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Analyzing an agile solution for intelligent distribution grid development: A smart grid architecture method

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Abstract—The design of future electricity markets requires Distribution System Operators (DSOs) to emerge as an active player by implementing advanced technical solutions which improve their market responsiveness, process adaptability and meet their business needs. This paper presents a methodology that helps DSOs carry out such a complex task. The proposed methodology enhances the Smart Grid Architecture Model (SGAM) framework in the context of transactive energy and multi-agent system (MAS). The proposed method is referred to as agile methodology because it made the SGAM architectures Adaptive, Goal-oriented, Intelligent, Linked and Expandable (AGILE). It is implemented using an object-oriented application that facilitates the analysis of agility in the network management.

Index Terms—Agility, Distribution system, Network management, Multi-agent system, Smart Grid, Transactive energy.

I. INTRODUCTION

The transformation to a smart grid is a crucial step in this century and is supported and accompanied by regulations to encourage a reduction in energy consumption and investment in intelligent infrastructure. One prominent example is the European Union effort to reduce greenhouse gas emissions by 20% compared to 1990s and increase the share of energy produced to 20% by 2020 [1]. However, this vision has led to new challenges on electric distribution systems. For example, the distribution networks should be able to integrate Distributed Energy Resources (DERs), Electric Vehicles (EV), or Demand Response (DR), while guaranteeing the quality of supply to customers at a cost-effective price. To address these challenges, numerous solutions have already been proposed as well as efforts have been made to standardize such solutions [2]. Therefore, in the current scenario, DSOs have an increasing need to analyze these solutions and standards and decide a complementing paradigm that should be used in their automation and management systems to meet the Smart Grid requirements, while optimizing the investments.

This paper presents a methodology that helps DSOs to cope the upcoming challenges. The methodology makes it easier for DSOs to decide which control mechanisms, DR solutions, and standards should be implemented to achieve multiple objectives in their systems. The methodology is based on the Smart Grid Architecture Model (SGAM), which is a reference framework defined by EU Mandate M/490's Reference Architecture working group for representing Smart

Grid architectures [3]. Until recently, the SGAM has been used mainly by standardization bodies to identify standardization gaps [4]. In this paper, the SGAM has been enhanced for enabling DSOs to analyze Smart Grid architectures, while taking into account their objectives. The proposed enhanced model is referred to as an agile methodology.

Further, the research revealed that the future electricity market models of the smart grid are yet to be established. There is no agreed-upon standard for DR paradigm. Specifically, in Europe, there are developments about the future market model but standardization in parts of the smart grid is still at premature stage. Based on these facts, the proposed methodology also provides interoperability towards a reference specification, thus expecting to improve the market responsiveness of the DSO.

This paper is organized as follows: section II presents the literature related to the proposed methodology proposed. The section III presents the SGAM-based approach, and then it briefly analyze the network management which support in the development of tool for the methodology. section IV focuses on the implementation of the methodology by using object-oriented programming. Finally, section V concludes the paper and provides an outlook on future work.

II. LITERATURE OVERVIEW

The section provides a review of the existing control mechanisms, advanced technologies, and approaches to achieve multiple objectives that DSOs essentially require to define the functional requirements of the system under design.

A. Control Mechanisms

Research in control mechanisms used by DSO for network management is strongly interdisciplinary, involving the state-of-the-art in power engineering, computer science, economics and control engineering. Table I presents the selected research that assesses the transition of the present trends to an innovative market-based mechanism (referred to as transactive energy). It has been inferred from Table I that an agent-based transactive control mechanism (TCM) is a solution to improve market responsiveness as well as to cope complexity induced by the system. Herein, the discussion is extended for TCM by describing its attributes, which are necessary for DSO to emerge as an active player in future market models.

In TCM, DSO has the right or freedom to override DR by altering explicitly or implicitly a control-space of an

Table I: Descriptions of control mechanisms in view of system organizations verses DR control strategies.

		Organization			
		Decentralize	Centralize	Hierarchical	Hybrid
Controls	Frequency based
	Direct load	Short et al. [5]; Mallada et al. [6]	Pourmousavi and Nehrir [7]; Trovato et al. [8]	Vrettos et al. [9]	
	Forecast based	Essakiappan et al. [13]; Hanif et al. [14]	Wang and Tang [10]; Georges et al. Georges et al.; and Xue et al. [12]	Lampropoulos [15]; Long et al. [16]	
	Price based		Gyamfi et al. [17]	Wang et al. [18]; Yoon et al. [19]	
	Incentive based	Elmenreich and Schuster [20]	Farahani et al. [21]; Babar et al. [22]	Babar [23]	
	Market based	Negnevitsky et al. [24]; Torbaghan et al. [25]		Peppink et al. [26]	Haque et al. [27]
	Transactive		Yue et al. [28]	Kok et al. [29]; De Craemer [30];	Babar et al. [31]; Babar [32]

aggregator/prosumer, which represents dispatchable loads and generations in the system. The control-space, which is a set of variables, is specific to primary process parameters of dispatchable loads and generations. Moreover, DSO and every aggregator/prosumer in TCM should communicate value-propositions (i.e., a bids/ schedules) with each other within a defined time horizon. The value-proposition does not necessarily reflect actual energy price used for revenue and billing purposes. However, it may consist of control parameters or energy costs or both that should be weighed relatively in the form of a local normalized currency.

Furthermore, TCM empowers DSO to make its value-proposition to aggregators/prosumers for DR in real-time. In general, the TCM empowers DSO such that it can dispatch demand continuously, not merely for a few critical stressed periods of the year. In addition, TCM is an open platform, such that it allows multiple communication media, protocols, and vendors to coexist and compete. Together with hierarchical design, it also offers reduced overall communication bandwidth due to a reduction in an amount of information flowing throughout the hierarchy.

B. Multiple Objectives

The network management in future market models has been influenced by the operational objectives and DR benefits, which value most for the design of active DSO. Among the most important are:

1) *Demand Elasticity*: It is about the responsiveness of DERs to the changing environment. By applying demand elasticity, more efficient network behaviors can be achieved in the short term, and the system can be better balanced in the long term [33].

2) *Demand Flexibility Schedule*: It referred to a system efficiency by deferring, pre-empting or both the use of dis-

patchable loads to achieve objectives (like cost minimization). Moreover, it facilitates the consumption of DERs. For instance, the charging of electric vehicles (EVs) or storage can be altered to mitigate congestion [34, 35].

3) *Demand Flexibility Dispatch*: It mitigates operational constraints by dissuading the consumption if served power threatens to damage or shorten the asset's life time. For instance, in the case of over-voltage or unpredicted congestion, DSO should be permitted to incentivize aggregators/prosumers when the local constraint is violated. In this way, the incentivization persuaded aggregators/prosumers to either use less power from or provide distributed generation to the system. [27, 31] provides an application of demand flexibility dispatch for congestion management.

C. Agent Technology

Currently, agent technologies are emerging because they offer flexibility, distributed, openness, responsiveness, redundancy, and scalability. To achieve a combination of goals concerning multiple objectives of a DSO, agents in the MAS are organized in strategic layers. Within these layers the MAS allows the agents to share the strategic objectives and knowledge about the environment explicitly. Each agent in a layer showed coordination but limited to a particular strategic process, technology, and local process parameters.

There are numerous works in the field of DR which use the Multi-Agent System (MAS) for demand flexibility acquisition, scheduling, and dispatch. A spatially distributed hierarchical control architecture is discussed in [26, 27, 28, 29, 30], that incorporates the network reconfiguration possibilities along with market-based flexibility. The presented MASs determine optimal dispatch of a grid-connected DERs and dispatchable home appliances (referred to as domotics) providing flexibility services to the market and the network. In this way, DSOs can take

actions shortly after the congestion has perturbed the network or DSOs can act proactively to cope the network issues or both.

III. AGILE METHODOLOGY

The methodology proposed in this work is aimed at helping DSOs decide which new solutions should be complement in their systems. The methodology comprises two steps: Enhancing SGAM architecture to achieve agility in network management and its step-wise analysis.

A. Enhancing SGAM architecture

Many relevant studies, as mentioned in Table I, provide MAS based intuitive high-level framework for representing DR solutions. For such frameworks, SGAM was introduced to identify interoperability issues in systems under design [4]. The agile methodology enhances the SGAM by introducing multiple intelligent agents, coordinating in a hybrid fashion to achieve multiple objectives.

In the SGAM, if agents and their objectives, strategies, and interactions are design carefully, a DSO can be leveraged to achieve three prime goals of agility (i.e., the improved responsiveness, the process adaptability and the customer enabling). The improved responsiveness in agility is initially a concept which realizes the primary processes through the advanced technologies. The empowerment of DSO in agility is a way of integrating the DERs uncertainty in the design. Instead of minimizing uncertainty with detailed requirements and specifications, agility enables the DSO by taking feedback or preferences on a predictable timeline from the grid. However, the process adaptability in agility is a method that combines an iterative and incremental learning in the strategic processes with a focus to increase total social welfare of the community. Therefore, in agile methodology, as shown in Figure 1, each agent possesses a strategy to achieve single or multiple objectives continuously.

The architecture is hybrid due to two main reasons. Firstly, agents across different strategic layers possess different goals and objectives. In this way, each agent performs its tasks nearly autonomously and communicate via the hierarchical transactive control. Secondly, the architecture can readily partition tasks or workloads among agents at the same layer in a distributed fashion. Thus, the interaction between the agents is mapped to explicit mechanisms for peer-to-peer communications. Agent(s) showed agility but limited to a particular strategic process, technology, and customer retention. As shown in Figure 1, for an agent in a layer, the customer enabling is based on its knowledge about the surrounding environment. For instance, in case of an end-consumer, the control space by the appliance agent provides knowledge to help in strategic decisions. However, the strategic processes are algorithms that use the available expertise and make a decision based on a particular objective and a focused, agile goal.

In the business layer, depending on the DSO's business at hand, agent(s) has to fix its combination of goal and objective. So, the strategic processes at the functional layer are algorithms that use the available expertise to make a decision based on a particular objective and a focused agile goal. At information layer, the agents gather all the knowledge about the surrounding

Figure 1: The SGAM based agile methodology.

environment to support in strategic decision-making. Agent in communication layer enables the end-consumer or prosumer to participate actively in DR programs. Moreover, each physical DER at physical layer has its agent representation in the communication layer. Therefore, the SGAM showed agility but limited to a particular business objective with suitably selected strategic process and technology.

B. Step-wise Analysis

The agile methodology also allows defining the requirements of the agents that should be introduced in the MAS to implement the new solution or functionality.

The brief analysis of the agile evolution of SGAM architecture is as follows. Firstly, the DSO should identify the business objectives. For instance, the DSO is interested in the solutions whose objective is to mitigate network congestion. In that case, the agile methodology helps the DSO to achieve its business needs. Secondly, the DSO must add an agent to implement the new strategy. For the same objective, let suppose that one of the strategies chosen by the DSO is direct load control of DERs. In this way, the current agents at functional layer do not include any downstream agents with the ability of demand shifting. Thirdly, the DSO identify the physical components that should be taken into consideration to implement the strategy. For instance, the DSO can identify large HVAC systems or thermal units as potential dispatchable loads for direct control to mitigate congestion. Finally, for each physical component, the DSO should assign agents in

the communication and information layers, where information must be exchanged hierarchically, or hybrid and communication protocols are recommended to enable the standardized exchange of information.

Hence, this step-wise analysis of the agile methodology enables DSO to identify which are the agents representing DERs that must be added to MAS, to implement a new strategy that will help DSOs to achieve their business needs.

Figure 2: UML Class Diagram as a conceptual model of an Agent-oriented Agile Methodology.

IV. IMPLEMENTATION

With the aim of providing tool support to the methodology, an object-oriented approach is presented herein. Alongside the requirement for the SGAM architecture, the use of a knowledge-based ontology mitigates the effort required for the standardization of strategies for the development of the agile methodology. Models which elucidate these functional modeling of knowledge management are at this moment referred to as Micro-Models.

Micro-modeling within agent-oriented programming is instantiated with specific agents and their interactions to create a comprehensive knowledge base. Figure 2 shows a UML Class Diagram as a model that illustrates the agents of the agile methodology for the behavior of software implementation using agent-oriented programming. It includes the structural agent operation, its run-time instance execution, the communication agent message, and traces, which organize related performances or interactions. The timed scenarios of the agents' interactions with peer agents are captured by a UML sequence diagram as shown in Figure 3. It displays two UML sequence diagrams generated for day-ahead and real-time execution of the methodology. Moreover, in the sequence diagram, messages between agents are only an implicit representations of the

starting requests and the ending responses. The boxes represent the functional responsibilities of the agents.

Figure 3: UML Sequence Diagram of the agile methodology.

Although the section only shows some agents that might be required to achieve business objectives of a DSO, the detailed micro-modeling of the agents within the paradigm are discussed in [31]. Briefly, appliance agent and its instances (i.e., Logger and Elasticity agents) are micro-modeled for communication layer. They altogether represent the DERs. On the other hand, intermediate agents (like allocation, grouping, percept, and dispatch agents) are micro-modeled for the information layer because they receive data of DERs and send information to the aggregator or network agent or both. An aggregator agent(s) (i.e., micro-modeled at functional layer) is to provide solutions to improve the market responsiveness. On the contrary, the network agent(s) can be identified by the DSO to increase process adaptability. Collectively, the objective agent(s) has a responsibility to achieve agility by complementing the strategies, to empower the DSO in the future electricity market.

A. Use Case

As discussed earlier, an agent-oriented solution for intelligent distribution grid is designed as a distributed management framework that can handle multiple objectives simultaneously.

For an explanation, let assume the DSO's prime objective is to mitigate congestion at a network by the help aggregators, that can dispatch demand explicitly by using TCM. Together with the case of a single aggregator, in which an aim is to shift demand for congestion mitigation, in the case of multiple aggregators the DSO has an additional business case. That is to find the set of aggregators which can provide the most optimal solution for the mitigation of congestion.

Figure 4: Performance of agile methodology for a business case, related to congestion management under different aggregators, of a DSO.

To evaluate the business case, a tool that analyzes the methodology was developed in MATLAB programming. Figure 4 draws the performance of the solution for the different number of aggregators. It shows that as the number of aggregator increases, the congestion duration decreases. On the other hand, the maximum net generation has a drastic improvement., although the maximum net consumption has a slight decrease. This examination depicts that DSO would be better off if there are more than one aggregator. However, at some point, a large number of aggregators per the hosting network will not make any significant effect. In summary, DSO with the proposed methodology can successfully coordinate DERs to use their resource more efficiently for congestion management in the electricity market environment.

V. SUMMARY

Since being agile is different from being flexible, so the study related to agility in network management is in the early stages, and further understanding and research is required. Therefore, this paper provided further understanding and research for the design and development the methodology that addresses how DSO can achieve its business objectives with a clarity of purpose, focus, and goals. This paper also reviewed possible interpretations of the agility in light of the existing control mechanisms, advanced technologies, and DR approaches DR.

Later, the paper presented a novel methodology that helps DSOs to identify which new technical solutions could be implemented in their systems to meet their business needs. Moreover, the methodology enables the identification of agents that would be added to MAS based SGAM for implementing a new solution. Thus the architecture of control methods and mechanisms proposed herein is referred to as the agile methodology. Within the agile methodology, SGAM is enhanced by considering TCM as a control method. Moreover, it explores hybrid structuring of multi-agents and exploits it by describing

micro-models of applied agents. Lastly, the paper identifies the implementation of the agile methodology through object-oriented programming. In this way, the methodology can be easily integrated into toolchain of a DSO.

In future work, the proposed methodology can be validated in large projects, where DSOs might use it to evaluate their technical solutions and to be agile in achieving their goals in future market models.

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