Harmonic Analysis of 110 kV Filter Facility in Power System of Eastern Croatia Using "EasyPower Spectrum" Program

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Abstract - **Traditionally, the power factor of electric power systems has been improved using capacitors. Capacitors can interact with harmonics injected into the power system by non-linear loads, causing damage to the capacitors or other power system components. Due to the shortage of reactive power in the power system of eastern Croatia, capacitors were installed on a 110 kV busbar at the Djakovo 220/110 kV transformer station. Voltage distortion was measured on the 110 kV busbar before the installation of capacitors. Due to a possible resonance with the network, a filter facility was designed. Prior to the installation of the filter facility, the network was modelled, and harmonic results were calculated. The filter facility is modelled using the "EasyPower Spectrum" program for harmonic propagation analysis. Before and after the installation of filters, network and filter frequency characteristics, and all standard distortion indices were determined. Voltage and current indices, V_{THD}, I_{THD}, I_{RSS}, V_{RSS}, were determined.**

Keywords: Harmonic analysis, filter design, power factor correction, harmonics software.

I. INTRODUCTION

In recent years there has been an increasing interest in the subjects of harmonic generation, propagation and its effects on power system components. The effects of harmonics are becoming a growing problem in transition counties, such as Croatia, where the utilities are facing these problems now and will be even more in the future. This is caused by the extensive use of power electronic devices in the industrial andresidential sectors.

The tendency is to use more and more non-linear electronic power devices with higher rated power. Thus, there is a great need for reliable harmonic analysis and mitigation. Limiting harmonic distortion is necessary for both utilities and consumers to thus eliminate the risk of equipment damage and malfunction, or extra incurred losses in normal operation [1].

War destruction has created a radial power supply of an entire region. The main 400 kV power supply overhead transmission line between the Mraclin 400/220 kV transformer station and the Djakovo 220/110 kV transformer station was used at a lower 220 kV voltage level. Also two 110 kV lines from the Medjuric transformer station to Daruvar and Nova Gradiska were used for power supply of the same region. Interconnection with the Hungarian power system by a 110 kV line from transformer station Siklos has served as an additional power source in this highly critical supply situation.

The region itself has only one power plant, TE-TO Osijek, with an installed capacity of 1x50 + 2x25 MVA. Since recent evaluations and measurements indicate load peaks of about 360 MVA, with the expectation of reaching 400 MVA in the near future, insufficiency in supplying both active and reactive power is obvious. The power flow analysis of eastern Croatia performed in [2] indicates a shortage in reactive power of about 100 MVAr. This shortage was overcome by projecting and installing reactive compensation at the Djakovo 220/110 kV transformer station, and with distributed compensation in the 35 kV distribution network of eastern Croatia. System capacitive compensation was installed on the 110 kV bus at Djakovo in the amount of 50 MVAr. An installation of capacitors this size could easily cause a resonant condition between the capacitors and the inductance of the equivalent network impedance (reactance). And, the presence of harmonic sources in that part of the eastern Croatian power network could excite the resonance. To avoid a resonant situation, filters where designed by ABB to avoid resonance and mitigate problem harmonics. The filter facility included three filters for the 3rd, 5th and 7th harmonic.

II. MATHEMATICAL MODEL

A. Filter modeling

Several sources of harmonic currents (static converters, battery chargers, arc furnaces, fluorescent lamps, pulse modulated devices, etc.) connected near the compensation devices could excite a parallel resonance if capacitors were directly connected to a bus. In the case of the 110 kV Croatian network, a significant spectrum of harmonic currents was detected and measured at the 110 kV busbar at Djakovo.

The frequency spectrum of the driving point impedance and possible resonant frequencies depends on the short circuit impedance at the observation point, which is related via the topology of the network. That situation can be presented as seen in Fig. 1. A known current source which is measured at an observation point, I_h for h^{th} harmonic, is injected into the network. The network reacts with an equivalent driving point impedance Z_{hn} , and the filters are seen as a filter impedance Z_{hF}.

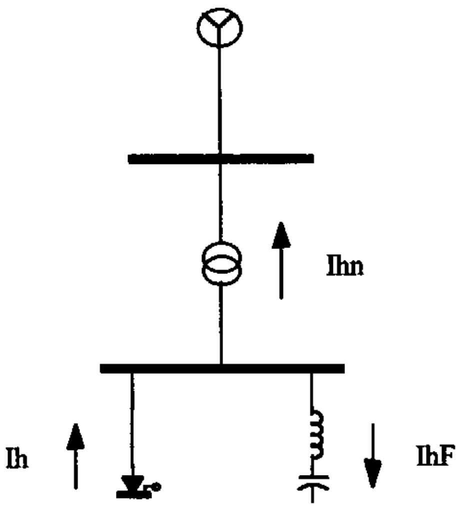

Fig. 1. One-line Diagram of Harmonic Source, Filter and Network.

The resulting voltage of the parallel impedance of network Z_{hn} and filter Z_{hF} can be calculated according equation (1) from [3]:

$$\bar{U}_h = \frac{\bar{Z}_{hn} \cdot \bar{Z}_{hF}}{\bar{Z}_{hn} + \bar{Z}_{hF}} \cdot \bar{I}_h \tag{1}$$

The current of h^{th} harmonic passing throughout the filter is given by:

$$\bar{I}_{hF} = \frac{\bar{U}_h}{\bar{Z}_{hF}} = \frac{\bar{Z}_{hn}}{\bar{Z}_{hn} + \bar{Z}_{hF}} \cdot \bar{I}_h \tag{2}$$

The current of h^{th} harmonic passing throughout the network impedance is given by:

$$\bar{I}_{hn} = \frac{\bar{U}_h}{\bar{Z}_{hn}} = \frac{\bar{Z}_{hF}}{\bar{Z}_{hn} + \bar{Z}_{hF}} \cdot \bar{I}_h \tag{3}$$

The ratio between current passing through the network and the injected current of h^{th} harmonic is given by:

$$\bar{r}_{hn} = \frac{\bar{I}_{hn}}{\bar{I}_h} = \frac{\bar{Z}_{hF}}{\bar{Z}_{hn} + \bar{Z}_{hF}} \tag{4}$$

The ratio between current passing through the filter and the injected current of h^{th} harmonic is given by:

$$\bar{r}_{hF} = \frac{\bar{I}_{hF}}{\bar{I}_h} = \frac{\bar{Z}_{hn}}{\bar{Z}_{hn} + \bar{Z}_{hF}} \tag{5}$$

Filter impedance is given by:

$$\bar{Z}_{hF}(\omega) = R_{hF} + j\left(\omega \cdot L_F - \frac{1}{\omega \cdot C_F}\right) \tag{6}$$

where R_{hF} is the filter resistance for the h^{th} harmonic, L_F is inductance of the filter, C_F is the capacitance of the filter, and $\omega = 2\pi f$ is the circular frequency.

The resonant frequency of filter is given by:

$$\omega_r = \frac{1}{\sqrt{L_F \cdot C_F}} \tag{7}$$

The resonant frequency at which parallel resonance appears (without resistance of network and filter) is given by:

$$\omega_r = \frac{1}{\sqrt{(L_F + L_n) \cdot C_F}} \tag{8}$$

Substituting (7) and (8) to equations (1), (2) and (3) the next equations can be written:

$$\bar{U}_h = j \cdot \omega \cdot L_n \cdot \frac{\left(\frac{\omega}{\omega_p}\right)^2 - 1}{\left(\frac{\omega}{\omega_p}\right)^2 - 1} \cdot \bar{I}_h \tag{9}$$

$$\bar{I}_{hF} = \frac{\left(\frac{\omega}{\omega_r}\right)^2 - 1}{\left(\frac{\omega}{\omega_p}\right)^2 - 1} \cdot \bar{I}_h \tag{10}$$

$$\bar{I}_{hF} = \frac{\left(\frac{\omega}{\omega_p}\right)^2 - \left(\frac{\omega}{\omega_r}\right)^2}{\left(\frac{\omega}{\omega_p}\right)^2 - 1} \cdot \bar{I}_h \tag{11}$$

At the resonant frequency $\omega = \omega_r$ from relations (9), (10) and (11) we can conclude that: the current of the h^{th} harmonic injected into the network is zero ($\bar{I}_{hn}' = 0$), all h^{th} injected current from the current source passes through the filter ($\bar{I}_{hF} = \bar{I}_h$), and the induced voltage of the h[th] harmonic is zero ($\bar{U}_h = 0$).

Thus, the search for resonant conditions amounts to the search for extremes of the impedance function Z (ω). The most usual type of study involves the determination of the driving point impedance function at a bus, and for parallel resonance, we search for the maximum within the impedance function [4]. This driving point impedance is available in the frequency scan option of "EasyPower Spectrum". In this operation, the program runs current flow simulations at each individual frequency of interest (run in user defined steps), and stores point-by-point information for plotting. For harmonic scans, the current injection is pre-defined at 1.0 pu, so that per unit voltages indicate per unit driving point and transfer impedances.

The second method of simulation uses modifications to many current injections that include the spectral content of non-linear loads. These "Summation" results include standard figures of merit such as:

- V_{THD}, I_{THD} - Voltage and Current THD.
- V_{RSS} - Root Sum Squared Voltage and Current.
- V_{SUM} - The linear summation of harmonic voltages for capacitor bank peak voltage stress.
- K_{Factor} - Transformer K-Factor.
- Total Losses - Including Harmonic Losses.
- TIF and IT Product.
- ANSI C57.110 Transformer Derating.

"EasyPower Spectrum" employs the nodal current injection technique for all simulations. All network impedances are lumped parameters, and are modified according to each harmonic frequency simulated. This modification includes resistance skin effect for all appropriate components, as well as modification of line and cable parameters using the long line equation.

B. Harmonic indices

The harmonic indices calculated using EasyPower Spectrum are defined as follows:

Voltage total harmonic distortion

$$V_{THD} = \frac{\left[\sum_{h=2}^{n}\left(V_h\right)^2\right]^{1/2}}{V_1} \cdot 100 \qquad (\%) \tag{12}$$

Voltage root sum squared value

$$V_{RSS} = \left[V_{pu-sys1}^2 + \sum_{h\neq 1}^{n}\left(V_{h\,pu-sys}\right)^2\right]^{1/2} \cdot \text{kVBase} \quad (\text{kV}) \tag{13}$$

Voltage telephone influence factor

$$V_{TIF_{pu}} = \frac{\left[0.25 \cdot \left(V_{1kV}\right)^2 + \sum_{h\neq 1}^{n}\left(V_{hkV}\right)^2 \left(TIF_{FACTOR}\right)^2\right]^{1/2}}{V_{RSS}} \tag{14}$$

This indices is dimensionless. The TIF Factor is well defined in literature [4].

$$V_{SUM} = V_{1pu} + \sum_{h\neq 1}^{n}\left(V_{h\,pu-sys}\right) \qquad (\text{per-unit}) \tag{15}$$

Branch current indices are:

Current total harmonic distortion

$$I_{THD} = \frac{\left[\sum_{h=2}^{n}\left(I_h\right)^2\right]^{1/2}}{I_1} \cdot 100 \qquad (\%) \tag{16}$$

Current root sum squared value

$$I_{RSS} = \left[I_{RATING}^2 + \sum_{h\neq 1}^{n}\left(I_h\right)^2\right]^{1/2} \cdot \qquad (\text{A}) \tag{17}$$

Current IT product

$$IT_{PRODUCT} = \left[0.25\left(I_{RAT}\right)^2 + \sum_{h\neq 1}^{n}\left(I_h\right)^2\left(TIF_{FACTOR}\right)^2\right]^{1/2} (\text{A}) \tag{18}$$

Transformer derating factor in % of fundamental rating

$$TD\% = \frac{\left[1 + P_{EC-R}\right]}{\left[1 + P_{EC-R} \cdot K_{FACTOR}\right]} \cdot 100 \qquad (\%) \tag{19}$$

where the transformer K Factor given by

$$K_{Factor} = \frac{\left[I_{RATING}^2 + \sum_{h\neq 1}^{n}\left(I_h\right)^2 \cdot (h)^2\right]}{\left[I_{RATING}^2 + \sum_{h\neq 1}^{n}\left(I_h\right)^2\right]} \cdot 100(\text{dimensionless}) \tag{20}$$

III. SAMPLE CASE

In our sample case, the power network of eastern Croatia has been studied. It has 52 buses, 4 generators, 2 utilities, 22 load buses, 38 transformers, 32 transmission lines, 3 filters on the 110 kV and 12 filters on the 35 kV network. The network is shown in Fig. 2.

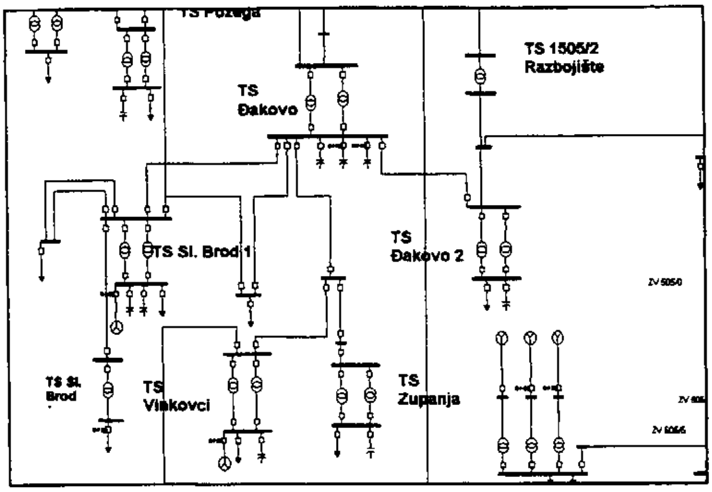

Fig. 2. Part of Eastern Croatian 110 kV Network

At the 110 kV busbar at Djakovo, measured values of harmonics are given in Table 1.

Table 1. Measured Harmonic Voltages and Currents at Djakovo 110 kV.

h	*3*	*5*	*7*	*9*	*11*	*13*	*15*
u_h%	0.77	2.36	1.15	0.05	0.11	0.12	0.08
I_h(A)	7.9	14.6	5.1	0.2	0.3	0.3	0.2

The three phase short circuit capability at the Djakovo 110 kV bus depends on the topological state of the power network, and can reach 200 to 1100 MVA. The inductance of the network and the capacitive reactance of capacitors can create parallel resonance circuits. The number of harmonics at which resonance occurs can be estimated by equation 16.

$$h_r = \sqrt{\frac{S_k}{Q_c}} \tag{16}$$

The most common topological state of the 110 kV network has short circuit capacity between 435 and 589 MVA, which, for 450 MVA, gives a value of h_r = 3 for 50 MVAr of power capacitors. Short circuit capability on the 110 kV bus can also be calculated directly using the short circuit focus of the EasyPower software.

Table 2. Resonant Frequency Harmonic for Different Short Circuit Levels.

S_k(MVA)	*222*	*377*	*435*	*665*	*857*	*1086*
16 (MVAr)	3.72	4.85	5.21	6.45	7.32	8.24
32 MVAr	2.63	3.43	3.69	4.56	5.18	5.83
48 MVAr	2.15	2.80	3.01	3.72	4.23	4.76

One can see that as short circuit levels increase, resonant frequencies move to higher harmonics. In our case, we can expect resonance near the 5th, 7th, 9th and 11th harmonics. To confirm this, several plots are presented below.

For a short circuit level of 464 MVA with all three capacitors switched on (48 MVAr) resonance can be expected near the 3rd and 11th. harmonics. The resultant frequency scan showing driving point impedance Z(ω) is given in Fig. 3.

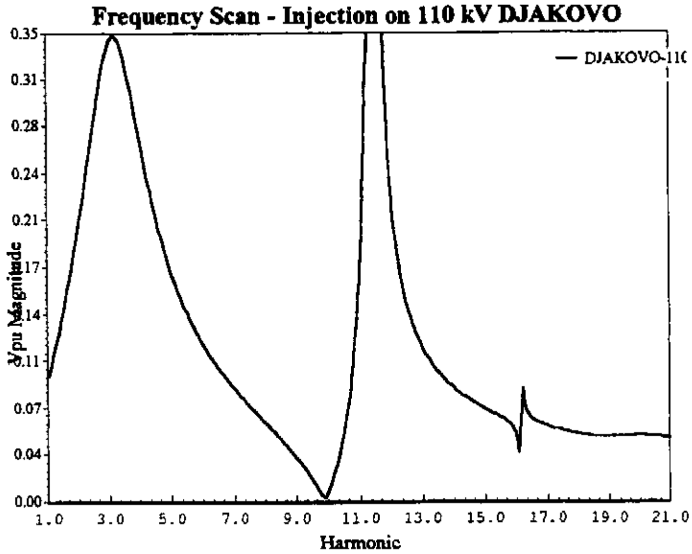

Fig. 3. Frequency Scan of Z(ω) for 464 MVA without Filters.

For a short circuit level of 958 MVA with all three capacitors switched on (48 MVAr), resonance can be expected near the 5th and 11th harmonics. The resultant frequency scan showing driving point impedance Z(ω) is given in Fig. 4.

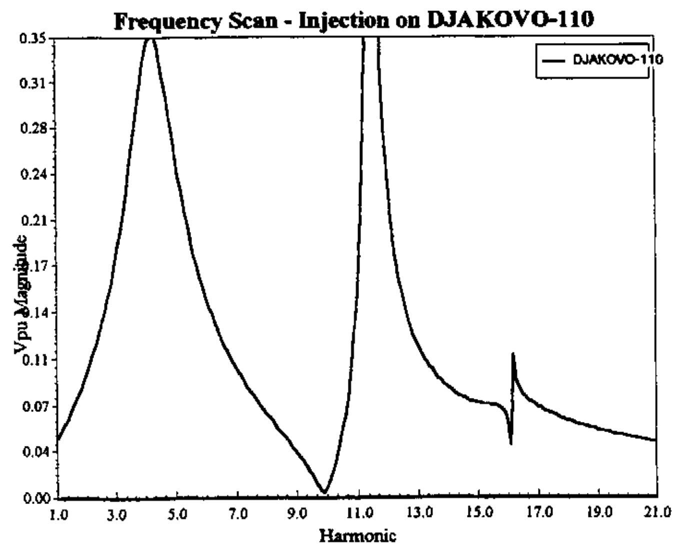

Fig. 4. Frequency Scan of Z(ω) for 938 MVA without Filters.

Because the amount of 9th and 11th harmonic current is very small, they can be eliminated from the harmonic analysis. Non-linear loads can be modelled in the *EasyPower Spectrum* program by simply modifying a load type through a windows dialogue box. Once made non-linear, a spectrum defining injection current in percent of fundamental can be defined in the dialogue spectrum spreadsheet. The program accommodates both integer and non-integer frequencies of injection. The secondary side of the transformer at the TS 220/110 kV at Djakovo is shown in Fig. 5.

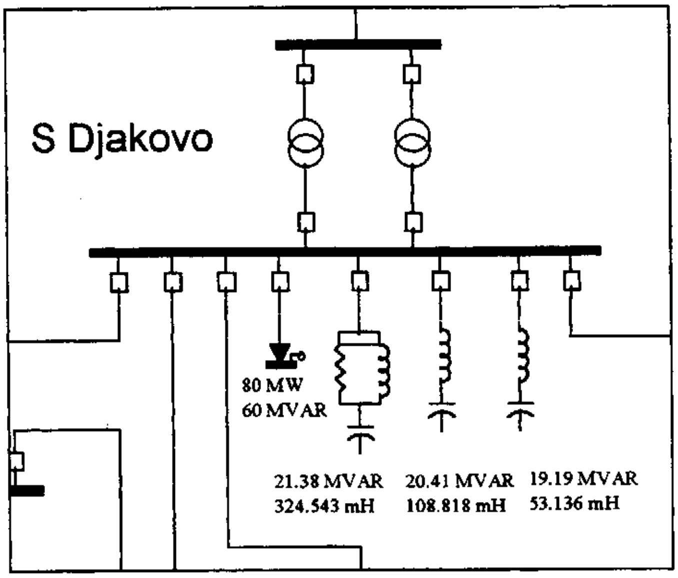

Fig. 5. Non-linear Load and Filters at Djakovo 110 kV.

Four different types of filters can be modelled and chosen in *EasyPower Spectrum*. These include the notch filter (series connection of inductance L and capacitance C_1, first order filter (series connection of resistance R and capacitance C_1), second order filter (parallel connection of resistance R and inductance L in series with capacitance C_1), and third order filter (series connection of capacitor C_2 and resistor R in parallel with inductance L and all together in series with capacitor C_1). For our case, ABB designed filter facilities with first order filters for the 3rd harmonic, and notch (L-C) filters for the 5th and 7th harmonic. The data for each filter is presented in Table 3.

Table 3. Filter Data.

Filter	*3rd*	*5th*	*7th*
Rated inductance (mH)	324.9	109.2	53.2
Rated resistance (Ω)	888	0	0
Rated capacitance (μF)	3.71	4.03	4.12
Rated three phase power (MVAr)	21.39	20.41	19.19
Rated phase current (A)	91.1	92.8	91.0
Resonant frequency (Hz)	153.8	239.9	339.9
Rated line voltage (kV)	135.45	126.95	121.76

The frequency scan of the 3rd harmonic filter (notch) is shown in Figure 6. The Y-axis is in voltage per unit, which for frequency scans which utilise a 1.0 per unit current injection, gives Z = V in per unit. Base impedance can be calculated as $Z_B = U^2_B/S_B = 110^2/40 = 302.5\ \Omega$. The frequency scan of the 3rd + 5th filter is shown in Figure 7.

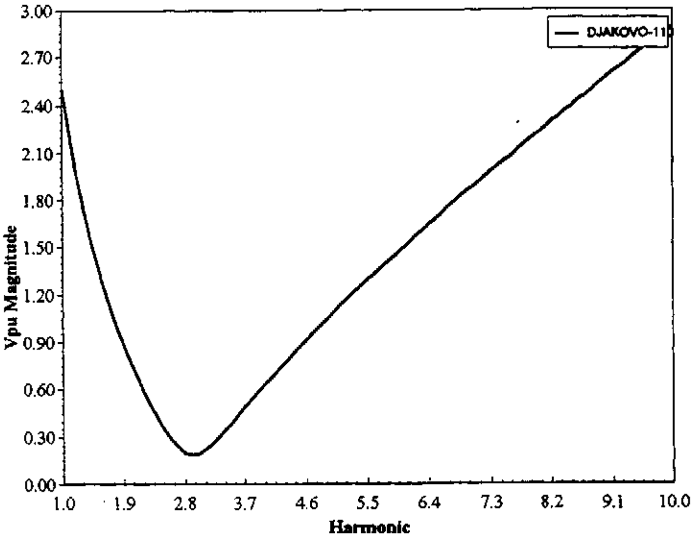

Fig. 6. Frequency Scan of 3rd Filter

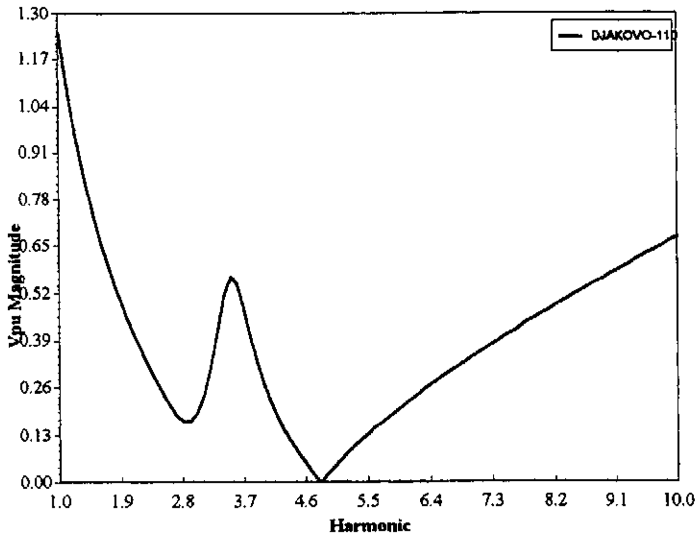

Fig. 7. Frequency Scan of the 3rd + 5th Filter.

After modelling the filters, frequency scans were performed, and the driving point impedances Z(ω) and harmonic bar charts were plotted. First the 3rd filter is switched on alone. One can see from Fig. 8. hamonic bar chart at 110 kV bus Djakovo without filters.

When the 3rd and the 5th filters are switched on the 3rd and the 5th harmonics are reduced on acceptable level (see Figure 9)

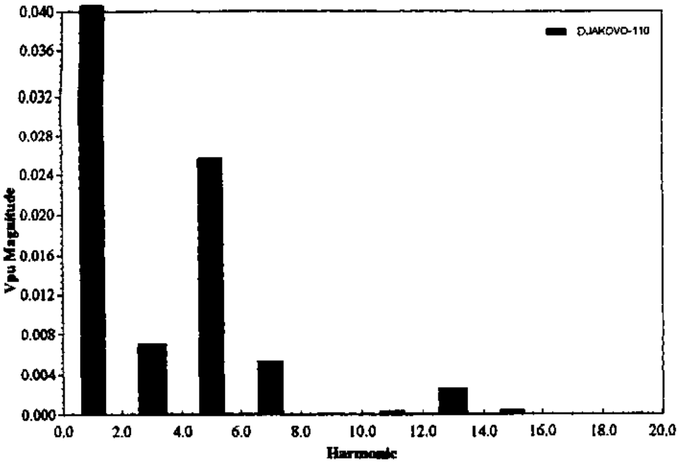

Fig. 8. Harmonic Bar Chart for 601 MVA without Filters.

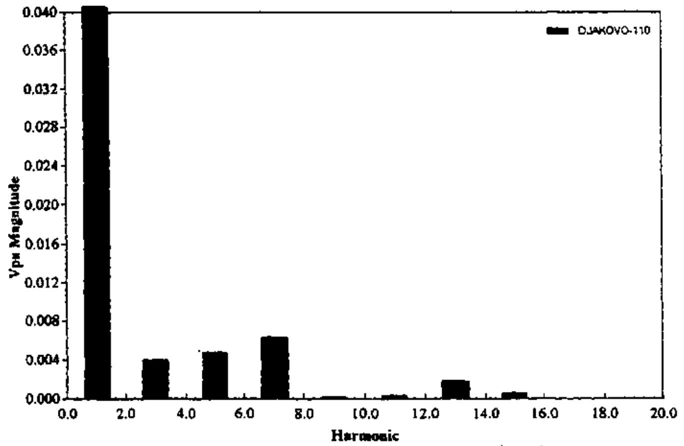

Fig. 9. Harmonic Bar Chart for 601 MVA with 3rd + 5th Filters

From measurements in Table 1, we can calculate using (12) total voltage harmonic distoration V_{THD}. One can see that before the filter compensation V_{THD} = 2.74%. After injecting non-linear load currents (with different current sources) according the values from Table 1, harmonic indices appear as shown in Table 4.

Table 4. Harmonic Indices at Djakovo 110 kV.

VTHD(%)	*VRSS(kV)*	*VTIF*	*VSUM(kV)*
2.7%	110.004	1 137	114.6

The simulation results show an excellent correlation with the measured values. From measurements and calculations, V_{THD} = 2.74%, and simulation results give V_{THD} = 2.7%.

After the 3rd harmonic filter is switched on harmonic indices are:

Table 5. Harmonic Indices at Djakovo 110 kV with 3rd Filter.

VTHD(%)	*VRSS(kV)*	*VTIF)*	*VSUM(kV)*
2.6	110.002	1 059	114.1

After compensation with 3rd + 5th harmonic filters, indices are:

Table 6. Harmonic Indices at Djakovo 110 kV with 3rd + 5th Filters.

VTHD(%V)	*VRSS(kV)*	*VTIF*	*VSUM(kV)*
0..9	110.000	784	111.9

After compensation with 3rd+5th+7th harmonic filters indices are:

Table 7. Harmonic Indices at Djakovo 110 kV with 3rd + 5th + 7th Filters.

VTHD(%V)	*VRSS(kV)*	*VTIF*	*VSUM(kV)*
0.7	110.000	542	111.4

IV. CONCLUSION

The shortage of reactive power caused by war destruction in eastern Croatia demanded the installation of approximately 100 MVAr of reactive power. The main goal of this paper was to show that high voltage compensation can cause resonance, and if harmonic currents exist at these resonant points, that excessive distortion levels could result. Measurements have shown the existence of harmonic currents at the planned 110 kV bus for compensation. The whole eastern Croatia power network was modelled using the EasyPower Spectrum program. Different network topologies reflected changes of the three-phase short circuit capability. It was determined that for higher values of short circuit capability, resonant frequencies move to higher values (i.e. 7th, 9th and 11th). For the most common network topology, resonance can be expected at the 3rd, 5th and 7th harmonics, which resulted in the design and installation of filter facilities (3rd, 5th and 7th harmonic). Since the level of harmonic distortion was acceptable before (V_{THD} = 2.74%), and after (V_{THD} = 0.7%) filter installation, the primary goal to avoid resonance was achieved.

V. ACKNOWLEDGEMENTS

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