Analysis and Control of Harmonic Overvoltages during System Restoration

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Abstract - **This paper presents a new method which facilitates power system restoration planning with respect to the control of harmonic resonance overvoltages. The frequency-domain analysis of the Electromagnetic Transients Program (EMTP) in combination with analytical calculations is applied to find an optimum resonance condition. The analytical equations are based on sensitivity analysis for single frequencies and are extended to total sensitivity calculation. After a general introduction to the phenomenon of overvoltages during power system restoration and harmonic resonance overvoltages, basic principles of their control are explained using a simple power system. Then the new algorithm is presented and demonstrated for a practical power system.**

Keywords: Power system restoration, harmonic overvoltages, sensitivity analysis.

I. INTRODUCTION

A rising number of major power system blackouts in recent years emphasizes the importance of detailed restoration plans, in order to restore electric service after a blackout as fast as possible. While most restoration plans have been developed on a trial-and-error principle, there is a tendency to more systematic planning and analysis of restoration procedures. This requires the development of new, and the integration and automation of existing power system simulation tools [2, 5, 6, 7].

So far, most of the restoration studies have been performed using steady-state or quasi-steady state analysis in order to find a suitable restoration sequence. Several problems encountered during practical restoration procedures, however, were found to be related to electromagnetic transients [1, 3, 8]. One of the major concerns, especially at the beginning of a system restoration, is related to temporary overvoltages. Whereas the control of steady-state overvoltages can be dealt with thoroughly using conventional load flow programs, a systematic method to deal with resonant overvoltages has not yet been developed. Therefore, the research project presented in this paper focuses on the analysis and control of harmonic overvoltages during power system restoration.

During the early stages of the restoration procedures following a partial or complete blackout of the power system, the system is lightly loaded and resonance conditions are different from the ones at normal operation. If the frequency characteristic of the system shows resonance conditions around multiples of the fundamental frequency, very high and weakly damped temporary (transient oscillatory) overvoltages (TOVs) of long duration may occur when the system is excited by a harmonic disturbance, such as the switching of lightly loaded transformers or transformer overexcitation.

This phenomenon is usually investigated with the Electromagnetic Transients Program (EMTP) [4]. In order to study a large number of possible system configurations, it is necessary to run many time-domain simulations resulting in a large amount of simulation time. A way to limit the overall calculation time is to reduce the number of simulations by applying analytical or knowledge-based rules to discard a number of system configurations before an actual time-domain simulation is carried out.

Our paper describes a new approach to power system restoration planning using the EMTP in combination with analytical calculations. The procedure is based on harmonic analysis of the system and sensitivity analysis. Examples are presented on how the optimum system configuration for controlling harmonic resonance can be calculated in a fast and efficient way, and how the number of time-consuming EMTP time-domain simulations based on the common trial-and-error method can be reduced significantly.

II. OVERVOLTAGES DURING RESTORATION

A. Overview of Overvoltages

One of the major concerns in power system restoration is the occurrence of overvoltages as a result of switching procedures. These can be classified as transient overvoltages, sustained overvoltages, harmonic resonance overvoltages and overvoltages resulting from ferroresonance. Steady-state overvoltages occur at the receiving end of lightly loaded transmission lines as a consequence of line charging currents (reactive power balance). Excessive sustained overvoltages may lead to damage of transformers and other power system equipment. Transient overvoltages are a consequence of switching operations on long transmission lines, or of switching of capacitive devices, and may result in arrester failures. Harmonic resonance overvoltages are a result of system resonance frequencies close to multiples of the fundamental frequency. They may lead to long lasting overvoltages resulting in arrester failures and system faults. Ferroresonance is a non-harmonic resonance characterized by overvoltages whose waveforms are highly distorted and which can cause catastrophic equipment damages [1].

B. Harmonic Overvoltages

This research project concentrates on the analysis of harmonic overvoltages. These are a result of network resonance frequencies close to multiples of the fundamental frequency. They can be excited by harmonic sources such as saturated transformers, power electronics, etc.

The major cause of harmonic resonance overvoltage problems is the switching of lightly loaded transformers at the end of transmission lines. Thereby inrush currents with significant harmonic content up to frequencies around $f = 600\,Hz$ are created. They can be represented by a harmonic current source $\mathbf{I}(h)$ connected to the transformer bus [8]. The relation between nodal voltages, network matrix and current injections can be represented by

$$\mathbf{V}(h) = \mathbf{Z}(h) \cdot \mathbf{I}(h) \tag{1}$$

where h represent the harmonic frequencies $f = 120, 180, \ldots\, Hz$. The harmonic current components of the same frequency as the system resonance frequencies are amplified in case of parallel resonance, thereby creating higher voltages at the transformer terminals. This leads to a higher level of saturation resulting in higher harmonic components of the inrush current which again results in increased voltages. This can happen particularly in lightly damped systems, common at the beginning of a restoration procedure when a path from a blackstart source to a large power plant is being established and only a few loads are restored yet [1, 8].

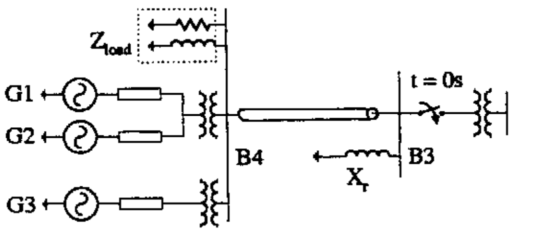

Fig. 1. Power system at the beginning of a restoration procedure

C. Example

In the following, the sample system shown in Fig. 1 is used in order to study conditions leading to harmonic resonance overvoltages. It represents a power system at the early stages of a restoration procedure in which, starting from the generators connected to bus B4, a path to a large power station is built. Fig. 2 shows the result of the EMTP frequency analysis at bus B3. The magnitude of the Thevenin impedance, seen from bus B3, Z_{B3} shows a parallel resonance peak at the third harmonic. When the transformer is energized, this resonance condition results in the overvoltage $V_{B3}\,(t)$ shown in Fig. 3.

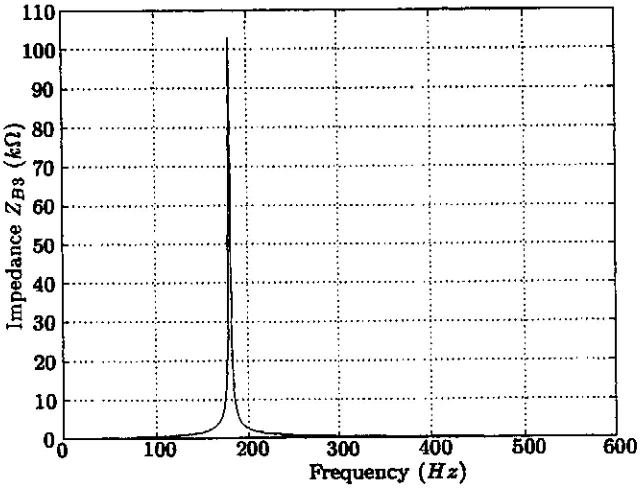

Fig. 2. Impedance at bus B3

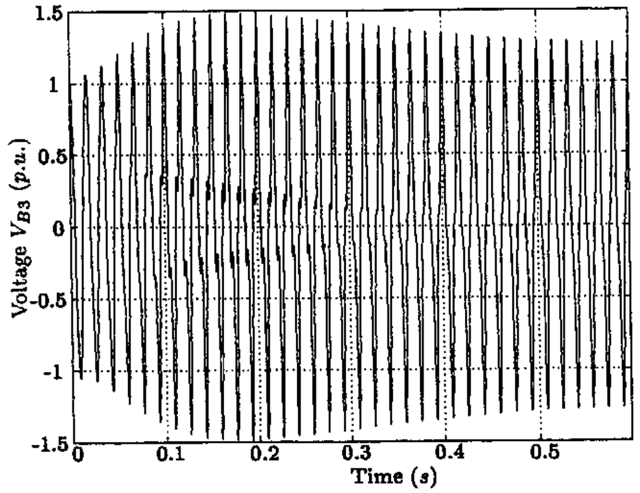

Fig. 3. Voltage at bus B3 after switching of transformer

Several methods to prevent harmonic resonance overvoltages are common. A highly resistive load can be added to bus B4, leading to a decrease in the magnitude of the impedance Z_{B3} and consequently to a reduced amplification of the injected harmonic currents. Another method to prevent resonant overvoltages is to bring additional generators online: a higher number of generators results in a lower overall inductance, and consequently in a higher resonance frequency, according to the equation

$$\omega_r = \frac{1}{\sqrt{L \cdot C}}$$

This means that if generators are added to bus B4, the resonance peak is shifted to higher frequencies—if generators are omitted, it is shifted to lower frequencies. Another possibility is to decrease the generators' scheduled voltage, leading to a proportional decrease of the pre-switching steady-state voltages.

III. SENSITIVITY ANALYSIS

A. Overview of Algorithm

In cases where the power system during a restoration procedure has already grown to a considerable size, it is not always clear at which nodes admittance changes should be made in order to obtain an optimum impedance-frequency characteristic at the switching node. Therefore, in the following, a method is developed which determines the nodes where changes are most effective. The method is based on EMTP harmonic analysis and sensitivity analysis for the harmonic frequencies. It is important to note that only those frequencies are of interest since the major components of the frequency spectrum of the voltages and currents in the system (as a result of transformer saturation) are multiples of the fundamental frequency $f = 60\,Hz$.

The algorithm consists of four steps, which will be described in detail in the following sections:

1. Calculate the Thevenin equivalent circuit for the system.
2. Determine the sensitivity for each harmonic frequency.
3. Determine the weighting function for the inrush current.
4. Calculate the total sensitivity.

B. Thevenin Equivalent Circuit

In the first step of the procedure the multi-node Thevenin equivalent circuit is determined for the desired frequency range (here the frequencies up to $f = 600\,Hz$ are considered to be sufficient). The terminals of this circuit consist of the bus where the next switching operation is to be performed and buses where parameters can be changed, i. e. where capacitors, reactances, generators, etc. can be switched in or out. Examples for buses with variable parameters are those where the number of generators can be varied, where loads can be changed or shunt reactances can be added. In order to find the matrix representing the Thevenin equivalent circuit, currents of magnitude 1 $p.u.$ are successively injected into each of the terminals. For this calculation, the voltage sources in the system are short circuited and other current sources are open circuited. The voltages at the nodes of the Thevenin equivalent circuit then give—column by column—the matrix elements. More details about multi-node Thevenin equivalent circuits can be found in [4].

C. Individual Sensitivity

We define the sensitivity of an impedance as its magnitude's derivative with respect to an admittance change at each node of the Thevenin equivalent circuit. For a harmonic frequency h the sensitivity with respect to a change at node k is defined as:

$$S_{jk}(h) = \frac{\partial |Z_{jj}(h, \Delta Y_k)|}{\partial |\Delta Y_k|}\Big|_{\Delta Y_k = \partial(\Delta Y_k)} \tag{2}$$

where Z_{jj} stands for the self impedance at bus j, ΔY_k for a change in admittance at bus k, and $\partial(\Delta Y_k)$ for a very small number representing an incremental perturbation. Performing the same operation for all the nodes $1 \ldots, k, \ldots, n$ of the Thevenin equivalent circuit then gives the sensitivity vector for the harmonic frequency h:

$$\mathbf{S}(h) = \begin{bmatrix} S_{j1}(h) \\ \vdots \\ S_{jk}(h) \\ \vdots \\ S_{jn}(h) \end{bmatrix} \tag{3}$$

If only sensitivities for single frequencies are considered, the vectors can be normalized by referring the vector $\mathbf{S}(h)$ to the value of its maximum element, i. e. we get

$$\overline{\mathbf{S}}(h) = \frac{1}{max_i\,(S_{ji}(h))} \cdot \begin{bmatrix} S_{j1}(h) \\ \vdots \\ S_{jk}(h) \\ \vdots \\ S_{jn}(h) \end{bmatrix} \tag{4}$$

Since we deal with either resistive, inductive or resistive-inductive changes depending on the available devices, two different sensitivity vectors can be defined—one for resistive ($\mathbf{S_R}$) and one for inductive ($\mathbf{S_I}$) changes. This is also reflected in the incremental change $\partial(\Delta Y_k)$, which in the case of resistive changes can be defined as a real number and in the case of inductive changes as an imaginary number. Capacitive changes can be considered as negative inductive changes.

D. Total Sensitivity

Calculating the sensitivities for each of the harmonics results in a sensitivity matrix, defined as

$$\mathbf{S} = \begin{bmatrix} S_{11,120} & S_{11,180} & \cdots & S_{11,600} \\ S_{12,120} & S_{12,180} & \cdots & S_{12,600} \\ \vdots & & & \vdots \\ S_{1n,120} & S_{1n,180} & \cdots & S_{1n,600} \end{bmatrix} \quad (5)$$

An overall sensitivity taking into account the sensitivities for all the harmonics up to a frequency of $f = 600\,Hz$ can then be calculated using a weighting vector

$$\mathbf{I_w} = \begin{bmatrix} I_{w,120} \\ I_{w,180} \\ \vdots \\ I_{w,600} \end{bmatrix} \quad (6)$$

and the matrix multiplication

$$\mathbf{S_{total}} = \mathbf{S} \cdot \mathbf{I_w} = \begin{bmatrix} \sum_{h=2}^{10} (S_{11,h} \cdot I_{w,h}) \\ \sum_{h=2}^{10} (S_{12,h} \cdot I_{w,h}) \\ \vdots \\ \sum_{h=2}^{10} (S_{1n,h} \cdot I_{w,h}) \end{bmatrix} \quad (7)$$

where n stands for the number of buses where changes are possible.

E. Weighting Vector

The lower harmonics of transformer inrush currents are of higher magnitude than the higher ones. Therefore a resonance peak at a lower harmonic is worse with respect to resonant overvoltage conditions than one at a higher harmonic. Consequently, changes at lower harmonics are considered more important than changes at higher harmonics. This is taken into account by a weighting vector $\mathbf{I_w}$ which is based on the harmonic characteristic of the transformer inrush current. This characteristic is either given by the manufacturer or can be obtained by simulating the energization of an unloaded transformer using the EMTP and taking the Fast Fourier Transform (FFT) of the inrush current. Another method is to use approximate equations such as given e.g. in [3, 9].

In order to find a suitable weighting vector $\mathbf{I_w}$, a normalized current for each transformer terminal voltage V_T is calculated as

$$\overline{I}(h, V_T) = \frac{I(h, V_T)}{max_h\,(I(h, V_T))} \quad (8)$$

where h stands for the harmonic frequency and V_T for the pre-switching steady-state transformer voltage. We then obtain the normalized average by

$$I_w(h) = \frac{\sum_{V_T=V_{T_{min}}}^{V_{T_{max}}} \overline{I}(h)}{max_h \left(\sum_{V_T=V_{T_{min}}}^{V_{T_{max}}} \overline{I}(h) \right)} \quad (9)$$

IV. CASE STUDY

As an example the system in Fig. 4 is examined. It represents the same system as the one in Fig. 1, but a few restoration steps later. The impedance sensitivity at bus B1 is investigated with respect to changes at buses B2, B3, B4, B5, B6 and B7. This is shown schematically in Fig. 5.

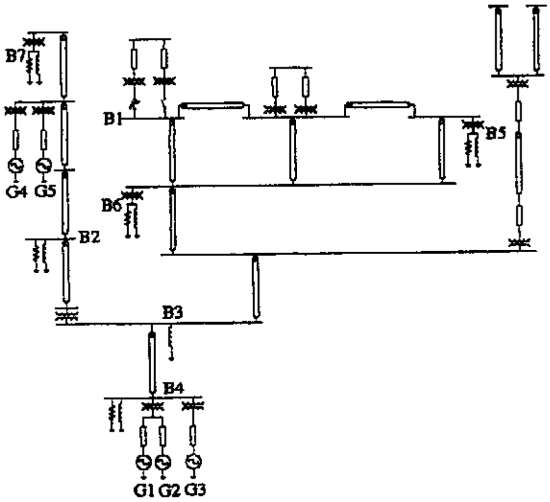

Fig. 4. Studied system

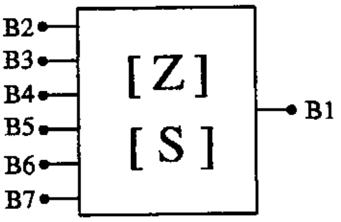

Fig. 5. Thevenin equivalent circuit, sensitivity

A. Thevenin Equivalent Circuit

As mentioned earlier, the EMTP frequency scan can be utilized to calculate the Thevenin equivalent circuit for the desired range of harmonics. Usually, only the frequencies from $f = 120\,Hz$ to $f = 600\,Hz$ are of interest. The frequency $f = 60\,Hz$, however, should be added as well, since it might be used in order to calculate fundamental frequency overvoltages.

B. Individual Sensitivity

Representatively for all harmonics up to $f = 600\,Hz$, the determination of the sensitivity for the frequency $f = 120\,Hz$ is presented in this section.

The elements of the resistive sensitivity vector $\mathbf{S_R}$ and of the inductive sensitivity vector $\mathbf{S_I}$ can be found in Table I. In order to investigate the validity of those results, the impedance at bus B1 as function of impedance changes at the other nodes is calculated.

Those are varied in the range $\Delta Y_k = (0.2 \ldots 2)\, Y_0$. For the inductive case the value $Y_0 = -j \cdot 4.421 \cdot 10^{-4}\, S$, corresponding to an inductance $L = 3000\, mH$ at the frequency f=120 Hz and for the resistive case $Y_0 = 2 \cdot 10^{-3}\, S$, corresponding to a resistance of $R = 500\, \Omega$ are chosen. The results are shown in Fig. 6 and Fig. 7. The numbers in the graphs refer to the number k in Table I. The results show a good agreement with the corresponding sensitivities in Table I. The most effective change of the impedance for the frequency $f = 120\, Hz$, at bus B1 can be achieved by changing the impedance values at either bus B1 or B3.

Table I
Sensitivity vectors for $f = 120\, Hz$

Bus k	1	2	3	4	5	6	7
$S_{R(1k)}$	-1.0000	0.1174	-0.3297	0.0140	-0.0034	-0.0033	-0.0022
$S_{I(1k)}$	0.6388	0.4081	1.0000	0.1966	0.0022	0.0022	0.0006

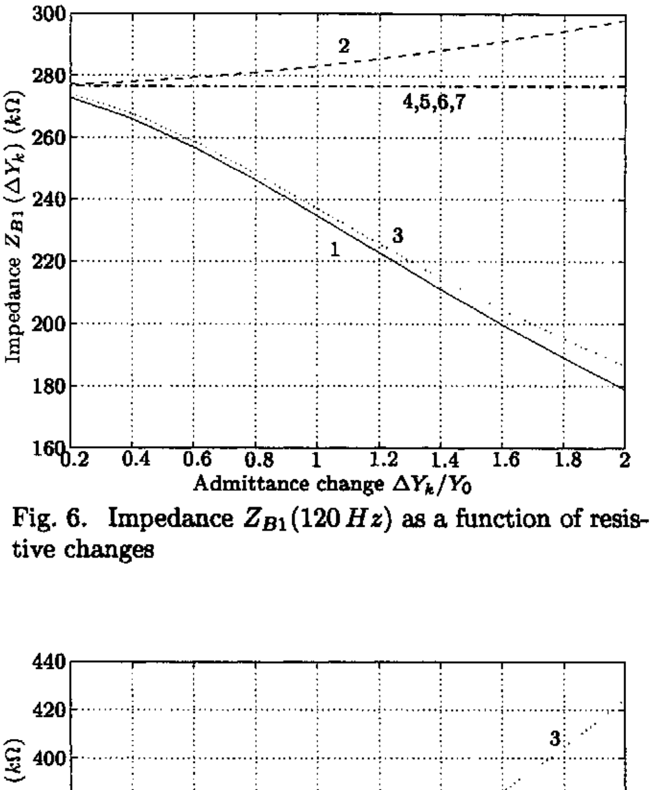

Fig. 6. Impedance $Z_{B1}(120\, Hz)$ as a function of resistive changes

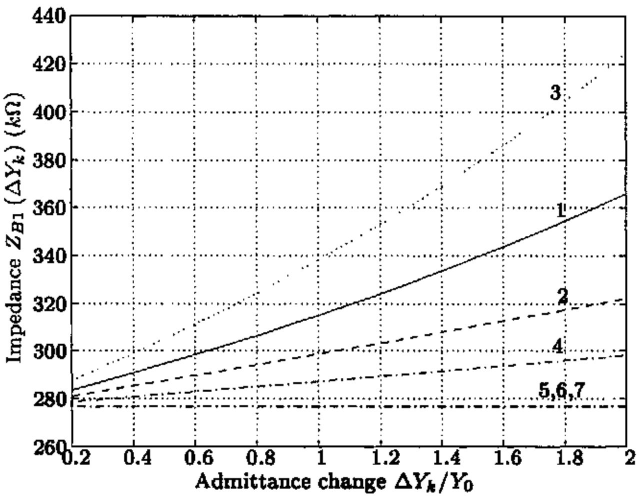

Fig. 7. Impedance $Z_{B1}(120\, Hz)$ as a function of inductive changes

C. Weighting Function

Fig. 8 shows the FFT results of the transformer inrush current, for the voltages $V_{Tmin} = 0.95\, p.u.$ to $V_{Tmax} = 1.05\, p.u.$ and the frequencies $f = 120\, Hz$ to $f = 600\, Hz$. The result for the weighting function is depicted in Fig. 9.

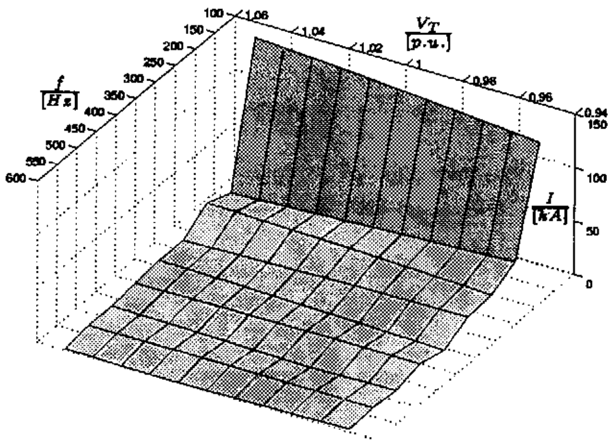

Fig. 8. Harmonic characteristic of transformer

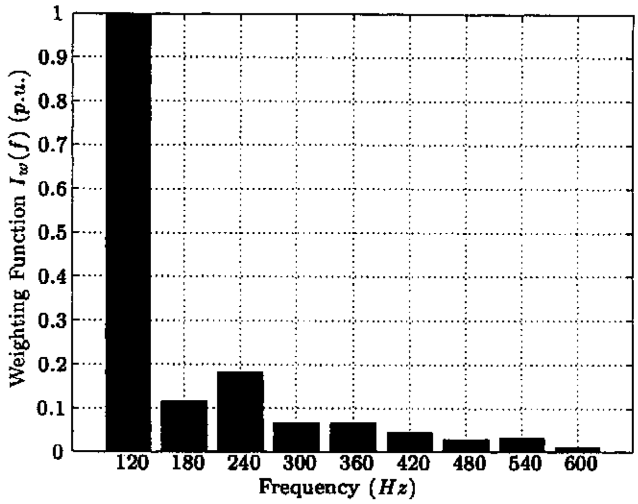

Fig. 9. Weighting function Iw

D. Total Sensitivity

The results for the total resistive and inductive sensitivities can be found in Table II. In order to verify their validity, the impedance at the switching bus B2 as a function of frequency is calculated. Fig. 10 shows the results for resistive changes at the buses of

Table II
Total sensitivity vectors

Bus k	1	2	3	4	5	6	7
$S_{R(1k)}$	-1.0000	-0.0306	-0.1406	-0.2630	-0.0034	-0.0034	-0.0001
$S_{I(1k)}$	1.0000	0.0455	0.2051	0.2636	0.0035	0.0034	0.0002

the Thevenin equivalent circuit. The index 0 stands for the case where no change is made and 1, 3 and 4 stand for resistive changes of $R = 100\,\Omega$ at the respective nodes listed in Table II. Only the sensitivities with a magnitude of relevance are shown. The same procedure was carried out for inductive changes of $L = 2000\,mH$ and its outcome is depicted in Fig. 11. The results correlate well with their total sensitivities. The most effective changes in order to reach an optimum resonance condition are changes of the resistances at bus B1. Inductive changes should be avoided at all of the buses.

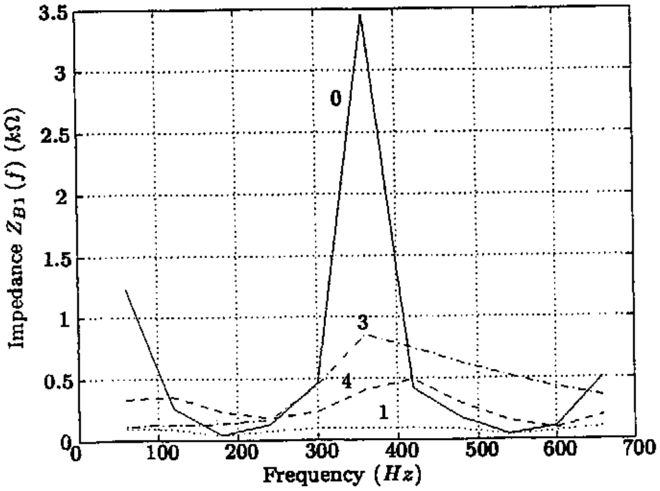

Fig. 10. Impedance Z_{B1} for resistive changes as a function of frequency

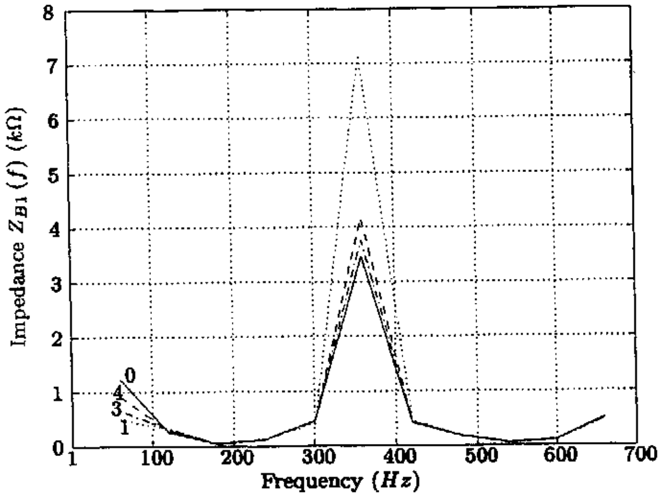

Fig. 11. Impedance Z_{B1} for inductive changes as a function of frequency

V. Conclusions

This paper describes a method for systematic power system restoration planning with respect to the control of harmonic overvoltages. In order to explain the phenomenon of harmonic overvoltages and basic means for their control a simple power system was chosen. The sensitivity analysis on which the new algorithm is based is explained and its effectiveness demonstrated using a practical power system. The new method helps to reduce the number of trial-and-error simulations necessary for restoration planning significantly, by choosing the most efficient system configuration with respect to harmonic overvoltages.

VI. Acknowledgement

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