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Study of the Performance of Electrical Equipment of Electric Power Complexes and Systems Under the Influence of Higher Harmonics of Voltage and Current

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***Abstract*—In this article the main aspects related to the influence of higher harmonics on the work of electrical equipment are considered. The relevance of this study is determined by the fact that at present in electrical systems and networks it is very difficult to maintain a proper level of electricity quality. This is due to the widespread introduction of semiconductor control systems, which are non-linear load and source of high harmonics of current and voltage. A big problem in electrical networks containing high harmonic sources is reactive power compensation with capacitor batteries. The connection of capacitor batteries together with the valve transducers was found to cause resonance phenomena in these networks. In this case, normal operation of capacitor units is not possible without special measures aimed at eliminating capacitor overload. The invention makes it possible to use a circuit for connecting protective filter reactors to work in parallel with capacitor batteries. Also, in order to identify the problems associated with higher harmonics in low-voltage we made measurements of harmonic components of voltage of municipal electrical receivers of apartment buildings. As a result of the connection of the quality analyzer on the input panel of the apartment building, a schedule of three-day measurement of the nonlinear voltage distortion coefficient of the network was obtained. Sinusoidal voltage distortion coefficient increased to 7.4% during the maximum evening electricity consumption.**

***Keywords*—higher harmonics, electricity quality indicators, philtocompensate devices, non-linear load**

I. INTRODUCTION

Due to the saturation of power supply networks with non-linear and asymmetrical electric consumers nowadays, the power consumed from the network contains a significant proportion of inactive components, which causes an increase in power losses in the network, a decrease in electric power quality (PQ) at the connection points and, accordingly, leads to a negative impact on the operation of other consumers connected to the same network. The quality of electricity significantly affects the reliability of power supply. Therefore, there is a need to comply with the standards for the quality of electricity both worldwide – IEEE 1159-1995, IEEE 519-1992, "Customs Code of the Eurasian Economic Union", and adopted for Russian networks – GOST 32144-2013.

II. OVERVIEW OF THE SITUATION OF THE INFLUENCE OF HIGHER HARMONICS ON THE OPERATION OF ELECTRICAL EQUIPMENT

A violation such as higher harmonics in electrical networks often occurs due to the presence of nonlinear elements in it. A common nonlinear load can include uninterruptible power supplies, frequency converters (FC), LED lighting, control gear for gas-discharge lamps, most of industrial heat treatment units, welding equipment containing semiconductor rectifiers. The number of used semiconductor systems which are sources of higher harmonics of current and voltage is growing every year, which becomes a big problem to maintain the required level of PQ.

In particular, frequency regulation of electric equipment operation mode has become widespread in low-voltage electric drives. Frequency converters, which are used for regulation, contain an uncontrolled (diode) rectifier, a smoothing filter and a voltage inverter with pulse-width modulation. Since the rectifiers are made in a three-phase bridge circuit, the FC input current is the sum of odd harmonics, except for multiples of three. At the same time the most intense are harmonics with numbers 5 and 7 [1, 2]. When 12-pulse rectification schemes are used, the generation of distortion power of 11th, 13th, 23rd, 25th harmonics takes the highest parameters.

Higher harmonics of voltage and current have unfavorable effects on the operation of electrical equipment, automation systems, relay protection, telemechanics and communications. Such impacts are expressed by the appearance of additional losses in these networks, as well as the possible failure of network elements as noted in [1-5]. In the presence of high-frequency harmonic components, reactive power compensation becomes difficult, the service life of insulation of electrical machines and apparatuses is reduced, and the fault rate in cable networks increases. Failures of relay protection, automation, telemechanics and communication systems often appear in these cases [6, 7]. Voltage and current higher harmonics affect the power factor and torque values of electric motors. The level of additional active losses from higher harmonics in the main networks of electrical systems is several percent. In the networks of enterprises, large industrial centers, as well as in the networks of electrified railway transport, these losses can reach 10-15% [8]. Failures in the channels of information transmission through power circuits in the presence of harmonics lead to incorrect commands to control switching equipment. High harmonic levels can be carried to neighboring devices on the network, which can cause problems with their operation, especially if they are not protected against harmonic distortion.

Resonance phenomena occur in electrical networks having consumers with valve converters and capacitor banks connected to the source busbars (Fig. 1). In almost all cases, this leads to overloading of capacitors by current and power and their failure. As a result of these phenomena, normal operation of capacitor installations is impossible without the application of special measures aimed at eliminating of capacitor overloading. Capacitor units are switched off, but then there will be no compensation of reactive power of consumers.

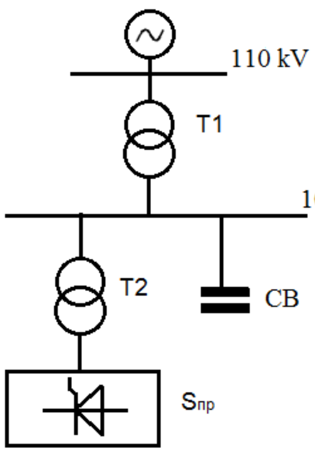

Fig. 1. Power supply circuits of a powerful valve converter with a bus-connected capacitor battery.

The resonant mode is characterized by zero value of the total reactive conductance of the resonant circuit:

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

where L is the total inductance of the branched part of the network, C is the total capacity of the branched part of the network, R_1 and R_2 are the active resistance of the parallel parts of the network.

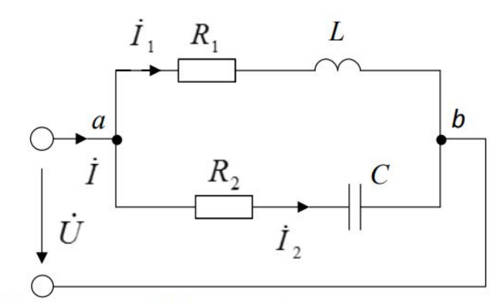

Fig. 2. Electrical network with current resonance mode.

The expression can be used to determine the resonant frequency in this network:

$$\omega = \sqrt{\frac{L - CR_\Sigma^2}{CL^2}}, \quad (2)$$

where R_Σ is the total active resistance of the network.

In traction and industrial power grids with valve converters overloads were recorded at resonance at frequencies of harmonics even of very high orders (40-50), and at frequencies of 3-7th harmonics in grids with electric arc furnaces and welding units [8–9]. Capacitor batteries do not fulfill their functions in this mode and fail, due to irreversible physical and chemical processes, occurring under the influence of fields of higher harmonics [4, 9].

For the majority of noise-sensitive elements, the dependence of the failure threshold $\Pi_{\text{от}}$ on the undervoltage depth δV and its duration τ is approximated with a high degree of accuracy by an expression of the following form:

$$\Pi_{\text{от}} = \delta V \sqrt[n]{\tau}. \quad (3)$$

For example, for T-series logic elements it turns out that n=3.5; for "Translog" series logic elements (GDR) n=2.7.

III. Solution of the Problem

The installation of capacitors must be carried out with the installation of higher harmonics protection devices in non-linear loads supplying networks. The simplest solution may be to install protective filter reactors for parallel operation together with capacitors [9]. It is necessary to create a voltage resonance in the circuit at a frequency less than the smallest harmonic v that occurs during the operation of a nonlinear load in this case. For this purpose, the inductive reactance of the reactor at 50 Hz is determined from the condition:

$$x_p \geq \frac{x_c}{v^2} = \frac{U^2_{\text{БК ном}}}{v^2 Q_{\text{БК ном}}}, \quad (4)$$

where $Q_{\text{БК ном}}$ is the actual total capacitor battery power, $U^2_{\text{БК ном}}$ is the rated capacitor battery voltage.

In other cases, resonant filter-compensating devices (FCD) based on capacitors, filter reactors, inductors and shunt resistors are used as protection against higher harmonics. The main disadvantage of resonant filters is their limitation to only one resonant frequency.

Currently, resonant filters are gradually being replaced by active harmonic filters (AHF) [10-12]. The AHF consists of a power part built on IGBT-transistors and a control system. The principle of operation of the AHF consists in the active generation of a compensating current in antiphase with the current of harmonic distortion of the load, which results in a sinusoidal current. AHF is a universal tool that can perform several functions simultaneously: reducing the level of higher harmonic components, correcting the power factor, reducing power loss, reducing flicker, etc. AHF are "flexible" devices, which means that the parameters of AHF vary depending on the operating mode of the network load characteristics. The principle of operation of the AHF is to generate the necessary harmonic components of the current by power electronics to supply nonlinear consumers so that the shape of the sinusoidal curve has minimal deviations from the norm.

First of all it is necessary to analyze the source and nature of higher harmonics occurrence, which depend on factors caused by the operation of electrical equipment when choosing way to reduce them.

IV. Experimental Study of the Problem in Low-Voltage Networks

In order to identify problems related to higher harmonics in low-voltage networks, we measured harmonic components of the voltage of household electric consumers (EC) of the apartment building.

Household ECs include electrical appliances with single-phase induction and universal collector motors, power supplies of consumer electronics and computer equipment with passive and active correction schemes of cos φ, lighting (all types except incandescent lamps), voltage inverters of control systems, microwave ovens, frequency converters installed on elevators and ventilation systems, etc.

The research was carried out using the AR5 power quality analyzer, which is capable of simultaneously recording the following power grid quality parameters: voltage (phase-to-neutral, phase-to-phase) of each phase and average; currents of each phase and average; grid frequency; cos φ in each phase; 3-phase power factor; active, inductive, and capacitive power by phase and total; load irregularity; active, inductive, and capacitive (consumed and output) energy.

Three-phase portable analyzer AR5 measures, calculates, records AC voltage and current parameters, including harmonics up to 49th order, in single-phase and three-phase networks. This device allows analyzing short-term disturbances: AC fails, pulses, overvoltages, presence of flicker (low-frequency modulation).

As a result of connecting the quality analyzer at the input panel of the apartment building, a graph of three-day measurement of the nonlinear distortion coefficient of the mains voltage was obtained (Fig. 3).

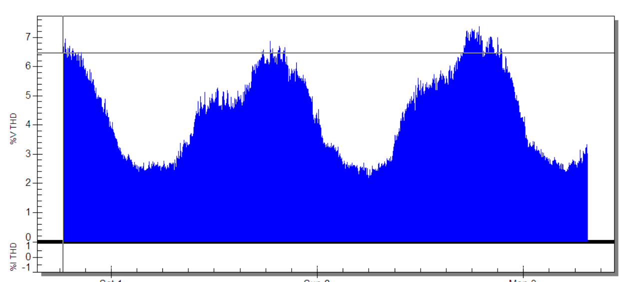

Fig. 3. Schedule of three-day measurement of nonlinear voltage distortion coefficient in apartment building.

The figure shows that the sinusoidal voltage distortion coefficient depends on the level of electricity consumption by household EC.

The voltage sinusoidality distortion factor increases to 7.4% during maximum power consumption in the evening hours and decreases to 2.1% during periods of minimum power consumption in the night hours. This allows us to conclude that household ECs serve as a cause of deterioration in the quality of electricity, and the persistence of non-sinusoidal voltage waveform in the night hours is explained by the fact that the underloaded transformer at the transformer substation acquires the properties of a nonlinear element due to ferromagnetic properties, which was also shown in the researches [13].

The voltage of the multi-apartment building was measured in parallel with the non-linear voltage distortion coefficient for three days.

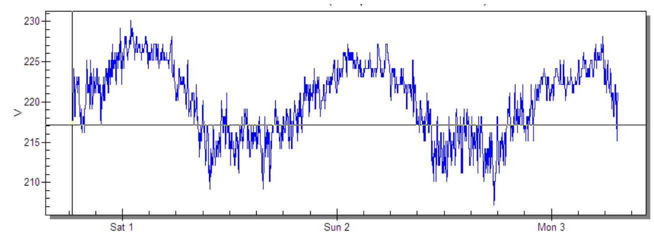

Fig. 4. Schedule of three-day voltage measurement of the multi-apartment building network.

There is a voltage drop to 207 V during times of maximum power consumption in the evening hours and the voltage is between 217 and 230 V during periods of minimum power consumption in the night hours.

There is two ways to solute the problem:

- installation of the CB on transformer substation busbars using a filtering reactor that will prevent it from entering resonance under the influence of high-frequency disturbance sources of EC;
- installation of the AHF on the busbars of the supplying transformer substation.

AHF can perform reactive power compensation and grid voltage stabilization in parallel. The functioning and application of the AFG is regulated by GOST R 59031-2020. It is also possible to use hybrid solutions in household networks. A non-resonant power factor correction system - capacitor battery and an active filter to reduce the level of higher harmonics are installed in this case.

It is planned to develop a program complex, which will allow to determine the optimal method of higher harmonics neutralization in the household network [14]. It is necessary to evaluate the amplitude-frequency characteristic of the resistance in various network configurations in the design of the FCD, to select the optimal way of the higher harmonics neutralization, as well as assessment of power losses and calculation of possible damage from violation of power quality indicators to determine the economic efficiency of the devices introduced into the network.

V. Assessment of Damage Caused By Faults in Electricity Quality

It's necessary to assess the losses caused by higher harmonics in assessing the economic feasibility of changing the schemes with the use of FCD. High harmonic levels can cause additional power losses in the network. This can lead to increased energy costs and reduced system efficiency [15].

Power losses caused by voltage fluctuations can be estimated from the expression:

$$\Delta P_{\text{к,п}} \approx 2\Delta P_{\Sigma} m, \tag{5}$$

where ΔP_{Σ} is the total active loss in the network without fluctuation; $m = (U - U_{min})/2$ is the modulation index; U and U_{min} are the voltage in the network without fluctuation and the minimum value of the modulation voltage.

In practice it turns out that $\Delta P_{\text{к,п}}/\Delta P_{\Sigma} \approx 0{,}05 \div 0{,}09$

The power loss values of $LP_{\text{к,п}}$, caused by voltage fluctuations are proportional to the relative variance value of the current fluctuations of D_I^* (relative to the nominal value):

$$\frac{\Delta P_{\text{к,п}}}{\Delta P_{\Sigma}} \approx D_I^* \tag{6}$$

Energy losses $\Delta A_{\text{к,н}}$ due to fluctuations:

$$\Delta A_{\text{к,н}}^{(\Sigma)} = \Delta P_{\Sigma} \sum_{j=1}^{n} D_{I_k j}^* t_j \tag{7}$$

where $D_{I_k j}^*$ and t_j are current oscillation variances at any time interval of duration t_j.

For an approximate assessment of the electromagnetic component of the damage caused by voltage deviations, it is assumed that deviation to negative values leads to an increase in the current of consumers ΔI and additional losses of active power:

$$\Delta P_{\text{доп}} = 6I\Delta I r \tag{8}$$

where r is the equivalent active resistance of the power supply system of consumers.

Relative increase in loss compared to $\Delta P_{\text{н}}$ at $U = U_{\text{ном}}$:

$$\frac{\Delta P_{\text{доп}}}{\Delta P_{\text{н}}} = 2\frac{\Delta I}{I} \tag{9}$$

The economic evaluation of the installation of a certain FKD includes the determination of damage caused by electricity quality violations. To calculate the consumer's loss of electricity quality, account must be taken of specific factors related to consumer activity, the cost of equipment, the cost of production or services, and possible data and time losses.

The values of economic damage in the generalized case without voltage fluctuations are expressed by the continuous and differentiable functions of the corresponding voltage-based electricity quality indicators. In the absence of a relationship between individual electricity quality indicators, the damage caused by each of them may be represented by a power polynomial relative to the corresponding indicator:

$$Y = \sum_{s=1}^{m} \left\{ \sum_{k=1}^{3} \left[a_{s_k}^{(Э)} + a_{s_k}^{(T)} \right] \cdot V_*^k + \sum_{p=1}^{2} \left[b_{s_k}^{(Э)} + b_{s_p}^{(T)} \right] \cdot \varepsilon_{2*}^p + \right. \left. + \sum_{l=1}^{2} \sum_{\upsilon=1}^{n} \left[c_{s_v}^{(Э)} l + c_{s_v}^{(T)} l \right] U_{\upsilon*}^2 \right\} \tag{10}$$

where $a_{s_k}^{(э,т)}$, $b_{s_p}^{(э,т)}$, $c_{s_v}^{(э,т)}l$ are the coefficients determined by electromagnetic (e) and technological (t) parameters of s-type electrical equipment or process flow or production; V_*, ε_{2*}, U_{v*} coefficient of inverse voltage sequence and v harmonic component in relative units.

When the voltage is not linear, the electromagnetic component is determined by:

- a) Increase in active power losses;
- b) increased consumption of active and reactive capacity;
- c) Acceleration of insulation of electrical equipment;
- r) Limit the scope of the capacitor batteries to increase the power factor.

The technological component arises as a result of:

- a) Increase in the cost of production by increasing the specific consumption of electricity when capacitors cannot be used to increase the power factor;
- b) Reducing the reliability of the network elements due to the increased probability of single-phase ground closures in 6-10 kV networks and their transition to multi-phase short-circuits to the ground;
- c) Failure of the pulse-phase control systems of the thyristor converters of the actuators of technological installations [16].

VI. Conclusion

Transition to widespread automation of various technological and domestic processes, digitalization of electrical engineering systems entails increase in them of semiconductor non-linear elements. Therefore, it is not sufficient to correct the power factor alone, as was the case in the past. Changes in load structure and network make harmonic filtering more and more important. This is especially important for systems that, for various physico-chemical reasons, can resonate under the influence of higher harmonics. This is the case, for example, with the BC used in each stage of the power supply system. In the design of electrical networks with BC, the installation of devices for protection against high harmonics, to exclude resonance phenomena, should be provided. We propose a method of protection - the use of filtering reactors for parallel operation together with BC. In this case, a resonance of voltages is generated in the circuit at a frequency smaller than the smallest harmonic v that occurs during the operation of non-linear load.

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