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DESIGN OF ENERGY MANAGEMENT SYSTEMS FOR MICROGRIDS

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ABSTRACT
Microgrids are low-voltage, reliable, economic, renewable energy resources that help to reduce the increasing demand of energy. Microgrids are environmentally friendly because of their renewable energy resources. The installations of various renewable energy resources are increasing day by day to produce vast amounts of energy. The management of produced energy is operated by a central software system, called Energy Management System (EMS). According to our literature review of microgrid EMSs, we notice that the capabilities of traditional EMSs are limited, and these are tightly coupled with the EMSs. This is considered as an obstacle for sustainable development of microgrid EMSs. We need EMSs whose capabilities have to be flexible, reusable, and interoperable against the traditional EMSs that ensure the sustainability of EMSs. Based on our literature review, we find that the Service Oriented Computing (SOC) is a computing paradigm that helps to develop a flexible, reusable, and interoperable EMS. In this thesis, we propose to design EMS based on the design principles of SOC. We design five categories of REST ful Web services to develop service-oriented EMSs for microgrids. By using these REST full Web services, a sustainable microgrid EMS can be developed. We design and implement a small service-oriented microgrid EMS by using our designed Web services that simulate distributed energy resources (wind turbine, photovoltaic) and distributed energy storage (battery). We use real energy consumption data with the simulated data to make the system operational.

INTRODUCTION

Microgrids are becoming more popular because of the integration of renewable energy resources. Renewable energy resources do not create any major adverse effect on the environment for producing electricity. Usually, renewable resources emit a small amount of carbon for power generation in contrast to the traditional power grids. Due to the improvement of technologies, the climate change issues, and the demand of economic electricity, the traditional power grids are being reshaped day by day. Currently, microgrids are considered as a promising technology for their reliability and economic supply of electricity. Generally, a microgrid is constructed based on energy storage, controllable and uncontrollable loads, and various renewable energy resources. An Energy Management System (EMS) operates a microgrid, which is a software system that controls and monitors the loads, supply, and demand of the microgrid. An EMS is also responsible for making decisions on the economic power distribution of a microgrid. A microgrid EMS is needed to be scalable, reusable, and interoperable to support its enormous heterogeneous end users. According to the previous studies of microgrid EMSs, such as, most of the EMSs are tightly coupled with the microgrids. The entire EMS fully depends on its microgrids. A small modification of a microgrid directly affects the associated EMS and its energy consumers. A single EMS of a microgrid must be developed multiple times depending on the executing environments. To design and develop a platform-independent microgrid EMS, it is essential to ensure scalability, reusability, and interoperability. Service-Oriented Computing (SOC) is a paradigm that utilizes services asthe basic constructsto design and develops flexible, reusable, and loosely coupled systems. SOC has been suggested as a suitable paradigm for the smart grid. The aim of this thesis is to look at the functionality of microgrid EMSs from the service orientation point of view and design a service-oriented EMS for microgrids.

Describe an overall picture of EMSs in microgrid operation. They have mentioned different aspects related to the microgrid EMS operation. They identify several components of a microgrid EMS that are very much essential, such as distributed generator, distributed energy storage, controllable loads, critical loads and point of common coupling. The authors also mentioned some real-world examples of the centralized and decentralized control of microgrid EMSs. The most important fact is that the authors figure out four very important functional requirements of microgrid EMS. The functional requirements are optimization, forecast, human–machine interface, and data analysis. This paper gives the idea of what should be considered for a microgrid EMS, but it does not clarify how to

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do that. For example, the paper just mentions the human–machine interface functionality, but it does not point out any graphical instance or what are the common properties of the human–machine interface. We design a conceptual model for microgrid EMSs where we describe each of the basic functional requirements separately.

MICROGRID SYSTEM

A microgrid is a low-voltage distribution network that is generally formed by combining a collection of loads, distributed energy storage (DES) and distributed energy resources (DERs). The definition of microgrid is not unified yet. The microgrid definition varies depending on various loads, storages, and resources.

Define a microgridas a distribution network of low-voltage energy resources which is placed in a distribution substation by using a point of common coupling (PCC). Define a microgrid as a low-voltage distribution network. It is formed by using different types of components such as controllable energy loads and DERs. Amjad Ali et al. define a microgrid as a network of different DERs, energy storage system (ESS), loads, supervisory control, protection, and energy management systems. For the U.S Department of Energy, a microgrid forms electrical boundaries based on interconnected various loads and a collection of distributed energy resources and it is considered as a single controllable unit from the perspective of main grid.

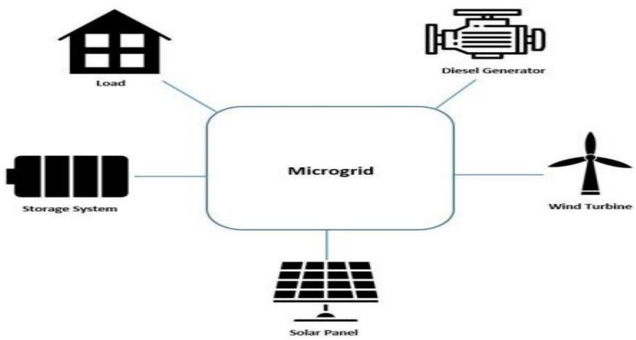

Figure 1: A conceptual design of a microgrid

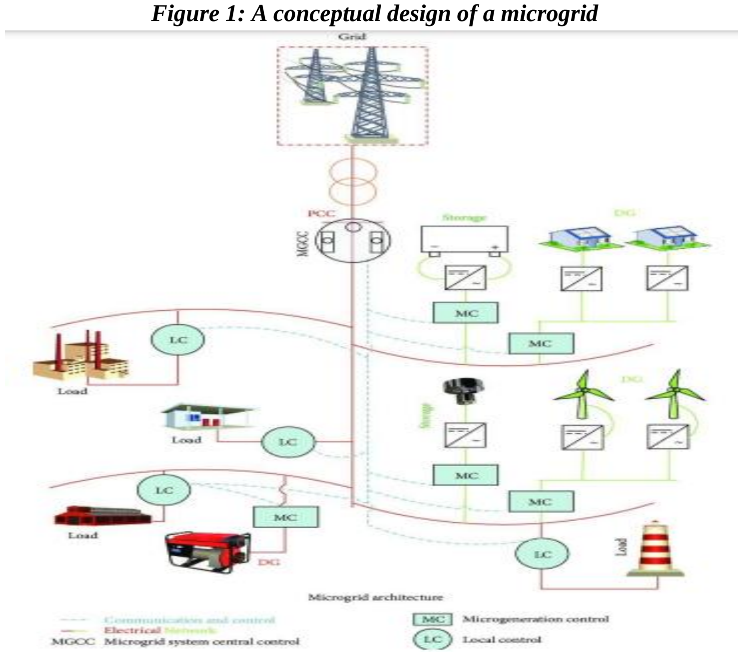

Figure 2: A simple microgrid infrastructure

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MICROGRID ENERGY MANAGEMENT SYSTEM (EMS)

To manage the loads and real-time operating conditions of microgrids, a central software system is used, called Energy Management System (EMS). An EMS performs multiple tasks simultaneously, such as collecting and forecasting energy production, storing and demanding information from DERs, DESs and loads, respectively, maintaining an equilibrium level of energy based on demand and supply of energy, maintaining an interaction with the heterogeneous users. The short-term power balancing and long-term energy management requirements are maintained by the EMS. Listing 3.2 represents those requirements.

Efficient control strategy is obviously essential for any kind of management systems. It helps to achieve the desired goal of a system. An EMS is a heterogeneous component-based energy management system, whose control strategy can be of two types:

1. Centralized control
2. Decentralized control

The centralized control of EMS is a root decision point for the entire microgrid system. To take an economic, cost effective and goal-oriented decision, it must depend on associated LCs. Each of LCs communicates with MGCC to provide information based on their own setting. For example, energy production status, storage condition and load requirement information are provided by LC of DER, DES, and load unit, respectively. A two-way communication medium is used by MGCC and LCs to perform communication between them. MGCC receives bids from LC of DER and load. After that, by considering the market price, it defines an optimal energy scheduling (set points), and the aim of the scheduling is to fulfill the objective function, such as minimization of power cost, maximization of renewable energy usage, and economic balance of power supply and demand requirements. MGCC delivers the defined energy scheduling decision to the LCs. In addition, MGCC observes the operational condition of the whole system and decides whether to change the operational mode (interconnected or islanded) of the microgrid. The centralized control approach should be computationally more strong to facilitate the whole system to process real-time data coming from multiple LCs (DER/DES/Load). Network security issues and network capacity are a concerning factor for such kind of frequent communication. Therefore, there is a single point of failure possibility of the centralized control approach. Since a microgrid is formed based on geographical conditions so its communication and associated component's structure is changeable. For that reason, the centralized approach would not be an effective approach for future grids . Figure 3.4 illustrates the centralized control of microgrid EMS.

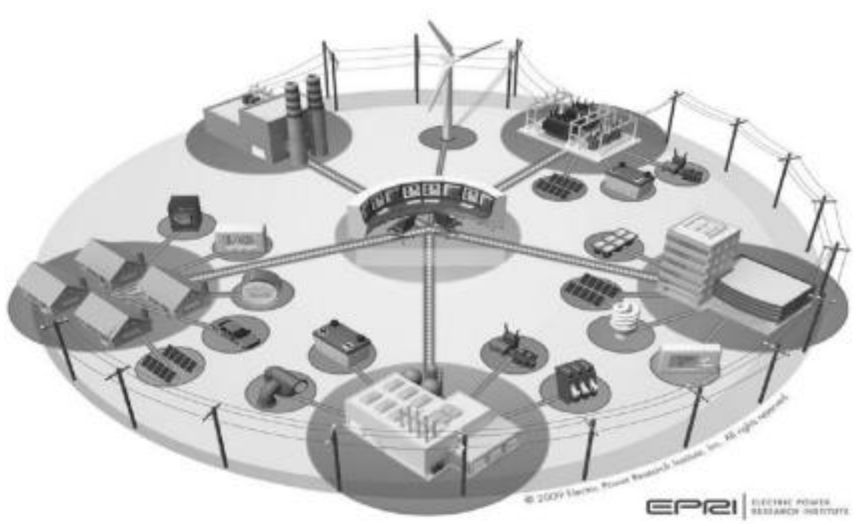

Figure 3: Centralized control of microgrid EMS

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DECENTRALIZED CONTROL OF EMS

Distributed decentralized control strategy is appropriate to maintain a complex microgrid system. Microgrid components like DER, DES and loads are controlled by one or multiple local controllers (LCs) and each of the local controller is responsible to make an operational decision by itself in contrast to the centralized local controllers of EMS. By using a communication network, each local controller communicates with another local controller that helps those local controllers to share their information with the neighbour controller within a minimum effort. Therefore, local controllers do not need to wait for set points which are provided by MGCC in centralized microgrid EMS. In this decentralized distributed control approach, local controllers are more flexible to perform their tasks, and, in addition ensure parallel computation of components of the whole system. Figure 3.5 represents the decentralized control of EMS. Distributed decentralized control of EMS is very effective in preventing the single point of failure issue in comparison to the centralized control. As the local controllers work independently, any disturbance in one of them does not badly affect the entire microgrid system. This approach potentially reduced the computational burden across different local controllers, and, for that reason, it can find a cost-effective solution.

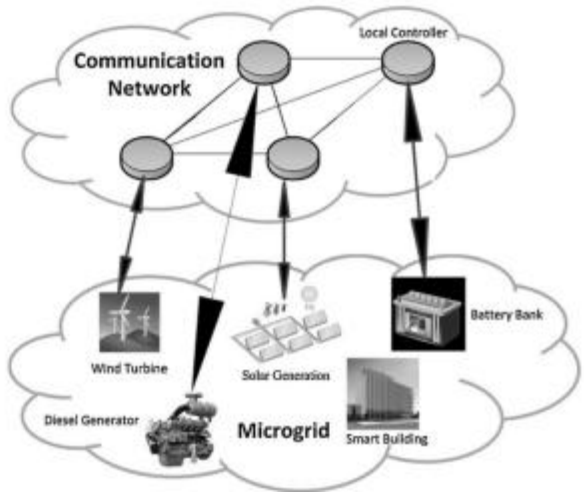


Figure 4: Decentralized control of EMS

FUNCTIONALITIES OF MICROGRID EMS

Functionalities always represent the capability of a system. There are a lot of functions used in a microgrid EMS. Type and number of functionalities vary depending on business logic of microgrid EMS. Although there is no fixed number of functionalities for a microgrid EMS, there are four key functions to build any type of microgrid EMS that optimizes the microgrid operation while satisfying the technical requirements. The key functions of microgrid EMS are forecasting, data analysis, optimization, and human machine interface. Figure 3.6 represents the functions of microgrid energy management system.

In a microgrid EMS, forecasting is obviously vital to predict the future condition of distributed energy resources, energy market and loads. Generally, to generate an effective forecast model, historical data and other data, such as weather, geographical location etc. are determined as prerequisite requirement. As some renewable energy resources (wind turbine, photo voltaic) are variable power providers and some controllable loads (electric vehicle) are adjustable based on microgrid conditions, it is really hard to predict with 100% accuracy. In optimization processes, forecast data also plays an important role. It is quite clear that the forecast data is so crucial to support the real-time demand response situation in microgrid EMS.

DESIGN OF MICROGRID EMS

Our proposal for the design of a microgrid EMS. A service-oriented microgrid EMS has to ensure interoperability of the system that helps heterogeneous users and systems to communicate with the system without knowing of location or platform. Services are considered as a key component for designing a service-oriented system. We divide this chapter into three parts, such as a conceptual model, service design principles, and microgrid Web services. The conceptual model represents a general structure of the microgrid EMS. In the service design principle's part, we discuss the application of the design principles on the capabilities of the microgrid EMS. In the microgrid Web services part, we design some Web services for the microgrid EMS including interfaces, request, response, and accessible methods of the Web services.

we discuss our conceptual model of a microgrid EMS. Our conceptual model consists of four parts based on the basic functionalities of microgrid EMSs (Chapter 3, Section 3.2.2). The parts are Web Interface, Data Collection, Optimization, and Forecast & Data analysis. To construct this model, we follow the architectural concept of the SCADA system because it enables on demand scalability by adding new component to the system and removing existing component from the system without affecting the overall energy management of the microgrids. The detail description of the SCADA system is in Chapter 3 under Section 3.2.3. Figure 4.1 represents the conceptual model of the microgrid EMS.

DATA COLLECTION

Data Collection is responsible for the collection of two types of data for the EMS. Internal data and external data are the main data sources of the EMS to make the system operational. The loads data, DERs data and DESs data are the internal data sources of the EMS. To collect internal data from microgrid devices(wind turbine, photovoltaic, battery etc.) via a central controller, which has been described in Chapter 3 under Section 3.2.3, Message Queuing Telemetry Transport (MQTT), IEC 61850 or other proprietary communication channels can be used. The internal data will be collected through the HTTP communication protocol because, the REST full Web services (Section 4.3) use HTTP as a communication protocol which is a global standard and highly interoperable. The external data are collected from different external service providers via a HTTP communication channel. Weather data and real-time market price data are an example of external data of the EMS.

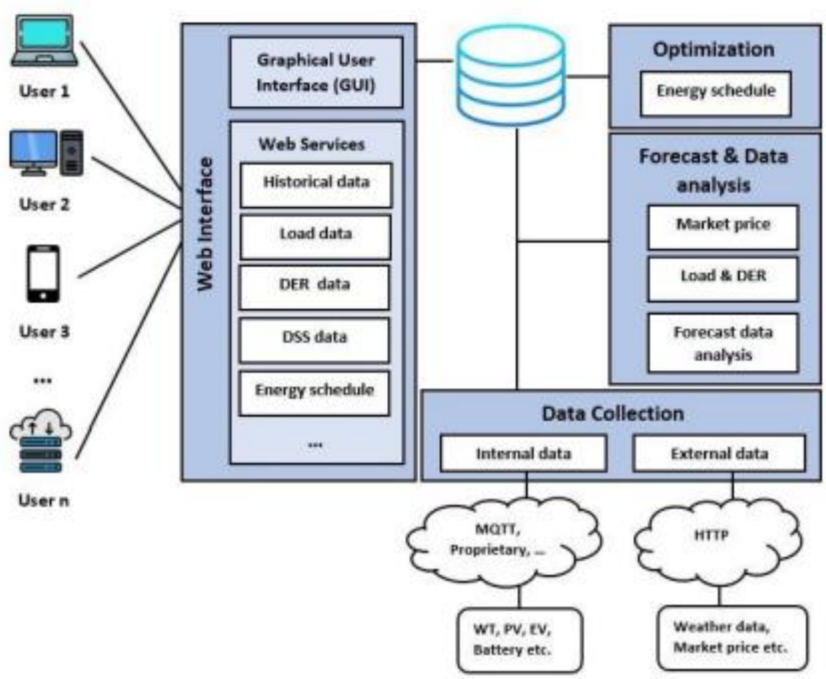


Figure 5: Conceptual model of microgrid EMS

Web Interface is responsible for the communication with the external heterogeneous end users and systems, such as commercial users and household users. The Web interface part is divided into two sub-parts, namely Graphical User Interface (GUI), and Web services. The main goal of the Web interface is to facilitate the users by visualizing and collecting real-time data of the EMS. The GUI sub-part of the Web interface provides data visualization, monitoring, and control facility to the end-users of the system, and the Web services sub-part of the Web interface delivers a real-time data, analyzed data, historical data, and other types of data of the EMS to the end-users. The Web service's sub-part is accessible via different generic methods, such as GET, POST, PUT, and DELETE which have been discussed in Chapter 3 under Section 3.3.2.

Implementation

we describe the implementation of our EMS. We organize this chapter into three parts, such as model of EMS, data collection & implementation, and data visualization. The model of EMS part presents a graphical model of our microgrid EMS as well as a service-oriented structure of the EMS. The data collection & implementation part describes the process of data collection and implementation of our Web services. The data visualization part presents some graphical figures, such as wind turbine energy generation, photovoltaic energy generation as a proof of implementation of the EMS.

As a proof-of-concept implementation, we consider a micro grid EMS with a wind turbine, a photovoltaic, and a battery. Figure a represents the concrete micro grid EMS. The EMS consists of four basic functionalities as follows:

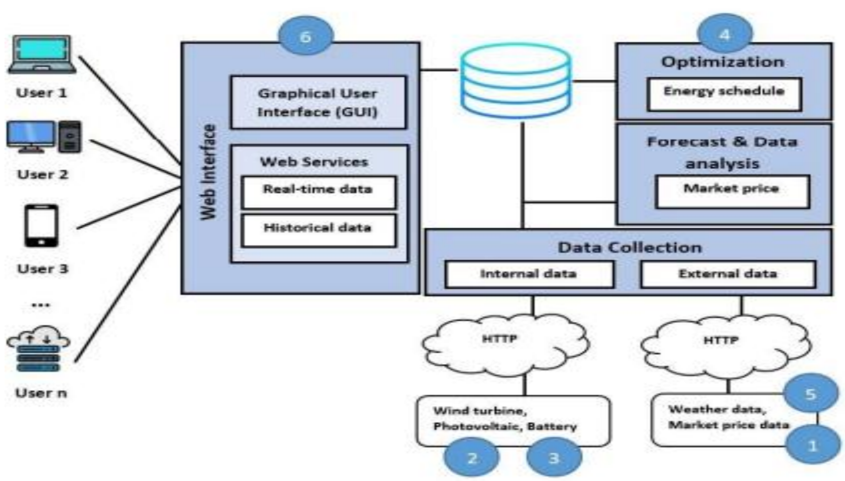
• Data collection: Two types of data are required for the EMS, such as internal data and external data. We collect internal data (wind turbine, photovoltaic, battery) by using our designed DER service and DES service HTTP communication channel. We collect external data (weather, market price) from the third party service provider via HTTP communication channel.

• Web interface: Graphical User Interface (GUI) and Web service are the sub-parts of the Web interface. The GUI represents the graphical view of energy generation of wind turbine, photovoltaic etc. for the end-users. The Web service provides current and historical energy generation and storage data of the EMS to the end-users of the system.

• Forecast & Data analysis: By analyzing the real-time market prices and hourly supply & demand of the EMS, the amount of profit or loss of the EMS is determined in each hour.

• Optimization: Provides the optimal energy schedule of the EMS by using the Energy Schedule service

Figure represents the service-oriented structure of the EMS. In that figure, one can notice that we have a central logical component thisis called Coordinator. The coordinator calls various services, such as DER service, DES service, Weather service, and it receives various types of data from those respective services, after that it stores those data to the central database of the EMS. To collect hourly energy generation data of the photovoltaic and wind turbine, the coordinator calls the DER service each hour. The coordinator provides the EMS data through the data service to the GUI component to visualize the EMS data. The end-users of the EMS can also collect the current and historical raw data (wind turbine, photovoltaic, battery) from the Coordinator via the Data service of the EMS.



(a) A simple micorgrid EMS

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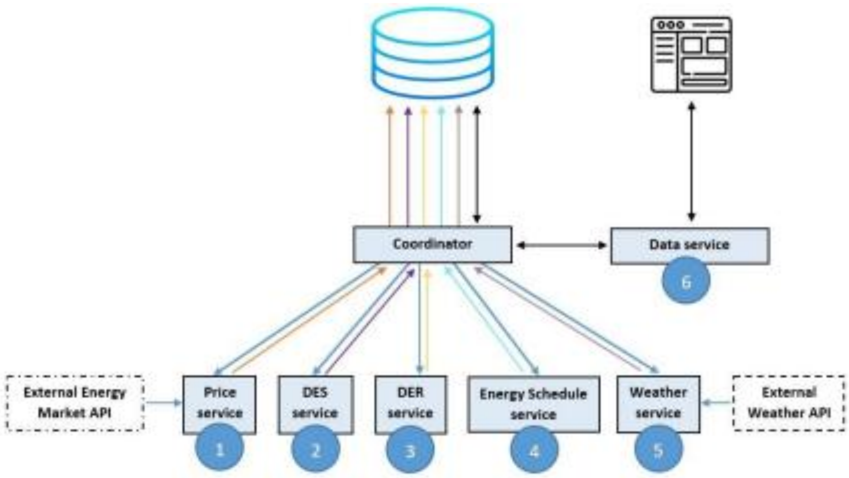


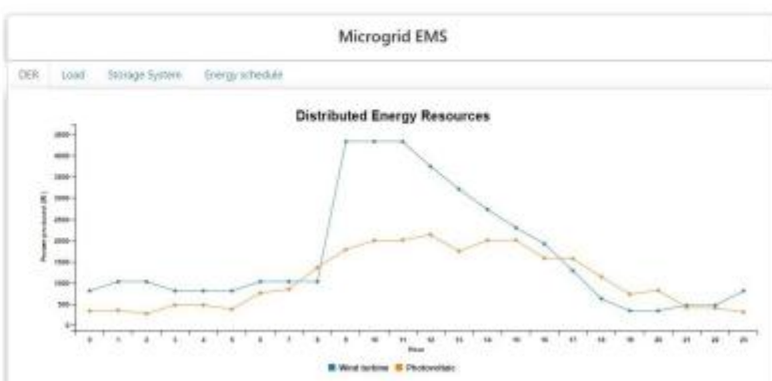
(b) Service-oriented structure of the EMS

Figure 6: A microgrid EMS and its service-oriented structure

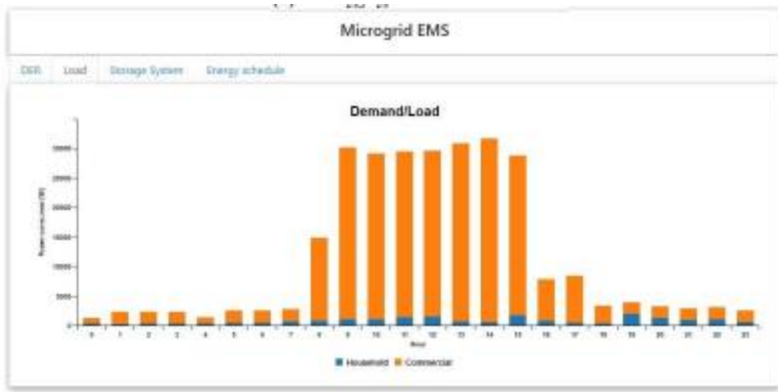
DATA COLLECTION & IMPLEMENTATION

The simulations of wind turbine, photovoltaic, battery, and energy schedule are already implemented in an existing EMS (https://gitlab.svccomp.de) which is developed by the students of the Service Computing Department at IAAS at University of Stuttgart. We use the implementation of an existing EMS to collect the energy generation data, storage data, and energy schedule data. For implementing our services, we add few lines of code to the existing implementation, because our designed Uniform Resource Identifier (URI) structure and parameters do not match with the parameters of the existing system. For example, we use some parameters, such as solar Horizon, panel Angle, panel Areain our read photovoltaic interface but the existing system which simulates a photovoltaic that uses S_horizontal, angle Of Module, area as the name of parameters, respectively. We add four route elements/blocks to the existing frontend service file and call the associated functions with our defined parameters that simulates the wind turbine, photovoltaic, battery, and optimal energy schedule. The frontend service file contains all route elements/blocks that are used to receive HTTP GET, POST requests, and send the required data to the requesters. The following lines of codes are an example of such modification of the existing implementation of photovoltaic.

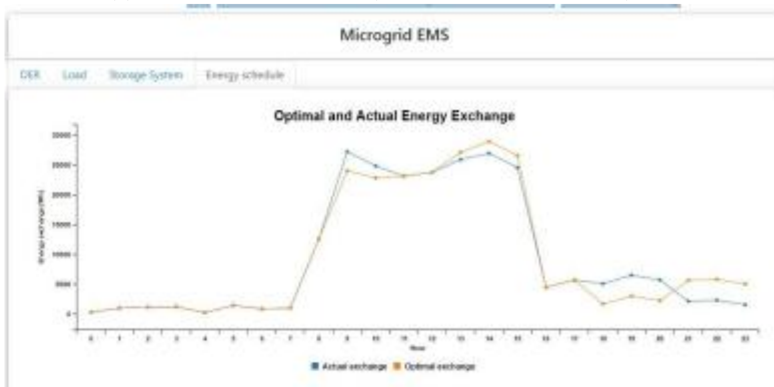
We use GET method instead of POST method. According to the interaction design rules, POST method is used to create a resource and GET method is used to retrieve a resource. The existing implementation uses POST method to create resource (logically) and stores data to the database. We use GET method because we do not need to store data, we need only simulated data (wind turbine, photovoltaic) of the existing implementation, and sends back these data to our system.



(a) Energy generation of DERs



(b) Uncontrollable loads (household & commercial)



(c) Optimal and Actual energy exchange

Figure 7: DERs, Loads and Energy Schedule data of the EMS

CONCLUSION

The perfect utilization of a microgrid is ensured by an effective EMS. An effective microgrid EMS always has to consider the functional and non-functional properties. In this thesis, we identify some essential functional and non-functional properties of EMSs and discuss the application of the non-functional properties on the capabilities of microgrid EMSs. As services are the basic constructs of SOC, we design five categories of RESTful Web services to build a service-oriented EMS for microgrids. We define interfaces, resources, accessible methods for each of the Web services. By considering the basic functionalities of EMSs, we design a conceptual microgrid EMS model that is applicable for any types of microgrid EMSs. According to our contribution of this thesis, we find that the application of the design principles of SOC ensure a sustainable development of EMSs for microgrids. A service oriented EMS is loosely coupled, scalable, reusable, interoperable, and platform independent against the traditional EMSs. We identify that a microgrid EMS needs at least four basic functionalities, such as Human-Machine Interface (HMI), Data collection, Optimization, and Forecast & Data Analysis. The Web services ensure rapid, sustainable, and low-cost development of EMSs. The Web services are easy to use for the end-users without requiring the huge knowledge of a specific domain. By using our designed Web services, we construct a concrete EMS that represents a working example of a service oriented EMS. There are some limitations of our thesis. First, our designed conceptual model of microgrid EMSs only supports four functionalities of EMSs rather than other functionalities, such as load profiles, balance plans, CO2 signals [17]. Second, we are not able to design the Web services for uncontrollable loads, such as household, commercial because, these requirereal energy consumption data. Third, we implement a concrete EMS depending on the simulated data of DERs and DES. Generally, the standard RESTful Web services, such as Google APIs, Facebook APIs etc. have an authentication mechanism for the end-users of the Web services. To design a standard authentication mechanism for accessing the Web services is one of the future work. As there can be many types of controllable loads and DERs, we design some interfaces of such types, so, to design more interfaces of the DERs (diesel, fuel cells) and controllable loads (air conditioner, electric vehicle) can be a potential future work. Defining a standard for microgrid Web services will be a remarkable work in future. The RSDL is very essential to describe the RESTful Web services, but it is not stable yet. Therefore, doing more research on RSDL that can support any type of data types will be a great future work.

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