Some aspects regarding harmonic’s distortions propagation in large medium voltage distribution system

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Abstract: - This paper presents a frequency-scan analysis of a large medium voltage distribution system. The objective of this study is to determine the frequency characteristics of currents and voltages produced in loads substations and in distribution substation by the frequency dependent current sources located in loads substations. An analytical relationship for calculating the potential of medium voltage point is deducted. In order to differentiate harmonic currents due to actual sources from harmonic currents due to resonance involving a capacitor bank an SPICE simulation has been performed. Useful conclusions for analyzing the propagation of harmonic distortions are derived.

Key-Words: - power quality, harmonics distortions, power system, resonance, frequency analysis

1 Introduction

The progress in penetration of modern technology that uses power electronics led to the appearance of other nonlinear loads which absorb nonsinusoidal large currents and create harmonic voltages throughout power system. Distribution system cases are difficult to deal with since due to power factor correction capacitors a harmonic source can pollute all adjacent feeders connected to the same distribution substation transformer. The presence of power factor correction capacitors can result in local system resonances, which lead in turn to excessive currents and possibly subsequent damage to the capacitors.

2 Distribution system case study

Power quality measurements performed at a customer’s 10/0.4 kV load substation indicate significant harmonics content for 17th, 19th, 23rd and 25th harmonics order, they exceed 2 – 3 times the permissible values [5]. The high voltage distortion and a very large amount in harmonics for the current of 0.4 kV capacitor bank from load substation indicates that the capacitor is participating in a resonant circuit within distribution power system.

For our study a case of all n = 107 load substations fed from a 110/10 kV distribution substation has been analyzed. Distribution substation has two 25 MVA power transformers, one is in use. Supplier has a 10 kV, 2.7 MVAr capacitor bank for power factor improvement in use in distribution substation. On the 110 kV transmission side of the distribution substation a simple Thevenin equivalent circuit using the short circuit impedance [2, 6] was considered.

Load substations of the medium voltage distribution system fed from distribution substation can be classified into 10 groups according to the rated power and number of transformers of load substation: 2 loads substations of 160 kVA, 6 of 250 kVA, 55 of 400 kVA, 2 of 2x250 kVA, 21 of 630 kVA, 6 of 2x400 kVA, 3 of 1000 kVA, 6 of 2x630 kVA, 2 of 1600 kVA and 4 loads substations of 2x1000 kVA. Many load substations have capacitor banks for power factor correction. A case with all capacitors from load substation on and also other scenarios has been studied. According to the eight Grady’s rules [4] we include in our study all 36 feeder attached to the distribution substation and all 107 loads substations. Because that load distribution along actual feeders is not known with great accuracy load distribution are estimated by assuming that the total feeder load is distributed in proportion to individual load transformer ratings. In the study it has been assumed that each transformer from load substation is loaded with 50% of their nominal kVA rated power. A case with a loading of load substations by 10 % was also considered.

In Fig.1 it is presented the equivalent electric circuit of the medium voltage distribution system. For modeling of the nonlinear loads, in the study was considered in each load substation a unit current source Ik(f) which is a function of frequency.
Examining equivalent electric circuit, we can see that following resonant circuits are possible:
- load substation parallel/series resonant circuit of LTk leakage inductance and Ck capacitance connected in parallel against unit current source Ik and in series against the medium voltage point MV,
- distribution substation parallel resonant circuit of LTS = LT + LS inductance and CS capacitance

Resonant frequencies for series/parallel combination of the LTk and Ck elements of the loads substations to a loading of 50% and 10% of the transformers ratings are presented in Table 1

<table>
<thead>
<tr>
<th>Nr.</th>
<th>Transformer apparent power</th>
<th>Resonant frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>50% loading</td>
</tr>
<tr>
<td>1</td>
<td>2x630 kVA</td>
<td>461.5 Hz</td>
</tr>
<tr>
<td>2</td>
<td>160 kVA</td>
<td>530.6 Hz</td>
</tr>
<tr>
<td>3</td>
<td>400 kVA</td>
<td>460.5 Hz</td>
</tr>
<tr>
<td>4</td>
<td>2x400 kVA</td>
<td>475.6 Hz</td>
</tr>
<tr>
<td>5</td>
<td>2x1000 kVA</td>
<td>459.8 Hz</td>
</tr>
<tr>
<td>6</td>
<td>630 kVA</td>
<td>471.0 Hz</td>
</tr>
<tr>
<td>7</td>
<td>1000 kVA</td>
<td>459.8 Hz</td>
</tr>
<tr>
<td>8</td>
<td>2x250 kVA</td>
<td>487.5 Hz</td>
</tr>
<tr>
<td>9</td>
<td>1600 kVA</td>
<td>473.8 Hz</td>
</tr>
<tr>
<td>10</td>
<td>250 kVA</td>
<td>462.5 Hz</td>
</tr>
</tbody>
</table>

Resonant frequency of the parallel combination of LT+LS and CS combination from distribution substation are 417 Hz.

2 Problem Formulation. Calculus.

It is required to calculate the frequency characteristics of currents and voltages of transformers and capacitors banks from loads substations and from distribution substation.

Each load substation LSk is modeled by the following electrical parameters: RTk, LTk - equivalent resistance and leakage inductance of the 10/0.4 kV transformer (or transformers), Rk - resistance corresponding to conventional load of the load substation and capacitance Ck of capacitor bank for power factor improvement. Approximate R simple shunt models are used for conventional loads sized according to active power. There are no significant lengths of underground cables and therefore cable capacitance was neglected. We can write for each load substation the formulas for impedances and admittances, as functions of frequency f:

\[ Z_{T_k}(f) = RT_k + j \omega L_{T_k} \quad (1) \]
\[ Y_{T_k}(f) = \frac{1}{RT_k + 2 \pi f C_k} \quad (2) \]
\[ Z_{T_k}(f) = \frac{1}{Y_{T_k}(f)} \quad (3) \]

For distribution substation we can calculate: RT, LT - equivalent resistance and leakage inductance of
110/11 kV Load Tape Changing power transformer, RS and LS – equivalent resistance and inductance of power system and transmission lines and CS capacitance of the 10 kV power factor improvement capacitor bank. The impedances and admittances from distribution substation are:

\[
Z_{TS}(f) = R_T + R_S + j \left( X_T(f) + X_S(f) \right) \quad (4)
\]

\[
Y_{CS}(f) = \frac{1}{Z_{TS}(f)} + j \frac{2 \pi f C}{Z_{TS}(f)} \quad (5)
\]

\[
Z_{TCS}(f) = \frac{1}{Y_{CS}(f)} \quad (6)
\]

Writing the node-voltage equations for equivalent circuit that contain unit independent current sources [6] we can express the value of medium voltage point MV potential:

\[
MV(f) = \sum_{k=1}^{n} \frac{Z_k}{Z_k + Z_{Tk}} I_k + \sum_{k=1}^{n} \frac{1}{Z_k + Z_{Tk}} + \frac{1}{Z_{TCS}} \quad (7)
\]

where \( MV(f), Z_k(f), Z_{Tk}(f) \) and \( Z_{TCS}(f) \) are functions of frequency. The node voltages of load substations yields:

\[
V_k(f) = \frac{I_k + \frac{1}{Z_{Tk}} MV}{Z_k + Z_{Tk}} \quad (8)
\]

The currents can be written as follows:

\[
I_T(k, f) = \frac{V_k(f) - MV}{Z_{Tk}} \quad (9)
\]

\[
I_C(k, f) = j 2 \pi f C_k V_k \quad (10)
\]

\[
I_{TS}(f) = \frac{MV}{Z_{TS}} \quad (11)
\]

\[
I_{CS}(f) = j 2 \pi f C MV \quad (12)
\]

The formulas obtained allow performing power system harmonics analysis using computer programs. The results of harmonic analysis can be plot as function of voltages and currents versus frequency. Also the electric equivalent circuit can be modeled using computer aided programs such as PSPICE.

3 Frequency-scan analysis

Figure 2 shows a frequency scan of voltage modulus versus frequency for the medium voltage point MV produced by a unit current source located in 1600 kVA load substation.

Fig. 2 The voltage in medium voltage point MV(f) expressed in mV versus frequency, produced by an unit current source located in 1600 kVA load substation.

Note two maximum values of voltage for frequencies (169 Hz and 1175 Hz) that differ a lot from the resonant frequencies calculated above. It is present a substantially shift of oscillatory frequency due to the parallel connection between all loads substations and capacitor CS from distribution substation [5]. The value of 1175 Hz is a common oscillatory frequency of parallel connection between inductance LT+LS and capacitance CS of the distribution station which are in turn connected in parallel with loads substations (LTk connected in series with Ck for each load substation) [5]. The value of 169 Hz is also a common oscillatory frequency of all the loads substations connected in parallel.

It can be see that the oscillatory frequencies vary over wide limits and so does the harmonic current flow in distribution system. The oscillatory frequency swings with the change in system operating conditions [5] and this may bring about a
resonant condition, however the capacitors were sized in the initial phase [1,2].

In Fig. 3 we present the frequency characteristics of currents through transformer ITk and through capacitor Ck from 1600 kVA load substation produced by unit current source located in this load substation. The harmonics currents throughout the spectrum are amplified. While the injected current is 1 A, the current in the load substation capacitor bank and transformer are 3.5 A for frequencies close to the resonant frequency of 473 Hz of the 1600 kVA load substation. The predominant influence of parallel connection between inductance Lk and capacitance Ck can be seen. The resonance curves of the load substation currents are very broad due to the small value of resistance Rk (0.2 Ohm corresponding to 50% loading). Note that resonant frequency of load substation can be analytically calculated. It is also possible to determine that value by testing. We present in Fig. 4 the transient inrush current on switching of 0.4 kV capacitor bank from load substation. The transient current presents a n oscillatory decaying component whose oscillation frequency is the resonance frequency of the load substation.

We can see, in Fig. 3 for both values of the currents a sharp parallel resonance point near the value of 1175 Hz.

To determine the common oscillation frequency of parallel connection between inductance LT+LS and capacitance CS connected in parallel with loads substations we simulate a CS capacitor switching. We present in Fig. 5 the transient inrush current on 10 kV capacitor bank switching in distribution substation.

Fig. 3 The currents ITk and ICk versus frequency, in 1600 kVA load substation produced by unit current source located in this load substation.
The resonant frequency computed on the basis of system short-circuit reactance and the value of capacitance of capacitor bank [2, 3, 4]. The value of oscillation frequency is near 1175 Hz.

If a frequency scan is made without the capacitor CS from distribution substation the frequency characteristic of the tension of medium voltage point MV is show in Fig. 6. It is important to mention that all the frequency characteristics of MV point produced by a unit current source located in any of the loads substations are almost identical. The same situation is in the case of frequency characteristics presented in Fig. 2 where CS capacitor bank is connected. In the case of Fig. 6 only the lower value of the oscillatory frequency is present (near 181 Hz in this case) in the frequency characteristic. If we make a frequency scan with capacitor CS disconnected and also the capacitor banks from all 1600 kVA load substations disconnected the frequency characteristic of the voltage of the medium voltage point MV look like in Fig. 7.

In this case a voltage magnification can be see for the lower oscillatory frequency of 175 Hz. In order to identify the influence of loading of the transformers from loads substation on the frequency characteristics of the voltages were simulated the voltages for loading of 10% of loads substations. The values of the resonance frequencies of the loads substations for 10% loading of the loads substations are higher as can be see in table 1.

The frequency characteristics of the voltage from the medium voltage point MV for a loading of 10% are shown in Fig. 8. The common oscillatory frequency of parallel connection of the loads substations with distribution substation is about 1600 Hz and the common oscillatory frequency due to common parallel connection of the load substations is about 300 Hz. It is visible in the graphic the influence of resonant frequencies of the load substations, the frequency characteristics are unlike for various ratings of loads substations.

4 Conclusion

- The phenomenon of harmonics distortion propagation is very complex, for accurate investigation it is important to know the values of the transformers parameters from load substations, their loading and the reactive power of capacitor banks.
- An analytical formula for calculation of voltage of medium voltage point has been deducted useful for harmonics analysis using computer programs.
- The frequency characteristics of voltage of
medium voltage point has two maximum values, the higher value is the common oscillatory frequency of parallel connection of the loads substation with distribution station and the lower value is due to the parallel connection of loads substation. This frequency characteristic does not depend on the place where the current source is located.

- The value of resonant frequency of the load substation can be computed and can be determined experimentally, the common higher oscillatory frequency can be determined experimentally.
- The loading of the loads substations influence the significant frequency characteristics of the voltages and currents from the distribution system.

References: