Preprint - Encyclopedia of Wireless Networks, X. Shen, X. Lin, K. Zhang (Ed.s), Springer Nature, 2018

Using Communications for Grid Discovery and Diagnostics

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Synonyms

Grid surveillance, grid monitoring and anomaly detection using power line communications.

Definitions

Grid discovery and diagnostics refers to characterizing both the electrical and topological properties of the grid, and to monitor their evolution over time. It can be performed using two technical approaches. The first approach employs a series of electrical meters that are directly branched to the network and specifically designed to sense different electrical quantities. The gathered information is then shared between the nodes or directly with a central unit using a separate communication device. The second approach exploits power line communications (PLC) both as sensing and communication technology. PLC transmitters generate signals according to their specific communication standard, while the receivers, apart from the classical communication function, exploit those signals to perform grid discovery and diagnostics. The sensing signals have a frequency range from few Hz to few kHz in the first approach, while in the second, as per PLC standards, the frequency range goes from few kHz to several MHz.

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Historical Background

Grid discovery and diagnostics are traditionally performed using two separate devices. The first is a dedicated hardware, normally an electrical meter, that is branched to the grid and continuously senses the network. The second is a communication device endowed with a modem that is used to share the sensed data and possible control commands. The most common measurement device is called phasor measurement unit (PMU). Many PMUs are normally deployed across the grid and measure in a synchronized fashion the values of the mains voltage and current about 30 times per second. When required, they can reach up to few thousand measurements per second. Concerning communications, there are different possibilities, including PLC, radio system, fiber optic and satellite communications (Chairman et al 2011). This monitoring system is well established in the context of high-voltage transmission networks and in wide medium-voltage distribution networks. However, conventional PMUs are not usually deployed in small-sized distribution networks or in microgrids. In fact, given the average length of the power cables in such networks, frequencies higher than few kHz are preferable to efficiently perform grid discovery and diagnostics. In such networks utilities have a very low level of control.

For these reasons, a novel stream of research is proposing to use the high frequency of PLC to absolve discovery and diagnostic tasks in small-size grids. This has a double advantage. On one hand, with high frequency measurements, greater resolution can be obtained. On the other hand, since PLC are both used to monitor the network and to send communication signals, they embed in a single technology the role of sensors and modems. The idea is similar to what has been done for internet access networks. In that context, digital subscriber line (DSL) modems have been used since the nineties to monitor the ”last-mile” of telephone networks. The characteristics of power networks are however completely different, which requires a separate treatment.

Background on grid discovery

Grid discovery has emerged as a practical and research problem with the advent of convoluted and interconnected networks. The term refers to the ability of an ensemble of network nodes to infer the physical structure and the electrical parameters of the network. The nodes are enabled to discover their relative position within the grid, to detect the presence of other nodes and, ultimately, to derive the grid topology. Furthermore, they are enabled to infer the electrical parameters of the cables, the impedance value of the loads, the current and voltage at each termination. A complete knowledge of the structure of the grid allows utilities to optimize different aspects: the flow of the delivered power, the values of the balancing loads, routing strategies of information signals for control and defensive strategies against possible intruders.

Grid discovery is normally treated as a state estimation problem based on the data provided by PMUs. The produced measurement are used in combination with state estimation algorithms to infer, depending on the application, different properties of the network (Huang et al 2012). In transmission networks, it is of interest to estimate the voltage and current phasors at every node. In micro-grids, on the other hand, it is of interest to monitor the topological changes of the grid, since they occur too often to be manually controlled by an operator. Such techniques are always based on complete or at least partial knowledge of the set of the possible topologies of the grid.

In recent years, interest has grown towards the inference of the topology of a distribution or micro-grid with no previous information about it. Some approaches, presented in the following, exploit high frequency signals provided by PLC modems. Their use is of particular interest in medium and low voltage distribution networks, where the utilities have limited knowledge of the actual structure of the network.

Background on grid diagnostics

Grid diagnostics involves the constant monitoring of the grid with electrical signals in order to detect and possibly localize possible anomalies that might jeopardize the distribution of electrical power. Every consequent damage on the grid has to be repaired withing the shortest time possible, in order to maintain a high service quality for the costumers. However, since transmission and distribution grids cover wide areas and they are often rather convoluted, detecting and localizing anomalies in a short time is a complex task. Given the huge economical and social impact that strong anomalies like short-circuits can have, grid diagnostics has been performed on power grids since the beginning of the twentieth century. The proposed monitoring techniques have since then constantly evolved.

Grid diagnostics is typically based on power flow analysis (Grainger et al 2016), and it focuses on the detection and localization of electrical faults. The basic technique consists of deploying one or more relays across the grid to monitor the delivered voltage and the total current absorbed by the loads. The presence of a fault is detected when the expected values of voltage and current exceed a pre-determined threshold. The location of the fault is determined analyzing the phase of the fault current. Older systems exploited just mechanical relays that used fuses to detect overcurrents and trigger a circuit breaker. Modern micro-processor enabled evolutions of these systems are still applied nowadays, especially in transmission networks (Das et al 2014).

Along the years, more complex analysis techniques have been layered on basic threshold methods in order to detect and localize faults in topologically complex networks, to classify different kind of events and to detect them even if they are very short or very weak (Shafiullah and Abido 2017; Sedighizadeh et al 2010). Such techniques make use of various tools that can be broadly divided into deterministic and heuristic approaches. Deterministic approaches exploit time-domain or frequency-domain analysis applied to each new sensing event. Heuristic approaches, like neural or fuzzy networks and genetic algorithms, are based on training data and the available information about the grid. They are able to automatically detect and localize faults based on all the system history. Conversely from deterministic approaches, they require much more computation power, but they can better adapt to system changes.

In recent years, lot of interest has grown toward diagnostics in underground grids and small scale overhead grids which, as previously discussed, are not well controlled by the utilities. Given the small dimension of these grids, monitoring at high frequency is needed. For this reason, a series of methods that make use of PLC modems has been proposed not only to detect faults, but also to track the aging of cables (particularly important in underground grids) and eventual changes of the loads. In the following, a description of these methods is presented.

Foundations

In order to optimize the communication rate, every communication protocol requires to perform channel estimation in order to apply equalization algorithms at the receiver. The channel is composed by the physical medium, the couplers and the analog part of the transceivers. In the context of PLC, the medium is the power grid. If the couplers and the analog transceiver at the transmitter and at the receiver are well characterized, it is possible to estimate the medium transfer function (MTF). The MTF does not depend on the transmitted signals (although its estimation depends on it), but it is an intrinsic property of the medium.

Each receiving modem can estimate the link transfer function (LTF) with respect to a transmitting modem. When the receiving modem starts a communication with another transmitter, then a new LTF is estimated, referring to the new link. If a modem is equipped with an impedance measurement circuit, it can also estimate the echo transfer function (ETF), i.e. from the transmitter modem to itself. Conversely from the LTF, the ETF is an intrinsic property of the node the modem is branched to.

The LTF and the ETF contain all the structural and electrical information about a specific power grid. The analysis of such information is based on the transmission-line theory (Paul 2007; Passerini and Tonello 2018b). For example, from the time-domain ETF depicted in Fig. 1 it is possible to infer the following information. Each peak determines the position of a discontinuity in the grid, which might be a cable branch, a termination node, or even an anomaly. The amplitude of each peak is determined by the amount of the mismatch of the discontinuity with the line. This ultimately depends on the characteristic impedance of the power line and on the equivalent impedance of the load or the anomaly. Finally, the shape and the amplitude of the peaks depend on the electrical characteristics of the power line. Due to signal attenuation, frequency and time spread, the access to this information is often limited, especially regarding the parts of the grid that are distant from the

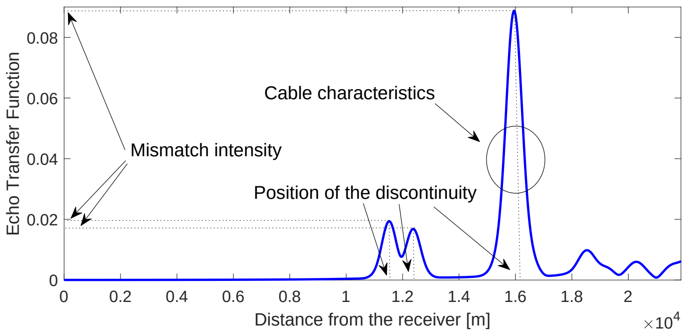

Fig. 1 Example of a time-domain ETF and associated information about the medium.

measurement point. For this reason, it is often preferred to fuse the information provided by the LTF of multiple links or the ETF of multiple nodes. Furthermore, the closer the nodes are to each other, the higher the frequency bandwidth required to distinguish them is.

Application: Grid Discovery

Three main approaches have been proposed to date to perform grid discovery, i.e. to estimate the grid topology. The first approach is based on reflectometry, that is the estimation of the echo signal from one modem deployed on a network termination. Assuming the presence of no anomaly, the peaks in the time-domain ETF unveil the presence of either branching points or terminations. Different algorithms have been proposed to emulate the peak sequence of the ETF by guessing node-by-node (Zhang et al 2016) or peak-by-peak (Ahmed and Lampe 2012) the topology of the grid. This approach has the advantage of relying on just one measurement point, but the grid discovery is limited to few nodes next to it.

The second approach avoids peak analysis by operating on the data-link layer. A set of modems is deployed on all the grid terminations (Lampe and Ahmed 2013), or even on every node (Erseghe et al 2013). Every modem has to establish a connection with each one of the others. During the hand-shake phase, the modem is capable of computing the round-trip time and, thus, to estimate the length of the link. When the length of all the possible links in the network is known, different algorithms based on decision and graph theories can be applied to infer the topology. This approach has the advantage of being scalable to high complex networks, but requires an extensive deployment of broad-band PLC modems.

The third approach relies on impedance measurements performed on the network nodes (Passerini and Tonello 2017). If the user has some prior information about the cable parameters and the loads, it is possible to infer both the node-to-node distances and the topology in a unified algorithm by using the classical propagation equations from transmission line theory. This approach requires a lot of prior information and extensive deployment of PLC modems, but can work both with wide-band measurements or using a single frequency down to few tenths of kHz.

A summary of the grid discovery methods using PLC is shown in Tab. 1.

Table 1 Grid discovery methods using PLC

Method	Class	Advantages	Disadvantages
Reflectometry and model-based search	Echo	PLC modem on just one node, few prior information needed	Topology inference limited to few branches, requires wide band
Handshake and inference algorithm	Link	Scalable, few prior information needed	PLC modem on every termination or even on every node, requires wide band
Impedance	Echo	Single or multiple frequencies allowed, works also using low frequencies, cable length and connections in a single algorithm	Many parameters required, PLC modem possibly on every node

Application: Grid Diagnostics

High frequency grid diagnostics can be performed when at least one reference measurement, performed during the normal operation of the grid, is available. Then, the medium is continuously monitored and every new estimation of the MTF is subtracted from or divided by the reference measurement, depending on the system model used (Passerini and Tonello 2018b), providing a test trace. Since the power line medium is periodically time variant in the 3 kHz to 10 MHz range, using just one reference measurement would often provide non null test traces. In order to discover anomalies, it has been proposed to analyze the features of the test traces with a machine learning algorithm. Such algorithm has been tested to track the aging of underground cables, providing promising results (Förstel and Lampe 2017).

On the other side, considering the periodicity of the channel variation as composed by a series of invariant states, it is possible to use an equal number of reference measurements. This way, if no anomaly is present, the amplitude and phase of the resulting trace is limited to a noise component. Every time a threshold set consistently to the average noise power level is exceeded, an anomaly is detected. This approach has been presented considering a single LTF or a single ETF (Passerini and Tonello 2018a), but of course the detection performance is improved when relying on measurements from multiple node or links. Different classification algorithms based on the features of the test trace can then be conceived to identify the type of the detected anomaly (Passerini and Tonello 2018a).

For what concerns the localization of an anomaly, it is performed by analyzing the test trace in time domain and it mostly relies on the knowledge of the network topology. When the topology of the grid is not known, it is only possible to retrieve the distance of the anomaly from a communication node, which corresponds to the position of the first peak in the time-domain MTF (either LTF or ETF). In the case of the ETF, the distance is univocally referred to the measurement point, but in the case of the LTF an ambiguity is left, since the distance might be either referred to the transmitter node or to the receiver node (Passerini and Tonello 2018b). When the topology of the grid is known, then the precise branch where the anomaly takes place can be identified by a peak analysis of the test trace.

A summary of the grid diagnostic methods using PLC is shown in Tab. 2.

Table 2 Grid diagnostics methods using PLC

Method	Class	Advantages	Disadvantages
Deterministic LTF	Link	Detection both close to the transmitter and the receiver	Ambiguity on the location
Heuristic LTF	Link	Detection both close to the transmitter and the receiver	Requires huge database, ambiguity on the location
Deterministic ETF	Echo	Reduced complexity algorithms, univocal localization	Detection only close to the sensing modem

Cross-References

Advances in Distribution System Monitoring and Implications for Grid Operation

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