Application of higher harmonics in protection against single-phase earth faults in resonant grounded cable networks of medium voltage

T.Yu. Vinokurova, O.A. Dobryagina, E.S. Shagurina, V.A. Shuin
Department of electric power systems automatic control
Ivanovo State Power Engineering University, ISPEU
Ivanovo, Russian Federation
tanya-vinokurova@mail.ru

***Abstract*—Protections based by higher harmonics absolute measurements the zero sequence currents of the protected object connections against single-phase earth faults in resonant grounded cable networks of medium voltage industrial and urban energy supply systems have been widely applied in Russia since the late 60s of the 20th century. However, some operational problems connected with sufficient selectivity and sensitivity of these protection devices appeared with time. Sensitivity and selectivity of this protection are considerably determined by the instability degree of the higher harmonics total level in single-phase earth fault current of the protected network. Well-known Russian expert Kiskachi V.M. gave approximate estimate of the higher harmonics instability degree at the end of the 60s. Nowadays due to load changes in the main substations load in resonant grounded cable networks of medium voltage higher harmonics fluctuations in single-phase to earth fault current. The simulation models of this networks application and the accumulated experimental data about real networks allow to specify the existing estimates of higher harmonics instability in single-phase to earth fault current and their applicability conditions.**

Keywords—resonant grounded cable networks of medium voltage, single-phase to earth fault, higher harmonics, ground faults relay protection

I. INTRODUCTION

The major part of electric power in industrial and urban energy supply systems is distributed to consumers through resonant grounded cable networks of medium voltage through arc-suppression coil (ASC) (with capacitive currents compensation). Single-phase to earth faults (SPEF) prevail in these systems (up to 70–80% of total number [1])

In Russia, to protect cable networks from these faults they use devices based on measuring of higher harmonics (HH) general level in the zero-sequence current connections of the protected object and comparing it with the setting [2–4 and others]. This type of relay protections includes the device USZ–2/2, developed in VNIIE at the beginning of the 60s and serially produced by Cheboksary Electric Apparatus Plant from the end of the 60s of the 20th century. Current protection function by absolute measurement of HH general level is provided for in microprocessing terminals for medium voltage connections.

Some operational problems appeared with time when using current protections by HH absolute measurement in resonant grounded cable networks of medium voltage (e.g., [5]). Therefore, the researching in limiting operation factors and developing ways of operation improvement are a relevant objective.

II. APPLICABILITY CONDITIONS OF CURRENT PROTECTIONS BY HIGHER HARMONICS ABSOLUTE MEASUREMENT

Applicability conditions of current protections by HH absolute measurement in the $3I_0$ currents depend on offsetting from the external SPEFs and sensitivity to internal faults. Limited HH range, including harmonics $\nu = 5, 7, 11, 13$ is generally used [2–4 and others]. Operating frequency range of protection devices is caused by the mentioned HH generation in cable medium voltage networks [6]. At frequency range of up to 650 Hz, the distribution of HH in zero sequence currents corresponds to the distribution of capacitive power frequency currents (50 Hz) in isolated systems [7]. The operating current of i-th connection $I_{0t\,i}$ should be chosen from [8]:

$$I_{0t\,i} \geq K_a\, \alpha_1\, I_{c\,i}, \tag{1}$$

where K_a – offsetting ratio; $I_{c\,i}$ – own capacitive current of i-th connection; α_1 – the highest possible level of HH current $I_{c\,i}$ in controlled network.

Selected from (1), the pickup current should not be less than the minimum operating current $I_{0t\,i\,min}$ defined by the technical capabilities of protection device:

$$I_{0t\,i} \geq I_{0t\,i\,min}, \tag{2}$$

The sensitivity ratio of protection for internal SPEF on the i-th connection is defined as:

$$K_{s\,i} \geq (\alpha_2\,(I_{c\Sigma} - I_{c\,i}))/I_{0t\,i} \geq K_{s\,min}, \tag{3}$$

where $I_{c\Sigma}$ – total capacitive current ; α_2 – a minimum HH level of $I_{c\Sigma}$ and $I_{c\,i}$ currents; $K_{a\,min}$ – minimum allowed sensitivity factor.

When $I_{0t\,i} = I_{0t\,i\,min}$ sensitivity ratio is as follows:

$$K_{s\,i} = \alpha_{min}(I_{c\Sigma} - I_{c\,i})/I_{0t\,i} = \alpha_{min}\, I_{c\Sigma}(1 - I_{c\,i*})/I_{0t\,i} \geq K_{s\,min}, \quad (4)$$

where $\alpha_{min}\, I_{c\Sigma} = I_{HH\,min}$ – the minimum possible HH level for SPEF current of resonant grounded systems of cable medium voltage networks.

Application conditions (selectivity and sensitivity) of relay protection result from (1) – (4):

$$I_{c\,i*} = I_{c\,i}/I_{c\Sigma} \leq 1/(1 + Z_{max}\, K_a\, K_{s\,min}), \quad (5)$$

$$I_{0t\,i\,min} \leq \alpha_{min}\, I_{c\Sigma}(1 - I_{c\,i*max})/K_{s\,min}, \quad (6)$$

where $Z_{max} = (\alpha_1/\alpha_2)_{max}$ – the maximum parameter value of $Z = \alpha_1/\alpha_2$ characterizing the instability degree of the total HH level in SPEF current in the protected cable medium voltage network.

From (5) and (6), it can be concluded that 2 major factors influence applicability of current protections by HH absolute measurement:

1) minimum level of harmonics in SPEF current (and thus, in $I_{c\,i}$ current of damaged connection) characterized by the value of $I_{HH\,min}$ and defining sensitivity requirements to relay protections against SPEF based on HH;

2) instability degree of the total HH level in SPEF current characterized by Z_{max} value.

Evaluation of the minimal HH level in SPEF current of $I_{HH\,min}$ on the basis of simplified equivalent circuits of resonant grounded cable networks of medium voltage was given by Kiskachi V.M. and Zhezhelenko I.V. at the end of the 60s of the 20th century. The evaluation mentioned was adjusted in [11] using simulation models of cable medium voltage networks and took into account more factors influencing total HH level in SPEF current than the simplified models used in [9, 10].

Kiskachi's work [7] also provides value Z assessment characterizing the instability degree of HH in SPEF current. It based on simplified analytical calculation methods, cable 6–10 kV networks models, and some experimental data: $Z \approx 2.5–3$. To be on the safe side in [7] they recommend to take $Z_{max} = 4$ value.

When $K_a = 1.5$, $K_{s\,min} = 1.5$ and $Z = 4$, it can be concluded from (5) that current protection by HH absolute measurement is applicable at connections with own capacitive current $I_{c\,i*} \leq 1/(1 + 4 \cdot 1.5 \cdot 1.5) = 0.1$, it considers with recommendations in [7].

According to [12], such connections of medium voltage main substation (MS) buses amounts to 70 % of total number for main step down substations (SDS) and 90% for main cogeneration stations (MGS). However, practical selectivity indicators of current protection by HH absolute measurement in resonant grounded cable networks of medium voltage installed on MS are significantly worse than would be expected under the mentioned applicability conditions [5]. It may be assumed that the main reason for insufficiently high selectivity of these protections against single-phase to earth faults is higher than accepted instability degree of the total HH level in the SPEF current. When Z > 4, the values of $I_{c\,I\,*}$, with which it is possible to provide conditions of selectivity and sensitivity of current protection by HH absolute measurement, according to (5) decrease, and as a result the area of possible application on resonant grounded cable networks of medium voltage reduces as well. Therefore, the assessment of possible variation range of Z value is relevant both for clarification application area of current protection by HH absolute measurement, and for increasing their technical excellence.

III. ASSESSMENT OF LIMITTING Z VALUES IN RESONANT GROUNDED CABLE NETWORKS OF MEDIUM VOLTAGE

The limiting Z value characterizing the instability of HH in SPEF current is defined as

$$Z_{lim} = \alpha_{max}/\alpha_{min}, \quad (7)$$

where $\alpha_{max} = I_{HH\,max}/\ I_{c\Sigma}$ – maximum possible level of higher harmonics in SPEF current in resonant grounded cable networks of medium voltage; $\alpha_{min} = I_{HH\,min}/\ I_{c\Sigma}$ – minimum possible level of HH in SPEF current.

When assessing Z_{lim} (8) only harmonics of operating range of protection devices from SPEF based on the use of HH zero sequence currents of $\nu = 5, 7, 11, 13$ should be considered. As mentioned above, the estimated assessment of minimum HH level in SPEF current is given in [9–11]. In these papers, it is assumed that the minimum HH level in SPEF current is defined in the limiting case, only by harmonics generated by power transformers 6–35 / 0.4 kV at receiving substations. In practice, these modes of operation of cable networks of medium voltage can occur at daily load curves when production interruptions are possible in night shifts and on weekends [13]. In cable networks where the main substations are medium voltage buses of cogeneration stations, not only power transformers can be a HH source determining their minimum level in SPEF current but also generators operating on busbars. Therefore, the minimum HH level in SPEF current should be expected in cable networks, where main substations are medium voltage buses of step-down substations.

Under these assumptions, the level of harmonics in SPEF current depends on the ratio of total supply transformers power S_{sup} to the power of receiving step-down substation transformer ΣS_{rec}: $s = S_{sup}/\Sigma S_{rec}$. According to real power systems analysis in [9] $s = 0.7–3$.

5th and 7th harmonics predominate in magnetizing currents of power transformers and consequently in SPEF currents [6–11]. Table 1 shows the values of the minimum levels of these harmonics in SPEF current in resonant grounded cable network where $I_{C\Sigma} = 25$ A (for cable 10 kV networks $I_{C\Sigma\,min} = 20$ A, for 6 kV networks – $I_{C\Sigma\,min} = 30$ A), at the average value of $s = 1.5$ received by calculation results given in [9–11].

TABLE I. EVALUATION OF MINIMUM LEVELS OF HIGER HARMONICS IN SPEF CURRENT IN RESONANT GROUNDED CABLE NETWORKS OF 6–10 KV

Data Source	**I_5, %**	**I_5, %**	**α_{min}, %**
Calculations based on simplified equivalent circuits of cable networks [9, 10]	2.65	2.05	~3.37
Calculations on simulation models of networks [11]	1.0	0.5	~1.12

The harmonic composition of SPEF current and zero sequence currents of damaged and undamaged connections is determined with sufficient accuracy by harmonic composition of voltage of damaged phase at the site of grounding [7]. Therefore, the maximum level of HH in SPEF current α_{max} can be approximately estimated for networks 6–10 kV by the maximum permissible (GOST 13109–97) non-sinusoidal voltage factor $K_{ns\ max} = 0.08$ and maximum permissible factors $K_{U\nu\ max}$ of separate harmonic components $\nu = 5, 7, 11, 13$ defined as by $K_{U\nu\ max} = 1.5\ K_{U\nu\ norm}$ (table II).

TABLE II. VALUES OF NORMAL AND MAXIMUM PERMISSIBLE NON-SINUSOIDAL FACTORS FOR VOLTAGE HARMONICS OF OPERATING FREQUENCY RANGE

ν	**5**	**7**	**11**	**13**
$K_{U\nu\ norm}$, %	4	3	2	2
$K_{U\nu\ max}$, %	6	4,5	3	3

Let's assess $K_{ns\ max}$ at $K_{U\nu\ max}$ values specified in table II:

$$K_{ns\ max} = \mathrm{sqrt}\ (\Sigma K^2_{U\nu\ max}) = \mathrm{sqrt}\ ((K^2_{U5\ max} + K^2_{U7\ max} + K^2_{U11\ max} + K^2_{U13\ max})/100) = 0.0862,$$

that is more than the maximum allowable value of $K_{ns\ max} = 0.08$.

To fulfill $K_{ns\ max} \leq 0.08$ for harmonic of minimum order $\nu = 5$ it is necessary to assume $K_{U\nu\ max} = 5.1\% < K_{U\nu\ max}$. Then according to assumed relative levels of voltage harmonic components, the total relative level of HH in SPEF current will be equal to:

$$\alpha_{max\ \%} = 100\%\ \mathrm{sqrt}\ (\Sigma I^2_{\nu *}) = 100\%\ \mathrm{sqrt}(\Sigma((\nu \cdot K_{U\nu\ max}/100)^2) = \mathrm{sqrt}\ ((5\ K_{U5\ max})^2 + (7\ K_{U7\ max})^2 + (11\ K_{U11\ max})^2 + (13\ K_{U13\ max})^2) = 65\%.$$

The value of $Z_{lim} = 65/1.12 \approx 58$ corresponds to the obtained $\alpha_{max} = 65\%$ value and the most conservative assessment [11] $\alpha_{min} = 1.12\%$ value.

Measurements of harmonics in SPEF currents of real cable networks of medium voltage show that this assessment of α_{min} is more likely underestimated, because the influence of several additional sources of higher harmonics (system, ASC and others) were not taken into account during calculation. According to [15] the minimum level of HH in SPEF current as a rule is not less than 4% in resonant grounded cable networks of medium voltage as a rule.

In [16] based on measurements in real cable networks of medium voltage it is shown that the maximum level of harmonics in SPEF current can reach over 35–40%. It is evident that the experimental assessment ($\alpha_{max} = 40\%$ and more) is relatively close to the mentioned above limiting assessment $\alpha_{max} = 65\%$. Assuming that $\alpha_{min} = 4\%$, and $\alpha_{max} = 65\%$, then $Z_{lim} = 65/4 \approx 16$.

For a particular cable network of medium voltage the value of $Z \leq Z_{lim}$.

IV. THE MAIN FACTORS AFFECTING INSTABILITY LEVEL OF HIGHER HARMONICS IN SINGLE-PHASE EARTH FAULT CURRENT

In a particular cable network of medium voltage the value of the Z parameter depends on many factors. The main ones are:

1) composition of higher harmonics sources in complex load of MS in cable network of medium voltage;

2) daily MS load curves;

3) operating modes features of the main HH sources;

4) parameters of cable network elements (the ratio of supply transformer power to total power of receiving substations transformers, supply system resistance, cable lines resistances connecting MS medium voltage buses with receiving substations and others).

The harmonic composition in SPEF current is determined by harmonic composition of phase voltages [7]. Sources of HH in cable networks of medium voltage are (Fig. 1): supply system S, supply transformer T_{sup}, power transformers of receiving and distribution transformer substations T_{rec}, non-linear load NL, electric motors M. When an earth fault happens an additional source of HH in SPEF current is also ASC.

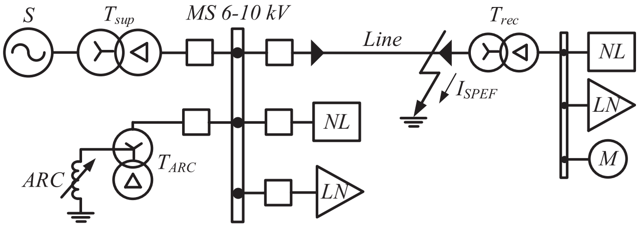


Figure 1. The HH sources in resonant grounded cable networks of medium voltage

In the considered networks, the main sources of HH are nonlinear load [6]: controlled and uncontrolled valve inverters (VI), electroheat installations (EI), electric welding installations (EWI), and in case their absence (for example, outage) – receiving substations transformers. In average, relative values of HH currents generated by nonlinear valve inverters in load currents are: ~20% for 5-th harmonic; ~14% for 7-th harmonic; ~9% for 11-th harmonic; ~8% for 13-th harmonic [6]. Electric welding installations with AC to DC converters also generate similar HH levels. Among electroheat installations, the main sources of HH are different types of electric furnaces (electric arc steel-smelting, ore-smelting, ferroalloy and others). The harmonics source generated by electric furnaces is non-linear electric arc but in DC electric furnaces, it is brushless AC to DC converters. The HH level in load currents generated by electric furnaces compares with harmonics level generated by the nonlinear converters [6]. The harmonics level in load currents generated by power transformers is usually some percentage [6, 9–11]. The relative values of harmonics generated by an equivalent system, supply transformer, electric motors, non-liner lighting load together do not exceed some percent in load currents, and the influence of these sources on the total HH level is negligible [6].

Non-linear load primarily exists in power supply systems of industrial enterprises. Table III shows a typical composition of complex load with the main HH sources for different industries [13].

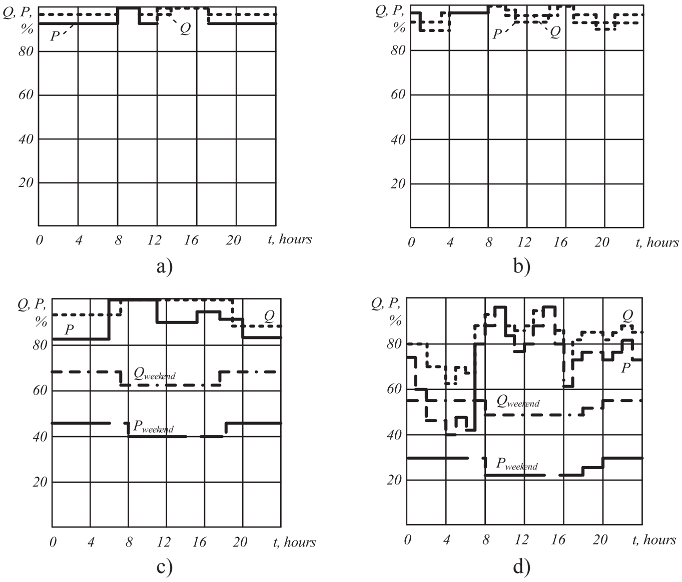
TABLE III. TYPICAL COMPOSITION OF COMPLEX LOAD WITH MAIN HIGHER HARMONICS SOURCES [13]

Industry sector	**Consumers composition, %**						
	SM	***IMH***	***IML***	***EL***	***EI***	***WI***	***NC***
Non-ferrous metallurgy	10	5	27,5	1,5	10	-	46
Chemical industry	35±7	15±6	29±8	~2,4	~3	~1	~12
Coal mining	4	7	67	15	-	-	7
Ferrous metallurgy	25	8	29,5	2,5	22	3	10
Automobile industry	9	10	48	5	19	3	6
Machine building	8	5	52	5	13	14	3
Electric motion	-	-	5	5	-	-	90

Notes to table III: SM – synchronous motors, IMH – high voltage induction motors, IML – low voltage induction motors, EL – electric lighting, EI – electroheat installation, WI – welding installation, NC – nonlinear AC to DC converters.

The share of the main sources of higher harmonics (non-linear load) as part of the total load of MS cable medium voltage specified in table III in average amounts to 15–50%, and for some industries can reach 90% (for example, electric motion, rolling production, powerful electric arc DC furnaces on metallurgic plants, ferroalloy industries and others). The change in modes or complete deactivating (disabling) of the main HH sources are the main cause of significant changes of the total harmonics level in voltage and consequently in single-phase to earth fault current in cable networks of medium voltage.

The relative values of harmonics in load currents substantially depend on daily MS load curves. Typical daily load curves [14] for industries considered in table 3 are shown in Figure 2.



a)

b)

c)

d)

Figure 2. Typical daily load curves for different industries:
a – non-ferrous metallurgy, b – chemical industry,
c – ferrous metallurgy, d – automobile industry

Large fluctuations of general HH level within 24 hours and weeks should be expected first of all in enterprises working in shifts with weekends, when a significant decrease of the total load accompanied by partial or complete blackouts of the main HH sources are possible (for example, ferrous metallurgy, automobile industry). A more stable level of HH should be expected in continuous production enterprises (non-ferrous metallurgy, chemical industry).

The level of harmonics generated by uncontrolled valve inverters is determined by the current load value. The level of HH generated by the controlled valve inverters varies significantly when the delay angle α and switching angle γ change [6]. For example, when these angles change from $\alpha = 0^0$, $\gamma = 0^0$ to $\alpha = 30^0$, $\gamma = 60^0$, the relative values of fundamental harmonics in load currents in this type of converter are reduced in 3–5 times [6].

Welding installations have cyclic operation causing fluctuations of the HH level. According to [17] the level of fundamental harmonics generated by welding installations with AC to DC converter, depending on the operation mode can change 3–6 times. Therefore, when assessing of HH level instability in load currents, caused by valve inverters and EWI, it can be assumed that their level varies depending on their operating mode from 3 to 5–6 times. In the operation cycle of different furnaces there are some periods connected with their load and metal unloading when the electric furnace is not a HH source. This fact should also be taken into account when assessing HH instability degree in SPEF currents.

The largest instability HH degree in voltages and accordingly in SPEF currents should be expected in cable networks of medium voltage fed by electrotraction substations due to the large share of non-linear load and its abruptly variable load. However, application of current protections by HH absolute measurement against SPEF was never recommended, and they are not considered below.

V. INVESTIGATION OF TOTAL HIGHER HARMONICS INSTABILITY IN SPEF CURRENT ON SIMULATION CABLE NETWORKS MODELS OF MEDIUM VOLTAGE

The account of influence of the mentioned above factors on higher harmonics level in voltage and single-phase earth fault current is not possible without using simplified networks equivalent circuits. Therefore, the simulation models of cable networks of medium voltage allowing the maximum number of influence factors were used in this paper to assess the possible harmonics fluctuations in SPEF current.

Simulation models calculations are performed for MS cable network of medium voltage for industries, the daily curves of which are shown in Figure 2.They are characterized by a large share of non-linear converters, electric welding installations, electrothermal plants in the load composition. The simulation model for assessment of HH instability degree in SPEF current in cable networks of medium voltage of power supply systems for the specified industries is shown in Figure 3.

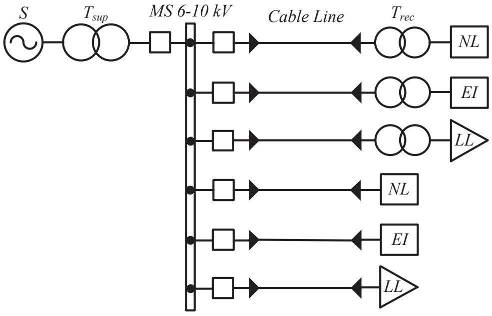


Figure 3. Calculation model of resonant grounded cable networks of medium voltage for industry power supply system to assess of higher harmonics instability degree in SPEF current

Complex MS load composition varied depending on industry in accordance with Table III. Simulation scheme parameters were defined by means of statistical data analysis for cable networks of medium voltage of various industries power supply systems (Table IV).

TABLE IV. CALCULATION SCHEME PARAMETERS FOR ASSESSMENT OF HIGHER HARMONICS INSTABILITY IN SPEF CURRENT

Parameter	**Value**
Total capacitive current network $I_{C\Sigma}$, A	25
Short-circuit current at buses of MS $I^{(3)}_{sc\,MS}$, kA	10–20
Power of supply transformer on MS S_{sup}, MVA	25–100
Receiving substations transformer load factor K_{load}, pu	0.7
Cable length L, km	0.3–2.5
Average length of the cable line L_{aver}, km	0.8
$s = S_{sup}/\Sigma S_{rec}$, pu	0.7–1.5
Factor for non-linear load $s_{nl} = S_{nl}/\Sigma S_{rec}$, pu	0.1–0.9
average factor for non-linear load $S_{nl\,aver}$, pu	0.3
Maximum system voltage $U_{s\,max}$, V	6300
Minimum system voltage $U_{s\,min}$, V	6000

In maximum higher harmonics level simulation in SPEF current the following assumptions were made:

- An industrial enterprise has on-peak operating conditions according to its daily curve;
- All main higher harmonics sources are switched on (in operation);
- main harmonics sources are operating providing the mode of the maximum HH level in load currents mode;
- MS buses voltage equals $U_{s\,max}$.

In minimum higher harmonics level simulation in SPEF current the following assumptions were made:

- An industrial enterprise has off-peak operating conditions according to its daily curve;
- The non-linear load share decrease proportionally to decreasing the total power load;
- electroheat installations can be completely switched off as a HH source;
- the minimum HH level generated by non-linear converters and electric welding installations is 2–3 times less than the maximum one;
- MS buses voltage equals $U_{s\,min}$.

Table V shows the assessment results of cable networks simulations parameter Z for harmonics ν = 5, 7, 11, 13, and their amounts used in protections against earth faults based on HH. The calculations are performed for the following conditions:

- system nominal voltage $U_{s\,nom} = 6$ kV;
- system total capacitive current $I_{C\Sigma} = 25$ A;
- the supply transformer power $S_{sup} = 31.5$ MVA (63/2);
- parameter $s = S_{sup}/\Sigma S_{rec} = 1.5$;
- $K_{load} = 0.7$.

TABLE V. CALCULATED VALUES OF INSTABILITY LEVEL Z_ν AND Z_Σ FOR HARMONICS ν = 5, 7, 11, 13 IN SPEF CURRENT

Industry sector	**Z_ν**				**Z_Σ**
	ν = 5	***ν = 7***	***ν = 11***	***ν = 13***	
Non-ferrous metallurgy	3,36	2,77	1,25	0,85	2,01
Chemical industry	5,29	5,11	3,96	3,44	4,38
Ferrous metallurgy	9,22	7,57	3,98	2,98	4,99
Automobile industry	11,1	8,61	4,9	2,59	5,87

Table V shows that HH instability level in the SPEF current is predictably higher in cable networks of medium voltage of supply systems for enterprises working in shifts. The obtained Z values is higher than it is recommended in [7] for using in current protections based on HH calculations, but it is significantly less than the above mentioned limiting values.

If $Z_{max} = 6$, it was founded from (5) that current protections with absolute HH measurement can be applied for connections, the own capacitive current of which does not exceed values: $I_{ci*} \le 1/(1 + Z_{max}\,K_a\,K_{s\,min}) = 1/(1 + 6 \cdot 1.5 \cdot 1.5) \cong 0.07$. The share of such connections on cable networks of medium voltage MS according to [12] does not exceed 65–70%, which considerably limits the possible application area of current protections by HH absolute measurement.

Additional limits of this protection are related to the approximate method of pickup current selection that leads to increasing K_a in (5). For example, it is recommended in [15] to assume $K_a = 3–4$ because of impossibility to find maximum and minimum HH levels. For these values of K_a current protections with absolute HH measurement don not practically apply to cable networks. Therefore, in developing protective devices based on HH, they should prefer methods providing selectivity in spectrum instability and harmonics level in SPEF current, such as directional or adaptive current protections.

VI. CONCLUSIONS

1. The possible application area of current protections by HH absolute measurement is considerably limited by instability degree of total harmonics level in SPEF current.

2. The main factors affecting HH instability levels are determined: composition of harmonics non-liner load sources of MS cable network of medium voltage, daily load curves, operation modes of main harmonics sources and parameters of cable network elements.

3. It is shown that the most HH instability should be expected in resonant grounded cable networks of medium voltage for power supply systems for enterprises, which have a significant share of nonlinear converters and electro-thermal installations working in shifts with weekends.

4. Based on simulation models, the values of instability parameter for enterprises with continuous load curve $Z_{max} \cong 4.5$, for enterprises with fluctuating load curves $Z_{max} \cong 6$ are defined. When $Z_{max} = 6$, current protections with absolute HH measurement can be applied only for connections with their own total capacitive current not more than 7% $I_{C\Sigma}$.

5. According to results, preference should be given to development of protections with independent of Z selectivity and sensitivity conditions, for example, directional and adaptive current protections.

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