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MatLab Simulink Modeling for Network-Harmonic Impedance Assessment: Useful Tool to Estimate Harmonics Amplification

Alexandru Băloi and Adrian Pană

Additional information is available at the end of the chapter

Abstract

The importance of the subject is given by the fact that harmonics are making their presence felt in electrical distribution networks, and the cheapest and most widespread solution for power factor correction is the capacitor banks. This chapter proves that the harmonic impedance is an efficient tool for assessing the state of distribution networks containing harmonics. The unfavorable operating conditions are anticipated based on the network harmonic impedance values, and the means of intervention are selected. Harmonic impedance monitoring and using it in expert systems for operating condition optimization will increase in the future. Power factor correction by shunt capacitor switching in electrical networks containing harmonics can lead to harmonics amplifications by harmonic voltage increasing and capacitors thermal overstressing by great values of the currents flowing through them. This chapter proposes a method for practical determination of harmonic impedance. Based on its values, a quick method is developed to anticipate the harmonic voltages and current amplifications that can occur when a shunt capacitor is installed for power factor correction. Amplification factors are calculated depending on the equivalent harmonic impedance of the network seen in the compensation bus. A distribution network containing harmonics is modeled using MatLab Simulink, and harmonic impedance is determined by simulation in different operating conditions. Using the values of the harmonic impedance and the capacitive reactance of the capacitor bank that is connected for power factor correction, the amplification of the harmonic voltages and currents is estimated by calculus. The results obtained by calculus are then compared with the values obtained by simulation after the connection of the capacitor bank to the network. In conclusion, the chapter proves that the network harmonic impedance is a useful tool to estimate the harmonics amplification caused by power factor correction using shunt capacitor banks.

1. Introduction

Harmonics are making their presence felt in electrical distribution networks due to both the use of nonlinear devices in the consumers' area and the high development of distributed generation [1, 2].

The harmonics of the electrical networks have negative effects like increasing active power losses, resonance over voltages, increasing the potential of the transformers' neutral point, over currents in three-phase networks which can lead to difficulties regarding the protection relay selectivity, and capacitor banks overstressing. The effects of some types of loads like office equipment, air conditioning units, lighting devices, motor drives, and household equipment are presented in [3]. This study discusses the influence of capacitor banks on the network harmonics conditions.

Connecting a capacitor bank to the electrical network leads to the resonance phenomena, which, superimposed over the harmonic current flow on frequencies close to the resonance frequency, result in high harmonic voltage values at the capacitor terminals and high harmonic currents flowing through the capacitor bank. Over voltages lead to insulation overstressing, and high currents produce a capacitor bank heating that is also reflected in insulation damage [4, 5].

There are many methods for network harmonic impedance determination, which are presented in many literature works [6–12]. Even the operation of switching the capacitor bank can be used for harmonic impedance measuring [13], and online determination of the harmonic impedance is the subject of many works [14, 15]. One problem that is less noticed in these works is how to determine the phase of the complex harmonic impedance.

This chapter presents a method, which uses the network harmonic impedance like a tool to anticipate the harmonic condition amplifications in the case of reactive power compensation by capacitor banks.

In order to reach this objective, Section 2 presents a method to determinate the complex harmonic impedance. In order to find the phase of the impedance, the series–parallel circuit transformation is used. A mathematical model to anticipate the harmonic currents and voltage amplification, based on the harmonic impedance values, when a capacitor bank is connected to the network, is also described in Section 2. The mathematical model is validated, in Section 3, by a MatLab Simulink simulation for an electrical distribution network that comprises a bus with a capacitor bank installed for power factor correction. The results obtained by simulation are compared with those obtained by calculus from the mathematical model. Section 4 presents, step by step, how the distribution network is implemented on a Matlab Simulink model. Section 5 comprises the conclusions of the chapter.

2. Amplifying harmonic conditions assessment

2.1. Determination of the network harmonic impedance

The simplest method for harmonic impedance measurement supposes the changing of network status. The disturbance can be created by switching a network component in the bus where the network harmonic impedance must be measured. The main steps of this method are as follows [16]:

1. Voltage and current waveforms recording before the disturbance.

2. Changes are then made to the status of the network.

3. Voltage and current waveforms recording after the disturbance.

4. Network harmonic impedances determination:

$$\underline{Z}_k = \frac{\underline{U}_{k-\text{pre}} - \underline{U}_{k-\text{post}}}{\underline{I}_{k-\text{pre}} - \underline{I}_{k-\text{post}}} \tag{1}$$

where $\underline{U}_{k-\text{pre}}$ and $\underline{I}_{k-\text{pre}}$ are the pre-disturbance harmonic voltage and current, and $\underline{U}_{k-\text{post}}$ and $\underline{I}_{k-\text{post}}$ are the post-disturbance harmonic voltage and current.

The impedance $\underline{Z}_k$ does not include the switched load.

Because the harmonic impedance determined using the expression (1) is parallel impedance, to obtain the phase of the impedance, we have to transform the parallel schema into series schema.

The series harmonic impedance can be determined using the following expression:

$$\underline{Z}_{kS} = R_S + j \cdot X_{kS} \tag{2}$$

The parallel harmonic impedance can be determined using the following expression:

$$\frac{1}{\underline{Z}_{kp}} = \frac{1}{R_p} + \frac{1}{jX_{kp}} \tag{3}$$

$$\underline{Z}_{kp} = \frac{1}{\frac{jX_{kp}+R_p}{jX_{kp}\cdot R_p}} = \frac{jX_{kp} \cdot R_p}{jX_{kp} + R_p} \cdot \frac{R_p - jX_{kp}}{R_p - jX_{kp}} = j \cdot \frac{R_p^2 \cdot X_{kp}}{R_p^2 + X_{kp}^2} + \frac{R_p \cdot X_{kp}^2}{R_p^2 + X_{kp}^2} \tag{4}$$

Knowing that:

$$\underline{Z}_{kp} = \underline{Z}_{kS} = R_S + j \cdot X_{kS} \tag{5}$$

Results:

$$R_S = \frac{R_p \cdot X_{kp}^2}{R_p^2 + X_{kp}^2}$$

$$X_{kS} = \frac{R_p^2 \cdot X_{kp}}{R_p^2 + X_{kp}^2}$$

(6)

We write now these parameters of the series impedance depending on the absolute value of the harmonic impedance, which can be practically determined using (1).

$$Z_{kp}^2 = Z_{kS}^2 = R_S^2 + X_{kS}^2 = \frac{R_p^2 \cdot X_{kp}^2}{R_p^2 + X_{kp}^2}$$

(7)

Using expressions (6) and (7), we can write the series resistance as follows:

$$R_S = \frac{R_p \cdot X_{kp}^2}{R_p^2 + X_{kp}^2} \cdot \frac{R_p}{R_p} = \frac{Z_{kp}^2}{R_p}$$

(8)

The value of the parallel resistance, R_p, from the expression (8) can also be practically determined; it is actually the value of the harmonic impedance corresponding to the resonance frequency. Using the expression (7), the value of the series reactance can now be determined:

$$X_{kS} = \sqrt{Z_{kS}^2 - R_S^2}$$

(9)

With the values of the series parameters of the harmonic impedance, we can now determine the phase of the complex harmonic impedance:

$$\varphi_k = arctg\left(\frac{X_{kS}}{R_S}\right)$$

(10)

2.2. Mathematical model of amplifying the harmonic conditions by reactive power compensation

Switching shunt equivalent impedance in a network containing harmonics, conduce to more or less influence on the harmonic conditions, depending on the character and the value of the impedance.

Switching a shunt capacitor bank in order to improve the power factor in a bus of a distribution network containing harmonics can conduce to the amplification of the harmonic conditions. This is possible only when the harmonic currents are flowing in the network, with the frequencies close to the parallel resonance frequency. The resonance frequency occurs between the capacitance of the capacitor bank and the equivalent inductance of the network.

Figure 1 presents the equivalent schema for the k range harmonic, for the cases before and after the shunt capacitor impedance switching ($\underline{Z}_{kCB}$) in the point of common coupling (PCC).

The notations used in **Figure 1** are:

$\underline{I}_k$ is the harmonic current provided by an equivalent fictive current source. It corresponds to all the k range harmonic current sources existing in the network, and it produces the harmonic impedance corresponding to PCC, $\underline{Z}_{knet}$, and the harmonic voltage drop $\underline{U}_k$.

The harmonic equivalent current source for k range ($\underline{I}_k$) does not change its value after connecting the capacitor bank (CB) represented by the equivalent reactance, $\underline{Z}_{kCB}$.

In order to determinate the mathematical expressions that will be used, the harmonic impedance "seen" in the *PCC* before the installation of $\underline{Z}_{kCB}$ is separated in two components:

$\underline{Z}_{kload}$ is the transversal impedance of the load existing before the disturbance, usually a load impedance and

$\underline{Z}_{knet}$ is the equivalent impedance of the rest of the network.

The harmonic voltage of k range in PCC is:

$$\underline{U}_k = \underline{I}_k \cdot \underline{Z}_k = \underline{I}_{kload} \cdot \underline{Z}_{kload} \tag{11}$$

in which: $\underline{Z}_k = \underline{Z}_{knet} \| \underline{Z}_{kload} = \frac{\underline{Z}_{knet} \cdot \underline{Z}_{kload}}{\underline{Z}_{knet} + \underline{Z}_{kload}}$.

Results of the component of the harmonic current distributed through $\underline{Z}_{kload}$:

$$\underline{I}_{kload} = \underline{d}_{load} \cdot \underline{I}_k \tag{12}$$

where

$$\underline{d}_{kload} = \frac{\underline{Z}_k}{\underline{Z}_{kload}} \tag{13}$$

We can also write:

$$\underline{I}_k = \underline{I}_{kload} \cdot \frac{\underline{Z}_{kload}}{\underline{Z}_k} \tag{14}$$

a)   b)
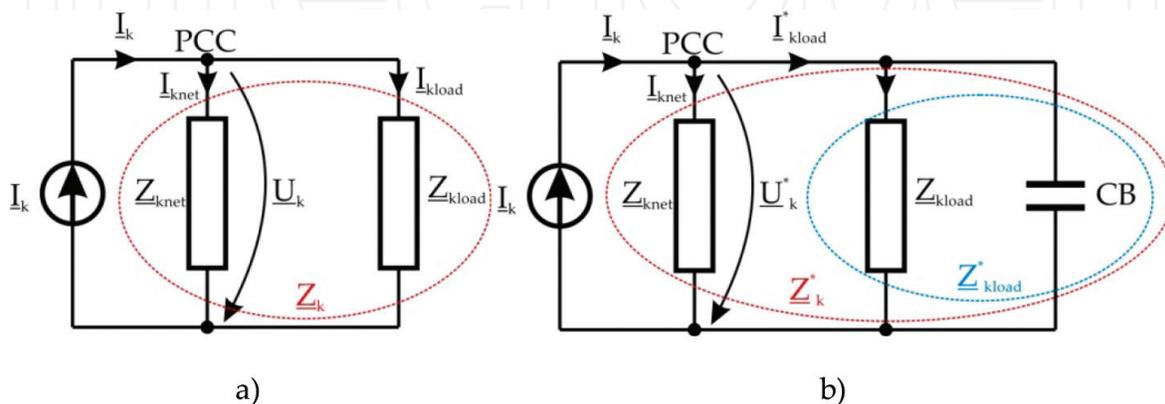
Figure 1. The equivalent circuit: (a) before the capacitor connection; (b) after the capacitor connection.

After the shunt capacitor bank connecting, $\underline{Z}_{kCB}$, supposing that the harmonic current sources and the harmonic impedance of the network do not change, we can write:

$$\underline{U}_k^* = \underline{I}_k \cdot \underline{Z}_k^* = \underline{I}_{kload}^* \cdot \underline{Z}_{kload}^* \tag{15}$$

Consulting expressions for the harmonic impedance corresponding to PCC after the reactive power compensation ($\underline{Z}_{kCB}$ switching):

$$\underline{Z}_k^* = \underline{Z}_k \big\| \underline{Z}_{kCB} = \frac{\underline{Z}_k \cdot \underline{Z}_{kCB}}{\underline{Z}_k + \underline{Z}_{kCB}} \tag{16}$$

The total transversal impedance:

$$\underline{Z}_{kload}^* = \underline{Z}_{kload} \big\| \underline{Z}_{kCB} = \frac{\underline{Z}_{kload} \cdot \underline{Z}_{kCB}}{\underline{Z}_{kload} + \underline{Z}_{kCB}} \tag{17}$$

From (15), we have the following result:

$$\underline{I}_{kload}^* = \underline{I}_k \cdot \frac{\underline{Z}_k^*}{\underline{Z}_{kload}^*} \tag{18}$$

Using the expression of $\underline{I}_k$ for the regimen before the reactive power compensation, $\underline{Z}_{kCB}$ (expression (14)):

$$\underline{I}_{kload}^* = \underline{I}_{kload} \cdot \frac{\underline{Z}_{kload}}{\underline{Z}_k} \cdot \frac{\underline{Z}_k^*}{\underline{Z}_{kload}^*} \tag{19}$$

or

$$\underline{I}_{kload}^* = \underline{F}_{I_{load}} \cdot \underline{I}_{kload} \tag{20}$$

where the notation $\underline{F}_{I_{load}}$ represents the load current amplification factor, pursuant to the reactive power compensation, $\underline{Z}_{kCB}$:

$$\underline{F}_{kI_{load}} = \frac{\underline{Z}_{kload}}{\underline{Z}_k} \cdot \frac{\underline{Z}_k^*}{\underline{Z}_{kload}^*} \tag{21}$$

Using expressions (16) and (17) in (21), we obtain:

$$\underline{F}_{kI_{load}} = \frac{\underline{Z}_{kload} + \underline{Z}_{kCB}}{\underline{Z}_k + \underline{Z}_{kCB}} \tag{22}$$

So, knowing the impedances $\underline{Z}_k$ and $\underline{Z}_{kCB}$ from the initial regimen, and the initial load harmonic current ($\underline{I}_{kload}$), we can find the final load current $\underline{I}_{kload}^*$ and also the harmonic voltage in PCC after the capacitor bank connection $\underline{Z}_{kCB}$:

$$\underline{U}_k^* = \underline{I}_{kload}^* \cdot \underline{Z}_{kload}^* \tag{23}$$

The harmonic voltage amplification factor in PCC is calculated by the following expression:

$$\underline{F}_{U_k} = \frac{\underline{U}_k^*}{\underline{U}_k} = \frac{\underline{Z}_k^*}{\underline{Z}_k} = \frac{\frac{\underline{Z}_k \cdot \underline{Z}_{kCB}}{\underline{Z}_k + \underline{Z}_{kCB}}}{\underline{Z}_k} = \frac{\underline{Z}_{kCB}}{\underline{Z}_k + \underline{Z}_{kCB}} \tag{24}$$

and

$$F_{U_k} = \frac{|\underline{U}_k^*|}{|\underline{U}_k|} = \frac{|\underline{Z}_{kCB}|}{|\underline{Z}_k + \underline{Z}_{kCB}|} \tag{25}$$

The total harmonic distortion (THD) of the PCC voltage after connecting to the capacitor bank must be lower than the highest value:

$$THD_{U^*} = \frac{\sqrt{\sum_{k=2}^{n} U_k^{*2}}}{U_1} = \frac{\sqrt{\sum_{k=2}^{n} (F_{U_k} \cdot U_k)^2}}{U_1} \le THD_{U\max} \tag{26}$$

In addition, the voltage in PCC must be lower than the highest value imposed by the capacitor bank manufacturer, usually 10% over the nominal voltage.

Knowing the voltage bus in PCC and the capacitor bank reactance, we can also check if the current trough in the capacitor bank is lower than the highest value imposed by the capacitor bank manufacturer, usually 30% over the nominal current:

$$I_{CB} = \sqrt{\sum_{k=1}^{n} I_{kCB}^2} \le I_{CB\max} \tag{27}$$

3. Simulation results, discussions

In order to estimate the changes regarding the harmonic conditions in a bus of a network, due to the installation of transversal impedance, it means to determinate the new harmonic voltages and harmonic currents, using the initial state of the network.

The validation of the mathematical model was done on a distribution electrical network comprising three voltage levels: 20, 6, and 0.4 kV, respectively. The configuration of the network and the main characteristics of its elements are presented in **Figure 2**.

To simulate the permanent normal operating conditions, the MatLab Simulink soft is used.

The harmonic regimen was obtained using harmonic current sources for the harmonics 5, 7, and 13, in three of the busses of the network (noted 1, 2, 3)—the load busses. These harmonic sources model the nonlinear components of the loads.
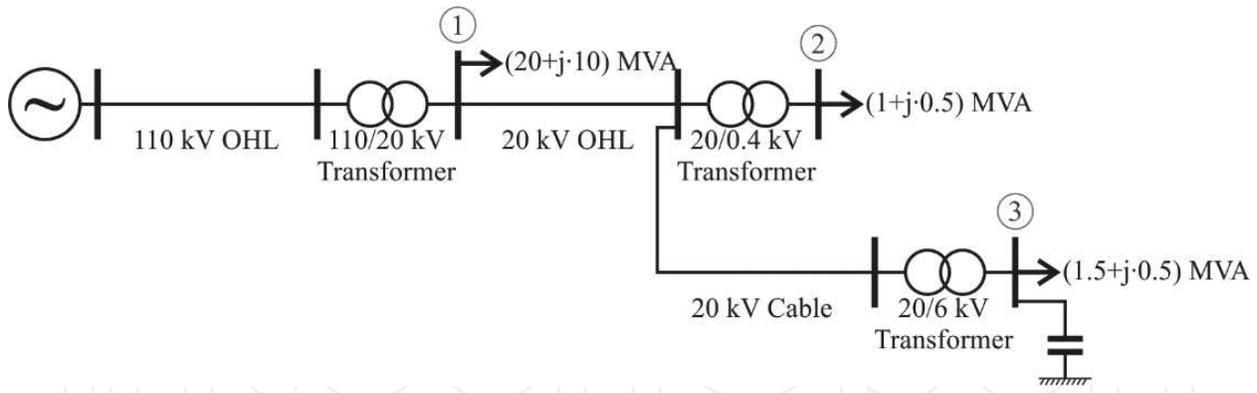
Figure 2. The electrical distribution network used to validate the mathematical model.

For the validation of the mathematical model, bus no. 3 was selected.

The transversal impedance that will be installed has a capacitive character, and it corresponds to 0.3 MVAr capacitive reactive power on the fundamental frequency. The installation of a CB for power factor correction or the voltage control is an operation with a high impact for both the network and the capacitors. If the network contains harmonics, the effect of connecting a capacitor bank will be harmonic conditions amplification and capacitors thermal overstressing risk.

The ampleness of both effects can be anticipated using the state values of the network before the installation like it was proved earlier.

The amounts obtained by MatLab simulation before the installation of the CB are presented in **Table 1**. The notation represents the equivalent impedance of the linear component of the load.

By the successively installation of a CB having 0.3 MVAr capacitive reactive power, the values obtained using the method presented in this chapter, respectively, by MatLab simulation, are written in **Tables 2** and **3**.

The simulation was deliberately done for a case with high harmonic conditions—see the values in **Table 1**. It results in $THD_U = 20\%$ for the bus 3, before the reactive power compensation. For the bus 3, where is connected also a load, for the current absorbed by this, we have $THD_I = 19\%$. We only concentrate on the linear component of the load connected in bus 3. From **Table 3**, we observe that after the reactive power compensation, the voltage THD in the

k	$\underline{Z}_k$		$\underline{Z}_{k\,load}$		U_k (V)	THD_U	$I_{k\,load}$ (A)
	$|\underline{Z}_k|$ (Ω)	Phase (deg)	$|\underline{Z}_{k\,load}|$ (Ω)	Phase (°)			
1	1.633	51.06	22.76	18.43	3182	0.2	15.75
5	6.376	62.21	23.946	86.18	430.34		13.92
7	8.542	57.2	23.972	87.27	524.09		14.00
13	13.58	39.74	23.992	88.53	376.01		17.75

Table 1. The values from steady-state operation before the capacitor bank switching.

k	F_{u_k}	U_k^* (V)	THD_{U^*}	$F_{kI_{load}}$	I_{kload}^* (A)	$THD_{I_{load}^*}$	I_{kCAP}^* (A)
1	1.01	3215.9	0.241	0.967	135.1	0.457	26.799
5	1.29	430.27		1.76	24.52		17.928
7	1.56	524.06		2.622	36.72		30.5708
13	0.88	376.16		2.43	43.27		40.7543

Table 2. The values calculated after the capacitor bank switching.

k	U_k^* (V)	THD_{U^*}	I_{kload}^* (A)	$THD_{I_{load}^*}$	I_{kCAP}^* (A)
1	3216.0	0.2411	135.18	0.4573	26.8
5	430.31		24.526		17.93
7	524.09		36.728		30.57
13	376.01		43.268		40.73

Table 3. The values obtained by MatLab simulation after the capacitor bankswitching.

bus 3 will increase to 24.11%. This is due to the high distortion of the current that will flow through the capacitive impedance after its installation.

Comparing now the values obtained by calculus (**Table 2**) with the values measured in MatLab (**Table 3**), we observe a good proximity.

4. MatLab implementation of the proposed model

MatLab Simulink simulation software is frequently used in a large area of engineering fields like communications, electrical engineering, mechanical engineering, digital image processing, and others, both for research and education [17, 18].
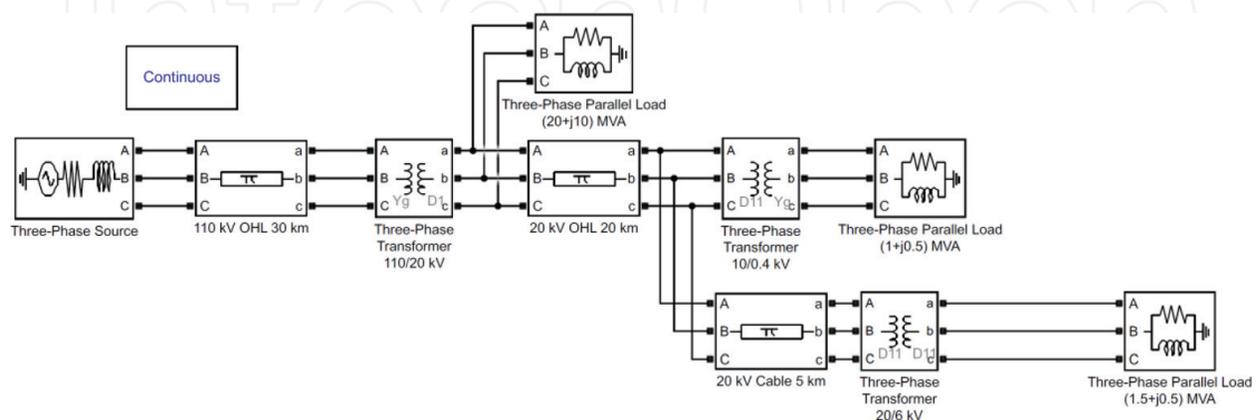
Figure 3. The electrical distribution network implemented in MatLab Simulink before the reactive power compensation.

In this chapter, the proposed mathematical model was validated using Matlab Simulink. The electrical network presented in **Figure 2** was modeled in Simulink, **Figure 3**, as follows:

The electrical system was modeled using a 110-kV three-phase balanced source having Y grounded connection.

The electrical overhead lines (OHL) and cables are modeled using three-phase PI section lines. The line parameters resistor (R), inductor (L), and capacitor (C) are specified as positive- and zero-sequence parameters that take into account the inductive and capacitive couplings between the three-phase conductors, as well as the ground parameters. This method of specifying line parameters assumes that the three phases are balanced.

A three-phase two windings transformer model is used for all the transformers of the network. The connection of the windings is Y grounded for high voltage (110 kV) and D for medium voltage (20 and 6 kV). The parameters can be written in pu units or SI units. Changing the Units parameter from pu to SI, or from SI to pu, automatically converts the parameters displayed in the mask of the block.

The loads are modeled using parallel R L C circuits defined by active and reactive powers. Only the elements corresponding to non-zero powers are displayed. In this example, the reactive power of the loads is inductive reactive power.

This model is used for the steady-state operation condition before the capacitor bank switching.

Figure 4 presents the MATLAB Simulink model of the electrical distribution network with the capacitor bank for power factor correction connected in bus No.3. The capacitor bank is modeled as a capacitive load defined by the capacitive reactive power.

A detail of the compensation bus is presented in **Figure 5**. Here, the harmonic current sources for the 5th, 7th, and 13th harmonics are presented. These are ideal current sources having the following parameters: peak amplitude, phase, and frequency. A three-phase measurement
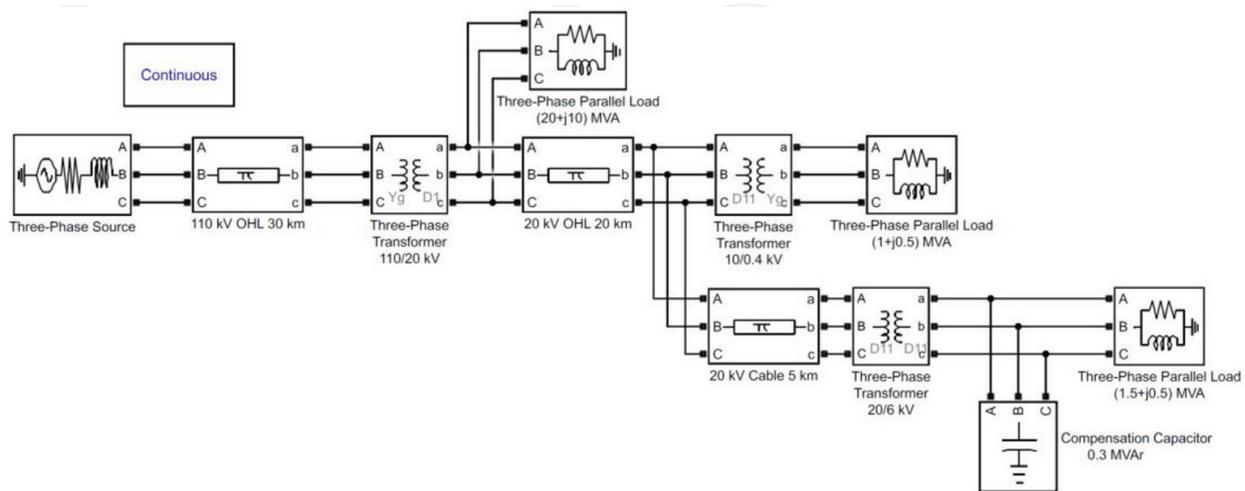
Figure 4. The electrical distribution network implemented in MatLab Simulink after the reactive power compensation.
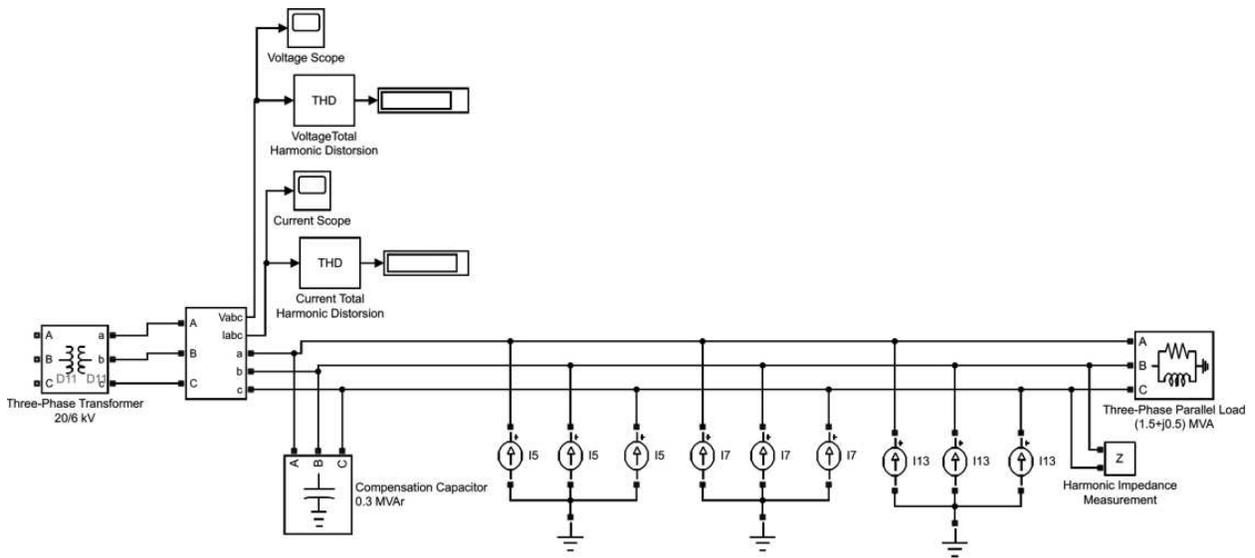
**Figure 5.** Details of the compensation bus.
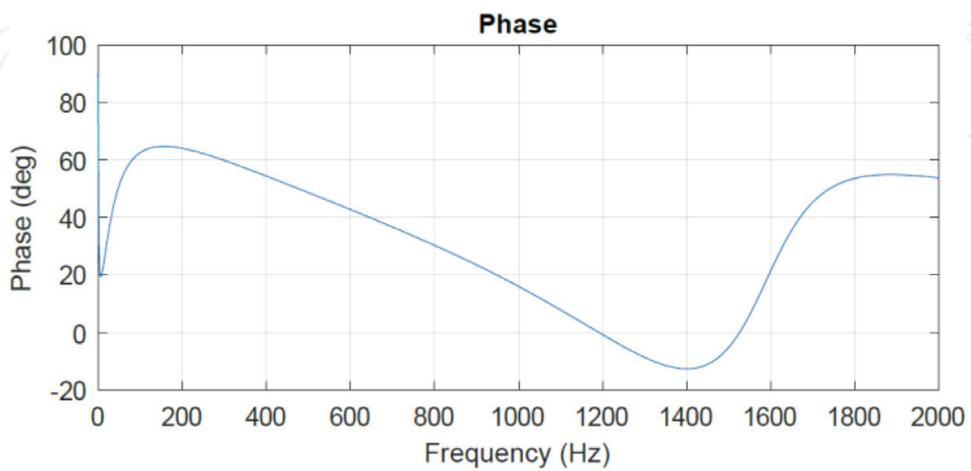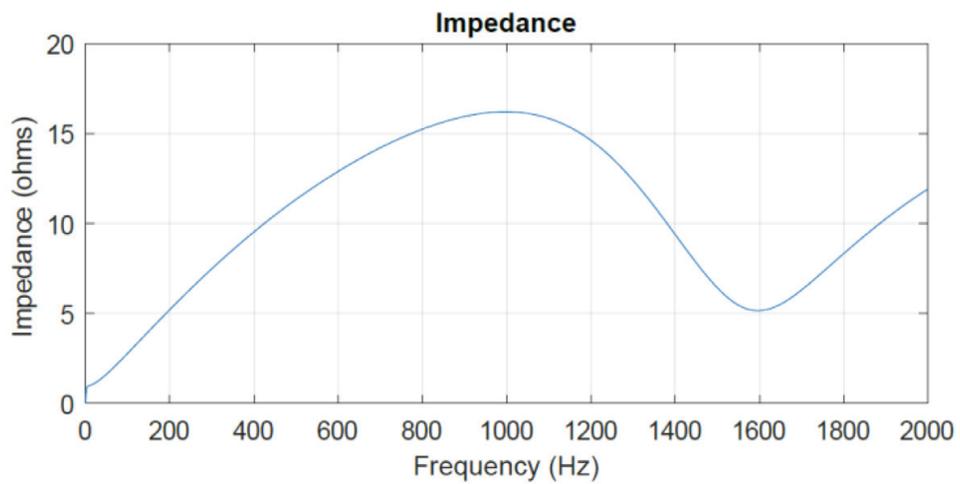
Figure 6. Harmonic impedance before the compensation.

block for both voltages and currents are also inserted in the model. The user can choose phase-to-phase or phase-to-ground measuring. Knowing the harmonic currents and harmonic voltages, the total harmonic distortion (THD) factor both for voltage and current can be calculated.

The harmonic impedance of the network is measured using a dedicated block named "Impedance Measurement" which measures the impedance in a bus of the network as a function of the frequency (harmonic impedance). The harmonic impedance (magnitude and phase) is displayed by using the appropriate tool from the Powergui block. The results obtained in the two cases are presented in **Figures 6** and **7**.

In order to highlight the influence of the capacitor reactive power amounts on the values of the harmonic impedance, the following compensation steps are considered: 0.2, 0.3, and 0.4 MVAr. Corresponding to these steps of the capacitor reactive power, the resonance frequency is much lower, while the reactive power increases: 404 Hz for 0.4 MVAr, 460 Hz for 0.3 MVAr, and 550 Hz for 0.2 MVAr. The results are presented in **Figure 8**.

The influence of the load active power is also interesting to study. For a constant reactive power of compensation (0.3 MVar), the resonance frequency does not change, but the
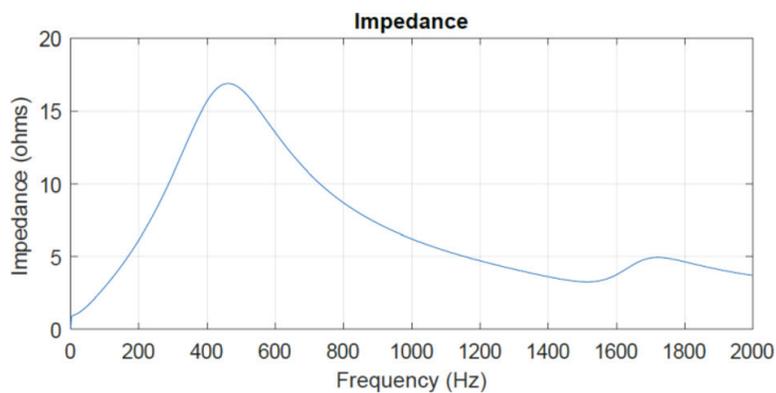

**Figure 7.** Harmonic impedance after the compensation.
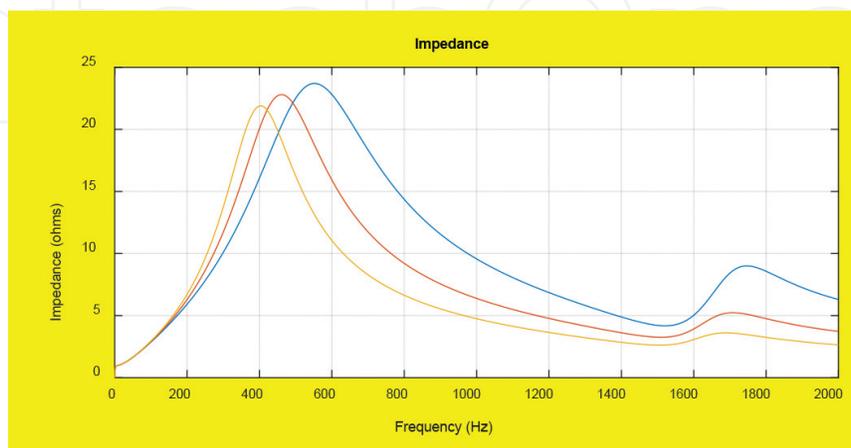
Figure 8. The influence of the amount of reactive power compensation.
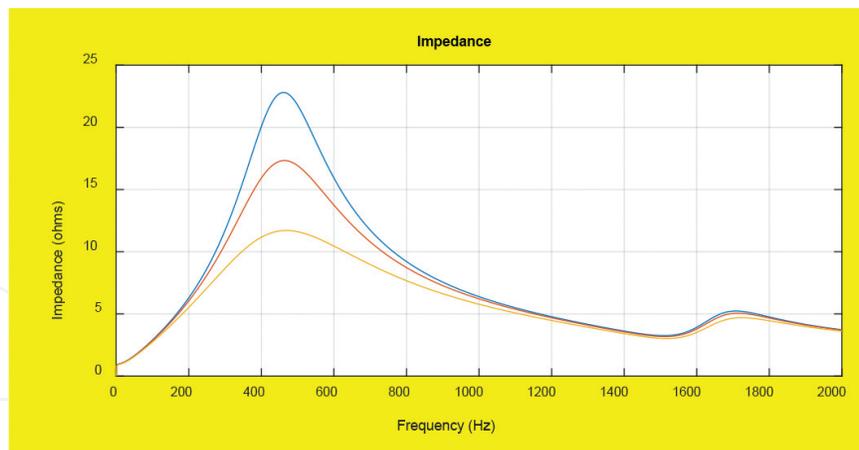
Figure 9. The influence of the amount of load active power.
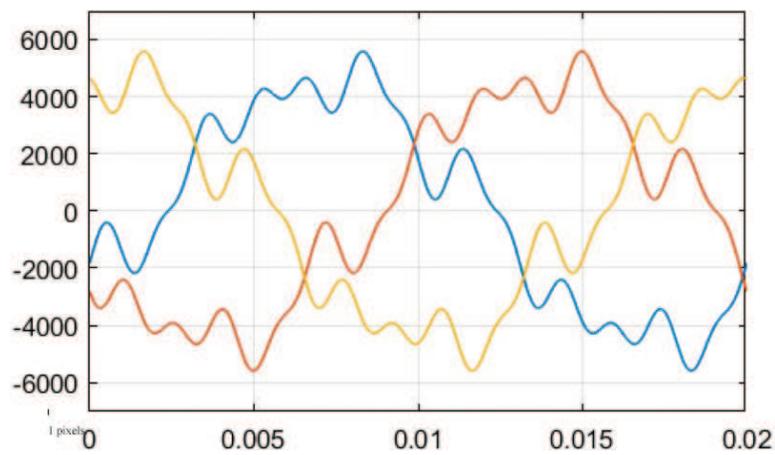
Figure 10. Voltages waveforms in bus 3 after the capacitor bank switching.
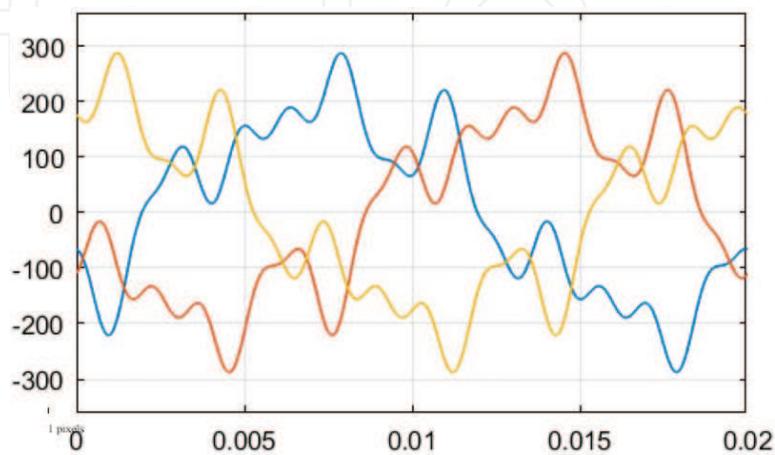
Figure 11. Currents waveforms in bus 3 after the capacitor bank switching.

amplification factor is changing. For different values of the load active power (1, 1.5, and 2.5 MW), the harmonic impedance has different values (22.8, 17.32, and 11.7 Ω) and the resonance frequency has a constant value: 460 Hz. The results are presented in **Figure 9**. Changes of the load reactive power do not influence the results of the harmonic impedance.

Scopes are installed for both voltage and current. The results for time-domain simulation for one cycle (0.02 s), after switching the capacitor bank, are presented in **Figure 10** for voltages and in **Figure 11** for currents.

5. Conclusions

The scope of this chapter consists in highlighting the importance of harmonic impedance study in a bus of an electrical network with harmonics where a capacitor bank will be installed. Capacitor bank switching leads to an amplification of the harmonic impedance for the frequencies close to the resonance frequency.

The harmonic voltage amplification will lead to high values of voltage to the capacitor terminals and the effect will be an electrical overstressing of the capacitor banks. Harmonic current amplification will lead to high values of current trough the capacitor bank and the effect will be a thermic overstressing of the capacitor banks.

A mathematical model for harmonic impedance determination is presented, and, based on its values, anticipation of harmonic amplification is proved. A numerical example is presented for a distribution network containing harmonics and capacitor banks for power factor correction.

The validation of the mathematical model was done by MatLab Simulink simulation. The presented electrical distribution network is modeled using elements from the Library Browser like: three-phase balanced source for electrical system modeling, PI section lines for overhead lines and cables, three-phase two windings transformers, and three-phase loads. Harmonic conditions are simulated using ideal current sources for different frequencies. Three-phase measurement blocks are used for measuring harmonic voltages and currents, and harmonic impedance is also measured using a dedicated block.

We observe a good proximity of the results obtained by calculus and by simulation, MatLab Simulink being a useful tool for research and education in the field of power engineering.

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