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Concept of a Novel Energy Management System for Microgrids and Energy Communities

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The green transition of the global energy system presents considerable economic and technological challenges. One of them is the local and temporal difference between available energy sources and energy demand. To overcome this problem, two conceptual solutions can be considered: one is the use of an energy carrier that is suitable for medium- and long-term storage and safe transportation of energy. Carbon-based fuels (or novel alternatives, like hydrogen) or electric energy are the solutions currently used; however, we are facing their environmental or technical limitations. The other one is the synchronisation and intelligent control of sources and consumers, which could significantly decrease the storage and transportation needs. The current article discusses such a solution through a conceptual example. For the conceptual design of an advanced energy management system, the main related system elements shall be defined, and characteristic properties must be assigned to them. Input parameters for the energy management strategy must be given and prioritised. All this information enables the system to calculate and define instantaneous operational optimum. Also, an intelligent control system should take time-dependent processes and parameters into account, which can be deterministic or stochastic. As a result of this study, an energy management system concept that is based on realistic components and use cases is proposed, and its applicability to a local energy community is evaluated.

1. Introduction to the electrical grid and its operation

Electrical energy is a special product that requires extensive infrastructure to be delivered to consumers with the appropriate quality. Maintaining a continuous balance between production and consumption is crucial for the operation of an integrated electrical grid. Energy management systems can assist in maintaining this balance in an economically efficient manner.

1.1 Electrical grid operational characteristics

The alternating current (AC) electrical grid has three main operational characteristics that can be observed at any point of the electrical network: frequency, voltage, and power factor. The voltage and frequency quality requirements at the customer’s connection points to the low voltage and middle voltage electricity distribution systems are defined in the standard EN 50160 (CENELEC - 50160). Other parameters (e.g., harmonic distortion, rapid voltage changes, voltage dips) are defined in the EN61000 standard, but it focuses more on the equipment connected to the grid than on the grid itself.

The nominal voltage levels are different at various levels of the grid hierarchy to accommodate the designed transmission and distribution capacity at a relatively high efficiency to minimise grid losses. The actual voltages fluctuate around the nominal levels and are different (and independent to some degree) in the grid subsections – in accordance with Kirchhoff’s and Ohm’s laws.

The power factor is the ratio of the active power to the apparent power (where apparent power is the sum of the active and reactive power). It represents the phase difference between the voltage and the current in the AC grid – the difference caused by the inductive and capacitive characteristics of grid elements that consume/produce reactive power as the magnetic and electric fields change.

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The nominal frequency is the same at any given point in the grid, while the actual values fluctuate as well (shown in Figure 1.), but still, it is the same over the whole grid - the alternating current (AC) grid is synchronous. The frequency control of the grid is a major technical challenge addressed in the operational handbook (ENTSO, 2009). The frequency of the grid is stable if the load demand and the generated active power are in balance.

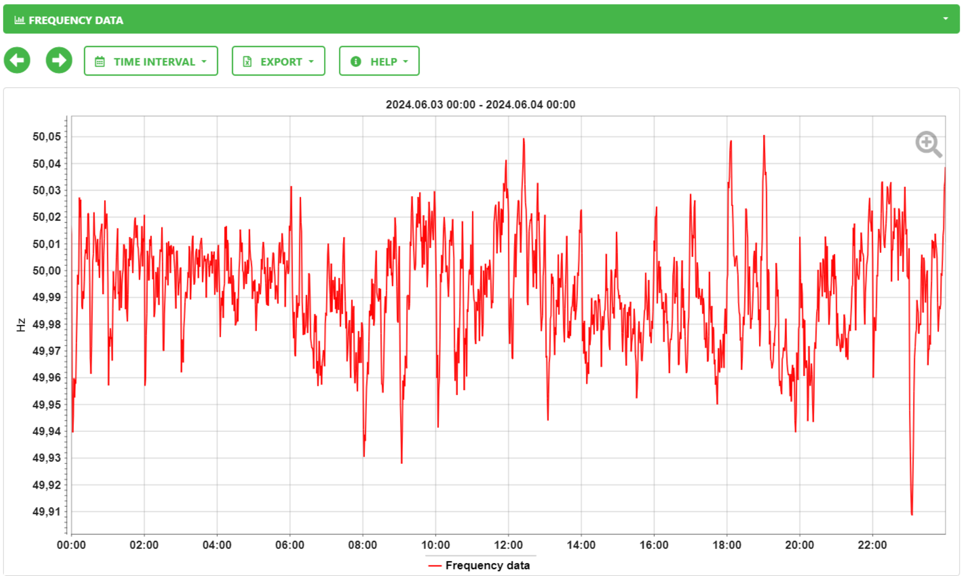

Figure 1: Grid frequency data (MAVIR, 2024)

1.2 Grid operational responsibilities

The operation of the grid within the guaranteed range of the operational characteristics is the shared task of the transmission system operators (TSOs) and distribution system operators (DSOs) – the exact responsibilities are regulated; it is not in the scope of this article. The tasks to control these characteristics are always present in the grid, although they pose different difficulties. The grid voltage and power factor are intertwined: the voltage and reactive power (and power factor) are controlled at the generator units (by excitation), but the voltage can also be adjusted by changing the transformer tap positions at grid-level boundaries. Petinrin and Shaaban (2016) have reviewed the voltage rise in the distribution system caused by the high penetration of renewables, which network operators may not be able to control effectively without demand-side measures.
The frequency of the grid, on the other hand, is synchronous in the whole grid; any deviation from the nominal frequency is a result of active power imbalance. The rotating mass of the generator and turbine units exhibit an inertia that can absorb or extract energy to compensate for the disturbances, enabling the grid to withstand short load fluctuations (Kroposki et al., 2017).

1.3 Uncertainties in the grid

There are uncertainties on both the demand side and the generator side – and as we have seen, the active power imbalance needs to be zero to stabilise the grid frequency deviation from the nominal (50Hz in Europe). On the demand side of the grid, millions of consumers constantly change their actual demand. Although the load profile of any single consumer is impossible to predict and plan, the millions of customers are segmented into groups and assigned to a load curve, resulting in a manageable forecast (Wang et al., 2015).
The other source of the uncertainty that needs to be handled by the grid operator is coming from the generator side: if any of the scheduled generators fail to follow their respective schedule, the grid must have reserve capacity ready and available to compensate (ENTSO, 2009).
The grid operators have decades of experience and practices with centralised synchronous generators and distributed consumers in the grid, but as the technology evolves and renewable share is expanding, the grids become inverter-dominated - compared to conventional synchronous generator domination-, which requires better supply and demand matching (Kroposki et al., 2017).
The approach proposed in this article suggests limiting the mentioned uncertainties in the grid by better understanding the energy use cases on the demand side, as well as by prioritising and controlling the consumers. By involving the demand side in meeting the challenge of keeping the active power balance of the grid close to zero, the task of controlling and keeping the above-discussed grid parameters in the guaranteed range is more manageable.

1.4 Challenges of the integrated electrical grid

Given the operational characteristics presented earlier, it can be stated that maintaining and operating an integrated electrical grid is currently a complex task due to the growth of renewable energy sources, fluctuations in energy demand, and the inherent limitations of centralised grid management. The uncertainty of the system can be reduced if energy balance discrepancies are compensated locally. Existing energy management systems primarily focus on reducing energy consumption and economic optimisation. Most existing solutions lack flexibility in addressing real-time, localised imbalances, especially in scenarios where distributed energy resources play a significant role. This article addresses an energy management system aimed at handling local imbalances in the case of on-grid operation. Unlike traditional approaches, the proposed system enables a bottom-up strategy, empowering localised energy clusters to achieve real-time balance with minimal central intervention. This approach is both novel and relevant as it directly enhances grid stability, increases adaptability for renewable integration, and promotes a more resilient and scalable grid structure suitable for evolving energy demands.

2. Impact of renewables and the storage concept

The growing renewable capacity in the electrical grid has many different implications. Well-known and clearly advantageous property is being free of direct pollution, so they make for a greener electricity mix (Figure 2. shows an average day in the Hungarian grid photovoltaic production covering approximately 30 % of the grid load between 8:00 and 16:00 on that given day), being ‘cheap energy’ and making ‘home-sized small power plant’ possible. In Hungary in 2023, the industry-sized photovoltaic total generation capacity (units above 50kWp installed capacity) reached 3,300 MWp, while the home-sized capacity reached 2,300 MW (Ministry of Energy, 2023) – for reference, the peak demand is 7,441 MW (recorded in 2024-01-22). While the industry-sized units may commit to and follow a schedule – depending on the energy framework and their respective category – and can be connected both to the transmission network and the distribution network, they introduce a high uncertainty into the grid, as they are deterministic to some degree (daily and annual weather patterns) but are stochastic based on the daily weather conditions. The home-sized units are connected directly to the distribution network without a schedule or any control over their production. There are some safety measures like inverters automatically switching off if the network voltage goes above the guaranteed maximum voltage level of the distribution grid (e.g., 253 VAC phase voltage) – but it is a protection functionality that signals a problem already present. From the operational point of view, the intermittency renewables introduced into the grid must be managed (Sovacool, 2009).

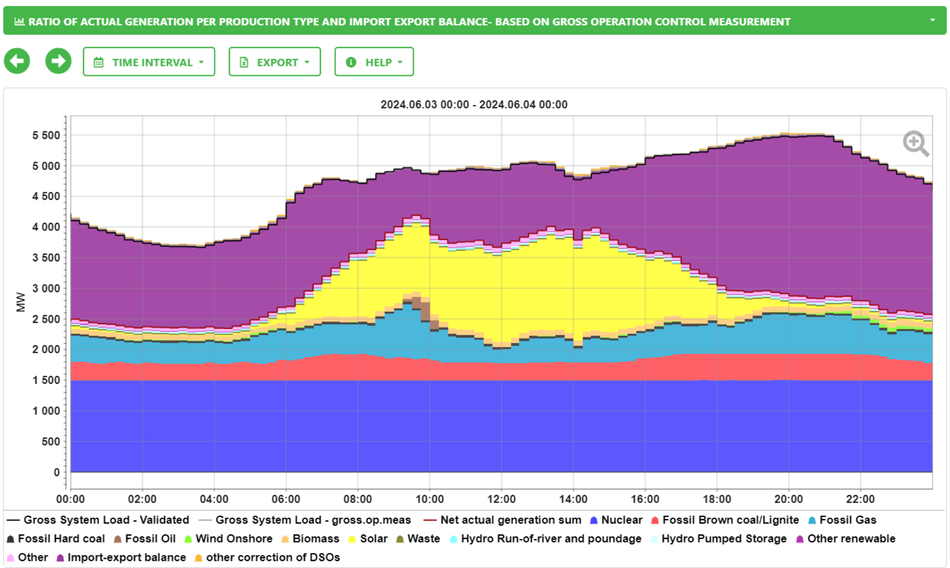

Figure 2: Electricity mix data, yellow shows photovoltaic (MAVIR 2024)

2.1 Storage technologies

The trivial solution for the energy produced by the uncontrolled renewables and not needed in the distribution grid (overproduction) is to put it into storage for later use. The storage has many advantages; it can serve as a backup source or cover loads above the grid connection capacity. Also, if paired with renewable generators (typically photovoltaic and wind), they make off-grid systems possible. From the grid's point of view, the biggest advantage and opportunity storage technologies offer is that they can turn the renewable's overproduced clean energy into a peak shaving capacity, otherwise typically covered by gas turbine technology, which has a high levelized cost of energy among conventional generation technologies (LAZARD, 2023). There are different technologies for such storage systems. The actual state of technology in terms of power output range and storable energy range is shown in Figure 3.

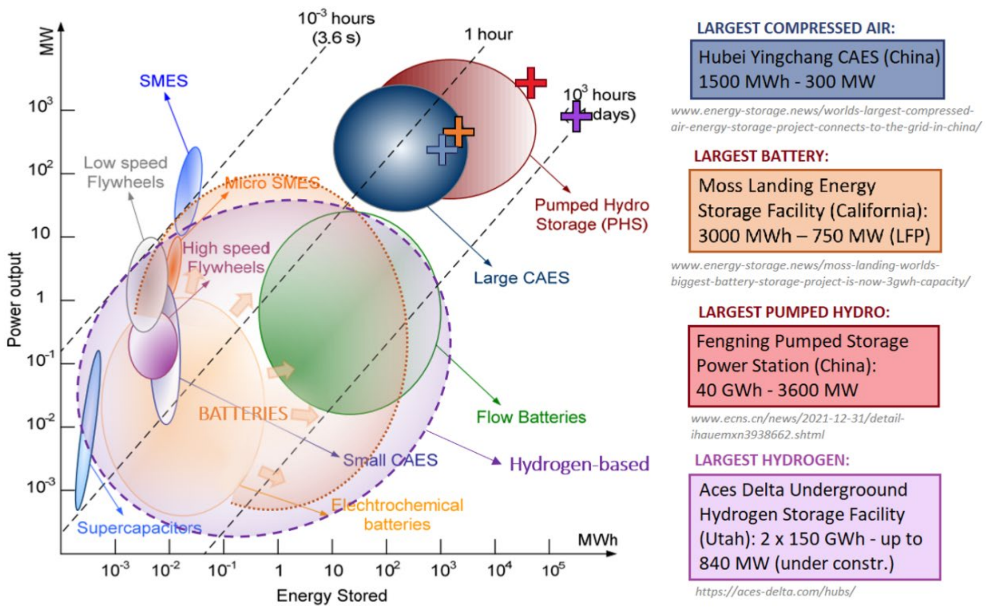

Figure 3: Energy storage solutions and the largest projects in the world (Vehovszky et al., 2024)

3. Energy management and microgrid

The rapid expansion of solar power plants and the increasing importance of energy storage are reshaping the responsibilities of grid operators (TSOs and DSOs). Traditionally, these operators take the actual power demand in the network as a boundary condition, and they work with shared responsibility to satisfy the demand while maintaining reliability, quality of service and efficiency. But the question can be asked, is really all the demand equally important and are there consumers who are more/less flexible than others? If they are not all equal, then an energy management system that can prioritise and control - at least a portion of - the demand side could provide better results in optimising the green energy utilisation, improve the electricity mix and serve for higher reliability by reducing the stress on the grid. Also, if the local active energy imbalance can be avoided by better management, it is much more cost-effective compared to the installation cost of the storage solution.
The proposed bottom-up approach starts from the physical energy units and introduces energy clusters as a concept, which is similar to a microgrid (a distribution system with distributed generation, storage, and controllable loads), but while microgrids have the ability to work either in island mode or connected to the utility network (Kroposki et al., 2008), the proposed clusters do not need to have island mode capability.
The legal framework for establishing such clusters is available: in 2019, the EU introduced the concept of energy communities as citizen energy communities and renewable energy communities (European Commission, Directorate-General for Energy, 2019).

3.1 Energy management strategy

The proposed solution uses energy management to address the issue of local imbalance of active power generation and consumption in a bottom–up approach. The design of such a management system starts by looking at the general types and features of electrical energy units. Different characteristics and properties can be identified and assigned to the different types: there are generators, storages and energy consumers, which all possess energy characteristic properties like power, capacity, priority or flexibility (energy use-case), cost efficiency – the list is not exhaustive, and some properties are functions of the operational conditions (e.g. nominal power vs available power). With the energy characteristics, the elements can be described as generalised abstractions and can be used for effective energy modelling.

A critical design input for the energy management system is the energy strategy (or energy goals in some form). The system is meant to find an optimum for it. Various energy strategies could be defined, e.g., to avoid loss of power for the highest priority consumers or one that aims to utilise the most green energy produced. For the first strategy, a properly designed cluster needs enough back-up options to make the probability of the total loss of power almost zero. For the second strategy, the minimum supply taken from the grid would be optimal. From the high-level grid management's point of view, an important strategy could be one that aims to follow a load schedule with a minimum deviation.

Based on the strategy, the first step to a working solution is to form the cluster in such a way that its elements together form a feasible system in terms of energy. For a well-formed cluster, the probability of energy scenarios having no valid set of energy management actions to fulfil the energy strategy is extremely low (virtually zero). By energy management action, any viable control to cluster elements is meant, e.g., switch-on or switch-off elements or changing inverter of consumer load setpoint.

The size of the cluster has an optimal range, certainly depending on the use-case mix, including the power demand, energy unit mix and flexibility. Below the range, the control options are too limited. Clusters also can be organised into further clusters, with the same purpose of fulfilling an energy strategy, as shown in Figure 4. For lower-level clusters, the energy strategy typically aims to balance the local power demand and minimise the grid supply usage; for higher-level clusters, the strategies should aim to minimize the deviation from the committed schedule.

This approach bears strong similarities to problems in other fields, which can be interpreted as resource allocation problems, where concurrent demands (with different priorities) compete for access to limited resources (e.g., CPU scheduling in computing). By treating energy management as a scalable resource allocation challenge, the proposed model provides an adaptable, resilient framework well-suited to a future grid powered increasingly by solar and supported by flexible storage solutions.

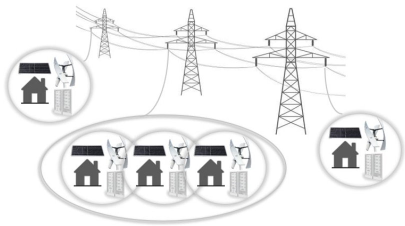

Figure 4: Energy clusters (generator, storage, and consumers) and clusters in a cluster attached to the grid

3.2 Conceptual proposal

Given a hospital complex with its numerous buildings and facilities which contain many different consumers (or energy use-case), some with high priority, where power outage, in general, is not acceptable (e.g., life support equipment), some with low priority, which can tolerate – for at least a period of time – a limitation in available power (e.g. heat pumps or air conditioning). As outlined in Section 2, battery storage systems enable the temporal shifting of photovoltaic (PV) production, enhancing its flexibility.

In the example, the hospital complex has PV panels and battery storage installed along black-out diesel aggregators, and it also has a contract for a scheduled consumption (overuse bears the additional cost, no refund for underuse). Additionally, the complex has street lighting installed in the yard and around the buildings.

The energy strategy of the hospital complex consists of three energy goals:

- To be able to power all high-priority consumers for at least 2 h
- To supply all mid-priority consumers and keep the building temperature and hot water temperature in the defined operational range
- To minimise the energy cost of the hospital complex

The streetlight represents a use-case with flexibility in one direction: it is necessary for safety/security reasons overnight but can be switched on in the daytime without any side effect to help balance the load if there is no better option. For example, if the hospital had a penalty clause in the contract for the scheduled but not consumed energy, the streetlight could be turned on to compensate.

If the complex energy cluster was designed properly, most of the time, the renewables (plus the scheduled grid supply) cover the total demand in such a way that the HVAC (heating, ventilation and air conditioning) and other low-priority consumers may or may not be available all the time, but the required conditions are in the expected range (e.g., temperature and humidity). Most days of the year, during the day, the renewables (plus the scheduled grid supply) not only just cover the operational minimum requirements but also produce energy that can be stored in the batteries. With the batteries and the black-out diesels, the 1st goal can be achieved (at least with an extremely high confidence level). The 2nd and 3rd goals can be achieved with the available resources (renewable, grid supply and storage) and the energy management that balances the battery and HVAC consumption in such a way that the renewables are 100 % used or stored and the schedule can be followed (never overused).

4. Conclusion

The grid operation today cannot differentiate between energy use cases based on priority, and with the centralised controllable generator units, it must fulfil all demands and keep the service within the guaranteed quality limits. The proposed energy management system concept takes a bottom-up approach to the consumers; by aggerating their properties, it makes effective energy management on lower levels of the grid possible. Energy management systems can leverage the flexibility of the energy use cases and achieve optimal energy solutions. This flexibility is crucial for integrating renewable sources, which are inherently variable, into the energy mix while minimising disruptions. Additionally, the scalability of the solution suggests that it can be applied not only to small, localised grids but also to larger networks, potentially transforming how energy management is handled on a broader scale.
The construction of an energy test ecosystem with an energy management software solution on the ZalaZONE proving ground has started. It will serve as a development and test environment for further research in energy management. On the one hand, the proposed solution will be implemented and tested physically in this environment; on the other hand, the management software is being designed in a way that it can handle energy clusters with individual production and consumption characteristics; thus, the solution will be scalable as well.

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