Concepts and Representations to Analyse the Grid Services Provided by Electrical Systems and Buildings

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Abstract. The increasingly higher energy system integration requires the formulation of multi-energy system representations that account for the interactions among electrical and thermal phenomena, satisfying technical and comfort constraints. The traditional models for analysing electrical and thermal systems have been developed independently, also because of the different time scales involved in the related phenomena. Thermal systems and buildings are becoming possible contributors of services to the electrical grid, mainly owing to energy shifting. Therefore, the role of the thermal side in providing grid services has to be appropriately established. This paper recalls the types of analyses carried out for an electrical grid, shows the differences with respect to the analyses of thermal systems, and highlights the representation of the thermal phenomena associated with the buildings in the models used to study the provision of grid services.

Keywords: Grid Services, Electrical and Thermal Models, Thermal Capacity.

1 Introduction

The operation of electrical systems in the electricity market framework has been established and refined over two decades. The energy transition process with progressive electrification of the final needs is leading to substantial changes in how the energy systems are analysed to determine their operation and performance. The wholesale market structure typically includes the day-ahead energy market, the intraday market, and the balancing market, activated at different time scales. The eligible market players may participate in one or more of these markets.

In the balancing market (close to real-time), the eligible players submit offers for reducing or increasing generation and/or demand. The balancing of supply and demand has become challenging, primarily because of the growing diffusion of variable renewable energy sources, which generation is uncertain. This makes it difficult to balance generation and demand during time properly. Moreover, unbalance could result from sudden changes in the net power (i.e., generation minus demand) seen from the nodes of the electrical grid.

The characteristics of the eligible players have changed during time, progressively opening the participation to the balancing markets to more providers. For example, at the European Union level, a guideline on electricity balancing was established in 2017 by the Commission Regulation 2017/2195, amended by the successive Regulations 2021/280 of 22 February 2021 and 2022/828 of 25 May 2022 (the consolidated text currently adopted is available [1]). Among its aims, the regulation explicitly indicates "*facilitating the participation of demand response including aggregation facilities and energy storage while ensuring they compete with other balancing services at a level playing field and, where necessary, act independently when serving a single demand facility*". This aim allows new players providing demand response services to participate in the balancing market. A further aim refers to facilitating the participation of renewable energy sources.

In this evolving context, the growing interactions among multiple energy systems and carriers have opened new opportunities to provide services in various markets. For this purpose, the possibility of exploiting more sources to provide grid services is increasingly considered. The impact of thinking buildings as grid service providers has been analysed recently and is the subject of an increasingly higher number of research contributions. A current research gap is how to quantify the power demand variation of the buildings without sacrificing the quality of the internal services of the buildings (e.g., indoor thermal comfort) [2].

There are different ways to address the contribution of buildings in the analysis of the power and energy system referring to the grid connection point:

1. The buildings are considered *individual entities* (for example, to understand temperature variations), modelled by using the relevant parameters of the envelope and the indoor ambient through grey-box models [3]. Incorporating the buildings model into the electrical network model is still a challenging task. Building inertia can be considered as a special type of thermal energy storage, where external energy sources charge the thermal energy content, while the discharging is represented by a discharge losses coefficient [4].
2. The buildings are considered by modelling the relevant *parameters* of the envelope and indoor ambient, together with the *sources* of heat/cooling (for both the model of the building and the grid), as in the dynamic thermal model of aggregate buildings [5], adopting a data-driven approach for multi-zone buildings aggregated into a single zone. The virtual battery model has also been used to address energy storage and building flexibility [6]. For using the virtual battery model, the resolution in time of the data should be sufficiently high (the classical 15-min resolution is not sufficient).
3. The buildings are addressed by considering *all the internal systems* (including internal electrical generation such as photovoltaic systems or electric vehicles, as well as thermal generation and different kinds of energy storage systems), managed by a buildings energy management system (BEMS) to determine the power flow at the grid connection point that satisfies the operational grid constraints [7]. The models of the buildings managed by the BEMS could include the RC model of the building, the heating, ventilation, and air conditioning (HVAC) system, inflexible and flexible loads, electric vehicles, local energy storage, and photovoltaic generation [8]. If the BEMS has an interface with the grid, the grid services could be market-related (for energy, regulation and reserves), system-related (considering peak power, voltage control, or grid losses), or community-related (taking

into account the power and energy exchanges inside the community). Multiple buildings can be considered within a coordination framework developed to provide grid services [9]. More generally, the overall model includes the flow of information, becoming a cyber-physical system interconnected with the grid and interacting with the energy markets [10].

There is an ongoing debate on how buildings can provide effective grid services. For this purpose, the grid services can be partitioned in different ways, e.g. [11]:

- *Energy shifting*, with changes in the operational scheduling with respect to a reference situation considered as the baseline (established by considering constraints on these changes expressed as limits in the shifting windows).
- *Flexibility reserve*, for managing the ramps occurring in the net power demand and the fluctuations depending on the errors in forecasting the variable energy resources, with a time scale of about 20–30 min.
- *Contingency reserve*, aimed at increasing the available generation after missing a generation or grid component, with a time scale of about 10 min.
- *Regulation reserve*, for balancing demand and supply in the time scale of seconds to minutes, to mitigate frequency variations in normal operation or immediately after contingencies.

Some of the major challenges are remarked on in [2], mainly concerning how the system modelling for grid-connected electrical systems and thermal systems interacting with the grid has to be established. Most models come from the specific background of electrical engineers and specialists in buildings, who developed these models without direct interactions. Therefore, simply adapting these models is a critical issue. Moreover, using only one type of model that satisfies all the requirements could be difficult or even impossible. The conclusions indicated in [2] point to the directions of equation-based modelling, co-simulation with the coupling of the different types of models, and automation of the simulation workflow, as well as model-based co-design (to optimise the design and the operation strategies), and incorporation of model-based approaches with machine learning techniques.

This paper follows the line drawn in [12] for identifying the aspects that could create a bridge between applications in power and energy system analysis and applications referring to buildings, aiming to provide services to the electrical grid. Other aspects concerning planning and adequacy studies are not discussed. Section 2 recalls the electrical phenomena and typical types of analysis of the electrical systems, which rarely have a connection or a counterpart in the analysis of the thermal systems in buildings. Section 3 refers to thermal phenomena and representations of buildings interacting with the grid. The last section summarises the conclusions.

2 Assessment of electrical grid phenomena

2.1 Steady-state power flow calculations

In power system studies, the *power flow* solver is the basic tool for determining all the grid operational variables in steady-state conditions, starting from the electrical network data, load data, reference active power generation data (with the generations at one or mode nodes not fully assigned a priori, to compensate for the grid losses), and the constraints on components and the grid. The power flow equations are a set of non-linear algebraic equations solved by using specific techniques depending on the characteristics of the electrical network. One of these characteristics is the voltage level, which affects the types of network parameters qualitatively. For example, in the high-voltage transmission meshed network, the branches are typically reactive, leading to the conceptual decoupling between the active channel (linked to active power and frequency) and the reactive channel (linked to reactive power and voltage magnitude), enabling effective use of the fast decoupled power flow [13]. Conversely, in medium-voltage distribution networks, the network is radial or weakly-meshed, and the branches are prevailingly resistive, so that a simpler power flow solver can be used [14] with no decoupling between the active and reactive channels.

About load models, the typical load representations consider the variations of active and reactive power with respect to voltage magnitude and frequency. The dependence of power on temperature is generally not represented in the load models for power flow calculations. Some representations have considered the dependence on the temperature of the network parameters [15]. The relation between temperature and conductor resistance is expressed in analytical form, depending on the ambient temperature and on the current flowing in the conductor. An extensive temperature-dependent representation of network, generations and loads may lead to the formulation of a fully temperature-based power flow, provided that the information on the ambient temperature is available with sufficient accuracy and resolution in time.

2.2 Variable time series in normal conditions

The power flow calculations do not specify any time frame at which the calculations are carried out. The data and results refer to power, not to energy. Virtually, the power flow could consider instantaneous power. However, the instantaneous power is not measurable in practice, being determined as the average power in each time interval. Thereby, power flow calculations refer to the time interval at which the data are provided. Considering that the electrical quantities in the grid could have a large variability during the day, solving the power flow for a remarkably long interval (hours or days) does not make sense. The typical calculations are carried out by considering, at most, the average power for hourly time intervals. Suppose the analysis of interest spans over a longer time frame and the time series of the data are available at given time intervals. In that case, executing more power flows for successive time intervals is possible. Hence, no time coupling among the variables is generally considered, and the power flows are solved independently. However, if time couplings over the variables must be included, it is crucial to introduce the constraints from a time interval to the next one.

The *Quasi-Static Time Series* (QSTS) analysis of the grid [16] considers the variability in time of generations, controls and other aspects depending on time. Generally, the time intervals range from seconds to minutes. The instances of the involved variables depend on the previous history of the system. The power flow is solved by using at each time interval the instances of the time-varying quantities that change with respect to the previous time interval according to a pre-defined model. However, there is no numerical integration of differential equations. The discrete variables can change their status from a time interval to another. The QSTS is suitable to incorporate the effects of the temperature-dependent components that appear in the model of the building (e.g., thermostat-controlled loads, water heaters, or storage systems), provided that the time-dependent features are represented appropriately without integrating the differential equations at each time interval (e.g., using the analytic solutions of the differential equations once available [17]).

2.3 Time scales for variable electrical phenomena under disturbances

The classical analysis of the electrical systems under disturbances is carried out by distinguishing between large and small disturbances [18]. Large disturbances are analysed by considering different time frames because of the different natures of the phenomena involved. Typically, the phenomena referring to significantly faster time scales are neglected at each time frame, while the quantities referring to significantly slower time scales are considered constant. In particular, the types of analysis considered are as follows:

- *Electromagnetic transients*: refer to high-frequency transients and are analysed over very short time periods. Many years ago, specific modelling and powerful solution schemes were introduced to speed up calculations [19]. Since then, electromagnetic transient simulators have been widely used for electric and electronic systems. More recently, multi-rate methods have been used to deal with systems that exhibit different time constants [20]. By adopting these concepts, enthalpy transfer has been modelled by using electric circuit equivalents, establishing a co-simulation framework for electrical systems and district heating networks with different time constants [21].
- *Large-disturbance stability*: the dynamics of the power system are considered under large disturbances and are analysed over time periods of some seconds to tens of seconds. The dynamics refer to electromechanical phenomena linked with low-frequency transients, or voltage stability aspects linked to possible cascaded events that may cause power system blackout. Large-disturbance calculations are carried out through simulations, in which the coexistence of continuous and discrete variables (including the events that cause the disturbance) leads to a problem with differential-algebraic-discrete structure [22].
- *Small-signal stability*: each power system component is represented by using a set of differential-algebraic equations (DAE) linearised around a given steady-state operating point. The components are connected to the network by using the network algebraic equations, obtaining the generalised model with state-space equations in the form $\Delta\dot{\mathbf{x}} = \mathbf{A}\,\Delta\mathbf{x} + \mathbf{B}\,\Delta\mathbf{u}$, where $\mathbf{x}$ is the vector that contains the state variables (i.e., the variables that appear under derivatives in the model), $\mathbf{u}$ is the vector that contains the input variables, while $\mathbf{A}$ and $\mathbf{B}$ are the coefficient matrices. The eigenvalues and eigenvectors of the state matrix $\mathbf{A}$ are then calculated, and the small-signal stability is studied by analysing the eigenvalues of the state matrix using modal analysis techniques [23].

In the last years, the growing integration of power converters in energy systems has raised specific issues due to the interactions between the power converters and the grid, among which there is *harmonic stability* [24]. The critical aspect of these interactions is that the control dynamics of the power converters involve a wide range of time scales.

Therefore, these control dynamics interact with both the electromechanical phenomena and the electromagnetic transients, causing possible oscillations within a wide frequency range.

Developing microgrids that host distributed generation with massive grid interfaces through power converters has led to establishing a specific categorisation of the stability in microgrids [25]. The strong coupling between the involved variables creates a strong link between frequency and voltage, so that the categorisation also considers the type of the equipment and controller used. A distinction is made between phenomena related to the control systems and phenomena referring to the active and reactive power balance.

The time scales considered for the electrical phenomena described above are typically faster than the time scales referring to the *thermal phenomena* that appear in the analysis of the energy efficiency and performance of the buildings. Therefore, the variation of ambient parameters (e.g., temperature and humidity) is generally not considered in the analysis of variable electrical phenomena under disturbances.

3 Assessment of the thermal phenomena and representations of buildings interacting with the grid

3.1 Time scales for variable thermal phenomena

When addressing the possibility of providing grid services from thermally related applications, the key aspect is that variations in the electrical input can be imposed in a very fast way, while the corresponding thermal effects appear more slowly. The thermal effects are governed by thermal dynamics, where the thermal capacity results in a "thermal inertia", e.g., the building thermal mass can be used to set up pre-cooling strategies [26]. The thermal dynamics are generally assessed starting from the differential equations that represent the temperature variation in selected points of the energy system.

The effect of the thermal capacity has some important implications:

- The temperature change must be monitored to avoid exceeding the temperature limits associated with *thermal comfort* [27]. For automatic regulation, e.g., in thermostat-controlled loads, the change in the electrical power could be limited by temperature constraints.
- When the temporary change in the electric power occurring to satisfy the requests of the grid is elapsed, restoring the reference conditions requires an *energy payback* (or *rebound effect*) with a further transient in the electrical power.
- For thermal quantities, it is important to account for the *dissipation* that occurs in thermal storage, water heating, or space cooling.

In periods of stress for the grid, demand response actions aimed at curtailing the electrical demand of the buildings can offer flexibility to the grid without the need for significant capital investments [28]. Suitable means include re-scheduling HVAC systems, performing energy shifting from multi-energy systems with power-to-heat conversion systems such as heat pumps [29], shifting the demand of the occupants, and exploiting energy storage and the thermal mass of the building envelopes.

Phase-change materials (PCMs) are typically adopted to limit the energy consumption of buildings by exploiting their property of operating at an almost constant temperature during phase change. Load shifting in multi-energy systems can benefit from the thermal energy buffer made available by PCMs. These benefits can be analysed by resorting to combined electrical and thermal models solved, for example, with a two-stage model for day-ahead and real-time dispatching [30].

3.2 Operational scheduling

Most of the studies in which the buildings interact with the grid are based on *operational scheduling*, using a given time step for the analysis. The scheduling model considers the energy balance and the electricity prices variable according to specific time windows. In a mixed electrical-thermal analysis, the coupling in time between the time steps cannot generally be neglected, especially in the presence of energy storage (also in the form of virtual energy storage [31]). Because of that, the operational scheduling may be challenging to solve, especially in an optimal way, even considering a known system. The operational scheduling is also the basis for determining the size (and/or location) of the energy systems at the design stage.

3.3 Summary of the types of analysis

The characteristics of the types of analysis relevant to the electrical systems are summarised in Table 1. For these analyses, a significant aspect is the possibility of considering the coupling between the time intervals or the dependence of the results on the time frame considered.

Table 1. Types of analysis for electrical systems.

Type of analysis	Time coupling
Power flow calculations	No (only successive independent executions)
Quasi-static calculations	Yes, with sufficiently short time intervals
Operational scheduling	Yes, with different time intervals
Dynamic analysis (electromechanical)	Yes, with short time intervals
Electromagnetic transient analysis	Yes, with very short time intervals
Small-signal stability analysis	No (local analysis on the linearised system)

3.4 Integration of electrical and thermal models

The framework presented in [32] integrates the models for grid-connected buildings in normal operating conditions. The thermodynamic aspects referring to the building envelope and heat transfer are represented by using thermal resistance and capacitance (RC) parameters, assuming steady-state heat transfer through the building envelope. An optimal control problem is formulated considering the different time scales referring to the dynamics of buildings and the grid. In particular, the building dynamics are modelled as $\dot{\mathbf{x}}_\mathrm{b} = \mathbf{A}_\mathrm{b}\,\mathbf{x}_\mathrm{b} + \mathbf{B}_\mathrm{b}\,\mathbf{u}_\mathrm{b} + \mathbf{B'}_\mathrm{b}\mathbf{w}_\mathrm{b}$, where the vectors $\mathbf{x}_\mathrm{b}$ and $\mathbf{u}_\mathrm{b}$ contain the state and control variables for the building, respectively, and $\mathbf{w}_\mathrm{b}$ contains the non-controllable (random) input variables. For the grid, the state-space model is represented as $\mathbf{E}_\mathrm{g}\dot{\mathbf{x}}_\mathrm{g} = \mathbf{A}_\mathrm{g}\,\mathbf{x}_\mathrm{g} + \mathbf{B}_\mathrm{g}\,\mathbf{u}_\mathrm{g} + \mathbf{B'}_\mathrm{g}\mathbf{w}_\mathrm{g} + \mathbf{C}_\mathrm{b}\,\mathbf{u}_\mathrm{b} + \mathbf{f}_\mathrm{g}$, where the vectors $\mathbf{x}_\mathrm{g}$ and $\mathbf{u}_\mathrm{g}$ contain the state and control variables for the grid, respectively, $\mathbf{w}_g$ contains the random load variables (available from forecasting) and $\mathbf{f}_g$ contains the vectorised non-linear part of the model. The input control vector $\mathbf{u}_b$ of the building is included in the state-space model of the grid to create interdependency among the models. Moreover, the variable internal loads of the buildings are included in the vector $\mathbf{w}_g$. The state-space model of the grid is a DAE, with the issue of including the non-linear algebraic power flow equation. This model is discretised using Gear's method [33] by considering the linearised power flow equations.

3.5 Buildings-to-Grid and related constraints

The grid connection of buildings, also indicated as buildings-to-grid (B2G) [32], considers electrical variables and constraints (for voltage, current and frequency) [34], in addition to the constraints on the buildings, in the formulation of the framework of analysis [35]. On the grid side, the objectives that have been considered include voltage variations and/or active power losses. On the building side, the objectives are typically to minimise the use or cost of energy while satisfying the thermal comfort of the occupants. The optimisation problem can be formulated as a joint optimisation problem [35] or as a hierarchical scheduling model [36]. An optimal strategy can be found by including multiple flexibility services in a joint market framework that addresses energy and grid services [8].

3.6 Flexibility aspects

The EBC Annex 67 programme launched by the International Energy Agency [37] aims to provide insights into the energy flexibility obtained from buildings. Various indicators have been defined in this framework [38]. The categories and requirements of building energy flexibility have been recalled in [26]. The categorisation includes response duration, direction and speed. Various aspects concerning flexibility in buildings have been summarised in the review [39] and in [12]. The more recent review [40] provided updated information on datasets and use cases for B2G services.

Flexible load models include *white-box* models (for thermostatically controlled loads, for optimising the scheduling of electric water heaters, and for single appliances [41]); *grey-box* models for HVAC systems, wet appliances (e.g., dishwashers, washing machines and clothes dryers), and sparse applications to refrigerators, and *black-box* models used for modelling the wet appliances using statistical methods on empirical data to evaluate the flexibility of aggregated loads [42].

Considering the ability of the buildings to adapt their demand, various methodologies can be defined [31] by addressing aspects of temporal, power, and energy flexibility, with the possible inclusion of costs and revenues and the definition of the energy-shifting potential that corresponds to profitable changes with respect to the baseline.

4 Concluding Remarks

The engagement of the buildings in supporting the electrical grid operation is increasingly becoming more and more interesting, especially in the presence of unexpected power unbalances. In fact, the intrinsic characteristics of the buildings (mainly their thermal capacity) enable for applying sudden variations of the electrical power supply to thermal equipment fed by electricity without immediately affecting the comfort of the occupants. Moreover, the buildings may become providers of (relatively) long-term flexibility. Scheduled actions (i.e., pre-heating or pre-cooling) can actively involve buildings in providing energy-related grid services, exploiting the load-shifting capability of the multi-energy system. Buildings may also increase energy system integration, especially involving several infrastructures with different energy carriers to satisfy the final uses in the buildings. However, the different time frames for thermal and electrical phenomena do not allow the direct coupling of the two systems. Hence, co-simulation of electrical and thermal systems, where only boundary variables are exchanged, is a viable approach for coupling buildings and electrical grids.

In conclusion, buildings with a proper energy management system may become an active part of the operation of more integrated energy systems, enabling the decarbonisation of the non-electrical final uses thanks to the conversion of renewable electricity to supply either heating or cooling needs. Tools for co-simulation of electrical and thermal systems, with interactions among the corresponding energy networks and storage systems, are expected to develop further to enable mutual benefits for the electrical and thermal sectors. Extended benefits are also expected from incorporating models of social aspects, crucial for successful energy system development following recent trends towards local energy markets and energy communities.

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