Modelling and Aggregation of Loads in Flexible Power Networks – Scope and Status of the Work of CIGRE WG C4.605

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Abstract: High penetration of renewable energies presents a new challenge for conventional power system. Such penetration of renewables resulted in renewed interest in load modeling which may include small renewable generation as a portion of loads. A new CIGRE working group was established to provide guidance with respect to load modeling of new types of load including renewables using measurement data and historical data. This paper summarizes major results of the work of this WG after two years' activities. Although the deliverables are not fully completed, beneficial recommendations of the load modelling such as selection of load model structure, picking up suitable data, proper approach for deriving load model parameters, requirement of measurement data, etc. are introduced in this paper identifying clearly advantage and disadvantage of various load modelling approaches.

Keywords: Load model, load modelling, transmission and distribution network analysis.

1. INTRODUCTION

An important requirement for the correct analysis of planning, operation and control of both distribution and transmission networks is accurate representation of steady state and dynamic characteristics of system loads. However, load models and their parameters currently used by utilities and system operators for power system analysis are generally not in public domain (IEEE Task Force on Load Representation for Dynamic Performance, [1993]), and there is a level of uncertainty regarding industry acceptance of research efforts in this area. For example, during the power system stability analysis, the emphasis is mainly placed on modelling of power generating units, while load models are regarded as secondary, although the influence of load representation on the stability was recognized a long time ago (e.g. Mauricio et al. [1972], Concordia et al. [1982]). Power system engineers began to pay more attention to the load modelling since the Sweden blackout of 1983 (Brereton et al. [1957]), as inappropriate representation of system loads has usually led to the discrepancies between the recorded and simulated system responses (e.g. Brereton et al. [1957], CIGRE Committee No. 13, [1964], IEEE Task Force on Load Representation for Dynamic Performance, [1995]). Recently, there is a renewed interest in both industry and academia for load modelling, due to appearance of new types of loads and modern nonlinear electrical and electronic equipment offering increased efficiency and controllability (e.g. CFL/LED light sources, adjustable speed drives, inverter-interfaced distributed generation, plug-in electric vehicle chargers, etc.)

A new CIGRE working group (WG) C4.605: "Modelling and aggregation of loads in flexible power networks" was established in February 2010, in order to address above mentioned and other relevant issues related to the general area of load modelling. Members of the WG C4.605 are Jovica V Milanovic (UK) - (Convener), Odin Auer (AR), Alberto Borghetti (IT), Sasa Djokic (UK), Zhao Yang Dong (AU), Anish Gaikwad (US), Andrew Halley (AU), Karim Karoui (BE), Lidija Korunovic (RS), Dmitry Kosterev (US), Joseph Leung (AU), Bernard Lesieutre (US), Sergio M Villanueva (ES), Jin Ma (CN), Julija Matevosyan (US), Dumisani Mtolo (ZA), Pouyan Pourbeik (US), Fernanda Rosende (PT), Stefan Sterpu (FR), Fortunato Villella (BE), Koji Yamashita (JP). This paper presents the scope and status of the work of CIGRE WG C4.605 until November 2011. After about one and a half year of work, WG C4.605 published two papers (Matevosyan et al. [2011], Yamashita et al. [2011]) and produced other results discussed further in this paper. The work is roughly divided in six areas, each of which will have a separate chapter in the final report:

Chapter 1: Introduction, Index of Terms and Nomenclature

Chapter 2: Overview of Existing Methodologies for Load Model Development

Chapter 3: Overview of Existing Load Models

Chapter 4: Recommended Methodologies for Development of Load Models (Measurement based and component based load modelling)

Chapter 5: Load Models for Typical Classes of Customers

Chapter 6: Modelling of Active Distribution Network Cells

2. OVERVIEW OF EXISTING METHODOLOGIES FOR LOAD MODEL DEVELOPMENT (CHAPTER 2)

This part of the work in WG C4.605 will provide a critical overview of existing methodologies for load modelling, with a detailed discussion of component-based and measurement-based approaches, clearly identifying their advantages and disadvantages.

As mentioned, load characteristics have significant influence on both steady state and dynamic performance of power systems. Accordingly, correct analysis of power systems requires accurate load models, together with appropriate representations of generation, transmission and distribution parts of the system. Load modelling, however, is not a simple task, as there are a number of factors that should be taken into account during the analysis:

1) Diversity in the types and characteristics of loads, which change both spatially (from one geographic or network location to another) and temporally (short-term, medium-term and long-term variations in both individual and aggregate load demands);

2) Lack of accurate and continuous information about the changes in load structure (what types/components of loads are connected) and load composition (what are the percentage contributions of different load components to the total demand);

3) Difficulties during the assessment and validation of load model accuracy, which apply to both laboratory tests of electrical equipment and field/network measurements with naturally occurring or intentionally made disturbances.

Fig. 1 illustrates general procedure for load modelling and identification of load model parameters. Only one procedure is required for deriving parameters of a static load model, while in case of combined dynamic and static load models, also known as “composite load models”, percentage contributions of static and dynamic load components to the total demand should be also identified.

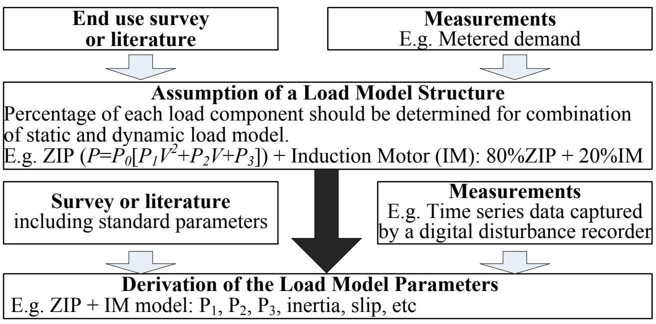

Fig. 1. General load modelling procedure.

As shown in Fig. 1, measurements, end-use surveys and results from available literature can be used to determine percentage of each load component and load model parameters. Accordingly, two general approaches can be distinguished for determining load characteristics and formulating corresponding load models:

Measurement-based load modelling, also known as “top-down” approach, uses normally occurring or intentionally made disturbances and events, which are recorded by the measurement and data acquisition equipment located at representative substations and feeders (e.g. at bulk load supply points), to derive the aggregate load characteristics. The available measurements are usually post-processed, in order to select events/disturbances suitable for parameter identification of the assumed aggregate load model, i.e. to match postulated load model to the measured data. Measurement-based approach has the advantage of obtaining aggregate load model directly from the actual system/network to which the modelled load is connected. The main disadvantage is that aggregate load model obtained at one network location may not be applicable to the other parts of the system, unless the load composition there is very similar to the initial load model. Another disadvantage is that the assumed aggregate load model, although providing good mathematical representation of the measurements, may not correspond to the actual load structure and may not be accurately decomposed in the actual load components.

Component-based load modelling is also known as “physical” or “knowledge-based” modelling approach. It is a standard approach for modelling an individual type of load during its design or performance assessment. When component-based load modelling is used to obtain composite load models, this is often denoted as a “bottom-up” modelling approach, as the aggregation is performed starting from the individual load components. Composite load model can be obtained without any measurements if the following information is available: a) the knowledge of the load structure connected at a point of aggregation, b) the typical characteristics/models of the individual loads in the corresponding load structure, and c) the load composition of the total aggregate demand. The main advantage of this load modelling approach is that it does not require field measurements if the characteristics and percentage contributions of all load components in the aggregated demand are *a priori* known (e.g. from available statistical data on equipment use). The main disadvantage of this approach is difficulty in gathering accurate information on the actual load compositions. Another disadvantage is potential error in the load model when a new or undefined type of load, which does not belong to any previously available load category, is present in the load mix.

Measurement-based and component-based load modelling approaches can be combined, in order to obtain more accurate load models (e.g. Han et al. [2009]). For example, when measurements are performed at the locations where load components are known (i.e. at substations supplying specific residential or commercial load sectors), measurements can be used to derive more reliable percentage contributions of known load components to the total aggregate demand (instead of using statistical data on equipment use). It is expected that combining measurement-based and component-based load modelling will increase in the future.

3. OVERVIEW OF EXISTING LOAD MODELS (CHAPTER 3)

Another important part of the work in WG C4.605 is a comprehensive overview of existing load models, which can be generally divided into two main groups: static load models and dynamic load models (See Fig. 2). Both static and dynamic load models should provide information on relevant load characteristics, usually active and reactive power demands and responses to variations in system voltage and system frequency. The main difference is that dynamic load models provide this information as a function of time, while static load models are time-invariant.

Static load models are used for representing the loads that respond instantaneously to a change in voltage and/or frequency (e.g. resistive loads, or loads generally found in residential load sector). Dynamic load models are used for representing the loads with time-dependent response to a change in voltage and/or frequency (e.g. induction motors, or loads generally found in industrial load sector), which is based on the previous states of both system and load, and additionally influenced by system-load interactions during and after the transition from the previous to the next state.

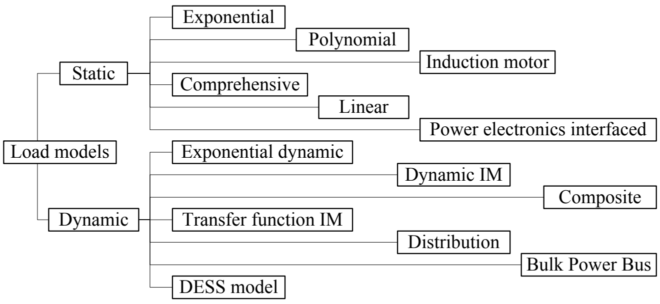

Fig. 2. Classification of static and dynamic load models.

Most frequently used static load models are exponential, second order polynomial (also called "ZIP model") and linear models. These load models have several variants, e.g. with and without frequency-dependent terms, as frequency variations during the steady state operating conditions (for which static load models can be directly used) are very small and usually can be neglected. They are valid for relatively small variations of voltage/frequency, while comprehensive static load model (consisting of a combination of polynomial and two exponential models) can be used for larger disturbances. For aggregate static load models with a large participation of induction motors, static models of induction motors should be used. The overview of existing load models by WG C4.605 will also discuss models of power electronic load, whose participation in the total demand was steadily increasing over the last few decades and is expected to grow even more in the future.

Among a number of discussed existing dynamic load models, the most frequently used are exponential dynamic load model (for modelling predominately residential loads) and dynamic induction motor load models (for modelling loads consisting mostly of induction motors). For modelling aggregate loads containing both static loads and induction motor loads, composite load model (consisting of a static load model in parallel with an equivalent induction motor model) should be used. One broadly used variant of composite load model is ZIP-motor model, while some other models incorporate saturation characteristic of transformers and motors. Other discussed dynamic load models include: distribution load model, bulk power bus load model and the model of Distributed Electric Storage System (DESS), as well as the load models of new and emerging devices.

This part of the WG C4.605 work will also provides tables of identified load parameters for all types of loads and load classes available in existing literature. Some of the examples include full/equivalent circuit models of power electronic loads, and single-phase induction motor models (as in e.g. residential air conditioners), capable of representing stalling operating conditions.

4. RECOMMENDED METHODOLOGIES FOR DEVELOPMENT OF LOAD MODELS (CHAPTER 4)

In this part of the work, WG C4.605 will provide set of recommendations for load model development, regarding both measurement-based and component-based load modelling approaches. Currently, there are eight recommendations for measurement-based approach and six recommendations for component-based approach.

4.1 Recommendations for Measurement-based Approach

i) Recommended Types of Measured Data: Suitable types of measured data depend on the type of system study, or analysis of the specific power system phenomena. In general case, instantaneous values are not necessary, as rms values can be used for the development of most load models. Typically, the types of signals to be measured come from system fault measurement data out of the system operations department of a network service provider company. The RMS and phase values of three phase voltages and currents together with system frequency are normally available from measurement. Further analysis are needed to calculate the values for real and reactive powers in order to perform load model identification work.

ii) Recommended Locations of Monitoring Devices: The recommended locations are bulk load supply points at primary or secondary substations. The circles in Fig. 3 represent monitors of current at the feeder head, or low voltage side of a step-down transformer, while square represents location for monitoring load bus voltage. Recommended duration of measurements depends on the type of study or analysed power system phenomena. For example, 2 seconds of measurement data might be sufficient for short-term voltage stability studies, while 10 seconds measurements are necessary for frequency stability studies.

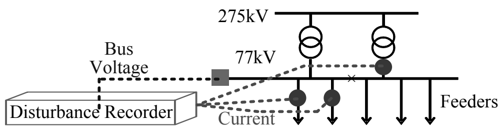

Fig. 3. Example locations of measurement devices.

It is worth noting that it is difficult to perform specific system disturbances in order to obtain system response data for load modelling purpose. Historical data on system faults are needed for this purpose. The disturbance data recorded need to have sufficient variations in voltage and real and reactive power data series to facilitate the load model parameter identification functionality.

iii) Recommended PQVF Data Collection Procedures: Measurement data are normally captured using digital fault recorders, power quality monitors and similar measurement devices. They normally use an electrical transducer to convert instantaneous three-phase voltages and currents into required quantities, such as rms active/reactive powers and voltage/current values with phase values. The response time and sample rate of the electrical transducers are very important for derivation of load model parameters in measurement-based approaches, as system faults are normally cleared within 70 ms-250 ms. The desired range of the response time and sample rate are between 10 ms and 100 ms and higher than 64 samples/cycle, respectively.

iv) Recommended Data Filtering and Processing Techniques: Although the high sample rates are necessary for the PQVF data conversion, they are not always required for the derivation of load model parameters. Accordingly, various data filtering, such as DFT-based sliding window, moving average and resampling techniques are often applied. For example, 0.5-1 sample/cycle rate is sufficient for the development of a static load model, as transient/dynamic behaviour of load can be ignored. When the transient behaviour of loads is to be captured and subsequently modelled, a rate of 50-60 samples/cycle should be used.

v) Recommended Type of Field Test: Measurement data are normally captured when naturally occurring system disturbances are recorded, such as system faults, load changes, or power plant tripping. Again, suitable disturbance from the load modelling point of view will depend on the type of the study. For example, frequency deviations occur when there is an unbalance between the total supply and total demand, and data measured after plant tripping are suitable for the development of frequency-dependent load models, which should be used in frequency stability studies. On the other hand, measurements of deep voltage sags should not be used for deriving load model parameters, as undervoltage self-disconnection of loads is normally not considered for the load models (see also *Section 4.1.viii*). As collecting the random naturally occurring system events is a time consuming process, measurement data for load modelling can also be captured when intentional disturbances are applied, e.g., transformer tap changes, or shunt capacitor/reactor switching. However, because the resulting voltage/power changes are usually small, such data are generally suitable only for deriving static load model parameters.

vi) Recommended Typical Load Model Structures: Nonlinear optimization techniques are widely used for deriving load model parameters from the measurement data. Normally, measurement-based approach is applied to static load models and simple dynamic load models. If measurement-based approach is applied to composite load models, the number of parameters to be identified becomes very high, and selecting the proper set of initial values is vital for sufficient accuracy of the derived load model parameters.

vii) Suggestions on Continuous Measurements: In the past ten years, capabilities of various measurement devices have been significantly improved and their numbers in power systems have substantially increased. This opened a possibility for the continuous measurement and capture of data required for load modelling. In general, longer and more detailed data sets will result in better solutions and improved accuracy for nonlinear least-square modelling methods., However, in case of measurement data for identifying load model parameters from the load responses, longer data records are not always suitable, due to the existence of the natural changes in load structure after the initial voltage or frequency change.

viii) Suggestions on Undervoltage Load Self-disconnection: It is a well-known fact that most system loads will disconnect (or "trip") on undervoltage conditions after a deep and long voltage sag (so called load self-disconnection). Unless the target load models incorporate load self-disconnection, the measurement data which include voltage sags and undervoltages below 80% of nominal voltage should not be used.

4.2 Recommendation for Component-based Approach

i) Recommended Method for Development of Aggregate Load Models: Based on billing data or load inventory surveys, system loads can be classified in many ways. However, only three general classes of loads are typically considered: residential, commercial and industrial, with each class subdivided further into related individual load components. It is generally not possible to define generic aggregate load models for the industrial class, as the specific industrial processes/loads at different sites are usually not comparable across the whole industrial load sector. However, general aggregate load models may be defined for residential and commercial load classes, as there is less diversity between the individual load components used there.

ii) Recommended Individual Load Components: Practically all types of electrical equipment and devices found in residential load class can be divided into five general load modelling categories (Collin et al. [2011]): a) power electronics, or switch-mode power supply (SMPS) loads, b) resistive loads, c) energy efficient light sources (CFL and LED loads), d) single-phase and three-phase directly-connected motors, and e) drive-controlled motors (adjustable speed drive, ASD loads). Harmonic legislation and technology/circuit variations in equipment design effectively introduced sub-categories within some of the general load modelling categories. As a part of the aggregate low voltage (LV) load model, some micro and small-scale distributed generation (DG) may be connected in parallel to the LV loads, while medium and large-scale DG units may be connected at medium voltage (MV) and higher voltage levels. Fig. 4 shows general load modelling categories and sub-categories commonly found in the residential load class.

The above classification of load components makes difference between the "end-use load type" (i.e., a group of individual loads with the same purpose, which may have same or different electrical characteristics) and "load modelling category" (i.e. a group of different electrical devices which, for the purpose of load modelling, have the same or similar electrical characteristics). For example, incandescent lamps, compact fluorescent lamps, high-intensity discharge lamps and LED light sources all belong to the same end-use type ("lighting load"), but they have different electrical characteristics and should be represented with different load modelling categories.

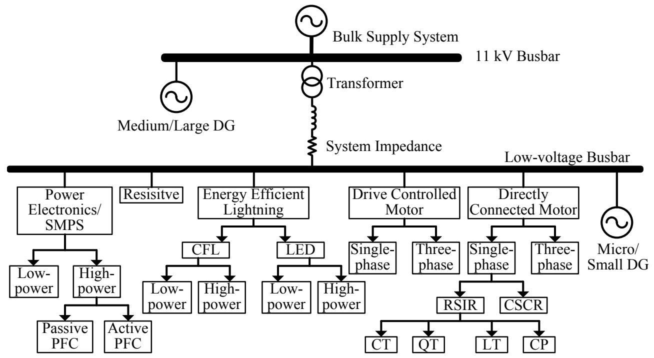

Fig. 4. Load categories and sub-categories in the residential load class.

iii) Recommended Types of Data: After identifying individual load components (i.e. structure of aggregate load), the next step is to identify load composition (i.e. percentage contributions of individual load components to the aggregate demand). This information can be obtained from billing records and surveys, or from the representative statistical data. Both structure and composition of aggregate load change on a short-term, medium-term and long-term basis, but typically these variations are represented for different times of the year (e.g. summer peak, winter peak, fall, spring, etc.), so that a specific load model for the given season can be used.

iv) Recommended Mathematical Models for Individual Load Components: Most of the aggregate loads which do not include directly connected motors can be represented with static load models, such as exponential or second order polynomial model. Aggregate loads with directly connected motors should include induction motor model, while loads with drive-controlled (i.e. inverter-driven) motors can be represented as the static load model with constant power characteristics, or using a designated power electronic load model.

v) Recommended Representation of the Distribution and Subtransmission Network: Due to their number, volume and complexity, system loads connected at MV and LV distribution networks are generally represented as aggregate load models in power system analysis. These aggregate load models will typically include all network components (overhead lines, cables, transformers, etc.), the actual connected load and, possibly, some micro, small and medium-scale distributed generation systems. Therefore, the development of accurate aggregate load models requires correct representation of both network components and network configurations (supplying, e.g. minimum or maximum system loads), as well as the network voltage/reactive power controls (volt-var regulation) and distributed generation.

vi) Recommended Dealing with Missing Data: When some data or information required for the development of component-based load models is missing, a dedicated measurement campaign can be devised, or general statistics on energy consumptions and ownership of different electrical devices can be used in combination with processing of habitual and equipment end-use statistics. When some data are missing for measurement-based modelling approaches, the model structure should be selected according to the available data set. It is noted that the data set should be informative enough to estimate the model parameters of the model structure to be selected. Since system behaviour that is not represented within the data set cannot be described by the model unless prior knowledge is explicitly incorporated, the model structure to be adopted should be selected accordingly.

5. LOAD MODELS FOR TYPICAL CLASSES OF CUSTOMERS (CHAPTER 5)

In this part of the work, WG C4.605 will provide models of typical "load classes" (also known as "load sectors"), which are generally defined as the aggregations or collections of loads from different load categories (see *Section 4.2.ii*), representing the typical structure and composition of electrical devices found in specific end-use applications, where similar activities and tasks are performed. This usually results in inherent similarities in characteristics and patterns of active and reactive power demands of end-users from the same load sector, allowing the use of same or similar load models for the representation of their aggregate demands.

The aggregate system loads will typically consist of many load classes/sectors, which are usually grouped into the three general sectors: residential, commercial and industrial. Variations in type, location and size of the buildings where these loads are present, as well as in the ways the loads are used, will introduce further load sub-sectors. For example, although the purpose of every residential dwelling is identical and, generally, the individual loads used there will be similar, it is possible to divide residential sector into four sub-sectors based on the location, size and type of dwelling, as well as the characteristics of supply network: highly-urban, urban, sub-urban and rural. Commercial load sector has greater variations and more sub-sectors, as the functions of the buildings and businesses found there are much more diverse. One of the possible classifications of commercial load sector is in: offices, communication & transport, retail, sport & leisure, health, hotel & catering, warehouses, and education. Existing and newly developed load sector models will be discussed, and one example of the aggregation methodology will be provided in this part of work.

6. MODELLING OF ACTIVE DISTRIBUTION NETWORK CELLS (CHAPTER 6)

This part of the work is dedicated to modelling of active distribution network cells (ADNC) and micro-grids (MG). The ADNC represents a network bus, or part of the network consisting of several buses, where a significant amount of DG is connected and which at specific periods of time (e.g. at minimum loading conditions) is a net exporter of active power, but at other time periods (e.g. at maximum loading conditions) may be a net importer of active power. MG is a particular case of ADNC which, according to (European Research and Development Project MICROGRIDS [2002]), comprises a LV network with loads and several microgeneration systems connected via power electronic interfaces. Additionally, MG implements a hierarchical control and management system at both local and central levels, allowing MG to operate as a flexible active cell either when interconnected with the MV distribution network, or when isolated from it.

Increasing penetration levels of both medium/large DG in MV networks and micro/small DG in LV networks require development of new aggregate models suitable to represent the behaviour of ADNC and MG with reduced complexity and computational requirements in the corresponding numerical simulations. Similarly to the component-based approach in load modelling, the ADNC can be modelled as a combination of aggregate system load components (using, e.g. composite load models) and aggregated generation components (using, e.g. suitable model(s) of DG present in the ADNC). This approach is directly applicable to relatively simple distribution network cells with a small number of distributed generators. Since wind-based generation is currently one of the main DG technologies, the work so far covered state of the art in aggregated modelling of wind-based generation (at all scales: large, medium, small and micro), while other distributed generation technologies will be considered in the future.

For complex ADNCs with a large number of distributed generators of diverse types and sizes, the entire ADNC can be represented by an equivalent model. Since conventional dynamic equivalenting techniques are not recommended for deriving aggregated models of ADNC, suitable modelling approaches are based on system identification techniques: black-box approach and grey-box (physical) approach.

The black-box approach is applicable in cases when ADNC model structure is not *a priori* known. The concern of the modelling is, therefore, to map the input data set to the output data set, so that the response from the model and the actual system are as close as possible. This approach is based on Artificial Neural Networks. On the other hand, the grey-box approach is suitable when some information about the ADNC structure is available, but not the exact composition of physical components. The ADNC can then be represented as a combination of physical components, e.g. as shown in Fig. 5. The model parameters are estimated based on measurements.

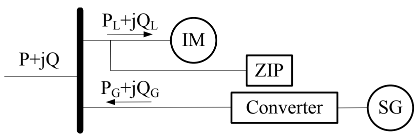

Fig. 5 Equivalent ADNC model including distributed generation.

This part of the work also discusses system identification procedures, data collection and processing, model structure selection, estimation of model parameters and model validation procedure for both modelling approaches. Available grey-box and black-box ADNC and MG models are presented, and their advantages and limitations are discussed. Generally, black-box models are capable of representing the behaviour of an ADNC and MG under different operating conditions with high accuracy, but they require considerable computational effort, frequent user interaction, large data sets and their validity is restricted to the systems for which they were developed. The grey-box models can overcome these weaknesses, as the computational efforts are significantly reduced and their validity is extended. Knowledge about the system allows selecting an appropriate model structure and the size of the data set can be significantly reduced, since prior knowledge is explicitly incorporated into the model. In addition, grey-box models can be more easily integrated in power system simulation tools.

6. CONCLUSIONS

This paper reports on the scope and status of work of CIGRE WG C4. 605 as of November 2011. Currently available results and outcomes are presented and discussed, while the final CIGRE Technical Report with guidelines for modelling and aggregation of loads in existing and future power networks will be published in June 2013.

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