Calculation of resonant modes for power supply systems and development of measures on higher harmonics filtering

D S Osipov¹, D V Kovalenko¹, E N Eremin¹, O A Sidorov², A Ya Bigun¹

¹Omsk State Technical University, 11, Mira ave., Omsk, 644050, Russia
²Omsk State Transport University, Omsk, Russia

e-mail: Dmitrii_Kovalenko92@mail.ru

Abstract. This paper presents the calculation of non-stationary non-sinusoidal mode of the power supply system (PSS) under the condition of current resonance (parallel resonance). Evaluation of the need for higher harmonics (HH) filtering was carried out. To achieve this, measurements of the actual level of HH and other unified power quality indexes were conducted, and oscillograms of the network mode parameters and HH spectrum were constructed. The measurement of unified power quality indexes was carried out with certified and calibrated power quality analyzers Metrel 2792A. These instruments satisfy the effective world standards on power quality and other reference documentation. Resonance frequencies where resonance modes emergence is possible were determined by calculation. Maximum overvoltage ratios for different points of the examined PSS were also determined.

1. Introduction

Higher harmonic currents cause voltage distortion depending on current and resistance component amplitude of the PSS within the examined frequency. The greater the frequency range of current components is the greater is the risk of unwanted resonant phenomena that could increase voltage distortion and lead to overload and abnormal operation of user equipment. Capacitor banks under non-sinusoidal voltage can get into the mode close to the current resonance on a frequency of any harmonic. As a result capacitors are destroyed because of leads to systematic overloads.

In [1] novel options optimization problem (for optimal mounting location of capacitor banks) in terms of resonant modes in PSSs are shown.

The authors in [2] propose an algorithm to determine the limits of the resonant modes in the PSSs. The algorithm is based on finding the so-called "resonance indexes" for each harmonic of the signal. The resonance index for the n-th harmonic component is determined as the ratio of the total conductivity of the anti-resonant circuit on the frequency of the n-th harmonic (Yn) to the total conductivity of the same circuit on the fundamental frequency (Y1):

\[ \text{RI}_n = \frac{Y_n}{Y_1}, \quad n = 1, 2, 3, \ldots \]  \hspace{1cm} (1)

Next, the dependency graph of the resonance index on the system voltage maximum IHD is constructed, this graph defining the limits for the system resonant modes.

The works [3, 4] became a further development of this approach.

The practical application of the «resonance index» calculation method for determining potential resonant frequencies of the PSSs is shown in [3]. The authors note that the exact calculation of the
«resonance index» is difficult if there is a wide range of higher voltage harmonics in the PSSs. Besides, the proposed algorithm for determining the HH frequencies when changing the degree of compensation of reactive power in the PSS by switching capacitor banks steps is demonstrated.

In paper [4] the authors apply «a posteriori method» for search optimal allocations of capacitor banks in the PSSs. This integrated approach consists of two methods: «multiobjective metaheuristic NSGA-II» and «resonance index». The first method is needed to find the optimal allocations of capacitor banks in the PSSs (optimization problem). The second method (the «resonance index» calculation method) allows identification of possible resonant modes in the PSSs. Thus, the work [4] can be considered as a further modernization of the approaches, methods and algorithms described in detail in [1-3].

In paper [5] the authors apply the method of modal frequency response analysis of the PSS in the current resonant mode.

In paper [6] the authors decompose the matrix of the resultant susceptance of the PSS into the "right hand" and the "left hand" matrix. These mathematical transformations are aimed at the reduction of the number of elements included into the parent matrix.

In computing the resonant mode the authors in [7] additionally take into account capacitive components of cable lines, and the possibility of ferro-resonant modes at low load factor of feed transformer is also evaluated.

Permissible levels of HH currents in the PSSs of different voltage classes are represented in [8].

If capacitor banks are mounted in the PSS with the parameters different from those ones specified in [9], then harmonic filtering is required as far as it contributes greatly to the resultant mode parameters of the PSS.

In [10] different calculation techniques for harmonic filters are proposed. Moreover, the comparison of different types of HH filters is carried out.

Some authors, for instance in [11], propose to connect in series capacitor banks and reactors to lower the level of HH currents.

In paper [12] the authors consider the shared use of the shunt active front end and capacitor banks in the PSS to exclude the possibility of occurrence of parallel resonance around the HH frequencies.

Recently, a mathematical apparatus of the wavelet transform has become popular for analyzing resonant modes [13-15] and solving the problems in power systems [16-20].

The authors [15] conducted a research of the PSS under non-stationary non-sinusoidal mode. Sources of HH in the PSS were asynchroneous motors with variable-frequency electric drive. Regulated capacitor banks are used to compensate for reactive power in the PSS. The results are showed that parallel resonance can occurs around 11th and 13th harmonics under certain conditions. Also, the calculation of currents of the branched part of the PSS in the resonant mode was performed. The identification of the resonant modes and the calculation of the currents of the resonant mode are performed using with the packet wavelet transform.

In [16] the authors developed of power losses calculation algorithm in case of interharmonics with the wavelet packet transform.

In papers [17, 18] calculation technique for power system transient is proposed.

In [19] the authors apply the mathematical apparatus of the wavelet transform for identification of single phase to earth in PSS.

A detailed technique of non-stationary non-sinusoidal mode calculation with the wavelet packet transform is proposed in [20].

2. Fundamental principles of current resonance theory
The current resonance (parallel resonance) is known to arise in systems with parallel inductive and capacitive elements. The resonant mode in these systems occurs under the admittance equality of paralleled branches of the system (figure 1).

Thus, the condition of current resonance generally takes the following form:

$$\frac{\omega L}{R_1^2 + \omega^2 L^2} = \frac{1/\omega C}{R_2^2 + \frac{1}{\omega^2 C^2}},$$

where $L$ is the inductance, $C$ is the capacity, $R_1$ and $R_2$ are ohmic resistances of circuit branches.

Performing simple algebraic transformations of expression (2) we obtain the formula to define the frequency of current resonance in the system:

$$\omega = \sqrt{\frac{L - CR_2^2}{CL^2}},$$

where $R_2$ is the equivalent resistance of the circuit.

In the mode of parallel resonance the current in the unbranched section of the system ($I$) will be of an active nature, and it will be of the lowest value. In this case the circuit acts as a rejector circuit for the resonant mode currents of the external part of the system. However, in the branched sections the components of the net (minimum) current ($I_1, I_2$) will exceed the currents of the normal operating condition tenfold and by a factor of hundreds.

3. Development of algorithm for calculating resonant modes of the PSS

Currently, there are empirical methods for estimation of system resonance frequencies [21]. Based on the frequency analysis of currents and voltages under condenser switching, the authors construct the dependences of impedance on frequency. The studies are carried out for the case of linear load and under harmonic distortions [21].

Let us define the probability of resonance overvoltages and currents in power networks for voltage classes of 0.4, 6 and 35 kV.

A single-line diagram of the power network is shown in figure 2.
Figure 2. Diagram of the examined network.

The load fed through the voltage source converters (VSC) is connected to 0.4 kV buses in the prototype system. As shown in [22] the capacity of the long cable in this case can have a significant impact on the series and parallel resonance conditions. The study was carried out in the program EMTP [22].

To evaluate resonant modes on the basis of the power system diagram we draw an equivalent circuit. The equivalent circuit of the power system under study is shown in figure 3.

Figure 3. Equivalent circuit of the power network section.

We compose an operator format equation based on the obtained equivalent circuit, transformer parameters, electric power lines and load to calculate the mode by the nodal solution (calculations
were executed in the program complex MathCAD). Let us present reactive resistances (inductive and capacitive ones) in the operator format before executing of equivalent circuit convolution.

The inductive resistance in the operator format takes the following form:

$$X_L(p) = pL,$$

(4)

capacitive

$$X_C(p) = \frac{1}{pC}.$$

(5)

We need to perform the convolution operation for the right hand section of the equivalent circuit relative to nodes «2» and «0». Thus, we will convolute the equivalent circuit from left-to-right. We perform resistance equivalence based on the rules of series and parallel resistance transformation.

Now we consider the first stage of the equivalent circuit transformation as an example.

The static capacitor bank is mounted in series to the load of 0.4 kV, this load being represented by the active inductive brunch of the equivalent circuit – R, X_L. This bank of capacitive resistance X_C5 is intended for the power factor compensation. The resultant resistance of this network section by the rule of series elements in the operator format equals to:

$$Z_6 = \frac{1}{pC_5} \frac{(R_L + pL_L)}{1 + R_L + pL_L} = \frac{R_L + pL_L}{1 + pC_5R_L + p^2C_5L_L},$$

(6)

Further transformations of the power network equivalent circuit will be fulfilled in a similar manner with the use of equivalent resistances.

We conducted the convolution operation for the right hand section of the equivalent circuit. Now the right hand section of the equivalent circuit will appear as one equivalent resistance (Z_EQ) in the operator format. The left hand section of the equivalent circuit includes the following elements: ohmnic (R_AT) and inductive (X_AT) resistances of an autotransformer installed at substation 1, ohmnic (R_SPD), inductive (X_SPD) resistances and capacity (C_1) of a PTL connecting substation 1 and the bus section distribution point, ohmnic (R_SF) inductive (X_SF) resistances of HH source and the power supply (E_50). The resultant equivalent circuit is shown in figure 4, and the parameters of its elements are given in Table 1.

**Table 1. Parameters of equivalent circuit elements.**

| The parameter name and designation | Numeric value       |
|-----------------------------------|---------------------|
| Ohmnic resistance of autotransformer R_AT   | 0.024 Ohm           |
| Inductive resistance of autotransformer X_AT  | 5.949 x 10^{-3} Ohm |
| Ohmnic resistance of transmission line R_SPD | 2.531 Ohm           |
| Ohmnic resistance of transmission line X_SPD | 0.014 Ohm           |
| Capacitance of transmission line C_1      | 8.593 x 10^{-6} F   |
The system of equations compiled by the nodal-voltage method for this system takes the following form:

\[
\begin{align*}
\varphi_1(Y_{AT} + Y_{SDP} + Y_{C1}) - \varphi_2 Y_{SDP} &= 0 \\
\varphi_2(Y_{SDP} + Y_{WT} + Y_{SF}) - \varphi_1 Y_{SDP} - \varphi_3 Y_{WT} &= E_{SF} Y_{SF} \\
\varphi_3(Y_{WT} + Y_{35} + Y_{C2}) - \varphi_2 Y_{WT} - \varphi_4 Y_{35} &= 0 \\
\varphi_4(Y_{35} + Y_6 + Y_{C3}) - \varphi_3 Y_{35} - \varphi_5 Y_6 &= 0 \\
\varphi_5(Y_6 + Y_{04} + Y_{C4}) - \varphi_4 Y_6 - \varphi_6 Y_{04} &= 0 \\
\varphi_6(Y_{04} + Y_{L} + Y_{C5}) - \varphi_5 Y_{04} &= 0
\end{align*}
\]

The overvoltage ratios can be defined for different voltage classes if the node potentials are calculated.

4. Numerical experiment. Results of HH measurement

The characteristic curves of the overvoltage ratio and frequency for different voltage classes are shown in figures 5-7. In Table 2 we present the maximum overvoltage ratios \( (K_u) \), possible resonant frequencies \( (f) \), and the sequence of HH around which resonant mode \( (n) \) is possible for different voltage classes \( (U) \).
Figure 6. Dependence of overvoltage ratio on frequency (voltage class 6 kV).

Figure 7. Dependence of overvoltage ratio on frequency (voltage class 0.4 kV).

Table 2. Higher harmonics with possible resonance around.

| Voltage (U), kV | Overvoltage ratio (K_U), pu | Resonance frequency (f), Hz | Number harmonic, n |
|----------------|----------------------------|-----------------------------|--------------------|
| 35             | 2.905                      | 258                         | 5                  |
|                |                            | 537                         | 11                 |
|                |                            | 638                         | 13                 |
| 6              | 2.1                        | 537                         | 11                 |
|                |                            | 638                         | 13                 |
|                |                            | 844                         | 17                 |
| 0.4            | 1.97                       | 258                         | 5                  |
|                |                            | 537                         | 11                 |
|                |                            | 638                         | 13                 |

The dependence of current on frequency is shown in figure 8.
Figure 8. Dependence of current on frequency (voltage class 0.4 kV).

Table 2 and graphs in figures 5-8 show the resonance mode under the frequencies of 258 Hz (around 5th harmonic), 537 Hz (around 11th harmonic), 638 Hz (around 13th harmonic), and 844 Hz (around 17th harmonic). In other words, there are resonant modes under the nonlinear load which has in its spectral distribution 5th, 11th, 13th, and 17th harmonics into the PSS.

We conducted measurements of unified power quality indexes with using instruments Metrel 2792A on the bus section of 6 kV to evaluate the need for HH filtering in the examined PSS (figure 2). The measurements were carried out in accordance with the regulations in effect [23, 24]. The oscillogram and the spectral distributions of voltages on the bus section 6 kV are shown in figures 9 and 10 respectively.

Figure 9. Voltage oscillogram on bus section of 6 kV.

Figure 10. Spectral distribution of voltage signal on the bus section of 6 kV.
The results of measurements demonstrate the harmonics in the network of 6 kV where a resonant modes and dangerous overvoltages are probable. In this case it is necessary to use filters to protect PSS. Currently the studies on new types of filters are under way. For instance, in paper [25] the authors propose a new high frequency passive filter. The underlying concept of this filter is based on the frequency dependent resistive bank «that can perform characteristics harmonic filtering and can avoid resonance at dominant noncharacteristic harmonics simultaneously» [25]. Passive [26], hybrid or active filters can be used for HH suppression [27]. Final decision on the type of the device is taken on the grounds of a feasibility study.

5. Conclusion

HH cause additional non-sinusoidal currents in a PSS. They result in supplemental heating, current overload, and accelerated insulation aging of a dielectric between the charge plates. In other words, a capacitor bank under this operating mode fails to expire its standard service life.

The fulfillment of the conditions for the resonant modes on frequencies close to HH frequencies also brings to the accelerated wear of a capacitor bank. A capacitor bank has shorter life in that case compared to a simple HH effect in a PSS, with a resonant modes being absent.

References
[1] Atkinson-Hope G, Folly K 2004 Decision theory process for making a mitigation decision on harmonic resonance IEEE Transactions on Power Delivery, Vol. 19, Issue 3, pp. 1393-1399.
[2] Huang Z, Xu W and Dinavahi V R 2003 A practical harmonic resonance guideline for shunt capacitor applications IEEE Transactions on Power Delivery, Vol. 18, Issue 4, pp. 1382-1387.
[3] Hamouda S H, Abdel Aleem S H E, Ibrahim A M 2017 Harmonic Resonance Index and Resonance Severity Estimation for Shunt Capacitor Applications in Industrial Power Systems 19th International Middle East Power Systems Conference (MEPCON) (Cairo, Egypt), pp. 527-532.
[4] Onaka J H D, Bezerra U H, Tostes M E L, Lima A S 2017 A posteriori decision analysis based on Resonance Index and NSGA-II applied to the capacitor banks placement problem Electric Power Systems Research, Vol. 151, pp. 296-307.
[5] Cui Y, Wang X 2012 Modal Frequency Sensivity for Power System Harmonic Resonance Analysis IEEE Transactions on Power Delivery, Vol. 27, Issue 2, pp. 1010-1017.
[6] Xu W, Huang Z, Cui Y and Wang H 2005 Harmonic Resonance Mode Analysis IEEE Transactions on Power Delivery, Vol. 20, Issue 2, pp.1182-1190.
[7] Rahimi S, Wiechowski W, Rundrup M, Ostergaard J, Nielsen A H 2008 Identification of problems when using long high voltage AC cable in transmission system II: Resonance & Harmonic resonance Transmission and Distribution Conference and Exposition (IEEE/PES) (Chicago, IL, USA), pp. 1-8.
[8] IEEE Recommended Practice and Requirements for Harmonic Control in Electric Power Systems IEEE Std. 519-2014.
[9] IEEE Standard for Shunt Power Capacitors IEEE Std. 18-2012.
[10] Xu W, Ding T, Li X, Liang H 2016 Resonance-Free Shunt Capacitors Configurations, Design Methods and Comparative Analysis IEEE Transactions on Power Delivery, Vol. 31, Issue 5, pp. 2287-2259.
[11] Chaladying S, Charlangsut A, Rugthaichareoncheep N 2015 Parallel Resonance Impact on Power Factor Improvement in Power System with Harmonic Distortion TENCON 2015-2015 IEEE Region 10 Conference (Macao, China), pp. 1-5.
[12] Zhang Y, Dai K, Chen X, Kang Y, Dai Z 2017 An Improved Method of SAPF for Harmonic Compensation and Resonance Damping with Current Detection of Power capacitors and Linear / Nonlinear Loads 2017 IEEE Applied Power Electronics Conference and Exposition (APEC) (Tampa, FL, USA), pp. 3286-3291.
[13] Gomez-Luna E, Silva D, Aponte G, Pleite J G, Hinestroza D 2013 Obtaining the Electrical Impedance Using Wavelet Transform From the Time Response IEEE Transactions on Power Delivery, Vol. 28, Issue 2, pp.1242-1244.

[14] Li P, Gao J and Sun J 2016 Resonance analysis using wavelet packet transform in clustered grid-connected PV system IEEE Power and Energy Society General Meeting (PESGM), pp. 1-5.

[15] Osipov D S, Kovalenko D V, Dolgikh N N 2017 Calculation of currents resonance at higher harmonics in power supply systems based on wavelet packet transform Dynamics of Systems, Mechanisms and Machines (Dynamics) (Omsk, Russian Federation) pp. 1-6.

[16] Osipov D S, Goryunov V N, Faifer L A, Kisselyov B Yu, Dolgikh N N 2017 Development of conductive parts power losses calculation method in case of interharmonics Przeglad Elektrotechniczny, No. 6, pp. 146-149.

[17] Osipov D S, Lyutarevich A G, Gapirov R A, Goryunov V N, Bubenchikov A A 2016 Applications of wavelet transform for analysis of electrical transients in power systems: The review Przeglad Elektrotechniczny, No. 4, pp. 162-165.

[18] Osipov D S, Gorunov V N, Bubenchikov A A and Katerov P V 2016 Wavelet transform – a new tool for analysis of harmonics in power systems 3rd International Conference on Manufacturing and Industrial Technologies (ICMIT) (Istanbul, Turkey), Vol. 70, pp. 1-5.

[19] Goryunov V N, Osipov D S Dolgikh N N 2016 The application of wavelet transform for identification of single phase to earth fault in power system 2nd International Conference on Industrial Engineering, Applications and Manufacturing (ICIEAM) (Chelyabinsk, Russian Federation), pp. 1-6.

[20] Osipov D S, Dolgikh N N, Goryunov V N, Kovalenko D V 2016 Algorithms of packet wavelet transform for power determination under nonsinusoidal modes Dynamics of Systems, Mechanisms and Machines (Dynamics) (Omsk, Russian Federation), pp. 1-5.

[21] Santos S and Maitra A 2005 Empirical estimation of system parallel resonant frequencies using capacitor switching transient data IEEE Transactions on Power Delivery, Vol. 20, Issue. 2, part I, pp. 1151-1156.

[22] Temma K, Ishiguro F, Toki N, Iyoda I and Paserba J J 2005 IEEE Transactions on Power Delivery, Vol. 20, Issue 1, pp. 450-457.

[23] Electromagnetic compatibility (EMC). Part 4-30: Testing and measurement techniques. Power quality measurement methods, IEC 61000-4-30:2008.

[24] IEEE Standard Definitions for the Measurement of Electric Power Quantities Under Sinusoidal, Nonsinusoidal, Balanced, or Unbalanced Conditions, IEEE Std 1459-2010.

[25] Li X, Xu W, Ding T 2017 Damped high passive filter—a new filtering scheme for multipulse rectifier systems IEEE Transactions on Power Delivery, Vol. 32, Issue 1, pp.117-124.

[26] de Lima Tostes M, Bezerra U, Silva R, Valente J, de Moura C and Branco T 2005 Impacts over the distribution grid from the adoption of distributed harmonic filters on low voltage customers IEEE Transactions on Power Delivery, Vol. 20, Issue 1, pp. 384-389.

[27] Herman L, Papic I and Blazic B 2014 A proportional-resonant current controller for selective harmonic compensation in a hybrid active power filter IEEE Transactions on Power Delivery, Vol. 29, Issue 5, pp. 2055-2065.