PREDICTIVE AND REAL-TIME CONGESTION MANAGEMENT TO ENHANCE GRID HOSTING CAPACITY

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Abstract

The article explores the confluence of congestion issues in distribution grids, flexibility as a solution, and the enabling role of cloud and edge computing. Implementing such a solution effectively requires the integration of expertise from both electrical engineering and information technology, emphasizing the need for a structured approach to development and knowledge sharing among developers. The paper proposes following the Smart Grid Architecture Model to develop business use cases and system use cases, both formatted using the IEC 62559-2 standard template. Business use cases address the 'what' and 'why,' while system use cases focus on answering the 'how.' Recognizing that the placement of algorithms impacts response time, bandwidth costs, data security, and privacy, the article suggests placing predictive congestion management algorithms in the cloud and real-time congestion management algorithms at the edge. Predictive congestion management, hosted in the cloud, can participate in the flexibility market (also cloud-based) and leverage extended time and computational resources for optimization-based processes. Conversely, lightweight, rule-based algorithms deployed at the edge address immediate, localized needs quickly and efficiently.

1 Introduction

In 2023, the European Commission estimated that €584 billion in investment will be required in the European Union (EU) for electricity grids by 2030, with €375-425 billion specifically allocated for distribution grids [1]. This underscores the significant scale of public funding needed to support the energy transition, while also emphasizing the substantial portion of investments directed toward distribution grids. Since the costs of grid investments are recovered through grid tariffs, customers will bear the financial burden. Therefore, it is crucial to minimize these costs by optimizing the use of grid management solutions.

Flexibility is a tool in the grid management toolbox, and it can be classified based on its source of provision as grid-side, demand-side, and generation-side [2]. A DSO, using a combination of them, should be able to operate the grid and prevent congestion in most cases because grid investment is based on the worst-case scenario, and often, there is unutilized capacity in the grid. Grid-side flexibility includes flexibility initiated from grid components such as transformers with tap changers, reactors, capacitors, controllable switches, etc., which are utilized in real-time for congestion management (CM). Demand-side flexibility includes flexibility initiated from controllable loads such as heat pumps, electric vehicles (EVs), and energy storage, while generation-side flexibility could come from energy storage and generation units. A distribution system operator (DSO) could access demand and generation-side flexibility for CM through a market process such as the local flexibility market (LFM) or based on a bilateral flexibility contract with the flexibility owner.

In addition to requiring flexibility, DSOs must have substantial resources to access and process data from an ever-growing number of distributed systems while making intelligent control decisions. This presents a significant challenge, as it involves processing a massive volume of data for monitoring, decision-making, and control. The common solution is cloud computing, which centralizes data on a cloud server for streamlined grid management. However, this approach has notable downsides concerning response time requirement, bandwidth cost saving, data safety and privacy [3]. As a complementary approach, edge computing has gained recognition for its ability to minimize data transfer and leverage edge resources by shifting certain decision-making algorithms from the cloud to the edge, a process known as cloud offloading [3]. That would allow the data that is increasingly produced at the edge of the

network to also be processed at the edge of the network [3]. According to [4], edge computing has a transformational impact on DSOs, ranking highest among 30 reviewed technologies, including artificial intelligence. A balanced strategy would involve distributing algorithms between the edge and the cloud, combining their strengths while mitigating their respective limitations.

From a DSO's perspective, stress on the grid that manifests itself in congestion is increasing due to the deeper penetration of distributed energy resources. Meanwhile, there are solutions based on flexibility that can help the DSO deal with grid congestion which means theoretically solutions are available. However, utilizing flexibility for grid management requires enhanced grid monitoring, decision-making, and control which can be enabled by cloud-edge computing technology. Therefore, the full picture is that there is an increasing problem, but there are solutions to it. This paper is the confluence of the congestion problem, flexibility as a solution, and cloud-edge computing as a technological enabler, as shown in Fig. 1. The paper aims to clarify how DSOs could utilize different types of flexibility in their grid operations while also utilizing the potential of could-edge computing technology. It is worth noting that several articles discuss the use of edge computing for smart grids, particularly in the context of CM [5], [6]. However, to the best of the authors' knowledge, none have proposed a system that comprehensively addresses the congestion problem by integrating both real-time and predictive timeframes as complementary solutions. Furthermore, the literature lacks a systematic approach to distributing functions between the cloud and edge based on specific requirements while enabling CM to leverage flexibility from a market.

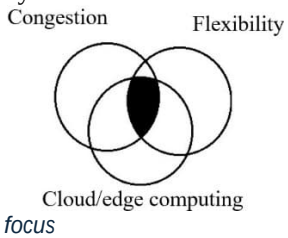

Figure 1- Article's focus

2 Methodology

Given that the solutions presented in this paper must be piloted within the EU project HEDGE-IoT [7], and considering the need for an iterative collaboration among multiple parties with diverse expertise, a structured process was essential to foster a common understanding and facilitate effective teamwork. To achieve this, the **use case (UC) methodology** was employed to define the real-world objectives related to **CM** in a technology-neutral way. Subsequently, the **Smart Grid Architecture Model** (SGAM [8]) was utilized to map these use cases across distinct SGAM layers, providing clarity and supporting the development process. Following a top-down approach, starting from SGAM's **business layer**, discussions clarified the DSO's business objectives for CM using flexibility. This led to the creation of a Business Use Case (BUC) in IEC 62559 standard format [9]. The BUC emphasized the need to enhance grid hosting capacity within a short timeframe, enabling the connection of more customers without requiring grid reinforcement. In essence, the BUC defined the 'what' and 'why' of the development.

Next, at the **function layer**, four System Use Cases (SUCs), also developed using the IEC 62559-2 standard, outlined 'how' the BUC could be realized. These included two SUCs focused on predictive CM and two on real-time CM. The standardized IEC template proved instrumental by framing the work and fostering iterative collaboration among project partners.

In the **information layer**, the SUCs were mapped to algorithms distributed across the cloud and edge, detailing their placement and the information flow between them. This step bridged the gap between electrical engineering and information technology (IT) disciplines. While CM is primarily an electrical engineering challenge, the cloud-edge paradigm, as the technological enabler of CM solutions, falls within the IT domain. The structured framework of the use cases made the problem comprehensible to IT experts, facilitating interdisciplinary collaboration to address the complexities of CM effectively.

3 Use cases

The use case aims to represent a case where a DSO utilizes predictive and real-time CM solutions to give customers quicker access to a grid connection (than otherwise would be using grid reinforcement) by enhancing its grid's hosting capacity (HC). Flexibility resources within the use case encompass grid-side, demand-side, or generation-side solutions. The following summarizes the benefits of predictive and real-time CM from the perspectives of DSOs and customers.

DSO's point of view:

- Providing grid connection services quicker to new customers.
- Improving the utilization rate of the existing grid infrastructure.
- Grid reinforcement deferral.

Customers' point of view:

- Quicker connection to the grid. (short-term)
- Cheaper grid connection costs compared to when grid reinforcement is done. (short-term)
- Reduced tariffs due to reinforcement deferral. (long-term)

The UC includes two timeframes: predictive and real-time. The HC enhancement starts in the predictive timeframe followed by the real-time timeframe, allowing the DSO to do the preparatory actions in the predictive timeframe and utilize them for a more effective real-time CM. The prediction occurs in the day ahead and aims to prepare the DSO and flexibility service providers (FSPs) for any

possible upcoming congestion problem. In real-time, the DSO combines already-agreed flexibility (i.e., demand and generation side) with grid-side flexibility to mitigate/avoid congestion.

As shown in Fig.2, in a predictive timeframe, two main services are realized: state forecast (SUC 1) and predictive CM (SUC 2). State forecast include a microservice: load and generation forecast. As the name implies, it forecasts consumption and generation in the grid. State forecast utilizes the load and generation forecast time series and generates a forecast of the grid's state variables to be used by predictive CM. Based on predicted grid states, SUC 2 decides if market-based flexibility is required to prevent congestion in the coming day. In fact, SUC 02 also includes a microservice that participates in the flexibility market if needed. Similar to the predictive one, two main functions are performed in the real-time timeframe: state estimation (SUC 3) and real-time CM (SUC 4). State estimation, in fact, provides inputs for real-time CM, which decides what actions are required in real-time.

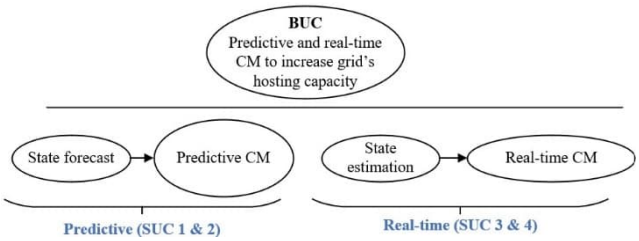

Figure 2- Use cases

Starting from the predictive time frame, the DSO predicts a potential congestion problem in its grid for the next day and plans a solution in advance. The process starts with SUC 1, where the DSO performs a load and generation forecast followed by a state forecast algorithm. After the forecast is performed, SUC 1 compares forecasted values (i.e., grid state variables, voltage and current) with grid constraints (e.g., voltage and ampacity of grid components). If a potential congestion problem is detected, SUC 2 is triggered. Predictive CM can select either a market-based solution, grid-side flexibility, or both. The CM solution is forwarded to the control room operator, and they can be seen as recommendations to the operator in the control room. The control room operator has to make a decision based on the recommended solutions and take action if required. If a market-based solution is chosen, SUC 2, using the market utilization microservice, creates a bid/s request and takes care of market participation and message exchange with the nominal electricity market operator (NEMO). If the control room operator selects grid-side flexibility based on the recommended settings of controllable grid assets (e.g., tap changer control, reactive power control, etc), the operator stores those data concerning that recommended action (e.g., change of grid component settings). If the predicted congestion is realized in real-time, the control room operator can utilize the recommended settings to remove/alleviate congestion.

In real-time, the DSO aims to identify and address any congestion problems as they occur. The process begins with the DSO initiating SUC 3, which performs a load and generation estimation followed by a state estimation function. After the estimation is calculated, the grid's current state becomes evident. Next, SUC 3 compares the grid state with the grid constraints and if congestion is observed, SUC 4 is triggered. The congestion-related data (e.g., location, intensity) is sent to the CM decision-making function if congestion is found. The CM decision-making can utilize grid-side flexibility based on available options and make recommendations based on those to the control room operator. Ideally, the whole process should be automated with little/no human input. However, that would require rigorous testing and validation before automating the real-time CM algorithm; this is why the grid operator has been placed in the loop. In the future, with a higher technology readiness level (TRL), a fully automated system is envisioned.

4 Placement of algorithms in cloud-edge servers

This section explains the placement of already presented SUCs to edge and cloud servers. As shown in Fig.3, the edge server contains the functionalities related to real-time CM elaborated in SUC 03 and SUC 04, while the cloud server hosts the functionalities related to predictive CM elaborated in SUC 01 and SUC 02.

- **Edge server components**

The edge server, as shown in Fig. 3, executes several components. The components are as follows:

- Real-time data link:

The real-time data link is used to efficiently share measurement data and status information within the edge server. The data is received from intelligent electronic devices (IEDs) and merging units (MUs) located at the primary substations and possibly also along the feeders using IEC 61850 process bus capabilities [10]. Measurement data (voltages and currents) is transferred using IEC 61850 sampled value (SV) streams, and Generic Object-Oriented Substation Event (GOOSE) is used for status information and control signals. The data link is capable of sharing both raw data and preprocessed values.

- Data router:

The data router receives IEC 61850 standard data from the real-time data link, performs preprocessing (e.g., averaging), and publishes the data to the message bus.

- Load and generation estimation

This component performs an estimation of load and generation values based on the profiles of historical measurement values and publishes them to the message bus.

- State estimation

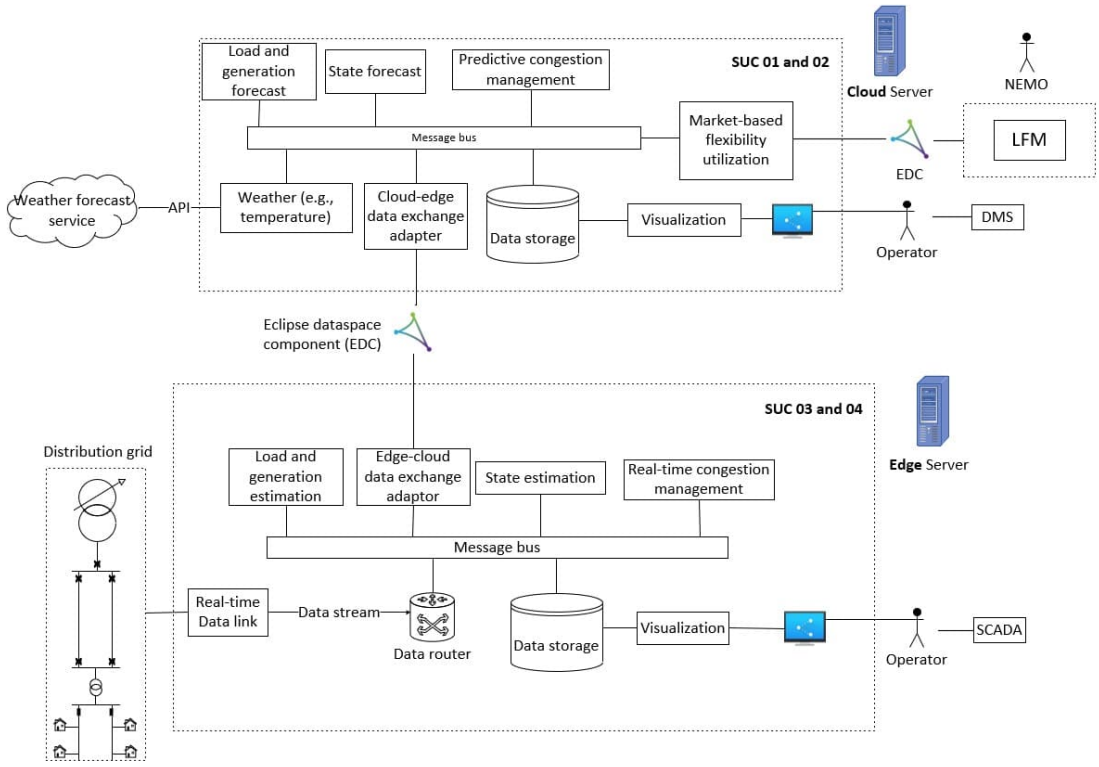

Figure 3- Architecture

The component calculates an estimation of the grid state variables (i.e., voltage and current) and publishes them to the message bus.

- Real-time CM

The component's function is triggered if congestion is observed in the real-time operation of the grid. It finds a CM solution (e.g., from controllable grid components) and publishes it to the message bus.

- Edge-cloud data exchange adaptor

The component performs protocol conversion between Eclipse data space component (EDC) [11] and publish-subscribe (pub-sub) protocol used in the message bus. It also ensures that the data flow between EDC and internal pub-sub systems is correctly routed and formatted.

- Data storage

It stores all the messages published to the message bus, as well as grid data, load, and generation profiles.

- Visualization

The component reads from the data storage and visualizes the data for the grid operator.

- **Cloud server components**

From a functional perspective, there is a duality in some of the algorithms between edge and cloud, including the load and generation forecast and load and generation estimation, state forecast and state estimation, and real-time CM and predictive CM. Therefore, only the components for market-based flexibility utilization and weather that do not exist on the edge are explained here.

- Market-based flexibility utilization

The component is used when the predictive CM algorithm chooses and recommends flexibility as an alternative to a market for CM, and the grid operator follows the recommendation. In that case, the component will take care of bid-making, message exchange with the market, and bid selection toward procurement of flexibility in the market.

- Weather

The component fetches weather forecast variables such as temperature and solar irradiance from a weather forecast service provider through an application programming interface (API) request and publishes the data to the message bus.

5 Implementation

The algorithms used on the edge and in the cloud share functional similarities, allowing certain sub-functions to be reused across both environments. However, notable differences exist, particularly from a non-functional perspective. For instance, in CM algorithms, real-time CM and predictive CM have distinct convergence requirements. Real-time CM must converge rapidly—typically within seconds—to enable immediate action when grid congestion is detected. In contrast, predictive CM can tolerate longer convergence times and often involves more complex objective functions. This distinction enables the deployment of lightweight, rule-based algorithms on the edge to address

immediate, localized needs, while more computationally intensive, optimization-based algorithms run in the cloud, forecasting future scenarios and supporting real-time grid operations. From a scalability perspective, it is recommended that components adhere to service-oriented architecture (SOA) principles, ensuring they remain manageable in size and facilitating the reuse of sub-function classes (when possible) across both environments.

6 Conclusion

The article connects three key topics: congestion as a problem, flexibility as a solution, and cloud/edge computing as a technological enabler for the solution. Developing such a system, which spans various disciplines and areas of expertise, requires iterative collaboration. Therefore, a structured road map is essential to organize the work and foster mutual understanding among stakeholders. To achieve this, the use case methodology was employed to define real-world objectives for congestion management in a technology-neutral manner. Building on this foundation, the Smart Grid Architecture Model was applied to map these use cases across its distinct layers, following a top-down approach that starts with the business layer and progresses through the function and information layers. The use cases were documented using the IEC 62559-2 standard template, further enhancing their clarity and ensuring presentation consistency.

The article proposes addressing the congestion management problem by splitting it into two timeframes: predictive and real-time. The predictive timeframe, which predicts congestion a day ahead of actual grid operation, is recommended to be hosted on the cloud. This placement allows for the execution of computationally intensive optimization algorithms, enabling the evaluation of various future scenarios for grid operation. The real-time timeframe, on the other hand, addresses immediate grid congestion and is recommended to be deployed on the edge. Placing it at the edge ensures proximity to local congestion-related data, enabling rapid data acquisition, processing, and decision-making. Given the real-time requirements (typically within seconds to a minute), rule-based algorithms are favored over complex optimization algorithms for real-time congestion management.

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