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Interaction of smart grid applications supporting Plug & Automate for intelligent secondary substations

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Abstract: The digitalisation of power grid infrastructure reaches the distribution grid level. Novel applications on substation level and their implementation on thousands of automation components will result in an increase in operational efforts that is likely to exceed the economic advantage of the applications. To counteract this negative trend, this work presents an approach for smart grid and smart city applications. The authors introduce applications developed for an Austrian Smart City project, show their interaction, and present first results and field experiences.

1 Introduction

The Austrian flagship project *Smart City Demo Aspern* (SCDA) and its sister project *intelligent Network Information System* (iNIS) investigate a smart city concept, which integrates the domains smart grid, smart buildings, and smart users by modern information and communication technology (ICT) components under the umbrella of the joint venture *Aspern Smart City Research* (ASCR) in Aspern – hereafter referred to as Testbed Aspern. The overall goal is to investigate the migration path from traditional engineering-based automation towards an innovative ‘Plug & Automate’ (P&A) approach. In the future, smart grid solutions have to deal with a wide and heterogeneous spectrum of distributed automation components, sensors, and actuators. To ensure the scalability of these solutions, it is necessary to reduce the efforts for manual engineering of those components as much as possible. Based on grid monitoring applications, numerous – potentially interacting – higher level applications (e.g. control, optimisation, market participation) are envisioned as shown in Fig. 1. Some of the applications are already implemented and running as field trials within the Testbed Aspern; some are currently in development and further applications are specified. In this paper, a system environment is proposed and results of the P&A approach in an urban low-voltage (LV) distribution setting are presented.

The basic software environment (presented in [1]) for all higher level applications consists of

- the Gridlink message bus [2, 3],
- the storage module to persist information of other modules [2, 4],
- the application manager module to execute application provisioning tasks [2, 3],
- the grid representation module (GRM) [1, 2], and
- the building representation module (BRM) [1, 2].

Based on this framework, further modules will be introduced in this work. This contribution focuses on the design of application interaction and dependencies to support the P&A feature for the setting shown in Fig. 1.

2 Benefit of smart grid applications supporting plug and automate

As discussed in the introduction, previous projects showed that the growth of operational efforts within utilities’ operational processes have to be given more attention. Solutions of technical problems are only feasible in the field, if the emerging economic advantages are not offset via increased operational effort.

Figs. 2 and 3 show that the effort for monitoring and automation will strongly increases in the lower grid levels. Hence, classic automation solutions cannot be used for these applications, since they use very secure but due to necessary efforts cost-intensive engineering processes.

Therefore, P&A solutions tailored for the requirements in lower grid levels should contain functionalities, which are as easy to use as to plug a USB flash drive into a PC. This bold vision can be mapped to a substation via the following example scenario: an intelligent device is mounted into the substation and added to the IP network. Then, the device automatically registers to the overlay system to scan for monitoring data and perform self-learning to fulfil tasks like voltage control. Human operational support is needed only for basic configurations, starting tasks, or in the case of failures. As long as the application works as intended, the overlay system is not cluttered with messages.

The previously described example scenario can be either simple (e.g. temperature sensor in substation) or complex (state estimation-based decentralised load flow optimisation), depending on the device to be integrated. Obviously, full P&A functionality is not achievable in every scenario. Similarly to the smart grid migration path as introduced in [6], a development path should be developed to achieve the goal of P&A step wise. ‘Low Engineering’ concepts are one point on this path. This means to optimise classical approaches by doing as much process steps automatically as possible and only accompany and release them manually.

3 Applications in detail

Future smart grid and smart city solutions have to cope with the advantages and disadvantages of digitalisation and a consistently rising share of generation from renewable energy sources (RES) and ‘new’ load behaviour of e.g. smart buildings. The digitised

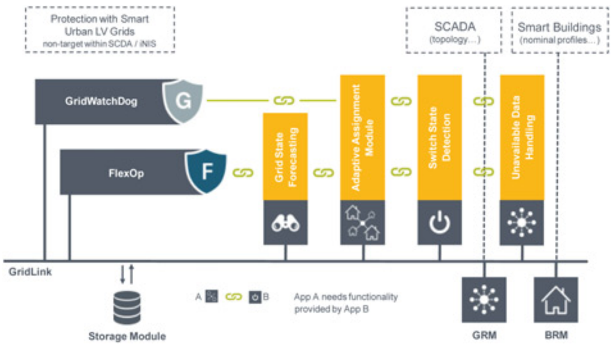

Fig. 1 *Set of applications supporting a P&A approach within an intelligent secondary substation*

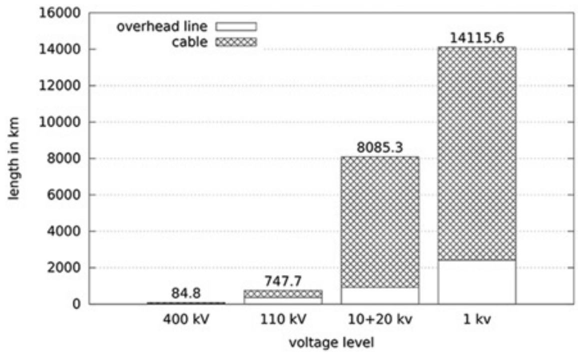

Fig. 2 *Overview line/cable length of Wiener Netze GmbH (as of 2014, [5])*

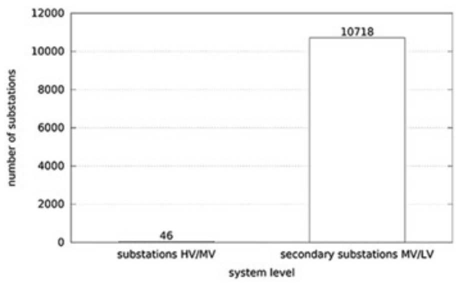

Fig. 3 *Number of Wiener Netze GmbH substations (as of 2014, [5])*

infrastructure together with novel actuators such as controllable inverters, EV chargers, and other facilities within cities and novel services such as pooling and virtualisation allow for demand response on two levels: technical and market-based.

These two classes of measures for the adaptation to the fluctuating generation by RES units can be put into practice by specialised software applications (Fig. 1) operated on smart grid automation devices (e.g. in secondary substations).

Smart grid and smart city applications running on secondary substation level are manifold. Each of these applications is often responsible for only one specific purpose and may operate on distributed nodes in the distribution grid and its supplied nodes.

Taking these challenges into account, the following set of applications was defined demonstrating P&A in the special context of projects SCDA and iNIS. These selected applications validated within the Testbed Aspern are described subsequently.

In the presented solution, all applications communicate over a decentralised distributed message bus, the so-called Gridlink [2, 3].

3.1 Unavailable data handling – UDH

In case a sensor is temporarily unavailable, this unavailable data needs to be substituted by an unavailable data handling module (UDH). Substitution of voltage measurements has already been successfully presented by Schwalbe *et al.* [7], who analysed both topology-based and history-based algorithms. Following the presented approaches, also substitution of unavailable power measurements is envisioned by methods like Kriging [8] or weighted *K*-nearest-neighbour regression.

3.2 Switch state detection – SSD

Many applications (e.g. demand response, load shedding, topology changes) require sophisticated knowledge about the current distribution grid topology. Even though digital representations of topologies can be provided by the DSO in a machine-readable format (e.g. in the common information model – CIM), it is subject to change (i.e. due to manual switches, or triggered fuses etc.). To be able to keep the digital representation up to date with the current grid topology, two switch state detection (SSD) implementations have been elaborated; both of them making use of load profiles collected by distributed sensors in the field (accessible via the GRM).

The first SSD implementation is responsible for topology validation (TOV). From a given CIM representation, TOV extracts the grid topology as a matrix, represented as directed graph, and evaluates the summed power of child nodes with the power of their parent node in a recursive way. By traversing through the whole topology tree, TOV is able to calculate a confidence value based on the Pearson correlation. By comparing the confidence with an adjustable threshold, it is possible to determine whether the given CIM reflects the correct current grid topology or not.

The second SSD implementation – and TOV successor – performs topology identification (TID) based on the load profile's correlation. The TID module holds a set of potential topologies (e.g. provided after previous switching activities). It evaluates all these digital topologies with the current power flow measurements in the distribution grid. By applying the same method like TOV, the TID module is able to calculate a confidence for each potential grid topology and thus, is able to identify the digital topology representation that most likely fits the current grid situation.

3.3 Adaptive assignment module – AAM

The AAM uses similar correlation methods as the two SSD implementations do, with the goal of assigning (e.g. building) nodes to a specific location (node) of the power grid topology, based on their power profiles. In a multistage process, the confidence that a set of given nodes are child elements of a specific set of grid nodes is calculated. Then the nodes are ranked according to these confidence values and assigned to grid nodes, respectively. To validate the result of the assignment of buildings to specific nodes, the sum of the child profiles is compared with the power profile of this node, again by using the Pearson correlation.

For this assignment process, the AAM needs topology information, e.g. provided by a SCADA or GIS system which is, if existing, possibly validated by SSD modules. This information is provided by basic module GRM and consists of element information (e.g. cable, transformers, fuses) and actual switch states. Additionally, AAM needs access to BRM for day-ahead prognoses of nominal power profiles on points of common coupling (PCC) from cooperating smart buildings as well as a forecast of offered flexibilities. Within such a smart building, the building energy management system (BEMS) optimises the power consumption aiming cost minimisation taking the forecasted generation, available storage capacities, flexible pricing, and the user behaviour into consideration. The resulting 'nominal power profile' at the buildings PCC is very dynamic and can hardly be compared with a standard load profile due to its sensitivity to weather conditions and price signals. A local need for flexibility, which could be offered as a service for DSO, will be integrated in cost functions of BEMS internal optimisation.

Beside the schedule information of the active contributor, BEMS for all passive customer nodes profiles have to be build up using historical data.

3.4 Grid watch dog – GWD

The GWD provides SCADA-like functionality in the LV grid. While the module is currently used to monitor the grid, future versions will be able to dispatch control actions to smart grid appliances if certain system parameters (e.g. voltage, current, voltage asymmetry) are not within their required range. The GWD's core is a data stream reasoner. Rules (in the form of declarative logic) can be instantiated on the reasoner. Given that a certain rule is instantiated on the reasoner (e.g. *rule1* is *true* if the measured currents in the grid are above a certain threshold), the GWD will notify the user if the event defined in the rule becomes true. The GWD is connected to the data concentrator, which provides data streams of current grid measurements (active power, reactive power, voltages) into the reasoner. In addition, composite measurements data streams (such as cosö, apparent power, current, phase angles) are generated within the GWD module. In its current version, the used data stream reasoner allows to reason on instantaneous as well as integrated and averaged grid measurements. In addition, rules can be combined with the logical *AND* and *OR* operators allowing for the generation of complex rules.

A REST interface allows a user to dispatch new rules onto the GWD, to manage rules currently deployed on the GWD (activating/pausing/resuming rules), as well as to retrieve information on the currently deployed rules. If a rule fires, the reasoner can dispatch a REST call to a location specified by the user as a notification. In addition, a rule event is published on the Gridlink message bus. This allows other modules to incorporate rule events in their logic and will be used in later versions to include the GWD in an automated system operation process.

3.5 Grid state forecasting – GSF

The GSF allows a restricted view on the expected network loading to obtain accurate information of what will happen in the next 6 h. Additionally, the GSF performs an estimation of the needed flexibility for the forecast period. In principle, the problem is the same as in classical state estimation, but it is based on predicted load and generation profiles and the optimisation problem needs to be formulated in terms of minimum energy that needs to be 'bought' from prosumers, to solve voltage/current problems.

GSF needs to access power profiles of both grid nodes (from GRM) and building nodes (from BRM) as already described for AAM.

After receiving the nominal power profiles, the GSF will validate those and perform a state estimation, by combining the received power profiles with the most recent available measurements. If violations of system boundaries are found, the GSF will calculate solutions for these problems on the basis of flexibilities of the flexibility providing BEMS located in the grid (in the case of ASCR Testbed Aspern the Smart Buildings). It will return suggestions to avoid the estimated grid problems based on calculated sensitivity of voltage and currents to the active/reactive power. The flexibility operator receives flexibility requests from GSF which specify the flexibilities required from each BEMS involved in the flexibility operation process to resolve the estimated grid problems.

Table 1 Functional dependencies of the applications

	UHD	TOV	TID	AAM	GWD	GSF	FlexOp
104	M	M	M	M	M	M	M
storage	M	M	M	M	—	M	M
GRM	M	M	M	M	M	M	M
BRM	M	—	—	M	—	M	M
UHD		I	I	I	I	I	I
TOV	I		M	I	I	I	I
TID	I	—		I	I	I	I
AAM	—	—	—		—	I	I
GWD	—	—	—	—		—	—
GSF	—	—	—	—	—		M

M, mandatory; I, improves operation.

3.6 Flexibility Operator – FlexOp

A FlexOp is a novel grid instance to mitigate LV grid problems using available local flexibilities provided by smart buildings and/or other smart grid installations. As already mentioned, the FlexOp uses the prediction of future grid problems as well as suggested solutions provided by GSF. As the primary communication partner of the BEMS concerning the smart grid interaction, FlexOp operates the flexibility requests. In a first step, the required flexibility is reserved at selected BEMS in order to solve the estimated problem. The GSF provides online updates of the forecasted grid loading, so in some cases, the estimated problems will be solved by increasing forecast quality or due to the fact, that e.g. reserved market offers have not been called. One 15 min step ahead, FlexOp has to confirm the flexibility offer if the problem is still predicted. Therefore, a BEMS as described above has to be able to communicate with the FlexOp and react to new situations and affordances. The aim behind the communication of FlexOp and BEMS is the local trading of intraday flexibilities to avoid violations of limits with a time frame of maximal 6 h.

4 Application interaction and functional dependency

Within this section, the relationships between the P&A applications outlined above are discussed. None of the outlined applications is atomic in the sense that each application requires input from other applications for its full functionality. There are two modules which differ in this respect: the storage module and the IEC 60870-5-104-Stack. The storage module allows other applications to store and retrieve smart grid data, while the '104'-Stack is an information gateway to the field data concentrator and thus, allows for the integration of smart grid data in the applications.

The functional dependencies were already implicitly outlined within the descriptions of the applications in the previous section. Here, the functional dependency of two applications will be outlined in detail.

4.1 Interaction with UDH

When current smart grid data is retrieved via the 104-Stack, it will be automatically stored within the storage module, allowing other applications to access the information at a later point in time. Given that the data received via the 104-Stack can exhibit gaps, the unavailable data handling (UDH) module is used to substitute missing measurements and thus, to increase data quality. UDH improves both live and stored data and any application using this data.

4.2 Interaction with TOV

In order to perform a TOV, historical smart grid data (received via the 104-Stack and subsequently stored by the storage module) is required. In addition, this process requires a current grid topology which is provided via the GRM and the storage. While this information is mandatory to perform a TOV, the additional application of UHD can improve the TOV performance as it will pre-process and mend incoming smart grid data, thus improving the data quality for applications depending on historical smart grid data.

The dependencies of the other applications can be found in Table 1. It should be noted that some applications are mandatory (M) in the context of other applications, whereas other applications are not required per se but improve an applications performance (I).

The functional dependency of all the applications outlined in Table 1 must also be resolved during the provisioning process in order to guarantee the applications availability for use after installation.

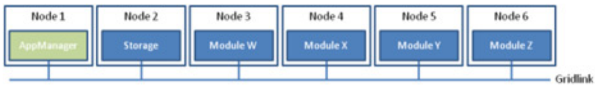

Fig. 4 *Current solution with one module per node*

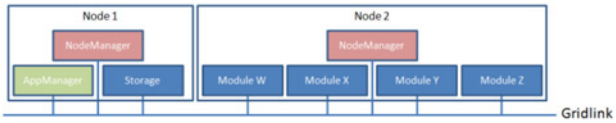

Fig. 5 *Solution with multiple modules on one node*

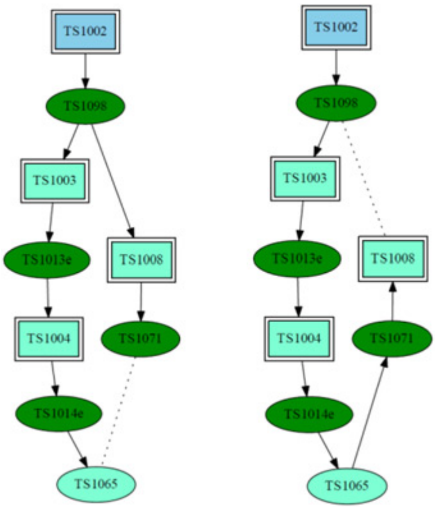

Fig. 6 *Valid (left) and an invalid topology (right)*

5 Performance issues

For optimal results, taking all dependencies into consideration, a high number of applications have to be executed simultaneously. To enable highest flexibility concerning requirements and dependencies, the first approach a full JVM (Java Virtual Machine) instance is used for each module (Fig. 4), i.e. for each module, a new process is initialised. This introduces a high memory overhead for small modules, requiring resources that cannot be provided by the restricted embedded hardware in use.

Therefore, a NodeManager module was developed allowing multiple modules to run on the same node, and thus in the same JVM instance (Fig. 5); consequently, preventing high overhead for functionally small modules.

6 Field experiences

This chapter presents some experiences from the TOV application in the field.

To show the correct behaviour of the TOV, two different topologies are used, the left side of Fig. 6 depicts a segment of the valid topology of the testbed, whereas the right side shows the grid after a switching procedure. In both figures, a dotted line represents an open connection between two nodes and a solid one a closed connection. The rectangles illustrate the grid monitoring devices and circles represent lines and busbars between them. Obviously, the monitoring device *TS1008* is a child of *TS1002* in the left side of Fig. 6, whereas it is connected to *TS1004* on the right side. The corresponding power profiles of these grid monitoring devices are shown in Fig. 7 (recorded from 1 November 2016 until 7 November 2016 every 150 s).

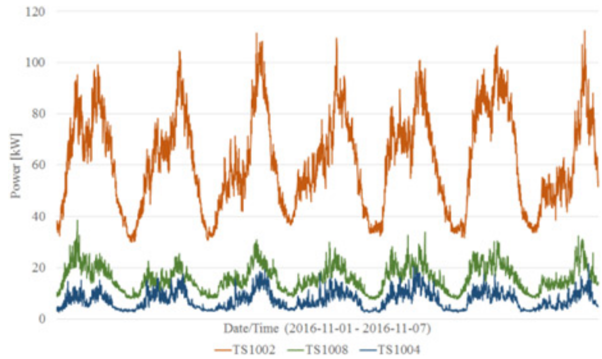

Fig. 7 *Power profiles of three grid monitoring devices*

The TOV is executed for both topologies and – as expected – the result for the invalid topology ($r = 0.695$) is less than the result of the valid topology ($r = 0.862$). For the TOV, a period of 1 month was used. The results will still be valid for shorter periods, but it might lead to some non-meaningful outputs if the period is too short.

7 Conclusion

In this paper, we proposed a P&A approach that solves the challenge of high configuration and maintenance efforts in distribution automation for smart grid and smart city applications and serves as a foundation for automated application operation on thousands of automated, mostly secondary substations. We presented a set of developed applications and how they interact, as well as first field experiences. During the next months, the remaining applications will also be deployed and validated within the Testbed Aspern.

The presented and already deployed P&A features (e.g. remote application deployment, automatic configuration) have proven extremely useful in the field evaluation. It can be anticipated that the proposed system environment meets future requirements of LV distribution automation and supports multiple innovative applications.

8 Acknowledgments

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