Quantifying the Resilience of Future Smart Distribution Grids

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Preface

My special gratitude goes to my mentor Monica for believing in me, for the dynamic cooperation, her wise advise, and her continuous encouragement during the writing of this thesis. Sincere thanks are also due to teacher Roberto Villafáfila for motivating me to embark in the project. I also want to thank my family and friends for their kind and supportive words. The guidance of all these people has enabled me to conduct this analysis.

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Abstract

Smart distributed power systems are an important part of the energy shift that is currently taking place. Electricity generation, as well as power system control is moving from central operation towards local distribution grid operation, mainly due to the new possibilities that come along with distributed energy resources (DERs). These allow local consumers to generate their own electricity (prosumer), and offer support services to the grid, such as frequency control for example. Smart distributed grids can improve the local operation of DERs by coordinating demand and supply in real-time, and as such improve the power quality of the distribution grid, as well as improve the security of energy supply on local level. However, intelligent control systems, such as design of the H2020 project EMPOWER that will be used in this work, bring along complex new interconnections in the distribution grid, that may lead to increased risk of failure propagations in the distribution grid. As this, and several other challenges of the smart distributed grid could counteract the anticipated benefits, the need arises to evaluate how well an intelligent control system can cope with constantly evolving interconnections in the distribution grid, with the addition of new technologies, with the grid vulnerabilities regarding cyber security, etc. Evaluating how a system behaves when going through changing conditions, or when undergoing a disturbance, can be defined as resilience analysis, and this is what this thesis will be about. First, resilience will be defined in the context of smart distributed power systems through an extensive literature review, after which a resilience framework will be developed, based on the existing EMPOWER smart distribution grid. The technical characteristics, as well as the functionalities of the system will be defined and represented in an entity-relationship model. This model will serve as a basis to assess the level of dependencies that each main system functionality has in relation to three elements: the physical infrastructure of the system, its socio-economic environment, and the ICT network. Moreover, the attributes, or properties of the system components will be used to formulate resilience indicators against different types of disturbances of the smart distribution grid.
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List of Abbreviations and Symbols

Abbreviations

CH Switzerland
CHP Combined Heat and Power plant
CI Customer Interface
CP Customer Premises
DB Database
DE Germany
DER Distributed Energy Resource
DERUC DER Unit Controller
DoS Denial of Service Attack
DSO Distribution System Operator
EIP External Information Provider
ERM Entity-Relationship Model
ES Spain
FK Foreign Key
GDP Gross Domestic Product
HH Household
HLF High Level Function
KPI Key Performance Indicators
LC Local Controller
MT Malta
NO Norway
OR Optimal Resilience
PCC Point of Common Coupling
PF Primary Function
PK Primary Key
PV Photovoltaic
RDR Recovery Dependent Resilience
RES Renewable Energy Sources
SCADA Supervisory Control And Data Acquisition
SESP Smart Energy Service Provider
SGAM Smart Grid Architecture Model
SDG Smart Distributed Grid
TSO Transmission System Operator
WS Weather Station
Chapter 1

Introduction and Objectives

During the last decade, it has become clear that climate change and the scarcity of fossil fuels can no longer be perceived as an isolated problem that only concerns a set of specialized scientists whose duty is to preserve nature’s biodiversity. On the contrary, the effects of global warming are clearly visible today, increasingly affecting the entire human society. Extreme weather events, sea level rises, desertification, and the scarcity of natural resources such as fossil fuels, clean water, and clean air have tremendous economical impacts on countries and moreover, these phenomena result in demographic shifts that will put stress on the cultural frameworks that shape the world as it is today. In other words, climate change affects all humans and their environment, hence becomes a problematic that has to be dealt with on all levels of society, from worldwide and European collaboration to household level participation.

This introductory chapter will first highlight how climate change and fossil fuel scarcity push the global energy system to undergo a transition, making it highly dynamic and involving many actors on different levels. The main problems related to this energy transition are identified, and broken down further in order to get to the problem treated in this thesis, namely analyzing how well an energy control system on distribution grid level can cope with evolving energy trends or sudden disturbances, which is also called resilience analysis. The expected outcomes of the thesis are then presented, and the structure of the report is given.

1.1 Context

Efforts against climate change and the import dependency of primary energy resources have led Europe to integrate renewable energy resources in its electrical network, leading to an energy transition from a centralized generation and transmission network to a bi-directional decentralized grid infrastructure with active participation of end-consumers in the electrical market. Generation from renewable energy resources has the disadvantage of being unpredictable and can affect power quality due to technologies based on power electronics. To tackle these problems, electrical grids are being transformed in smart grids and complemented with smart distribution
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grids, as further explained in this section.

1.1.1 Climate change and import dependency

Western countries largely depend on fossil fuels to provide the primary building blocks of their socio-economic systems such as transportation, heating and cooling, and electricity production. To reduce the negative climate impact of greenhouse gas emissions associated with fossil fuel combustion, energy policies such as the Kyoto protocol in 1997 have been implemented worldwide over the last decades. As such, greenhouse gasses have been reduced by 19% while having an economical growth of 45% between 1990 and 2012 in Europe [14]. On the other hand, industrializing China has tripled its carbon emissions in the same time period, but reduced its CO$_2$ emissions per unit of GDP [6]. In other words, the decoupling between economical growth and carbon emissions is key for global emissions reduction, but as shown by the case of China, not sufficient. On worldwide level, the latest climate agreement took place in Paris in the end of 2015, where 185 countries, including the United States and China, submitted their plans to contribute to climate change mitigation. Already 178 of these countries have signed the legally binding agreement to maintain their targets and track their progress, which will be assessed every five years from 2018 [6]. Europe has recently updated its climate and energy framework to the 2030 objectives aiming for a 40% reduction in greenhouse gas emissions, 27% of renewable energy resources and 27% of energy efficiency, as well as a 15% of interconnection in the European electricity market by 2030 [6].

Climate mitigation efforts are therefore driving Europe to adopt more renewable energy resources in its energy mix. Another important driver is Europe’s dependency on external countries for the supply of fossil fuels, as it makes it vulnerable when it comes to energy resources scarcity and consequent political issues. According to studies from the European Commission [13, p. 24], the EU-28 import dependency has risen from 21.5% in 1995 to 44.2% in 2013 for petroleum and coal, and from 43.4% to 65.3% for natural gas in the same years.

The total share of renewable energy sources (RES) in Europe’s energy generation mix was 5% in 1995 and evolved to 12% in 2013 [13]. This evolution can be compared to the evolution of traditional fuels in fig. 1.1. For electricity generation, the RES share was about 25% in 2013 [13].
1.1. Context

1.1.2 Energy transition trends

The growing use of electrical heating systems and electrical transportation modes have started to modify the load profile of the electricity network, that has to endure more important peak loads. Additionally, physical services and consumption goods are increasingly controlled by electronics, and electronics have even started to replace mechanical core components of physical goods. For example, financial transactions take place electronically by card instead of cash, mobile phones require more frequent charging, flight bookings are almost infeasible without an electronic device, the hand brake of a car has become a simple electronic button, shopping facilities and education programs are available on-line and require electronic data acquisition and storage. In other words, services and goods increasingly depend on electrical power supply.

Moreover, the integration of RES in the global energy system is leading to important changes, especially in the electrical network. As such, small-scale local electricity generation on the low voltage level, through for example photovoltaics (PVs) or small wind turbines, is shifting the traditionally centralized and unidirectional electricity generation and transmission framework to a decentralized bidirectional electricity network, where end-consumers can produce the electricity they consume or send it to the local distribution grid. Consumers producing their own electricity are called prosumers. RES in general, from large wind farms to residential photovoltaic panels, also affect the load profile of the electricity grid by creating large peaks of electricity supply when weather conditions are favorable. By consequence, the supply
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rate of renewable resources cannot be controlled in the same way as traditional fossil or nuclear fuel based generation plants and control has to be shifted to the demand side of electricity. Demand response on consumer level can be achieved by controlling all sorts of small-scale devices that locally complement RES, such as storage devices, small-scale combined heat and power plants (CHPs), intelligent loads, etc. which together with small-scale RES are described with the term distributed energy resources (DERs).

The shift from central to decentral generation and control as mentioned above has also enabled a transition in the business model for the electricity market, as the DSO (Distribution System Operator) can extend his traditional services of distribution grid security and maintenance with customized services for proactive end-consumers. As Hermans P. states in [15], the electricity market on distribution level will undergo a transition similar to what the telecom sector has undergone, namely a decoupling of services and infrastructure provision. The telecom sector has shifted from the service of connecting a customer to a telephone line towards an information services oriented business model, focussing on services such as keeping the same telephone number when changing mobile operator. Similarly, DSOs will be able to offer services related to quality and flexibility of service on top of its primary duty of connecting consumers to the distribution grid.

1.1.3 Obstacles and solutions for the integration of renewables

A first obstacle for the integration of renewables in the electrical grid is that the existing infrastructure and regulations built are outdated and inflexible, making it difficult to enable bi-directional power flows. Moreover, as mentioned above, it is challenging to maintain the power quality of the grid as renewable energy technologies bring along many power electronic devices, affecting the power factor and bringing along harmonics. The unpredictable nature of renewable energy generation, and their tendency to create generation peaks (intermittency), can lead to grid instability, grid congestion and increased electricity market volatility. In conclusion, the overall security and quality of supply becomes more difficult to manage and maintain when renewable energy resources become part of the electrical grid.

To overcome these drawbacks, grid operators have to make a cost-effective tradeoff between infrastructure investment and more flexible control of the grid. The latter is what led to the concept of smart grids: bi-directional electricity grids that connect DERs to the main grid while automating grid control as much as possible. Moreover, the main (smart) grid can be complemented by smart distribution grids that make the main grid even more flexible and reliable. Smart distribution grids can either act as a load or as a generation resource according the the state of the main grid, in order to act as a buffer to intermittent and unpredictable renewable energy supply. By reacting to the real-time changes in the main grid status, smart distribution grids increase the stability, power quality, and flexibility of the main grid.
Fig. 1.2 gives an overview of the previously discussed energy transition trends, its obstacles and the solutions to overcome them.

![Figure 1.2: Schematic overview of the energy transition](image)

### 1.2 Problem Statement and Objectives Identification

Smart distribution grids are a key component to enable the energy transition from a fossil fuel to a renewable energy based market, as they offer the required flexibility to the main grid in order to absorb the variability of supply of renewable energy resources. As will be elaborated further in the report, smart distribution grids bring along many new technologies, developed by different manufacturers. The real-time reaction ability of smart distribution grids also requires complex interconnected communication infrastructures. However, there is little or no standardization yet when it comes to communication between the different technologies that are being deployed, and further integration of new technologies in the smart distribution grid may lead to incompatible communication technologies, making the system vulnerable.

Because of the unpredictable character of renewable energy resources, the optimization problems related to demand-supply balancing are becoming more complex, as uncertainty has to be inserted as a new parameter. This challenge can be assessed through smart distribution grids too, that can reduce the risk associated with renewable energy supply by enabling real-time control of the different smart distribution grid assets, such as storage devices, and intelligent loads.

By complementing the main smart grid with real-time controlled smart distribution grids, the system becomes more reliable and flexible, but brings along a new level of complexity in infrastructure and dependencies between the elements of both the main grid and the smart distribution grids. Therefore, it is important to assess how effectively a smart distribution grid can improve the operation of a grid through real-time control of its generation, load, and storage devices. One could for instance
analyze if smart distribution grids will still be performant when for example new technologies are added to its infrastructure, new communication standards are applied, when end-users change their behavior, or when the smart distribution grid is subject to an external cyber attack or extreme weather event. The analysis of the system’s response to changes can be defined as resilience analysis, and this will be the focus of this thesis. In other words, this thesis will attempt to quantify to which extent a smart distribution grid is capable of enhancing the operations of the main grid that is undergoing an extensive integration of renewable energy resources.

1.3 Expected Outcomes

In the first place, the this work will define resilience and give an overview of the state of the art regarding resilience analysis in power systems. Afterwards, a resilience analysis will be performed for an existing smart distribution grid project: the H2020 EMPOWER project. To do this, all the essential functionalities of EMPOWER’s smart distribution grid control system, defined as the "Smart Energy Service Provider" (SESP) will be listed, and all the system elements contributing to these functionalities will be identified. As such, indicators can be established to analyze how changes in the existing system affect its resilience. Additionally to these indicators, an entity-relationship model will be created to map the dependencies between the different system components and communication infrastructure, allowing to quantify the criticality of each system’s component for the global performance of the SESP.

1.4 Structure of the Report

This thesis text will be structured as follows: chapter 2 will start by giving an extensive description of smart distribution grids in general, then define resilience in the context of power systems, and give an overview of the state of the art of resilience indicators. Chapter 3, the methodology will present the EMPOWER project and define its structure, functionalities, and participants. Additionally, this chapter will propose several methods for resilience analysis that are suitable for application on the presented project. Chapter 4 will give the resilience indicators that are specific for the EMPOWER project, as well as present a more global measure of the system’s resilience, namely a measure for the level of dependencies through an entity-relationship model. Finally, chapter 5 will draw some general conclusions, propose further research in the field of smart distribution grid resilience, and briefly give a summary of how smart distribution grids can improve the resilience of the main grid.
Chapter 2

Literature Review: Resilience in Power Systems and its Quantification

2.1 Introduction

In the field of power systems, resilience has started to get more attention after a seemingly higher occurrence of high impact, low probability events, such as extreme weather events, or cyber attacks. It is enough for these types of disturbances to cause a minimal amount of physical damage to the grid, to initiate extensive failure propagations on distribution level, affecting many local electricity consumers.

There is no standardized framework for resilience analysis yet, which is partly due to the fact that there is no clear definition for the term resilience either. The term has been interpreted differently depending on the field of expertise in which it is applied. The following sections will first give a general definition of resilience and develop it further in the context of smart distributed power systems. It will propose a first set of suitable resilience indicators found in literature, and discuss a number of assessment methods that are relevant to the topic of smart distributed grids.

2.2 Definition Resilience

The first definition of resilience came from the ecologist C.S. Holling in 1973, who formulated resilience as follows:

"The capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure, identity, and feedbacks." [21]

Definition 2.1 was meant for ecosystems, systems that evolve from one equilibrium point to another, but got adapted to other fields of expertise too. According to [28], in social sciences the term resilience indicates the ability of a community to
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Conceptually, resilience is the ability of a system to adjust and adapt to disturbances and changes. In this context, resilience can be described as the ability of a system to gracefully adapt to new social, political, or economical equilibria. In engineering, the term often refers to the ability of a system to bounce back to the initial state of equilibrium after a disturbance [1]. Even within engineering, however, different disciplines have adapted the initial definition to suit their specific applications. The lack of a formal definition makes it challenging to develop a standardized framework for resilience assessment. In other words, the first step to develop a model for resilience assessment is to find a proper definition for the concept of resilience.

Within the power systems discipline, resilience gets different meanings when applied to specialized parts of the power system. The term is interpreted differently when exploring the effect of cyber-security on resilience [2], or when looking at a system's response to natural disasters [27], for example. Moreover, most of the existing metrics to assess resilience, such as proposed in [1], [23], have been made for the traditional, centrally operated transmission grid, and don’t take into account the new developments of the electrical power system, which is currently moving towards a dynamic system with significant portions of generation and control taking place at distribution level. One of the few works on resilience that acknowledges the transition towards the distribution grid so far is [17], which proposes a resilience framework for power systems on distribution level. The work suggests that resilience is not only dependent on the intrinsic characteristics of a system, but also on how the system evolves with its environment.

The traditional centrally operated transmission grid is a complex, but mainly steady system with only a few well-defined functionalities and a rather static infrastructure. Therefore, much of the literature found in electrical engineering defines resilience based on the ability of a system to 'bounce back' to its initial, invariable state. This will be defined as short term resilience.

On the other hand, the shift towards decentralized smart distribution grids is characterized by the dynamics of integrating new technologies and new participants into the grid. Therefore, resilience for smart distributed power systems will have some additional features that take into account the grid's capacity to evolve towards new equilibria, which will be categorized as long term resilience.

In sum, resilience can be described by five characteristics: reliability, adaptive capacity, elasticity, plasticity, and evolvability. The first three terms are describing short term resilience, whereas the last two terms, plasticity and evolvability, describe long term resilience. Moreover, resilience can further be categorized into static and dynamic resilience, as will be elaborated further on. Table 5.1 gives an overview of how resilience can be decomposed.
2.2. Definition Resilience

<table>
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<tr>
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<th>Static</th>
<th>Dynamic</th>
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<td>Short term</td>
<td>Reliability</td>
<td>Elasticity</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Adaptation capacity</td>
</tr>
<tr>
<td>Long term</td>
<td>Plasticity</td>
<td>Evolvability</td>
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Table 2.1: Overview of the components of resilience.

2.2.1 Short Term Resilience

Despite the different interpretations of resilience that relate to power systems, a common core can be found in existing definitions, such as in [21], [23], and [25], which can be formulated as follows:

\[
\text{Resilience is the ability of a system to remain functional under the event of a disturbance, while minimizing the time and effort it requires to return to its functional state.} 
\]

(2.2)

Definition 2.2 implies that resilience can be assessed by evaluating the change of the systems performance during different phases of a disturbance, namely before, during, and after the disturbance. How a system responds in each phase will be characterized by the different short term characteristics of resilience. Fig. 2.1 shows the performance characteristic of a system in function of time, and resilience is assessed by evaluating the change in performance during a disturbing event. In the case of power systems, the performance function could be the percentage of small scale end customers that still receive power in the event of a storm that has damaged transmission lines. It should be noted that physical damage is caused on transmission level, but that the consequences are mainly experienced on distribution level, because of failure propagation. This shows that it is more relevant to assess the loss of performance of a system than to assess the structural damage caused by a disturbance, as little physical damage can have major consequences for the end consumers on distribution level.

Four different phases can be distinguished in fig. 2.1. The fully functional state before the disturbance \((t_e - t_0)\), the phase where the disturbance occurs \((t_d - t_e)\), the phase where the system is in fully degraded state \((t_s - t_d)\), and the recovery phase \((t_f - t_s)\).
2.2. Definition Resilience

Figure 2.1: System performance during a disturbance, and the four components of resilience. Adapted from [1].

2.2.1.1 Static Component

Reliability: the term is used to describe how well a system can withstand anticipated disturbances, namely high probability, low impact events. For instance, power line failures are foreseeable failures, and can be resolved by building redundancy into the system, making it more reliable. The reliability of the system is about building a system that is robust enough to resist disturbances. Therefore reliability is a property that has to be implemented in the design stage of the system. It requires a top-down approach, by anticipating on the possible disturbances that can occur during the systems lifetime. Moreover, as reliability only assesses if a system is functional or non-functional, it is a static characteristic, that doesn’t change over time.

In fig. 2.1, the system is fully functional during the time period \((t_e - t_0)\). The longer this period, the more reliable the system is.

2.2.1.2 Dynamic Components

Adaptive Capacity: if a system can’t withstand a certain disturbance, it will be degraded to a lower level of performance, and this process is represented in time period \((t_d - t_e)\) in fig. 2.1. This period represents the adaptive capacity of a system, or how well the system can tolerate a disturbance before getting fully degraded. The longer this period, the more controlled the degradation will be, which can limit the overall damage caused by the disturbance, and indicates a higher ease of adaptation of the system.
2.2. Definition Resilience

**Elasticity:** similar to metallurgy, elasticity in this context refers to the ability of a system to fully return, or *bounce back*, to its original state after undergoing a deformation. In fig. 2.1, elasticity encompasses the fully degraded state of the system \( t_s - t_d \), as well as the recovery period \( t_f - t_s \). If the system fails to fully recover the damage, then the loss of performance is irreversible and becomes a long term characteristic, described as plasticity. The more efficient the recovery, the more resilient the system.

2.2.1.3 Difference Between Resilience and Reliability

In academic literature, the terms resilience and reliability are sometimes used to refer to the same thing. However, there is a distinction to be made, as reliability is in fact a part of resilience.

Resistance assesses the withstanding capacity of a system against an anticipated disturbance. It is therefore a binary characteristic, only distinguishing a functional state from a non-functional state. Resilience, on the other hand, goes further by also evaluating the ability of a system to return to its initial state after a disturbance. Hence, resilience not only evaluates the withstanding capacity against but also the impact of a disturbance. It is therefore a quantitative characteristic, assessing many states of the system.

Even if reliability often improves resilience, a reliable system is not always more resilient. Namely, increasing the robustness (reliability) of a system can reduce its restoration capacity when the system nevertheless gets damaged. For example, a TSO can choose to install underground cables to reduce the risk of line damage. As such, the probability of the lines getting damaged is reduced, but in the event where the lines get damaged anyways, the impact on the system performance is much higher as it requires more time and effort to repair underground lines than for instance overhead lines [17].

Table. 2.2 summarizes the differences between resilience and resistance.
2.2. Definition Resilience

Reliability evaluates system in response to low impact, high probability disturbances.

Resilience evaluates system in response to high impact, low probability events.

Evaluation range:
- Reliability: binary: functional/non-functional
- Resilience: quantitative: different levels of performance

Design:
- Reliability: top-down
- Resilience: bottom-up

Type of characteristic:
- Reliability: static
- Resilience: changing

Achieved by:
- Reliability: robustness/redundancy
- Resilience: robustness, adaptability, elasticity, ...

<table>
<thead>
<tr>
<th>Reliability</th>
<th>Resilience</th>
</tr>
</thead>
<tbody>
<tr>
<td>evaluates system in response to</td>
<td>low impact, high probability</td>
</tr>
<tr>
<td></td>
<td>disturbances</td>
</tr>
<tr>
<td>evaluation range</td>
<td>high impact, low probability</td>
</tr>
<tr>
<td></td>
<td>events</td>
</tr>
<tr>
<td>design</td>
<td>top-down</td>
</tr>
<tr>
<td>type of characteristic</td>
<td>static</td>
</tr>
<tr>
<td>achieved by</td>
<td>robustness/redundancy</td>
</tr>
</tbody>
</table>

Table 2.2: The differences between resilience and resistance.

2.2.2 Long Term Resilience

Since the power system is evolving towards distributed operation and generation, where many new technologies and ICT networks get integrated to the power system, it is no longer feasible to perceive the grid as a steady system with only one equilibrium point. The increasing complexity of the power system on transmission and distribution level is creating many new parameters of uncertainty in the grid, hence it becomes more difficult to predict how it will operate under certain conditions, or what the best design for reliability would be. Hence, for smart distributed power systems, the definition of resilience needs to take into account the ability of the system to evolve to new and unknown equilibria, maintaining its core functionalities, but not necessarily performing these in the same way.

Therefore, definition 2.2 will be extended with another characteristic, evolvability, to assess how well a system improves itself by learning from the disturbing events it has undergone. In order to do so, one can consider a certain disturbance as part of a cycle of disturbances, and evaluate the evolution of the way the system copes with these repeating disturbances over the long term, which will be defined as dynamic resilience. The U.S. Presidential Policy Directive 21 has included the dynamic aspect of resilience in its definition:

"The ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions." [17] (2.3)

2.2.2.1 Static Component

Plasticity: as stated earlier, the terminology used in metallurgy can be applied in the context of resilience too. When a system undergoes irreversible damage, in other words, can no longer bounce back to its equilibrium state, it loses its elasticity and
the loss of system properties is described by plasticity. In fig. 2.1, this is shown by the difference between the initial fully performant state (at 100% performance rate), and the degraded state after recovery (at 80% performance rate). Once a system has plasticity, it won’t change over time, hence it is a static characteristic. Plasticity is not a favorable characteristic of resilience, as an elastic system is much more flexible.

2.2.2.2 Dynamic Component

Evolvability: this term refers to the ease with which a system can adapt itself to changes, or improve itself by learning from the disturbances it undergoes. For instance, fig. 2.2 shows how a system adapts its behavior after a first disturbance, resulting in improved operation during a second disturbance cycle, where the system recovery initiates faster and the recovery time is shorter (improved elasticity) and doesn’t suffer from additional plasticity. Evolvability is a characteristic that changes over time, together with the changes undergone by disturbances.

Figure 2.2: System evolution between two cycles of disturbance. Adapted from [1].

2.3 Factors Characterizing a Systems Resilience

The previous section showed how resilience is a multi-attribute property, composed by the characteristics of elasticity, adaptation capacity, reliability, plasticity, and evolvability. These characteristics are not only defined by the system properties itself, but also by how the system is being used and how it interacts with its environment. Consequently, the task of evaluating resilience begins with identifying a system’s characteristics and defining how these are composed. For example, certain characteristics or properties of the global system are a simple sum of the same properties on component level, such as for example the total power of a system, being the sum of the individual powers of each component of the system. Other characteristics can be the result from more complex relationships between the system and its components, and even other characteristics are defined by how the system interacts with its environment.
2.3. Factors Characterizing a Systems Resilience

2.3.1 Composition of Resilience Characteristics

[5] distinguishes five types of system characteristics, in function of how they are composed, which is discussed in this section.

1 Directly Composable Properties

These properties are combination of the same properties on component level. For example, power measurements or static memory of the system. The function $f$ will change in function of the used technology to assemble components. For instance, static memory is a constant, whereas dynamic memory can be seen as non constant.

$$P(A) = f(P(c_1), P(c_2), ..., P(c_n))$$

2 Architecture Related Properties

Properties dependent on the combination of the same property on component level, and the system architecture. For instance, the geographical location of DERs in the distributed grid. In software development, the architecture can be changed in order to improve properties of the system without changing the properties of the components. An example of this is an architecture that easily allows the addition of new components, which improves the variability and scalability of the system.

$$P(A) = f(P(c_1), P(c_2), ..., P(c_n), SA)$$ with $SA =$ Software architecture

3 Derived Properties

These are characteristics that depend on more than one type of component properties. In other words, the system properties are a composition of different component properties. Latency belongs to this category, as well as the special case of the emerging attribute, which is an attribute visible on system level, but not on component level, hence for which the challenge is to find out which component properties have an impact on them.

$$P(A) = f\left(\begin{array}{c} P_1(c_1), P_1(c_2), ..., P_1(c_n), \\ P_2(c_1), P_2(c_2), ..., P_2(c_n), \\ \vdots \\ P_3(c_1), P_3(c_2), ..., P_3(c_n) \end{array}\right)$$

4 Usage-dependent Properties

This type of system property is defined by the usage profile of the system. The difficulty here is to determine the usage profile of a component in order to define its properties when only the usage profile of the system is given. Moreover, it is difficult to predict the usage profile of a system even before it is designed! The main challenge of this type of property is that it change constantly with the change in usage. An example of such a property is reliability.
### 5 System Environment Context Properties

This type of property is defined by a combination of other properties with the state of the environment in which the system exists. Resilience belongs to this type of system properties, and encompasses characteristics of all the other categories.

Table 2.3 shows some resilience characteristics for a smart distribution grid, both short term and long term, organized into the previously discussed categories.

<table>
<thead>
<tr>
<th></th>
<th>Short Term</th>
<th>Long term</th>
</tr>
</thead>
</table>
| Composable and Architecture dependent | - **adaptation capacity/tolerance**: it can take the disturbance in a slow and controlled manner  
- **elasticity**: it can restore itself quickly | - **flexibility/plasticity**: it can maintain its functionalities even if the system has changed  
- **autonomy/self learning capability**: it can improve itself based on the disturbing event, to be able to handle the next disturbance better  
- **scalability**: it can extend gracefully  
- **security**: depends on the systems components, and how these are interconnected |
| State of the system dependent/ Derived | - **level of performance**: a system that is degraded will have a lower resilience  
- **self-sufficiency**: how much the system depends on other systems to maintain it’s functionality | - **stage in lifecycle**: if the system is in its design stage, construction stage, begin of operational lifetime, end of operational lifetime affects its resilience |
| Usage dependent | - **reliability**: a system is only robust against a limited amount of usage profiles, hence this characteristic depends on how the system is used | - **criticality**: if a system is very critical for its users (as is increasingly the case for electricity), it changes the system requirements, consequently also changing its resilience. |
| System environment | - **presence of lifelines**: repairing team, transport infrastructure, fuel delivery | |

Table 2.3: Types of characteristics that characterize the resilience of a smart distributed grid.

In the bottom row of the table, dependency on *lifelines*, is a term used in [18], and refers to the external systems on which a system relies to operate. The more dependent a system is on its lifelines, the less resilient it is.

### 2.3.2 Dimensions of Resilience Characteristics

Another way of categorizing the factors that contribute to a systems resilience is to look at these factors in different dimensions. In [16], the factors influencing a systems resilience are divided into three dimensions: a physical, cybernetic, and socio-economical dimension. Each of these dimensions contains elements which define how the system operates and how it improves or reduces the systems resilience. Fig. 2.3 represents this graphically and gives examples in each dimension for the smart distribution grid.
2.4 Resilience Metrics

This section presents a set of resilience indicators found in literature. However, more specific indicators will be given in the next chapters.

2.4.1 System Performance Indicators

The transition distributed energy system with active participation of the end consumer requires resilience metrics for two aspects of the power system, one for the customer services perspective, and one for the power infrastructure itself. This can be done by switching between system scale and individual component scale. In order to use measures that are easily integrated into the existing system of standard metrics,[17] proposes to adapt existing reliability metrics such that these are suitable to measure system resilience in the event of a high impact, low probability event. As such, the ASAI (Average Service Availability Index) can be changed adapted to a first resilience metric, as shown in this section.

Figure 2.3: The three dimensions of a system that influence its resilience. Adapted from [16].
Quantitative Approach

Figure 2.4: Time intervals between the phases of a disturbance [17].

In fig. 2.4, \( T_U \) represents the up time of the system, which is related to the physical robustness of the system, being its design and infrastructure strength, hence this duration represents the systems withstanding capacity. \( T_D \), on the other hand, represents the systems recovery speed and depends on the repairing difficulty of damaged infrastructure components, as well on human and organizational features, such as maintenance policies. \( T \) is then the total time considered for resilience calculation.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Formula</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( R_I )</td>
<td>( \frac{T_U}{T_U + T_D} )</td>
<td>single load resilience</td>
</tr>
<tr>
<td>( R_B )</td>
<td>( \frac{\sum_{i=1}^{N} T_{U,i}}{NT} = \frac{\sum_{i=1}^{N} T_{U,i}}{\sum_{i=1}^{N} (T_{U,i} + T_{D,i})} )</td>
<td>power supply base resilience</td>
</tr>
<tr>
<td>( \theta )</td>
<td>( \frac{n_0}{N} )</td>
<td>outage incidence</td>
</tr>
<tr>
<td>( v_r )</td>
<td>( \frac{d\theta}{dt} )</td>
<td>restoration speed for ( N ) customers</td>
</tr>
<tr>
<td>( V_{r,i} )</td>
<td>( \frac{1}{T_D} )</td>
<td>individual restoration speed</td>
</tr>
<tr>
<td>( v_{d}(t) )</td>
<td>( \frac{d\theta}{dt} ) for ( t &lt; t_\theta = \theta_{max} )</td>
<td>disruption speed for ( N ) customers</td>
</tr>
<tr>
<td>( V_{d,i} )</td>
<td>( \frac{1}{T_U} )</td>
<td>individual disruption speed</td>
</tr>
<tr>
<td>( \phi_I )</td>
<td>( \frac{T_{1,U}}{\Delta t_1} )</td>
<td>individual resistance</td>
</tr>
</tbody>
</table>

Table 2.4: Resilience indicators [17].
The difference between $R_I$, $R_B$ and the traditional availability indicator $ASA_I$ is that the latter are calculated on the basis of an infinite number of cycles, whereas the former are based on a single cycle duration $T$, hence they can be used to assess the performance during a disturbance too, which distinguishes it from a simple reliability metric. Moreover, with these resilience metrics, it is also possible to implicitly measure adaptation capacity and planning capacity, when subsequent cycles (subsequent values of $T$) are compared.

### 2.4.2 Recovery Speed and Effort Indicators

In their paper about resilience of infrastructure systems [28], Vugrin et al. evaluate system resilience by measuring the impact of a disturbance as well as the recovery effort that is required by the system to regain an acceptable level of performance. As such, resilience is determined by two metrics, namely the impact on the system performance and the system recovery effort. Both metrics have a weighing factor to determine a system’s resilience. For example, a fast recovery at high cost might not be more resilient than a slower but less expensive recovery process. This is illustrated in fig. 2.5.

![Figure 2.5: Systems with the recovery speed do not necessarily have the same level of resilience, as one might need more recovery resources than the other.][28]

### Quantitative Approach

From fig. 2.6, two metrics can be derived, which in turn allow to define two resilience indicators. The systemic impact ($SI$) is quantified by calculating the area between the targeted system performance ($TSP$) and the actual system performance ($SP$) curves:

$$SI = \int_{t_0}^{t_f} [TSP(t) - SP(t)]dt$$
The total recovery effort is represented by the area under the recovery effort (RE) curve in fig. 2.6:

\[ TRE = \int_{t_0}^{t_f} [RE(t)]dt \]

![Figure 2.6: Systemic impact (a) and total recovery effort (b) are measured by calculating the shaded areas under the curves [28]](image)

From these two metrics, [28] assesses resilience in two different ways:

**Optimal resilience (OR):** which is the resilience cost for a particular disruption when optimal recovery, which means the most cost-effective combination of limiting impact and the required efforts, is deployed:

\[
OR(d) = \min_{RE} \frac{\int_{t_0}^{t_f} [TSP(t) - SP(t, d)]dt + \alpha \times \int_{t_0}^{t_f} [RE(t, d)]dt}{\int_{t_0}^{t_f} TSP(t)dt} \quad (2.1)
\]

**Recovery Dependent Resilience (RDR):** this indicates the resilience costs when a specific recovery solution is chosen. This metric is therefore useful to compare
2.4. Resilience Metrics

the resilience of different recovery solutions.

\[ RDR(d, RE) = SI + \alpha \times TRE \int_{t_0}^{t_f} TSP(t) dt \]  

(2.2)

In equations 2.1 and 2.2, \( \alpha \) is a weighing factor that assigns more or less weight to the system impact relative to the recovery effort. This can be changed in function of the system that is assessed.

2.4.3 Tolerance Range Indicators

Many systems have a built-in tolerance range for several parts of the system. For instance: redundancy, or the N-1 criterion stating that when 1 transmission line fails, the remaining transmission lines should be able to redistribute the extra power flow from the failed component [19]. This approach makes the system more robust, but also less flexible for unknown disturbances. Therefore, a resilience metric could be to measure how much built-in tolerance range of a system can be used as a buffer for disturbances, rather than a necessary tolerance range for predictable disturbances.

Quantitative Approach

- **Hosting capacity**: the degree of DERs in the power grid that can be accepted without endangering reliability or quality of power. This can be measured with performance indicators:

  - voltage magnitude
  - voltage dips
  - risk of overloads

- **Key Performance Indicators (KPI) related to voltage control**: how much the voltage tolerance range becomes a safety band? This is illustrated in fig. 2.7: the bigger the green surface, the more resilient the system is. Hence, more accurate voltage control results in higher resilience.

- **Forecasting accuracy**: reducing the required safety margins taken on forecasting calculation results.

- in general: how much room is there to capture/deal with contingencies
2.5. Resilience Quantification Methods

2.5.1 Step-by-step Approach

Fig. 2.8 shows a step-by-step framework to follow for the resilience assessment of a composed system. In the procedure, [5] puts emphasis on the external systems that can affect the properties of the system that is analyzed. As such, the specialty of resilience quantification is that it doesn’t restrain its field of evaluation to the system boundaries, but on the contrary tries to quantify the impact of external factors on the behavior of the resilient system.

Figure 2.8: A graphical explanation of the voltage performance evaluation adopted by the IGREENGrid project. (a) Voltage quality $0 < VQ < 1$. (b) Voltage quality $VQ \approx 1$. (c) Voltage quality $VQ < 0$ [26]

Figure 2.8: system resilience evaluation [5]
2.5.2 Importance Attribution

[1] proposes a Markov Imbeddable Structure Technique for reliability and importance evaluation of systems with interdependent components. By evaluating the dependencies in a system, one can evaluate which components are the most critical to guarantee the system's best performance. According to [1], metrics for such an evaluation could be:

- Operation criticality index: the ratio of a specific component downtime to the main system downtime
- Restore criticality index: evaluates the impact of the restoration of a specific component
- Failure criticality index: ranks components according to their criticality for allowing the main system to perform a function, so how efficient the system is when a specific component fails.

2.5.3 Graph Theory

Graph theory is a straightforward, but time consuming way of analyzing systems and processes, by following an "if-then" logic, building tree structures for analyzing different scenarios [17].

2.5.4 Axiomatic Design

In [17], Kwasinski states that resilience can be assessed through axiomatic design, and in the EMPOWER Deliverable 3.4 [10], axiomatic design is described as follows: a methodology based on matrices formulation to study the transformation of customer needs into functional requirement, design parameters, and process variables. Functional requirements may be calculations, technical details data manipulation and processing and other specific functionality that define what a system is supposed to accomplish. The so-called non-functional requirements (also known as quality requirements), define constraints on the design or implementation like performance requirement, security, or reliability.
Chapter 3

Methodology for Evaluating Resilience in Future Distribution Grids

3.1 Introduction

The objective of this thesis is to find a suitable set of indicators and a framework to quantify the resilience of a distributed power system (a smart distribution grid), and more specifically of its intelligent control system. The previous chapter gave an extensive definition of resilience in the context of distributed power systems, and presented existing models for resilience analysis. This chapter will elaborate by proposing a framework that is particularly set up to analyze a practical use case, namely the smart distribution grid designed by the H2020 project EMPOWER.

Figure 3.1: Workflow of the methodology

In this chapter, the project will first be introduced, after which an in depth description of its functionalities and technical architecture will be presented. A subsequent section will focus on the intelligent control system of the smart distribution grid: the Smart Energy Service Provider (SESP), by making a functional decomposition. More specifically, each functionality of the SESP will be decomposed into sequences that
3.2 Use Case: H2020 Project EMPOWER

consist of a set of primary functions that process certain attributes of the system components. To specify the relationships between the different elements of the smart distribution grid, an entity-relationship model will be created. For this, a general definition will be given, the entities of the system will be defined, and will then be related to each other in a conceptual entity-relationship model. Then, the reference requirements of the EMPOWER smart distribution grid will be given and quantified by adding reference attributes to the entities in the entity-relationship model. Based on previously studied methodologies, each entity will be attributed a degree of importance in function its role in the operation of the SESP. The entity-relationship model, together with the functional decomposition of the SESP will form the basis for the resilience analysis framework. As such, the chapter will conclude by suggesting a framework for resilience quantification that fits in the EMPOWER architecture, with a special focus on the resilience of the SESP. The proposed methodology will be tested and discussed in chapter 4. Fig. 3.1 summarizes the workflow of the methodology that is presented in this chapter.

3.2 Use Case: H2020 Project EMPOWER

To develop a resilience quantification model that goes beyond a merely theoretical feasibility, a practical use case has been selected as the starting point of the model, and more specifically, the smart distribution grid designed by the H2020 project EMPOWER. By analyzing a smart distribution grid architecture that is already developed in detail, more parameters are available to make a realistic analysis of the systems resilience. Moreover, the resilience quantification framework can even be tested on the EMPOWER pilot sites in the future, and be improved accordingly.

3.2.1 Project Presentation

EMPOWER is a project supported by the European H2020 program that started in January 2015. The project is a collaboration between eight companies and research centers from across Europe. These are: Schneider Electric (NO), SmartIO (NO), eSmart Systems (NO), Fredrikstad Energi Nett (NO), University of St. Gallen (CH), CITCEA-UPC (ES), MIEMA (MT), and NewEn (DE). Together, they are combining different fields of expertise, from power electronics and industrial automation to energy markets and business modeling. The project aims to create local energy markets where prosumers (consumers that can generate their own electricity or heat) can get involved in energy trading as well as offer flexibility services to the main grid, hence empowering the local consumer and encouraging microgeneration. Moreover, because of the smart meter roll out together with the increasing number of DERs, the DSO is gaining responsibility and the EMPOWER project aims at offering support services to the DSO, by asset management on distribution level, demand response, etc. including local storage devices into the distribution grid. This is done through a cloud based intelligent control system. Three pilot sites are currently being installed to test different set-ups of the EMPOWER control system, in respectively Hvaler in Norway, Wolpertshausen in Germany, and Malta. [24]
To gain customer involvement, EMPOWER develops innovative business models for local energy markets that maximize the potential benefits for prosumers. Moreover, EMPOWER characterizes itself through its intelligent control system, the Smart Energy Service Provider (SESP). The SESP is a cloud based control platform that monitors and controls the components of the smart distribution grid, analyses and processes the monitored data, and communicates with the participants of the local market, such as prosumers, DSOs, ancillary service providers, etc. In other words, it delivers the necessary real-time flexibility to manage energy assets on a local level, hence facilitating the integration of renewable energy resources in the distribution grid.

3.2.2 Smart Grid Architecture Model (SGAM)

The Smart Grid Architecture Model (SGAM) is a three dimensional representation of the smart grid architecture established by the Smart Grid Coordination Group, a working group that is in charge of fulfilling the M/490 EU Mandate on smart grids standardization [4]. The SGAM distinguishes different levels of functionality of the smart grid by decomposing it into different layers of operability, zones, and domains. More specifically, the smart grid plane is spanned by five domains and six zones, and five layers of interoperability represent the viewpoints that different stakeholders have on the smart grid plane. As such, the SGAM model standardizes the definition of smart grid functionalities, and allows to define both overarching generic use cases as well as specific use cases to describe its functionalities.

The advantage of the multidimensional framework is that smart grid functionalities can be expressed independently from the physical set-up of the system, or from its participants. As such, a system represented through an SGAM can be adopted by different technologies, different actors, and fit into different regulatory delimitations. By making the right delimitations of the system, the SGAM can also be used to represent a smart distribution grid.

Domains and Zones

As can be seen in fig. 3.2, five domains categorize the physical assets of the smart grid, going from domains representing bulk generation and high voltage transmission, to the domains that represent distribution, DERs on medium and low voltage level, and the customer premises which is the smallest scale of the electricity conversion chain, for instance households and commercial buildings.

The SGAM also distinguishes six levels or zones in which a power system can be managed, namely the process, field, station, operation, enterprise, and market zones. The zones are represented by the axis perpendicular to the domain axis in fig. 3.2. In the process zone, the physical power system equipment is managed, while the remaining zones represent information management. For instance, the field level
encompasses metering systems and sensors to collect data, that is in turn processed on operation level, by for example a SCADA system.

Together, the domains and zones form the basis of the SGAM smart grid plane on which the five layers of interoperability are built.

**Interoperability Layers**

The third dimension of the SGAM is formed by five interoperability layers, namely the component, communication, information, function, and business layers. They represent the hierarchical levels on which stakeholders interact in a smart grid system. Each of these layers can be seen on fig. 3.2, and will be described below. The subsequent section will define the architecture of the EMPOWER smart distribution grid by using the five layers of interoperability.

- **Component layer:** represents the infrastructure and the participants of the smart grid in each zone and domain.

- **Communication layer:** represents the communication protocols and mechanisms required for information exchange within the system.

- **Information layer:** this layer describes which information is exchanged in each part of the smart grid plane.

- **Function layer:** here, the use cases are giving the functionalities of the system.

- **Business layer:** represents the business capabilities of the system, as well as the regulatory framework in which the system has to be operated.
3.3 SGAM Interoperability Layers for EMPOWER Smart distribution grid

Since the smart distribution grid is a system that is only operating in the distribution part of the power system, only a part of the SGAM framework is required to represent it. Therefore, the architecture of the EMPOWER smart distribution grid will only include three domains, namely the Distribution, DER, and Customer Premises domains.

In section 3.6, the resilience analysis framework will use the structure of the SGAM interoperability layers to evaluate what effects changes in lower level layers have on the two upper layers, Function and Business. This section will go through each of the five layers of the EMPOWER smart distribution grid.

3.3.1 Business Layer

Local Market Models

The main objective of EMPOWER is to encourage small scale consumers and prosumers to get involved in local energy management, as their participation could be beneficial for both themselves as for the power system reliability. Therefore,
EMPOWER has established several models for local energy markets. More specifically, three different markets are proposed, one for energy trading, one for flexibility services, and one for ancillary services. Moreover, three options can be adopted: the basic, continuous, or complete package, according to the requirements and constraints of the implementation site, these differences are respectively shown in fig. 3.3, fig. 3.4, and fig. 3.5, and further explained in [8].

Figure 3.3: Basic local market structure [8]

Figure 3.4: Continuous local market structure [8]
3.3. SGAM Interoperability Layers for EMPOWER Smart distribution grid

![Diagram of complete local market structure](image)

**Function Layer**

To guarantee security of supply (no electricity shortages) and a high quality of service (no interruptions, flicker, good customer service, etc.) to the consumers connected to the distribution grid, it is of major importance to coordinate supply and demand on local level by managing all the DERs connected to the grid in real time. A first responsibility of the SESP is to monitor the physical assets of the system, such as solar panels and appliances in households, EV charging points, storage devices, etc. It also communicates with the participants of the distributed grid, such as the DSO and households, giving them visual representations of consumption patterns and other graphics. Moreover, the SESP uses data analytics to create control plans and sends the necessary commands to its physical assets for the execution of the control plans.

In summary, the SESP control system is responsible for executing several functions to manage the smart distribution grid and its local energy market. For this research, the following six functionalities or high level functions (HLF) of the SESP have been selected:

**HLF 1 Asset managing:** to manage the distributed energy resources of the local market participants, such as registering their technical and commercial characteristics, or notifying the market participant of eventual resource status changes

**HLF 2 Forecasting:** the SESP estimates future load and generation profiles on the basis of which it can then estimate the flexibility that will be available for the next dispatch in the local market.

**HLF 3 Control plan creation:** given a flexibility request from the DSO and the forecasted flexibility prediction, the SESP calculates an optimal dispatch for each participating resource.

**HLF 4 Remote control:** based on the control plan created by the SESP, it sends control commands to the local controllers of each participation resource to adapt their operation (production, consumption, turning on or off, etc.).
3.3. SGAM Interoperability Layers for EMPOWER Smart distribution grid

**HLF 5 Monitoring:** on field level, smart meters and other sensors are installed to periodically measure the consumption and generation values of each resource. Moreover, special events, for example when a device gets disconnected, violates its safety limits, or when a customer denies to follow the instructions of the control commands, are monitored too by the SESP.

**HLF 6 Customer Service:** this HLF encompasses everything that is related to communication with the customer, such as graphical overviews of their production and consumption made available through smartphone or web browsers. The monthly billing notifications, contact for the help desk, etc.

These high level functions represent the overall functionality of the SESP, and each of them consists of a series of sub-functions or use cases that can be seen in table 3.1. These use cases are based on an EMPOWER deliverable made by eSmart Systems [12] and will be described in detail in section 3.4.

<table>
<thead>
<tr>
<th>HLF 1</th>
<th>Asset managing</th>
</tr>
</thead>
<tbody>
<tr>
<td>UC 1.1</td>
<td>Collect resource technical characteristics</td>
</tr>
<tr>
<td>UC 1.2</td>
<td>Collect resource technical status</td>
</tr>
<tr>
<td>UC 1.3</td>
<td>Collect resource commercial status</td>
</tr>
<tr>
<td>UC 1.4</td>
<td>Collect resource commercial characteristics</td>
</tr>
<tr>
<td>UC 1.5</td>
<td>Manage configurations</td>
</tr>
<tr>
<td>UC 1.6</td>
<td>Report to customers</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>HLF 2</th>
<th>Forecasting</th>
</tr>
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<tbody>
<tr>
<td>UC 2.1</td>
<td>Load and generation forecasting</td>
</tr>
<tr>
<td>UC 2.2</td>
<td>EV charging forecasting</td>
</tr>
<tr>
<td>UC 2.3</td>
<td>Load and generation flexibility forecasting</td>
</tr>
<tr>
<td>UC 2.4</td>
<td>EV charging flexibility forecasting</td>
</tr>
<tr>
<td>UC 2.5</td>
<td>Storage flexibility forecasting</td>
</tr>
<tr>
<td>UC 2.6</td>
<td>Send market notification</td>
</tr>
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<table>
<thead>
<tr>
<th>HLF 3</th>
<th>Control plan creation</th>
</tr>
</thead>
<tbody>
<tr>
<td>UC 3.1</td>
<td>Handle control request</td>
</tr>
<tr>
<td>UC 3.2</td>
<td>Create a control plan</td>
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<td>UC 3.3</td>
<td>Send market notification</td>
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<table>
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<tr>
<th>HLF 4</th>
<th>Remote control</th>
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</thead>
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<tr>
<td>UC 4.1</td>
<td>Send control command to EV charging station</td>
</tr>
<tr>
<td>UC 4.2</td>
<td>Send control command to load resource</td>
</tr>
<tr>
<td>UC 4.3</td>
<td>Send control command to generation resource</td>
</tr>
<tr>
<td>UC 4.4</td>
<td>Send control command to storage resource</td>
</tr>
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<table>
<thead>
<tr>
<th>HLF 5</th>
<th>Monitoring</th>
</tr>
</thead>
<tbody>
<tr>
<td>UC 5.1</td>
<td>Handle meter data</td>
</tr>
<tr>
<td>UC 5.2</td>
<td>Handle event signals</td>
</tr>
<tr>
<td>UC 5.3</td>
<td>Detect local overriding of control plan</td>
</tr>
<tr>
<td>UC 5.4</td>
<td>Log all actions and events</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>HLF 6</th>
<th>Customer services</th>
</tr>
</thead>
<tbody>
<tr>
<td>UC 6.1</td>
<td>Consumption/production overview</td>
</tr>
<tr>
<td>UC 6.2</td>
<td>Controllable unit status overview</td>
</tr>
</tbody>
</table>

Table 3.1: HLFs and their respective use cases (UC) [12]

**SESP Control Platform**

The SESP platform is fully cloud based, which means that servers, data storage databases, and applications for calculation purposes are all accessed and operated through a wireless cloud network. The communication from and to the SESP is also using cloud services. The EMPOWER research team has chosen to use the cloud computing facility Azure, from Microsoft.
Cloud based computing and communication has several advantages. First of all, it reduces the cost and the required physical space for installing servers. The available storage space can be increased easily when it is not dependent on a limited number of servers anymore, hence cloud services allow to scale a business more easily. Cloud computing is fast and responsive, allowing to create more flexible control systems. In other words, cloud services result in energy and costs savings, and facilitate real-time bi-directional communication between the system components and its control platform.

Fig. 3.6 shows how the cloud based SESP control platform is built: the orange cylinders represent data transfer and processing components, the blue cylinders represent the different databases, and the hexagons represent the cloud services of the SESP control platform. The yellow hexagons represent the SESP functionalities regarding resource monitoring and control, while the green hexagons represent the local energy market management and operation. As can be seen on fig. 3.6, the orange cylinders are the elements of the SESP that process incoming data, and that are in charge of sending output data, through several communication platforms.

Figure 3.6: SESP high level ICT architecture. Modified from [11].

3.3.2 Component Layer

Applying the SGAM framework, the most important components of the system will be represented in the component layer, and organized in function of their respective zones (process, field, station, operation, enterprise, and market). Moreover, components in the process zone will have different properties depending on their domain. For
3.3. SGAM Interoperability Layers for EMPOWER Smart distribution grid

instance, components belonging to the DER domain will differ from components in
the Customer Premises domain. In the component layer, the physical components
as well as the actors of the system are represented in their respective zones. The
following description of the main system components is based on the EMPOWER
deliverable D3.1 [7].

Physical components

**SESP Platform**  The physical infrastructure including computers, servers, databases
etc. The SESP platform is cloud based, which allows for better flexibility in data
management and storage. Because the SESP platform manages the local market as
well as the real-time control of the system, it is situated in both the enterprise zone
and the market zone. Moreover, since the SESP monitors and controls resources from
the DER and Customer Premises domain and offers services to the main distribution
grid, it also operates in all of the three domains of the EMPOWER smart distribution
grid system.

**DERs**  Distributed Energy Sources are small power sources, including generation
and storage, that are normally close to the demand centers. Small PV generators
and small wind turbines are examples of DERs. DERs are part of the process zone
in the DER domain.

**Customer premises (CP)**  These include loads and customer appliances that
provide an interface to influence their consumption behavior. It can also include
generation, storage and electric vehicles, similar to DERs but on a smaller scale, and
thus CP belong to the process zone and the Customer Premises domain. Resources
from the Customer Premises domain are typically distinguishable from resources on
the DER domain by being single phase power devices, instead of three phase.

**SCADA**  The SCADA system provides the basic functionalities for energy man-
agement and demand response, especially providing the communication with the
substations to monitor and control the grid. SCADA will receive data from DER
meter-local controllers in order to have a real time vision of the network. This
physical infrastructure is part of the Operation zone, and belongs to the Distribution
domain.

**DER Unit controller**  The controller of a DER that allows the adjustment of its
active or reactive power output according to a received set point. The DERUC is a
field device in the DER domain.

**Local controller**  Controls the energy consumption of a load according to a re-
ceived set point. The system can consist of several decentralized controllers and
each controller will be connected to the SESP to monitor and control the heating,
ventilation, air conditioning, light and other facilities within a building. It can also
include a customer portal or a HAN gateway to establish the communication between external systems and the local controller. Local controllers are field devices that belong to the Customer Premises domain.

**Data concentrator** A device or application typically in a substation, which establishes the communication with smart meters to collect the metered information and to send it in concentrated form to the SESP. A data concentrator is used in the Customer Premises domain and operates in the Station zone.

**Metering System** All the equipment (normally electronic devices) that registers the consumption of electric energy in intervals of an hour or less, and communicates this information for monitoring and billing purposes. Meters are installed in both DER and Customer Premises domains, and operate in the Field zone.

**Actors**

**DSO** The Distribution System Operator is the entity responsible for operating and ensuring the maintenance of the distribution system. The DSO is represented in the Enterprise and Market zone, and operates from the Distribution domain.

**Customers** These represent the actors that participate in the EMPOWER energy market on local level. Customers can either be consumers or prosumers, owning households or buildings with controllable loads, small generators, storage devices, or EVs. Customers can also be DER owners on facility level. Customers can be in the DER and Customer Premises domain, and are part of the Market zone of the system.

**SESP operator** The Smart Energy Service Provider is the party that handles the operation of the market place, the coordination between the participants, also offering services to the market participants. The operator can override automatic controls from the SESP platform when required. Similar to the SESP platform, the operator is part of the Market and Enterprise zone, operating in all three domains.

**External information providers (EIP)** These actors provide additional services and information to the system. For instance, in the smart distribution grid architecture presented in this work, the EIP is a weather forecasting service. As the weather forecasting service is information coming from outside the smart distribution grid, it is not part of any of the three domains, but the information will be processed by the SESP in the Enterprise zone.

**Overview:**

Fig. 3.7 gives an overview of how the components and actors are organized within the SGAM smart distribution grid plane. In the figure, the SESP platform and the
SGAM Interoperability Layers for EMPOWER Smart distribution grid

SESP operator are both represented by the same icon, denoted as SESP. How these components are related will be detailed in section 3.5.

Figure 3.7: The component layer of the EMPOWER smart distribution grid.

3.3.3 Communication Layer

The SESP has to communicate with the other components of the smart distribution grid in order to fulfill its role of intelligent control system. The communication technology that is used varies with the type of data that has to be exchanged. For instance, communication with power system field components will be different than the communication with customers. However, the communication with the SESP mainly goes through web services, that are part of the Azure cloud service.

Table 3.2 describes the communication between the SESP and other system components. Moreover, an explanation, based on [9], of the used protocols is given below.

**Azure Event hub:** this is a processing service that can handle a large data stream very fast, and is especially useful to process real-time telemetry data, improving the
customer visualization experience. The technology is highly reliable and has a low latency (delay between signal and response).

**Web services:** these are used by web servers or mobile applications, and are the most suited for representing graphical user interfaces.

**Private protocols:** these are protocols developed by manufacturers, especially design to run on their devices. Because of this, many private protocols co-exist in the same complex systems such as intelligent distributed grids.

**IEC 60870-5-101 and -104:** Standard protocols used for the communication with SCADA systems.

**Modbus TCP/IP:** typical protocol used to connect industrial electronic devices, such as PLCs and SCADAs.

**Pulse reading:** this is a way of transmitting measurement data from an electronic telemeter that doesn’t have the smart meter port.
3.3. SGAM Interoperability Layers for EMPOWER Smart distribution grid

<table>
<thead>
<tr>
<th>Name</th>
<th>From</th>
<th>To</th>
<th>Protocol</th>
<th>Type of transmitted data</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>CL1</td>
<td>SESP</td>
<td>SCADA</td>
<td>Web services</td>
<td>- control signals&lt;br&gt;- request signals</td>
<td>SCADA manufacturer dependent, for EMPOWER, the SCADA system is developed by Schneider electric.</td>
</tr>
<tr>
<td>CL-1</td>
<td>SCADA</td>
<td>SESP</td>
<td>Azure Event hub</td>
<td>- technical information&lt;br&gt;- measurement data&lt;br&gt;- event signals</td>
<td>Azure Event hub is a processing service that can handle a large data stream very fast, and is especially useful to process real-time telemetry data, improving the customer visualisation experience. The technology is highly reliable and has a low latency (delay between signal and response).</td>
</tr>
<tr>
<td>CL2</td>
<td>SCADA</td>
<td>DER Unit controller</td>
<td>IEC 60870-5-101/104&lt;br&gt;Modbus TCP/IP</td>
<td>- control signals&lt;br&gt;- request signals</td>
<td>* Control signals may be active and reactive power setpoints for the concerned controllable resource.&lt;br&gt;* The installed communication will use the Modbus protocol but the implementation will differ among manufacturers.</td>
</tr>
<tr>
<td>CL3</td>
<td>DER Unit controller</td>
<td>SCADA</td>
<td>IEC 60870-5-101/104&lt;br&gt;Modbus TCP/IP</td>
<td>- technical information&lt;br&gt;- measurement data&lt;br&gt;- event signals</td>
<td>The way the smart- or telemeter is connected to the DER unit controller depends on the meter manufacturer.</td>
</tr>
<tr>
<td>CL4</td>
<td>SESP</td>
<td>Customer Interface</td>
<td>Web services</td>
<td>Graphical user interface for:&lt;br&gt;- notifications&lt;br&gt;- data visualizations&lt;br&gt;- customer services&lt;br&gt;- etc.</td>
<td>The customer interface can be accessed through mobile phones or desktop browsers.</td>
</tr>
<tr>
<td>CL5</td>
<td>Local Controller</td>
<td>SESP</td>
<td>Azure event hub</td>
<td>- technical information&lt;br&gt;- measurement data&lt;br&gt;- event signals</td>
<td>Control signals to customer premises (via the local controller) are ON/ OFF commands.</td>
</tr>
<tr>
<td>CL6</td>
<td>SESP</td>
<td>Customer Premises</td>
<td>Private protocol</td>
<td>- control signals&lt;br&gt;- request signals</td>
<td>Control signals to customer premises (via the local controller) are ON/ OFF commands.</td>
</tr>
<tr>
<td>CL7</td>
<td>Local Controller</td>
<td>SESP</td>
<td>Private protocol</td>
<td>- energy consumption data&lt;br&gt;- energy generation data</td>
<td>manufacturer dependent</td>
</tr>
<tr>
<td>CL8</td>
<td>Meter</td>
<td>Local Controller</td>
<td>Private protocol</td>
<td>- energy consumption data&lt;br&gt;- energy generation data</td>
<td>manufacturer dependent</td>
</tr>
</tbody>
</table>

Table 3.2: The protocols used for communication within the EMPOWER smart distribution grid [12], [9].

Overview:

Fig. 3.8 gives an overview of the communication protocols used to communicate with the SESP control platform.
3.3.4 Information Layer

Overview:

Fig. 3.9 gives an overview of the information exchanged with the SESP control platform.
3.4 Functional Decomposition

In order to relate the SESP HLFs and use cases to the system architecture, each of the use cases will be represented by several sequences, that are instances of pre-defined primary functions. These primary functions can be executed by different physical components, actors, and/or ICT links of the system, that will be grouped under the term "entity" in anticipation of the model presented in section 3.5. Each primary function can process certain attributes with a specific time resolution or frequency. More specifically, each sequence is defined by a certain entity that is performing a primary function with specific attributes as an input, at a specific frequency. As such, it becomes possible to describe the entire SESP functionality by using a set of primary functions that will have different outputs depending on the executing entity, the attributes, and the time resolution.
3.4. Functional Decomposition

3.4.1 Primary Functions

The primary functions (PFs) represent the basic actions that can be executed by different entities of the system. It can be compared to a method in object oriented programming. These functions get input parameters in brackets, and deliver an output accordingly. The following input types can be required:

**Entities:** represent the physical components, actors, or ICT links that execute the primary function. Some PFs require more than one entity to be executed, namely when the executing entity needs to send something to a receiving entity, or when intermediary entities are required. Hence the possible entities are:

- **executing entity:** the entity performing the primary function
- **receiving entity:** the entity receiving data from the executing entity
- **intermediary entity:** the entity that processes the output of the executing entity to complete the function execution.

**Attributes:** attributes represent the data that is processed by the PF. They refer to a set of variables characterizing the concerned entity, and for the same attribute, the set can vary depending on the entity. For example, the attribute 'technical characteristics' would include maximal charging capacity if the entity would be a storage device, which wouldn’t be included when for a controllable load. There can be three types of attributes:

- **primary attributes:** the attributes defined by entities (technical status, customer information, etc.)
- **composed attributes():** these are the result of applying a PF on primary attributes, and can be a combination of primary attributes, a calculation, or a notification for example. Composed attributes are denoted by adding brackets, and the input parameters can be primary or composed attributes.
- **[set of attributes()]:** some entities will receive primary attributes from several identical executing entities, and aggregate these in a set of identical attributes with different values. This is comparable to an `array[]` in object oriented programming. A set of attributes is denoted by enclosing the input attribute type with square brackets.

**Time resolution:** the time resolution refers to the moment at which a function is executed. This can either be periodically, or at discrete moments.

- **periodically:** every 5 min (e.g. data acquisition), 60 min, 24 hours (e.g. data retrieval by SESP from SCADA), monthly (e.g. billing), etc.
3.4. Functional Decomposition

- **discrete**: on request (e.g. SESP requests customer information), event triggered (e.g. send alarm if resource gets disconnected), executed by other PF (when PF monitor() registers and event, PF send() will consequently be executed).

**Algorithm**: the mathematical model that is used to calculate a certain output. The algorithm won’t be specified in this work, it will be considered as a black box with input parameters, and returning composed attributes as output parameters.

**send**(executing entity, receiving entity, intermediary entity, attributes, time resolution)

This function refers to the action of sending data from one entity to another entity. It requires as input parameters the executing entity that sends the attributes, the receiving entity, the data to be exchanged, as well as the time resolution.

**set**(executing entity, attributes, time resolution)

This function represents the action of changing the values of a certain attribute for an entity. Most of the time, an entity will execute this PF after receiving a command from another entity, in other words in discrete time periods, but it can also be done periodically through an automated system.

**get**(executing entity, intermediary entity, attributes, time resolution)

This function is executed after receiving a request message or periodically. It returns the values of the input parameters, that can be primary or composed attributes.

**calculate**(executing entity, attributes, time resolution, algorithm)

This function is the basis for every calculation that has to be performed by the SESP. By defining this function with an algorithm as input parameter, the actual calculation algorithm can be considered as a black box, and only the input and output variables can be considered.

**aggregate**(executing entity, attributes, time resolution)

This represents the action of putting together a set of attributes. For instance, when entities send the same attributes to a central entity, the latter will aggregate the received attributes for further data processing.

**distribute**(executing entity, attributes, time resolution)

This represents the action of decomposing a set of attributes into individual attributes. It is the opposite function of the PF aggregate, and is executed when an entity receives a set of attributes from which each individual attribute needs to be transferred to a specific receiving entity.
3.4. Functional Decomposition

**store**(executing entity, receiving entity, attributes, time resolution)

This function receives data from a certain entity and stores it into a database, the receiving entity.

**monitor**(executing entity, attributes, time resolution)

This function is giving a trigger to its executing entity when values of attributes change, so that the change in values (event signal) can be processed further through other primary functions.

The next section will show how the PFs are used for communication with the SESP.

### 3.4.2 Secondary Functions

The following secondary functions show which primary functions are used to exchange information between the SESP and respectively the DER resources, the CP resources, the Customer interface, and the Weather station.

**SESP and DER resource**

Fig. 3.10 is a graphical representation of the set of sequences to communicate between the SESP and the DER Unit Controller. The figure also indicates which attributes can be sent in each direction.

**time resolution**: [periodical, event based]. Each used PF is executed through this SF, hence have an event-based time resolution: one PF triggers the next one to start its execution.

![Diagram of SESP and DER resource](image)

(a) SESP to DER Unit controller  
(b) DER Unit Controller to SESP

Figure 3.10: Sequence of primary functions to exchange data between the SESP and the DER Unit Controller.
• from SESP to DER Unit Controller:
  
  entities: the intermediary entity is always a communication link CL.
  attributes: [request(), command()].

  – send(SESP, SCADA, CL1, attributes)
  – distribute(SCADA, attributes, send())
  – send(SCADA, DERUC, CL3, attributes, distribute())

• from DER Unit Controller to SESP:
  
  attributes: [technical status, technical characteristics, operational characteristics, operational status].

  – get(DERUC, Resource DER, attributes, request())
  – OR set(DERUC, Resource DER, attributes, command())
  – send(DERUC, SCADA, CL-3, attributes, get())
  – aggregate(SCADA, attributes, send())
  – send(SCADA, SESP, CL-1, [attributes], aggregate())
  – store(SESP, attributes, send())

• resulting secondary functions: combining the two previous sets of sequences gives two secondary functions, Request() when the SESP sends a request() attribute, and Command() when it sends a command() attribute:

  – Request(SESP, DER Unit Controller, attributes)
  – Command(SESP, DER Unit Controller, attributes)

SESP and CP resource

(a) SESP to Local controller

(b) Local controller to SESP

Figure 3.11: Sequence of primary functions to exchange data between the SESP and the Local Controller.
3.4. Functional Decomposition

Fig. 3.11 is a graphical representation of the set of sequences to communicate between the SESP and the Local Controller. The figure also indicates which attributes can be sent in each direction.

**time resolution:** [periodical, event based]. Each used PF is executed through this SF, hence have an event-based time resolution: one PF triggers the next one to start its execution.

- **from SESP to Local Controller (LC):**
  - **entities:** the intermediary entity is always a communication link CL.
  - **attributes:** [request(), command()].
    - send(SESP, LC, CL2, attributes)
    - distribute(LC, attributes, send())

- **from LC to SESP:**
  - **attributes:** [technical status, technical characteristics, operational characteristics, operational status].
    - get(LC, Resource CP, attributes, request())
    - OR set(LC, Resource CP, attributes, command())
    - send(LC, SESP, CL-2, attributes, get())
    - store(SESP, attributes, send())

- **resulting secondary functions:** combining the two previous sets of sequences gives two secondary functions, Request() when the SESP sends a request() attribute, and Command() when it sends a command() attribute:
  - Request(SESP, Local controller, attributes)
  - Command(SESP, Local controller, attributes)
3.4. Functional Decomposition

**SESP and Customer interface**

(a) From SESP to Customer Interface.

(b) From Customer Interface to SESP.

Figure 3.12: Sequence of primary functions to exchange data between the SESP and the Customer Interface.

Fig. 3.12 is a graphical representation of the set of sequences to communicate between the SESP and the Customer Interface. The figure also indicates which attributes can be sent in each direction.

**time resolution**: [periodical, event based]. Each used PF is executed through this SF, hence have an event-based time resolution: one PF triggers the next one to start its execution.

- **from SESP to Customer interface (CI):**
  - entities: the intermediary entity is always a communication link CL.
  - attributes: [request(), report()].

    - send(SESP, LC, CL4, attributes)
    - distribute(CI, attributes, send())
    - send(CI, Customer, CL10, attributes, distribute())

- **from CI to SESP:**
  - attributes: [commercial status, commercial characteristics, customer information, request()].

    - get(Customer, attributes, request())
    - send(Customer, CI, CL10, attributes, get())
    - aggregate(CI, attributes, send())
    - send(CI, SESP, CL4, attributes, aggregate())
    - store(SESP, attributes, send())
3.4. Functional Decomposition

- **resulting secondary functions**: combining the two previous sets of sequences gives two secondary functions, Request() when the SESP sends a request() attribute, and Report() when it sends a report() attribute:
  - Request(SESP, Customer, attributes)
  - Report(SESP, Customer, attributes)

**SESP and Weather station**

![Diagram](image-url)

(a) From SESP to WS

(b) From WS to SESP

Figure 3.13: Sequence of primary functions to exchange data between the SESP and the Weather station

Fig. 3.13 is a graphical representation of the set of sequences to communicate between the SESP and the Weather Station. The figure also indicates which attributes can be sent in each direction.

- **time resolution**: [periodical, event based]. Each used PF is executed through this SF, hence have an event-based time resolution: one PF triggers the next one to start its execution.

- **from SESP to Weather station (WS)**:
  - **entities**: the intermediary entity is always a communication link CL.
  - **attributes**: [request()].

  - send(SESP, WS, CL9, attributes)

- **from WS to SESP**:
  - **attributes**: [weather forecast, technical characteristics].

  - get(WS, attributes, request())
  - send(WS, SESP, CL9, attributes, get())
  - store(SESP, attributes, send())

- **resulting secondary function**: combining the two previous sets of sequences gives the secondary function: Request(SESP, Weather Station, attributes)
3.5 Entity-Relationship Model

After defining the component layer (physical components and actors), the communication layer (communication protocols), the information layer (the exchanged information), and the function layer (functional decomposition), all this information can be organized and represented graphically in an entity-relationship model (ERM), in order to get an idea of how the system components interact with each other.

3.5.1 General Description

An ERM is a way of structuring the data of a system based on how system components are related with one another. The concept is used in relational database modeling, where the relationships between system components are used as the key element to organize data, which facilitates data look-ups within large databases. To avoid data duplication, relational databases need to be normalized according to three normalization rules. Since the SESP control system will have to process large amounts of data, the entity-relationship model seems to be a useful tool to understand the structure and operation of the EMPOWER smart distribution grid.

Four components form the building blocks of an entity-relationship model, namely entities, attributes, relationships, and cardinality.

Entities

Entities are defining the elements that interact with each other in a certain system. Each entity has a set of properties, or attributes, and every entity instance has its own values for each of these attributes. In database modeling, entities are represented by tables where each column represents an attribute of the entity. The table is then filled with instances, also called tuples [20].

For example, assume an entity is defined to represent a DER. If there are four DERs in the EMPOWER smart distribution grid, for instance two generation units, a storage unit, and a load, there are four instances of the DER entity, and the relational database table would contain four rows, as shown in fig. 3.14. In this example, the DER has three attributes, namely its identification number (DER_ID), its type of resource (Resource_type), and the ID of the customer that owns it (Customer_ID).
Super-type and sub-type entities  As is the case for a DER entity, certain entities can be divided into more specific categories, or sub-type entities. Sub-type entities will inherit the properties (attributes) of a super-type entity, and in addition have their own characterizing attributes. For instance, in the EMPOWER smart distribution grid, there are four types of DERs: a generation unit, a storage unit, a load, and an EV charging point. As such, the DER entity has four sub-type entities.

There is a distinction between inclusive and exclusive sub-types.
For inclusive sub-types, the super-type has to be one, and only one of the sub-types. In the smart distribution grid presented in this thesis, the type of customers included in the system are strictly restrained to a DSO, a household customer, or a facility customer, and a customer cannot be more than one of these types at the same time. Hence, these types are inclusive sub-types of the super-type entity 'Customer'.

For exclusive subtypes, the super-type entity can be one or more sub-types. As such, it might be possible that another type of DER is added to the smart distribution grid over time in which case the DER is none of the currently presented sub-type entities. Moreover, a distributed resource can be different subtypes at the same time, for instance when a storage device is taking electricity from the grid, it can also be considered as a load.

In the extended ER-diagram notation, inclusive sub-types are related to their super-type entity through a crossed dot, whereas exclusive sub-types are related through a plain dot [3]. Fig. 3.15a (a) shows how inclusive and exclusive subtypes are represented for the DER and Customer entities. To indicate the existence of sub-type entities in the super-type entity, a discriminator is used. In the example in fig. 3.15, the discriminator is the attribute 'Resource_type', and therefore it is repeated next to the connecting dot.
3.5. Entity-Relationship Model

(a) Exclusive sub-type

(b) Inclusive sub-type

Figure 3.15: Super-type entities and their respective sub-type entities using the extended ER-notation.

Attributes

Attributes are characteristics that define an entity, such as its name, color, dimensions, etc. Each attribute has a data type (integer, string, etc.), and can have other properties too, such as a text description, whether or not a null value is allowed, etc.

Primary keys For each entity, there has to be an identifying attribute, that is unique for each tuple, and thus can be used to look up specific rows in a database table. Such an attribute is called primary key (PK) and is usually an identification number such as DER_ID in fig. 3.14, which is underlined because it is the primary key.

Foreign keys Foreign keys are used to relate different entities. For example, each DER resource has to be owned by a customer. To indicate this relationship in the entity-relationship model, the primary key of the Customer entity (Customer_ID) is transmitted to the DER entity as a foreign key (FK), see fig. 3.14.

Compound keys Some entities are identified by more than one key. For example, the relationship between two entities can become a third entity, defined by the primary keys of the two entities it relates, forming a compound primary key of two foreign keys. This is the case when a customer signs a contract with the SESP. The contract will be an entity that is defined by two foreign keys, namely the PK of the SESP entity (SESP_ID) and the PF of the customer entity (Customer_ID), which is shown in fig. 3.16.
Cardinality and Relationships

Cardinality indicates the type of relationship that connects two entities. In the entity-relationship model, cardinality is indicated with symbols on the extremities of the lines that connect entities. Different notations exist, but the Extended ER-diagram notation will be adopted in this work. Fig. 3.17 gives the meaning of the symbols, and show the possible relations for each type of relationship: one to one, one to many, and many to many.

One to one: one instance of an entity can be linked to one instance of another entity. For instance, each DER Unit controller controls only one resource, which is a one to one relationship.

One to many: indicates that one instance of an entity can be related to several instances of another entity. An example is the Local controller entity, since one local controller controls all the resources of a certain customer, hence Local controller and Resource CP have a one to many relationship.

Many to many: When many instances of an entity can be related to many instances of another entity.

Fig. 3.16 shows two different types of relationships and different cardinalities:

- a Customer can have zero or one contract
- a Contract has one and only one customer, as well as one and only one SESP
- a SESP can have zero or many contracts (each with another customer)

Figure 3.17: Cardinality symbols following the Extended ER-diagram notation [3].
3.5. Entity-Relationship Model

3.5.2 Entities of the EMPOWER Smart Distribution Grid

This section will present each entity of the ER-diagram. The entities are presented in an adapted way from the original entity relationship model, as some of the entities also have methods, corresponding to the primary functions discussed previously. These methods will form the relation between two entities, as they define how entities interact. Basic entities are entities that are identified by a primary key, whereas joint entities have foreign keys as part of their primary key.

Each attribute has an sql data type (see Appendix A for a description of each data type), a description to clarify the attribute name, and optionally a more detailed explanation in notes. Moreover, primary keys and foreign keys are respectively denoted as PK and FK. If an entity has a sub-type entity, the super-type entity will have a discriminator attribute, denoted by disc. Most of the attributes are taken from the EMPOWER functional specification for WP5 [12]. Finally, several attributes are highlighted in dark purple, which means that these attributes can be the basis for resilience indicators, as will be detailed later on.

Basic Entities

**SESP**  Fig. 3.19 represents the SESP, the central element of the EMPOWER distributed grid. It has a foreign key referring to the SESP Database, and their relation is the primary function store, as the SESP stores all the processed data into an elaborated database.

**cardinality:** "one, mandatory". There is only one SESP platform in the EMPOWER distribution grid.
3.5. Entity-Relationship Model

Figure 3.19: The SESP entity.

<table>
<thead>
<tr>
<th>key</th>
<th>attributes</th>
<th>data type</th>
<th>description</th>
<th>notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>PK</td>
<td>SESP_ID</td>
<td>VARCHAR</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FK</td>
<td>Database_ID</td>
<td>VARCHAR</td>
<td>foreign key relating to the Database entity</td>
<td></td>
</tr>
</tbody>
</table>

**methods**

- `get(SESP_ID, attributes, time resolution, time resolution)`
- `calculate(SESP_ID, attributes, algorithm, time resolution)`
- `send(SESP_ID, receiving entity, intermediary entity, attributes, time resolution)`
- `store(SESP_ID, attributes, time resolution)`

**SCADA** Fig. 3.19 shows the SCADA entity, which is the data controller for resources on facility level. The entity has been described in 3.3.2. **cardinality:** 'one, mandatory'.
### Entity-Relationship Model

#### DER Unit Controller

Fig. 3.21 shows the DER unit controller entity, which is the unit controller for resources on facility level. The entity has been described in 3.3.2. Each DER Unit controller has an integrated metering device, which is represented separately on the entity-relationship model that will follow, but can be considered as a part of the controller.

**Cardinality:** "one or many, optional". There can be zero or more DER UCs in the system, but the number is dependent on the number of resources on facility (DER) level.

---

**Table: SCADA**

<table>
<thead>
<tr>
<th>key</th>
<th>attributes</th>
<th>data type</th>
<th>description</th>
<th>notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>PK</td>
<td>SCADA_ID</td>
<td>VARCHAR</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Technical status</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>is_connected</td>
<td>BOOLEAN</td>
<td>is connected</td>
<td>if the device is connected to the system</td>
<td></td>
</tr>
<tr>
<td><strong>Operational characteristics</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>is_functional</td>
<td>BOOLEAN</td>
<td>is functional</td>
<td>if the device is operational</td>
<td></td>
</tr>
<tr>
<td><strong>Methods</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>send(SCADA_ID, receiving entity, intermediary entity, attributes, time resolution)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>distribute(SCADA_ID, attributes, time resolution)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>aggregate(SCADA_ID, attributes, time resolution)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 3.20: The SCADA entity.
3.5. Entity-Relationship Model

Figure 3.21: The DER Unit controller entity.

<table>
<thead>
<tr>
<th>key</th>
<th>attributes</th>
<th>data type</th>
<th>description</th>
</tr>
</thead>
<tbody>
<tr>
<td>PK</td>
<td>DERUC_ID</td>
<td>VARCHAR</td>
<td></td>
</tr>
<tr>
<td>FK</td>
<td>Meter_ID</td>
<td>VARCHAR</td>
<td>foreign key of the meter that is connected to the controller</td>
</tr>
</tbody>
</table>

Technical status

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>is_connected</td>
<td>BOOLEAN</td>
<td>is connected</td>
<td>if the device is connected to the system</td>
</tr>
</tbody>
</table>

Operational characteristics

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>is_functional</td>
<td>BOOLEAN</td>
<td>is functional</td>
<td>if the device is operational</td>
</tr>
</tbody>
</table>

methods

<p>| |</p>
<table>
<thead>
<tr>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>send(DERUC_ID,receiving entity,intermediary entity,attributes,time resolution)</td>
</tr>
<tr>
<td>set(DERUC_ID,attributes,time resolution)</td>
</tr>
<tr>
<td>get(DERUC_ID,attributes,time resolution)</td>
</tr>
<tr>
<td>monitor(DERUC_ID,attributes,time resolution)</td>
</tr>
</tbody>
</table>

Local Controller  Fig. 3.22 shows the Local controller entity, which is the unit controller for resources on household level. The entity has been described in 3.3.2. Each local controller has an integrated meter device, which is represented separately on the entity-relationship model that will follow.

cardinality: "one or many, optional". There can be zero or more LCs in the system, however, the number of LCs is constrained to the number of customer premises resources, as will be seen in the entity-relationship diagram.
3.5. Entity-Relationship Model

<table>
<thead>
<tr>
<th>Local Controller</th>
</tr>
</thead>
<tbody>
<tr>
<td>key</td>
</tr>
<tr>
<td>PK</td>
</tr>
<tr>
<td>FK</td>
</tr>
</tbody>
</table>

**Technical status**

| is_connected | BOOLEAN | is connected if the device is connected to the system |

**Operational characteristics**

| is_functional | BOOLEAN | is functional if the device is operational |

**methods**

- `send(LC_ID,receiving entity,intermediary entity,attributes,time resolution)`
- `set(LC_ID,attributes, time resolution)`
- `get(LC_ID,attributes, time resolution)`
- `monitor(LC_ID,attributes, time resolution)`

Figure 3.22: The Local controller entity.

**Resource**  
Fig. 3.23 shows the Resource entity. This is the super-type entity for four types of resources, load, generation unit, storage unit, and EV charging point, respectively shown in fig. 3.25, fig. 3.26, fig. 3.24, and fig. 3.27. Each sub-type resource has its own sub-type entity, to distinguish the DER resources from the CP resources. This has to be done because CPs are operated by Local controller, for instance, whereas DERs are operated by DERUCs. The hierarchy of sub-type and sub-sub-type entities is shown in the entity-relationship diagram detail in fig. 3.35.  
**cardinality**: "one or many, optional". There can be zero or more resources in the system.
### 3.5. Entity-Relationship Model

#### Figure 3.23: The Resource super-type entity.

<table>
<thead>
<tr>
<th>key</th>
<th>attributes</th>
<th>data type</th>
<th>description</th>
<th>notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>PK</td>
<td>Resource_ID</td>
<td>VARCHAR</td>
<td></td>
<td></td>
</tr>
<tr>
<td>disc.</td>
<td>Resource_type</td>
<td>[A, B, C, or D]</td>
<td>type of resource</td>
<td>discriminator for sub-type.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>A: Load</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>B: EV charging point</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>C: Generation unit</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>D: Storage unit</td>
</tr>
<tr>
<td>FK</td>
<td>Customer_ID</td>
<td>VARCHAR</td>
<td></td>
<td>foreign key referring to the owner of the</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>resource</td>
</tr>
</tbody>
</table>

#### Technical Status

<table>
<thead>
<tr>
<th>t_con</th>
<th>TIMESTAMP</th>
<th>connection date</th>
</tr>
</thead>
<tbody>
<tr>
<td>t_disc</td>
<td>TIMESTAMP</td>
<td>disconnection date</td>
</tr>
<tr>
<td>is_connected</td>
<td>BOOLEAN</td>
<td>is connected</td>
</tr>
</tbody>
</table>

#### Technical characteristics

<table>
<thead>
<tr>
<th>control_type</th>
<th>BINARY</th>
<th>control type</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>0: continuously metered</td>
<td>1: ON/OFF</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>(CP resources are 1, DER resources are 0)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>is_metered</th>
<th>BOOLEAN</th>
<th>individually metered</th>
<th>the resource has its own metering device</th>
</tr>
</thead>
</table>

#### Operational Status

<table>
<thead>
<tr>
<th>is_functional</th>
<th>BOOLEAN</th>
<th>is operational</th>
<th>if the device is functional</th>
</tr>
</thead>
<tbody>
<tr>
<td>is_controllable</td>
<td>BOOLEAN</td>
<td>is controllable</td>
<td>if it has the ability to be controlled remotely</td>
</tr>
<tr>
<td>is_reserved</td>
<td>BOOLEAN</td>
<td>is reserved</td>
<td>will be used for a flexibility control plan in the future</td>
</tr>
<tr>
<td>is_in_control</td>
<td>BOOLEAN</td>
<td>is in control</td>
<td>is being used for a flexibility control plan</td>
</tr>
<tr>
<td>control_start</td>
<td>TIMESTAMP</td>
<td>start date control</td>
<td>start of control plan</td>
</tr>
<tr>
<td>control_end</td>
<td>TIMESTAMP</td>
<td>end date control</td>
<td>end of control plan</td>
</tr>
</tbody>
</table>

---

55
### Storage unit

<table>
<thead>
<tr>
<th>key</th>
<th>attributes</th>
<th>data type</th>
<th>description</th>
<th>notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>PK, FK</td>
<td>Resource ID</td>
<td>VARCHAR</td>
<td></td>
<td></td>
</tr>
<tr>
<td>disc.</td>
<td>Storage_type</td>
<td>VARCHAR</td>
<td>type of storage unit</td>
<td>discriminator of subtype 0: customer premise 1: DER</td>
</tr>
<tr>
<td></td>
<td>C_max</td>
<td>DECIMAL</td>
<td>maximal capacity</td>
<td>unit: [W]</td>
</tr>
<tr>
<td></td>
<td>P_max</td>
<td>DECIMAL</td>
<td>maximal charging power</td>
<td>unit: [W]</td>
</tr>
<tr>
<td></td>
<td>P_discharge_max</td>
<td>DECIMAL</td>
<td>maximal discharging power</td>
<td>unit: [W]</td>
</tr>
<tr>
<td></td>
<td>eta_charge</td>
<td>DECIMAL</td>
<td>discharging efficiency</td>
<td></td>
</tr>
<tr>
<td></td>
<td>eta_discharge</td>
<td>DECIMAL</td>
<td>charging efficiency</td>
<td></td>
</tr>
<tr>
<td></td>
<td>E_in</td>
<td>DECIMAL</td>
<td>input energy</td>
<td>unit: [Wh]</td>
</tr>
<tr>
<td></td>
<td>E_out</td>
<td>DECIMAL</td>
<td>output energy</td>
<td>unit: [Wh]</td>
</tr>
</tbody>
</table>

**Technical characteristics**

**Operational characteristics**

---

### Load

<table>
<thead>
<tr>
<th>key</th>
<th>attributes</th>
<th>data type</th>
<th>description</th>
<th>notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>PK, FK</td>
<td>Resource ID</td>
<td>VARCHAR</td>
<td></td>
<td></td>
</tr>
<tr>
<td>disc.</td>
<td>Load_type</td>
<td>VARCHAR</td>
<td>type of load</td>
<td>discriminator of subtype 0: customer premise 1: DER</td>
</tr>
<tr>
<td></td>
<td>type</td>
<td>[...]</td>
<td>type</td>
<td>type of appliance</td>
</tr>
<tr>
<td></td>
<td>P_max</td>
<td>DECIMAL</td>
<td>maximal capacity</td>
<td>unit: [W]</td>
</tr>
</tbody>
</table>
### 3.5. Entity-Relationship Model

#### Figure 3.26: The generation unit sub-type entity.

<table>
<thead>
<tr>
<th>key</th>
<th>attributes</th>
<th>data type</th>
<th>description</th>
<th>notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>PK, FK</td>
<td>Resource ID</td>
<td>VARCHAR</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Gen_type</td>
<td>VARCHAR</td>
<td>type of generation unit</td>
<td>discriminator of subtype</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0: customer premise</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1: DER</td>
</tr>
<tr>
<td></td>
<td>unit_type</td>
<td>more than one option</td>
<td>type</td>
<td>type: solar panel, wind plant, combined heat and power plant, etc.</td>
</tr>
<tr>
<td></td>
<td>capacity_max</td>
<td>DECIMAL</td>
<td>maximal capacity</td>
<td>unit: [W]</td>
</tr>
<tr>
<td></td>
<td>w_velocity_max</td>
<td>DECIMAL</td>
<td>maximal wind speed</td>
<td>unit: [m/s]</td>
</tr>
<tr>
<td></td>
<td>irradiance_max</td>
<td>DECIMAL</td>
<td>maximal sun level</td>
<td>unit: [W/m^2]</td>
</tr>
</tbody>
</table>

#### Figure 3.27: The EV charging point sub-type entity.

<table>
<thead>
<tr>
<th>key</th>
<th>attributes</th>
<th>data type</th>
<th>description</th>
<th>notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>PK, FK</td>
<td>Resource ID</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>disc.</td>
<td>EV_type</td>
<td>BINARY</td>
<td>type of EV charging point</td>
<td>discriminator of subtype</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0: customer premise</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1: DER</td>
</tr>
<tr>
<td></td>
<td>cp_type</td>
<td>[A, B, or C]</td>
<td>charging point type</td>
<td>A: AC single phase</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>B: AC single/three phase</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>C: DC fast charge coupler</td>
</tr>
<tr>
<td></td>
<td>charging_mode</td>
<td>[A, B, C, or D]</td>
<td>charging mode</td>
<td>A: mode 1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>B: mode 2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>C: mode 3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>D: mode 4</td>
</tr>
<tr>
<td></td>
<td>capacity_max</td>
<td>DECIMAL</td>
<td>maximal capacity</td>
<td>unit: [W]</td>
</tr>
<tr>
<td></td>
<td>EV_status</td>
<td>BINARY</td>
<td>charging status</td>
<td>0: charging</td>
</tr>
<tr>
<td></td>
<td>end_time</td>
<td>TIMESTAMP</td>
<td>time of disconnection</td>
<td>1: discharging</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>is filled in by the user of the charging point</td>
</tr>
<tr>
<td></td>
<td>time_to_disc</td>
<td>INTERVAL</td>
<td>time to disconnection</td>
<td>number of remaining charging minutes</td>
</tr>
</tbody>
</table>
received data to the right customers, according to the content. **cardinality:** "one, mandatory".

<table>
<thead>
<tr>
<th>key</th>
<th>attributes</th>
<th>data type</th>
<th>description</th>
<th>notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>PK</td>
<td>C1ID</td>
<td>VARCHAR</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**methods**

- **send**(Customer_ID, receiving entity, intermediary entity, attributes, time resolution)
- **distribute**(Customer_ID, attributes, time resolution)
- **aggregate**(Customer_ID, attributes, time resolution)

Figure 3.28: The Customer interface entity.

**Customer**  
Fig. 3.29 shows the entity representing the customer. It is a super-entity of DSO, Household customer, and Facility customer, but these are not shown in detail. **cardinality:** "one or many, mandatory". Since the DSO is a sub-type entity of the super-type entity Customer, and there is one mandatory DSO in the system, the super-type entity inherits the cardinality of "one mandatory", but there can be zero or many customers of the type household (HH), or facility customers.
3.5. Entity-Relationship Model

![Customer entity diagram](image)

Weather Station an external information provider that delivers the weather forecast, with a certain accuracy. cardinality: *one, mandatory*.
3.5. Entity-Relationship Model

Figure 3.30: The Weather station entity.

Joint Entities

Joint entities are entities that are formed by coupling two or more entities. For example to specify the attributes of their relationship.

**Contract**  this is the entity that represents the agreement between the SESP and its customers. In there, one can find the commercial specifications, but also the profile of the customer, which can influence the terms and conditions of the contract. The entity is shown in fig. 3.31. **cardinality**: 'one, mandatory', per customer.
3.5. Entity-Relationship Model

### Customer Resource Portfolio

This entity gives the commercial specifications of the resources belonging to a certain customer. The relational database table will be identified by the pair (Customer_ID, Resource_ID), and the resource portfolio of a specific customer can be looked up by selecting all the rows with the same Customer_ID. The entity is shown in fig. 3.32. **Cardinality:** "one or many, optional", per customer. If a customer doesn’t have resources, it won’t have portfolio items.

---

#### Table: Contract

<table>
<thead>
<tr>
<th>key</th>
<th>attributes</th>
<th>data type</th>
<th>description</th>
<th>notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>PK_FK1</td>
<td>Customer_ID</td>
<td>VARCHAR</td>
<td>foreign key referring to Customer entity, used as a primary key</td>
<td></td>
</tr>
<tr>
<td>PK_FK2</td>
<td>SESP_ID</td>
<td>VARCHAR</td>
<td>foreign key referring to SESP entity, used as a primary key</td>
<td></td>
</tr>
</tbody>
</table>

**Commercial characteristics**

- **contr_renew_type:** binary, contract renewal type
  - 0: manual renewal
  - 1: automatic renewal

- **contr_type:** binary, contract type
  - 0: flexibility contract
  - 1: other contract

- **transp_level:** [1, 2, or 3], transparency level
  - 1: basic contract conditions
  - 2: advanced contract conditions

---

**Customer profile**

- **beh_score:** [1, 2, 3, 4, or 5], behavioral score
  - Start with 5/5, but reduction of one point per three overrides of flexibility commands

- **activity_score:** [1, 2, 3, 4, or 5], activity score
  - 5: highest
  - 1: lowest
  - Score increases when commercial availability periods are considerably long and steady over time.

- **load_perc:** DECIMAL, load percentage
  - Percentage of the total amount of load resources that is owned by the customer of this contract.

- **stor_perc:** DECIMAL, storage percentage
  - Percentage of the total amount of load resources that is owned by the customer of this contract.

- **EV_perc:** DECIMAL, EV percentage
  - Percentage of the total amount of load resources that is owned by the customer of this contract.

- **gen_per:** DECIMAL, generation percentage
  - Percentage of the total amount of load resources that is owned by the customer of this contract.

---

Figure 3.31: The contract entity, formed by a SESP entity and a Customer entity.
3.5. Entity-Relationship Model

![Table: Customer Resource Portfolio](image)

<table>
<thead>
<tr>
<th>key</th>
<th>attributes</th>
<th>data type</th>
<th>description</th>
<th>notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>PK, FK</td>
<td>Resource ID</td>
<td>VARCHAR</td>
<td>maximum power per activation</td>
<td>unit: [W]</td>
</tr>
<tr>
<td>PK, FK</td>
<td>Customer ID</td>
<td>VARCHAR</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Commercial characteristics**

<table>
<thead>
<tr>
<th>key</th>
<th>data type</th>
<th>description</th>
<th>notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>P_max</td>
<td>DECIMAL</td>
<td>maximum power</td>
<td>unit: [W]</td>
</tr>
<tr>
<td>days</td>
<td>MULTISET</td>
<td>days for activation</td>
<td>set of days at which the resource can be activated</td>
</tr>
<tr>
<td>intervals</td>
<td>INTERVAL</td>
<td>permitted intervals</td>
<td>time durations in which the resource can be activated</td>
</tr>
<tr>
<td>t_max</td>
<td>INTERVAL</td>
<td>maximum allowed activation time</td>
<td></td>
</tr>
<tr>
<td>t_min</td>
<td>INTERVAL</td>
<td>minimum time between activations</td>
<td>time between two activations</td>
</tr>
<tr>
<td>tolerance</td>
<td>DECIMAL</td>
<td>tolerance</td>
<td>allowed percentage of deviation from requested and provided flexibility</td>
</tr>
<tr>
<td>non_conf</td>
<td>CHARACTER</td>
<td>non conformance clause</td>
<td>consequences of not meeting required flexibility</td>
</tr>
<tr>
<td>act_price</td>
<td>DECIMAL</td>
<td>activation fee</td>
<td>price for flexibility activation paid to customer</td>
</tr>
</tbody>
</table>

Figure 3.32: The customer resources portfolio.

**Communication Links**  Fig. 3.33 shows the entity corresponding to the communication link between the SCADA and the DER Unit controller, and is significant for representing the other communication links too. The communication links have many quality attributes, such as security, latency, reliability, etc. to specify which type of data requirements they can fulfill. For example highly secure communication network would be required for confidential data, but perhaps not for weather data. **Cardinality:** 'one or more, mandatory'.

---

[Image: Diagram showing communication links between SCADA and DER Unit controller]
3.5. Entity-Relationship Model

3.5.3 Entity-Relationship Model of EMPOWER Smart Distribution Grid

Now that the entities are defined, the relationships between each of them can be represented in an entity relationship diagram, as in fig. 3.34. The diagram will be detailed from top to bottom, starting with the entity customer.

- The customer entity is the super-type entity of three subtypes: DSO, Household Customer, and Facility Customer, the discriminant is the attribute Cust_type. The relation is inclusive (shown by the crossed dot), which means that in this system, the Customer has to be (mandatorily) one and only one of the three available subtypes. The customer is connected with the SESP through a contract, where their agreement details are stored. As shown by the cardinalities, a customer may have no contract, or one contract, and the contract can’t exist.
without being related to a customer. This is a one to one type of relationship. The SESP on the other hand, has a many to one relationship with the contract entity, as it may have many contracts (with different customers), but a contract always involves one and only one SESP entity.

- The customer communicates through communication network CL10 with the customer interface entity. Customer communicates with one and only one CL10, whereas CL10 can have 0 or many Customers, as indicated by the cardinalities between the two entities.

- There is only one Customer Interface in the whole system, hence there is a mandatory one to one relationship between the Customer Interface and CL10.

- Similarly, every relation between the SESP and its communication links is one to one mandatory (not all the FKs of the SESP that refer to Communication links (CL) are shown in the ERM). The exception are the CL2 and CL-2 communication links, since each Local Controller has a one to one mandatory relationship with the CL2 and CL-2 entities, but the SESP has an optional one to many relationship with the Local controller entity (the SESP may communicate with many Local controllers, each through their own CL2, and CL-2).

- There is only one element of the SCADA entity in the system, which can in turn communicate with optionally one or many DER Unit Controller entities, through CL3.

- Each DER Unit Controller and Local controller are connected to a unique meter entity.

- The DER Unit controller controls one and only one Resource, whereas the local controller can control one or many Resources (all from the same customer).

- the Resource entity has an 'zero or one' relationship, but with a crossed dot, with both DER Unit Controller (through CL7) and Local controller (through CL8). This is because it has to communicate with either one of the two, it can’t communicate with none of the two entities, or with more than one of them.

- finally, fig. 3.35 shows the detail of the entity super-type entity Resource and its sub-type entities, which have been previously described.
Figure 3.34: Entity-relationship model of the EMPOWER smart distribution grid.
3.6 Conclusion: building blocks for the SESP Resilience Quantification Framework

So far, this chapter has determined the technical architecture of the EMPOWER distributed grid through the multidimensional SGAM framework, and set up primary and secondary functions that can be used to describe the full functionality of the SESP. Moreover, each component and derivate components of the system have been translated into entities that have a set of attributes that characterize both the functional properties of the entity, as well as properties indicating its quality. To understand the relations and possible interactions between every entity, the system is represented in an entity-relationship model.

With these elements, it becomes possible to make a resilience quantification framework with two approaches.

In the first approach will look at the requirements of each high level function, and use the quality attributes of entities to define resilience indicators for each dimension of resilience: physical infrastructure, the socio-economic environment, and the ICT network. As such, when the potential disturbances in the specific case of smart distri-
3.6. Conclusion: building blocks for the SESP Resilience Quantification Framework

bution power systems are evaluated, these attributes can serve as metrics to translate these disturbances into quantifiable consequences for the system. For example, to quantify the system resilience against a denial of service (DoS) attack, which sends a very large amount of requests to a certain monitoring device (for instance the Local controller), one can use the quality attributes of the communication link entities, to quantify the available memory space and data flux capacity to deal with the attack.

The second approach will be based on importance analysis, and criticality assessment. By decomposing each high level function (HLF) into sequences of primary functions, it is possible to quantify on how many entities the HLF depends, and which one of them weighs through the most. The more a HLF is dependent on a specific entity, the more critical this entity is to the performance of the global system.

The next chapter will give the potential disturbances for the SESP environment, list the requirements for each high level function, and present the two approaches of the EMPOWER framework for resilience quantification.
Chapter 4

Results and Discussion

4.1 Introduction

To analyze the resilience of the SESP, it is fundamental to first define the factors that can affect the resilience of the system. These factors will be called changes, and can be categorized into two groups. On one hand, the system has to be resilient against discrete changes or disturbances, and on the other hand against continuous evolution of the system itself and its environment. As mentioned in the previous chapter, change can originate from three different dimensions: socio-economical, physical, or cyber dimension. Discrete change can be a cyber attack or a component failure, or human error, in each dimension respectively. Continuous change is more related to regulatory changes, aging infrastructure, new economical recessions, change of mindset of different actors, etc. Resilience can be analyzed from the perspective of the system operator, the SESP, and also from the perspective of the end-consumer. For the end-consumer, resilience is measured in function of the quality of service provided to them. In contrast, the resilience for the SESP operator is measured in function of the level of performance of the high level functions.

The chosen approach is on one hand to assess the resilience of the SESP by evaluating its high level functions in function of its dependence on the different entities of the system. Therefore, for each HLF, an appropriate metric has to be chosen that can quantify the the system’s ability to perform this functionality. On the other hand, each component of the EMPOWER smart distribution grid will be assessed a level of criticality in relation to each HLF, as to determine how much the resilience of the global system is dependent on the resilience of one specific component of the system.

4.2 Potential Disturbances of the EMPOWER System

The distributed power grid that is controlled by the SESP forms a complex system where physical power system components are controlled by and connected through various ICT networks. Each participating household has different controllable appliances, such as solar panels, controllable tumble dryers, electrical vehicles, etc., and
all of these resources are made by different manufacturers. By consequence, different qualities of resources, using different communication technologies, operating at different frequencies, requiring more or less power, etc., are combined in the same system and need to communicate with the same communication network. Moreover, the introduction of smart meters in households presents a weak link in the power system, hence an easy target for cyber attacks. Because of the increased interconnectedness between physical and ICT elements in an intelligent system, failure propagations can occur faster and extend further. For this reason, it becomes necessary to weigh the benefits of intelligent control against its potential weaknesses it brings along. This can be done through resilience analysis.

Besides the increased complexity that comes with intelligent control, and in general with the introduction of distributed (renewable) energy resources, it also means that the distributed power system behaves in a much less predictable manner than in a traditional, centrally operated power system. It is therefore more difficult to design an intelligent distributed grid than it is to design a traditional distributed power system, because its exact behavior is unknown on forehand. In other words, it is no longer enough to build robustness in the system, often by creating redundancy in the power system, in order to anticipate on "worst case scenarios", since these worst case scenarios are getting more complex with the complexity of the system. Therefore, to analyze how the desired benefits of the intelligent control of distributed power systems are noticeable in reality, one can perform a resilience analysis. This means that resilience refers to the evaluation of the desired functionalities of a system, while this system evolves or undergoes a disturbance. The literature review already indicated that change can occur in three different dimensions: in the physical dimension, the ICT network, and in the socio-economical dimension. Specifically to the EMPOWER grid and the SESP functionalities, the potential disturbances or evolutions are represented in table 4.1.

<table>
<thead>
<tr>
<th>Discrete events (de)</th>
<th>Continuous change (cc)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Internal (int)</td>
<td></td>
</tr>
<tr>
<td>- physical component failure (meter, generation device, computer, sensor, PCC, etc.)</td>
<td>- upscaling: increasing number of system components</td>
</tr>
<tr>
<td>- ICT network component failure</td>
<td>- diversification of system components: different manufacturers, different levels of quality</td>
</tr>
<tr>
<td>- inaccurate computational models</td>
<td>- increasing system interconnection by continuous addition of ICT network components</td>
</tr>
<tr>
<td>- human error (considered that human is a system actor)</td>
<td>- diversification of used protocols and communication technologies</td>
</tr>
<tr>
<td>- loss of connection with cloud</td>
<td></td>
</tr>
<tr>
<td>- network congestion/overload</td>
<td></td>
</tr>
<tr>
<td>External (ext)</td>
<td></td>
</tr>
<tr>
<td>- cyber attack</td>
<td>- customer acceptance of the system</td>
</tr>
<tr>
<td>- data theft</td>
<td>- level of self sufficiency of the system</td>
</tr>
<tr>
<td>- unreliable customer behaviour (overriding of control plans)</td>
<td>- policy and regulatory changes</td>
</tr>
<tr>
<td>- heavy weather/natural disaster</td>
<td>- customer responsibility: evolving contract terms</td>
</tr>
<tr>
<td></td>
<td>- level of welfare and education of customers</td>
</tr>
</tbody>
</table>

Table 4.1: Potential disturbances of the EMPOWER Distributed Grid.
4.2.1 Potential Consequences of Disturbances

Each of these disturbances have different effects on the operation of the SESP intelligent control, or some are causing a more severe damage than other disturbances. Table 4.2 shows a selected set of attributes that quantify the consequences of the previously proposed disturbances.

<table>
<thead>
<tr>
<th>Potential causes</th>
<th>Discrete events</th>
<th>Description of quantification</th>
<th>indicator</th>
<th>applicable entities</th>
</tr>
</thead>
<tbody>
<tr>
<td>[ext,cc] natural infrastructure aging</td>
<td>component failure</td>
<td>changes the operational status of the device</td>
<td>is_functional: from true to FALSE</td>
<td>[DER Unit Controller, SCADA, Local Controller, Resources, SESP Server]</td>
</tr>
<tr>
<td>[ext,de] deliberate attack</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>[int,de] operator error</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>[int,de] server overload/congestion</td>
<td>ICT network component failure: database failure</td>
<td>- measure the amount of data that is lost</td>
<td>indicator 1: data_loss=X-X'</td>
<td>[SESP Database]</td>
</tr>
<tr>
<td>[int,de] incompatible data transfer</td>
<td></td>
<td>- measure the time it takes before restoration takes place</td>
<td>indicator 2: time interval between two technical status changes (first from is_connected TRUE to FALSE, second from is_connected FALSE to TRUE)</td>
<td></td>
</tr>
<tr>
<td>[ext,cc] heavy weather</td>
<td>ICT network component failure: communication line</td>
<td>- measure data transfer delay</td>
<td>latency</td>
<td>[Communication links]</td>
</tr>
<tr>
<td>[int,cc] wrong usage profile</td>
<td></td>
<td>- measure data transfer loss</td>
<td>bit error rate</td>
<td></td>
</tr>
<tr>
<td>[int,cc] bad manufacturing quality</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4.2: Examples of consequences for disturbing events and possible resilience indicators

4.3 General SESP Resilience Indicators

In the previous chapter, it was already mentioned that some attributes of the system entities could be used as quality or reference attributes to define resilience indicators. Table 4.3 gives examples of such attributes.
4.4 SESP HLF Resilience From the Three Dimensions Perspectives

This part of the resilience framework looks at each of the SESP high level functions from the perspective of the three resilience dimensions:

- Physical infrastructure dimension
- ICT network dimension
- Socio-economical dimension

In each dimension, specific resilience indicators will be defined in function of the requirements that every component of the dimension has in order to perform the HLF.

As a result, one can assess which resilience dimension plays a more important role for the performance of the assessed High level function. As an example, the resilience assessment of the High Level Function 5: (Remote) Monitoring is shown below.

<table>
<thead>
<tr>
<th>transparency level</th>
<th>description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1: basic contract conditions</td>
<td></td>
</tr>
<tr>
<td>2: price volatility risk sharing</td>
<td></td>
</tr>
<tr>
<td>3: resilience parameters risk sharing</td>
<td></td>
</tr>
</tbody>
</table>

the level of transparency refers to how much information is shared with the customer, in order to share the risks involved in energy market management between the SESP and the customer. In level 1, the entire risk is taken by the SESP. In level 2, the flexibility prices are based on real-time electricity prices, hence the price volatility risk is shared between the SESP and the customer. Level 3 adds the parameters for resilience calculation, such that the customer is aware of the cost of system recovery in the event of disturbances, and can also share this risk.

<table>
<thead>
<tr>
<th>behavioral score</th>
<th>description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Start with 5/5, but reduction of one point per three overrides of flexibility commands</td>
<td></td>
</tr>
</tbody>
</table>

the behavioral score is a measure for the reliability of the customer. If his score is too low, he won’t be allowed to participate in the flexibility market for a certain period of time.

<table>
<thead>
<tr>
<th>load percentage</th>
<th>description</th>
</tr>
</thead>
<tbody>
<tr>
<td>percentage of the total amount of load resources that is owned by the customer of this contract</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>storage percentage</th>
<th>description</th>
</tr>
</thead>
<tbody>
<tr>
<td>percentage of the total amount of load resources that is owned by the customer of this contract</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>EV percentage</th>
<th>description</th>
</tr>
</thead>
<tbody>
<tr>
<td>percentage of the total amount of load resources that is owned by the customer of this contract</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>generation percentage</th>
<th>description</th>
</tr>
</thead>
<tbody>
<tr>
<td>percentage of the total amount of load resources that is owned by the customer of this contract</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>geo-location</th>
<th>description</th>
</tr>
</thead>
<tbody>
<tr>
<td>array of two elements: set of geographical coordinates</td>
<td></td>
</tr>
</tbody>
</table>

this type of attribute can give an overview of the level of geographical concentration or on the contrary of homogeneity of the DERs and CPs, and identify the bottleneck zones for congestion, or risk of supply shortage, etc.

<table>
<thead>
<tr>
<th>commercial status</th>
<th>description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0: active customer</td>
<td></td>
</tr>
<tr>
<td>1: inactive customer</td>
<td></td>
</tr>
</tbody>
</table>

indicates the reliability of a customer, when looked at a histogram of customer status. Longer inactivity means disengaged, short but unpredictable periods of inactivity indicate unreliable usage profile.

Table 4.3: Examples entity attributes serving as a basis for resilience indicators

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4.4. SESP HLF Resilience From the Three Dimensions Perspectives

4.4.1 Remote Monitoring

Use Cases

UC 5.1 Handle meter data
UC 5.2 Handle event signals
UC 5.3 Detect local overriding of control plan
UC 5.4 Log all actions and events

Requirements

- send metering data from different meter reliably and at desired frequency
- archive data securely
- report data to utility/customer reliably and at desired frequency

Physical Infrastructure Dimension

Requirements per related entity:

- DER Unit Controller: is functional, is connected
- SCADA: is functional, is connected, can interpret the transferred data
- Local controller: is functional, is connected
- SESP computer: is functional, can access the required data

Potential disruptions:

- anticipated: aging infrastructure,
- unanticipated: natural disaster, unusual load profile of components

Resilience Indicators:

- Failure criticality Index: ranks importance of elements based on a parameter of interest. contribution to system failure of a specific component
- Restoration criticality index: percentage of times that system restoration results from the restoration of this component. assesses the impact of restoration of a specific element
- Operation criticality index: percentage of a component’s down time over the system down time
ICT network Dimension

Requirements per related entity:

- SESP Database: is functional, is not full, is well programmed
- Customer interface: is functional, is responding fast, can handle large amounts of data
- Communication links: is connected, has the required speed, has the required latency, has the required throughput, etc.

Potential disruptions:

- cyber attack (denial of service, etc.)
- change of used standards/protocols
- addition of new standard
- change of communication technology

Resilience Indicators [2]:

- Packet Delivery Ration (PDR): number of packets successfully received over the expected number of packets
- Average End-to-End Delay: average time to transmit packages from sending application to receiving application
- Average Packet Hop Count: average number of intermediate nodes through which the packets sent by a sender are routed (for example the number of meters traversed)

Socio-economical dimension:

Requirements per related entity:

- Customer: takes the right decisions when getting event notifications, understands periodical reports

Potential disruptions:

- wrong human interpretation of data
- level of collaboration of customers
- unavailability of maintenance crews
- regulatory limitations on information exchange?
4.5. SESP HLF Resilience in function of Component Criticality

Resilience Indicators:

- reputational score of customer: the more active a customer participates, the better his score, the more flexible he is for the system.
- level of transparency of agreements: if the customer knows about potential disruptions and their influences, the risk of disturbances is shared between the SESP operator and the customer, making the system more resilient.

4.5 SESP HLF Resilience in function of Component Criticality

This resilience assessment approach makes use of the entity relationship diagram to calculate the number of sequences of primary functions that are necessary to perform a certain HLF use case. It makes use of the cardinality to multiply the number of primary functions executed by an entity by the number of instances of that entity that are present in the system.

Once again, the example of the HLF 5. Remote Monitoring can be taken as an illustration:

Assumptions

- there are N DER Resources
- there are M CP Resources

Executed Use Cases

- periodically handle metering data of all resources
- store in database
- report to customer interface

Sequence dependencies

- For all N DER Resources: send(DER, DER Unit Controller, [P,Q,V,I],1min)
- + send(DER Unit Controller, SCADA, [P,Q,V,I],1min)
- + send(SCADA, SESP, [P,Q,V,I],1min)
- For all M CP Resources: send(CP, Local Controller, [P],1min)
- + send(Local Controller, SESP, [P],1min)
- 1 time: send(SESP, SESP Database, [Array of N attributes + Array of M attributes],1min)
4.5. SESP HLF Resilience in function of Component Criticality

- For each customer Customer_ID_i (C in total): send(SESP, Customer, [individual update of P, or P,V,Q,I],1min)

Result: depends on $N \times 3 + M \times 2 + 1 \times (3 \times N + 2 \times M) + C_{DER} \times N + C_{CP} \times M$
PFs of equal parameter size.
Chapter 5

Conclusions and Further Research

5.1 Conclusions

5.1.1 Motivation

The objective of the thesis was to find indicators to assess the resilience of the smart distributed grid (SDG), or how well the anticipated benefits of SDGs are accomplished and counterbalance the anticipated and unanticipated challenges of SDGs. The motivation behind the research is the increasing integration of renewable energy resources into the distributed power system. As these represent challenges to the grid operators, for example to balance the irregular generation profiles of renewable resources, research is done to develop local energy markets, which can control the power system at distribution level in a flexible way. Distributed control enables more flexible control, and enables local consumers to participate in the energy market by offering ancillary services. However, these advantage may be counteracted by the fact that local control brings along more complex interconnections between the physical power system infrastructure, and new intelligent control ICT networks. A resilience analysis aims at quantifying the net benefits of smart distributed grids, in the present and in the future.

5.1.2 Resilience as a Multi-Attribute characteristic

Table 5.1 shows five characteristics that together can assess resilience: reliability, adaptive capacity, elasticity, plasticity, and evolvability. Short term characteristics evaluate a system during and right after a disturbing event occurred, whereas long term characteristics assess the capability of the system to learn from the events and adapt itself to prepare for the next cycle of disturbance or change.
5.1. Conclusions

<table>
<thead>
<tr>
<th>Resilience</th>
<th>Static</th>
<th>Dynamic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short term</td>
<td>Reliability</td>
<td>Elasticity, Adaptation capacity</td>
</tr>
<tr>
<td>Long term</td>
<td>Plasticity</td>
<td>Evolvability</td>
</tr>
</tbody>
</table>

Table 5.1: Overview of the components of resilience.

5.1.3 System Resilience from Different Perspectives

The resilience of a system depends on the perspective from which it is being analyzed. For instance, this report showed that the resilience of the smart distributed grid from customer perspective refers to the ability of maintaining a certain quality of service. For the system operator, on the other hand, resilience can be interpreted as the ability of the grid to recover in the most efficient way after a disturbance, and gracefully adapt itself to continuous change. Resilience can be assessed for a specific component of the system, or for the whole system, etc. The SGAM model is very suitable to illustrate the multidimensional character of resilience. Fig. 5.1 shows how resilience can be seen as an additional plane in the SGAM framework, having different definitions or interpretations depending on which part of the smart grid plane is considered.
5.1.4 Resilience Assessment Method: Entity-Relationship Diagram

This work suggested a method for resilience assessment based on a technical decomposition of the EMPOWER smart distributed power system, together with a functional decomposition of the functionalities of the intelligent control system of the distributed grid, called the SESP (Smart Energy Services Provider). The technical architecture and the functions of the SESP were then combined in an entity-relationship model, in order to have a clear overview of which elements of the system interact with each other, and which attributes are exchanged between them.

With the entity relationship model as a tool, the resilience of each high level functionality of the SESP could be assessed. An example high level functionality would be remote monitoring of controllable resources, or customer services. The proposed resilience framework consists of two approaches. The first approach is based on
assessing the resilience of each high level function from three different dimensions: the physical infrastructure dimension, the ICT network dimension, and the socio- economical dimension. The other is based on assessing the dependence of these high level functions on critical system components. The more a functionality of the SESP depends on a specific system component, the more this component weighs through in the resilience of the global system.

5.2 Further Research

Even within power systems, the field of resilience is very broad and one can easily get overwhelmed by the amount of parameters that influence this characteristic. Therefore, it would be useful to split up the analysis of resilience of distributed power systems into different sub-disciplines. For example by using the SGAM Model, and making a resilience analysis in the domain of Customer Premises and the Market Zone, or in Operation zone for the DER domain, etc.

5.2.1 In Depth Resilience Analysis per Type of Dependency

Another approach would be to divide the scope of research into the three domains, and focus solely on resilience indicators with respect to cyber security, for instance, or on the other hand, specialize in behavioral science, and analyze the role of the prosumer in the resilience of the smart distributed power system.

5.2.2 Model Development

Since Entity-relationship models are often used to model relational databases, the model presented in this work is in fact a first step into designing an interactive database model, where the number of dependencies could automatically be calculated by implementing the developed entity model into a real computer programme. As such, indicators could be tested with the help of real data gathered from the EMPOWER pilot sites, starting an iterative learning process of comparing different indicators to see which work better, as well as use the entity relationship model to compare potential solutions to improve the resilience of the smart distributed grid.
Appendix A

SQL Datatypes

<table>
<thead>
<tr>
<th>Data type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CHARACTER(n)</td>
<td>Character string. Fixed-length n</td>
</tr>
<tr>
<td>VARCHAR(n) or CHARACTER VARYING(n)</td>
<td>Character string. Variable length. Maximum length n</td>
</tr>
<tr>
<td>BINARY(n)</td>
<td>Binary string. Fixed-length n</td>
</tr>
<tr>
<td>BOOLEAN</td>
<td>Stores TRUE or FALSE values</td>
</tr>
<tr>
<td>VARBINARY(n) or BINARY VARYING(n)</td>
<td>Binary string. Variable length. Maximum length n</td>
</tr>
<tr>
<td>INTEGER(p)</td>
<td>Integer numerical (no decimal). Precision p</td>
</tr>
<tr>
<td>SMALLINT</td>
<td>Integer numerical (no decimal). Precision 5</td>
</tr>
<tr>
<td>INTEGER</td>
<td>Integer numerical (no decimal). Precision 10</td>
</tr>
<tr>
<td>BIGINT</td>
<td>Integer numerical (no decimal). Precision 19</td>
</tr>
<tr>
<td>DECIMAL(p,s)</td>
<td>Exact numerical, precision p, scale s. Example: decimal(5,2) is a number that has 3 digits before the decimal and 2 digits after the decimal</td>
</tr>
<tr>
<td>NUMERIC(p,s)</td>
<td>Exact numerical, precision p, scale s. (Same as DECIMAL)</td>
</tr>
<tr>
<td>FLOAT(p)</td>
<td>Approximate numerical, mantissa precision p. A floating number in base 10 exponential notation. The size argument for this type consists of a single number specifying the minimum precision</td>
</tr>
<tr>
<td>REAL</td>
<td>Approximate numerical, mantissa precision 7</td>
</tr>
<tr>
<td>FLOAT</td>
<td>Approximate numerical, mantissa precision 16</td>
</tr>
<tr>
<td>DOUBLE PRECISION</td>
<td>Approximate numerical, mantissa precision 16</td>
</tr>
<tr>
<td>DATE</td>
<td>Stores year, month, and day values</td>
</tr>
<tr>
<td>TIME</td>
<td>Stores hour, minute, and second values</td>
</tr>
<tr>
<td>TIMESTAMP</td>
<td>Stores year, month, day, hour, minute, and second values</td>
</tr>
<tr>
<td>INTERVAL</td>
<td>Composed of a number of integer fields, representing a period of time, depending on the type of interval</td>
</tr>
<tr>
<td>ARRAY</td>
<td>A set-length and ordered collection of elements</td>
</tr>
<tr>
<td>MULTISET</td>
<td>A variable-length and unordered collection of elements</td>
</tr>
<tr>
<td>XML</td>
<td>Stores XML data</td>
</tr>
</tbody>
</table>

Figure A.1: Source: [weschool]
Bibliography


