View-based and Model-driven Outage Management for the Smart Grid

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***Abstract*—The integration of renewable energy resources is challenging the traditional electricity network. To manage this, the smart grid has been defined as a cyber-physical system consisting of a physical component, which is the electricity grid, and a computational component consisting of a communication network, metering network, and software components. Therefore, the smart grid can not just be seen as an electrical grid, but also as a system of software systems. Currently, control centers of the smart grid use an outage management software system to react to reported outages.**

In this paper, we present an extended outage management system that solves one main problem of the smart grid: software systems of the different domains are using different standards. Consequently, cross-domain data exchange and analysis are difficult. Therefore, we use the model-driven view-based VITRUVIUS approach to build a unified model of the smart grid. We then combine it with system stability analysis methods presented as views on the model. The result is a model-driven run-time monitoring, analysis and control framework to increase the reliability of power supply. The evaluation with statistical data of the German power grid shows that outage time can be reduced with our approach.

I. INTRODUCTION

The smart grid is a cyber-physical system that spans the physical structures of the electricity network and the system of software systems that monitor, control, and repair the system in case of outages. Currently, many heterogeneous systems and standards have to interoperate to achieve the desired reliability, stability, and efficiency of the electricity network. Many of these standards are based on UML and other metamodeling standards, or can at least be expressed as such. Thus, model management systems that were originally designed mainly for the development of software can be used to integrate information from these heterogeneous systems.

In this paper, we present a concept for an extended outage management system (OMS) for the smart electricity grid. The extended OMS is used during run-time to monitor and control the smart grid, as well as for simulation. The goal of the introduction of the OMS is to increase the reliability of the grid by detecting outages and by preventing outages by detecting of instabilities and imbalances. The extended OMS is realized with the view-based and model-driven VITRUVIUS approach [1, 2] and uses its capabilities for runtime analysis and control of the electricity grid. The system is prototypically implemented in the Eclipse Modeling Framework using the description languages for model correspondences and view generation of VITRUVIUS. Thus, the contribution of this paper is twofold: We have created a unified model of the smart grid that makes cross-domain analyses possible, and in addition, we have created view types that implement these analyses. They offer insights into the smart grid that can only be gained by combining information from heterogeneous systems of the grid.

For the evaluation of the prototype, we have evaluated the system using historical data of the the German electricity grid. We have used the SAIDI index to demonstrate how the outage management systems shortens the outage time per person per year. The results show that the average annual outage duration can be reduced by at least 2 min 28 s if our approach is applied.

II. FOUNDATIONS

A. Smart Grid

The smart grid [3] integrates modern IT infrastructure into the traditional physical infrastructure of the electricity network. It is thus a *cyber-physical system*. The motivation behind its introduction are the integration of renewable energy resources into the network, improvement of efficiency, and the reduction of transmission losses. Furthermore, new load profiles, such as electrical vehicles and smart homes, shall participate in balancing the grid and its self-healing abilities [4–6].

Control centers manage the grid via the *supervisory control and data acquisition system (SCADA)*, which monitors and controls the technical processes of the electricity system. *Smart meters* are electronic devices that are installed at the consumers' places. They measure electricity production and consumption, and are connected in the *advanced metering infrastructure (AMI)*, which can also receive commands to shape electricity consumption. The *wide area monitoring system (WAMS)* connects metering data in real-time. The WAMS consists of *Phasor management units (PMU)*, which are high-precision sensors that measure electrical waves with a frequency of 10 to 30 times per second. A power outage is a longer interruption in the electricity supply that can either be planned or unplanned. The causes for unplanned outages can be categorized into the following types [7]:

- *Atmospheric Interferences* are caused by events of nature, such as thunderstorms, sub-zero temperatures, avalances, etc.
- *Internal Failures* are caused by maloperation of systems, malfunction of network internal systems and all other

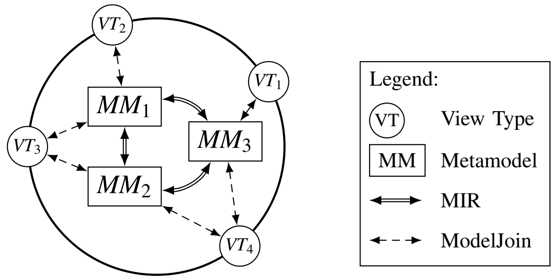

Figure 1. The Modular SUM Metamodel concept of VITRUVIUS

causes that are directly related to the operations of the network.
- *Outside Influences* are not caused by network operators, but, e.g., by construction work, traffic accidents, etc.
- *Supply Failures/Cascading Outages* are caused by a network other than the one controlled by a specific energy supplier, but have an effect on the supplier's network.

In case that despite the monitoring and control systems, a disturbance causes a power outage, an *outage management system (OMS)* becomes active to restore the power supply.

From an architectural viewpoint, the smart grid can be seen as a system of software systems that is connected by a communication network. A large number of standards exists, which cover the various aspects of the smart grid systems. The key standards will be presented in the following.

IEC 61970/61968: The IEC 61970 standard defines the *Common Information Model (CIM)*, which is used to describe the physical components, measurement data, control and protection elements, and the SCADA system. It is defined in UML notation. The IEC 61968 standard is an extension of the CIM for the distribution network [8]. It is also called *distributed CIM (DCIM)*

IEC 61850: This is a series of standards for substations with the purpose of supporting interoperability of intelligent electronic devices (IED) in substation automation systems. It defines the *Abstract Communication Service Interface* with a mapping to concrete communication protocols, the XML-based *Substation Configuration Description Language (SCL)*, and the *Logical Node (LN)* model, which describes power system functions [9].

IEC 62056: COSEM (Companion Specification for Energy Metering) is the international standard for data exchange for meter reading, tariff and load control in the domain of electricity metering. It works together with the *Device Language Message Specification (DLMS)*. Together, they provide a communication profile to transport data from metering equipment to the metering system and to define a data model and communication protocols for data exchange [10].

B. Vitruvius

VITRUVIUS [1, 2] is a view-based, model-driven framework for the mangement of heterogeneous models, i.e., models that are instances of different metamodels. It is based on the concept of a *single underlying model (SUM)* [11], which represents all the information that is available about a system. The metamodel for this model is specific to the domain in which the VITRUVIUS approach is used. It combines several metamodels to form a modular SUM metamodel (see Figure 1). The metamodels are included non-intrusively and do not have to be adapted. To express the semantic relations between the elements of the metamodels, VITRUVIUS defines the consistency description language *MIR* (mapping/invariant/response). Since VITRUVIUS is a view-based approach, all information in the SUM can only be retrieved or manipulated via specialized views. A view is a special kind of model and conforms to a *view type*, i.e., its metamodel. For the definition of view types and views, VITRUVIUS uses the *ModelJoin* language [12]. VITRUVIUS has been implemented as a prototype[1] in the Eclipse Modeling Framework and can thus be used with any Ecore-conforming metamodel. So far, it has been applied to software architecture models [13] and model-based representations of programming languages [14].

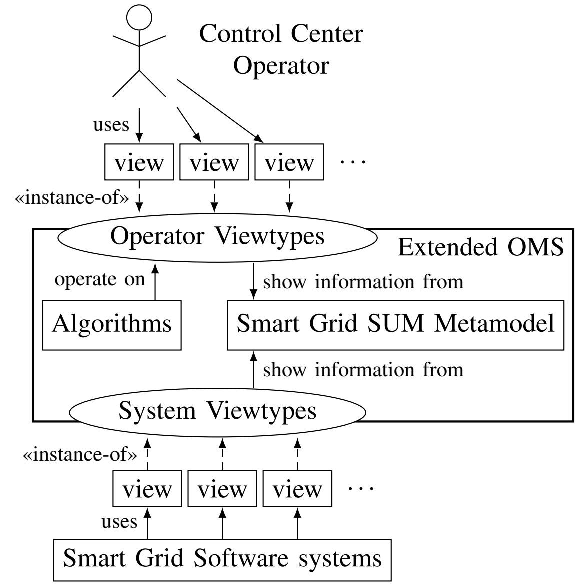

Figure 2. Concept for the extended OMS

III. AN EXTENDED OUTAGE MANAGEMENT SYSTEM

In this section, we present the elements of the extended outage management system that are developed with VITRUVIUS.

A. Concept of the extended OMS

The *Extended Outage Management System* is a model-driven analysis and control framework, which is used during run-time of the electrical system to monitor and control the smart grid, as well as for simulations. The framework enables network stability analysis, grid balance analysis, failure detection and location analysis, and direct controlling interactions with the electricity system to correct faulty sections of the network.

The structure of the system, displayed in Figure 2, can be seen from two perspectives: From an *inside perspective*,

[1]https://sdqweb.ipd.kit.edu/wiki/Vitruvius, retrieved 2016-09-13

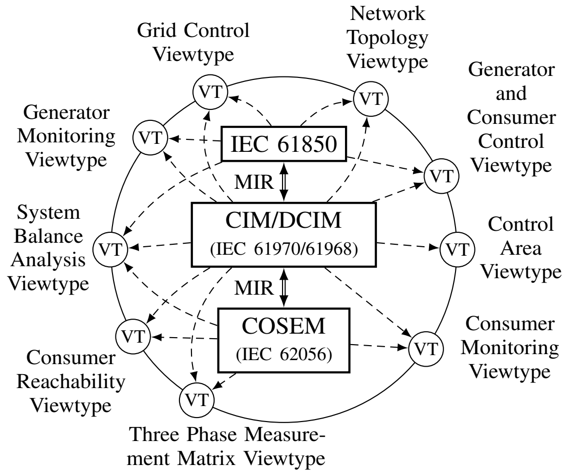

Figure 3. The smart grid SUM metamodel and view types for the extended outage management system

developers can see the inner structure of the system, whereas operators and existing software systems only have and *outside perspective* on the system.

The inner structure of the system consists of three elements: The first one is the *Smart Grid SUM Metamodel*, which is displayed in detail in Figure 3. Following the VITRUVIUS approach, it is a modular metamodel that combines four separate elements of the electricity system: the physical network topology, the SCADA control system, the WAMS for grid monitoring, and the AMI for customer monitoring. In the metamodel, these elements are modeled using the IEC smart grid standards introduced in section II: The network topology model is based on the CIM and DCIM standards; the SCADA control system uses the logical node model of the IEC 61850 standard; the data collected from the WAMS are modeled applying the logical nodes for system measurements from the IEC61850 standard; finally, the AMI smart metering data are modeled using the COSEM standard. Since these metamodels overlap at certain points, they are complemented by MIR correspondence rules to specify the relationships between them. Together, the four metamodels of the elements of the electricity system and the correspondence rules form the modular SUM metamodel. The framework uses an instance of this metamodel as a basis for all further analysis and control actions.

The second important element are the different outage and instability detection and location algorithms, which are used for the different types of failure and stability analysis.

The third important element are the viewtypes, which define the different possible perspectives on the smart grid model. The viewtypes need to be differentiated between viewtypes for the system operator and such for the electricity system. The *viewtypes for the operator* implement the algorithms for balancing input and output of the network to stabilize the voltage, and for failure detection analysis. They define views on the network topology and control regions. Furthermore, they define views for the interaction with and control of the physical equipment of the electrical system. The *viewtypes for the electricity system* provide possibilities for the grid to provide new measurement data, and make system changes to keep the smart grid model of the extended OMS system always up to date. Consequently, system and operator viewtypes are defined based on the smart grid SUM metamodel, and, in case of the operator viewtypes, on the analysis algorithms. Instances of the operator viewtypes are the result of the evaluation of the viewtypes on the instance of the smart grid model. These views are presented to the operator and the smart grid system for them to interact with the smart grid model.

This leads directly to the structure as seen from the outside by the operators and the electrical system. They see the complete analysis framework as a 'black box', and never interact directly with the models and algorithms inside, but only with the views presented to them. The operators can request certain views that they need for monitoring, analysis, and controlling purposes, which are delivered to them by the extended OMS system. The extended OMS system presents them the data and results from the smart grid system in a compact and consistently modeled view, which contains only the information that they need at that special moment, to reduce the complexity for the operators.

B. *The Smart Grid SUM Metamodel*

The modular SUM metamodel of the extended OMS consists of the IEC smart grid standards to model the four required elements. The necessary elements are the advanced smart meter infrastructure modeled by the IEC 62056 COSEM standard, the wide area monitoring system for phasor measurements from the grid modeled by a part of the IEC 61850 standard, the substation control functions modeled by another part of the IEC 61850 standard, and the network topology and overview, modeled by the two standards IEC 61970 and IEC 61968, also known as the CIM and DCIM standards.

COSEM for the Smart Meter System: The smart meter metamodel is not freely available as a digital UML model, so we built it manually as an Ecore model in Eclipse, based on the IEC 62056 standard. An excerpt of the smart meter Ecore model can be seen in Figure 4: The smart meter is represented by the PhysicalDevice class, which is identified by its ID. It is associated with the ManagementLogicalDevice class and the LogicalDevice class. The logical device class has a relation to each electricity-related COSEM object class. Each COSEM object class implements its interface class. For example, the class ElectricityValues contains the attributes for current and voltage measurement data of the power import and export. For later modeling and containment purposes, the physical device also references each COSEM object class.

CIM/DCIM (IEC 61970/61968): To use the CIM and DCIM standard as a part of the SUM metamodel, they both need to be in the format of an Ecore model. The CIM User Group[2] provides the two metamodels as an integrated Sparx Enterprise Architecture Model ready to download as an xmi file. These metamodels are based on the most current release of the two standards in 2014. The CIM User Group offers the metamodel

[2]http://cimug.ucaiug.org, retrieved 2016-09-13

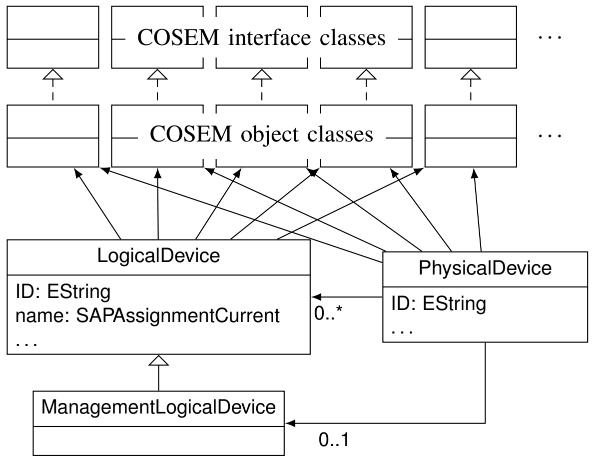

Figure 4. The Smart Meter Ecore Model (Excerpt)

together with the open source Eclipse plugin "CIMtool"[3]. With this tool, it is possible to browse through the models and to export them as an Ecore model, which can then be directly imported into the VITRUVIUS environment.

IEC 61850 for Substation Control and PMU: Analogous to the CIM/DCIM metamodel, the IEC 61850 logical node model needs to be in the format of Ecore in order to be integrated into the SUM. Our Ecore-based metamodel of the standard realizes parts 5 and 7 of the IEC 61850 standard. The metamodel has been created by adapting an Enterprise Architect UML model by ABB. ABB has donated this metamodel to the IEC technical committee (TC) 57. It is accessible as a web-based UML model on their website.[4] The web-based model can be browsed, but unfortunately, it cannot be downloaded. To integrate the metamodel into the SUM Metamodel as an Ecore model, we have rebuilt it manually in Eclipse. Since the ABB model is not completely compatible with Ecore, a few changes had to be made, which are described in detail in [15].

C. Correspondence Rules

```
map CIM.CIM.IEC61970.Wires.Breaker as Breaker
and substation.substationStandard.LNNodes.LNGroupX.
    XCBR as XCBR {
    when-where {
        Breaker.mRID == XCBR.NamePlt.IdNs
        Breaker.mRID = XCBR.NamePlt.IdNs
    }
}
```

Listing 1. Example Mapping Rule for Breaker

The correspondence rules for the extended Outage Management System (OMS) have been defined in the MIR language of VITRUVIUS. They describe the semantic overlaps between the metamodels of the modular SUM metamodel. Since it is not mandatory in the VITRUVIUS approach to define rules for all binary combinations, and since there were no semantic correspondences between IEC 61850 and COSEM, rules have only been defined for the combinations IEC 61850/CIM and CIM/COSEM (see Figure 3). An example for such a rule can be seen in Listing 1, where the correspondence is defined for metamodel elements that describe circuit breakers in both the CIM and the IEC 61850 metamodel, which has the package name "substation". For a complete listing of all rules, we refer the reader to [15].

D. Viewtypes

The second part of the extended OMS are the viewtypes designed for the interaction with operators and the smart grid software systems (cf. Figure 2). Each of the three metamodels in the modular SUM metamodel is exposed as a legacy viewtype to support existing software and visualization methods, and for data exchange with the systems of the smart grid. In addition, nine specific view types have been defined using the declarative ModelJoin language. Each viewtype combines information of either a single or multiple sub-metamodels of the modular SUM metamodel, as displayed in Figure 3.

For network monitoring, the *Network Topology Viewtype* defines a view on the electricity system elements and their topology. The *Control Area Viewtype* focuses on the segmentation of the electricity system into control areas, where each area is regulated by one control center.

Four viewtypes have been defined to support balancing of the electricity grid: The *System Balance Analysis Viewtype* compares production and consumption with predicted values to detect fluctuations. The *Generator Monitoring* and *Consumer Monitoring* view types observe the current situation of generators and consumers. They serve as a basis of decision-making on how to react to imbalances in the system. After this decision, operators use the *Generator and Consumer Control Viewtype* to control the production and demand of electricity.

The *Consumer Reachability Viewtype* is used to detect outages. The detection algorithm exploits the fact that when a smart meter is cut off from power supply, it cannot send any data. Together with the network topology viewtype, it is possible to see the system in a tree structure, and to mark the nodes that failed by searching for the failed consumers in the topology view. Thus, it is possible to detect the outage, and to locate the area of its origin. If a failure is detected, the *Grid Control Viewtype* can be used to stabilize the situation again.

Finally, the *Three Phase Measurement Matrix Viewtype* combines measurement data from phasor measurement units and smart meters. Thus, instabilities and disturbances in the transmission and distribution network can be detected, so that outages can be prevented before they occur. For a complete definition of all view types, we again refer the reader to [15].

IV. EVALUATION

A. The SAIDI Index as Benchmark

The overall goal of the extended Outage Management System (OMS) is to reduce the outage duration and to lower the amount of outages. To evaluate how well the system is performing in doing this, the SAIDI index is used.

[3] http://wiki.cimtool.org/HowToValidateCPSM.html, retrieved 2016-09-13

[4] http://www.nettedautomation.com/download/std/61850/uml/, retrieved 2016-09-13

Outage Type	Perc.	Outages Low Voltage	Outages Med. Voltage	Outages Total
Atmospheric Interferences	45.1 %	66658	11726	78384
Internal Failures	29.51 %	43616	7673	51289
Outside Influences	22.59 %	33388	5873	39261
Supply Failures, Cascading Outages	2.8 %	4138	728	4866

Table I
OUTAGE TYPES OF AUSTRIA USED FOR GERMANY 2014

Consumers	49600000
Outages Low-Voltage	147800
Outages Medium-Voltage	26000
SAIDI Low-Voltage	2.19
SAIDI Medium-Voltage	10.09
SAIDI Total	12.28

Table II
ANNUAL OUTAGE AND SAIDI VALUES FOR GERMANY IN 2014

Definition 1. *The SAIDI (System Average Interruption Duration Index) index is the average outage duration for each served customer. It is an indicator for the reliability of power supply of an electricity system. It is calculated as:*

$$SAIDI = \sum_{j=1}^{C} \sum_{k=1}^{K_j} \varphi_{j,k} \frac{N_{j,k}}{N}$$

where C is the amount of areas the grid is divided into, K_j is the number of annual outages in area j, and $\varphi_{j,k}$ is the duration of the k-th outage in area j, and $N_{j,k}$ is the number of consumers in area j affected by outage k, and N is the total number of consumers in the system [16].

B. Datasets used for the Evaluation

To evaluate the extended outage management system in the German smart grid, four main datasets are used:

1) Germany: Each year, the federal electricity agency of Germany releases a monitoring report about the electricity system. Besides data about production, renewable production and consumption, it includes numbers about the reliability of power supply and the amount of outages per year. The report is freely available and will be used as a basis to calculate the SAIDI index and for comparison, since it includes the SAIDI index for the current German system. For this evaluation, the report from 2014 will be used [17].

2) Austria: Similar to the German report, E-Control publishes the outages and disturbances statistic for Austria each year. The report includes data about the number and type of outages in Austria in 2014, together with the SAIDI index. Since the German and Austrian systems are neighbours, we will assume for the evaluation that the types of outages (as introduced in section II) are the same [7].

3) entsoe: To analyze balancing the grid, statistical data about the actual and forecasted production and consumption for 2015 provided by *entsoe* is used. The dataset includes quarter hourly data for every day and can be used to detect differences between forecasted and actual production and consumption.

The duration of the system restoration after an outage is an important aspect. According to literature [4, 16], two cases need to be differentiated: In both cases, the detection of an outage relies on customer feedback. On average, an outage is reported after 5 to 10 minutes. In the first case, the system has an implemented infrastructure to automatically detect and restore the faulty section. In this case, the outage is repaired after 2 minutes. If this is not the case, the detection and restoration of the failure takes up to one hour. Since these two cases cannot be differentiated here, an average outage restoration duration is calculated based on them. Since this evaluation is conducted in a modern smart grid, it is assumed that the first case happens slightly more often than the second one (60:40). Consequently, the average outage restoration duration is about 30 minutes (using 7.5 minutes for the outage reporting time): $0.6 * 2\,\text{min} + 0.4 * 60\,\text{min} + 7.5\,\text{min} = 31.5\,\text{min}$.

Besides these, some more general assumptions are made for all of the following evaluations.

- The percentages of the types of outages from the Austrian report will be used for the German system, since they are neighbors with similar infrastructure and weather (see Table I).
- The outage restoration duration is 30 minutes.
- Based on this duration and the SAIDI values in Table II, the average number of people affected by an outage in the low and medium voltage network is 24 in the low-voltage network and 640 in the medium-voltage network.

C. Evaluation Views

For the evaluation of our approach, we have analysed several properties of a smart grid using model and the views as described in subsection III-D.

1) Grid Balancing: The main purpose of the viewtypes for grid balancing is to prevent outages by keeping electrical inflows and outflows at balance. We have recalculated the SAIDI index to measure the improvement gained from using the viewtypes. The calculation is based on the numbers from 2014 in Germany and Austria and makes some specific assumptions:

- The fourth outage type *Supply failures and cascading outages* combines two kinds of outages, of which only the supply failures are of interest. For this evaluation, it is assumed that they have each a share of 50 % of the total 2.8 % of their appearance. This is 2069 outages in the low-voltage network and 364 in the medium-voltage.
- Since the views currently only focus on production and consumption and no models for the electricity market and special forecasts are included it is assumed that the views will not perform very well in preventing imbalance outages that currently occur. Therefore it is assumed, that only 30 % of the outages can be prevented. This makes 629 prevented outages in the low-voltage network and 109 in the medium voltage. The total amount of outages

would then be 147 151 in the low-voltage network and 25 891 in the medium-voltage.

The results for the low- and medium-voltage system are:

$$SAIDI_{low} = \sum_{j=1}^{4} \sum_{k=1}^{\frac{147151}{4}} 30\,\text{min} * \frac{24}{49\,600\,000} = 2.14\,\text{min},$$

$$SAIDI_{medium} = \sum_{j=1}^{4} \sum_{k=1}^{\frac{25891}{4}} 30\,\text{min} * \frac{640}{49\,600\,000} = 10.02\,\text{min}$$

Thus, the total is 12.16 min with an improvement of 0.16 min.

2) Outage Detection: The main objective of these views is to detect outages automatically and faster, since currently, this relies on customer feedback, which can take up to 10 minutes. Since in the modern smart grid with automatic remote control, it is possible to restore the power supply after an outage already after two minutes, it is important to reduce the time for detection in order to lower the total outage restoration duration.

The evaluation is based on the following assumptions:

- The low-voltage networks attached to a medium-voltage network do all have the same amount of customers.
- Each smart meter sends data once every 30 minutes.
- The smart meters in a medium-voltage network segment do not send all at the same time, but are distributed equally over the 30 minutes. They are rotating through the low-voltage networks attached to the medium-voltage.
- To differentiate between short temporal outages ($< 1\,\text{min}$) and long permanent outages, the detection time needs to be longer than 1 minute.

We use the formula of [15, section 5.3.4] to calculate the outage detection time based on the number of customers in the system: $3 * \frac{640}{25} * \frac{30\,\text{min}}{640} = 3.6\,\text{min}$. As explained in the general assumptions, there are now two cases of outage restoration. The same restoration times will now be combined with the new detection time. With 60 %, the restoration time is 2 minutes, and with 40 %, it is 60 minutes, which gives an average outage detection and restoration time of $0.6 * 2\,\text{min} + 0.4 * 60\,\text{min} + 3.6\,\text{min} = 28.8\,\text{min}$. This duration will become lower the higher the share of remote controls in the grid gets.

The results for the low- and medium-voltage system are:

$$SAIDI_{low} = \sum_{j=1}^{4} \sum_{k=1}^{\frac{147800}{4}} 28.8\,\text{min} * \frac{24}{49\,600\,000} = 2.06\,\text{min},$$

$$SAIDI_{medium} = \sum_{j=1}^{4} \sum_{k=1}^{\frac{26000}{4}} 28.8\,\text{min} * \frac{640}{49\,600\,000} = 9.66\,\text{min}.$$

Thus, the total is 11.72 min with an improvement of 0.56 min.

3) Instability and Cascading Blackouts detection: The main objective of these views is to prevent outages due to instabilities in the system and to detain cascading outages. It is the goal to prevent outages of two types: internal outages and cascading outages. To evaluate the functionality of these views, some further assumptions have to be made:

- The fourth outage type *Supply failures and cascading outages* combines two different kinds of outages of which only the cascading outages are of interest for these views. For this evaluation it is assumed that they each have a share of 50 % of the total 2.8 % of their appearance. This is 2069 outages in the low-voltage network and 364 in the medium-voltage.
- It is assumed that the external system to compare the values from the views with historic data has been built.
- Internal failures, especially if a device is broken, cannot always be prevented even if the disturbance is detected. However, due to the N-1 criterion it should be guaranteed in most of the cases that the outage can be prevented. But to estimate it carefully it is assumed, that only 50 % of the internal outages can be prevented.
- Concerning cascading outages, since they can be prevented by separating the faulty section from the rest of the grid, it is assumed that 70 % of them can be prevented.

The results for the low- and medium-voltage system are:

$$SAIDI_{low} = \sum_{j=1}^{4} \sum_{k=1}^{\frac{124\,539}{4}} 30\,\text{min} * \frac{24}{49\,600\,000} = 1.81\,\text{min},$$

$$SAIDI_{medium} = \sum_{j=1}^{4} \sum_{k=1}^{\frac{21\,909}{4}} 30\,\text{min} * \frac{640}{49\,600\,000} = 8.48\,\text{min}.$$

Thus, the total is 10.29 min with an improvement of 1.99 min.

Outage Type	Outages Low-Voltage	Outages Medium-Voltage	Outages Total
Atmospheric Interferences	66 658	11 726	78 384
Internal Failures	21 808	3837	25 645
Outside Influences	33 388	5873	39 261
Supply Failures, Cascading Outages	2061	364	2425

Table III
OUTAGES OF THE TOTAL EXTENDED OMS

D. The SAIDI Index of the overall extended OMS

The different views evaluated above are all used together in the extended outage management system. Therefore their functionalities can be combined to combine outage detection with prevention. This will further improve the SAIDI index of the extended OMS, since the single improvements are added up. In order to do that, this section summarizes the single improvements from the previous sections and calculates a combined SAIDI index. The main achievements are:

- Reduction of supply failure outages by 30 %, which are 629 prevented outages in the low-voltage network and 109 in the medium voltage.
- Detection of outages in 3.6 minutes with a total reduction of average outage detection and restoration time to 28.1.
- Reduction of internal failure outages by 50 %, which means 21 808 prevented outages in the low-voltage network and 3837 in the medium voltage.
- Reduction of cascading outages by 70 %, which are 1448 prevented outages in the low-voltage network and 255 in the medium voltage.

This results are displayed in Table III. The results for the extended OMS are:

$$SAIDI_{low} = \sum_{j=1}^{4} \sum_{k=1}^{\frac{123\,915}{4}} 28.8\,\text{min} * \frac{24}{49\,600\,000} = 1.72\,\text{min}$$

$$SAIDI_{medium} = \sum_{j=1}^{4} \sum_{k=1}^{\frac{21800}{4}} 28.8\,\text{min} * \frac{640}{49600000} = 8.10\,\text{min}.$$

In total, this is 9.82 min with a total improvement of 2.46 min, which is 2 minutes and 28 seconds.

This means if the extended OMS is used in the German smart grid, the average annual outage duration for each consumer could be reduced by at least 2 minutes and 28 seconds. Consequently, the analysis and control framework built can indeed help to improve the reliability of power supply.

V. Related Work

Related work on improving the reliability of the power supply using model-driven methods can be grouped in two categories: Approaches that treat the problem of improving the *reliability* of power supply, and approaches that examine the problem of *combining information* of the smart grid using model-driven or related methods.

There is quite an extensive amount of research about the *reliability* of electrical systems, also in connection with the smart grid. E.R. Brown [18] examines the challenge of a reliable power distribution system, and D. Elmakias introduces in his book methods to examine and improve the reliability of an electrical system [19]. Chowdhury et al. [20] and Waseem et al. [21] focus especially on the impact of distributed generation on system reliability, since the integration of distributed generation is a new challenge for the power system. Related to power distribution, Russell et. al [22] work on improving the reliability of the distribution system equipment in their research.

Since the unification of different smart grid elements in one model has been identified early in the NIST smart grid roadmap [3], different approaches have been developed:

The Electric Power Research Institute (EPRI) has harmonized the CIM model with the IEC 61850 substation equipment with a CIM-based unified UML model that includes the physical elements of both standards [23–27]. In contrast, the approach presented in this paper leaves the existing smart grid models unchanged and builds mappings to combine them. The EPRI approach includes only the substation equipment from the IEC 61850 SCL model, while our research focuses on the substation functions in the LN model.

Andrén et. al. use model-driven QVTo transformations to transform IEC 61850 LN models into IEC 61499 models, a standard for process automation. This is done to automate the substation processes. The authors use model transformations to combine the two standards, like it is done in this research. However, they focus on those two standards and do not have the goal to enhance smart grid integration [28].

Byunghun et. al. present in their work mappings between datatypes from the CIM and the IEC 61850 standard. The two standards can only be unified if their datatypes match. The IEC 61850 however defines special datatypes for the standard that need to be mapped onto the datatypes defined in the CIM model. For deeper research about the mapping of the two standards, this paper is of importance [29].

Another different approach to map the two standards CIM and IEC 61850 is the use of ontologies and semantic web methods. This can be found several times in literature [30–33]. Since currently the mapping of signals between the CIM and IEC 61850 standards needs to be performed manually, these papers suggest a mapping between the SCL and the CIM configuration file with ontology matching. This approach follows the same purpose like the model-driven approach presented in this research, however using a different method.

VI. Conclusion

In this paper, we have presented a model-driven and view-based framework, called the extended outage management system, for run-time analysis and control of the smart grid. The main purpose of the system is to increase the system reliability by faster detection of outages and by preventing the outages through the detection of system instabilities and imbalances. The system is built in Vitruvius, a model-driven and view based model management framework, which was originally created for software development purposes, but can be used with any kind of metamodel-based data. This paper has shown that the mechanisms and languages of Vitruvius for defining correspondences and viewtypes can successfully be applied to domains that do not purely concern software.

The framework has been evaluated using the SAIDI index. Using statistical data of the German power grid, a possible improvement of 2 minutes and 28 seconds in annual outage time. The system could be further improved by including further data sources, such as real-time data from the energy market.

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