Modeling of non-sinusoidal modes of operation of the power supply system at resonance

Zixuan Zhang* and *Vladimir* Serikov

Saint Petersburg Mining University, Department of Electric Power Engineering and Electromechanics, 2, 21st Line, St Petersburg 199106, Russia

Abstract. In this article, power systems operating modes with both non-linear and linear loads and a capacitor bank are analyzed. In particular, the power supply systems of industrial enterprises are considered. The studies covered a daily change of linear load with the corresponding regulation of capacitor bank powers. Moreover, the capacitor powers at which the resonant modes arise at canonical harmonics were determined. The results show that the with regulation of the capacitors' power on a daily basis, the voltage quality may not meet the requirements of power quality indicators. Furthermore, the capacitor units themselves may be overloaded with higher harmonic currents.

1 Introduction

The power converters, widely used in low-voltage industrial and urban networks, distort the current and voltage of the electrical network which negatively affect the operation of all equipment. The use of capacitor banks for reactive power compensation under non-sinusoidal voltage operations lead to failures in some cases due to the overload caused by current higher harmonics. Current overload reaches its greatest values at resonance between the inductance of the supplied network and the capacitance of the capacitor bank [1-6].

Research purpose is to obtain, based on software simulations, the main quantitative ratios for harmonic currents and asses their negative impact on capacitor banks. The research object is a three-phase power supply system, including a 10/0.4 kV transformer operating on a linear and non-linear (three-phase bridge rectifier) load and a capacitor bank. The simulation was carried out in *Multisim*.

2 Model of the power system

A model of an industrial power supply system has been developed as shown in Figure 1. This model will serve to analyze the non-sinusoidal modes that occur in networks having non-linear loads and capacitor banks. A typical range of powers transformers 10/0.4 kV ($S_{T\,nom}$ = 250, 400, .. 2500 kVA) was considered. The quality of the obtained results did not change with the change in transformer power.

---

* Corresponding author: s195035@stud.spmi.ru

However, a quantitative difference in the results was noticed, due to different short-circuit voltages U_C of transformers (4.5 ... 6%).

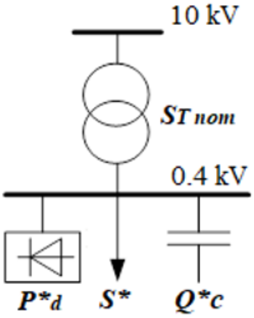


Fig. 1. Power supply system of an industrial enterprise.

The simulation results for a transformer with a rated power $S_{T\,nom}$ = 1000 kVA are given below. All adjustable powers are given in p.u. with respect to the transformer's rated power:

- non-linear load power: $P^*_d = P_d / S_{T\,nom}$;
- linear load power $S^* = S / S_{T\,nom}$;
- capacitor bank power $Q^*_C = Q_C / S_{T\,nom}$.

The simulation was performed under the following assumptions: all the active-inductive elements (transformers, lines, loads) are taken into account by the value of the inductance calculated from the inductive reactance for the first harmonic. In this case, the inductive reactance of these elements will proportionally increase with the number of higher harmonics. Active resistances are assumed to be unchanged for all harmonics and correspond to the first harmonic of the current. The powers of the capacitor banks were calculated in p.u. according to the following expression:

$$Q_C^* = \frac{100}{U_C\% \cdot n^2}, \tag{1}$$

At such powers the resonant mode arises for the canonical harmonics n = 6k + 1. Table 1 should be used.

Table 1. Powers of the capacitor banks where the resonance modes occur.

S_T nom, kVA	U_C, %	n	5	7	11	13	17	19
250 и 400	4,5	Q^*_C	0,89	0,45	0,18	0,13	0,08	0,06
630 и 1000	5,5		0,73	0,37	0,15	0,11	0,06	0,05
1600 и 2500	6,0		0,67	0,34	0,14	0,10	0,06	0,05

It should be noted that in the above power scheme, the resonance at the 5th harmonic is practically impossible, since the power of the capacitor banks is considered to be less than 67% of the transformer's nominal power $S_{T\,nom}$. The resonance at the 7th harmonic is unlikely also, because here the capacitor's power is from 34 to 45% of $S_{T\,nom}$. However, the appearance of resonance, at the 11th and higher harmonics is more likely, because here the power of the capacitor bank does not exceed 20% of $S_{T\,nom}$.

It was previously established that the parameters of the linear load slightly affect the processes, since the load resistance is an order of magnitude greater than the resistance of the supply transformer [7-9].

To keep the power factor of the linear load in the range of 0.92 ~ 0.95, during the modeling, the powers of the non-linear load P_d^* and the linear load S^* were changed; accordingly, the power of the capacitor bank Q_C^* was also modified.

3 Simulation results

During the simulation, power quality was estimated using the voltage total harmonic distortion factor THD_U, the current overload of capacitors was determined using the overload factor K_{OVL}, and the relative values of the higher harmonics of the network current were determined when the power of the linear and non-linear loads, and the capacitor units changed.

The simulation results with THD_U and K_{OVL} measurements are shown in Figure 2.

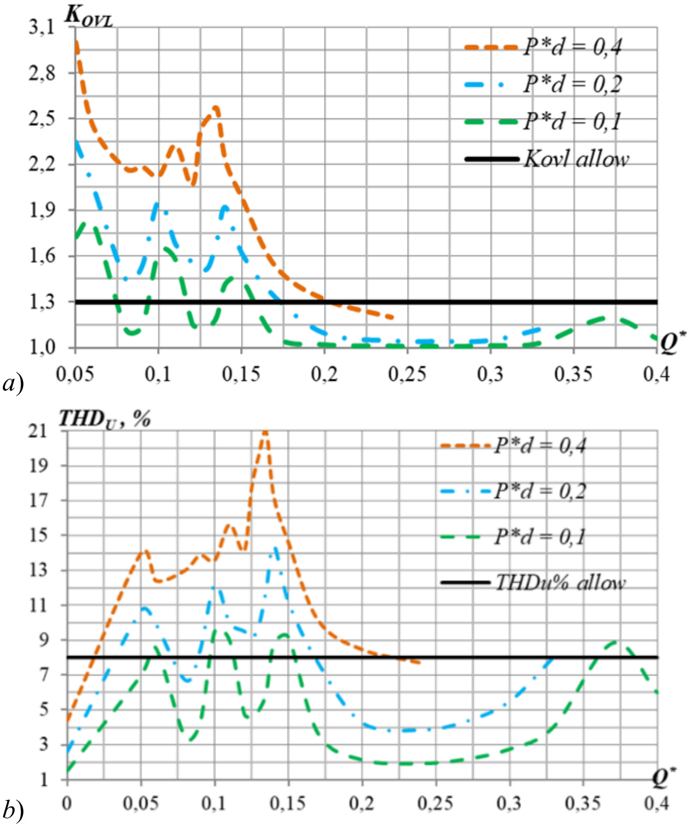


Fig. 2. The dependences of K_{OVL} (*a*) and THD_U (*b*) on the power Q_C^* for a 1000 kVA transformer power.

It has been established during power supply system studies under resonant modes the parameters THD_U and K_{OVL} significantly exceeded the allowable values.

Figure 2 shows the simulation results for a 10/0.4 kV transformer of power $S_{T\,nom}$ = 1000 kVA. The validity of expression (1) for the capacitor bank power Q_C^*, at which the resonance modes happen, is confirmed.

As can be seen from Figure 2, there are obvious problems with the quality of the mains voltage and the capacitors' current overload in the area $Q_C^*<0.2$ and $Q_C^*>0.35$, where the values of THD_U and K_{OVL} are much higher than the normalized values already at the power of the non-linear load $P_d^* > 0,1$.

Based on the results shown in Figure 2, it was revealed that, since the capacitor unit is power-adjustable, for the power supply system under consideration, it is possible to determine the relative power of the capacitors, at which the resonant phenomena will occur. Accordingly, in such modes, it is necessary to incorporate technical means and solutions to compensate for higher currents and voltage harmonics and thus, to protect the capacitors from current overload and reduce the voltage harmonic distortion.

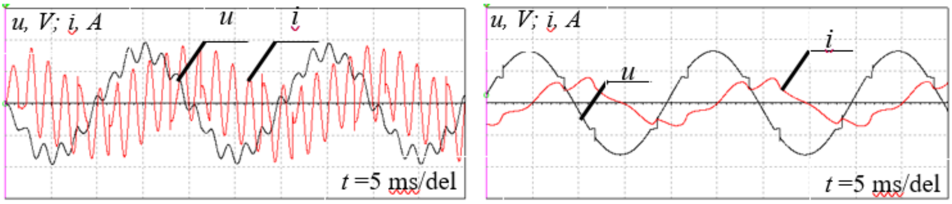
In the literature, the proposed technical recommendations and solutions for suppressing harmonics during the operation of capacitor units, based on the ratio of the power of the supply transformer and the non-linear load, are summarized in Table 2 [10-12].

Table 2. Application recommendations and solutions for harmonic mitigation for a low voltage circuit.

Non-linear load power	Recommendations for applying a technical solution
$P_d^* < 0,15$	Capacitors without filters
$0,15 < P_d^* < 0,25$	High Voltage Capacitors without filters
$0,25 < P_d^* < 0,6$	High Voltage Capacitors in the presence of anti-resonant chokes or passive filters
$P_d^* > 0,6$	Active or hybrid filters

However, the simulation results of the studied power systems, during resonant phenomena, show that technical means of protecting the capacitors from current overload are necessary even with nonlinear loads of power $P_d^* > 0.1$.

It has been established that during resonance phenomena with $P_d^* < 0.3$, anti-resonant chokes protect the capacitors from current overload and provide the required level of power quality without using additional filter-compensation devices. Such results are illustrated in Figure 3 that shows the capacitor's bank current and voltage oscillograms.



a) *b*)

Fig. 3. Oscillograms of the current (red signal) and voltage (black signal) of the capacitor bank: *a*) - resonant mode at the 11th harmonic in the absence of anti-resonant chokes; *b*) - the same, but with anti-resonant chokes.

Figure 3a corresponds to a resonant mode in the network at the 11th harmonic in the absence of anti-resonant chokes. The network parameters are: S_T nom = 1000 kVA, $P_d = 400$ kW, $P = 300$ kW, $Q = 300$ kvar, $Q_C = 150$ kvar.

Figure 3b corresponds to the same resonant mode with the same network parameters, but while adding the anti-resonant choke.

Figure 3 shows that in the absence of the anti-resonant chokes, the current overload coefficients $K_{OVL} = 2.1$ and voltage distortion $THD_U = 15.6\%$ are unacceptable. However, when the anti-resonant choke is included, avoiding amplification of current and voltage higher harmonics is achieved, and thereby K_{OVL} and THD_U are reduced to the respectively acceptable values 1.08 and 3%.

Therefore, the anti-resonant choke eliminates the increase in voltage harmonics magnitude when the capacitor banks are switched on. However, it is not able to provide normalized power quality indicators when current and voltage distortions are associated with a high proportion of non-linear loads.

4 Conclusion

Based on the simulation of a power supply system including linear and non-linear (three-phase bridge rectifier) loads and a capacitor bank in Multisim, the main quantitative relationships for harmonic currents in a three-phase model are obtained.

Based on the simulation results, the following conclusions were made:

- there exit resonant modes in which the overload coefficient of capacitor banks exceeded the allowable values;
- the inclusion of capacitors in a power system with non-linear load degrades the quality of the network’s voltage;
- with the daily regulation of the power of the capacitor bank, it is practically impossible to avoid the occurrence of current overload at the capacitors, resulting from higher harmonics.
- the anti-resonant choke eliminates the increase in the amplitude of voltage harmonics when capacitor banks are switched on. However, it is not able to provide normalized power quality indicators when current and voltage distortions are associated with a high proportion of a non-linear load.

References

1. W.J. Abdallah and et. al., Sustainability, **15**, 1579, (2023). Doi: 10.3390/su15021579.
2. B.N. Abramovich, D.A. Ustinov, W.J. Abdallah, IJPEDS, **13(2)**, 1007-1025, (2022). DOI: 10.11591/ijpeds.v13.i2.pp1007-1025.
3. G.I. Korshunov, A.M. Karimov, G.S. Magamedov, S.A. Tyulkin, MIAB, **7**, 132-144, (2023). DOI: 10.25018/0236_1493_2023_7_0_132.
4. I.A. Shammazov, A.M. Batyrov,. D.I. Sidorkin, T. Van Nguyen, Appl. Sci., **13**, 3139, (2023). Doi : 10.3390/app13053139.
5. D. Ustinov, A. Nazarychev, D. Pelenev, K. Babyr, A. Pugachev, Energies, **16**, 3690, (2023). Doi:10.3390/en16093690.
6. K. Babyr, D. Ustinov, D. Pelenev, Occupational Safety in Industry. 55-61. (2022). DOI: 10.24000/0409-2961-2022-8-55-61.
7. A.A. Khalturin, K.D. Parfenchik, V.A. Shpenst, J. Mar. Sci. Eng., **11**, 111, (2023). DOI: 10.3390/jmse11010111.
8. D.A. Ustinov, E.R. Shafhatov, Energies, **15**, 9630, (2023). Doi:10.3390/en15249630.
9. Y. Zhukovskiy, A. Buldysko, and I. Revin, Energies, **16(8)**, 3303, (2023). Doi:10.3390/en16083303.

10. Y.A. Sychev, M.E. Aladin, R.Y. Zimin, MIAB, **7**, 164-179, (2022). DOI: 10.25018/0236_1493_2022_7_0_164.
11. Yu.A. Sychev, V.B. Prokhorova, M.E. Aladin, Journal of Physics: Conf. Ser., **1753(1)**, 012045, (2021). DOI: 10.1088/1742-6596/1753/1/012045
12. Y.A. Sychev, M.E. Aladin, V.B. Prokhorova, FarEastCon 2020, 9271137, (2020). DOI: 10.1109/FareastCon50210.2020.9271137