; all

transmission lines have been modelled by the Pi model, and all transmission lines have been modelled by the distributed line model.

There is insignificant difference between the busbar characteristics for the harmonics lower than 9th harmonic; see Figure 1 and Figure 2.

The differences between the busbar characteristics became more significant as the harmonic order increased. It is important to notice that the network impedance angle changes its sign as well as amplitude at different harmonics as a result of different transmission line models.

Consequently, it is important to use the distributed parameter line model for all transmission lines for the frequency scan analysis. The discrepancy caused by different line models can have significant impact on the filter design and characteristics of the filter.

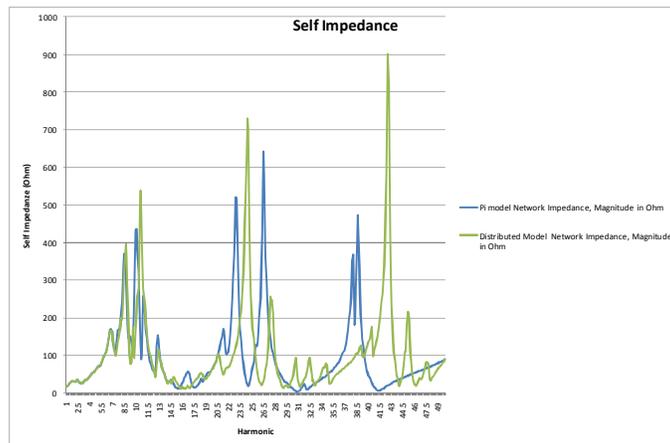


Figure 1. Self impedance (Pi line model / Distributed parameters line model)

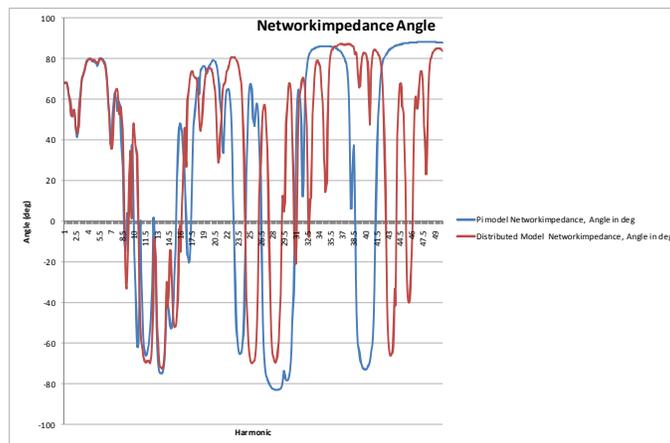


Figure 2. Network impedance Angle (Pi line model / Distributed parameters line model)

It has been published (Jos Arrillaga; Neville R. Watson; Power System Harmonics) that the transformer leakage admittance is equal:

$$Y_{th} = \frac{1}{R\sqrt{h} + jX_l h}$$

where R is the resistance at fundamental frequency and X_l is the transformer's leakage reactance. The variation of the transformer's resistance with the frequency is equal to the square root of the

harmonic order. The magnetising admittance can be ignored under normal operating conditions since there is no significant contribution of the magnetising admittance in this working regime. Modelling of the skin effect of transformers has insignificant impact on the amplitude of self impedance and amplitude of network impedance angle; see Figure 3 and Figure 4. The skin effect does not have any impact on the resonant frequencies as well.

The skin effect of the transformers contributes insignificantly to the accuracy of the busbars self impedance. Therefore to simplify frequency scan analysis the modelling of the skin effect of the transformers can be omitted.

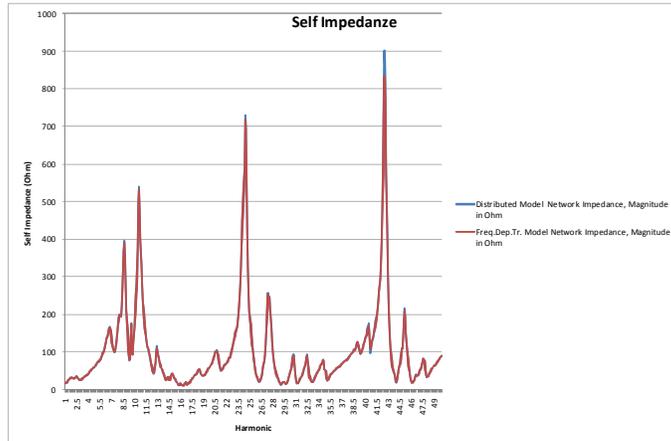


Figure 3. Self Impedance (Distributed line model / Freq. dep. resistance of Tr.)

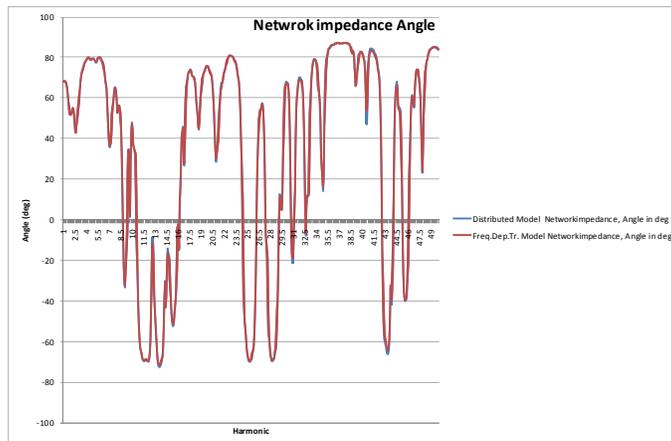


Figure 4. Network Impedance Angle (Distributed line model / Freq. dep. resistance of Tr.)

The analysis of the skin effect of the transmission line required rigorous mathematical analysis. The internal impedance of the conductor can be expressed as:

$$Z_c = \frac{j\omega\mu_0}{2\pi} \frac{1}{x_e} \frac{J_0(x_e)N'_0(x_i) - N_0(x_e)J'_0(x_i)}{J'_0(x_e)N'_0(x_i) - N'_0(x_e)J'_0(x_i)} \quad (*)$$

where

$$x_e = j\sqrt{j\omega\mu_0\sigma_c} r_e$$

$$x_i = j\sqrt{j\omega\mu_0\sigma_c} r_i$$

r_e the external radius of conductor (m)

r_i the internal radius of conductor (m)

J_0 is the Bessel function of the first kind and zero order

- J'_0 is the derivative of the Bessel function of the first kind and zero order
- N_0 is the Bessel function of the second kind and zero order
- J''_0 is the derivative of the Bessel function of the second kind and zero order
- σ_c is the conductivity of the conductor material at the average conductor temperature
- $\omega = 2\pi f$
- f is frequency (Hz)
- μ_0 is the permeability of free space

It is obvious from the equation (*) that both resistance and reactance are nonlinear function of the frequency. The Bessel functions and derivatives of Bessel functions can be solved only by means of their associated infinite series. Unfortunately in many cases convergence issues encountered and required accuracy cannot be achieved.

NGC (UK) and EDF (France) developed correction factors to model skin effect in overhead lines; see Table 1 (Jos Arrillaga; Neville R. Watson; Power System Harmonics).

Table 1: Correction factors for skin effect in overhead lines

	Voltage (kV)	Harmonic order	Resistance
NGC	400, 275	$h \leq 4.21$ $4.21 < h \leq 7.76$ $h > 7.76$	$R_1 \left(1 + \frac{3.45h^2}{192 + 2.77h^2} \right)$ $R_1(0.806 + 0.105h)$ $R_1(0.267 + 0.485\sqrt{h})$
NGC	132		$R_1 \left(1 + \frac{0.6465h^2}{192 + 0.518h^2} \right)$
EDF	400, 225	$h \leq 4$ $4 < h < 8$ $h > 8$	$R_1 \left(1 + \frac{3.45h^2}{192 + 2.77h^2} \right)$ $R_1(0.864 - 0.024\sqrt{h} + 0.105h)$ $R_1(0.267 + 0.485\sqrt{h})$
EDF	150, 90		$R_1 \left(1 + \frac{0.646h^2}{192 + 0.518h^2} \right)$

It has been stated (Jos Arrillaga; Neville R. Watson; Power System Harmonics) that skin effect has effect on the resonant voltage magnitude of transmission line. The series resistance and shunt conductance are dominant system components at the resonance. The impact of the series resistance is negligible if the transmission line is not at resonance.

For all summarised correction factors for skin effect in overhead lines, see Table 1, the ratios R_n/R_1 (resistance of the h^{th} harmonic over resistance of first harmonic) have been plotted on the Figure 5. Frequency dependencies of the resistance of the transmission lines have been modelled as vector characteristic and as frequency polynomial characteristic.

The two different modelling strategies of skin effect have been applied separately for the same busbar and identical network configurations, for multiple cases. The result summarised and presented in the paper is only one example of the analysis performed.

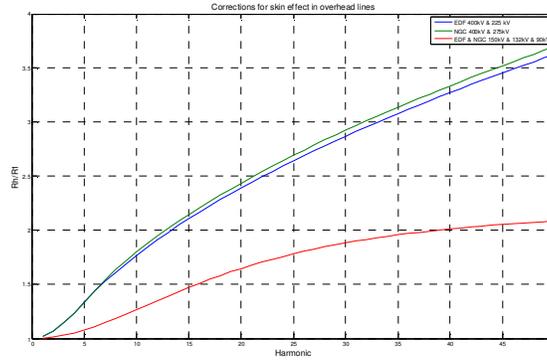


Figure 5: Correction for skin effect in overhead lines according to EDF & NGC

PowerFactory has only one form of the frequency polynomial characteristic:

$$k(f) = (1 - a) + a * \left(\frac{f}{f_{nom}}\right)^b \quad (**)$$

For the known functions of the correction factors, see Table 1, the coefficients a and b , see Equation (**), have been calculated as a minimum of a scalar function of several variables, *fminsearch* (Matlab). *fminsearch* uses the *Nelder-Mead* simplex algorithm.

The coefficients a and b have been calculated and summarised in Table 2.

Table 2: Coefficients a and b ; the frequency polynomial function; skin effect in overhead transmission line

	Voltage (kV)	Coefficient a	Coefficient b
NGC	400, 275	0.2401	0.6434
NGC	132	0.0985	0.6562
EDF	400, 225	0.2286	0.6486
EDF	150, 90	0.0985	0.6562

The frequency polynomial characteristic of the series resistance developed for the high voltage transmission lines 400 kV, 275 kV and 225 kV correlate with the origin functions published by NGC (UK) and EDF (France) satisfactorily; see Figure 6 and figure 7.

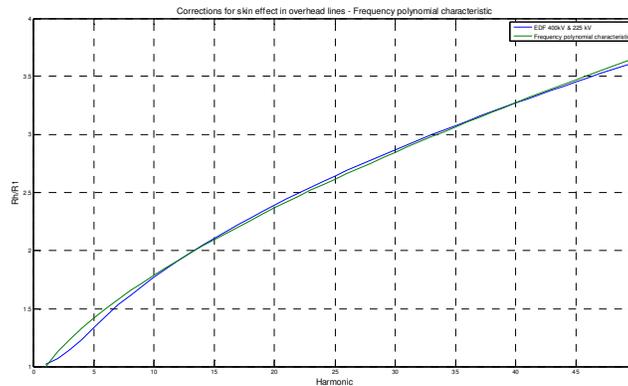


Figure 6: Correction for skin effect in over headlines - EDF 400 kV & 225 kV / Frequency polynomial function

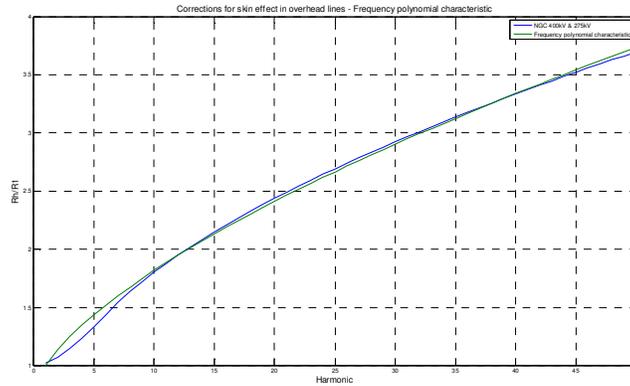


Figure 7: Correction for skin effect in over headlines - NGC 400 kV & 275 kV / Frequency polynomial function

Correlation of the polynomial characteristic of the series resistance of the transmission line for the voltage levels 150 kV, 132 kV and 90 kV is not equally good as the correlations of analysed functions for the higher voltage levels, see Figure 8.

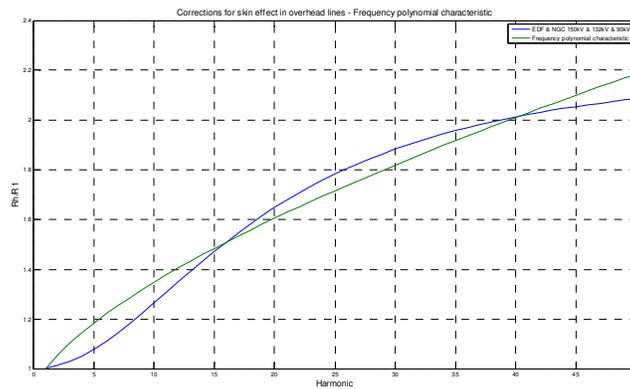


Figure 8: Correction for skin effect in over headlines - EDF / NGC 150 kV / 132 kV and 90 kV - Frequency polynomial function

The self impedances and mutual impedances of several busses have been calculated and analysed for the series resistance of the transmission lines calculated according to the frequency polynomial functions and vector characteristics calculated according to the equations summarised in the Table 1. The vector characteristics have been calculated with 1 Hz step and linearly approximated between two adjacent points.

We had chosen not to present all analysed cases in this paper. The self impedance and network impedance angle calculated according to frequency polynomial functions and vector characteristics for the chosen busbar have been plotted on the Figure 9 and Figure 10 respectively.

The following general conclusions related to the self impedances of the busbar concerning different modelling approaches of the skin effect can be made:

- There is no significant impact of the modelling of the skin effect on the complex self impedance for the harmonic lower than 8th harmonic.
- The impact of the skin effect on the self impedance of the busbar increase with the order of the harmonic
- Skin effect has the biggest impact on the busbar self impedance at resonance frequencies. At resonance frequencies, the amplitude of the self impedance can be reduced up to 50% if the

skin effect of the transmission lines has been modelled. Taking this into account the modelling of the skin effect of transmission lines can be seen as being critical for all frequency scan analysis.

- Modelling of skin effect does not have any impact on the resonance frequencies of the self impedances
- There are no significant differences between two analysed modelling methodologies of the skin effect: the frequency polynomial functions and vector characteristics. The frequency polynomial function is simpler and much easier to apply which is a major advantage of this methodology.
- We notice that modelling of the skin effect has impact on the network impedance angle; however we are not able to identify any importance of this on the filter design or harmonic allocation.

The conclusions that have been made to the busbar self impedance can be extended to the mutual impedance as well.

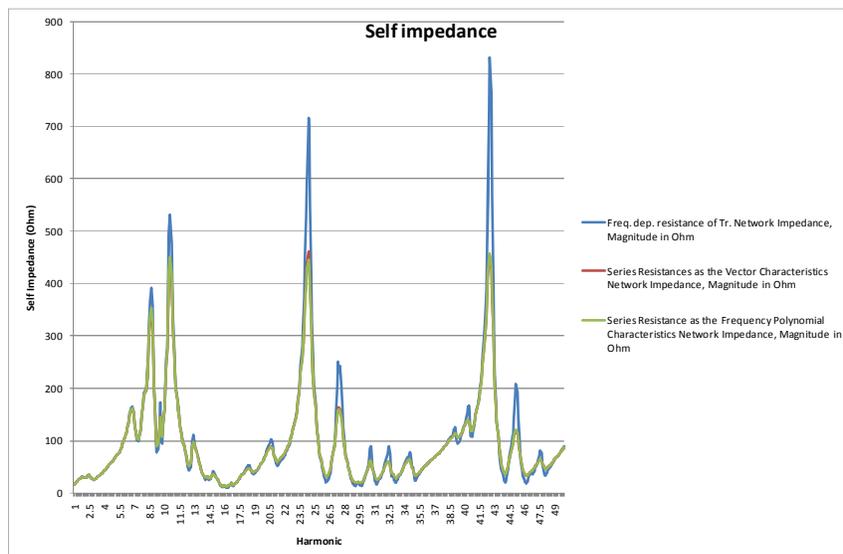


Figure 9: Self impedance taking into account skin effect of the series resistance of the transmission lines

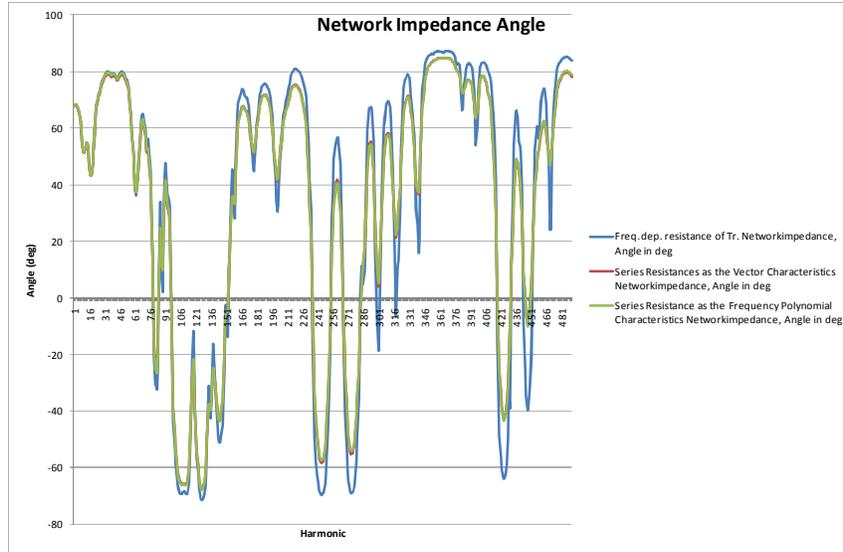


Figure 10: Network Impedance Angle taking into account skin effect of the series resistance of the transmission lines

Emission limits for distorting loads in HV - EHV systems

Emission limits for distorting loads in HV/EHV systems can be calculated according Stage 1 or Stage 2 methodology. Stage 1 is a simplified evaluation methodology that can be applied only for relatively small distorting loads connected to a strong busbar.

If the ratio of the admissible distorting power (S_{Di}) and network short circuit power at the point of common coupling (S_{SC}) is:

$$\frac{S_{Di}}{S_{SC}} \leq 0.1 - 0.4 \% (HV) \quad \text{or}$$

$$\frac{S_{Di}}{S_{SC}} \leq 0.1 - 0.2 \% (EHV)$$

the emission limits may be proposed as Stage 1 limits.

Stage 2 emission limits methodology is based on assessing the total available power and actual network characteristics. Stage 2 distinguishes two approximations. The software package presented in this paper has been based on the second approximation of Stage 2.

Stage 3 allows flexible interpretation of the Standard still preserving the general principles of the Standard.

If the existing background distortion and expected contribution from the considered loads are not causing significant harmonic voltages, Stage 3 can be used to endorse emission limits higher than the values calculated according to Stage 1 or Stage 2 methodology. Stage 3 requires special arrangements if the corrective measures are necessary in future.

It is well known that the simple approach explained in the first approximation of the Stage 2 is not correct if an important distorting load is connected in the neighbourhood of the considered load. Consequently we decided to use second approximation of the Stage 2 of the Standard as the foundation for calculation of the emission limits.

According to the Standard, S_t the total available power of the network at the point of common coupling can be expressed by the equation:

$$S_t = S_{t1} + K_{h2-1}S_{t2} + K_{h3-1}S_{t3} + \dots$$

where:

- 1 is the considered node and 2, 3, ... the other nodes
- $S_{t1}, S_{t2}, S_{t3}, \dots$ the total available power of the network at the point of common coupling (total supply capability)
- h harmonic order
- $K_{h2-1}, K_{h3-1}, K_{h4-1}, \dots$ the influence coefficients. The influence coefficient K_{hj-i} is the harmonic voltage of order h which is caused at node i when 1 p.u. harmonic voltage of order h is applied at node j .

To minimise manual calculations and data processing, we decided to evaluate S_t for the full network model of Queensland. The same approach can be applied on any network. The 'power living busbar', taking into account previously made presumption, is equal to the load connected to the analysed busbar. Consequently $S_{t1}, S_{t2}, S_{t3}, \dots$ the total available power of the network at the point of common coupling is the list of the connected loads of the analysed grid. The specially developed PowerFactory script creates list of the connected loads for the calculation of the harmonic emission limits.

The 1 p.u. harmonic voltage of order h applied at node j will cause current I_{h-jj} through the self impedance Z_{h-jj} of bus j .

The harmonic voltage of order h caused at node i when 1 p.u. harmonic voltage of order h is applied at node j can be approximated with the product of the mutual impedance of the order h between buses i and j Z_{h-ij} and current I_{h-jj} .

By definition, as presented in the Standard, the calculated harmonic voltages are the influence coefficients.

The Matlab script calculates all influence coefficients for the analysed grid.

For the known MVA rating of the load S_i at each harmonic order h , the allowed contribution E_{UHi} to the planning level L_{hHV} can be expressed as:

$$E_{UHi} = \frac{(L_{hHV}^\alpha - B_h^\alpha)^{\frac{1}{\alpha}}}{K_{hi-j}} \sqrt{\frac{S_i}{(S_t - S_B) F_{HV}}} \frac{1}{F_{HV}}$$

where

- E_{UHi} is the voltage emission limit of a consumer i at harmonic h
- L_{hHV} is the planning level of the h^{th} harmonic in HV or EHV systems see Standard
- S_i is the rating of the consumer
- α is the summation law exponent, see Standard
- F_{HV} is the coincidence factor for HV loads, typical values are between 0.4 and 1.
- B_h is the background harmonic level higher than normal share
- S_B is the already connected power responsible for background level B_h
- K_{hi-j} is the greatest influence coefficient greater than 1. If for a given harmonic number all influence coefficients are smaller than 1, K_{hi-j} is equal to 1. The resonances at some frequencies may appear at points in the network remote from the connection point. To ensure harmonic voltages at the remote buses lower than planning level the emission limit should be corrected for the amplification gained through the resonance effect.

For the known voltage emission limits the acceptable current harmonic emission limits can be expressed as:

$$E_{IHi} = \frac{E_{Uhi}}{Z_h}$$

where

E_{IHi} is the current emission limit of a consumer i at harmonic h
 Z_h is the self impedance at node i at harmonic h

Current and voltage emission limits PowerFactory and Matlab scripts

The software package developed for allocation of voltage and current emission limits for distorting load consist of the several scripts developed as PowerFactory DPL scripts and Matlab script.

The DPL PowerFactory scripts perform frequency scan analysis and prepare input data for calculation of the influence factors and total available power for each bus.

The Matlab script has as the input data: Frequency Sweep data calculated by PowerFactory (self and mutual impedances), nominal voltage of all buses, and apparent (complex power) of all loads. Additionally Matlab script has as the input the planning levels for harmonic voltage expressed in percent of the nominal voltage; in our case we accepted the indicative values published in the Standard, as the planning levels. The existing background harmonics expressed in the percent of the nominal voltage are required as the input data, see Figure 11. The background harmonics are accomplished by the connected power responsible for the background harmonics.

The summation exponents for harmonics have been offered as 1 for all harmonics lower than 5th harmonic, 1.4 for all harmonics in between 5th and 10th harmonics, and 2 for all harmonics higher than 10th harmonic. The suggested values can be accepted or replaced with any suitable values of choice.

Additionally, for the purpose of the sensitivity analysis, we defined following variables: future growth of the load (expressed in the percentage of the load), potential distorting power which can be varied from 0 to 1; where 0 is there is no distorting power and 1 is whole load is distorting.

The Matlab script can perform sensitivity analysis related to the total supply capability of the connected loads. The software can take into account participation of all connected loads in the harmonic share or calculation can take into account only participation of the loads which are bigger than some percent of the analysed load.

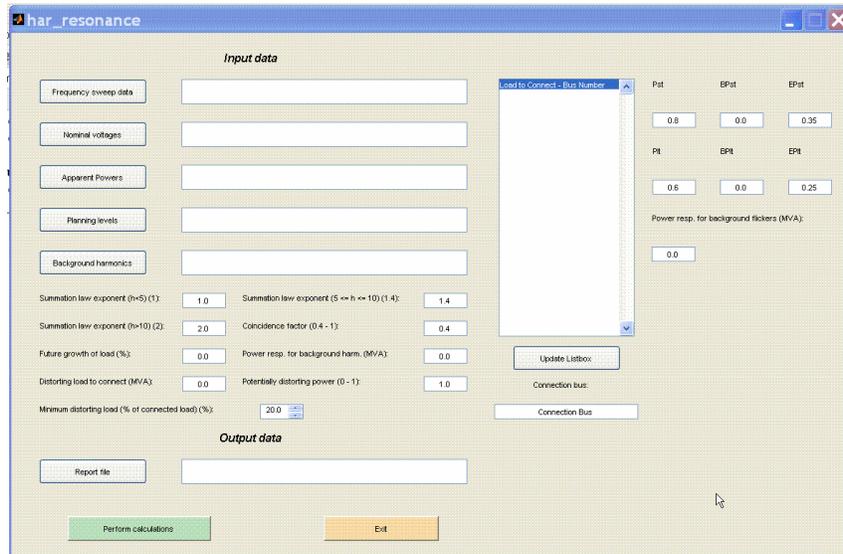


Figure 11: Input user interface of the Matlab script

The Matlab script creates Excel file as the report file. The report file is very extensive. The report file consists of the 14 spread sheets. Some of those are mainly for the evaluation and checking of the calculation methodology.

Besides voltage and current emission limits, the Matlab script also creates the list of the resonance frequencies and participating buses, list of the nominal voltages of all buses, list of the apparent power of all consumers, the voltage planning level of all harmonics, list of the existing background harmonics, list of the general input data used in calculation such as (summation law exponents, coincidence factor, expected future growth of load, etc.), list of distorting power and total distorting power for all harmonics, influence coefficients for all harmonics, list of the contribution of other loads in the total available power of the network at the analysed bus, and the self impedance at the connection busbar.

In this paper, we have presented voltage and current emission limits calculated for two different loads: 40 MVA load connected to a relatively weak bus at 132 kV, and 500 MVA load connected to the 275 kV strong network point.

First, we analysed the impact of modelling of the network components on the emission limits, see Figure 12.

We noticed that the biggest impact on the emission limits is the way the transmission lines have been modelled. It seems that the Pi equivalent models of the transmission lines are not adequate in most cases especially for the harmonics of higher order, see Figure 12.

The modelling of the skin effect for the transformers and transmission lines increase the emission limits. The increment is more obvious for the harmonics with higher order. However the skin effect does not have significant impact on the emission limits.

The skin effect of the transmission lines can be modelled according to one of two approaches presented in the paper.

The emission limits for all harmonics have showed insignificant variation as a result of different modelling techniques of skin effect of transmission lines. Consequently it is possible to conclude that the technique used for modelling of the skin effect of the transmission lines does not impact significantly on emission limits.

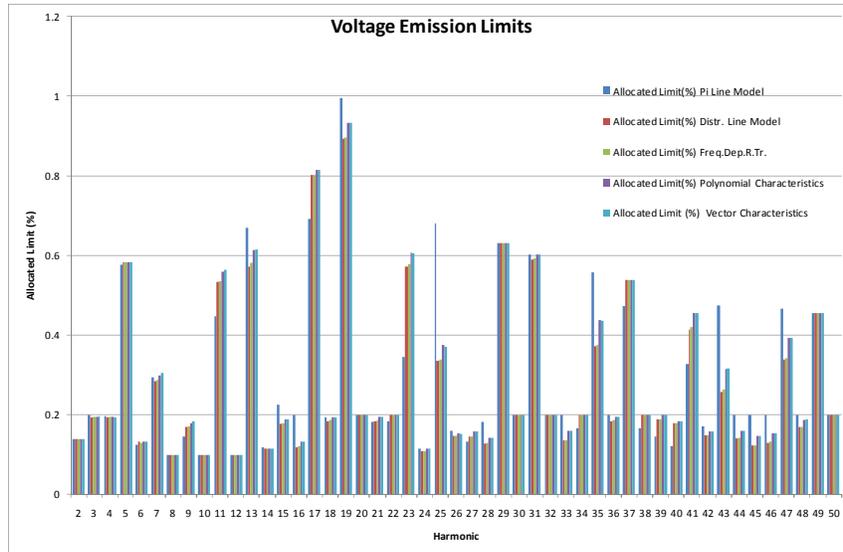


Figure 12: Voltage emission limits, 40 MVA load

The Matlab script calculates voltage emission limits applying two different rules regarding resonance and amplification at remote bus; see Figure 13:

- The first approach calculates the total available power taking into account all resonances and amplifications as a consequence of the resonance. This approach is as prescribed by the Standard.
- The second approach checks influence coefficients for all harmonics. If the influence coefficient is greater than 1, the existing value is going to be replaced by the 1. The total available power calculated this way does not take into account resonance at remote buses and is smaller compare to the value correct in first case. The emission limits calculated this way is consequently smaller. The second approach is not recommended by the Standard and can be used only for purpose of sensitivity analysis. The sensitivity analyses performed this way provides sufficient information about the impact of resonances on the emission limits. The presented information is useful if the emission limits seems too low and some adjustment of the calculated emission limits is necessary.

It is not usual to allocate Current Emission Limits to the new load. From a technical point of view, there is no difference between allocated voltage emission limits and current emission limits. In many cases the voltage emission limits expressed as percentage of the nominal voltage at the connection bus seems very low, however the current which the load can inject into the grid at connection point for many harmonics is around 10 Amperes or even higher, see Figure 14.

As can be expected the emission limits allocated to the significant load 500 MVA connected at the strong connection point are approaching $2/3^{\text{rd}}$ of planning level or even full planning level, see Figure 15. At the same time the allocated harmonic currents are around 50 Amperes, while for some harmonics, the current is approaching 230 Amperes; see Figure 16.

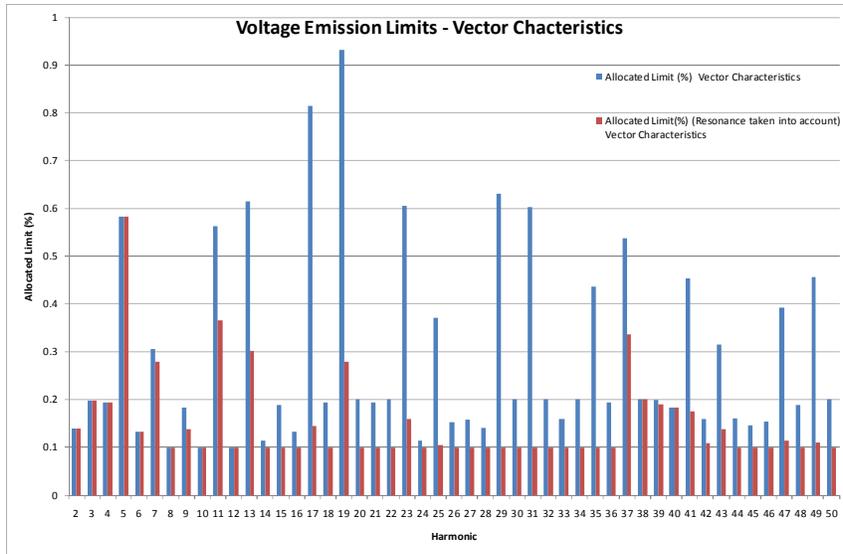


Figure 13: Voltage emission limits with and without resonance effect, 40 MVA load

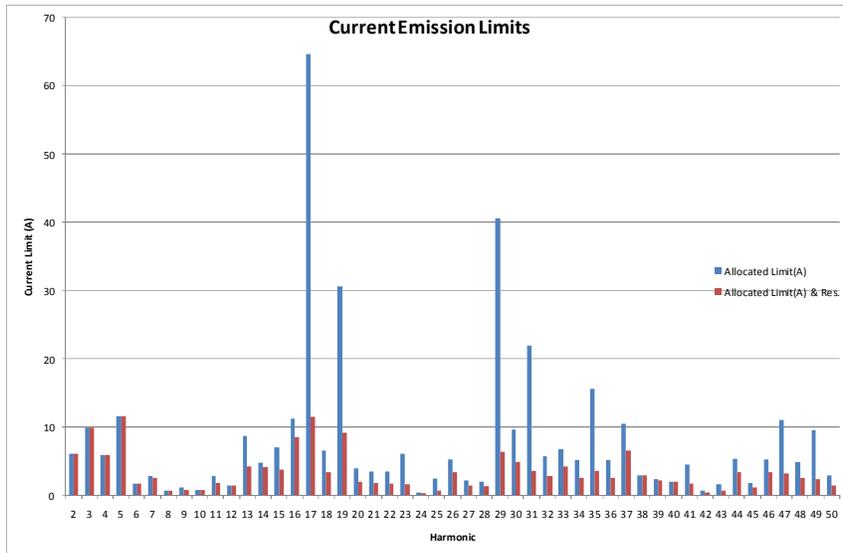


Figure 14: Current emission, 40 MVA load

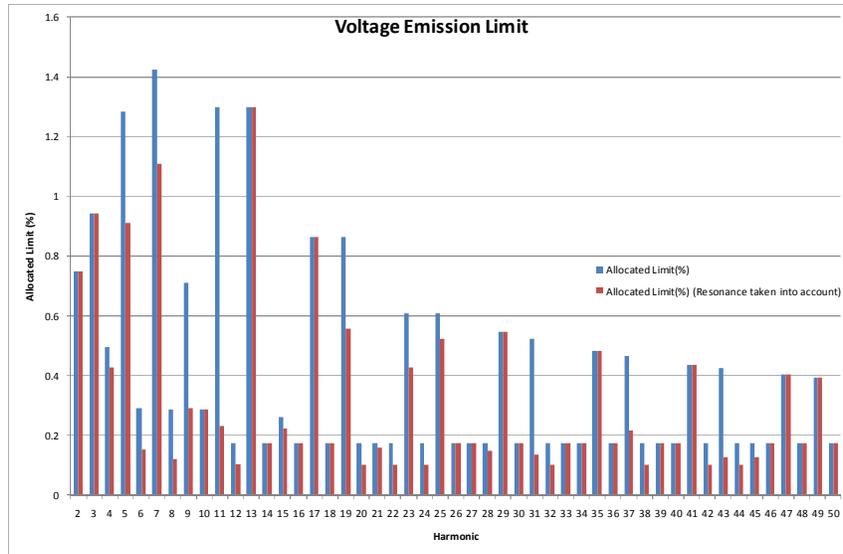


Figure 15: Voltage emission limits, 500 MVA load

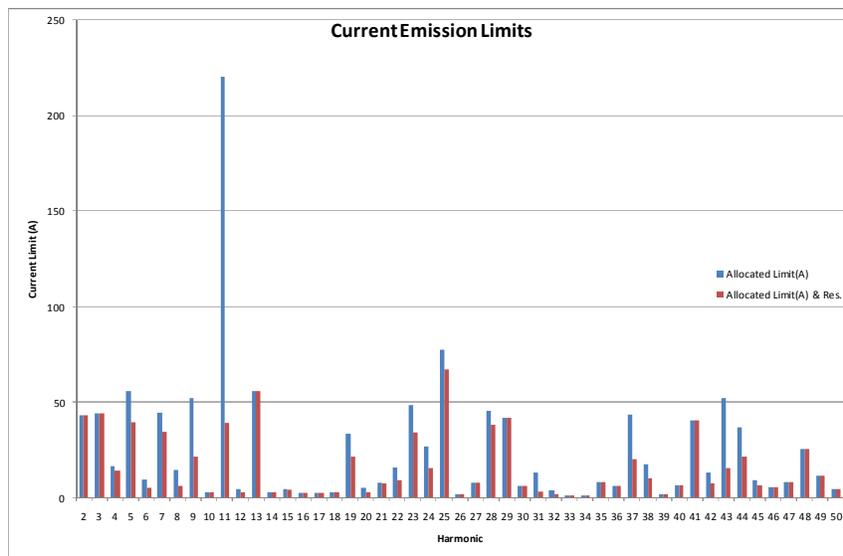


Figure 16: Current emission limits, 500 MVA

Conclusions

The allocation of emission limits for distorting loads is a very demanding task. In many cases, especially for the HV and EHV systems, it is very hard to define the acceptable grey zone. Uncertainty of the network configuration, difficulties related to the modelling of the network components; aging of the network components and temperature dependency of some network components, make the design of the filters very difficult. Coexistence and interaction of these two processes sometimes results in unnecessary compensation of the harmonic currents or unacceptable high harmonics voltages at the common coupling point.

We have not addressed interaction of the emission limits, modelling of the network components and filter design in this paper. However we have noticed the importance of the adequate modelling of the network components and impact of the modelling on allocation of the emission limits.

It is well known that harmonic filters in many cases overcompensate some of the harmonic currents to achieve the approved harmonic voltage at common coupling point for some other harmonics. Also, estimation of coincidence factors and summation law factors are not very accurate. These issues make the calculation of emission limits quite difficult, if the intention of the allocation is to have “just adequate emission limits”.

Our intention was to make at least one step toward more adequate allocation of the emission limits for distorting loads.