Selected Extreme Value Problems in Electric Power Engineering

Cost Efficient Operation of Distribution Systems

Doctoral Dissertation Theses

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1 Introduction

Distribution System Operators (DSOs) are under constant pressure to operate their systems more and more efficiently. Efficient operation means among other things lower operating costs. Cost reduction (or cost avoidance) can be achieved in several ways, some of them are explained below.

Low Voltage (LV) network losses are reported to be relatively high in Hungary compared to several other EU countries. In order to implement proper LV loss reduction measures a cost-benefit analysis is essential, this means that an accurate knowledge of the magnitude and components of LV network losses is necessary.

The accurate knowledge of LV network losses has several other advantages. On the one hand it can be helpful in detecting electricity theft. (If for example the difference between energy measured at the transformer and the sum of electricity meter readings in the supplied area is significantly higher than the expected network loss, then electricity theft can be assumed.)

On the other hand, network losses are a non-negligible part of the daily schedules used in electricity market operations. A balance group is a group of producers, traders and consumers in which the planned value of all purchases and sales correspond. These volumes, defined for every quarter of an hour (schedule), are given by the balance group managers to the transmission system operator. If the balance group differs from its schedule (the actual consumption is higher or smaller than planned) the difference is balanced by the transmission system operator and this balancing energy (BE) is settled later with the balance group.

Since the schedules include losses, accurate loss estimation is necessary.

Additional costs can also be avoided if the actual consumption can be influenced in order to match the planned consumption. This can be achieved by Demand Side Management (DSM) techniques, among them by using direct load control methods. Direct load control can be used to remotely switch on and off groups of appliances, typically thermostatically controlled loads like electric storage water heaters.

However, direct load control can not only be applied to decrease balancing energy, but also to level the daily load curve of large groups of consumers, i.e. to decrease the difference between the minimal and maximal consumption during a day. It can be proved that this peak-shaving and valley-filling reduces network losses. An even more severe cost avoidance effect is experienced by power plants – this was one of the main reasons why direct load control systems have been developed: if a well-shaped load curve can be achieved, base-load power plants do not need to lower their production and the excessive use of expensive peak-load plants can be avoided.

This dissertation aims to contribute to the cost-efficient distribution system operation by presenting new models and algorithms in the following two topics:

- Models and Computation Procedures Used in Low Voltage Network Loss Estimation
- Modeling of Direct Controlled Loads and Optimization of the Switching Schedules.

Thus the underlying dissertation is organized in two major Sections, both are reports on research work performed during several projects.

2 Models and Computation Procedures Used in Low Voltage Network Loss Estimation

The first group of projects was initiated by several Distribution System Operators between 2005 and 2008. The aim of these projects was to examine the sources of low voltage network losses, to build appropriate domestic load models and measurement procedures to estimate the magnitude of these loss components. (The present work deals with the current dependent LV line active loss powers, denoted hereafter by the term “network losses” or simply “losses”.)

Section 2 of the thesis contains the models and algorithms developed during these projects.

Thesis 1

Most low voltage network loss estimation methods published in the literature (see Chapter 2.2.1) rely on either of the following information about the load supplied by the network:

- the percent loading of the analyzed network
- load profiles applied to different types of consumers (these profiles may differ for days of the week and for days of the year)
- very detailed load models that are based on load research performed using a large number of questionnaires (these models aim at modeling human behavior in using electricity)
- stochastic load models that treat consumer currents at a certain point of time as samples of an appropriately chosen statistical distribution.

These methods are not designed to use as input the currents measured at the transformer, i.e. measurement data that is specific for one certain network.
Further, in the literature no method has been found that treats loss components (time-variant consumption, reactive power, unbalance and harmonics) accurately in a common framework. Therefore the first major result of this work is summarized as below:

A new (deterministic) network loss computation procedure for low voltage residential distribution networks has been derived. This procedure relies on

a. one-week measurement of transformer secondary currents (or optionally, measured feeder currents) of each sequence and harmonic order (including the fundamental frequency components)
b. feeder section lengths and resistances
c. annual energy consumption of each consumer
d. measured or estimated currents of consumers (like schools, shops, etc.) with load profile dissimilar to the load profile of the majority of the consumers (households).

The recommended resolution of the measurement is one minute.

This method is based on

- *assigning currents to individual consumers by dividing the measured currents in proportion of the annual energy consumption of the consumers consumers (see Eqs. (2-15) and (2-19)), and*
- *defining “equivalent resistances” based on the line section resistances and the ratios α_k (which is the ratio of the annual electricity consumption of consumer k to the total annual consumption of the consumers supplied by the network under investigation), see Eq. (2-17).*

Using this procedure it is possible to determine the average weekly network loss power of a certain LV network based on on-site measurements with accuracy (4.2 % on average) better than most other methods published in the literature. The standard deviation of the estimation errors for different network/consumption scenarios is smaller than for any other published method (see TABLE 2-V).

This method is called the "Unified Loss Theory", because unlike other methods, this procedure gives an estimate of the components of the network loss, and is therefore suitable for cost-benefit calculations of loss-reduction investments. (See Eq. (2-22) and (2-23)).

This thesis was published in [Dán, 0678], [DánRaisz, 07], [DanRaisz, 08], [Dán, 08], [Raisz, 08], [RaiszDán, 08].

Thesis 2

The stochastic residential load models published in the literature (see Chapter 2.2.2) are either based on extensive load research and behavior modeling, or treat the current of consumers at different time-instances independently from the hour of the day, and from each other. Therefore these models are not applicable without modification in a loss computation procedure that uses measured aggregated current time-functions of consumers. Moreover, it was found that the statistical distributions used in these models do not match the distributions obtained by evaluating own measurements. Further, the stochastic residential load models found in the literature do not contain models for harmonic currents. Therefore the second major result of this work is summarized as below:

A new stochastic residential load model (called the "method of elementary appliances") and an identification procedure for the model has been elaborated. The model of one elementary appliance (described in detail in Chapter 2.5.1.1) consists of several empirical cumulative distribution functions that describe the usage times and currents (at fundamental and harmonic frequencies) of the appliance. The cumulative distribution functions are determined based on the one-week measurement of currents (each sequence and harmonic order, including the fundamental frequency components) of a small number of households. (The identification procedure is described in detail in Chapters 2.5.1.2 and 2.5.1.3.)

The model yields time-dependent stochastic currents of a household for fundamental and harmonic frequencies. The model is suitable for the accurate simulation of the stochastic variation of household currents, and is therefore applicable e.g. to LV loss evaluation.

This thesis was published in [DanRaisz, 08], [Dán, 08], [Raisz, 08], [RaiszDán, 08].

Thesis 3

The drawback of the deterministic loss computation procedure was that it was not accurate enough because

- there is usually no information about the exact connection phase of each consumer
- the procedure neglected the stochastic nature of residential consumption and assigned currents to individual consumers by dividing the measured currents using time-invariant proportions.

In order to overcome this drawback and to keep all the advantages, the third major result of this work is summarized as below:

A new stochastic network loss computation procedure for low voltage residential distribution networks has been derived. This procedure relies on

- *a. a stochastic residential load model ("elementary appliances")*
- *b. one-week measurement of transformer secondary currents (or optionally, measured feeder currents) of each sequence and harmonic order (including fundamental frequency components)*
- *c. feeder section lengths and resistances*
- *d. annual energy consumption of each consumer*
- *e. measured or estimated currents of consumers with load profile dissimilar to the load profile of the majority of the consumers.*

The recommended resolution of the measurements is one minute. (For a detailed description of the method Chapter 2.6.)

Using this procedure it is possible to determine the average weekly network loss power of a certain LV network based on on-site measurements with accuracy (on average 1.1 % deviation from the real loss value with a standard deviation of 1.2 %) better than other methods published in the literature.

Unlike other methods published in the literature, this procedure gives an estimate of the components of the network loss, and is therefore suitable for cost-benefit calculations of loss-reduction investments.

The accuracy of the method makes it also suitable for detection of electricity theft in a certain LV network, if the total energy is metered on the transformer secondary and if the seasonal correction below is used.

This thesis was published in [DanRaisz, 08], [Dán, 08], [Raisz, 08], [RaiszDán, 08].

Thesis 4

The deterministic and also the stochastic loss computation procedures rely on one-week measurements, since a full year measurement of the currents in all three phases at the transformer secondary with a one-minute resolution and for all appropriate frequencies is not feasible for the loss estimation of one single LV network. (However, installation of a simple energy meter at each MV/LV transformer used to be common sense for distribution system operators, and an energy meter that is capable of storing energy data weekly has become an inexpensive option.)

If the week of the measurement is not chosen properly, the computed weekly average loss power may differ significantly from the annual average loss power.

Literature research revealed no published methods to estimate the average annual loss based on the computed weekly average loss power.

Therefore the fourth major result of this work is summarized as below:

A method has been elaborated that takes into consideration the seasonal effects when estimating the average annual loss power based on the average weekly loss power. This method relies on a correction factor (see Eq. (2.31)) that is derived based on the week-by-week energy consumption profile of the supplied area under investigation for a whole year. Data for this consumption profile can be obtained either by installing appropriate energy meters at the transformer secondary, or by approximating it using load data published by the TSO or by using a sinusoidal approximation of the profile. The detailed description of the method can be found in Chapter 2.7.

This thesis was published in [Dán, 0678].

The presented methods have been implemented in a software package that has been delivered to the aforementioned DSOs. The results presented in the dissertation have been obtained by the use of this software package.

3 Modeling of Direct Controlled Loads and Optimization of the Switching Schedules

The second group of projects was started in 2003 by the Hungarian Energy Agency and was set forth by some of the Hungarian Distribution System Operators. The aim of these projects, as well as the numerous discussions with different players of the Hungarian power industry was to explore the possibilities of direct load control.

As a result of large investments, by the end of the 1980's, Ripple Control Systems have been installed in order to be able to fill up load valleys and clip demand peaks by remotely switching on and off groups of electric storage water heaters and storage space heaters from the dispatcher centers of the utilities. The change in the regulatory environment since the 90's, the recent installation of Radio Ripple Control Systems and the appearance of Smart Metering possibilities on the horizon opened new perspectives in the effective usage of the existing and the future direct load control systems.
After deregulation the Distribution System Operators (referred to as DSOs or sometimes "utilities"), the new owners of RCSs, began to change their switching schedules (timetables), since the legislative regulation did not make valley-filling and peak clipping their interest and responsibility any more. This resulted several times in conflicts with the interest of the Hungarian Transmission System Operator (TSO) which is still the increasing of valley loads so that no power plant (including the state-owned Paks NPP) has to experience difficulties selling energy (or lowering its production below a certain limit) during the low-demand period at night.

Section 3 of the thesis contains contributions to the effective usage of these systems in form of algorithms that seek an optimum between several conflicting objectives and constraints.

An important contribution is the construction of an appropriate hot water usage model and the solution of the measurement-based identification problem of the load model (that includes the hot water usage model).

In the literature no such hot water usage model and such identification procedure has been found.

The main contribution of this research is a method that enables the usage of direct load control for the purpose of the quasi on-line minimization of balancing energy, in a way that the objective of valley-filling (and optionally peak-clipping) is respected.

No method has been found in the literature to solve (or even deal with) the above problem.

During the course of this research two further sub-problems had to be solved:

I. Separation of the load curve without direct controlled loads (the "undistorted load curve") from the RCS load. Though in the literature no solutions have been found for this problem, the results achieved by the author of this dissertation are not formulated as separate Thesis, for two reasons:
   - The author is aware that some system operators have developed methods to solve the separation problem. These are presumably based on an approximate trial and error

approach. These methods were not available to the author, and therefore a comparison is not possible.
- The enhanced algorithm designed by the author has not yet been published, as already mentioned in Chapter 3.3.

II. Construction of an algorithm that optimizes the switching schedule of controlled load groups with the objective of valley-filling (and optionally peak-clipping) and taking into consideration the 90 MW step constraint and the consumer thermal comfort constraint. The results achieved by the author of this dissertation are not formulated as separate Thesis, for the following reason. The DSOs, with coordination of the TSO, are using such a method which has proven to work well in practice.
It has to be stressed, that the comparison of Fig. 3-3 (Original and undistorted load curve for the whole Hungarian System) and Fig. 3-12 (Result of the valley-filling algorithm: the undistorted load curve, the sum of the undistorted load curve and the optimized goal function and the resulting total load curve) could lead to the conclusion, that the method proposed by the author is much better than the one used in current practice, since it results in a valley load that is ca. 300 MW (8 %) higher, and at the same time it reduces the peak load. (Constraints are satisfied.)
However, the currently used method is not available to the author, and therefore a thorough comparison of the two methods, applying them under the same circumstances, is not possible.

Based on the above statements, the new scientific results are summarized in the two Theses below.

Thesis 5

A new physical load model for electric storage water heaters (ESWHs) has been developed based on previous models found in the literature. The novelty of the model is the (temperature-independent) stochastic hot water extraction rate sub-model, which is described in detail in Chapter 3.4.1.2.
A parameter-identification procedure has been developed for the above model that is based on load curve measurement data. The identification procedure is able to take into consideration hot water usage measurements – if they are available. The standardization of the hot water extraction rate to a constant temperature makes it possible to use hot water extraction measurements for the parameter identification process.
The parameter identification procedure is described in detail in Chapters 3.4.1.2 and 3.4.1.3.

With this model it is possible to accurately simulate the effect of different switching schedules on the load curve. The accuracy of the method (see Fig. 3-11) makes this model suitable for being used in a quasi on-line algorithm that minimizes balancing energy costs.

This Thesis has been published in [RaiszDan, 05], [Raisz, 06], [RaiszDan, 08], [DanRaisz, 08], [Dan, 09], [Raisz, 09], [Raisz2, 09].

Thesis 6

A new algorithm has been developed that is able to decrease the balancing energy costs by applying minor changes quasi on-line to the "base schedule". The deviation from the "base schedule" can be limited in three proposed ways:

- *using a time-based constraint,*
- *using an energy-based constraint*
- *applying an additional penalty term to the objective function*

in order to either comply with the valley-filling objectives and the constraints, or to relax these to a controlled extent.

It has been shown that using such methods it is possible to achieve a reduction in the balancing energy costs with arbitrarily limited deviation from the base schedule.

The algorithm and its modifications are described in detail in Chapters 3.6.2 and 3.7.1, respectively.

This Thesis has been published in [Faludi, 04], [RaiszDan, 05], [Raisz, 06], [RaiszDan, 08], [DanRaisz, 08], [Raisz, 09], [Raisz2, 09].

The proposed methods are ready to be implemented in a load management program. There are however difficulties in the near-future application of these methods, since several stakeholders of the electric energy industry have to agree on the application of such procedures, and also the legislative/regulatory environment has to be changed. The reason for this is that the owner of the load control system is the DSO, the load-shaping is required by the TSO and the balancing energy costs are to be paid by the balance groups.
The calculations and simulations presented in Chapter 3 have shown that RCSs (or RRCSs or similar direct load control systems) are very useful tools in shaping the daily load curve and in minimizing the balancing energy. It is therefore concluded that such direct load control systems should be maintained in the future and an appropriate legislative/regulatory framework should be elaborated in order to use these tools in the most efficient way in the deregulated environment for the sake of cost-effective delivery of electricity.

Though the topics of the two major Sections are fairly independent of each other, they have another common point besides the cost-reduction issues mentioned earlier.
The algorithms developed for the appropriate switching of remote controlled groups, the parameter identification of the models of thermostatically controlled appliances and also the parameter identification of the models used for loss estimation based on measurements involve *optimization procedures or extreme value finding procedures*.
This was the reason for the choice of the title of the underlying dissertation.

4 Publications on the Theses

4.1 Pubications on Theses 1-4

Dán, 0678 — Dr. A. Dán, D. Raisz et.al.: Supervision of LV network and measurement losses (KIF hálózati veszteségek, valamint a KÖF/KIF transzformátor körzetek mérési veszteségeinek felügyelete, ellenőrzése), Technical Reports prepared for three Hungarian DSOs, Dept. of Electric Power Engineering, Budapest University of Technology and Economics, Budapest, 2006, 2007 and 2008 (in Hungarian)

DánRaisz, 07 — A. Dán, D. Raisz, I.Nagy, J. Libor, Á. Szemerei, Zs. Gombás, Zs. Babarczi: Knowledge-based modeling of LV network losses (Kisfeszültségű hálózatok veszteségeinek tudásalapú modellezése): MEE 54. Vándorgyűlés, Konferencia és Kiállítás (Annual Convention of the Hungarian Electrotechnical Association), Tihany, Hungary, 22-24. Aug. 2007 (in Hungarian)

DánRaisz, 08 — A. Dán, D. Raisz, I.Nagy, J. Libor, Á. Szemerei, Zs. Gombás, Zs. Babarczi: Knowledge-based modeling of LV network losses (Kisfeszültségű hálózatok veszteségeinek tudásalapú modellezése): MEE 55. Vándorgyűlés, Konferencia és Kiállítás (Annual Convention of the Hungarian Electrotechnical Association), Eger, Hungary, 10-12. Sept. 2008 (in Hungarian)

Dán, 08 — A.Dán, D.Raisz: Unified Loss Theory and its Application on Low Voltage Networks, Int. Conf. on Renewable Energy and Power Quality, ICREPQ'08, 12-14.03.2008, Santander, Spain

Raisz, 08 — A.Dán, D.Raisz: A Novel Methodology for Measurement-Based Low-Voltage Loss Estimation, 6th International Conference on Power Quality and Supply Reliability, Pärnu, Estonia, 28.08.2008.

RaiszDán, 08 — Raisz Dávid, Dán András: A stochastic residential load model and its application to the unified loss theory, EUROPEAN TRANSACTIONS ON ELECTRICAL POWER 19:(8) pp. 1118-1130. (2008)

4.2 Pubications on Theses 5-6

Dán, 03 — Dr. Dán András, Dr. Tajthy Tihamér, Raisz Dávid: A villamosenergia rendszerérdek közvetítésének árszabályozási lehetőségei, különös tekintettel a vezérelt, külön mért tarifakategória szerepére és az alkalmazott zónaidőkre, Kutatási jelentés a Magyar Energia Hivatal részére, (Possibilities of Price-Based Regulation Mechanisms in Mediation of the Power System Interests, especially in Connection with Direct Controlled Appliances; Research Report prepared for the Hungarian Energy Agency), Budapest, Hungary, 2003

Faludi, 04 — Faludi A, Raisz D.: Investigation of the Power Management System according to the requirements of the liberalized market. Enhancements of the Ripple Control System. (in Hungarian) Technical Report, Power Systems and Environment Group, Dept. of Electric Power Engineering, Budapest University of Technology and Economics, 2004

RaiszDan, 05 — David Raisz, Dr. Andras Dan: Ripple Control as a possible tool for daily load balancing in an open electricity market environment, IEEE PowerTech Conference, 27-30.06.2005, StPetersburg, Russia;
DOI: 10.1109/PTC.2005.4524451

Raisz, 06 Raisz Dávid: Optimization of Ripple Control Switching Timetables for Daily Load Balancing and Minimization of Imbalance Energy, INTERNATIONAL JOURNAL OF INNOVATIONS IN ENERGY SYSTEMS AND POWER, Vol. 1 No.1, pp. 53-61. (2006)

RaiszDan, 08 Raisz Dávid, Dr. Dán András: A hangfrekvenciás fogyasztói befolyásolásban rejlő lehetőségek (Unexplored Possibilities in the RCS, in Hungarian), in: Proceedings of the III. BMF Conference in Energy: "Fogyasztói együttműködés a fenntartható villamosenergia ellátásért" Budapest, Hungary, 2008.10.25. pp. 21-31. (ISBN: 978-963-7154-84-3)

DanRaisz, 08 Raisz Dávid, Dr Dán András: Vezérelt fogyasztói csoportok modellezése és különböző célfüggvények szerinti vezérlési programjuk meghatározása (On Modeling Groups of Remote Controlled Consumers and on the Determination of the Switching Schedules, in Hungarian), 55th Annual Convention of the Hungarian Electrotechnical Association, Eger, Hungary, 10-12.Sept.2008

Dan, 09 Dr Dán András, Raisz Dávid, Gombás Zsolt, Kovács Gábor, Torda Balázs: SMART metering, vezérlési lehetőségek a hálózat-üzemeltetés terén (Smart Metering – Control Options in System Operation, in Hungarian), 56th Annual Convention of the Hungarian Electrotechnical Association, Balatonalmádi, Hungary, 9-11.Sept. 2009.

Raisz, 09 Raisz Dávid, Dr Dán András: Vezérelt fogyasztói csoportok modellezése és különböző célfüggvények szerinti vezérlési programjuk meghatározása (On Modeling Groups of Remote Controlled Consumers and on the Determination of the Switching Schedules, in Hungarian), ELEKTROTECHNIKA 102:(1) pp. 5-8. (2009), Budapest, Hungary

Raisz2, 09 Raisz Dávid: Vezérelt fogyasztói modellek és a vezérlésből fakadó előnyök (Models of Remote-Controlled Load and Advantages of Remote Load Control, in Hungarian), Proceedings of the IV. BMF Conference in Energy, 17th Nov. 2009, Budapest, Hungary

Horváth, 10 Horváth Dániel: Vezérelhető fogyasztók kapcsolásának optimálása a mérlegköri kiegyenlítő energia csökkentése figyelembe vételével (Optimization of RCS switching time schedules), Project Laboratory Report (in Hungarian), Dept. of Electric Power Engineering, Budapest University of Technology and Economics, Budapest, Hungary, 2010; *supervisor: David Raisz*

4.3 References to Publications on the Theses

Kadar, 08 Dr. Kádár Péter: A fogyasztói és áramszolgáltatói együttműködés célja és lehetőségei (Goals and Possibilities in a User-Utility Cooperation, in Hungarian), Proceedings of the III. BMF Conference in Energy: "Fogyasztói együttműködés a fenntartható villamosenergia ellátásért" Budapest, Hungary, 2008.10.25. pp. 9-19. (ISBN: 978-963-7154-84-3), Citing [Dán, 03]