

# THE LOW COST METHOD OF MEASUREMENTS SYNCHRONIZATION IN THE LOW-VOLTAGE NETWORK ON FREQUENCY AND THE VOLTAGE PHASE

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**Abstract** – The work proposes and analyses a new low cost method of measurements synchronization in electric low-voltage networks. The method is based on a finding the maximum factor of correlation among (between) the graphs of frequencies variations. The efficiency of the method has been tested on acting 0.4 kV feeders by field synchronous measurements. Timing accuracy of measurements' synchronization for low-voltage networks via the suggested method is not worse than 3.5-70  $\mu$ s.

**Keywords:** synchronization of measurements, low-voltage networks, frequency variation, IED

## 1. INTRODUCTION

With the advent of satellite navigation systems in electric power systems WAMS technology the based on use synchrophasor, emerging from Phasor Measurement Unit PMU [1] are being actively implemented. In addition to PMU, the technology of synchronous measurements in electric systems is used in digital substations of Intelligent Electronic Devices (IEDs), optical measurement current and voltage transformers and Merging Units (MUs). These measuring devices provide synchronization of measurements by means of GPS-receivers with an accuracy of 1 microsecond, allowing to solve problems of monitoring of transients, a power system parameters identifications and other applications [2]-[3].

Application of the technology of synchronous measurements in distribution networks (including low voltage networks) within the framework of Smart Grid concept implementation has a considerable prospect. However, due to the relatively high cost of receivers, the complexity of GPS signal reception in constrained urban conditions and probability of its deliberate distortion [4], a search is required for new low-cost methods of synchronization. There is no doubt in promising use of universal synchronization methods based on IEEE-1588 [5] protocol and based on the use of telecommunication networks for this purpose. At the same time, there is interest in studies aimed at the development of low-cost methods of synchronization, using a voltage signal of power network as a synchronization source. Thus in [6] the method involving artificial distortion of a voltage signal of a low-voltage power network by producing pulses of a current using thyristors in time preceding voltage transition through a zero value is offered. This article explains the possibility of

application in the Smart Grid framework for synchronization a better and improved low-cost method which does not require the distortion of the network's voltage curve. The method is based on the synchronous power network (divergences between the phase angles of voltage in the nodes of the distribution network do not exceed a few degrees [7]) and the possibility of calculation of voltage phase shift in the nodes of the distribution network in the Distribution Management System (DMS). The main problems at implementation of the proposed method of synchronization relate to the need of primary synchronization with an accuracy less (better) than the voltage period of a power network.

Section II of the article describes the theoretical principles of the synchronization method, Section III provides description and results of experimental studies of acting 0.4 kV feeders voltage signals. Analysis of the accuracy of the proposed method and directions for the further research are presented in Section IV. Conclusions and prospects for the practical implementation of the suggested method are given in Section V.

## 2. DESCRIPTION OF THE THEORETICAL PRINCIPLES OF THE SYNCHRONIZATION METHOD

This method of synchronization implies availability of at least one node of a network in EES wherein an IED with GPS signal or other known method (master IED) high-precision synchronization of measurements is installed, and a number of low-cost IEDs or a Smart Meter, including monophasic ones, set at users and other nodes of a network. All IEDs are interconnected through communication channels and capable of two-way information interchange.

Each IED has its own internal clock and the microprocessor, synchronized by the quartz clock oscillator (CCG/CTG) and a clock pulse generator (CPG) with frequency of  $F_{os}$ . By means of the microprocessor (the signal processor) or digital and logic circuits and FPGA IED should perform the following functions:

1) Scaling of the period or frequency of a voltage signal of each phase to time of its transition through a zero value from minus to plus (or from plus to minus) for each period (the period should be measured with the resolution on one or two order of magnitude better, than the accuracy of CCG/CTG; for this purpose it is possible to measure the

number of CCG/CTG pulses) and assign a unique number to each period;

2) Counting the number of the clock oscillator pulses ( $N_o$ ) on the set number of the power network voltage periods ( $N_p$ );  $N_p$  value should be chosen so that to provide possibility to further adjust the accuracy of a slave internal clock IED.

The offered method of synchronization involves assigning initial time stamp to each measured instantaneous value of a current and voltage with the subsequent refinement of the values of these tags.

The slaves' internal clocks IED must be synchronized with the absolute time not worse than  $\pm 5$  seconds before connecting them to the network. In the settings of all IEDs, the equal value  $N_p$  is given corresponding, for example, to the time interval of 10 seconds ( $N_p=500$  for a power network frequency of 50 Hz).

Also it is assumed that IED is correctly phased in A, B and C phases.

The viewed synchronization method consists of two stages, varied in accuracy and periodicity:

1. The initial synchronization providing synchronization of a slave internal clocks IEDs with the leading IED clock with accuracy corresponding to divergence of a voltage phase in the nodes of their joining (connection, junction) ;

2. Periodic adjustment (correction) of the CCG/CTG regular instability factor (coefficient) of the slave IED  $K_s$ . Magnitude (value) of this factor is defined by the formula:

$$K_s = \frac{N_{o,m}}{N_{o,s}} K_m K_\varphi. \quad (1)$$

Where  $N_{o,m}$  – number of equivalent pulses per number of periods  $N_p$  counted by the master IED;

$N_{o,s}$  – number of equivalent pulses per number of periods  $N_p$  counted by the slave IED.

$K_m$  – factor of systematic instability of CCG /CTG of the master IED, determined according to PPS signal from the GPS receiver;

$K_\varphi$  – the correction factor that takes into account the phase difference in the nodes of a network to which the master IED, the slave IED are attached as well as defined in DMS system on the basis of calculation of the 0.4 kV network's power flow at the onset of the first period and the termination of period  $N_p$ .

Expedient periodicity of the  $K_s$ . factor correction is determined, on the one hand, by the required accuracy of synchronization as possible, and on the other hand, the constraints on the network bandwidth. Possible synchronization accuracy in this method depends on accuracy of definition of the phase shift of voltage signals in various nodes of the DMS network.

In addition to the universal synchronization methods based on IEEE-1588 protocol, it is suggested to use a method based on random variations of frequency in the power system and the possibility of high-precision measurement of voltage frequency at each period of the alternating current of the power network for initial synchronization. The master IED takes measurement for each period and stores them with reference to the exact time. The subordinate IEDs also measure frequency for each period with their time stamps. The frequency values at a given number of the periods of power network voltage are

transferred to the master IED (or the central computer) where mistiming value (magnitude) is determined by comparison and then is reported to the slave IED.

The efficiency and accuracy of this method of initial synchronization depends on the following factors:

1) The availability of sufficient magnitudes of frequency fluctuations in a network over time (in the incorporated power system in Europe, permissible frequency deviations in a normal power flows make  $\pm 0,02$  Hz, in Russia  $\pm 0,2$  Hz).

2) The accuracy of frequency measurements using IED (For PMU standard C37.118-2011 [8] provides frequency measurement with an accuracy of  $\pm 0,0005$  Hz).

3) Changes in the phases of voltage in network nodes (due to the dynamic change of loads, the voltage phases at different nodes of the network change over time with respect to each other) lead to a discrepancy of frequency change graphs at different nodes of the network.

In order to verify the proposed method and research of these factors, the field measurements have been conducted on a real feeder 0.4 kV of the electrical network of Stavropol.

### 3. DESCRIPTION OF THE MEASUREMENTS AND ANALYSIS OF RESULTS

The measurements were carried out using two identical cRIO based measuring systems with NI 9225 and SEA 9472 modules. The detailed description of these systems is given in [9].

The measurements were performed for two acting 0.4 kV power networks in the city of Stavropol.

Data on the conducted measurements is shown in Table 1.

Table 1. Field Tests Characteristics.

Feature	Network Number	
	1	2
Date	10/02/2015	02/06/2015
Start Time, UTC	13:28:00	15:16:00
Network Characteristics	0.4 kV Feeder, Bare Conductor Built	0.4 kV Two Feeders, Cable Conductor Built
Supplied Consumer Descriptor	Low-rise Buildings, Residential Consumers	University Academic Buildings No. 10 and No. 17
cRIO1 Location	Mounting Feeder Main Power Substation	Auditorium 10-208, Switchboard
cRIO2 Location	Mounting Feeder End Terminal	Auditorium 17-502, Switchboard

An instantaneous values of each phase voltage with the respect to the neutral conductor were converted with sampling frequency of 25 kHz and recorded simultaneously at the beginning of every minute for 10 seconds in separate csv format text files. The values of the measured currents of feeder phases at the beginning of the experiment was 51 A, 52 A and 90 A respectively.

The measurement results were then processed with the Excel to form arrays of frequency values for each period of a voltage signal. The frequency value is determined by scaling the transition time of a voltage signal through a zero in accordance with the expressions (2-3):

$$t_i = \frac{1}{F_d} \left[ \frac{U_{j+1}}{(U_{j+1} - U_j)} + N_i \right] \quad (2)$$

Where  $F_d$  – the sampling frequency, Hz;

$i$  – the serial number of transition of a voltage signal through 0 from negative to positive values;

$j$  – the index of the instantaneous voltage value corresponding to the condition of a signal transition through a zero from positive to negative values;

$N_i$  – the number of samples from the start of measurements to the  $i$ -th transition of a voltage signal from negative to positive values;

$$f_i = \frac{1}{t_{i+1} - t_i} \quad (3)$$

#### A. Measurements' Results Analysis, Network # 1

As an example, Figure 1. shows the results of calculations of frequencies for a phase A at the beginning ( $f1$ ) and the end ( $f2$ ) of the 0.4 kV feeder from 201 to 225 periods of observation. An initial measurement interval 01:30:00 PM.

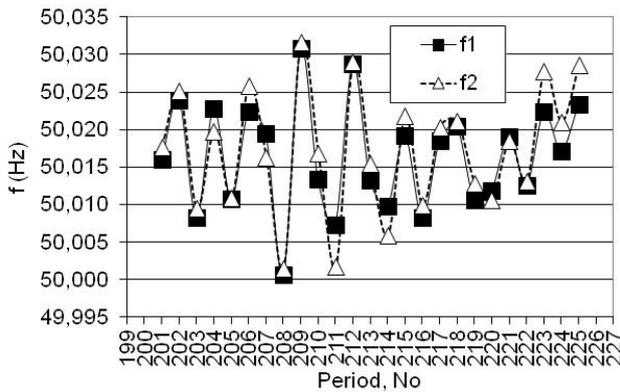


Fig. 1. The change of frequency at the beginning and the end of a 0.4 kV feeder.

As follows from the graph there is the considerable correlation between frequencies which numerical value equals 0.949.

To assess feasibility and effectiveness of synchronization on the analysis of correlation coefficient, graphs of the correlation coefficient change were constructed at shift of the frequency change graph of  $f1$  from 0 to 425 periods at 25 frequency values of  $f2$  (Figure 2). With precise timing of the graphs, the value of the correlation coefficient is maximum and close to 1. At the mistiming of the graphs, the value of correlation coefficient is less than 0.6. Thus, in this case the synchronization in the accordance with the proposed algorithm is provided with probability equal 1.

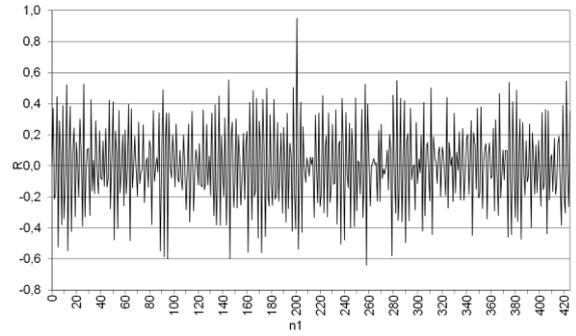


Fig. 2. The correlation coefficient between the graph change  $f2$  [200:224] and the graph  $f1$  [ $n1$ :  $n1+24$ ].

To check the reliability of synchronization with other comparable intervals of the graph  $f2$ , a surface representing the dependence of correlation coefficient  $R$  from two factors:  $n1$  and  $n2$ . was built with LabVIEW. Where  $n1$  is an initial index for the period of the frequency graph  $f1$ ,  $n2$  - an initial index for the period of the frequency graph  $f2$ .

Calculation of the correlation coefficient  $R$  is in accordance with the expression:

$$R(n1, n2, k) = \frac{\sum_{i=0}^{k-1} (f_{i+n1}^b - \overline{f_{n1,k}^b})(f_{i+n2}^e - \overline{f_{n2,k}^e})}{\sqrt{\sum_{i=0}^{k-1} (f_{i+n1}^b - \overline{f_{n1,k}^b})^2 \sum_{i=0}^{k-1} (f_{i+n2}^e - \overline{f_{n2,k}^e})^2}}, \quad (4)$$

Where  $k$  - number of points in graphs  $f1$  and  $f2$ , for which the calculation is performed;

$\overline{f_{n1,k}^b}$  and  $\overline{f_{n2,k}^e}$  - mathematical expectations of frequencies  $f1$  and  $f2$  at the interval, corresponding to the  $k$  periods.

The results of calculations for values of  $k$ , equal to 25, 50 and 250 are shown in Figures 3-5.

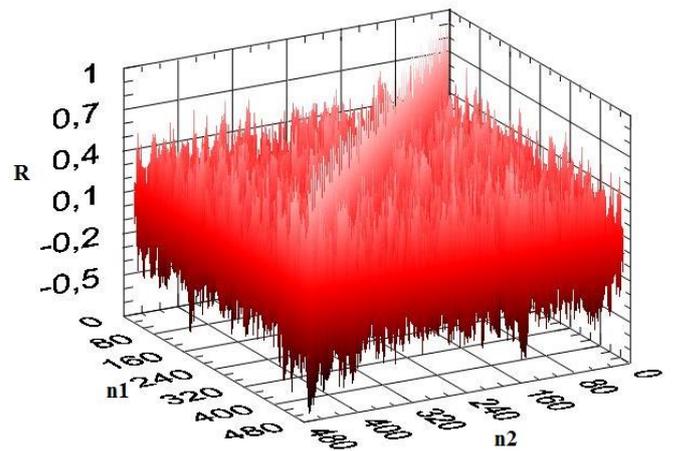


Fig. 3. The change of correlation coefficient at 25 graph points compared ( $k=25$ ).

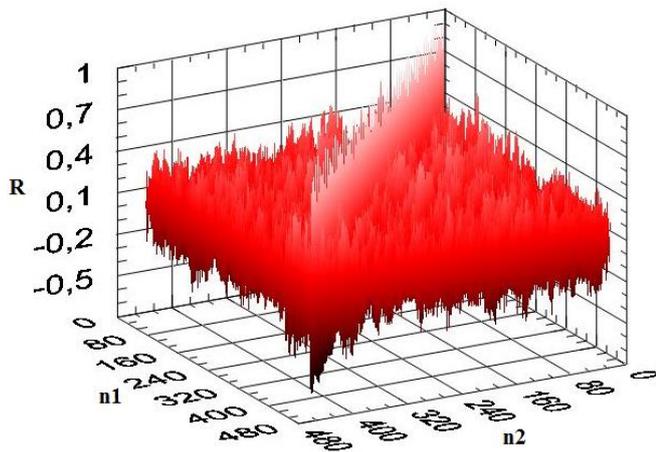


Fig 4. The change of correlation coefficient at 50 graph points compared ( $k=50$ ).

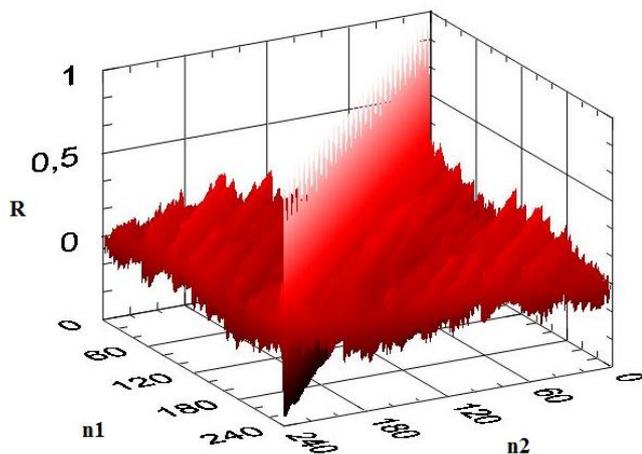


Fig 5. The change of correlation coefficient at 250 graph points compared ( $k=250$ ).

The analysis of the produced dependencies of the correlation coefficient from the magnitude of  $k$  allows to draw a conclusion that with increase in the number of points compared, the probability of correct synchronization also increases. However, the increase in number of compared points leads to an increase in load of the mainframe computer on which the calculation of the correlation coefficient is carried out. Furthermore, loading of the communication channels used to transfer the values of frequencies computed in a slave (subordinate) IED increases.

It can be assumed that the required value of  $k$  to insure reliable synchronization will be decreasing respectively along with the decrease of the initial mistiming magnitude of the master IED's and slave IED's internal clock.

In order to verify this thesis, minimum values of  $k$  were defined for the tested network power flows, which ensure accurate synchronization at three values of the master IED's and slave IED's internal clock initial mistiming: 1 second, 2.5 seconds and 5 seconds (Table 2 и Figure 6).

Table 2. Research of the minimum value of  $k$ , providing accurate synchronization.

Interval Investigated	Minimum Value of $k$ , at IED Internal Clock Initial Mistiming			Maximum Value of $R$ , at IED Internal Clock Initial Mistiming		
	1 s	2,5 s	5 s	1 s	2,5 s	5 s
13:28:00-13:28:09	16	20	30	0,954	0,984	0,972
13:29:00-13:29:09	10	19	28	0,966	0,965	0,954
13:30:00-13:30:09	18	29	31	0,958	0,970	0,971
13:31:00-13:31:09	39	56	56	0,490	0,676	0,831
13:32:00-13:32:09	46	56	56	0,462	0,706	0,887
13:33:00-13:33:09	33	39	39	0,840	0,884	0,884
13:34:00-13:34:09	19	23	26	0,910	0,952	0,928
13:35:00-13:35:09	19	22	33	0,859	0,944	0,919
13:36:00-13:36:09	16	24	32	0,926	0,913	0,924

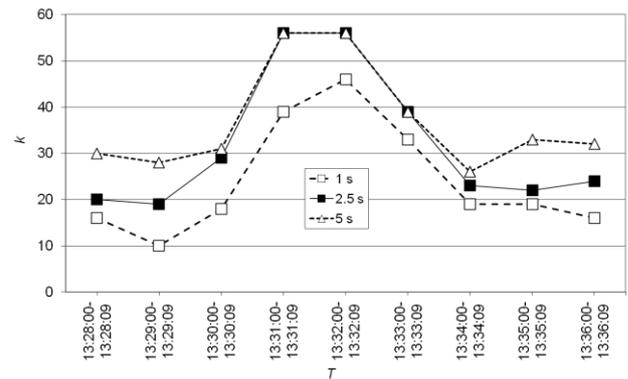


Fig 6. Correlation of the minimum value of  $k$ , ensuring accurate synchronization at various IEDs internal clock mistiming, to the interval investigated.

To study power flows of the feeder, the minimum values of  $k$ , which provide accurate synchronization (Table 1) were determined.

Hence, to ensure reliable and accurate synchronization of the feeder tested and power flows observed, it is required to compare no less than 46 periods at the 1 second initial mistiming and 56 periods at 5 second initial mistiming.

#### B. Measurements Results Analysis, Network # 2

Results of the correlation coefficient calculations for values of  $k$ , equal 50 and 150 are shown in Figure 6 and Figure 7.

Minimum values of  $k$ , ensuring accurate synchronization are shown in Table 3 and Figure 8.

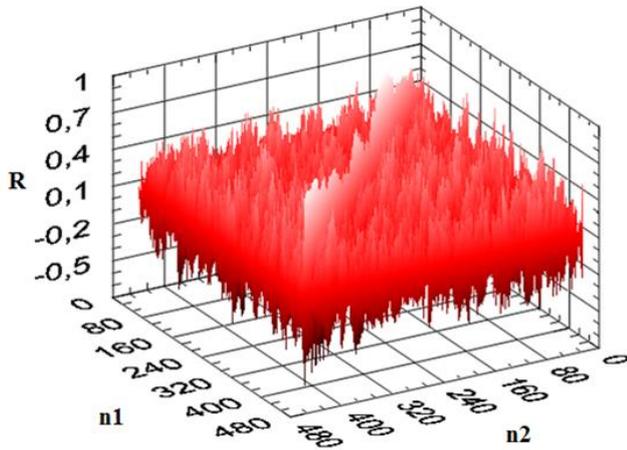


Fig 6. Correlation Coefficient Ratio at 50 points compared of the diagram ( $k=50$ ).

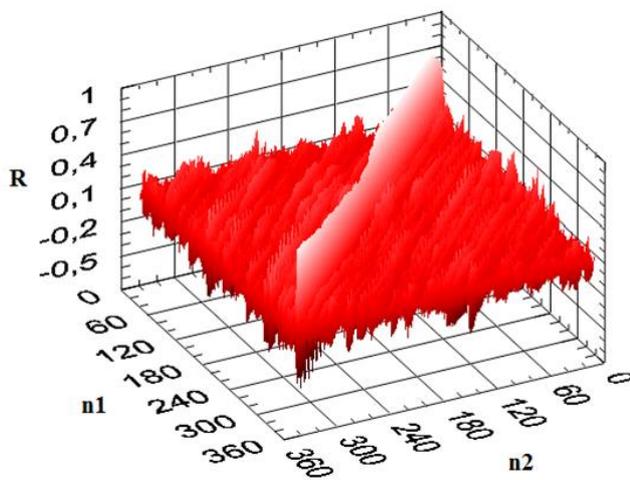


Fig 7. Correlation Coefficient Ratio at 150 points compared of the diagram ( $k=150$ ).

Table 3. Research of the Minimum Value of  $k$ , ensuring accurate synchronization.

Interval Investigated	Minimum Value of $k$ , at IED Internal Clock Initial Mistiming:			Maximum Value of R at IED Internal Clock Initial Mistiming:		
	1 s	2.5 s	5 s	1 s	2.5 s	5 s
15:16:00 - 15:16:09	31	54	106	0.638	0.863	0.868
15:17:00 - 15:17:09	44	56	80	0.854	0.808	0.895
15:18:00 - 15:18:09	30	49	50	0.958	0.922	0.909
15:19:00 - 15:19:09	14	42	75	0.668	0.843	0.862
15:20:00 - 15:20:09	32	38	55	0.840	0.805	0.795
15:21:00 - 15:21:09	24	49	59	0.686	0.842	0.836
15:22:00 - 15:22:09	30	45	79	0.700	0.743	0.845
15:23:00 - 15:23:09	31	71	81	0.695	0.707	0.821
15:24:00 - 15:24:09	33	70	72	0.567	0.353	0.368

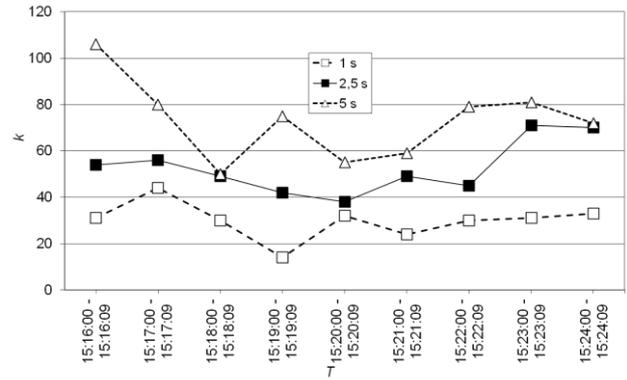


Fig 8. Correlation of the Minimum Value of  $k$ , ensuring accurate synchronization at various IED internal clock mistiming to the interval investigated.

Thus, to ensure accurate and reliable synchronization in Network # 2 it is required to compare no less than 44 periods at 1 second initial mistiming and no less than 106 periods at 5 second initial mistiming.

#### 4. THE ANALYSIS OF ACCURACY OF THE PROPOSED METHOD AND A DIRECTION FOR THE FURTHER RESEARCH

The synchronization accuracy by the proposed method depends on the accuracy of determination of the voltage phase angles in network nodes (in the absence of the possibility of determining these angles DMS mistiming will be determined by the magnitude of the voltage phase angle difference at the power center and maximum (by the module) voltage phase angle of the remaining nodes of the network. Thus, for a feeder with uniformly distributed load in the extent of 400 m, made of ASCR-35 wire, with a load power of 50 kW the transverse component of an anode drop will be equal in the most adverse case (the absence of jet loading) 9.21V, which corresponds to a phase shift of 1.25 electrical degree that corresponds to mistiming of 69.6  $\mu$ s. In DMS operation and calculation of a feeder power flow, the phase shift can be calculated with an accuracy of 1-5 % which corresponds to the mistiming of 0.7-3.5  $\mu$ s.

Reliability of the proposed method also depends on the accuracy of the determination of frequency for each network period. As previously indicated, the frequency deviation is normalized over the range of  $\pm 0.02$  Hz for an incorporated electrical power system of Europe. Proceeding from this, it can be assumed that the accuracy of frequency measurement of each period must be much higher and no worse than  $\pm 0.002$  Hz. The accuracy of the frequency measurement, is primarily affected by factors such as the frequency of the quartz oscillator and its instability. For instance, at the quartz oscillator frequency of 32767 Hz, the frequency measurement error, based on counting the number of clock oscillator pulses between transition of a voltage signal of a power network through 0 (from a minus to plus), makes  $\pm .023$  Hz. The instability of existing quartz oscillators is  $\pm 5 \cdot 10^{-6}$  which corresponds to the frequency measurement accuracy of  $\pm 0.00025$  Hz. Thus, to achieve the accuracy of  $\pm 0.002$  Hz a quartz oscillator operating with a frequency of at least 400 kHz is required. However, more research is needed which will allow to find interconnection between the

frequency measurement accuracy and the minimum value of  $k$ . This will minimize the frequency of the IED internal clock oscillator and therefore its cost.

The value of  $k$  can be decreased through optimization of the master IED installation location and sequential synchronization of the adjacent IEDs' internal clock. Installation of the master IED in the middle of a feeder should lead to the decrease of the value of  $k$ , by contrast with the master IED installation in the feeder's power substation. In addition, it is feasible to provide the sequential synchronization between adjacently located slave IED starting with the most electrically remote and gradually moving towards the master IED (in this instance, it is assumed that the master IED is set in the center of power substation.)

To improve the reliability of the synchronization method examined, there can be suggested additional criteria for the accuracy estimation of the mistiming magnitude determination:

1. Test for the proximity of the correlation coefficient  $R$  to 1 between the frequency graphs compared. Calculations show (Table 2 and Table 3), that the probability of inaccurate synchronization increases at  $R < 0.8$ . Demonstrably, the optimum boundary end value of  $R$  is separate and determined by the master IED to the slave IED electrical distance, as well as feeder power flows.

2. Test for the smallness of the correction if the correction under examination is not the first one and the time interval between the preceding and the current correction does not exceed the specified boundary limit value. The magnitude of this time interval boundary limit value can be determined based on instability of the IED internal clock rate. Thus, if quartz oscillator instability is  $5 \cdot 10^{-6}$ , the magnitude of this interval can be taken as 2000 seconds at allowable 10 millisecond clock offset (a half of voltage signal period of the power system).

The occurrence of users with sharply nonsinusoidal loading can lead to ambiguity for determining the frequency by the moment of a voltage signal transition through a zero value. In such cases, it can be suggested to perform the calculation on the first transition through zero and to lock the identification of the further transitions through zero for a time longer than  $3/4$  of a period and a shorter period.

The synchronization method proposed in this work fits well with the Smart Grid concept. This concept involves two-way information interchange between IED users and SCADA system and integration with DMS.

#### 4. CONCLUSIONS

1. The proposed synchronization method of measurements in a low-voltage network can be implemented with the minimal cost as a part of Smart Grid and Smart Metering concepts. The basis of the suggested method is to determine the voltage frequency of the power network for each period in its various nodes, followed by finding the magnitude of the internal clock mistiming in various IED by calculation of correlation coefficient between frequencies change graphs, computed by the master IED and slaves IED.

2. The efficiency of the method is confirmed by experimental synchronous measurements of voltage of the phases at the beginning and the end of 0.4 kV feeder's and the further calculations. Studies have shown that for reliable synchronization of measurements it is sufficient to analyze the correlation coefficient for frequency change graphs for 10-106 periods.

3. The calculations show that the accuracy of the relative synchronization for feeders of low-voltage networks without the possibility of calculating or estimating the network power flow is not worse 70 microseconds. In the conditions of integration with DMS and availability of calculation of a network power flow, the accuracy of synchronization is determined by the accuracy of voltage phase angles modeling and can be improved up to 0.7-3.5 microseconds.

4. The results show the need for further theoretical and experimental research aimed at the frequency optimization of IED quartz oscillators, studies of the effect of network parameters and power flows on the reliability of synchronization, as well as feasibility of application of the proposed method for the higher voltage networks.

#### ACKNOWLEDGMENTS

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