Evaluation of the Harmonic Impedance of Frydlant (Line 53) Power Network

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Abstract. *The harmonic impedance of the power system is an important quantity, which describes the behaviour of the power system with the existence of different frequencies beside the fundamental. The harmonic study belongs to the most difficult part of the electrical measurements and calculations even by using computer software. The main problem accompanying the calculating methods is to obtain the exact data of the electrical network parameters or to know the exact operational status of the system. In this paper the harmonic impedance of Frydlant (line 53, 22 kV in Czech Republic) power network was calculated by using a very specialized software and suitable for solving such calculations called "NetCalc. version 3.0" [1].*

Keywords

Harmonics, harmonics impedance, resonance and power system.

1. Introduction

The term harmonic impedance means the equivalent spectral impedance of the power system, as seen from the measurement point towards the supply source of the system [2]. From the knowledge of the harmonic impedance of the power system, studied in many literature [3], [4], behavior of the power system becomes well-known for different frequencies, that allows to evaluate the quality of the supply line i.e. its ability for harmonics transfer [5], the risk of failure in case of overload and the risk of resonance between the system and the loads [6]. It is also helps the engineers to make a decision whether it is safe or not to connect a new load to the existing power line or whether to redesign and rebuild the line. Moreover, the harmonic impedance value is used for designing passive harmonic filters and for controlling the active ones [7]. Some methods of harmonic source location also utilize the harmonic impedance value [8].

The electrical power networks are projected and operated at the fundamental frequency 50 Hz. At this frequency the electrical power network usually has total impedance with an inductive character, but with increasing the frequency (for different reasons, such as non-linear loads, line capacities, power factor correction capacitors, etc.) parallel and serial resonances can occur and the total impedance could have a capacitive character.

Non-linear loads are usually defining by harmonic currents, because of that it is frequently preferred to declare a harmonic issuing level in current unit before voltage unit. Because of this reason, it is necessary to transform the harmonic current, which is injected by the non-linear loads, into a harmonic voltage. In order to estimate the level of harmonics send by harmonic source better, we need to know the harmonic impedance of the system side or the user's side in a Point of Common Coupling (PCC); for harmonic currents reflected the non-linear load characteristic, which is usually expressed in current rather than voltage. In order to turn harmonic currents into harmonic voltage, we also need to know the system harmonic impedance [9].

If we declare this impedance with the relation of the frequency, we will get a curve, which is in most cases changing with a time. This relation is called a harmonic impedance. To find out the exact harmonic impedance the measuring method is the way for this, but the calculating methods (frequency and time methods [10]) also give acceptable results. The calculating methods have many problems, because of the lack of data and the computer algorithms are usually one-phase only, but the calculating methods are preferred, because of their great possibilities. By calculation we can make a useful database of the power system for a lot of different variants in a very short time and this will be helpful in the case of changing some parts of

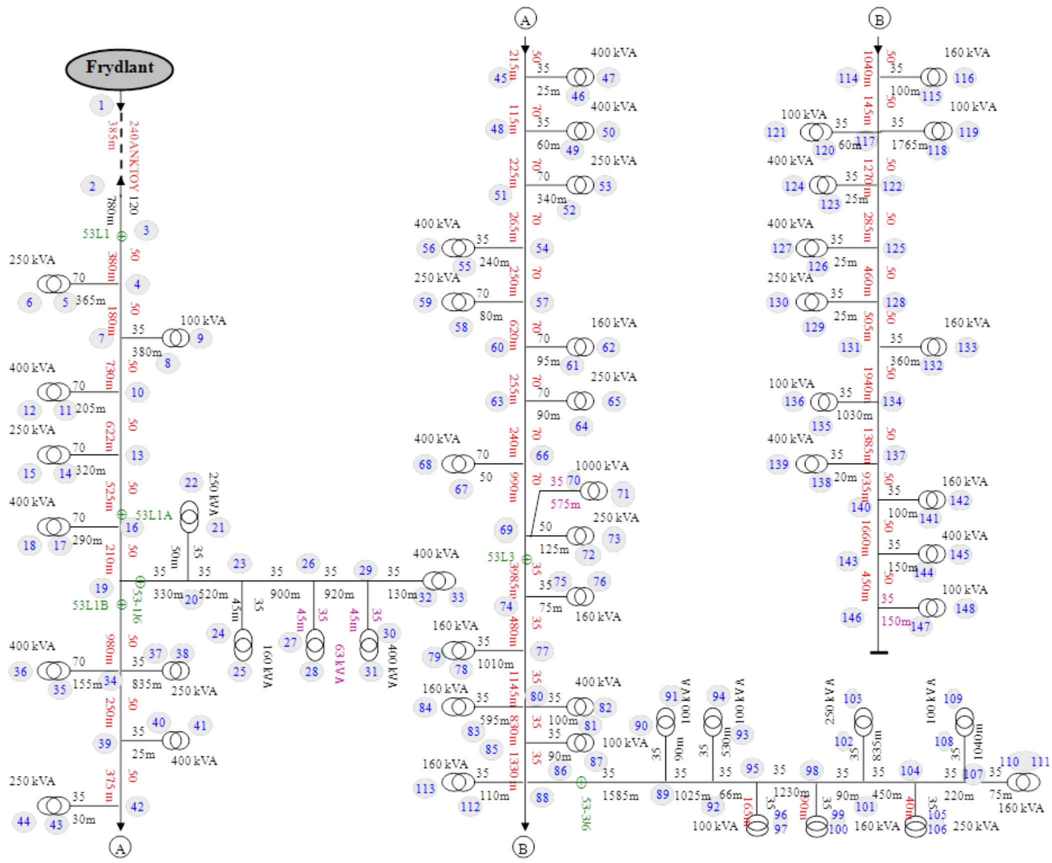

Fig. 1: The diagram of Frydlant network.

the system in the future and thus, not necessary to measure the harmonic impedance once again and also in the case of making a new project, it will be easy to find out if the technology of the project will not disturb the power system.

Both measurements and computations of harmonic impedance are difficult tasks without general solutions. Recommendations for measurements and computations of harmonic impedance are given in [2]. It is important to take notice that harmonic impedance is a time-varying quantity. It varies due to reconfiguration of the power system and due to variation of loads connected on the measured side of the system. Nevertheless the assumption of time invariance of the system parameters during the measurement is typically made [9]. Measurement and computation of harmonic impedance is a part of power system identification. Numerous methods of power system identification were developed over about 20 years of interest in the field. Most of them utilize the Thevenin model of the power system [7], [12]. The Thevenin model includes an equivalent voltage source in series with an equivalent impedance. It can also be generalized to include 3-phase systems.

As the equivalent voltage source value is unknown, the harmonic impedance has to be calculated from voltage and current harmonics changes ΔU_h and ΔI_h respectively [2].

$$Z_h = \frac{\Delta U_h}{\Delta I_h}, \qquad (1)$$

where ΔU_h and ΔI_h stand for the differences of harmonic currents and harmonic voltages respectively, caused by the change of the power system state. They are complex quantities, obtained using DFT (Discrete Fourier Transform) [2]. Harmonics changes ΔU_h and ΔI_h are the results of power system state change, which is caused by a load change, at the assumption of a constant source voltage and harmonic impedance values during the measurement.

The final results of the harmonic impedance evaluation are the amplitude spectrum of the harmonic impedance and the phase shift, which give a clear view about the existence of the resonance frequencies in the power system.

2. Analysis the Studied Case

The diagram of the network of Frydlant line 53–22 kV [13] as shown in Fig. 1 is very large, branched and contains a lot of elements; therefore, to get accurate results, feeding the required data to the used software must be done carefully. The main problem of the calculating process is to obtain the whole data for all elements [13]. By the close examination we can find, that the network includes the following elements:

1. 50 distribution transformers (represent also the loads):
   - 15 × 400 kVA
   - 12 × 250 kVA
   - 11 × 160 kVA.
   - 11 × 100 kVA.
   - 1 × 1000 kVA.
2. 1 cable:
   - ANKTOYPV 240.
3. 96 transmission lines:
   - AlFe 120.
   - AlFe 50.
   - AlFe 70.

3. Modeling the Elements

3.1. Transformers

The transformers are modelled by the asymmetrical T-model as shown in Fig. 2. This substitutional diagram respects the non nominal transformer ratio (respects the voltage regulation). Regulation branch is set as a percentage value of the nominal voltage. If the switch of the branch in normal position and transformer phase angle equals zero, then the asymmetrical T-model becomes symmetrical, i.e. relative transformer ratio equals 1 [14].

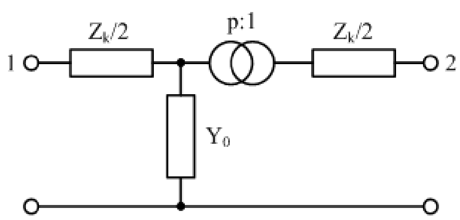

Fig. 2: Diagram of transformer.

The transformers input data needed to be entered to the software NetCalc are listed (briefly in some specific branches) in Tab. 1.

Tab. 1: The transformer input data.

=Branch TR; 2 windings transformer					
Connec. i-j	5-6	8-9	11-12	24-25	70-71
Code TR	TR	TR	TR	TR	TR
S_n **(MVA)**	0,25	0,1	04	0,16	1
U_{1n} **(kV)**	22	22	22	22	22
U_{2n} **(kV)**	0,4	0,4	0,4	0,4	0,4
u_k **(%)**	4,2	4,2	6	4,2	6
ΔP_k **(kW)**	4,45	2,13	8,51	3,9	15,6
i_0 **(%)**	0	0	0	0	0
ΔP_0 **(kW)**	0	0	0	0	0
X_{n1} **(Ω)**	0	0	0	0	0
R_{n1} **(Ω)**	0	0	0	0	0
X_{n2} **(Ω)**	0	0	0	0	0
R_{n2} **(Ω)**	0	0	0	0	0
$r_{01}(-)$	1	1	1	1	1
$x_{01}(-)$	1	1	1	1	1
Connec. $Sp_1 - Sp_2$	Y Yn	Y Yn	Y Yn	Y Yn	Y Yn
HU (-)	0	0	0	0	0
Reg (%)	0	0	0	0	0
BTr (-)	0	0	0	0	0

S_n - rated power (MVA).
U_{n1} - primary rated voltage (kV).
U_{n2} - secondary rated voltage (kV).
u_k - short-circuit voltage (%).
ΔP_k - short-circuit losses (kW).
i_0 - open-circuit current (%).
ΔP_0 - open-circuit losses (kW).
X_{n1} - primary earthed nod reactance (Ω).
R_{n1} - primary earthed nod resistance (Ω).
X_{n2} - secondary earthed nod reactance (Ω).
R_{n2} - secondary earthed nod resistance (Ω).
r_{01} - (R_0/R_1) zero-sequence and positive-sequence resistances ratio (-).
x_{01} - (X_0/X_1) zero-sequence and positive-sequence reactances ratio (-).
Sp_1 - primary winding connection (D, Y, Yn, Zn) (-).
Sp_2 - secondary winding connection (D, Y, Yn, Zn) (-).
HU - transformer phase angle - secondary voltage phase shift versus primary (-).
Reg - branch switch set-up - divergence of real voltage from nominal (%).
BTr - 0 = not a block transformer, 1 = block transformer (-).

These data are used to calculate the parameters of the transformer substitutional diagram for the fundamental frequency, which are explained in [14] and for the frequency dependence of the serial short-circuit impedance Z_k and magnetizing susceptance B_0 apply the following [14], where h is the harmonic order:

$$Z_h(h) = R_{k(1.h)} \cdot \sqrt{h} + R_{k(1.h)} \cdot h, \tag{2}$$

$$B_0(h) = \frac{B_{0(1.h)}}{h}. \tag{3}$$

Tab. 2: The transmission lines input data.

=Branch VK; transmission lines - kilometric parameters									
Con. i-j	**Code VK*0**	R_k ($\Omega\cdot$km^{-1})	L_k (mH$\cdot$km^{-1})	G_k (µS$\cdot$km^{-1})	C_k (nF$\cdot$km^{-1})	S (mm^2)	l (km)	r_{01} (-)	x_{01} (-)
3-2	VK	0,234	1,111	0	10,48	120	0,78	1	1
4-3	VK	0,635	1,199	0	9,616	50	0,38	1	1
5-4	VK	0,429	1,124	0	10,331	70	0,365	1	1
8-7	VK	0,857	1,195	0	9,692	35	0,38	1	1

R_k - one kilometer conductor's resistance ($\Omega\cdot$km^{-1}).
L_k - one kilometer conductor's operational inductance (mH$\cdot$km^{-1}).
G_k - one kilometer conductor's leakage conductance (µS$\cdot$km^{-1}).
C_k - one kilometer conductor's operational capacity (nF$\cdot$km^{-1}).
S - wire cross section (mm^2).
l - total length (km).
r_{01} - (R_0/R_1) zero-sequence and positive-sequence resistances ratio (-).
x_{01} - (X_0/X_1) zero-sequence and positive-sequence reactances ratio (-).

3.2. Transmission Lines and Cables

The transmission lines and the cable are represented by the Π-model as shown in Fig. 3 and given by kilometric parameters [14] as listed in Tab. 2 for transmission lines and in Tab. 3 for the cable, where the type of the cable is according to Kladno-Czech Republic.

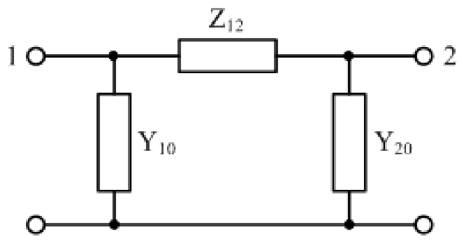

Fig. 3: Diagram of transmission lines.

The parameters above are for one kilometer transmission line and their frequency dependence are calculated as follows [14]:

$$R_k(h) = R_k \cdot F_{nRvar}(h), \quad (4)$$

$$L_k = \frac{X_k}{2\pi \cdot f_{(1.h)}}, \quad (5)$$

$$G_k = G_{k(\mu S)} \cdot 10^{-6}, \quad (6)$$

$$C_k = \frac{B_k}{2\pi \cdot f_{(1.h)}} \cdot 10^{-6}, \quad (7)$$

where:
h - harmonic order.
F_{nRvar} - functional dependence of resistance on a harmonic order.
$f_{(1.h)}$ - fundamental frequency.
B_k - one kilometer conductor's operational susceptance (µS$\cdot$km^{-1}).

3.3. Loads

It is very difficult to model the loads because their content is unknown. Loads could be motors, lights or a whole network with an industrial character. Because of that, in most cases, the model of load does not give the real situation, but in general the well-known models consisting of serial-parallel combination of resistance, inductance and capacitance and the total value of the load is taken as a percentage value of the transformer's power, assume to be 100 % at $\cos\varphi = 0,75$ as calculated in Tab. 4 below. NetCalc [1] offers a lot of load models, but in this study two types will be preferred as explained below. First one is the model according to CIGRE Fig. 4, which is usually using in the harmonic study and the second one is a model with compensational power adjusted at all loads to compensate the power factor from $\cos\varphi = 0,75$ up to $\cos\varphi_C = 0,95$ Fig. 5. The last model is suitable, where the value of the compensational power is unknown, therefore this model assumes that the compensational power compensates the power factor from $\cos\varphi = 0,75$ up to $\cos\varphi_C = 0,95$. The needed compensational power is listed in Tab. 4 below.

Values in Tab. 4 are calculated by the following equations [14]:

$$P = S_n \cdot \cos\varphi, \quad (8)$$

$$Q = S_n \cdot \sin\varphi, \quad (9)$$

$$Q_C = P(\tan\varphi - \tan\varphi_C), \quad (10)$$

where:
P - active power (MVA).
S_n - nominal apparent power (MVA).
Q - reactive power (Mvar).
Q_C - compensational power (Mvar).
$\cos\varphi$ - the power factor (-).

Tab. 3: The cable input data.

=Branch K3; three conductor cable										
Con. i-j	**Code K3*0**	ρ_0 (Ωmm^2·m^{-1})	d_i (mm)	d (mm)	a (mm)	ϵ_r (-)	S (mm^2)	l (km)	r_{01} (-)	x_{01} (-)
1-2	K3	0,3	30,6	18,6	12	2,3	240	0,385	1	1

ρ_0 - resistivity (Ωmm^2·m^{-1}).
d_i- wire diameter with isolation (mm).
d - bare conductor diameter (mm).
a - bare conductor distances (mm).
ϵ_r - relative permitivity (-).
S - wire cross section (mm^2).
l - total length (km).
r_{01} - (R_0/R_1) zero-sequence and positive-sequence resistances ratio (-).
x_{01} - (X_0/X_1) zero-sequence and positive-sequence reactances ratio (-).

Tab. 4: The loads input data.

=Branch ZC; Model according to CIGRE				=Branch ZK; Model with compensation				Comp. power
Con. i-j	**Code ZC**	P (MVA)	Q (Mvar)	**Con. i-j**	**Code ZK**	P (MVA)	Q (Mvar)	Q_c (Mvar)
6-6	ZC	0,1785	0,165	6-6	ZK	0,1785	0,165	0,104
9-9	ZC	0,075	0,066	9-9	ZK	0,075	0,066	0,041
12-12	ZC	0,300	0,265	12-12	ZK	0,300	0,265	0,166
25-25	ZC	0,120	0,106	25-25	ZK	0,120	0,106	0,066
71-71	ZC	0,75	0,66	71-71	ZK	0,75	0,66	0,415

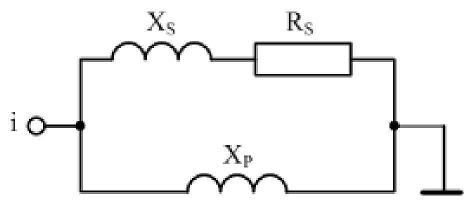

Fig. 4: Model according to CIGRE.

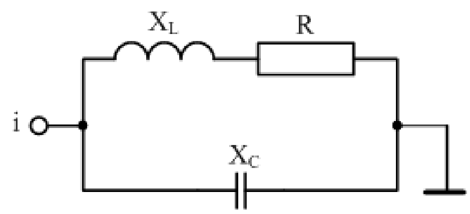

Fig. 5: Model with compensation.

The parameters of the model:

$$R_{s(1.h)} = \frac{U_{ref}^2}{P}, \qquad (11)$$

$$X_{s(1.h)} = 0,073 \cdot R_{s(1.h)}, \qquad (12)$$

$$X_{p(1.h)} = \frac{R_{s(1.h)}}{6,7 \cdot \frac{Q}{P} - 0,74}. \qquad (13)$$

Impedance:

$$\overline{Z_s} = R_{s(1.h)} \cdot F_{nRvar}(h) + jX_{s(1.h)} \cdot h, \qquad (14)$$

$$\overline{Z_p} = jX_{p(1.h)} \cdot h. \qquad (15)$$

Admitance:

$$\overline{Y} = \frac{1}{\overline{Z_s}} + \frac{1}{\overline{Z_p}}, \qquad (16)$$

where:
P - active power (MW).
Q - reactive power (Mvar).
h - harmonic order (-).
U_{ref} - referential voltage (V).

F_{nRvar} - functional dependence of resistance on a harmonic order.

The parameters of the model:

$$R = \frac{U_{ref}^2}{P} \cdot F_{nRvar}(h), \qquad (17)$$

$$X_L = \frac{U_{ref}^2 \cdot h}{Q_a}, \qquad (18)$$

$$X_C = \frac{U_{ref}^2}{Q_s \cdot h}. \qquad (19)$$

Admitance:

$$\Re(\overline{Y}) = \frac{P}{U_{ref}^2 \cdot F_{nRvar}(h)}, \qquad (20)$$

$$\Im(\overline{Y}) = \frac{Q}{U_{ref}} \cdot \left(1,683 \cdot h - \frac{2,683}{h}\right), \qquad (21)$$

where:
$Q_a = 2,683Q$.
$Q_s = 1,683Q$.
Q - reactive power demand by the load when compensate at $\cos\varphi = 0,95$.

Tab. 5: The harmonic impedance and the phase shift.

Harm. Order h (-)	Variant 1				Variant 2				Variant 3			
	$\Re Z$ (Ω)	$\Im Z$ (Ω)	Z (Ω)	Phase (°)	$\Re Z$ (Ω)	$\Im Z$ (Ω)	Z (Ω)	Phase (°)	$\Re Z$ (Ω)	$\Im Z$ (Ω)	Z (Ω)	Phase (°)
1	6,04	13,53	14,82	65,93	6,49	14,53	15,91	65,94	33,18	29,33	44,29	41,47
2	10,62	24,71	26,9	66,75	18,76	31,25	36,45	59,03	16,92	-13,35	21,55	-38,26
3	15,71	33,63	37,12	64,96	55,78	25,01	61,13	24,15	9,87	-0,93	9,91	-5,36
4	20,31	41,03	45,78	63,66	41,18	-10,67	42,54	-14,53	8,67	5,12	10,07	30,54
5	24,2	47,72	53,51	63,12	22,23	-5,22	22,83	-13,22	7,83	9,72	12,48	51,13
6	27,51	54,26	60,83	63,12	16,74	3,59	17,13	12,1	6,42	14,89	16,22	66,69
7	30,45	60,93	68,12	63,45	15,03	9,27	17,66	31,65	6,07	20,11	21	73,21
8	33,21	67,91	75,6	63,94	13,49	14,3	19,66	46,67	6,06	24,99	25,72	76,38
9	35,95	75,3	83,44	64,48	11,88	18,22	21,75	56,91	6,17	29,72	30,35	78,28
10	38,78	83,18	91,77	65	9,62	23,5	25,39	67,73	6,34	34,37	34,95	79,55
11	41,83	91,63	100,73	65,46	8,51	29,36	30,56	73,84	6,55	39,04	39,58	80,48
12	45,21	100,74	110,42	65,83	8,06	35,06	35,98	77,06	6,79	43,75	44,27	81,17
13	49,04	110,6	120,98	66,09	7,93	40,62	41,38	78,96	7,06	48,54	49,05	81,72
14	53,46	121,32	132,58	66,22	7,97	46,11	46,79	80,2	7,37	53,45	53,95	82,15
15	58,66	133,06	145,41	66,21	8,12	51,61	52,25	81,06	7,7	58,5	59,01	82,5
16	64,84	145,97	159,72	66,05	8,35	57,18	57,79	81,69	8,06	63,73	64,24	82,79
17	72,32	160,25	175,81	65,71	8,65	62,88	63,47	82,17	8,47	69,16	69,67	83,02
18	81,49	176,14	194,08	65,17	9,01	68,74	69,33	82,53	8,91	74,82	75,35	83,21
19	92,91	193,93	215,04	64,4	9,44	74,82	75,41	82,81	9,41	80,75	81,3	83,36
20	107,38	213,92	239,36	63,35	9,92	81,15	81,75	83,03	9,95	86,99	87,56	83,47

4. Calculations and Results

It is worth mentioning that the calculation will be done with some simplifications. For example the compensational power (Q_C) was calculated, hypothetically, to all loads to compensate the power factor from $\cos\varphi = 0,75$ up to $\cos\varphi_C = 0,95$, but in real situations it will be certainly different. The magnetizing impedances of the transformers were ignored (i_0 and $\Delta P_0 = 0$) just for simplification, because the sensitivity test by the used software, concerning to these parameters, showed that they have a neglected effect to the form of the harmonic impedance curve and, for the same reason, the branch lengths of transmission lines can be ignored too, but in this study they were within the calculation.

It is possible to make the calculation with many different variants of the network configurations, but this study will be simplified and the variants below will be discussed, where all loads are calculated as a 100 % at $\cos\varphi = 0,75$, taking into consideration that the transformer shunt impedance (i_0 and $\Delta P_0 = 0$) was ignored for simplification and the frequency spectrum of testing was $1 - 1000$ Hz (to the 20th harmonics) with a frequency step about 0,2 Hz. Extra-spectral resonances were ignored:

1. Using the load model according to CIGRE without compensational power.
2. Using the load model according to CIGRE with compensational power (from $\cos\varphi = 0,75$ to $\cos\varphi_C = 0,95$).
3. Using the load model with compensational power adjusted at all loads to compensate the power factor from $\cos\varphi = 0,75$ up to $\cos\varphi_C = 0,95$.
4. All the above three variants with decreasing the load to 50 %.

The results of the harmonic impedance (besides the real and imaginary components) and the phase shift of Frydlant network for the mentioned variants are listed in Tab. 5 and the harmonic impedance curves with the phase shift are shown in Fig. 6.

From Tab. 5 and Fig. 6 it is clearly seen that the variant 1 with using the model according to CIGRE without compensational power clarified an inductive character of the impedance with no resonance, but because of adding the compensational power in variant 2 a serial resonance around the 3rd harmonic with the value of impedance about 61,13 Ω immediately appeared, which confirms the effect of the compensational power on the curve of the harmonic impedance. Next, a parallel resonance appeared around the 6th harmonic with the value of impedance about 17,13 Ω and then the impedance curve continued with an inductive character with decreasing of the impedance amplitude.

In comparison with the model with compensational power (variant 3) the form of the harmonic impedance curve is similar to curve of variant 2, but the first resonance appeared around the 1st harmonic with value of impedance about 55,65 Ω and then around the 3rd harmonic a parallel resonance appeared with the value of impedance about 9,91 Ω and then the impedance curve continued with an inductive character.

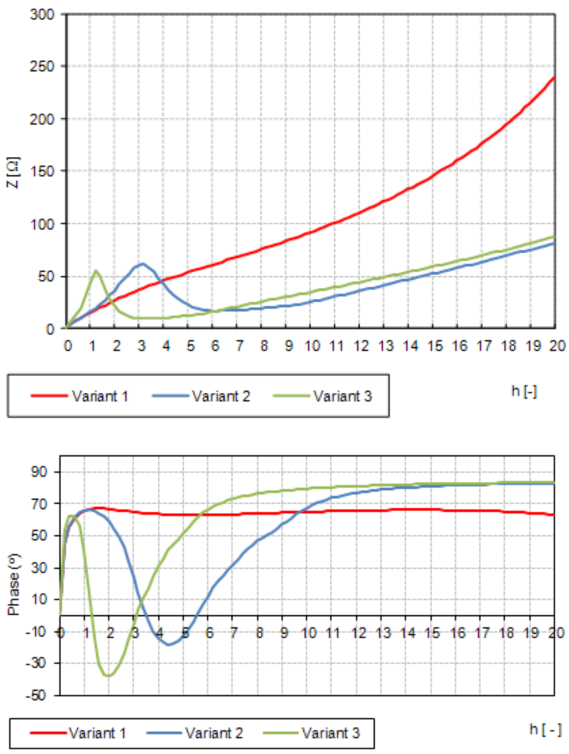

Fig. 6: The harmonic impedance and the phase shift of the network.

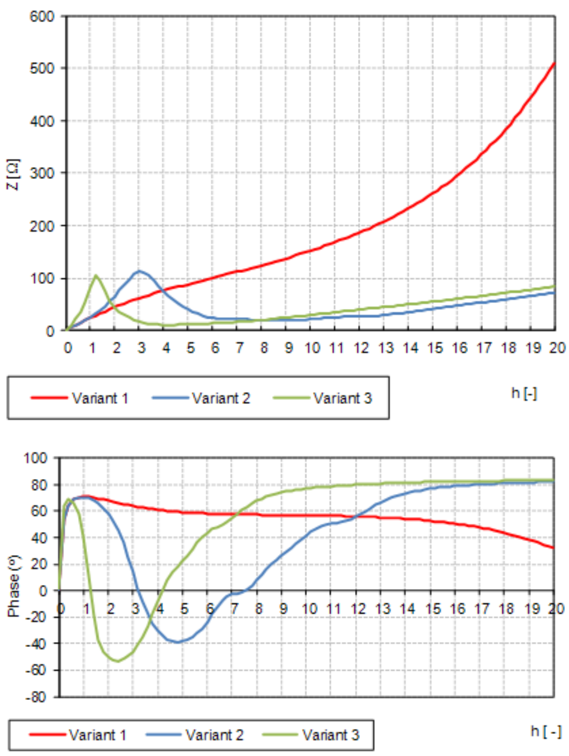

Fig. 7: The harmonic impedance and the phase shift of the network.

The calculations in variant 4 were repeated as in the first three, but with decreasing all loads to 50 % at $\cos\varphi = 0,75$. The results are illustrated in Fig. 7, where some changes are registered as explain in the following:

In the load models with the compensational power decreasing of the load value caused a rising in the values of the impedance at the lowest harmonics about two times. In variant 1 no resonances are registered, but a serial resonance appeared close to the 23th harmonic with a value about 700 Ω, but this frequency is out of the testing range.

The serial resonance in variant 2 reached the value about 113 Ω and appeared around the 3rd harmonic and then the parallel resonance with amplitude about 20 Ω appeared around the 7,5th harmonic. The serial resonance in variant 3 also reached the value about 106 Ω and appeared around the 1st harmonic and then the parallel resonance with amplitude about 10,5 Ω appeared around the 4th harmonic. The comparison between the results of the variants are in Tab. 6 below.

It is preferable before starting such calculations to make a sensitivity analysis for the used software and test it on some simple diagrams, to know which element of the power system has the operative effect to the form of the harmonic impedance, for example in the case of using compensational power to compensate the power factor, it may cause resonances; cables do so, too. The sensitivity analysis for this network was done and every parameter was tested, but the results of the sensitivity analysis are not the subject of this paper, therefore we will be satisfied with the calculations above, whereas the main problem of the calculations is to obtain the exact data of the whole network. But when the calculations are done it would be useful to be used in solving many of the power system problems. For example if the frequency of the mass remote control (HDO), which is about 217 Hz, will not causes a resonance, which leads to increasing or decreasing of the signal level ($0,3 - 1,2$ % U_n) [17] and the HDO receiver will not correctly react.

5. Conclusion

This study demonstrated the possibilities of the calculation method for investigation the harmonic impedance of the electric networks. The accurate results of the harmonic impedance of such large and branched network are depending on the input data accuracy. The data of the network are obtained from [13].

The obtained results confirmed that the harmonic impedance is strongly depending on the electric parameters of the power system. Figure 4 clarified, how

Tab. 6: Comparison between the results of the variants.

Variant	100 % Load				50 % Load			
	Serial resonance		Parallel resonance		Serial resonance		Parallel resonance	
	Z (Ω)	Harm. Order (-)	Z (Ω)	Harm. Order (-)	Z (Ω)	Harm. Order (-)	Z (Ω)	Harm. Order (-)
1	-	-	-	-	-	-	-	-
2	61,13	3rd	17,13	6th	113	3rd	20	7,5th
3	55,65	1st	9,91	3ed	106	1st	10,5	4th

the compensational power affected the form of the harmonic impedance, where serial and parallel resonances immediately appeared around the 3rd harmonic and around the 6th harmonic. Also the results illustrated in Fig. 5 clarified, that the value of the load has some impact to the harmonic impedance, where serial and parallel resonances appeared at the lowest harmonics.

This study clearly confirms that it must be taken into account, that the monitoring of harmonics must be done continually to avoid the negative effects of the resonances in case of their existing in the power system.

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