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Analysing the forecast of electricity grid losses

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Abstract. Electricity grid losses, having a relevant impact on the financial situations of all network operators, are a major concern both in the transmission and distribution sector. Understanding the physical phenomenon underlying electricity grid losses is important to identify proper measures for reducing it, without impacting the quality of service and/or supplied electricity. Forecasting the volume accurately is also a relevant and challenging objective. In this paper, we analyze the main aspects that have to be taken into account in the forecasting process. Furthermore, the sensitive issue of the "commercial losses" or non-technical losses is addressed briefly, pointing out the main characteristics and the associated perspective.

1. Introduction

The normal operation of electrical grids requires the consumption of a certain amount of energy. This self-consumption of the grid is often called "grid losses" although there is no specific consumer associated with it.

The self-consumption of the electricity grids manifested from the very beginning of the electricity grids operation; therefore it is a well-known physical phenomenon. Nowadays, the amount of the self-consumption is considered the most important technical and economic parameter related to the grid operation efficiency. The regulatory authorities are carefully monitoring the volume of the self-consumption in the electricity grids, for both transmission and distribution, and include in the tariffs bonuses or penalties based on the registered values. For instance, the U.S. Energy Information Administration (EIA) "estimates that electricity transmission and distribution (T&D) losses equaled about 5% of the electricity transmitted and distributed in the United States in 2015 through 2019" [1].

Considering the amount of electricity consumed nowadays, it is only obvious that the financial impact of the self-consumption is significant for all grid operators (transmission and distribution). Thus, a high interest for developing modern mathematical models and methodologies for an accurate calculation and prediction exist, both for short- and long-term.

From the technical perspective, the mathematical methods and methodologies did not change, basically because the physical phenomenon leading to self-consumption have not changed, namely: heating of the conductors, magnetization of the transformers, corona phenomenon, and others. The accuracy of the calculations has been improved by improving the calculation accuracy of the electrical parameters of the equipment.

In terms of forecasts, they are inseparable related to the load and generation forecasts. The recent improvements of the accuracy of load and generation forecast, based on extensive usage of Artificial Intelligence (AI), have had a significant impact on the accuracy of the self-consumption forecast. In SOGNO project, an innovative method has been developed and successfully tested, based on the use of Artificial Neural Networks (ANN), which is also designed to face the problem of poor availability of measurement information in the network. "The development of these solutions specifically aims at achieving accuracy performance as good as possible even in presence of few measurement devices in the field. To deal with the large size of the distribution networks, specific Power System (PS) architecture solutions have been devised to distribute the computational burden among different Low Voltage (LV) and Medium Voltage (MV) estimators. The proposed solution, presented in the final part of this section, allows multiple PS instances operating in parallel, with fast harmonization processes for refining the PS accuracy performance, and permits coordinating the PS process among different grid levels." [2].

In the following sections, we will briefly present a modern approach for calculating, and predicting the self-consumption in the electricity grids, and the main challenges for developing accurate assessments, considering the state-of-the-art developments in the power systems around the world.

2. Main features of the self-consumption calculations for the electricity grids

From the electricity grid operation perspective, the are two main areas: transmission and distribution. The features of the electricity self-consumption in the above-mentioned sectors are similar to some extent but not entirely.

In the electricity transmission sector, the causes of the electricity self-consumption have all a physical nature, as follows:

- Conductors heating. This includes, Over HeadLines (OHL), cables, transformers, and coils;
- Magnetization. This includes the energy consumed by the transformers for the magnetization of their iron core, also known as "iron losses";
- Corona phenomenon. This physical phenomenon is relevant only at High Voltage HV (>110 kV), as it consists of energy amounts transferred from the OHL conductors through air, causing noise, small lightings, and a supplementary consumption of electricity on the respective OHL.

In the electricity distribution sector, the causes of the electricity self-consumption are not only of physical nature, but also of administrative ones, as follows:

- Conductors heating. This includes, OHL, cables, transformers, and coils.
- Magnetization. This includes the energy consumed by the transformers for the magnetization of their iron core, also called as "iron losses".
- Commercial losses. The amount of electricity included in this category is correctly named "non-technical losses" because it is not a self-consumption of the electricity grid caused by physical phenomenon, as the previous ones. This type of losses is a direct consequence of the commercial relation existing in the electricity distribution activity in between the electricity grid operators and the electricity end-users. In these conditions, it is sometimes possible to register a difference between the financial amounts truly collected and the financial amount which should have been collected. The electricity volume associated to these financial losses are usually called "commercial losses". Obviously, there are no mathematical models and/or methods for calculating this type of losses.

The electricity transmission and distribution are considered "natural monopolies", and therefore they are fully regulated activities. The regulatory authorities by nature are pursuing the goal to maintain the price of electricity at a competitive level, therefore they are recognizing (including) in the tariffs challenging values (levels) for self-consumption, and other similar costs. As a consequence, the electricity grid operators are continuously monitoring the volume of the electricity grid self-consumption, and whenever or/and wherever is possibly take appropriate measures for reducing it.

3. Input data necessary for calculation of the self-consumption

There are different necessary input data for calculation of electricity self-consumed by the grid, for each type of self-consumption. In the following subsections, we will present the basic relationships used for calculations, and the associated input data. In case of the physical phenomenon common for transmission and distribution, the mathematical relationships are of course the same.

3.1. Heating of the conductors

The heating of the conductors is a direct result of the amount of current transferred through the conductor, in close correlation with the resistance of the respective wire. This is known as the "Joule effect". The conductors may be the wires of an OHL or cable, or inside of a transformer or coil, or other. The relationship used for calculating the lost energy is presented below.

$$\Delta E = 3 \times R \times I^2 \times t \quad (1)$$

where:

ΔE – the amount of electricity self-consumed by the respective equipment, during the period t;

t – period of time when the value of the current has been registered.

R – resistance of the wire, determined in line with (2).

I – total amount of current (including active and reactive components) transferred through the wire, during the period t.

The resistance of a wire is an electrical parameter, determined based to the constructive characteristics of the wire: cross-section, material, and length, as follows:

$$R = \rho \times \frac{L}{A} \quad (2)$$

where:

R – resistance of the wire;

ρ – electrical conductivity (electrical parameter of the material from which the wire is manufactured);

L – length of the wire;

A – cross-section area of the wire.

In line with (1) and (2), the necessary input data for calculating the electricity self-consumed by the grid, as a result of the heating process are: the electrical resistance of the equipment, the duration of the calculation, and the weighted average amount of the current.

3.2. Magnetization of the power transformers core

The technology used for building power transformers requires the utilization of a magnetic core, usually manufactured from steel alloys. For a better understanding, in Figure 1 a simplified schematic of this equipment is presented. The magnetic core is extremely important for the proper operation of the equipment because it allows the magnetic flux to be transferred from primary to the secondary windings (circuits), thus allowing the equipment to fulfill its purposes. For more details regarding the basics of the transformers please check [3].

The volume of the electricity consumed by the power transformed due to the core magnetization is entirely dependent on the characteristics of the material of which the core is manufactured. The load level, primary/secondary voltage levels, frequency, or other electrical parameters do not have any influence from this perspective.

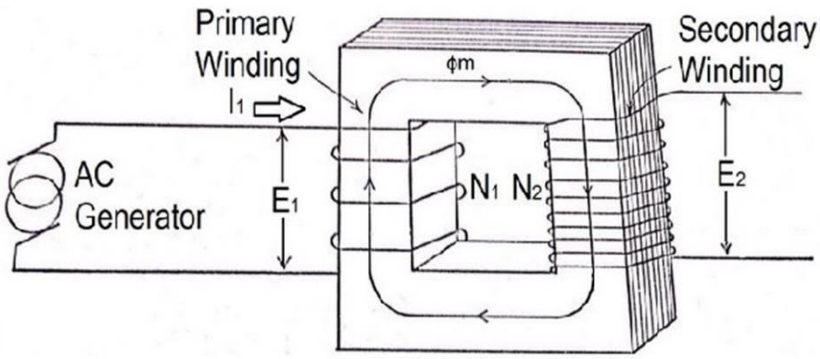

Figure 1. Elementary power transformer.

Normally, all power transformer manufacturers are indicating the power self-consumption for each type of equipment they are producing. This value is constant in time, therefore it is very easy to calculate the associated electricity, for a period of time.

3.3. Corona phenomenon

The so called “Corona phenomenon” is an electrical conductivity that generally occurs near equipment (usually conductors but not only) loaded with electricity, located in air or other gases. The intensity of the manifestation is directly and strongly related to the voltage level (higher voltage leads to higher intensity of the Corona phenomenon).

“In transmission lines, it causes power loss, audible noise, electromagnetic interference, purple glow, etc. Hence to minimize this negative effect, the conductor surface condition, size, distance to ground and other conductors have to be considered when planning and construction of overhead power lines.” [4].

The main parameters that are influencing the intensity of this phenomenon (with direct impact on the associated electricity consumption) are the voltage level, the physical dimensions and the geometry of the equipment, and the conductivity of the gases surrounding the equipment (usually the humidity of the air).

Due to the complexity of the physical phenomenon, it is very difficult to elaborate a mathematical model and relationship for calculating the associated volume of electricity consumed by the conductors. In this condition, several empirical formulas have been developed, proving an adequate level of accuracy.

In the following subsections, the results obtained by using two of the most widely recognized experimental formulas are presented, such as Peterson’s formula:

$$P_c = \frac{3.73 * K}{\left({}^{D}/_{r}\right)^2} * f * V^2 \text{ [kW/km]} \tag{3}$$

where:

P_c – power losses due to Corona phenomenon.
D – distance between the phase conductors.
r – radius of the phase conductors.
K – factor based on the ratio of the operating voltage (V) to the corona onset line voltage.
f – frequency.
V – operating voltage.

Using Peterson’s formula, A. Ersoy and A. Kuntman [4] have computed the power losses due to corona phenomenon, for different materials and conductor’s radius, as shown in the Table 1.

Table 1. Power losses due to corona phenomenon, Peterson’s formula [W/km].

Conductor type	P_C (at U_{iv})	P_C (at U_{ev})
Aluminum (r=2.1mm)	983.9	890.4
Aluminum (r=4.25mm)	6,202.5	5,540.9
Steel (r=2.1 mm)	754.5	686.0
Steel (r=4.25mm)	8,360.7	7,025.0
Copper (r=1.72mm)	570.1	503.3
Copper (r=2.68mm)	2,088.7	1,977.2

Where U_{iv} is the inception voltage – the voltage level at which the corona phenomenon becomes self-sustained and U_{ev} is the extinction voltage – the voltage level at which the corona phenomenon ceases to manifest.

The empirical formula developed by Peek[1], for fair weather conditions, is [5]:

$$P_c = \frac{212.4}{\delta} * (f + 25) * \left(V_p - U_c\right)^2 * \sqrt{{}^{r}/_{D}} * 10^{-5} \text{ [kW/km/phase]} \tag{4}$$

[1] Frank Willian Peek (1881 – 1933)

where:
δ – air density correction factor;
f – frequency;
V_p – phase-to-neutral voltage;
U_p – disruptive critical voltage;
r – radius of conductor;
D – distance between the phase conductors.

The values of power losses computed by Kittipong Tonmitra et. al. [5], using Peek's formula are similar (the same magnitude range) with the ones computed by other researchers using Peterson's formula.

However, a process of validation is required. Validation and eventually fine tuning may be achieved by comparing the computed results with measured results for a relevant period of time, for different weather conditions, and for a determined OHL.

3.4. Commercial losses

This type of losses is not caused by a physical phenomenon or other technical reasons. They are a result of the differences between the electricity volumes purchased from the generators as compared with the ones supplied to the end-users. Theoretically, these differences are a caused by the self-consumption of the electricity grid but in practice this is only partly correct.

The main causes consist in:

- Not-measured electricity consumption.
- Measurement errors above the rated margins.

The situation when a community is consuming electricity without being metered in any way is a social phenomenon, and it is closely related to the social and economic aspects known nowadays as "energy poverty". The lower are the income and quality of life in a certain region, the higher is the probability to meet relevant challenges related to the not-metered electricity consumption. Usually, the measures to mitigate these challenges are not technical (in some parts of the world are used meters with pre-paid function) and the electricity grid operators (this aspect is relevant only for distribution sector) require support from the local authorities for keeping this social phenomenon under control.

Any measurement equipment has a rated margin for errors. Normally this margin is very small, and thus the associated errors are not relevant. However, this situation is valid only in case the quality parameters of electricity are also within the regulated margins.

The electricity quality aspects that may have a relevant impact (in case the existing values are above the regulated margins) on the measurement errors level are the following:

- The level of current and/or voltage harmonics are above the regulated values;
- There are non-symmetrical loads on the electricity grid phases;
- The level of flicker is high.

In order to mitigate the risk for operating the electricity grid with reduced level of quality parameters, the electricity distribution operators must monitor carefully and periodically the existing levels. In case significant deviations are registered, the source must be promptly identified, and the appropriate technical measures implemented. The operation of the electricity grid with low quality conditions, for long periods, may lead to permanent deterioration of the equipment.

4. Main issues for the forecast elaboration

Considering the volumes of electricity self-consumed by the electricity grids, both in transmission and distribution sectors, and the associated financial values, it is only understandable that grid operators are very much interested in developing accurate forecasts.

In the present paper, we will briefly present the main challenges that must be overcome to perform an accurate forecast of the electricity grid self-consumption.

4.1. Joule effect

The value of the electricity self-consumed by the electricity grid due to this physical phenomenon is directly and strictly related to the volume and pattern of the load flows in the grid, see (1) and (2). In these conditions, an accurate forecast of the load flows is a pre-requisite for an accurate forecast of the self-consumption, considering that the topology and the electrical parameters (resistance, inductance, and other) of the electricity grid are fully known.

Load flow forecasts is a result of two separate forecasts: consumption and generation. In the last years, the forecasting activity has been significantly changed by the implementation of the AI techniques. A very modern approach has been developed, tested and implemented in [6]: "Machine learning based methods are considered as an appropriate approach to implement and develop the Load Prediction (LP) and Generation Prediction (GP) services by utilizing appropriate historical information. In case of LP service, the historical power consumption values are used as an input in order to understand the pattern of the power consumption in a certain day of the week, or a certain month of the year. The historical power consumption values are in the form of active and reactive power, which are sampled at a certain uniform rate, for example every 5, 10 or 15 minutes. Hence, the machine learning based prediction scheme is trained using such historical information and is used to predict the power consumption for the next hours ahead, always at the same rate as the starting data." [6].

The recent evolutions in the power sector (mainly the dramatic development of the electricity generation powered by renewable energy sources) have proved that electricity price (as a result of an electricity market behavior forecast) is a relevant parameter for an accurate load flow forecast.

4.1.1 Load forecast. Nowadays, a basic market principle for any electricity supplier is to provide its customers the freedom to consume electricity as much as they want/need any time they want/need. The implementation of this principle is related to a high pressure on the electricity grid operator (especially at the distribution level but not only) to be able to provide the operational flexibility required to maintain the quality level while not imposing any restrictions on the consumption at the end user level. In these conditions, it is only natural that load forecast was and continues to be a very interesting issue for the electricity grid operators.

In this paper, the authors will consider the most general situation, namely a large pool of end-users of different types (households, industry, commerce, services, and others), because this is the most complex situation and requires the largest effort to be properly analyzed and understood.

The first step is to determine the time horizon of the forecast. Considering that the final objective of this analyze is to forecast the electricity losses, in this paper we will focus on the long-term (several months up to one year) forecasts. In case of this time horizon, it is necessary to specify the associated season or seasons. For Romanian geographical area, four seasons are recommended: spring (March, April, May), summer (June, July, August), autumn (September, October, November), and winter (December, January, February).

For the selected time horizon, the next important step is to understand the characteristics of the consumption. This is a challenging objective in case of a heterogeneous pool of end-users, which is the most common situation.

The necessary input data is the records of the hourly electricity consumption registered in the past for a period longer (if possible) than the time horizon of the forecast.

The registered values will be grouped according to the day of the week. For the best accuracy, the days of the week is recommended to be divided in four categories:

- Monday to Friday – working days in the vicinity of the week-and.
- Tuesday, Wednesday, and Thursday – full-fledged working days.
- Saturday – first week-end day, following a working day.
- Sunday – second week-end day, preceding a working day.

The forecasts must be developed separately and independently for each season and period of the week, based on the hourly registered values from the past.

It has to be mentioned that irrespective the volume of input data, the results of the load forecast have a level of uncertainty. According to Tahreem Anwar et. al. [7]: "Forecasting, by nature, is a stochastic problem rather than being deterministic in nature. There is no "certain" in forecasting. Since the forecasters are dealing with randomness, the output of a forecasting process is supposed to be in a probabilistic form, such as a forecast under this or that scenario, a probability density function, a prediction interval, or some quantile of interest. In practice, probabilistic inputs cannot be taken in many decision-making processes, so the most commonly used forecasting output form is still point forecast, e.g., the future expected value of a random variable."

4.1.2 Electricity generation forecast. It is well-known that in the power systems, the electricity consumption and generation must be performed every moment, every time. Therefore, the volume of electricity generation is determined by the volume of electricity consumption. The objective of this forecast is the structure of the generation, meaning the generation units that are in operation, and how much they are producing, in each hour interval.

Nowadays, the structure of the electricity generation is closely related to the electricity market behavior. Therefore, a forecast of the electricity generation is actually a forecast of the electricity market behavior. Obviously, the main parameter is the electricity price, but it is not the only one. Possible/potential congestions in the electricity grid, priority for electricity generated based on renewable energy sources, and other priorities introduced by the regulations must be considered for an accurate forecast.

4.1.3 Electricity grid topology. In case of the long-term load and generation forecast, the topology of the electricity grid may change. The changes are related to operational issues and may be scheduled or unexpected (due to different types of outages).

The scheduled changes of the electricity grid topology are related to preventive maintenance actions, and their details are fully known months before. Therefore, the impact of this type of changes may be determined with a high level of accuracy.

The unexpected changes of the electricity grid topology are related to the corrective maintenance actions (actions required to correct the operation of the electricity grid following an outage). In contrast to the scheduled changes, their details (equipment involved, dates, durations, etc.) are not known in advance. Very relevant features of this type of changes are: normally the duration is limited (hours to maximum few days), and the frequency of occurrence is very reduced (one or two events per year, or even less).

Considering the features of the two types of changes, we are recommending that for long-term forecast od losses, only the scheduled changes to be considered in the calculations. In case the unexpected changes of the electricity grid must be considered, a stochastic approach is needed.

4.2. Transformers core magnetization.

This physical phenomenon is extremely stable. The values of the self-consumed electricity are fully determined by the tests performed at the manufacturer level. There is no significant variation during the operation of the equipment, therefore the forecasts are fully accurate in this case.

4.3. Corona phenomenon

The relevant parameters for this physical phenomenon are the frequency, the voltage, and the weather conditions.

The frequency and the voltage have a very reduced variation in time. The high voltage levels are allowed to swing only in a margin of ± 5%, while the frequency regulated swing margin is even more reduced. Accordingly, the impact of the frequency and voltage levels on the volume of the electricity self-consumption due to this phenomenon is negligible.

In case of the weather, the impact on the volume of electricity self-consumed by the grid (only appliable to the OHL) is much more significant. Thus, the weather forecast will be performed for a better quality of the corona losses forecast. For a fine tuning, it is recommendable a monitorization and results checking for a period including different weather conditions.

4.4. Commercial losses

This type of losses are actually financial losses and not physical ones, because the associated volume of electricity is not really self-consumed by the electricity grid, but it is the consequence of a lack of measurements or a metering error. These characteristics make it exceedingly difficult to forecast accurately because there are no mathematical apparatus or methods associated.

The only practical solution for developing a forecast for this type of losses is to collect and analyze the historical data. Based on the pattern identified in the past, possible trends may be designed for the future. In this process, relevant information from the society must be considered, such as measures implemented by the local authorities for mitigating the consequences of "energy poverty".

Normally each electricity grid operator must foresee a decreasing trend for this type of losses, until their volume becomes negligible.

5. Final remarks

Due to the relevant financial impact, the self-consumption of the electricity grid is a major concern for the grid operators, both in distribution and transmission sectors.

The volume of electricity self-consumed by the grid in normal operation conditions is a result of different complex physical phenomenon.

Considering the characteristics of each type of physical phenomenon involved, specific mathematical models and methods have been developed, tested, and implemented for accurately calculate the associated electricity volumes. Thus, we presented the most largely accepted and used concepts for elaboration of the forecast. The most complex issue is the forecast of the self-consumption caused by Joule effect, and the paper is highlighting the most relevant challenges and proposing adequate solutions for each case.

The main aspects of the issue of so called "commercial losses" is also addressed in the present paper. This type of losses, usually characteristic to the electricity distribution sector, have a financial nature (there is no electricity consumed by the grid). Due to some metering errors or lack of measurements, there is a difference between the purchased and sold electricity volumes, therefore an associated financial loss.

Forecasting the self-consumption of the electricity grids is a complex and challenging objective but nevertheless particularly important. Some of the technical components such as magnetization and corona losses are very stable in time and, therefore easier to forecast accurately. The situation is different in case of conductors heating (Joule effect) when a complex load flows forecast is required. Also, the forecasts of the commercial losses must consider very uncertain and volatile social and economic input data.

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