Optimizing the power quality by reducing harmonic distortion in the power supply network for isolated territories

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Abstract. New technologies of electric power generation, such as generation based on renewable energy sources, distributed generation, make extensive use of modern power electronics. All these non-linear elements generate harmonic components in the supply voltage. This leads to a deterioration in the quality of the supplied energy. In this regard, improving the quality of supplied energy is an urgent task. The article proposes a method of continuous distributed monitoring of the quality of electrical energy in the isolated power systems. This method is based on the use of the PMU infrastructure to continuously obtain information on instantaneous values of currents and voltages. It is proposed to use a smart meter proposed earlier by the authors as a primary measuring instrument for monitoring the level and direction of harmonics in various sections of the power system. This procedure is carried out in the current time mode, and thus there is a continuous adjustment of the power supply system to a mode close to optimal in terms of the content of harmonic components (harmonics) in the supply voltage at the selected points of connection.

1. Introduction

The active development of the isolated territories has led to new challenges in the production and use of electricity. As a rule, such areas are not covered by centralized power supply. New methods of electric power generation, such as generation based on renewable energy sources, distributed sources, widely use modern industrial electronics: rectifiers, frequency converters, inverters, etc. All these non-linear elements generate harmonic components in the supply voltage. This leads to deterioration in the quality of the supplied energy, which in turn reduces the efficiency of using electrical energy [1, 2]. In this regard, an urgent task is to control the distribution and reduce the level of harmonics in various sections of the supply network.

Problems caused by harmonics, such as overheating of transformers and rotating machines, overloading of neutral conductors, failure of capacitor banks, etc., lead to increased operating costs and can also lead to reduced product quality and productivity. In addition, changes in the structure of power generation towards the use of wind power and solar panels, which also generate harmonics, also lead to the fact that improving the quality of the supplied electricity becomes increasingly important for ensuring a stable power supply with an acceptable power quality [3, 4].
In the past, most loads were linear (induction motors, heaters, incandescent lamps), which means that the current of these devices when connected to a sinusoidal voltage will be sinusoidal. Nowadays, most loads are non-linear (for example, power electronics, that is, rectifiers, frequency converters, switching power supplies, vacuum tubes, etc.), which means that the current through these devices, when connected to a sinusoidal voltage, will be non-sinusoidal. Examples of some non-linear loads are shown in Fig. 1 and 2.

![Microwave Oven Current and Voltage Curves](image1)

**Figure 1.** Microwave Oven Current and Voltage Curves [5]

![Curves of current and voltage of a power supply of a personal computer](image2)

**Figure 2.** Curves of current and voltage of a power supply of a personal computer [5]

Such currents, in addition to the current of the fundamental frequency, contain currents with higher frequencies, which distort the shape of the sinusoid. Voltage harmonics are mainly due to current harmonics.

Problems arising from harmonics are, for example, overheating of transformers (K-factor) and rotating machines, overloading of the neutral, increased voltages between neutral and earth, failure of capacitor banks, triggering of circuit breakers and fuses, incorrect operation electronic equipment and generators, energy loss and lost network bandwidth (inefficient power transmission). These problems lead to additional costs such as higher energy consumption, costs due to faster aging of equipment, equipment downtime, increased maintenance and repair costs, as well as losses due to reduced product
quality and productivity (for example, when increasing rejects in the production of semiconductors) [6,7].

In addition, changes in the structure of power generation towards the use of alternative energy sources, which also generate harmonics, also lead to the fact that the control and reduction of harmonics become more and more important to ensure a stable power supply with acceptable power quality. Wind farms are susceptible to weakly damped resonances, which can lead to increased harmonics in the grid and increase the generation of harmonics in the wind farms [8]. The assumptions made in the modeling of harmonics and the corresponding methods are not suitable for wind farms, since voltage converters are not ideal current sources and the impedance of the network becomes very important.

2. Formulation of the problem
To ensure the survivability of the power system, devices for controlling its parameters are needed. On the one hand, these devices are autonomous, and on the other hand, they must be interconnected. For the successful and efficient functioning of the power system, it is necessary to create a distributed system for monitoring the quality of electrical energy. In this work, quality monitoring is limited to monitoring the level of harmonics in the supply voltage. For this purpose, it is proposed to measure the energy fluxes of harmonic vibrations in various sections of energy systems. Moreover, these measurements are made in a mode close to real time. To implement this task, there are the following prerequisites: the existing PMU infrastructure [9, 10], which makes it possible to measure instantaneous values of current and voltage in various sections and transfer them to the control center. Traditionally, this information is used to register the vector parameters of the power system. The authors propose to use this primary information also to determine the energy fluxes of the fundamental harmonic and harmonics in different sections using a smart meter developed by the authors [11-13]. The second prerequisite is that there are FACTS devices that allow you to remotely change the values of the reactive elements of the circuit [14].

3. The main provisions of the approach
The development of an algorithm for controlling the parameters of several reactive elements is a rather difficult task. In this regard, a method of successive approximations was proposed. In this case, by sequentially changing within small limits one of the parameters, for example, an adjustable capacitance, we monitor the response of the system as a whole. As an objective function, we use the ratio of the power of harmonics $P_{HH}$ to the power of the fundamental harmonic $P_1$ obtained from the output of the smart meter. In the general case, this objective function (1) depends on many variables:

$$\frac{P_{HH}}{P_1} = f(x_1, x_2, x_3, \ldots, x_n)$$

where $x_1, x_2, x_3, \ldots, x_n$ are the values of the reactive elements that affect the frequency properties of the circuit.

The quantities $x_1, x_2$ are variable, i.e. they can be changed remotely from the control center. Values $x_3, x_4, \ldots$ are quasi-constant, i.e. their change occurs at the rate of change in the operating modes of the system. In the calculations, we will make the assumption that there is only one harmonic in the voltage, for example, the third. This harmonic is generated by both a source $e_s$ and a non-linear consumer $e_c$, and there are two variable reactive elements: capacitance $C$, inductance $L$. As an example, in order to determine the fundamental possibility of automatic adjustment of variables, we consider a special case. Let it be necessary to ensure the highest possible quality of electrical energy at the point of connection of the consumer. For this case, the generator inductance $L_g$, distributed capacitance $C_d$, distributed inductance $L_d$ and consumer inductances $L_{nc}$ and $L_{lc}$.
will be considered constant values, and the values of the regulated capacitance $C_r$ and inductance $L_r$ will be considered variable.

Figure 3 graphically shows the procedure for determining the minimum of the objective function in the presence of two changing circuit parameters (in this case, $x_1$ - variable capacitance, $x_2$ - variable inductance).

![Figure 3. Illustration of the procedure for finding the minimum of the objective function.](image)

The initial numerical parameters of constants $x_1$, $x_2$, and other variables, as well as the minimum value of the range of variable changes $x_1$, $x_2$, are entered into the given model. Then, having fixed the first value of the variable $x_2$ at the beginning of the set range ($x_{21}$), we increase the variable $x_1$ with a constant step $\Delta x_1$, from the minimum $x_{11}$ to the maximum value $x_{1n}$ of the range. In this case, $n$ is the total number of cross-sections. For each value $x_1$, we determine by calculation the ratio of the power of harmonics to the power of the fundamental harmonic at the points of load connection, using the methods of calculating electrical circuits. With this value $x_{21}$, we find the value $x_{21m}$ that will correspond to the minimum of the objective function (1). The obtained values $x_{1m}$, $x_{21m}$, and the value of the objective function $f_{min1}$ are entered into the memory of the logical device.

Then the variable $x_2$ is incremented with a step $\Delta x_2$ and it turns out:

$$x_{21} + \Delta x_2 = x_{22}.$$  

The change operation $x_1$ is repeated over the entire range and $x_{2min}$ is calculated at the value of $x_{22}$. By analogy with the first case, $f_{min2}$ is determined. The calculation process continues until the variable $x_2$ reaches the upper limit of the range of its variation. It is necessary to achieve the ratio $x_2 = x_{2n}$, which will allow one to determine the value $f_{minn}$. The logical device processes the received data array and determines the final values $x_{1mn}$, $x_{2mn}$. Then the calculated local minima of the objective functions $f_{min1} - f_{minn}$ are compared, and the smallest value of them $F_{min}$ is found. This value will be the minimum of the objective function (1) (Fig. 3).
The values $f_{\text{min}1} - f_{\text{min}n}$ of the quantities are fed to a logical device, with the help of which an output signal is generated to control the actuators. These devices, in turn, change the values of $x_1$ and $x_2$.

As a result of this procedure, a preliminary determination of the optimal values of the variables was made. The fact is that the calculations did not take into account various influencing factors, in particular, not all higher-order harmonics, other sources of harmonics, etc.

4. The principle of the approach implementation

With the technical implementation of this method, to determine the true values of the variables $x_1$ and $x_2$ it is necessary to carry out the above procedure by real changing the parameters. As a registrar of the objective function (1) is an intelligent counter for the separate measurement of the energy of harmonics and the energy of the fundamental harmonic, which makes it possible to determine the value of the real objective function $F_{\text{min}}$ and the values of local maxima $f_{\text{min}1} - f_{\text{min}n}$. In accordance with this, the executive devices change the values of the variables $x_1$ and $x_2$.

To ensure the required power quality (the content of harmonics at the input of the substation) within the specified limits, it is necessary that the value of the objective function (1) be below the specified value $\varepsilon$:

$$\frac{P_{\text{HIL}}}{{P_1}} \leq \varepsilon.$$  \hspace{1cm} (2)

According to the European standard BS EN 50160: 2010, the permissible harmonic level in medium voltage networks does not exceed 0.08 in relation to the fundamental, i.e. the relation should be:

$$\frac{P_{\text{HIL}}}{{P_1}} \leq 0.08.$$

Figure 4 shows a scheme for controlling the quality of the supply voltage based on finding the minimum of the objective function (1). The value $F_{\text{min}}$ corresponds to the minimum value of harmonics in the supply voltage at the connection points. The values of the adjustable elements $x_1$ and $x_2$ (capacitance $C_r$ and inductance $L_r$) changed by means of the FACTS devices.

For the purpose of distributed monitoring of voltage quality in various sections of the network, smart meters are installed, proposed by the authors [15-17]. Analog signals of instantaneous values current $i$ and voltage $u$, at the substation input from current and voltage sensors are fed to the PMU vector parameter recorder, which transmits these values via a GPS satellite to the control center to the smart meter input. The smart meter measures the total energy, as well as separately the energy of the fundamental harmonic and the energy of harmonics of other orders. In addition, the meter determines the direction of the harmonics, that is, identifies the source of harmonic distortion. In the meter, the energy is converted into power and at the output; from it we receive separately signals which are proportional $P_1$ and $P_{\text{HIL}}$, then they are fed to the input of the digital divider.

From the output of the digital divider, the ratio $\frac{P_{\text{HIL}}}{{P_1}}$, which is the objective function (1), is fed to the input of the logic device.
After completing the procedure for changing the values of the variables $x_1$ and $x_2$, the logical device determines the minimum value of the objective function $F_{\text{min}}$ and the values of the variables $x_1$ and $x_2$ correspond to this minimum. In this case, the logic device generates a control signal for the FACTS elements, which in turn change the values of the variables $x_1$ and $x_2$ to their optimal value.

The value $\frac{P_{\text{HH}}}{P_1}$ is compared with the specified value $\varepsilon$ for compliance with condition (2). If this condition is met, the power quality meets the requirements and no further correction is required. If the condition is not met, then from the output of the logic device, the control signal is fed through the GPS satellite to the FACTS to control the variable parameters $x_1(L)$ and $x_2(C)$ according to the previously described successive approximation procedure. It should be noted that it is more expedient to make a coarse adjustment with $x_1(L)$, and a finer one with $x_2(C)$. The value $3\varepsilon$ is taken as a threshold value for fine or coarse adjustment.

In this case, the regulation of reactive parameters is carried out using static synchronous compensators (STATCOM). The use of these devices allows you to adjust the value of the output current in the full range of capacitive or inductive current, regardless of the voltage level of the AC system. Compared to other devices, for example, with a static reactive power compensator (STC), STATCOM has the following advantages [18, 19]:

- implements both modes of operation, inductive and capacitive;
- the occupied area is significantly reduced in view of the fact that there is no need to use bulky capacitor banks and reactors, which are used in STK;
- there is a possibility of using a large dynamic range of regulation;
• there is a high speed and better characteristics in transient processes;
• it is insensitive to harmonic resonances in the system, etc.

Since the monitoring system operates online, the operating conditions with minimum possible level of harmonic voltage at the points of connection are also continuously maintained. The considered methodology can be applied to more branched schemes as well. To this end, we should install a multiplexer in front of the meter, which will allow the optimization of frequency conditions at many points of connection.

The considered procedure is performed online and thereby the power supply system is continuously adjusted to the operating conditions close to optimal in accordance with the content of harmonics in supply voltage at the selected points of connection.

5. Conclusion

The content of harmonics in supply voltage is an important indicator of power quality which determines the efficiency of its use.

This article proposes a procedure for continuous distributed monitoring of the power quality for isolated Arctic power systems. The direction and level of harmonics are determined with the use of the smart meter developed by the authors. The data on instantaneous current and voltage values is transferred through the available infrastructure of PMUs.

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