A Specialized Software Package Useful In The Analysis Of The Harmonic Current Flow In Networks With Large Power Static Converters

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Abstract: - Together with the wide use of the non-linear elements in the electrical circuits, the appearance of the non-sinusoidal steady state is inevitably. Presently, we cannot speak about the avoidance of this problem and we must find methods to diminishing its negative effects.
In point of importance, the main distorted loads in the electrical networks are the large power converters, the electrical traction belonging to this category. In a real running state, the electrical network contains various circuit elements whose behavior during the harmonic steady state is difficult to be modeled, some computing simplifications being thus compulsory. Due to the cumulative effect, these simplifications can lead to an incorrect interpretation of facts, both from a quantitative and qualitative point of view. This is why it is recommended to use a specialized software package that allows the analysis of a complex electrical network in a non-sinusoidal state and which offers the possibility of simulating different energetic situations in which the network can run at a certain moment.

Key-Words: - power static converters, distorted steady state, harmonics

1 Introduction

From the harmonic point of view, for the study of an electrical network we must, first of all, make sure that the configuration of the network and the harmonic impedances of the system are known. For the fundamental frequency, the parameters of the network may be considered as having practically constant values, but with different frequencies their values modify.

The simultaneous study of the non-symmetrical and non-sinusoidal states using the three-phase model is difficult to achieve. That is why in the analysis of the non-sinusoidal state it is recommended to use the single-phase analysis, by considering the network to be symmetrical and by reducing it to a single phase.

The knowledge in detail of the network’s structure, in different running states, allows the design of an exact computing scheme, avoiding thus the possible errors that might occur when simplified schemes are used. Another requirement in the harmonic studies of the electrical networks is the knowledge of the frequency characteristic of the equivalent impedance [1], [2].

Large power converters [of MW order] represent the main source of harmonics in the power system [1], [2]. The electrical railway traction represents, at present, from the harmonic studies point of view, a non-linear concentrated load. The harmonic currents produced by it flow to the power system, to the capacitor banks and to the other linear or non-linear loads connected to the network.

In real operating conditions, referring to a point of the network, if the harmonic source is far away, it acts as an ideal harmonic voltage generator and if it is close it acts as an ideal harmonic current generator.

2 Software Package Presentation

The study of the frequency characteristic of the impedance seen from the harmonic generator bars, the behaviour of each of the network’s branch that is passed by the harmonic current and their contribution to the eventually amplifications of the voltages, represent decisive elements in harmonic current flow control in an electrical network [1], [2].

The railway traction represents an electrical load variable in time, the load variation being accompanied by a variation of the required power from the network. An important characteristic of the time evolution of the harmonic states is that it is the same for a long period of time (i.e. a year). In real operation states, for a given point of the network, if
The harmonic source is far away it works as an ideal harmonic voltage generator and if it is close, as a current one [3]. In the analyzed case, the electrical equipment of the locomotive, the main non-linear element of the circuit, is replaced with an ideal harmonic current generator, the other circuit’s elements being replaced with their harmonic impedances.

The equivalent scheme of the network that supplies the electric traction, reduced to a single phase is presented in Fig.1.

![Equivalent Scheme of the Network](image)

**Fig.1** - The equivalent single-phase scheme of a network that supplies the electric traction

The following notations were used: $Z_1$ - the system impedance seen from the 110 kV bars; $Z_L$ - the 110 kV line impedance which supplies the substation; $Z_T$ - the impedance of the supplying transformer 110/27.5 kV; $Z_{T1}$ - the impedance of the transformer of the electric locomotive 27.5/1 kV; $Z_B$ - the impedance of the capacitor bank installed on the electric locomotive; $Z_L$ - the impedance of the linear equivalent load supplied from the same 110 kV bars as the substation; $Z_D$ - the impedance of the equivalent power factor capacitor bank; $I_m$, $m = A, B, I, L, D$ - the harmonic current that flows in each of the branches of the network. The harmonic current on each of the network’s branches, $I_m$, may be estimated, depending on the harmonic current injected by the harmonic generator, $I_h$, with the help of some complex quantities, $\alpha_m$, defined as follows:

\[
I_m = \alpha_m I_h, \quad (m = A, B, I, L, D)
\]

\[
\alpha_B = \frac{Z_T + Z_l + Z_N}{Z_{T1} + Z_B + Z_T + Z_l + Z_N},
\]

\[
\alpha_D = \frac{Z_T + Z_B}{Z_{T1} + Z_B + Z_T + Z_l + Z_N},
\]

\[
\alpha_l = \frac{Z_l Z_D}{Z_l + Z_D},
\]

\[
\alpha_a = \frac{Z_l Z_D}{Z_l + Z_D},
\]

\[
\alpha_B = \frac{Z_l Z_D}{Z_l + Z_D},
\]

\[
\alpha_D = \frac{Z_l Z_D}{Z_l + Z_D}.
\]

Here, $\alpha_A$ represents the harmonic current in relative units (r.u.) that flows in the $A$ branch; $\alpha_B$ - the harmonic current (r.u.) absorbed by the capacitor bank installed on the $B$ branch; $\alpha_l$ - the harmonic current (r.u.) that flows to the $L$ and $D$ branches; $\alpha_A$ - the harmonic current (r.u.) that flows to system; $\alpha_D$ - the harmonic current (r.u.) that flows in the $L$ branch (to the linear load); $\alpha_D$ - the harmonic current (r.u.) absorbed by the equivalent power factor capacitor bank.

These quantities satisfy the following relations:

\[
\alpha_A + \alpha_B = 1, \quad \alpha_l + \alpha_A = 1, \quad \alpha_l + \alpha_D = 1.
\]

For the harmonic analysis of this kind of network, the authors imagined a software package that helps the computation of the complex harmonic impedance of the network seen from the 110 kV bars and of the complex harmonic currents (r.u.) that flow in each branch of the network. The variation of the apparent power of the linear equivalent load, of the equivalent reactive power installed on 110 kV bars and of the required power of the non-sinusoidal load can simulate different energetic situations in which the network may run.
The software may run for the implicit values assigned to the variables or for the input data provided by the user as regards the followings:
- the general parameters of the system,
- the distribution line and the parameters of the railway substation,
- the transformers,
- the capacitor banks.

Therefore, for a particular network, the following data must be provided:
- the value of the three-phase short-circuit apparent power [MVA] of the system on the 110 kV bars (S_i),
- the initial value (implicitly 1000);
- the value of the ratio between the reactance and the resistance of the system (n_j) - implicitly 10;
- the length of the 110 kV line [km], (l) - implicitly 5;
- the resistance value on the unit length of the distribution line [Ω/km], (r_0) - implicitly 0.175;
- the value of the voltage at which the harmonic generator is connected [kV], (U_i) - implicitly 27.5;
- the short-circuit voltage of the transformer from the A branch [%], (U_{scA}) - implicitly 10.5;
- the rated three-phase apparent power [MVA] of the transformer from the A branch (transformer 110/27.5 kV), (S_{nA}) - implicitly 16;
- the total active power losses of the transformer from the A branch [kW], (P_{eA}) - implicitly 108;
- the short-circuit voltage of the transformer from the B branch [%], (U_{scB}) - implicitly 7;
- the rated three-phase apparent power [MVA] of the transformer from the B branch (transformer 27.5/1 kV), (S_{nB}) - implicitly 10;
- the total active power losses of the transformer from the B branch [kW], (P_{eB}) - implicitly 81;
- the initial value (implicitly 1 E-10), final value (implicitly 20) and the variation rate (implicitly 0.1) for the reactive power [MVAr] installed on the B branch, (Q_B);
- the value of the ratio between the reactance and the resistance of the capacitor bank for the branch B, (n_{bB}) - implicitly 5000;
- the initial value (implicitly 1 E-10), final value (implicitly 20) and the variation rate (implicitly 0.1) for the reactive power [MVAr] installed on the D branch, (Q_D);
- the value of the ratio between the reactance and the resistance of the capacitor bank for the branch D, (n_{bD}) - implicitly 5000;
- the initial value (implicitly 5), final value (implicitly 29) and the variation rate (implicitly 3) for the reactive power [MVAr] required by the L branch, (Q_L);
- the initial value (implicitly 10), final value (implicitly 100) and the rate of variation (implicitly 10) for the active power [MW] demanded by the L branch, (P_L);
- the initial value (implicitly 50), final (implicitly 1150) and the variation rate (implicitly 10) for the frequency, (f);
- the r.m.s. value of the harmonic current injected by the harmonic generator, (I_{h}) – implicitly 1.

The situation when the power factor capacitor banks or those on the railway engine are not connected is focused upon by assigning the 1 E-10 value to Q_D, respective Q_B.

The user can obtain the running results of the software concerning the frequency value, the r.m.s values and the arguments of the complex equivalent impedance and of the harmonic current from each of the branches. The software allows, through the chosen variation rate of the frequency, the determination of those frequencies for which the equivalent impedance at the generator bars takes extreme values, with the possibility of finding out in which conditions the series or parallel resonances may appear. In order to identify the extreme values of each quantity, the software has been provided with a special option. By using the Extreme Option, the extreme values can be determined more quickly.

We must however specify which quantity is analysed (Z_e, α_A, α_B, α_D, α_L, α_D, ) with the loop variation of the f, Q_B, Q_D, Q_L, P_L quantities. When an extreme value was found, five values are displayed, two before and two after the critical point, together with the values taken by the frequency and by Q_B, Q_D, Q_L, P_L. The results of every running session of the software are displayed in Microsoft Excel, where the facilities offered can be used.

### 3 Harmonic State Analysis

Considering an electrical network of a given structure and corresponding to a certain energetic situation, we can analyse the harmonic variation of the equivalent impedance seen from the bars of the harmonic generator and the influence of different quantities upon it. For example, Fig. 2 shows how the harmonic current flows in different branches (the variation of the α coefficients) versus the harmonics order, for the situation in which the compensation of the reactive power is maximum,

\[
Q_B = 2.7, Q_D = 3.6 [MVAr].
\]

In the studied harmonic domain there take place three resonances. The first is a parallel one,
corresponding to the frequency \( f_{1P} \), a series one corresponding to \( f_{1S} \) and again a parallel one corresponding to \( f_{2P} \). On each harmonic, the currents are in phase or in opposition with the injected harmonic current.

\[
\begin{align*}
&\alpha_B (Q_B=2.7, Q_D=3.6) \\
&\alpha_1 \\
&\alpha_D \\
&\alpha_L
\end{align*}
\]

**Fig.2** - The harmonic currents flow in different branches (the variation of the \( \alpha \) coefficients) vs the harmonics’ order for the situation in which the compensation of the reactive power is maximum.

For frequencies lower than \( f_{1P} \) most of the harmonic current flows to the system and less to the linear receiver (\( \alpha_1 > \alpha_B > \alpha_D > \alpha_L \)). The quantities \( \alpha_m \), \( m=1,B,D,L \) show the availability in receiving the harmonic current of that branch, a high value meaning a high availability. The values on fundamental are low but have a high positive slope, a parallel resonance being prepared. The phases of the quantities \( \alpha_B \) and \( \alpha_L \) are approximately the same and are shifted 180 degrees in comparison with the phases of the quantities \( \alpha_B \) and \( \alpha_D \).

Corresponding to the \( f_{1P} \) frequency, the current that oscillates between the inductive reactance of the system and the capacitive reactance of the capacitor bank from the 1 kV bar is high because the current that corresponds to the harmonic which order is close to this frequency has an important amount. This current determines an important distortion of the voltage wave. The current that flows in the capacitor bank is 1.7 times higher than the fundamental current and can lead to the burn of the fusible and to the disconnection of a part of the battery.

Through the 110/27.5 kV transformer flows a current whose value equals the current that flows through the capacitors connected at the 1 kV bar. The distortion factor may exceed the imposed requirements. If the load of the transformer is high it works in the zone of non-linearity and it becomes a new source of harmonic current.

To the system can flow an important harmonic current because, corresponding to the parallel resonance frequency, the absorption coefficient \( \alpha \) is of an important value. Also, the voltage wave distortions on this side may be important.

The batteries connected for power factor improvement are less subject to important harmonic current flow as, for the first harmonic parallel resonance, the absorption coefficient \( \alpha \) of the harmonic current is low.

The linear consumer is passed, for the first parallel resonant frequency, by a small harmonic current and is less affected by the appearance of this state.

For frequencies \( f_{1P} < f < f_{1S} \), the harmonic current flow through the capacitors connected at the 1 kV bar becomes prevalent (\( \alpha_B > \alpha_1 > \alpha_D > \alpha_L \)); the \( \alpha_B \) coefficient takes values relatively important and can amplify the low-order odd harmonics that fall within this frequency domain so that, the effective or peak value becomes dangerous for capacitors.

All coefficients \( \alpha_m \) have a descending slope and prepare the emergence of a series resonance. The capacitor banks from the D branch and the linear consumer are less affected on this frequency range. The phase shift between \( \alpha_1 \) (its argument is about 180 degrees) and \( \alpha_L, \alpha_B \) and \( \alpha_D \) is almost 180 degrees.

For the frequency corresponding to the series resonance, the capacitive reactance of the capacitors from the 1 kV bar and the network’s equivalent inductive reactance seen from the same bar created a filter for the current of the same frequency.

The coefficients of absorption of all sides \( \alpha_m \), \( m=1,B,D,L \) take small values, the most important current passes through the capacitors from 1 kV bar.

For the frequency \( f_{1S}, \alpha_1, \alpha_B \) and \( \alpha_L \) are parallel (their arguments taking values around zero) and in opposition with \( \alpha_D \) (its argument taking values around 180 degrees).

For frequencies higher than \( f_{1S} \), the availability in receiving the harmonic current of the power
factor improvement capacitor branch, of the system and of the linear receiver increase and of the branch which contains capacitors connected at the 1 kV bar decreases.

After a certain frequency, $\alpha_L$ and $\alpha_D$ become dominant, $\alpha_L$ being small. The linear consumer absorbs the lowest harmonic current. The phase shift between $\alpha_1$, $\alpha_B$, and $\alpha_L$, is approximately zero (their arguments taking values close to 0 degrees) and is 180 degrees regarding $\alpha_D$. Since the availability in receiving the harmonic current of each side do not reach significant levels and the currents corresponding to these frequencies are small, for this frequency domain phenomena are not expected to deviate from normal functioning.

For the second parallel resonance, between the reactance of the capacitors connected to improve the power factor and the inductive reactance of the system (in particular) is established an energy oscillation. The $\alpha_D$ coefficient does not pose an extreme on this frequency, $\alpha_1$ has a maximum (of a value lower than that corresponding to the first parallel resonance), $\alpha_L$ and $\alpha_D$ have maximums (with upper values than those corresponding to the first parallel resonance). When resonance occurs, arg $\alpha_B$, arg $\alpha_1$, arg $\alpha_L$ are in the first quadrant (values around zero) and in opposition with arg $\alpha_D$ which has values around 180 degrees. From all sides, the system is affected most by the appearance of this resonance observing that the $\alpha_L$ coefficient is big. But, because the harmonic current corresponding to this frequency is small, no particular problems are expected. The operating state is characterized by:

- the capacitors from the 1 kV bar: because of the big current, the fuse can burn and a part of the battery is disconnected; so, the parallel resonant frequency decreases;
- the transformer from the traction substation: operating at a big load, the voltage distortion factor exceeds the maximum required by regulations;
- system: although the harmonic current that flows through the system is the most important as weight, because the short-circuit power at the bars is big, the operation does not deviate from the normal range;
- for the power factor capacitors: even if the second parallel resonance is felt significant by this side, because it takes place on a high frequency it doesn’t cause a significant increase of the current; the operation is registering as normal;

- the linear consumer: regardless the amount of the apparent power requested, the linear consumer is least affected by the existence of the distorting state.

4 Conclusion

The proposed software allows a complex analysis of the distribution networks that supply a concentrated non-linear load running in a non-sinusoidal steady state. It can be useful in the survey of the behavior of the networks where deforming elements of circuit are connected. With the help of the loop variable quantities, different energetic situations in which a complex network may run at a given moment, can be simulated.

The results may be useful in the design process for the establishment of the location where the railway substations must be connected to the power system or in the management process of the distribution networks, by identifying, in imposed situations, concrete solutions of running.

References:


