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Monitoring large-scale power distribution grids

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ABSTRACT

Power grids are distributed over vast geographical areas and have sophisticated multilayered architecture. The structure of the grid distribution layer is often poorly documented and sometimes unknown, presenting additional challenges to the development of systems for automated monitoring of power delivery to consumers.

The proposed system performs the simultaneous functions of estimating the power grid topology (map) and monitoring of the grid operation. The core of the system is the distributed network of sensors installed at the branching points of electrical conductors. The sensors periodically measure the RMS current in the conductor, and the phase shift between current and voltage. Localization and time synchronization of sensors are performed using GPS modules. The sensors communicate over the powerline conductor. Transformers block communication signals, separating the network into clusters. The maps of the grid segments are reconstructed for each network cluster and then combined into the full grid map. The map is used for real-time monitoring of inconsistencies in the grid behavior to detect conductor breakage, powerline overload and possibly electricity theft. The autonomous sensors are inductively powered; auxiliary solar cells are installed as backup power source.

1. Introduction

Smart electrical power distribution grids represent rapidly developing field. When implemented, smart grids will provide more efficient transmission of energy, quick restoration of power after breakdown, smooth integration of renewable energy sources, and reduced cost of management and operation for utility companies. Achieving those benefits is possible only if there exists a developed system for real-time monitoring of the grid. Monitoring of energy flows in the grid becomes particularly important as the role of distributed energy production from renewable sources (e.g. solar and wind power generation stations) is continuously increasing, contributing to complexity of the network. A monitoring system must collect, store and process the detailed information on the grid operation. The results of processing are used for control and management of the grid: some of the control functions may be automated, some functions are performed by human operators.

Currently, grid monitoring is implemented in high voltage transmission layers of the grid. The monitoring is performed by using expensive sensors, which require complicated installation procedures and use dedicated data transmission channels. Several manufacturers are offering such sensors. For example, the sensors manufactured by Aclara/Tollgrade Inc., are designed for monitoring medium voltage powerlines, with voltage in the range from 4 KV to 46 KV and current ranging from 0 to 17,000 RMS amperes. The sensor options include cellular and Wi-Fi communication modules. The sensor is powered by energy, harvested from electromagnetic field of the host conductor, with minimum operation current as low as 3 A. Sensor installation requires ground connection for monitoring the line voltage. Similar sensors are manufactured by GE, Cooper Power Systems, and Sentient.

Unfortunately, the existing technology is not suitable for monitoring local distribution layers of the network. The typical distribution layer represents a complicated system of interconnected conductors, connecting large number of individual consumers to transmission layer of the network. Detailed monitoring of such a system requires large number of inexpensive sensors. The cost and complexity of installation of the sensors is also important: the sensors should be installed without disconnecting the line voltage. This is possible only if there is no galvanic connection between sensors and the powerline. For example, the sensor can be “snapped” around the powerline conductor on top of the insulation. Such method of installation limits the monitoring capabilities of the sensor: all the monitored parameters should be estimated by analyzing the alternating electromagnetic field around the conductor. Current technology allows to equip each sensor with inexpensive and accurate GPS module, which determines location of each sensor, as well as allows global time synchronization of all sensors.

Organization of the sensor network is also important. Most of the proposed monitoring systems are based on wireless ad-hoc networks, in which sensors autonomously determine optimal paths for delivery of

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packets to nearest Ethernet connected hub. Another common option is to install a network Ethernet connected communication modules along the path of power distribution, with each module communicating to one or several sensors, located in its vicinity. The overview of wireless networks for grid monitoring may be found in [1]. Some existing solutions are using cellular networks to communicate the collected data to the central server. An example of such network for monitoring long distance transmission lines is presented in [2]. In this network, sensors, installed on a single support form a cluster and communicate wirelessly within the cluster. Only one sensor in the cluster, equipped with a cellular network modem, transmits integrated data from the whole cluster. Applications of wireless communication technology for grid monitoring may be found in [3].

Harvesting of energy from stray electromagnetic field around the powerline for application in smart grid sensors is well known in the industry. The discussion of inductive and capacitive power harvesters may be found in [4] and [5]. We use inductive energy harvesting as the main source of power for the sensor. The sensor is also equipped with auxiliary solar cells, for emergency operation during prolonged powerline failure

In this paper we discuss aspects of implementation of a system for monitoring of distribution layer of the grid. In Section 1 we describe the proposed method for grid monitoring. The method is based on measurement of real-time parameters of ac current in branches of the network, and subsequently using those parameters to estimate the topology of the network and monitor the network integrity. The GPS location information may be used together with the estimated topology to create geographical map of the network. In Section 2 we discuss the design of sensors. The method of measurement of amplitude and phase of ac current in a conductor, as well as the direction of energy flow, using stray electromagnetic field around the conductor is discussed. We also explore power harvesting options, useful for long-term autonomous operation of the sensor. The deployed sensors are self-organized into a network for communication and transmission of collected data. The architecture of the network is discussed in Section 3. The sensors are using the carrying conductor as the primary communication medium. We propose a method for clusterization of the network, reducing the communication load and simplifying data collection. In Section 4 we discuss the methods for collecting and processing of data from the sensor network. The method for estimation of grid topology and generation of the grid map is outlined. The approach to grid monitoring for detection and diagnostics of power outages, and detection of electricity theft is discussed.

2. Principles of power grid monitoring

Monitoring of smart power grid requires real-time acquisition of complete information about power flow in all branches of the network. Collecting data from local distribution grids is complicated by the fact that the topology of such grids is often unknown and orderly planning of the sensor network is rarely possible. This can be mitigated by deployment of dense sensor network, which collects sufficient information to recover the topology and build the map of the grid. The implementation of dense sensor network requires collection and processing of large quantities of real-time data. Collection of such amount of data is possible only if the communication channel is properly organized. Our method for grid monitoring employs a dense network of inexpensive sensors installed at each branching point of the powerline. This network is split into clusters so that sensors within each cluster communicate by sending high-frequency signals over the powerlineconductors.

The architecture of the distribution grid is shown in Fig. 1. The grid consists of conductors, electrically connected via step-down transformers to the conductors of upper layers. The conductors of the lowest layer are terminated with transformers, converting line medium voltage to low voltage, distributed to individual consumers. The sensor network is using powerline as the communication medium. The powerline communication is using frequencies in the range 150–500 kHz, which is much higher than powerline frequency 60 Hz. Due to high impedance of step-down transformers to communication carrier frequencies, communication between sensors installed on different conductors becomes impossible. Therefore, we can consider the sensor network to be separated into clusters, with the sensors installed on the same conductor belonging to the same cluster. The sensors may easily self-organize into clusters at the time of installation by identifying themselves to the network.

The most complete data on the grid may be obtained by installing sensors around each branching point. A segment of a grid conductor with two branching points and installed sensors are shown in Fig. 2. Each sensor is measuring several parameters that include RMS of the current in the conductor, phase of current with respect to global synchronization pulse and phase shift between voltage and current. The estimated phase shift between current and voltage may be used to determine the direction of energy flow through the conductor.

The principles of measurement of phase shift are demonstrated in Fig. 3. Phase shift is computed as difference between the times of zero crossing for current *I(t)* and voltage *V(t)* signals (see Fig. 3a). The precision of measurement of phase shift is limited by the accuracy of detection of zero crossing. Since voltage signal is noisy, phase shift may be estimated with any reasonable precision by averaging the results of many measurements. More accurate estimation of phase of current *I(t)* may be obtained by measuring time between global synchronization pulse and the point of zero crossing of *I(t)* (see Fig. 3b). Global synchronization pulse is generated by GPS modules in all sensors of the network simultaneously. Therefore, the phases of *I(t)* measured by each sensor may be used to accurately analyze phase shifts of current between any branches in the grid.

The method of grid monitoring is based on verifying match between currents at branching nodes using Kirchhoff's Current Law (KCL), which may be written in the phasor form as follows

$$\sum_i I_i e^{j\phi_i} = 0$$

where I_i and ϕ_i are the magnitude and phase of the current flowing into the node from the i-th branch. Verification of KCL for each node will indicate integrity of the grid. The currents may also be monitored over time, and the phasors of branch currents may also be compared with those measured by sensors installed at the other nodes of the network. The consistent match between currents reported by sensors indicates that those sensors are installed on the same branch of the network. If two sensors that belong to the same branch are located around two distinct nodes, it may be considered that the branch is connecting those two nodes. This principle, applied to the whole network, may be used to estimate the grid topology.

3. Design of sensors

The proposed monitoring method requires installation of a large number of sensors. The sensors must satisfy the following requirements:

- Low cost of manufacturing. Availability of inexpensive sensors facilitates deployment of large and dense sensor networks.
- Inexpensive installation. The sensors must employ contactless sensing technologies for measuring the electrical parameters. Then sensors could be "snapped" around electrical wires on top of the insulation: the installation will take seconds and will not require disconnecting the line power.
- Autonomous operation. Sensors must be designed for long term operation without maintenance, harvesting the necessary energy from magnetic field surrounding the host conductor. Some sensors may be equipped with optional solar elements for smooth operation during power outages. Periodic firmware updates should be

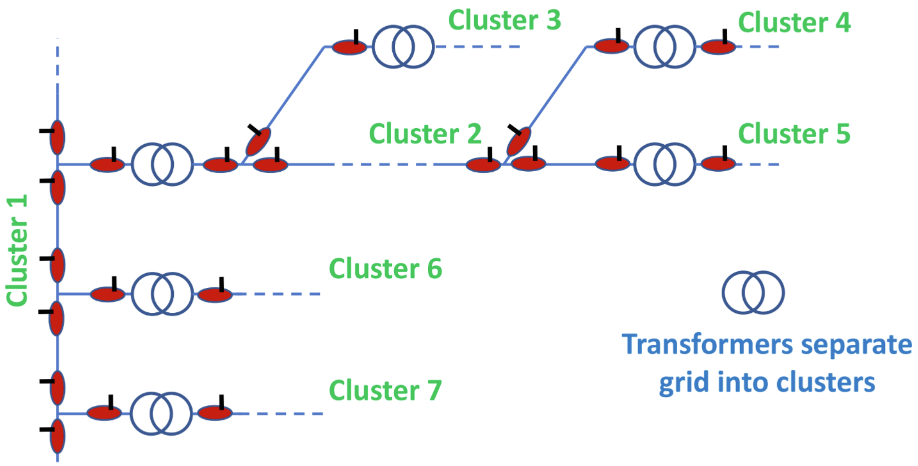

Fig. 1. Distributions layers of the power grid represent the set of conductors, electrically connected by transformers. Due to the high impedance of the transformers to communication signals, the sensors are naturally separated into clusters, composed of the sensors installed on single-line branched conductor.

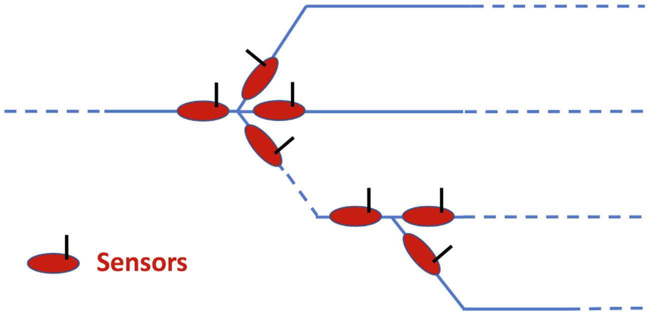

Fig. 2. The sensors are installed around each branching point (node) of the conductor and monitor the RMS and the phase of incoming and outgoing currents.

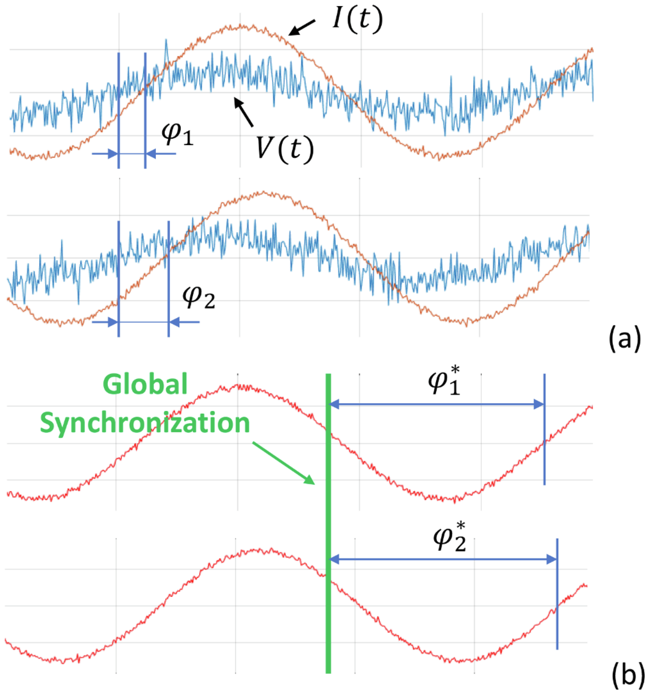

Fig. 3. Illustration of two options for measurement of the phase of current *I(t)*. The phase can be measured with respect to the phase of voltage signal *V(t)* (blue curve) (a) or global synchronization pulse (b) provided by GPS. Due to significant amount of noise in voltage signal, using global synchronization provides better accuracy of measurement. (Plotted data are obtained by simulation.) Multiple measurements of the phase of voltage signal are repeated continuously for improving the accuracy by averaging and for tracing its time variation. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

performed remotely, without physical access to the sensor.

- Robust communication features. Installation can be greatly simplified, if sensors will automatically connect to communication network by using host conductor as communication medium. Each segment of the network must contain dedicated Communication Units (at least one per conductor), which collect data from sensors and wirelessly transmit them to the remote server for processing. Sensors are also equipped with auxiliary wireless communication modules, used when data packets cannot be delivered over the powerline.

In order to satisfy those requirements, the sensor should implement non-destructive sensing technology: all the parameters should be measured without galvanic connection to the power line. The parameters include RMS value and phase of current in the conductor, and shift between phases of current and voltage at the point of measurement.

Measurement of RMS value and phase of current is performed non-destructively by observing changes in electromagnetic field around the host conductor. This may be achieved by installing Hall sensor in the vicinity of the conductor (see Fig. 4). The Hall sensor is installed at known distance from the surface of the conductor. When the AC current is flowing in the conductor, the variable voltage with proportional to instant value of the current, is observed at the output of the sensor. RMS of the conductor current may be estimated from measured RMS of the voltage. Since Hall sensor introduces very low angle delay, the phase of its output voltage is very close to the true phase of the conductor current. Therefore, the phase of the Hall sensor voltage may be used as an accurate estimate of the current phase.

Line voltage is difficult to measure accurately without connecting to the powerline. Therefore, our sensor is limited to measuring the phase of the voltage. The sensor is equipped with capacitive sensor, generating the variable voltage, proportional to change of the electric field around the conductor (see Fig. 5). Since change of the electric field is proportional to the derivative of line voltage, the output of the capacitive sensor may be used to estimate the phase of the voltage. The output voltage of the capacitive sensor being noisy, accurate estimation of its phase is possible only by averaging over large number of measurements.

The signal representing AC line voltage, obtained from the capacitive sensor, is too noisy to serve as reliable reference for measurement

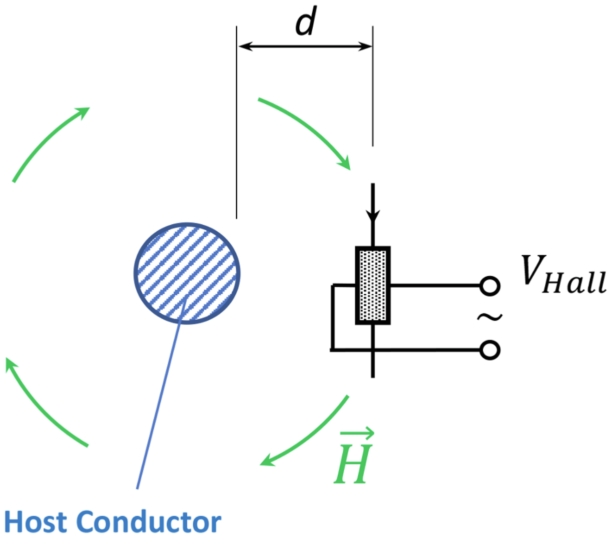

Fig. 4. Non-destructive measurement of current *I(t)* in the host conductor using Hall sensor. The sensor is installed at known distance *d* from the surface of the conductor. Variable magnetic field *H(t)* is causing voltage $V_{Hall}(t)$ at the output of the sensor, that is proportional to current *I(t)*.

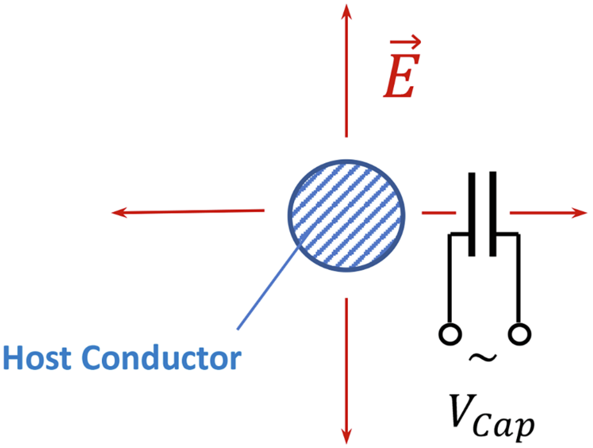

Fig. 5. Non-destructive measurement of voltage V*(t)* in the host conductor using capacitive sensor. The sensor is installed at known distance *l* from the surface of the conductor. Variable electric field *E(t)* is causing voltage $V_{Cap}(t)$ at the output of the sensor, that is proportional to the voltage *V(t)*.

of the phase of the line current. We are measuring the phases of line current and voltage as phase angles between the global synchronization pulse and the points of zero crossing. The principle of measurement of phase is demonstrated for line current in Fig. 3(b). Global synchronization pulse is produced by GPS simultaneously in all sensors of the network and serves as reliable reference for accurate phase measurement. If a sensor is installed at the location where GPS signal is weak and global synchronization pulse is not received, the sensor is switched to the mode of direct measurement of phase shift between current and voltage.

Block diagram of the sensor is shown in Fig. 6. The sensor is powered by energy, harvested from electromagnetic field around the host conductor. The harvester is based on the ferrite split core. As a sensor clamps on the host conductor, the halves of the core connect. The core with the winding around its lower half acts as a current transformer. The power collected by the transformer depends on the current in the host conductor. The sensor is implementing smart power management scheme: the mode of operation is selected depending on available power. The sensors placed on the root lines, constantly carrying significant current, collect and communicate data more frequently and are more likely to be used as gateways to retransmit wireless data from disconnected segments of the network (e.g. in case of power failure). The excess power is stored in the rechargeable battery for use in case of dramatic decrease of current in the host conductor or powerline failure. Each sensor is equipped with auxiliary solar cells for emergency operation during long-term power outage, when current in the host conductor is very low or non-existent.

Powerline communication is performed by injecting current in the powerline using high-frequency current transformer.

4. Architecture of the sensor network

The architecture of the network is designed to provide optimal throughput of communication channel for collection of measurement data. The sensors are using powerline as the preferable medium for communication. Individual conductors of the grid are separated from each other for communication signal and may be considered as clusters or segments of the grid. The sensors installed on one segment may communicate to each other, but they are isolated from sensors of other segments by high impedance of the transformers. Each cluster contains at least one dedicated Communication Unit (CU), which is equipped with wireless or wired interface (GPRS, Wi-Fi, Ethernet etc.), and acts as interface between the powerline network and the external Processing Server (PS). Multiple CUs may be installed in the same cluster for improved reliability. Since only a few CUs are required for monitoring of the grid, they could be powered from the grid and equipped with large processing capabilities. The typical block diagram of the network cluster is shown in Fig. 7.

The network is designed to self-organize into clusters. If additional CU is installed on one segment of the grid, the system can automatically assign it to an existing cluster, since it will communicate over the powerline to already existing CU. The sensors are also assigned to one of the clusters at the time of installation: the sensor identifies itself to the network by sending its ID, which is received by cluster CU(s). The sensor also receives and stores ID(s) of CU(s) of the cluster to which it communicates.

Each sensor is equipped with auxiliary wireless communication unit. If CU is not accessible, the sensor attempts to communicate with sensors or CUs of neighboring clusters. This situation may arise if the sensor was installed on the grid segment which does not contain CU, the existing cluster CU malfunctions or the powerline is damaged. For example, the sensors installed on short segments, running from a step-down transformer to a few houses, will form a small cluster, which does not justify installation of a separate CU. Those sensors may share the CU of the upper-level cluster by periodically reporting their measurements wirelessly across the transformer to sensors of the upper-level cluster. The data is then retransmitted to CU(s) of the upper-level cluster over the powerline.

If sensors are cut off from the CU due to CU failure or powerline damage, they attempt to communicate wirelessly with sensors from other clusters that have access to CU. If a sensor in cut-off segment succeeds, then the wireless communication link is established between the cut-off segment and the other segment. This link is used to transfer acquired data to the accessible CU and then to central PS. Such mode of operation is intended to be temporary, and may quickly drain the batteries of the sensors, transferring data between two segments. Therefore, only the data, which is necessary for diagnostic of the grid malfunction, should be transmitted by the sensors of the cut-off segment.

5. Sensor data collection and processing; grid topology estimation

Sensors are performing periodic synchronous measurements of RMS value, differences in phases of current and voltage at the point of measurement, as well as the phase of current with respect with global

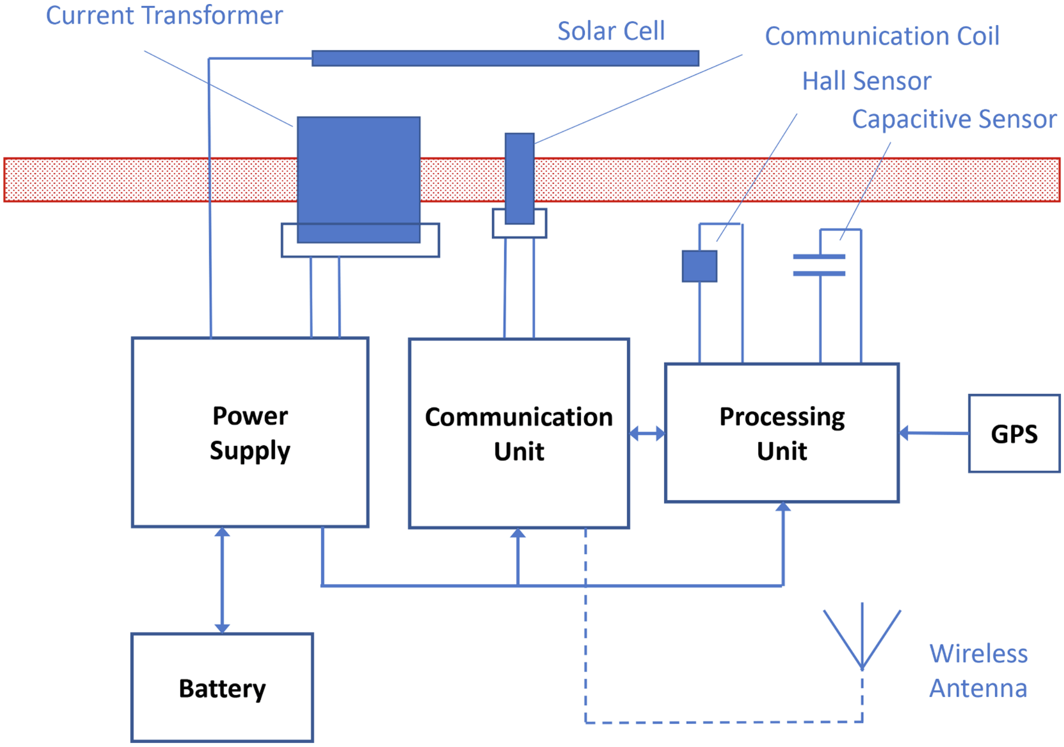

Fig. 6. Block diagram of the sensor. The sensor is using Hall and Capacitive Sensor to measure characteristics of current and voltage in the host conductor. GPS data is used for global synchronization of measurements. GPS also provides location of the sensor, used for grid map estimation. The Communication Unit is sending the processed measurement data over the powerline (Communication Coil). In case of powerline failure, the sensor may attempt to establish communication via wireless interface (Wireless Antenna). The sensor is powered by energy, harvested from the magnetic field around the host conductor (Current Transformer). The excess energy is stored in the rechargeable Battery. Auxiliary Solar Cells are used to replenish the Battery in case of long-term powerline failure.

synchronization impulse. Synchronization of measurements is achieved by using the GPS time. The results of measurements are then transmitted by the sensors over the powerline conductor to CU. The data is transmitted in the form of packets. The communication throughput may be improved by combining the results of multiple measurements by the sensor in one packet. Since the consecutively acquired data points from the same sensor are likely to be correlated, compression of data may reduce the total amount of transmitted data. Each measurement should be marked by the time stamp that indicates the time of data acquisition. If multiple periodically obtained data points are combined in one packet, only one timestamp for the first data point may be included in the packet. In this case, time for the remaining data points may be computed from time stamp of the first data point and known period between measurements. The data from all sensors that belong to one cluster are collected by CU, which converts data to the form, suitable for transmission to PS, and performs data transfer using suitable communication method, such as Ethernet, Wi-Fi and cellular wireless network. The communication method is selected based on the facilities available at the location of CU installation, taking into account cost of installation and data transfer fees. Depending on implementation, CU may also perform data preprocessing, including cluster map generation or validation of the existing cluster map, thus reducing the computational load on PS.

In the computer description of the cluster map, the connections between the branching points of a conductor, which is carrying the sensors that belong to one cluster, are performed using the data on RMS values and phases of current synchronously measured by all the sensors in the cluster and GPS coordinates of those sensors. The method designates one sensor of the cluster, which is installed on the conductor at the location where it is connected to the output of the step-down transformer, as the 'root' sensor. The computation procedure starts from the 'root' sensor and attempts to find a sensor or a combination of sensors, such that the current or the sum of currents reported by those sensors is equal to the current reported by the 'root' sensor. The currents should be added according to Kirchhoff Current Law (KCL), taking into account the synchronously measured phase of each current. Such sensor or a group of sensors is assumed to be directly connected to the 'root' sensor. To reduce the complexity of computations during search of connected sensors, the geographical area can be limited to the vicinity of the 'root' sensor by using GPS coordinates of the sensors. The same procedure is iteratively repeated for all the sensors, connected to the 'root' sensor, and then continued until connections for all sensors in the cluster are found. Since the accuracy of current measurements is limited, the first generated map may be only an estimate, and the

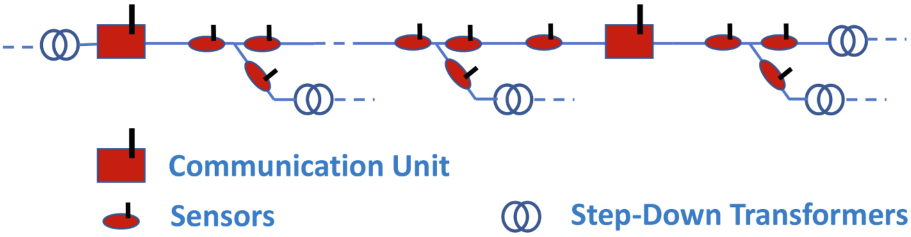

Fig. 7. Architecture of a cluster of the sensor network. Each cluster consists of sensors installed on the same host conductor. The sensors are using powerline communication to transmit data. The cluster contains at least one Communication Unit (CU), which collects data from sensors of the cluster and transmits it to remote Processing Server. Additional CUs may be installed to improve reliability of communication.

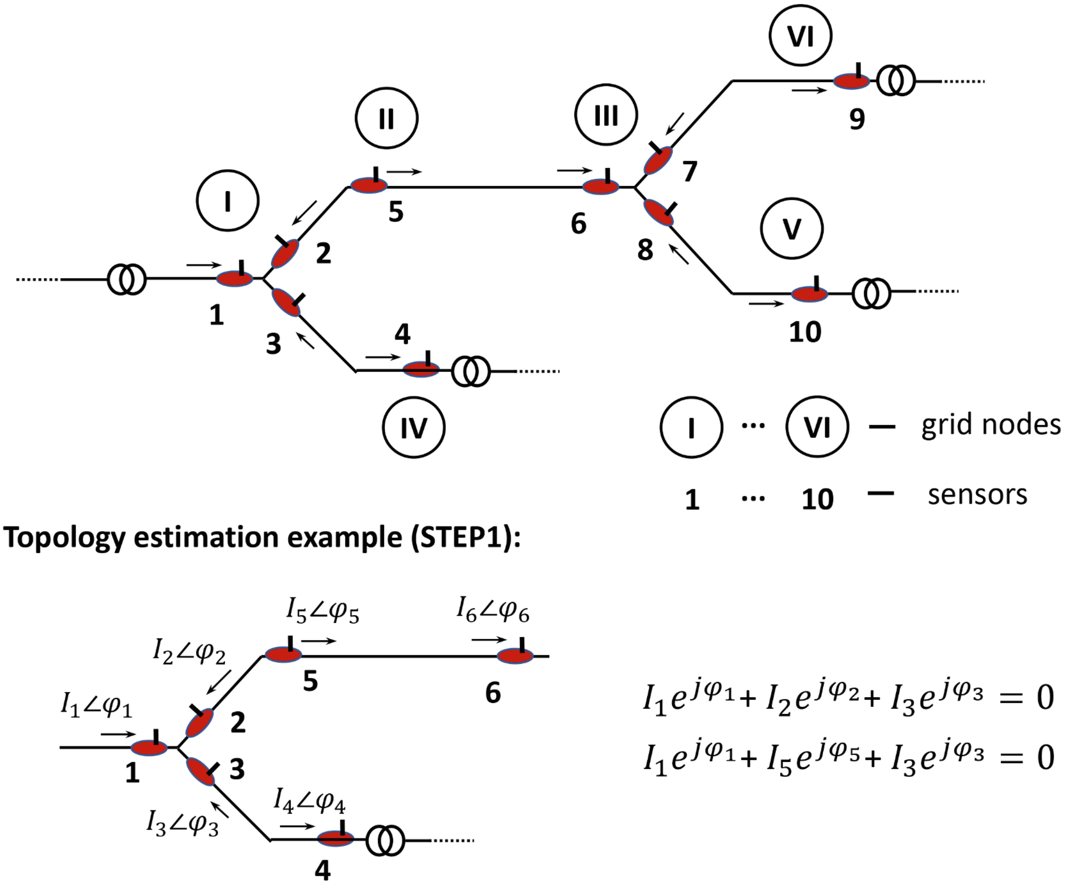

Fig. 8. Illustration of the cluster topology estimation and the generation of cluster map. The sensors are installed according to the following rules: if the sensors are installed at the branching node, the positive direction of current (used in writing the Kirchhoff's Current Law, shown by arrows) is always towards the node (sensors 1,2 and 3 at node I, sensors 6,7,8 at node III); if the sensor is installed at the transformer, the positive direction of current is always towards the transformer (sensors 4, 9 and 10), unless the sensor is at the branching node (sensor 1); if a sensor installed in the middle of the conductor, the direction of current may be selected arbitrarily (sensor 5). Sensor 1 is located at the point of connection to upper-level conductor of the network and designated as the 'root' sensor of the cluster.

procedure should be repeated multiple times with different distribution of currents, until accurate network map is generated.

The computation procedure is illustrated using simple, but non-trivial network, shown in Fig. 8. The network consists of 6 nodes, numbered from I to VI, and contains 10 sensors, numbered from 1 to 10. The arrows next to sensors are showing sensor orientation, which is used when writing KCL equations. The sensors are always installed according to the following rules: sensors placed at the split node are pointing towards the node; sensors at the load are pointing towards the load, unless those sensors are at the split node; single sensors installed on a wire could be arbitrarily oriented. The topology estimation starts from Sensor 1, which is placed at the 'root' of the network. An example of numerical information obtained from the sensors is shown in Table 1.

Table 1
Exemplary data, collected from the sensors of the network illustrated in Fig. 8.

Sensor	Current (Magnitude)	Current (Phase)	Geographical Coordinates (X,Y)
#1 (root)	43.2064	4.8275°	(1, 10)
#2	28.9963	177.0461°	(2, 12)
#3	15	−160°	(2, 8)
#4 (load)	15	20°	(3, 6)
#5	28.9963	177.0461°	(3, 14)
#6	28.9963	−2.9539°	(5, 14)
#7	17	−170°	(6, 16)
#8	13	160°	(6, 12)
#9 (load)	17	10°	(7, 17)
#10 (load)	13	−20°	(7, 10)

The information consists of the sensor number (sensor ID), magnitude and phase of current and coordinates of the sensor (GPS coordinates). For this simulation, the table was generated by selecting arbitrary current magnitude and phase values at each load, and then computing the remaining currents using the diagram in Fig. 8.

Initially, the topology estimation algorithm does not have information on connection within the network or which sensors are placed at the loads. The only available data includes the location of 'root' sensor, the values of currents measured by all sensors and the coordinates of all sensors. In the following discussion we will denote the magnitude of current measured by the i-th sensor as I_i, phase of the current as ϕ_i and the coordinates as (x_i, y_i). The topology estimation algorithm will execute the following steps:

1. The system starts at the 'root' Sensor #1 and attempts to find a set of sensors that includes Sensor 1, such that KCL is satisfied. In the following example, we will write the magnitude and phase of the currents in the phasor format: $I_i\angle\phi_i$, where I_i represents the magnitude of current and ϕ_i represents the phase of current measured by i-th sensor. The current measured by Sensor #1 can be found from the table in Table 1 as $43.2064\angle 4.8275°$. The algorithm explores two possibilities. Sensor #1 can be installed at the transformer and connected to the next sensor by the conductor without splitting. In this case, the next sensor will measure the same current, but, since its orientation is unknown, the phase may be shifted by 180°. The algorithm is checking the table to see whether there is any other sensor that reported current $43.2064\angle 4.8275°$ or 180° shifted current $43.2064\angle -175.1725°$. Quick verification of Table 1 shows that there

is no such sensor. Then the algorithm explores the second possibility, that the sensor is installed at the split node. Since the sensors on the split node are always oriented towards, the node, the following KCL equation must hold:

$$I_1 e^{j\phi_1} + \sum_i I_i e^{j\phi_i} = 0$$

Expanding exponential as $e^{j\phi_i} = \cos\phi_i + j\sin\phi_i$ yields

$$I_1 \cos\phi_1 = -\sum_i I_i \cos\phi_i$$
$$I_1 \sin\phi_1 = -\sum_i I_i \sin\phi_i$$

By trying combinations of currents from the table, it could be found that the following combinations of sensors satisfy the above equations:

Combination 1: Sensor #2 and Sensor #3
Combination 2: Sensor #5 and Sensor #3

In order to decide which combination to select, the algorithm is computing the sum of distances from Sensor #1 to all the sensors in the combination. The distance to sensors in Combination 1:

$$D_1 = d_{12} + d_{13}$$

$$d_{ij} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2}$$

and the distance to sensors in Combination 2:

$$D_2 = d_{15} + d_{13}$$

Substituting numerical values yields $D_1 = 4.47$ and $D_2 = 6.71$. The Combination 1 that consists of the sensors with closest geographical location is selected.

It is recorded that Sensors #1, #2 and #3 are located at the split node. The algorithm marks those sensors as already connected and does not use them in further search.

2. Search for the combination of connected sensors containing Sensor #3. The search is also performed in two stages. First, a single sensor that reported the same current as Sensor #3, $15\angle -160^\circ$ or the current $15\angle 20^\circ$, which is shifted by 1800. The search of the table of currents shows that Sensor #4 reported the current $15\angle 20^\circ$, which means that those sensors are installed on the same conductor but oriented in opposite direction. Sensor #4 is marked as connected.
3. Search for possible connections for Sensor #4 returns negative result, so Sensor #4 is marked as located at the node.
4. Search for the connections for Sensor #2 is performed. Sensor #2 reported the current $28.9963\angle 177.0461^\circ$. The table is searched for the identical current, or the current $28.9963\angle -2.9539^\circ$, which is shifted by 1800. Searching through the table, the algorithm finds two possible connections: Sensor #5 returning identical current, and Sensor #6 returning the current shifted by 1800. The closest sensor is selected. The distance between Sensor #2 and Sensor #5 $d_{25} = 2.24$ and the distance between Sensor #2 and Sensor #6 is $d_{26} = 3.61$. The Sensor #5 is selected as the closest and is marked as already connected.
5. Search for the connections for Sensor #5 is performed. Searching the table shows, that Sensor #6 returned the same current as Sensor #5 but shifted by 1800. Since this is the only matching result, the connection between Sensor#5 and Sensor #6 is recorded, and Sensor #6 is marked as already connected.
6. Search for the connections for Sensor #6 is performed. The search for sensors that reported identical or 1800-shifted current fails. Then the option, that the Sensor #6 is placed at the split node is explored. The search returned that for currents reported by Sensor#7 and Sensor #8 the KCL holds. Since there are no other combinations, it is recorded that Sensors #6, #7 and #8 are located at the split node. The sensors are marked as already connected.
7. Similarly, Sensor #9 returns the same, but 1800-shifted current as Sensor #7, so the connection between those sensors is recorded.
8. Sensor #10 returns the same, but 1800-shifted current as Sensor #8, so the connection between those sensors is recorded.

As a result of this algorithm, the graph of connections between all the sensors is created. This establishes the network topology. Plotting the graph of connections on a geographical map will give the map of the cluster. The maps of multiple connected clusters are joined to obtain the map of the distribution grid.

The presented algorithm may be directly applied to grid configurations represented as a tree graph. Some grid configurations may include loops, i.e. there may exist multiple paths from the root to some nodes. The algorithm may be adapted to work with loops at the expense of computational complexity by including already connected sensors in search if appropriate combination of unconnected sensors cannot be found. Reliability of the network is an important issue. The presented algorithm will succeed in estimating the grid map if some sensors in the dense network fail or produce inaccurate readings. For example, if Sensor #8 fails, the algorithm will establish connections between Sensors #6, #7 and #10.

In some cases, installation of dense sensor network may be unfeasible. In this case, different algorithm for grid reconstruction may be implemented, based on analysis of correlations between variations of currents measured by sensors. For example, let us assume that Sensors #6, #7 and #8 are not installed (or failed). Then, variations of currents measured by Sensors #9 and #10 are uncorrelated: it is highly unlikely that two homeowners will synchronously flip light switches on consistent basis. At the same time, variations of currents registered by each of the Sensors #9 and #10 is correlated with readings from Sensor #5. The correlations indicate existence of connections between Sensors #5 and #9, and Sensors #5 and #10. The algorithm based on correlations will successfully recover approximate grid map if sensor network is not dense (or even sparse). The accuracy of the map improves as additional sensors are installed. It is also expected that analysis of correlations is not influenced by inaccuracies in current and phase measurements, since in most practical cases of biased, incorrectly scaled or noisy data, the relationships between correlations will be preserved. In the rare case of meaningless data readings due to sensor failure, all data from the sensor may be completely ignored during the analysis.

6. Monitoring the grid operation

The constructed map may be used for monitoring of the grid. Power outages may be quickly detected by monitoring connectivity between branches of the grid. Damage to line conductors may be detected by monitoring the currents in the network and comparing the results with nominal values. Severe damage, such as short circuit or line breakage, is instantly detected as loss of powerline communication between sensors of the cluster (see Fig. 9). The precise location of the breakage may be accurately and instantly pinpointed by determining the number and locations of separated sensors. The conductors, connecting separated segments of the grid are considered damaged, and repair crews are directed to precise locations.

Detection of electricity theft is an important problem in the field of grid monitoring. The described network allows to perform monitoring 'true' power consumption in all branches of the grid independently from residential power meters. The data collected from the network may be compared to the data reported by the meters. The systematic discrepancy between 'true' and reported data indicates possible theft of electricity or damaged power meter. Further investigation may be initiated to find the reason for excessive power consumption. Unauthorized taps into the powerline may be detected by verifying KCL for all nodes of the network. Suspicious branches of the grid may be detected by comparing power consumption and supply data. The precise location of tap-in may be pinpointed by finding violations of KCL around the individual grid nodes.

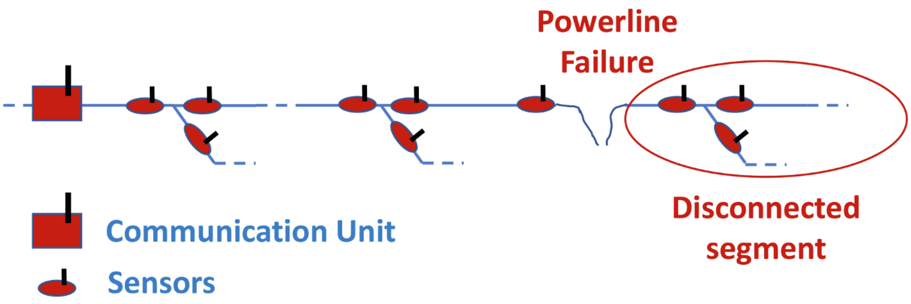

Fig. 9. Detection of powerline failure. The location of powerline failure may be detected by analyzing connectivity between sensors. Sensors are capable of communicating over the powerline between each other inside the disconnected segment, but they need to use auxiliary wireless module to reach the Communication Node.

7. Conclusion

In the paper we presented the architecture of a monitoring system for application in Smart Grids. The modern power distribution grids are increasingly employing distributed generation of electricity: substantial part of electricity is generated locally by the consumers using solar, wind and other sources. In such grid, accurate real-time monitoring of all elements of the system becomes increasingly important. The proposed novel architecture is employing a dense network of sensors for collecting real-time data about the state of the network. Monitoring on every element of the grid is achieved by using autonomous inexpensive sensors, which could be installed in large quantities to form dense network. The sensor design must provide capability of autonomous operation over the lifecycle. This may be achieved by using energy harvesting for powering the sensors and flexible communication capabilities for ad-hoc organization of sensors in the network, which is used to transfer the monitoring data from the sensors to the Processing Server, as well as to remotely control the sensors and update sensor firmware. The communication medium is optimally selected by the sensors, which give preference to communication over the powerline, switching to wireless communication only when necessary. The maximum utilization of communication over powerline allows to minimize power consumption and used wireless bandwidth.

The cost of sensor installation may be substantially lowered by using non-destructive sensing technologies for measurement of the grid parameters. Non-destructive measurement of some parameters may be challenging. It was shown, that all required parameter may be estimated by monitoring variations of the electromagnetic field around conductors at the points of interest if sensors of the network are synchronized in time. In order to achieve global time synchronization, each sensor is equipped with GPS receivers, which also provide sensors with their location data.

We demonstrated, that the proposed monitoring system is capable of estimating the topology and generate the map of the distribution grid. Our novel approach is using communication over powerline data to automatically split the network into clusters of sensors, so that all the sensors in the cluster are installed on the same physical conductor. The connections between the points of sensor installation may be estimated with high probability from the collected real-time electrical parameters received from the sensors. The topology is first estimated for individual clusters of the network, which allows to reduce the amount of required computations. The estimated topology together with GPS locations of the sensors are used to generate the grid map.

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