Exploiting Software Performance Engineering Techniques to Optimise the Quality of Smart Grid Environments

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ABSTRACT

This paper discusses the challenges and opportunities of Software Performance Engineering (SPE) research in smart-grid (SG) environments. We envision to use SPE techniques to optimise the quality of information and communications technology (ICT) applications, and thus optimise the quality of the overall SG. The overall process of Monitoring, Analysing, Planning, and Executing (MAPE) is discussed to highlight the current open issues of the domain and the expected benefits.

Categories and Subject Descriptors

C.4 [**Performance of Systems**]: Modeling techniques

Keywords

Smart grid environment; software performance engineering; quality optimisation

1. INTRODUCTION

An intelligent power distribution system, Smart Grid (SG), is a modernized electrical grid that uses information and communications technology (ICT) to gather and act on information in an automated fashion to improve the efficiency and economics, dependability and security, and resilience of the whole life cycle of electric energy[1] from generation and transmission to distribution and consumption of electricity [13]. SG is a term used to describe the broad scope of interdependent systems where ICT plays a crucial role that will bring significant economical and environmental benefits to consumers, organisations and countries deploying ICT-intensive SG technologies.

SG environments are complex, real-world aware systems of systems that must integrate and interoperate across a broad spectrum of heterogeneous business and operation domains involving multiple enterprises and customers. Numerous technological innovations will be required to enable smart grid environments. These innovations will come from multiple fields and disciplines including real world aware systems of systems, modelling, analysis, optimisation, security, silicon technology, and physical science [10]. Existing deployments of SG technology (e.g., Grid4EU[2] and SmartWatts[3]) operate only with few participants. However to meet the requirements for large scale deployments we have to evaluate in advance scalability of these technologies and ability to provide required processing capabilities. An estimation in [11] indicates that an overwhelming data would be generated by Smart Meters (SMs), 22GB of data per day from 2 million customers with 30s measurement rate per each SM.

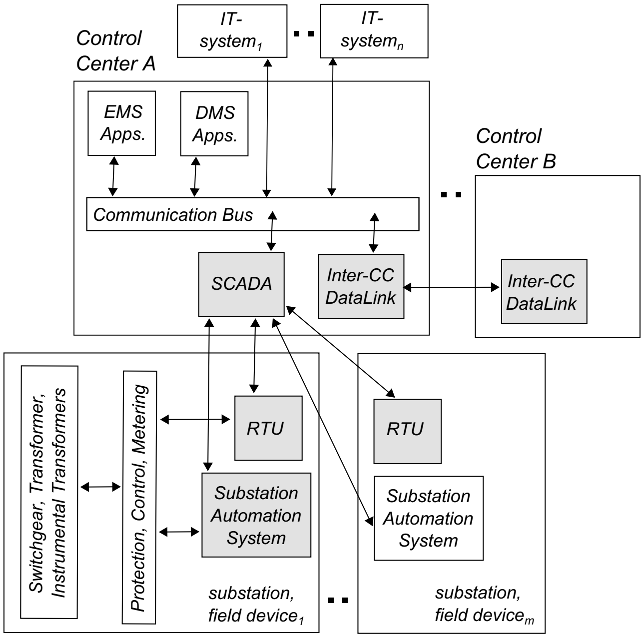

Figure 1: Smart grid environments - basic concepts.

In this paper we focus on ICT aimed at facilitating the distribution of power energy to improve the management of

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[1] Electric energy is called just "energy" throughout this paper. We also use the common terms "produce (electric) energy" and "consume (electric) energy" etc. while it is clear that energy is never created or lost, but always just converted to other forms of energy.

[2] http://www.grid4eu.eu

[3] http://www.smartwatts.de

ICPE'15, Jan. 31–Feb. 4, 2015, Austin, Texas, USA.

http://dx.doi.org/10.1145/2668930.2695532.

smart grid supply and demand. In particular we are interested to evaluate the quality of smart grid environments that brings novel challenges to the power grid engineers, such as the assessment of the suitable architecture that fits the metering system requirements (size and rate of measurement messages) or the tradeoffs involved to efficiently engineer the power distribution when of example the goal is to reduce the large-scale deployment cost.

Figure 1 reports the basic concepts [1] of an SG environment we target in this paper: (i) control centers (CC) need to handle unprecedented operational demands, (ii) substation field devices include remote terminal units (RTU) and substation automation systems that communicate with SCADA (system control and data acquisition). Goal of this paper is to provide a vision of the ICT challenges and opportunities of research in the area of designing high-quality SG environments. In particular, we envision to evaluate how the use of software performance engineering (SPE) techniques [12] can contribute to optimise the quality of ICT in SG environments. The MAPE (Monitoring, Analysing, Planning, and Executing) process is introduced to highlight the current open issues of the domain and the expected benefits.

The paper is organised as follows. Section 2 presents related work. Section 3 reports the challenges the SG domain entails, Section 4 discusses our vision towards the optimisation of SG environments. Section 5 provides our conclusions and plans for future research.

2. RELATED WORK

This section reports the surveys on smart grid communication infrastructures where motivations, requirements and challenges (in the context of optimising the quality of smart grid environments) have been sketched.

In [14] emerges the necessity of a control system and particularly a communication infrastructure that must be designed to adjust the performance metrics on the basis of the energy production as well as of the power distribution. Smart grid environments are required to meet the ever increasing efficiency challenges by harnessing modern information technologies to enable a communication infrastructure that provides monitoring and control capabilities.

In [5], smart grid security challenges are discussed. Such challenges basically concern the protection of smart metering data against unauthorized access and repudiation. Security solutions are required on different levels: end to end secure communication protocols need to be used, hardware components (e.g., smart meters) need to withstand physical attacks, the grid needs to detect forged/hacked components, etc. Hence, it arises the common challenge to design a system that will balance the trade-off between security and performance, i.e. use adequate security strength while minimizing its performance and cost overheads.

In [10] the quality-of-service (QoS) is highlighted as a cross-cutting issue of a grid-wise interoperability framework, and the monitoring of power distribution is indicated as an emerging area that will gain in importance as the fraction of renewable energy into the grid increases. Current monitoring systems must be adapted to become reporting systems performing prediction and optimisation functionalities.

Our previous work in smart grid environments includes the following contributions: (i) in [3] we proposed a methodology to assess the impact of different system parameters on the survivability of distribution automation power grids; (ii) in [7] we presented a mapping from a common information model to a holistic survivability analysis which allows to predict the survivability of distribution circuits with respect to power equipment and communication failures; (iii) in [9] we introduced a phased recovery survivability model that allows to assess the effect of backup power, demand response programs and effectiveness of distributed generation on survivability metrics.

3. SPE CHALLENGES OF THE SMART GRID

In this section we collect the challenges for SPE in the context of SG environments. We have identified three areas of issues that make the SG a particularly challenging domain for SPE, namely (a) that SG systems span multiple domains, (b) that SG systems are critical infrastructures, and (c) that SG systems are data intensive systems, as explained below.

Systems span multiple domain. The overall SG system covers a multitude of domains, from the physical generation, transmission and distribution of energy (governed by the laws of electromagnetism and analysed using differential equations) to the prediction of human end user demand and their response to incentives such as price signals. In many of these domains, timing is an issue but it is not feasible to capture all these timing aspects in an overall timing model. Thus, the challenge is to meaningfully decompose the system into scenarios amenable to timing analysis and in particular, for us as SPE researchers, to identify and delineate the scenarios related to software performance.

In doing so, the main challenge is to define the border of such scenarios. When studying the performance of control centre systems (cf. Fig 1) we need both to (1) capture the workload of the surrounding SG system properly and conversely (2) investigate what the impact of the determined software system performance is on the rest of the system. In particular, for the impact of the software system performance on the rest of the system, it is important to determine whether transient behaviour of the software part are relevant as well. Here, it may be the case that (a) any violation of a response time threshold may lead to undesired effects in the rest of the system (hard real time), that (b) certain amount of violation can be tolerated (e.g. in only 95% of cases within a defined time window the response time needs to be below the threshold (e.g. soft real time, firm real time, or due to user expectations) or that (c) only the average is relevant and no transient behaviour needs to be analysed.

For example, regarding metering and aggregation of data in substation automation systems, real-time monitoring of electricity usage permits accurate analysis of demands and allows to plan for higher efficiency in energy consumption dependent on real-time pricing. The SG technologies operate dependent on a huge number of meters and sensors and these synchronised technologies include fault detection systems (i.e., Fault Location Acquisition Reporter) or real-time monitoring systems (i.e., Phasor Measurement Units) using precision time down to microseconds.

Systems are critical infrastructures. As smart grids systems are critical infrastructures, the quality characteristics reliability and security are highly important. Performance is related to all these properties as performance degradation is often an indicator of system instability. Thus, additional performance requirements and scenarios may be derived from reliability, security, and cost requirements. This is most evident for reliability, where, on the one hand, the failure of a system to react in a certain time span may cause additional failures (as described above) but also, on the other hand, where failure scenarios such as electrical equipment failure might lead to changed workload conditions for the control centre systems. If the control centre systems in such contingency cases are not able to handle the workload, this might cause a propagation of the failure to other areas of the SG. As well as metering measurements collected by control centre and substations or other devices actually substitute the heart beat signalling and are used for fault detection.

For example, a disruption of multiple power lines due to a storm might cause sudden changes in the available generated power and its price, so that smart meters in the affected area (which are a special kind of field devices not shown in Fig. 1) might need to communicate intensively with the control centre to renegotiate and optimize their power consumption contracts. Furthermore, analysis results how well the control centre systems perform provides feedback to failure propagation analysis.

Also in security scenarios, performance is relevant. For systems running with constant load a performance signature for diverse attacks (e.g., DOS, MITM or SQL injection) can be identified. On the one hand, intruders might try to mask their attacks by causing more traffic in the system, causing workload that is higher than expected. Thus, attack prevention strategies might lead to additional performance requirements and scenarios. Similarly strategies using performance tests can be developed to detect or harden system against security attacks.

For example, forged signals being sent to a SCADA system need to be detected quickly enough so that the system does not become instable or at least to minimize the impact of the attack (and the potential blackouts), as e.g. considered by Esfahani et al. [4].

Systems are data intensive. As smart grid systems aim to optimize power generation, transmission, and distribution on all levels, enormous amounts of data will potentially be generated, transmitted, and analysed. Here, there is a trade-off between accurate analysis of the system state and performance. Perfectly accurate analysis and load prediction might require to transmit and analyse the detailed consumption patterns of individual houses or even devices. However, the increased processing effort of such detailed data may not pay off and it might be more desirable overall to aggregate the data in a meaningful fashion. Of course, another reason to avoid such detailed data are privacy concerns, which we do not discuss here further. To estimate the effect of more detailed or less detailed data on the sizing of the control centre systems and the networking infrastructure, performance prediction approaches are required. For SPE, we see an additional challenge in that many SPE methods and tools focus on control flow, less on data flow. Enhancing SPE methods and tools by models for data flow might be required to make them applicable for this challenge.

For example, SCADA systems collect the information about the state of the grid and in relation to data logging all data must be time stamped (performed by RTU within few milliseconds) in order to determine the correct sequence of events. With the granularity and scale of the future SG to provide for this operation the ICT challenges and synchronisation among diverse SG operations are much more complex.

4. RESEARCH VISION

This section discusses our vision to use SPE techniques to optimise the quality of ICT applications, and thus optimise the quality of the overall SG.

As stated in Section 3, SG systems are data intensive and critical systems that span on multiple domains, hence ICT applications need to manage a huge amount of data over heterogeneous devices and networks. As outlined in [8], there exist several challenges and needs to improve the quality of SG environments, such as new materials and alternative clean energy sources, advanced power electronics and devices, advanced computing and control methodologies, intelligent technologies, etc. It is unrealistic that ICT applications can automatically embed these techniques, human intervention is needed to design and validate the SG technologies and devise the refactorings that can be applied.

Figure 2 reports the MAPE process [6] at work in SG: an inner loop is identified to deal with ICT applications that can be automatically reconfigured with a set of pre-defined and non-invasive refactorings (e.g. the redeployment of a software component), whereas an outer loop is meant to consider the human intervention in the optimisation process (e.g. add a server for the SCADA system). The basic activities of the MAPE process are: (i) Monitoring, i.e. the most relevant energy-related services of software systems are monitored; (ii) Analysing, i.e. the QoS status of software systems is estimated to predict in advance their processing capabilities; (iii) Planning, i.e. if energy-related services suffer or will suffer from poor performance, then design alternatives are devised and compared; (iv) Executing, i.e. the selected design alternatives are actually realized to improve the processing capabilities.

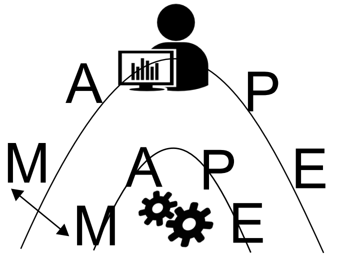

Figure 2: MAPE process at work in SG.

The monitoring activity is of key relevance and it is shared between the inner and the outer MAPE loop (see Figure 2): we aim to collect all the knowledge that help us to build a set of software models for the ICT infrastructure underlying the SG. Since SG are data intensive systems, as anticipated in Section 3, such software models need to embed not only the control flow but also the data flow is relevant. In fact, the data flow may influence the behavioural patterns of energy-related services that may include the possibility to aggregate data with different strategies. All these features need to be modelled to better characterise the software systems and its quality properties. Besides this, we also assume that the software models include the available hardware resources, i.e. platforms deploying energy-related services and communication networks along with their features, e.g. processor speed, network rate, etc.

Since SG systems span on multiple domains, it is necessary to identify a set of energy-related services of software systems that contribute to the quality of SG. For example, substation automation systems (see Figure 1) are aimed to provide protection, control, and metering of data while guaranteeing a high efficiency of the substation field devices. Real-time monitoring of these services help to identify their characteristics as well as the workload to which they are subjected thus to figure out the needed software and hardware resources of systems implementing such services.

Due to the complexity of SG systems, that include the physical generation, transmission and distribution of energy, the energy-related services are subjected to high variable, non-stable, and usually bursty workloads. In fact, natural factors (such as the wind or the sun) affect the expected energy generation, and consequently its transmission and distribution. Furthermore, natural disasters (such as a storm) suddenly require an higher energy provision depending on the criticality of the event to manage. Therefore, the real-time monitoring need to be further detailed with some contextual information (e.g. catastrophic event happening) of SG, thus to provide lower and upper bounds approximating the variability of workloads. In this way, we are able to evaluate scalability issues of ICT applications.

In order to apply model-based performance prediction techniques it is necessary to annotate the software model with quantitative data, i.e. the demand of software services (e.g. the number of requests to cpu/disk devices) as well as their usage (e.g. the number of service invocations). Furthermore, it is necessary to specify the required quality properties (e.g. the reliability of a software component, the confidentiality of some data). In fact, SG systems are critical infrastructures and other quality characteristics (such as reliability, security, and costs) are highly important and must be evaluated. In this way, the values of performance indices coming from the solution of the initial software model can be compared to the ones obtained for the same model: (i) without considering other quality properties, (ii) with different design alternatives improving other quality properties (e.g. reliability, security) and (iii) even with different design alternatives improving the same quality property. Such comparisons help software engineers to quantify the impact of improving other quality properties while meeting performance requirements.

Our goal is to consider multiple quality criteria of SG (such as reliability, security and costs), thus to support trade-off decisions and use multi-criteria optimization methods [2].

5. CONCLUSION

In this paper we envision the usage of SPE techniques for the ICT infrastructure underlying SG thus to optimise its quality. We identified challenges of SPE in the context of smart grids. First, smart grids span multiple domains, so it is necessary to collaborate between such different domains to identify the relevant performance scenarios. Second, smart grids are critical infrastructures, so the connection to other dependability attributes such as reliability and security should be considered. Third, smart grids are data-intensive systems, so models will need to consider data flow as well. Monitoring, Analysing, Planning, and Executing (MAPE) activities are discussed to highlight the current open issues of the domain and the expected benefits. We showed that ICT applications built for SG environments offer very promising challenges for SPE research.

As future work we plan to include the experience gained by SG experts, as this additional knowledge contributes to improve the MAPE process. Finally, SPE techniques must be experimented in real-world smart grids in order to assess their benefits.

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