SPREADING OF HARMONICS IN POWER DISTRIBUTION NETWORK

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SUMMARY

This paper analyses the impact of transformers and power lines on higher harmonics spread through distribution network. Shown are the results of measuring the higher harmonics on both sides of 35/10 kV 4 MVA power transformers and 35 kV power line. There are many replacement schemes for transformers and power lines on higher frequencies, followed by appropriate equations which calculate the parameters of those schemes. This paper analyses the accuracy of those formulas and deviation of calculated values from those obtained by measurement, and from that concludes about the usefulness of certain schemes in higher harmonics spreading analyses. It is impossible to take into account every single power consumer while modelling large power distribution networks, so modelling groups of consumers or bigger parts of network is more convenient. Groups of similar consumers as well as complete entities within the network should be modelled separately. Next come the models of power load in the presence of higher harmonics.

1. INTRODUCTION

The basic demand for the electric power distributor is that for reliable and quality delivery. Those demands are getting higher as the new generations of microprocessor-based devices show low immunity to higher harmonics and other disturbances in quality. On the other hand, massive deployment of electronic converters of all kinds and sizes in households, business and industries, increases the amount of higher harmonics in power distribution network. Therefore it is very important to analise the sources of higher harmonics, as well as their impact on the power line network they are connected to. In order to determine numerically the content of higher harmonics within the network, one must know the influence of network`s basic elements, power lines and transformers above all, on the spreading of higher harmonics.

2. MODELLING OF POWER TRANSFORMERS

Power transformers present one of the most important elements of electroenergetic systems, so their modelling is of a great important during numerical determination of higher harmonics at particular point of distribution plant. In view of the fact that distribution plant use two–windings transformers so at continuation it will be analyse and present models only two–windings transformers. While calculating harmonics flow, two windings transformers present very often suetable impedance of short circuit Z_t for direct, inverse or zero sequence. Impedance of short circuit is same for direct and inverse sequence, but for zero sequence it depends from transformer`s connection. If the transformer`s windings are Y connected, than zero current can flow only if the star point is grounded or if exists neutral conductor. If the windings are Δ connected, than zero currents can flow inside delta, but none in lines conductor. A grounding impedance Z_g in the neutral appears as $3Z_g$ in the zero sequence, so that the zero-sequence impedance becomes $Z_0=Z_T+3Z_g$. In the presence of harmonics with skin effect neglected,

$$Z_T(h) = R_T + jhX_T \qquad (2.1),$$ and transformer impedance becomes

$$Z_T(h) = \begin{cases} Z_T^0(h), & h = 3n = 3,6,9,12,... \\ Z_T^+(h), & h = 3n \pm 1 \end{cases} \qquad (2.2)$$

As for resistance changing due to higher harmonics, some authors have different approaches, so in literature we can find different formulas describing transformers resistance changing at higher frequency. Some expression claim that transformer resistance R_t is direct proportional harmonics order [1]:

$$R_T = h \cdot R$$

But, we can find some expressions, where resistance is proportional the square root of harmonics order [3]: $R_T = \sqrt{h} \cdot R$. Above expressions, which describes changes of transformer's resistance with frequency are made on experimental way, and it is sure that is higher or lower deviation from correct value. Some authors give different analitical functions according its transformer's resistence can determine depends of frequency (or harmonics order), or this dependent can be present with chart, or grafic way [2] as if it presents on Fig.1.

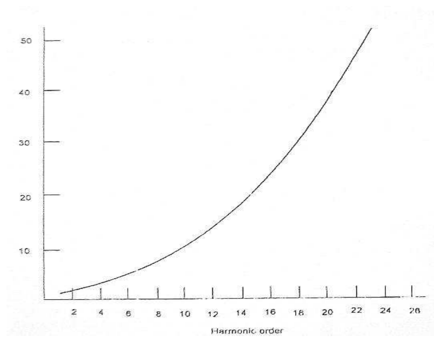

Fig. 1 – Power transformer's short circuit resistance at higher frequencies

The accurate present of power transformer is with conventional T sheme, with taking impedance magnetism branch. But this present has added complicated calculation, without influence on precision calculation from the reason that impedance branch is more higher from impedance short connection transformer. So, at the situation where the transformer isn't the harmonic's source, the branch magnetism can ignored.

However, the note is, that sometimes convencional T sheme of power transformer isn't enough precision. It is especially on calculations with frequencies more higher from basic frequence, when it will be necessary to take capacitites transformers windings, because by higher frequency, capacitative reactances are lower.

In continuation, the results of testings are done, and also calculation of voltage decrease on power transformer in TS 35/10 KV " Cable Factory Zajecar ". Testings are applied on transformer with following characteristics: Sn = 4 MVA, Dyo5, 35±2x2.5% / 10.5 kV, u_k=5.86%, $\cos\varphi_k$=0.1.

According connection of power transformer Dy05, and network 10 KV is isolated, it can be take that impedance zero sequence is boundless great.

Based on given characteristic of power transformer, direct ie inverse impedance can be calculated for fundamental frequency. From 35 kV side, this impedance is:

$$Z_{k(35)} = \frac{5.86 \cdot (35kV)^2}{4MVA \cdot 100} = 17.946\Omega \qquad (2.3)$$

where:

$R_{k(35)} = Z_{k(35)} \cdot \cos\varphi_k = 17.946 \cdot 0.1 = 1.795\Omega$ and

$X_{k(35)} = Z_{k(35)} \cdot \sin\varphi_k = 17.946 \cdot 0.995 = 17.856\Omega$

At the table 1 are done absolute and relative values of current and voltage, for fundamental and 7th harmonic, on primary and secondary side, reduced at voltage level 35 kV. All values are designed in table represent average values for all measuring interval.

TABLE 1 – ABSOLUTE AND RELATIVE VALUES OF CURRENT AND VOLTAGE FOR FUNDAMENTAL AND 7TH HARMONIC

Transf. 35/10 kV 4 MVA	**Primary side (35 Kv)** phase			**Secondary side (10 kV)** phase		
	1	2	3	1	2	3
U_1 [V]	20627 V	20616.3 V	20627 V	20464.3 V	20472.8 V	20478 V
U_7 [% , V]	0.913 % 188.22 V	0.939 % 193.7 V	0.85 % 175.33 V	0.724 % 148.2 V	0.55 % 112.6 V	0.96 % 196.6 V
I_1 [A]	31.15 A	28.37 A	29.57 A	30.18 A	27.62 A	28.42 A
I_7 [% , A]	8.69 % 2.71 A	7.48 % 2.12 A	6.982 % 2.06 A	8.33 % 2.51 A	6.865 % 1.9 A	8.84 % 2.51 A

At the table 2 are given average values for voltage and current on primary and secondary transformer side, according table 1, all values have meaning 35 kV

TABLE 2 – AVERAGE VALUES OF CURRENT AND VOLTAGE

Transf. 35/10 kV 4 MVA	**PRIMAR (35 kV)**	**SEKUNDAR (10 kV)**
U_1 [V]	20623.4	20471,7
U_7 [V]	185.75	152.47
I_1 [A]	29.7	28.74
I_7 [A]	2.3	2.3

From table 2 it can see that current fundamental harmonic on primary side is some greater from current fundamental harmonic on secondary side. Difference present current magnetism which for this transformer is about 1A (from side 35 kV) that corresponds measured values. Measuring instrument's error should also be considered, along with error of current measuring transformers. For present model of power transformer, average value of primary and secondary current can be used in calculation.
So, for fundamental harmonic is, as follows:

$$I = I_{sr} = \frac{I_{1(35)} + I_{1(10)}}{2} = 29.2A, \qquad (2.4)$$

Measured power factor in present moments was:
$\cos\varphi_1 = 0.91$ - on 35kV side, and $\cos\varphi_2 = 0.92$ - on 10kV side.

To analyse voltage changes on transformer it is good using Kap’s diagram. If coordinate system put that real axis covers with direction and course current vector, it makes Kap’s diagram as fig. 2, it can write:

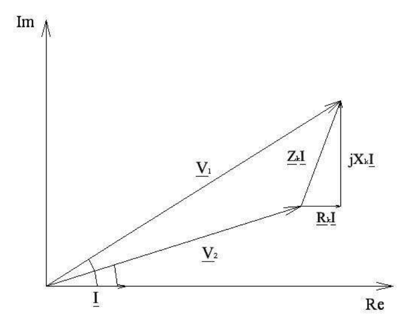

Fig. 2– Kap's diagram

$$\underline{V}_{1(35)} = \underline{V}_{1(10)} + \underline{I} \cdot \underline{Z}_k = V_{1(10)} \cdot (\cos\varphi_2 + j \cdot \sin\varphi_2) + I \cdot (R_k + jX_k) =$$
$$= 20471.7 \cdot (0.92 + j \cdot 0.392) + 29.2 \cdot (1.795 + j \cdot 17.856) =$$
$$= 18886.4 + j \cdot 8546.3, \text{ tj.}$$
$$\underline{V}_{1(35)} = 20730\,\text{V} \ \angle 24.35^0 \qquad (2.5)$$

Counted value primary voltage is different from measured value (20623.4 V) for 106.6 V, that is deviation of 0.52%, according error of measuring instruments and measuring voltage transformers, these values can be accept as satisfactory. Calculated phase shift between primary voltage and current, of 24.35^0 corresponds $\cos\varphi = 0.91$, what is completly agree with measured value. By fundamental harmonic analogy it can be make counting voltage drop for **7th harmonic**. Measured value phase angle between current and voltage 7th harmonic on 35KV side is 65.3^0 and on 10 KV side 305.5^0 (both values represent average value got as sum of average values phase angles for complete interval measured in each phase, divided by three).
It is accepted that transformer resistance is proportional to square root order harmonics. It is obtained

$\underline{V}_{7(35)} = \underline{V}_{7(10)} + \underline{I} \cdot \underline{Z}_{k7} = V_{7(10)} \cdot (\cos\varphi_2 + j \cdot \sin\varphi_2) + I \cdot (R_{k7} + jX_{k7}) =$

= 152.47·(0.58 - j·0.814)+2.3·($\sqrt{7}$ ·1,795 + j·7·17.856) =

= 99.36 + j·163.37 , tj.

$\underline{V}_{7(35)} = 191.2 \angle 58.7^0$. (2.6)

Comparing calculated value of 7[th] harmonic voltage on 35 kV side with measured value $\underline{V}_{7(35)} = 185.75 \angle 65.3^0$, it gets voltage deviation of 2.93% and phase angle deviation of 6.6^0. For that it didn't take error of measured voltage on 10 kV side. In respect of this, level higher harmonics in distribution network is relative low, and impedance of power transformer so inductive ($\cos\varphi_k \approx 0.1$), we see that with this type of measuring can't establish lawfulness of changing transformer's resistance at higher frequency. But, in fact of view that error of measuring instruments durring higher harmonics is greater from declare accuracy measuring instrument, so accepting power transformer's model for higher frequency, and dated results can be accept as satisfactory during analise harmonics flow in distribution network.

3. MODELLING OF POWER LINES

Power lines represent necessary elements in power system, and they are important causes of losses in transmission and distribution networks. From that, and many other phenomena, there are many analyses and different models of power lines and cables. Many simulation models related to higher harmonics can be adopted, depending of accuracy demand.

The simplest review of power line is serial conection of suitable resistance and reactance.

$$Z = z \cdot l = (r + jx) \cdot l = R + jX \qquad (3.1)$$

where z, r i x are impedance, resistance and reactance of the line in Ω/km, l is the line length in km. At higher frequencies from the reason skin effect, it comes to change line resistance. So, there are meaning that at higher frequencies resistance is proportional square root harmonics order [1], and at higher frequencies impedance of line can present as follows:

$$Z(h) = \sqrt{h}R + jhX \qquad (3.2)$$

More precision interpretation of line is present by PI scheme, fig. 3, when it can be take shunt admittance.

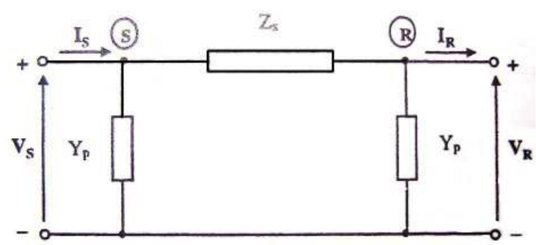

Fig. 3 - PI scheme

Shunt resistance is neglected for both lines and cables, what isn't the case with shunt capacitance. The shunt capacitive reactanse is smaller with harmonics order. It is especially case with cables, as cable's shunt capacitance is for order higher then on line. For detailed modelling power lines it is necessarry to use threephase presentation.

It has pointed that for analize of spreading of harmonics at real distribution networks, having in view lenght lines and voltage levels, very often it is enough monophase presentation of line with serial or PI model. Until the power transformer's resistance of short circuit impedance is for order lower from adequate reactanse, at power lines resistance and reactanse are the same order unit. Because is very important to know line's resistance and resistant change at higher frequencies. The bigger the difference in voltage on line's ends the better precision we get when calculating the line's parameters, based on measuring values. From this reason it is better that observed line is longer, that load is very strong, and without split on line. It is also necessary that both terminals of line have voltage measuring transformers, and current measuring transformers at least on one end. It needs in view that on higher voltage levels the presence of higher harmonics is lower, that practicaly measuring can make on 35 kV and lines lower voltage levels. But, on lower voltage levels, the lines are shorter and by that, their impedance is low. As result drop of voltage is lower, and calculation error is higher. According above, we can see that to desolve problem many contradictory requirements are impose, and there are low number of lines with possible necessary measurements.

In continous, it will be present results of measurements on 35 kV power line between TS 110/35 kV „Bor 1“ - TS 35/10 kV „Zagrađe“, length 10.6 km, AlFe, 95/15 mm^2 ($z = (0.316+j0.349)\ \Omega/km$).
Table 3 shows average values of fundamental and 5th harmonic voltage and current for each phase, and suitable phase shift between fundamental and 5th harmonic voltage and current, at the line's begining in TS 110/35 kV „Bor 1“.

TABLE 3 – VALUES OF CURRENT AND VOLTAGE AT THE LINE'S BEGINING

	Phase 1	Phase 2	Phase 3	∑
U_1 [V]	20237.9	20213.8	20140	**20197,2**
I_1 [A]	34,9	34,9	33,6	**34,45**
$\varphi_1 [^o]$	38.74	40.12	40.09	**39,65**
U_5 [V]	329,2 (1.627%)	332,8 (1.646%)	337,1 (1.674%)	**333**
I_5 [A]	0,763 (2.186%)	0,662 (1.897%)	0,673 (2.003%)	**0,7**
$\varphi_5 [^o]$	112,84	121,83	117,66	**117,45**

Table 4 shows average values of fundamental and 5th harmonic voltage and current for each phase, and suitable phase shift between fundamental and 5th harmonic voltage and current, at the line's end in TS 35/10 „Zagrađe“.

TABLE 4 – VALUES OF CURRENT AND VOLTAGE AT THE LINE'S END

	Phase 1	Phase 2	Phase 3	∑
U_1 [V]	19749	20029.8	20207	**19995.3**
I_1 [A]	35.3	35.3	35.5	**35.4**
$\varphi_1 [^o]$	40.66	39.47	40.41	**40.18**
U_5 [V]	357.8 (1.812%)	270.9 (1.352%)	291.3 (1.442%)	**306.7**
I_5 [A]	0,739 (2.093%)	0,724 (2.051%)	0,846 (2.383%)	**0,77**
$\varphi_5 [^o]$	131.4	117.9	115.1	**121.44**

From here on, average values (obscurity values in last column) will be used for calculating both fundamental and 5th harmonic, and line will be present by serial conection of resistance and inductance. Because there are some deviation between measured current values at the begining and the end of line, in following calculation it will use their average value, so as average value of fundamental current is done value I_1=(34.45+35.4)/2=34.9 A, and as average value of 5th current is done value I_5=(0.7+0.77)/2=0.735 A.
It is similary as during analize power transformer, coordinate system we will make that real axis is cover with direction and course current vector. At the begining of line (in TS 110/35 „Bor 1“) all values have sign „prim“ (U_1', I_1', U_5',I_5'), and at the end of line (in TS 35/10 „Zagrađe“) sign „secundum“ (U_1'', I_1'', U_5'', I_5'').
Therefore for **fundamental harmonic** it can write:

$$\underline{U}_1' = \underline{U}_1'' + \underline{I}_1 \underline{Z}_1 \qquad (3.3)$$

Based on measuring values at the end of line, we can calculated voltage and phase shift at the begining of line:

$$\begin{aligned} \underline{U}_1' &= U_1''(\cos\varphi_1'' + j\sin\varphi_1'') + I_1 \cdot (0.316+j0.349) \cdot 10.6 \\ &= 19995.3 \cdot (0.764+j0.645)+34.9 \cdot (3.35+j3.7) \\ &= 15393.3 + j13026.1 \\ &= 20165.1\ V \angle 40.24^0 \qquad (3.4) \end{aligned}$$

By comparison of calculated with measured values in table 3, we can see voltage deviation of 32.1 V (0.16%), and phase shift deviation of 0.59^0, so we can say that results can be accept as very satisfactory.

For **5^{th} harmonic** is obtained:

$$\underline{U}_5^{'} = \underline{U}_5^{''} + \underline{I}_5\underline{Z}_5 \qquad (3.5) \quad \text{odnosno ,}$$

$$U_5^{'}(\cos\varphi_5^{'} + j\sin\varphi_5^{'}) = U_5^{''}(\cos\varphi_5^{''} + j\sin\varphi_5^{''}) + I_5^{\cdot}(R_5+jX_5) \qquad (3.6)$$

where R_5 i X_5 are line's resistance and reactanse for 5^{th} harmonic. If we accept that $R_5=\sqrt{h}\cdot R_1$ and $X_5=h\cdot X_1$ their values will be:
$R_5=\sqrt{5}\cdot 10.6km\cdot 0.316\Omega/km = 7.5\ \Omega$ and $X_5 = 5\cdot 10.6km\cdot 0.349\Omega/km = 18.5\ \Omega$, so it can write:

$$U_5^{'}(\cos\varphi_5^{'} + j\sin\varphi_5^{'}) = U_5^{''}(\cos\varphi_5^{''} + j\sin\varphi_5^{''}) + 5.51+j13.6 \qquad (3.7)$$

According measuring higher harmonic errors can be some percents, so it can't be accepted measured values of voltage and phase angle at the end of line, and based on them calculate values of voltage and phase shift at the begining of line, or inverse.
At partial cases it can get equality without solution, or presented values are not accetable. Based on measured values at line's end and line's begining (table 3 and 4) as most acceptable values that satisfy equality (3.7) are following values:

$U_5^{'}=324.1$ V , $\varphi_5^{'}=118.44^0$; $U_5^{''}=315$ V , $\varphi_5^{''}= 120.5^0$

Comparing these values with values from tables 3 and 4:

$U_5^{'}=333$ V , $\varphi_5^{'}=117.45^0$; $U_5^{''}=306.7$ V , $\varphi_5^{''}= 121.44^0$

we get voltage deviation of 2.7%, and phase shift deviation of about 1^0. It can make some conclusion that calculated error is acceptable when power line is presented by serial connection of resistance and reactanse. On the basis above given, it can make conclusion that serial and PI model getting results with satisfactory precission and which model will use depends from concrete problem and from data having that. At the same time, we can see that this way we can't make lawfulness of changes line's resistance at higher frequency. Based on necessery conditions: enough high level higher harmonics, enough lenght line etc.,it's clear that it is not easily measuring on this way to determine change of resistance line according higher frequencies, but it is clear that at level harmonic which are appearing in distribution network, acceptable hypothesis for changing resistance line are for calculation flow higher harmonics at distributions network, are completely justified.

4. THE LOAD MODELLING

In order to get good modelling of a distributive network or a part of it, one needs to spot and then modell the harmonics sources. With some consumers like electric arc furnaces, fluorescentic lights etc., because of the way they work it is practicaly impossible to analiticaly calculate the presense of higher harmonics,because of that the results got by measuring are quoted in literature. On the other hand, with devices like rectifiers, invertors etc. it is posible to analiticaly determine the presence of higher harmonics, although, keep in mind that, because of assimetry which always exist, due to the caracteristics of switching elements etc., results gained in this manner are somewhat different from real values. In every distributive network the power is not entirely sinusoidal, but it contains higher harmonics in some extension. This is coused by connected users who produce the power distorsion, nevertheless the power of distributive network is also not completely sinusoidal. In this manner, the presence of higher harmonics on one hand comes from nonlineary consumers, and because of that it represents the source of higher harmonics. The other source is distorsion of the voltage used by consumer. Separation, that is, determination in wich extent higher harmonics are produced by nonlinerity of connected consumers, in case of distorsion of used power is exceptionally hard to determine, wich aditionally complicates the modelling of harmonics sources. These are some of occurrences which appear in distribution systems, and they affect the model quality of distributive network used in further calculations.
When modelling distributive networks, which have large numbers of different users, it is practicaly impossible to take in consideration and analize every consumer separatly. It is more convenient to model separate groups of consumers or parts of network. It is benefitial to determine and especially model the groups of similar consumers and typical parts of network. Thus in distribution network you

can determine highly populated city blocs or jagged country household, urban surroundings, market-business halls, light industries, parts of network with no compensation of reactive power on low voltage system etc. Consider that the loads are not the same in winter and summer period, also in night and day times. The basic parametars wich are used to describe some loads (parts of network or grups of consumers) are the voltage level, active and reactive power. By the most common use is the representation of load making parallel connection of resistance and inductivity when it is as follows:

$$S = P + jQ \tag{4.1}$$

$$Y_p = \frac{1}{R_p} - j\frac{1}{X_p} = \frac{P - jQ}{V^2} \tag{4.2}$$

Where is:

$$R_p = \frac{V^2}{P}\ ;\ \ X_p = \frac{V^2}{Q} \tag{4.3}$$

And then in the presence of higher harmonics:

$$Y_p(h) = \frac{1}{R_p} - j\frac{1}{hX_p} \tag{4.4}$$

skin efect apperance which produces the variation in resistence is not consider in upper calculation. So, for the passive ussers (households) one can find in the literature that the skin efect is making ressistence equal to square root of line of harmonics:

$$R_r(h) = k \cdot \sqrt{h} \cdot R_p \tag{4.5}$$

in which case it is recommended for factor *k* to use different values. Most commonly used *k=1*, although some authors recommanded *k=0.6*. Diferences that exist are mainly because given results are experimentaly gained.

In Fig. 5 we have the CIGRE type C model wich represents big loads between 5 and 30 harmonics, gained experimentally.

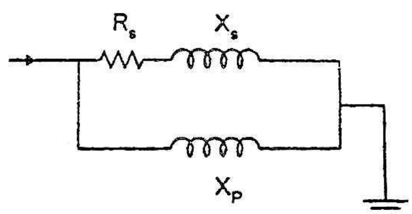

Fig.5 - CIGRE type–C load model

Where

$$R_S = \frac{V^2}{P}\ ; \qquad X_S = 0.073hR_S\ ; \qquad X_P = \frac{hR_S}{6.7\frac{Q}{P} - 0.74}$$

It is allso posible to make a presentation of ressistance and inductivity serial connection, when we knowing that:

$$Z = R + jX = \frac{V^2}{P - jQ} = \frac{V^2(P + jQ)}{P^2 + Q^2} = \frac{V^2(P + jQ)}{|S|^2} \tag{4.6}$$

Where

$$R = \frac{V^2}{|S|^2} \cdot P\ ; \qquad X = \frac{V^2}{|S|^2} \cdot Q$$

And then in the presence of harmonics:

$$Z(h) = R_h + jhX \tag{4.7}$$

All given equations reffer to passive loads, the loads which are not the source of higher harmonics. However, it gets rather complicated when it is referred to the part of distributive network. Higher harmonics in current exist partly because the aperrance of higher harmonics on busses which are in consideration, and partly because the network itself is a source of higher harrmonics to some extent. On the other hand distortion is affected by network itself, including local distribution and transmission network.

All this shows that numerical determination of higher harmonics in distribution network is not a simple task, even beside the accurate data about network elements it is desirable to have as much more data about distribution network gained by mesuring at different points of network, delivering different loads.

REFERENCES

[1] George J. Wakileh, 2001, "Power System Harmonics", Springer

[2] J.C.Das,"Power System Analysis", Marcel Dekker, Inc.

[3] Jos Arrillaga, Bruce C Smith, Neville R Watson, Alan R Wood,1997,"Power System Harmonic Analysis", John Wiley & Sons

[4] C. Sankaran,2001,"Power Quality", CRC Press