Environmental Modelling & Software 56 (2014) 37–51

Contents lists available at ScienceDirect

Environmental Modelling & Software

journal homepage: www.elsevier.com/locate/envsoft

Designing dependable and sustainable Smart Grids – How to apply Algorithm Engineering to distributed control in power systems☆

Astrid Nieße [a,*], Martin Tröschel [a], Michael Sonnenschein [b]

[a] OFFIS – Institute for Information Technology, Division Energy, Escherweg 2, D-26121 Oldenburg, Germany
[b] Department of Environmental Computer Science, University of Oldenburg, D-26111 Oldenburg, Germany

ARTICLE INFO

Article history:
Received 21 May 2013
Received in revised form
2 December 2013
Accepted 2 December 2013
Available online 6 January 2014

Keywords:
Smart grid
Distributed algorithms
Smart grid simulation
Scenario design
Information technology
Process model

ABSTRACT

In this work, we present the Smart Grid Algorithm Engineering (SGAE) process model for application-oriented research and development in information and communication technology (ICT) for power systems. The SGAE process model is motivated by the main objective of contributing application-oriented research results for distributed control concepts on a sound methodological background. With this process model, we strive for an engineering aspiration within the domain of Smart Grids. The process model is set up with an initial conceptualisation phase followed by an iterable cycle of five phases with both analytical and experimental parts, giving detailed information on inputs and results for each phase and identifying the needed actors for each phase. Simulation of large-scale Smart Grid scenarios is a core component of SGAE. We therefore elaborate on tooling and techniques needed in that context and illustrate the whole process model using an application example from a finished research and development project.

1. Software availability

The Smart Grid simulation framework mosaik is available for researchers within their PhD projects on request. More details are given at http://mosaik.offis.de.

2. Introduction

Smart Grids are expected to enable flexible, accessible, reliable and economically attractive electricity networks (SmartGrids European Technology Platform, 2010). Following this definition, control systems for Smart Grids should additionally enable the integration of high shares of renewable energy resources and thus contribute to a sustainable transformation of the power system, taking into account the effects of information and communication technology (ICT) itself (Hilty et al., 2006). The transformation of the existing power generation to renewable, distributed generation implicates an increase in complexity for the control of the overall system, as control methods have to cope with many individually configured, distributed, small generation units as well as with fluctuation in their feed-in depending on meteorological conditions.

Distributed control methods, such as self-organizing multi-agent systems, are a very promising approach to address both technical (flexibility, accessibility, reliability) and economic requirements for Smart Grids relying on distributed generation and demand-side management (Kok et al., 2005), (Penya and Jennings, 2008), (Lehnhoff, 2010), (Ramchurn et al., 2011), (Nieβe et al., 2012). Although some approaches are already under test in field trials, distributed control methods for Smart Grids are still subject to application-oriented research, not (commercial) software development. To facilitate the transition to the field however, a methodologically sound engineering process model that guides this way from the beginning is essential.

Smart Grids up to now lack such a standardised process model, but developments regarding standardisation are under way: with the Smart Grid Architectural Model (SGAM) a first conceptual framework has been defined in 2008, including a use case based methodology to manage the requirements engineering process (International Electrotechnical Commission, 2008), (Trefke et al., 2013). Use cases as a well established instrument from software engineering describe a system's intended behaviour, defining actors and system interactions as sequences of actions with the required intermediate results. The use case based methodology

☆ Thematic issue on Modelling and evaluating the sustainability of smart solutions.

* Corresponding author.
E-mail addresses: niesse@offis.de (A. Nieße), troeschel@offis.de (M. Tröschel), sonnenschein@informatik.uni-oldenburg.de (M. Sonnenschein).

1364-8152/$ – see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.envsoft.2013.12.003

maps a use case to the SGAM in several steps starting from a functional view, yielding refined requirements on the system to be developed for each layer. This model focuses on application development, with the involved parties being aware of the system's intended behaviour. As this does not hold for application-oriented research, this methodology is not applicable: for complex systems like Smart Grids, a process model is needed in order to actually define the systems' intended behaviour in a preliminary phase.

Within application-oriented research as a preliminary step to (commercial) software development, process models are less common than in commercial software development. A widespread process model in information technology is design science (Hevner et al., 2004). Design science is a general framework for the design and evaluation of any artefact in an arbitrary application domain. It introduces explicit steps for the description of

- the artefact with respect to a given research question,
- a design process (search heuristics),
- a grounding in a knowledge base,
- the type of evaluation,
- the kind of introduction of the artefact into the real world,
- the input to the knowledge base.

For specific artefacts at least the actual design process as well as the intended type of evaluation have to be refined. If the artefact is an algorithm, Algorithm Engineering (Sanders, 2009) as a process model for scientific algorithm development can be applied. Algorithm Engineering is a general model for the theoretical research on and development of algorithms, focussing on performance and complexity of algorithms. It is explicitely invariant to the application domain and therefore does not yield application-specific performance information. We therefore claim the need for a domain-specific extension of Algorithm Engineering for researching on and developing of Smart Grid control concepts – Smart Grid Algorithm Engineering. We derived the relevant topics to be considered for this extension from our experiences during many years of work in this field. While we do not imply any claim for comprehensiveness, we aim at developing a process model that solves the most relevant issues regarding application-oriented research on Smart Grid control algorithms. Therefore, we understand a later refinement of the process model itself as an iterative process. The list of topics considered for an extension of Algorithm Engineering comprises:

- *Smart Grid knowledge:* We aim at developing control concepts for the field and therefore have to be aware of the relevant legal and technical constraints regarding the real-world implementation from the beginning.
- *Dependability analysis*: The Smart Grid is a mission-critical system. We therefore have to consider dependable system behaviour, e.g. defined runtime behaviour, a priori.
- *Simulation models*: As we cannot perform experiments in the field for mission-critical systems like Smart Grids, the evaluation of control concepts under development can be performed only based on (large-scale) simulation studies.
- *Scenario design and usage*: We want to consider the applicability and domain-specific performance of control concepts in different contexts, represented by different scenario designs during simulation.
- *Knowledge management*: With personnel in research institutes and universities usually leaving to academia or industry after some years and new scientists following from universities (usually with disciplinary knowledge from the application domain), knowledge management is a big issue to achieve continuity.

In this paper, we therefore propose a domain-specific extension and refinement of Algorithm Engineering – a methodical combination of algorithmic research and engineering – as an engineering approach for the design of ICT-based control in power systems. First, we derive some key requirements for a suitable engineering approach regarding the above defined topics using the Smart Grid Architecture Model (SGAM). Following that, we discuss simulation as a key component especially for an experimental assessment of Smart Grid control systems, and we give some methodical background on the design of both Smart Grid scenarios and simulation-based experiments. We then introduce the concept of Algorithm Engineering and elaborate on our domain-specific extension, Smart Grid Algorithm Engineering. We conclude this paper with a discussion on the benefits of our approach, problems encountered in using this model and necessary extensions.

3. Requirements for a distributed Smart Grid control algorithms engineering approach

We rely on the Smart Grid Architecture Model (SGAM) as a reference design for Smart Grid systems to derive general requirements on how to adapt Algorithm Engineering to the Smart Grid domain (see Fig. 1). We first give an overview on the SGAM, after that map relevant topics within the research area of Smart Grid control algorithms to the layered view of this conceptual model and then derive requirements on the process model from this view.

The main issue addressed by the SGAM is interoperability of software and automation systems from business applications down to components in the field, each with specific interface requirements. The SGAM has been introduced by three European standardisation organisations (CEN, CENELEC, ETSI) as a result from the European standardisation mandate M/490. Volunteers from industry and manufacturers have been heavily involved in the process of defining the SGAM. Their common interest is to setup a reference architecture that facilitates the development of interoperable component interfaces, thus reducing costs and engineering overhead after deployment to the field. As already pointed out in the introduction, the SGAM can be regarded as a first step towards a standardised process model for system development in the Smart Grid.

On the domain dimension in the SGAM, the energy conversion chain from bulk generation down to the customer premises is depicted (see Fig. 1). The domain of distributed energy resources (DER) on the distribution level is integrated in this dimension. The management systems for each level form the second dimension of different zones, emphasising the different hardware, IT systems and actors involved from market down to field and process zone. In the station zone for the distribution grid domain for example, automation and protection systems in substations would be allocated. The plain formed by these two dimensions, domains and zones, is combined with the different abstraction levels from business level down to the communication and component layer as interoperability dimension. The different layers represent rising interoperability requirements for applications crossing the layer boundaries: communication with components in the field is a basic functionality for Smart Grid applications, thus it can be found on the lower component and communication layers. Modelling of information using standardised data models is a precondition of higher business functionality depicted in the upper levels, therefore the information layer can be found inbetween these layers (International Electrotechnical Commission, 2008). IT-based voltage control at a substation may serve as an example: depending on the current operational state of the underlying power grid, measurements in the connected higher voltage level grid and prognoses for both, a