21st IMEKO TC4 International Symposium and
19th International Workshop on ADC Modelling and Testing
Understanding the World through Electrical and Electronic Measurement
Budapest, Hungary, September 7-9, 2016

Detection and Identification of Bad Power Measurements in Distribution Networks Using State Estimation by Synchronized Voltages and Currents

Evgenii Zelenskii[1], Yury Kononov [1]

[1] Institute of Electricity, Electronics and Nanotechnologies
North Caucasus Federal University, Stavropol, Russia, zeg86@ya.ru, iukononov@ncfu.ru

Abstract – **The article presents a new approach to identify bad power measurement based on the use of synchronized measurements of voltage and current phasors. The proposed method is based on the assumption that in most instances the bad power measurements are caused by inaccurate measurements of a current. In this case, the availability of voltage phasors' measurements at consumers and in the main substation is a sufficient condition to identify bad power measurements. It has been proposed to use the instrument for state estimation theory and the recursive algorithm to identify good measurements of the currents' and voltages' phasors of the nodes in order to improve the reliability and accuracy of the method. The identification accuracy will depend primarily on the measurements synchronization accuracy and the passive parameters sizing error.**

Keywords – **detection of bad measurement, identification of bad measurement, state estimation, synchronized measurements, distribution networks.**

I. INTRODUCTION

It is generally known that a part of electric power is consumed inevitably while being transmitted at a distance. This part is called a loss of electric power. The actual losses of electric power are determined by the difference between the measured power at the main substation and at consumers. The actual losses involve technical losses and non-technical losses. The technical losses are caused by the physical processes occurring in the power grid. Non-technical losses (NTL) are caused by errors in measuring devices as well as by bad measurements. The causes of bad measurements may be quite different. There are devices or data channels failures, current and voltage transformers flaws, as well as the deliberate exposure to these devices and channels of communication for the purpose of illegal use of electric power.

II. AVAILABLE METHODS

Methods for the detection of bad power measurements can be divided into offline and online modes. There are various statistical methods based on the user load curve analysis that are employed quite often as the offline mode method [1-2]. Their disadvantage is the impossibility to clearly detect and identify nodes with bad power measurements. In addition, they require a large collection of the statistical data over a long period of time.

Introduction of AMI and SCADA/DMS in distribution networks enables implementation of more accurate and efficient online mode methods. To detect bad measurements within these methods, a theory of the state estimation followed by the analysis of the normalized residuals are employed [3-4]. One of the problems with the application of these methods is the impossibility to unambiguously detect and identify the bad power measurements in the event of a considerable number of the corrupted data.

The nowadays trend of transition from meters and current and voltage analog sensors to intelligent electronic devices (IED), which integrate the functions of meters and phase measurement units (PMU), enables to forecast the availability to use synchronized voltage phasors' and current measurements to increase the accuracy of the state estimation results. Application of low-cost methods to synchronize measurements [5], will accelerate the IED implementation process in distribution networks.

This paper discusses a new method for detection of bad power measurements, based on the application of synchronized measurements of voltage phasors and a current. The proposed method is based on the assumption that in most cases bad power measurements are caused by inaccurate measurements of a current. For example, a user's deliberate interference into the electric power accounting system, as a rule, leads to a phase change or a reduction in the effective value of the measured current's

value. There are certain, however less common, methods of electric power theft associated with an exposure to the circuit voltage of a meter that result in a 180 degree voltage phase change (which is easily detected if phasor registers are used) or reduction in the current effective value. Mostly, the user carries out a simple circuit break [6], which is also easily detectable.

III. PROPOSED METHOD

The essence of the proposed method is viewed by the example of the simplest three-phase feeder supplying two consumers. Let's assume that the feeder's mode is sinusoidal and symmetric which will be considered as a single-phase equivalent circuit (Figure 1).
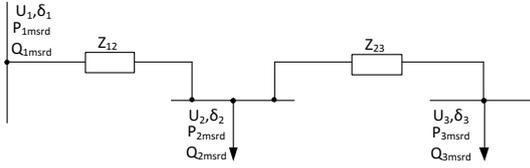

Fig. 1. The Simplest Feeder Supplying Two Consumers

Suppose that IED are installed at the main substation and at the consumers, allowing the measuring of currents' and voltage phasors, as well as the active and reactive power. Assume that the network has bad power measurements, ie:

$$S_{1msrd} \neq S_{2msrd} + S_{3msrd} + dS_{12} + dS_{23}, \quad (1)$$

where $\underline{S}_{1msrd} = P_{1msrd} + jQ_{1msrd}$ – full power of power supply;

$\underline{S}_{2msrd} = P_{2msrd} + jQ_{2msrd}, \underline{S}_{3msrd} = P_{3msrd} + jQ_{3msrd}$ – full power loads;

dS_{12} – technical power losses in line 12;

dS_{23} – technical power losses in line 23.

It is necessary to detect and identify bad power measurements.

Knowing the voltage and phase angles as well as impedance of Z_{12} and Z_{23} lines, it is feasible to calculate complexes of currents in lines:

$$\dot{I}_{12} = (U_1^{ej\delta_1} - U_2^{ej\delta_2})/\dot{Z}_{12},$$
$$\dot{I}_{23} = (U_2^{ej\delta_2} - U_3^{ej\delta_3})/\dot{Z}_{23}, \quad (2)$$

and complex of load currents:

$$\dot{I}_2 = \dot{I}_{12} - \dot{I}_{23}.$$
$$\dot{I}_3 = \dot{I}_{23} \quad (3)$$

As well as complex power of the load:

$$S_{2estd} = U_2^{ej\delta_2} \hat{I}_2.$$
$$S_{3estd} = U_3^{ej\delta_3} \hat{I}_3. \quad (4)$$

Having compared the measured S_{2msrd}, S_{3msrd} and estimated S_{2estd}, S_{3estd} power loads, a conclusion can be drawn to the reliability or unreliability of power measurements in the corresponding node. If $|S_{msrd} - S_{estd}| < \varepsilon$, where ε is an admissible calculation error, then the power measurements in a node are good.

This approach is equal to the classical calculation of a mode [7]: the nodes in which voltage phasors are being measured are set in the capacity of the balancing ones, whereas zero power loads are specified in the other nodes. On this basis, several conclusions can be drawn:

1. The availability of voltage phasors' measurements at consumers and at the main substation is a sufficient condition to calculate the arbitrary configuration circuit's (network) mode, including closed circuit (network).

2. A failure of even a single IED measuring the voltage at the load nodes or the main substation, results in an unobserved system and absolute failure of the method proposed.

To eliminate the drawback of the suggested method, which follows from the second conclusion, for the network mode calculation it is proposed to employ not only the measured voltage phasors, but also the injection currents' phasors measured in those nodes where the reliability of measurements is confirmed beforehand by other methods.

In the capacity of such a unit, it is suggested using primarily a main substation, owned by a power supply company, therefore the probability of bad measurements in this node is minute.

Furthermore, to detect additional good measurements of currents it is recommended to use a recursive algorithm to identify good measurements of currents' and voltages' phasors of the nodes.

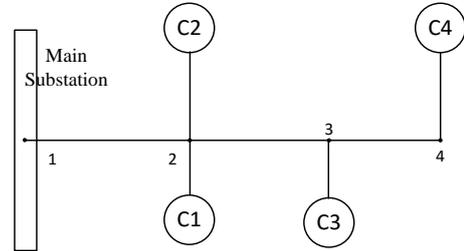The essence of the proposed algorithm is viewed on a small feeder as an example (Figure 2).

Fig. 2. Example of a Small Feeder

Being aware of the "3-C4" section impedance, node "3" voltage can be determined via voltage and load current at the consumer "C4" (marked U_3^{C4}) measured with PMU or IED. Similarly, node "3" voltage can be determined through voltages and load currents measurements at the

consumer "C3" (voltage denoted $U_3^{C3.}$) Having compared those two voltage values, it can be defined, whether the condition is fulfilled:

$$\left|U_3^{C4}-U_3^{C3}\right|<\varepsilon , \qquad (5)$$

where ε is an error margin of the calculation.

The failure to meet conditions (5) indicates that at least one of "C3" or "C4" has bad power measurements, i.e., the load current measurements can not be considered as valid a priori.

In the event the condition (5) is satisfied, then the IED detected current phasors measurements for the consumers denoted "C3" and "C4" are accepted as good.

The addition of good measurements of injection currents' phasors in the nodes of the circuit not only can increase the reliability of the suggested method to identify bad power measurements, but can also improve identification accuracy of the measurements through the transition from resolving the mode calculation problem to the task of state estimation by synchronized measurements of voltage and current phasors.

However, as distinct from the classical state estimation theory of electric power systems [7], a system of linear equations is employed in this case that greatly simplifies the problem solution algorithm and improves its performance.

The initial data are the topology and passive parameters of the circuit of a network, measurement of voltage' phasors at the main substation and at consumers as well as the current's phasor of a head section and some consumers' load currents which have been exposed by the algorithm as a priori good. The resulting solution are the voltage phasors in all network nodes through which the injections currents in the load nodes and power load are determined subsequently; having compared those to the measurements, the bad power measurements can be detected.

To account for non-sinusoidal modes of the distribution networks, one can exploit the principle of superposition and an independent solution of the state estimation task for each of their harmonics [8]. Respectively, IED measurements of harmonic components' phasors of currents and voltage will be required. If the IED is equiped with oscilloscope function the method of estimation of instanteneous currents and voltages values [9] becomes much more promising .

The accuracy of bad measurements detection with the proposed method depends on the network's passive parameters setting errors, as well as precision and synchronism of the current and voltage' phasors measurements.

IV. TEST RESULTS

The effectiveness of the method proposed has been verified via a physical experiment. The experimental setup consisting of a physical single-phase feeder model, which simulates a simple feeder that includes two lines and two loads (Figure 3), the measuring system comprised of NI-9225 and NI-9227 measurement units powered by National Instruments [10].
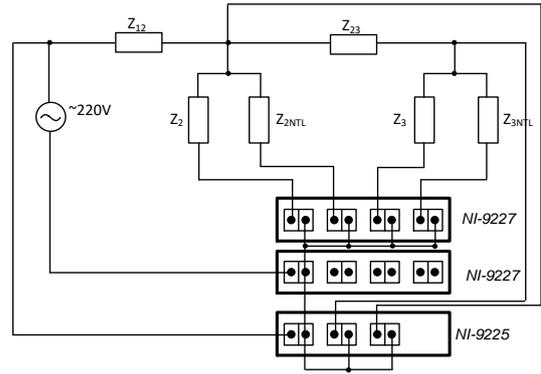

Fig. 3. The equivalent circuit of the experimental setup

Model scale factors: Current: 250 A or. / A mod., Voltage: 43.47 V or./V mod. Passive parameters of the circuit (network) model: $Z_{12}=8.895+j9.088$ the Ohm, $Z_{23}=9.151+j8.629$ the Ohm. The circuit loads has been modelled with active inductive $Z_2=581.482+j49.066$ Ohm and $Z_3=683.022+j211.517$ Ohm. Bad measurements has been modelled via parallel connection of resistors (shunts) $Z_{2NTL}=1135.882+j373.836$ Ohm and $Z_{3NTL}=1189.842+j219.239$ Ohm. The data of the experiment is tabulated below (Table 1.)

Table 1. Results of experiment.

	Consumer; Node 2	Consumer; Node 3
P_{msrd}, W	84.91	63.26
Q_{msrd}, var	7.17	19.60
P_{calc}, W	122.90	102.24
Q_{calc}, var	20.62	26.54
$dP_{NTL.calc.}$, W	37.99	38.98
$dQ_{NTL.calc.}$, var	13.46	6.95
$dP_{NTL.msrd.}$, W	39.49	38.49
$dQ_{NTL.msrd.}$, var	13.005	7.09

The table demonstrates that the detection error in the second node at the active power was (122.90/(84.91+39.49)-1) *100 = -1.2 %. and in the third node it was (102.24 / (63.26+38.49) -1) *100 = 0.48 %.

V. PILOT PROJECT

Nowadays, the proposed method to detect unreliable power measurements for non-technical electricity losses localization is being pilot tested in the distribution network of a power grid company associated with AMR of Energomera Company [11], Stavropol Territory, Russia. To perform synchronous measurements of currents and voltages, the IED experimental samples have been designed for the company. The pilot project has been implemented with a 10 kV feeder, which includes 12 transformer substations (TS).

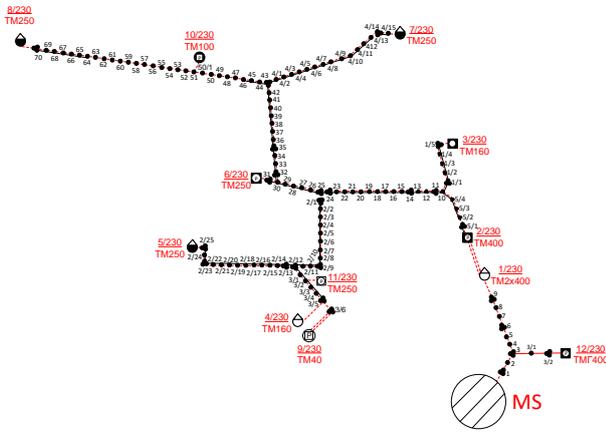Feeder scheme is shown in Figure 4.

Fig. 4. 10 kV Feeder Scheme.

The detailed description of the network settings, IEDs, current and voltage metering transformers, as well as data acquisition and processing circuitry are given in [12].

June 17, 2016 from 15:40 to 16:20, a full-scale experiment was carried out to test the efficiency and accuracy of the proposed method. At 15:45, an additional load (ADL) was cut in the TP-6 transformer. A fan heater with a nameplate capacity of 1800 W was used as a load. In order to model the "bad" current metering, the ADL connection was set prior to the current transformer that supplies a signal to the IED. To further assess the estimated accuracy of the proposed method, the measurement of the active power of the load was performed with an additional IED. At 16:15 this loading was cut off. Currents and voltages phasors for the fundamental wave measured synchronously every 10 minutes in the interval of one period were transmitted to AMR data collection server via GSM modems. Active power values, calculated under those phasors data for the direct sequence are shown in Table 2.

Table 3 shows the MS' active power and TS' load estimated values produced with the proposed method under the measured voltage phasors and the network's equivalent circuit parameters for the direct sequence.

Table 4 shows a comparison of the estimated and measured TS6 active power loads.

Table 2. Active Power Values Calculated Under the IED Measured Current and Voltage Data (P_{msrd}), kW.

	15:40	15:50	16:00	16:10	16:20
MS	-766,58	-783,04	-768,03	-772,45	-824,71
TS1	0,02	0,02	1,79	0,02	0,02
TS2	88,51	85,08	94,59	85,34	98,03
TS3	64,22	64,45	71,11	64,54	74,14
TS4	4,58	1,70	1,65	1,85	2,01
TS5	64,50	58,70	59,66	74,36	69,59
TS6 ADL	138,50 0	137,86 1,62	129,58 1,67	137,92 1,23	145,72 0
TS7	188,52	192,78	189,40	181,79	200,59
TS8	141,90	160,30	149,62	151,36	153,47
TS9	2,44	2,22	2,41	1,23	1,54
TS10	41,88	47,00	38,55	45,93	48,01
TS11	5,56	4,55	2,30	2,22	3,46
TS12	3,79	3,74	3,21	2,46	3,72

Table 3. Active Power Estimated Values (P_{estmd}), kW.

	15:40	15:50	16:00	16:10	16:20
MS	-752,44	-769,44	-755,65	-759,61	-810,66
TS1	-1,82	-1,72	-0,34	-1,82	-1,74
TS2	88,27	84,96	94,21	85,04	97,66
TS3	63,32	63,65	70,33	63,70	73,39
TS4	2,62	-1,36	-1,64	-1,49	-1,04
TS5	62,97	57,88	58,54	72,44	68,39
TS6	138,34	139,32	131,43	139,03	145,29
TS7	186,77	190,85	187,61	180,16	198,07
TS8	142,21	160,72	150,17	151,62	154,26
TS9	1,78	1,65	1,76	0,96	1,24
TS10	42,32	47,55	39,20	46,44	48,66
TS11	1,71	1,25	0,72	0,77	0,98
TS12	2,48	2,47	2,03	1,04	2,38

Table 4. Estimated and Measured TS 6 Active Power Loads Comparison.

	15:40	15:50	16:00	16:10	16:20
$P_{estmd} - P_{msrd}$, kW	-0,16	1,46	1,85	1,11	-0,43
$\dfrac{P_{estmd} - P_{msrd}}{P_{msrd} + P_{adl}}$, %	-0,12	1,05	1,41	0,80	-0,30
$\dfrac{P_{estmd} - P_{msrd}}{P_{adl}}$, %	-	-9,88	10,78	-9,76	-

The following can be drawn from the results shown in Table 4:

1. The measured and estimated loads vary by less than 0.5 kW in the points of ADL absence (15:40 and 16:20).

2. The difference between the measured and estimated loads exceeds 1 kW in the points of ADL presence (15:50, 16:00 and 16:10.).

Thus, if the value of power in the range from 0.5kW to

1 kW is set as a boundary value of difference between the "good" data and the "bad" data, then the TS-6 measurements taken at 15:50 to 16:10 can be classified as "bad" under the proposed method. This conforms to the conditions of the experiment and confirms the efficiency of the proposed method.

A more detailed data comparison given in Tables 2 and Table 3 shows that the "bad" data is identified in TP5 with the method proposed. Registration system test (of the metering circuit) on this substation detected the presence of an additional load connected prior to the current transformer transmitting a signal to the IED. A cellular telecommunication station acted as such a load.

A further increase in the accuracy of the proposed method is possible with due regard for the effect of temperature on the resistive impedance of lines' sections and transformer windings; more precise modeling of power transformers and the error reduction of metering current and voltage transformers.

VI. CONCLUSION

1. A new method has been proposed for the detection of bad power measurements, based on use of synchronized measurements of voltage and a current's phasors and the assumption that more often a consumer has an effect on the current circuits of measuring devices, and rather seldom on their voltage circuits.

2. It has been s shown that the availability of voltage phasors measurements at consumers and in the main substation is a sufficient condition to calculate the mode of arbitrary configuration circuit (network) with the known topology and passive parameters of lines. The differences between the calculated and measured nodal power capacities define the values of non-technical losses for each network node.

3. To improve reliability and accuracy of the method it has been proposed to use the instrument for the state estimation theory and the recursive algorithm to identify good measurements of currents' phasors and of nodes' voltage phasors.

4. The experimental studies on alternating current test bed have shown that when NI 9225 and NI 9227 measurement units are employed, the error in the detection of the bad power measurements via the proposed method in a single-phase two-line main network does not exceed 1.2 %.

5. The experimental studies with a 10 kV real-life feeder have confirmed the efficiency of the method proposed. The error of non-technical losses localization has not exceeded 11% at the maximum relative power capacity of TS' unaccounted load equal to 1.41%.

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