ELECTRICITY THEFT LOCALIZATION BASED ON SMART METERING

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ABSTRACT

This paper extends the methodology for detection of illegal abstraction of electricity from low voltage distribution networks, which has been introduced in [1]. The method uses measurements by smart meters and a model of the low voltage network to determine the exact location of illegal abstraction. The contribution of this paper is a detailed description of this method, which includes an accuracy analysis and simulations to determine the requirements for the measurements and the network model.

INTRODUCTION

Modern distribution networks are slowly evolving into smart grids. A part of this development is the installation of more advanced measuring equipment in distribution substations and increasing deployment of smart metering at customers installations. These developments offer more insight and opportunities for new applications for distribution network operators. One of the applications could be the automatic detection of illegal abstraction.

Illegal abstraction of electrical energy is a large problem in many countries. In the Netherlands for instance, 1200GWh of electrical energy is illegally abstracted from the distribution grid each year [1]. This represents approximately 1% of the total electricity generation in the Netherlands.

Currently, existing theft detection methods do not provide accurate localization or are not applicable for different types of loads [1]-[3]. Smart metering [4] and intelligent distribution substations [5], although not meant for it, may provide the network operators with new opportunities for fast and successful localization of illegally abstracted electricity.

In [1] a new approach for the localization of illegal abstraction of electricity was proposed, based on measurement data from smart meters and an intelligent distribution substation, and a sufficiently accurate model of the low voltage (LV) network concerned. This approach relies on the alteration of the voltage profile along the customers' points of connection (POCs), due to illegal abstraction.

The objective of this paper is to present the new approach in more detail and it focuses on the inaccuracies involved in this method. Simulation results are presented to demonstrate the feasibility of successful localization. Furthermore, measurement requirements will be presented for the smart metering infrastructure and the intelligent distribution substation. The measurements from the smart metering infrastructure and the intelligent distribution substation are essential for the presented theft localization method; both should be available for a successful localization.

First, a detailed description of the method is presented, followed by the accuracy evaluation of each component and the evaluation of the accuracy of the method as a whole. Finally, all measurement requirements are presented.

METHOD DESCRIPTION

The smart metering infrastructure will provide the distribution network operator with measurements of the energy consumption, but also with measurements of the active and reactive power, voltages, currents and power factors of all customers, which might be used for localization of illegal abstraction [4]. Similar measurements can be done inside a smart MV/LV substation for the whole substation on a per feeder basis. In addition a model of the network can be determined from documentation provided by the distribution network operator.

The proposed method consists of two phases. In the first phase the sum of the power consumption of each connected customer is compared with the total outgoing power from the distribution substation (including estimated losses). If there is a large difference between these two values, the presence of illegal abstraction is assumed and consequently the localization algorithm will be applied.

The presence of illegal abstraction at a certain POC on a feeder, influences the voltages at all POCs on that feeder. Therefore in the localization phase, the voltage profile along the feeder is estimated, based on measurements by the smart meters of the current and power factor of each customer, and a model of the feeder. This estimated voltage profile is compared with the actual measured profile and based on this comparison the location of illegal abstraction can be determined.

Each section of the feeder or a connection cable is modelled as a complex impedance. The voltage drop across a feeder or cable section can be described by:

$$\Delta V_i = I_i(R_i \cos\varphi_i + X_i \sin\varphi_i) \qquad (1)$$

where I_i is the current through section i, $\cos\varphi_i$ the power factor of the power transported through section i and R_i and X_i the resistance and reactance of the section respectively.

For the model of the network, the impedances of the feeder sections between all customers should be determined as well as the impedances of the cables that connect the customers to the feeder. These impedances can be determined from data provided by the distribution network operator.

With this network model and measurements of all currents and power factors, the voltage difference between the distribution substation and each customer can be estimated according to:

$$\boldsymbol{\Delta V_e} = \boldsymbol{Z_m} \cdot \boldsymbol{I_m} \qquad (2)$$

Where $\boldsymbol{\Delta V_e}$ is a vector with the expected voltage differences between the distribution substation and each POC, $\boldsymbol{Z_m}$ a square matrix constructed with impedance values (and measured power factors) according to (1) and $\boldsymbol{I_m}$ a vector with the measured currents of all customers.

The measured voltage difference between the distribution substation and each customer can be divided into a part caused by the measured currents and a part caused by the illegal abstraction, as shown in Fig. 1 for a feeder with twenty customers connected and illegal abstraction taking place at POC 9.

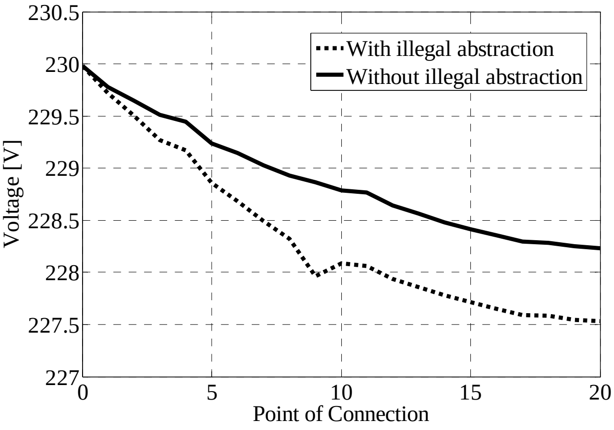

Fig. 1: Voltage profiles with and without illegal abstraction

Therefore the measured voltage difference between the distribution substation and each customer can be described by:

$$\boldsymbol{\Delta V_m} = \boldsymbol{\Delta V_e} + \boldsymbol{Z_t} \cdot \boldsymbol{I_t} \qquad (3)$$

Where $\boldsymbol{\Delta V_m}$ is a vector with the measured voltage drops between the distribution substation and each POC, $\boldsymbol{Z_t}$ a square matrix constructed with impedance values and power factors of the illegal loads, according to (1) and $\boldsymbol{I_t}$ a vector with the illegally abstracted ('theft') currents at all POCs.

To determine $\boldsymbol{I_t}$ from this equation, the matrix $\boldsymbol{Z_t}$ has to be determined. Therefore an estimate has to be made of the power factor of the illegal loads. With this estimated power factor, $\boldsymbol{Z_t}$ can be estimated and then $\boldsymbol{I_t}$ can be estimated with the following equation:

$$\boldsymbol{I'_t} = \boldsymbol{Z'_t}^{-1} \cdot (\boldsymbol{\Delta V_m} - \boldsymbol{Z_m} \cdot \boldsymbol{I_m}) \qquad (4)$$

Where $\boldsymbol{I'_t}$ is a vector of the estimated 'theft' currents at all POCs and $\boldsymbol{Z'_t}^{-1}$ the inverse of the estimated impedance matrix of the illegal loads.

The vector $\boldsymbol{I'_t}$ contains estimations of the illegally abstracted current from each POC. If the amount of 'theft' current estimated for a certain POC is high, illegal abstraction is probably taking place at that location.

The method is set up generically. Therefore the presence of distributed generation in the network doesn't affect the localization procedure. The reverse power flow will change the voltage profile but will not affect the method. In addition, the illegally abstracted current is estimated for each POC. Therefore the presence of more perpetrators on the same feeder simultaneously, is also feasible to detect.

INACCURACY ANALYSIS

A successful localization of the illegal abstraction depends on a number of factors. These are:

- Power factor estimation
- Network model accuracy
- Measurement accuracy

In this paragraph, the effect of each of these factors on the accuracy of the localization method is analysed. Furthermore an estimate is made of the total accuracy of the method.

Power factor estimation

The estimation of the power factor of the illegal loads is done by calculating the total active and reactive power consumption per feeder from all measured currents, obtained from smart meters and the distribution substation. This can be done according to the following equations:

$$P_m = V_{dss} \cdot \sum_i \left(I_{sm,i} \cdot \cos\varphi_{sm,i}\right) \qquad (5)$$

$$Q_m = V_{dss} \cdot \sum_i \left(I_{sm,i} \cdot \sin\varphi_{sm,i}\right) \qquad (6)$$

Where P_m and Q_m are the total active and reactive power consumption per feeder, due to all measured currents (including losses in the network), V_{dss} is the voltage measured in the distribution substation, $I_{sm,i}$ and $\cos\varphi_{sm,i}$ are the current and power factor measured by the smart meter at POC i respectively. The difference between the outgoing active and reactive power, measured in the distribution substation, and P_m and Q_m then represents the total active and reactive power consumed due to illegal abstraction, i.e. the sum of the power consumption at all locations of illegal abstraction on the feeder and the losses in the network due to illegal abstraction. Based on these values the power factor of the illegal loads can be estimated. In the case that illegal abstraction takes place on multiple locations on the same feeder, the estimated power factor will be the average of the power factors of all illegal loads.

Network model accuracy

In practice it can be difficult to obtain an accurate model of the LV network. First of all, the lengths of connection cables and feeders are often not documented very accurately. Also, during reparation work, certain parts of a feeder may have been replaced with a cable of another type, which changes the impedance of the repaired section. These repair actions are often not very well documented. Finally, the impedance of a cable is also dependent on the conductor temperature, which is influenced by the temperature of the soil and by the cable loading. The errors in the cable lengths and the poorly documented repair actions will result in a constant error in the network model. Due to the temperature dependency however, the error will vary in time, depending on the current through the cable.

The errors due to unknown cable lengths will have a fairly random character. All cables may be a little bit longer or shorter than documented.

If a section of a feeder has been replaced with a cable of another type, this can affect the impedance of that feeder section. This impedance can also be higher or lower than documented.

The resistance of a cable is strongly dependent on the conductor temperature. For XLPE cables, at the maximum operating temperature of 90 °C, the resistance is 28% higher than at 20 °C. In practice however, a cable section will not be fully loaded continuously. It is assumed that under normal operating conditions the resistance will not differ more than 10% from the specified value.

It is possible to account for these errors in the network model. In times when there is no illegal abstraction taking place, it is possible to use the smart meter measurements to improve the network model. In that case the error in the model due to the first two causes can be minimized. Furthermore it is possible to expand the network model, by taking into account the temperature dependency of the impedances, and to use the power flow measurements to estimate the temperature of each cable section and to determine the impedance more accurately. These possibilities are although not yet incorporated in the presented analysis of the accuracy of the localization method for illegal abstraction.

Measurement accuracy

Different measurements at the distribution substation and by the smart meters are used for the localization of illegal abstraction. All measurements are performed within a certain accuracy range. The measurement errors influence the accuracy of the estimation of the ‘theft’ currents.

The errors in the voltage measurements have the biggest impact on the total accuracy. This is because the voltages in the distribution substation and at all POCs are measured separately, with a certain accuracy, but only the voltage differences between the distribution substation and the customers’ POCs are used. This voltage difference is much smaller than the measured voltages, and therefore the relative measurement error is much higher. In a typical LV network, and with a voltage measurement accuracy of 0.5%, the relative error in the measurement of the voltage difference between the distribution substation and a POC can be as high as 200%.

We assume however, that the measurement errors have a normal distribution with a mean value of 0. This can be achieved by a correct calibration of the meters. It is therefore possible to use multiple measurements in order to obtain an acceptable accuracy of the localization method. The ‘theft’ current is then estimated by calculating the average of estimations based on different measurements. The amount of measurements needed to obtain a certain accuracy is determined in the next section.

Total accuracy

There are two classes of errors involved. The first class is caused by the measurement errors and can be attenuated by using repeated measurements itself. The second class, due to the estimation of the power factor and the errors in the network model, will not be attenuated by using a higher number of measurements. Therefore these errors define a minimum ‘theft’ current that can be detected by the localization method.

In this section, the minimum ‘theft’ current that can be detected is determined for a generic LV network. Furthermore the amount of measurements needed for a successful localization is also determined.

To be able to draw conclusions about the minimum ‘theft’ current and the number of measurements needed, simulations are done on a generic Dutch LV feeder, with 20 customers connected per phase. The typical consumption of all customers varies between 0.1 and 5kVA with a typical power factor between 0.85 and 1. The network consists of a main feeder, which is a 150mm^2 Al. cable, to which all customers are connected through a smaller connection cable. The connection cables are all 10mm^2 Cu. cables. All connection cables have a length of 5m. The length of feeder between two neighbouring customers is 10m. The distance between the distribution substation and the first customer is 100m. The method is generally applicable and distributed generation or illegal abstraction on more than one location should not cause any difficulties with the localization. Therefore, in the simulation we assume the worst case with two perpetrators on the feeder, one at POC 3 and one at POC 17. The power factor of illegal abstraction is assumed 0.5 at POC 3 and 1 at POC 17.

A Monte Carlo simulation was done to determine the minimum ‘theft’ current that can be detected. In this simulation a measurement accuracy of 0.5% was assumed for the estimation of the power factor of the illegal abstraction. The network model was corrupted with random errors of maximum 5% to account for the inaccuracy of the specified cable lengths. In addition random errors of maximum 10% were assumed to account for the temperature dependency. Moreover, for one section the impedance was increased with 10% to simulate a badly documented repair action. The results of simulations performed show that with a certainty of 99,7%, an illegally abstracted current of 6A or higher is possible to successfully detect. This corresponds with a power of 1,4kVA.

The error in the estimation of the ‘theft’ current, due to the different measurement errors, can be characterized by a normal distribution function, with mean value $\mu = 0$ and a standard deviation σ that is dependent on the measurement accuracy. The central limit theorem states that for a sufficiently large amount of estimations (n) based on repeated measurements, the standard deviation of the error in the average ‘theft’ current estimation can be given by:

$$\sigma_n = \frac{\sigma}{\sqrt{n}} \qquad (7)$$

Furthermore the empirical rule for a normal distribution states that 99,7% of all values lie within the interval $\mu \pm 3\sigma$. Because the mean value of the estimation error $\mu = 0$, the minimum theft current that can be detected with 99,7% certainty is equal to:

$$I_{min} = \frac{6\sigma}{\sqrt{n}} \qquad (8)$$

Using Monte Carlo simulations we can determine the standard deviation of the estimation error for different values of measurement accuracy. The results of these simulations are depicted in Fig. 2.

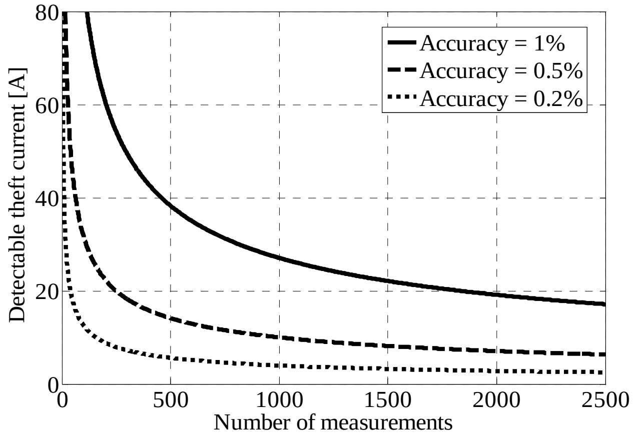

Fig. 2: Detectable theft current as a function of measurement accuracy

It can be seen from these results that the number of measurements needed for a successful localization, decreases rapidly with an increasing measurement accuracy. According to [4], the smart meters should perform interval readings at least every 15 minutes. Furthermore in the Netherlands, a typical instance of illegal abstraction consumes approximately 5kW. Reflecting results in Fig. 2 and assuming that measurements are done every 15 minutes with an accuracy of 0.2%, a perpetrator with an illegal load of 5kW (21A) will be localized within a day.

CONCLUSIONS

This paper presents a detailed explanation of a method for the localization of illegal abstraction, which was introduced in [1]. The method makes use of measurements by smart meters and an intelligent distribution substation and a model of the LV network to estimate the amount of illegally abstracted current for each POC. The accuracy of this estimation is dependent on a number of factors. These are:

- Theft power factor estimation
- Network model accuracy
- Measurement accuracy

Assuming a measurement interval of 15 minutes, in accordance with the Dutch smart metering standard [4], it was shown that a typical occurrence of illegal abstraction will be localized within one day. The speed of localization can be increased by decreasing the measurement interval of the smart meters.

For a successful localization, the following measurements should be available from the smart meters and the distribution substation:

- Voltage (RMS)
- Current (RMS)
- Power factor

It is recommended that all measurements are performed with an accuracy of at least 0.5%. Furthermore it is necessary that the measurements of all smart meters on a feeder are performed at the same moment.

The power factor estimation and the network model accuracy introduce a minimum ‘theft’ current that can be detected. It was shown that for a typical Dutch LV network, this minimum detectable ‘theft’ current is about 6A. It should be stressed out, that this minimum current was determined in a worst case scenario, for a feeder where two perpetrators where present. This is an exceptional situation. If only one perpetrator is present, the minimum detectable ‘theft’ current is much lower. The minimum detectable current can be lowered further, by improving the network model. The estimation error due to the different measurement errors can be attenuated by taking the average ‘theft’ current of different estimations based on repeated measurements. The amount of measurements needed to detect a certain ‘theft’ current with certain measurement accuracy was also presented. The localization method presented in this paper can be an important feature of smart metering infrastructure and can deliver additional benefits to distribution network operators.

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