A Holonic Multi-agent Control System for Networks of Micro-grids

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Abstract. Due to the rapid growth of distributed renewable energy production in the energy markets, future power production and consumption will be more localized. As a consequence, projects and research on Micro-Grids has increased substantially in the recent years. However, the management of energy grids as such will become more complex if numerous Micro-Grids with high levels of autonomy are to be integrated. Modelling energy grids which benefit from the autonomy of the localized energy production and consumption, and at the same time, provide reliable services to the rapidly increasing energy demand seems to be a challenging issue. Combining the advantages of Holonic structures with the distributed nature of Multi-Agent Systems makes it an excellent candidate for the management of this complexity. This paper addresses the need to have autonomous management of the localized generation and consumption, as well as to increase the level of reliability, by a means of forming a Holonic control network of Micro-Grids. This holonic control approach allows the bottom-up formation of the energy grid, from the actual physical components of the grid to a network of interconnected Micro-Grids.

Keywords: Holonic Multi-Agent system · Micro-grids · Two-layer architecture · Energy agent · Energy option model

1 Introduction

The application of Micro-Grids addresses the need for more reliable power supply and localizing power production and consumption, but at the same time it makes the control issues more complex. As the participation of prosumers (an entity capable of bidirectional exchange of power) is getting higher, the power system demand to control this domination, as well as the need to provide some levels of autonomy is being increased. Moreover, the formation procedure of the Micro-Grids is bottom-up rather than the top-down formation in the main grid. Therefore, current purely centralized control, which is designed to serve the traditional unidirectional power flow, does not seem to be a feasible approach to manage the growing change in the topology of the energy grid. Coordination benefits that Holonic structure add to the decentralized MAS, makes it an appropriate solution for management of this change. The Holonic system concept was proposed to combine benefits of the decentralized control and top-down hierarchical

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organization. In fact, it links the autonomous and cooperative behavior of the system in order to achieve its objectives [1]. The word Holon first used by Koestler [2], is referred to an entity which is a whole considering its sub-ordinated parts, and, at the same time, a part for a bigger entity. In the Holonic approach, agents are dynamically structured in hierarchies or so-called holarchies which can be recursively built. A popular application area for Holonic structures is in manufacturing control systems [3, 4]. Medical diagnostic systems [5], medical optimal decision making processes [6], and Holonic self-organization approaches to the design of emergent e-Logistics infra-structures [7] are also considered as important applications of Swarm Intelligence and the Holonic Multi-Agent System (Holonic MAS) paradigm.

In Holonic MAS simulation of the power grid, agents represent physical or functional components of the grid. They are able to be recursively modeled and dynamically reorganize themselves. We modelled our proposed Holonic Micro-Grids by the help of Energy Agent and Energy Option Model (EOM) [8] developed at DAWIS[1]. The Energy Agent is responsible to control any actual physical components of the Micro-Grid. The energy management of the aggregation of the entities is performed based on the detailed information about the behavior and flexibility of the system provided by EOM. In the following section, we will have a brief discussion about the related work. In Sect. 3, the concept and the main characteristics of our proposed network of Holonic Micro-Grids are introduced. Finally, in Sect. 4, we conclude and clarify the future work.

2 Related Work

One of the scaling solutions for energy grids is the local grouping of interconnected distributed generators and storages. This so-called Micro-Grid network operates both in connected to the main power grid and isolated mode. The number of Micro-Grid projects and testbeds being implemented around the world is increasing rapidly [9, 10]. In recent studies, there has been growing interest to utilize the Holonic MAS structure to simulate the control of smart grid.

There are different approaches proposed for the automation and control of the power grid, most work is still either on isolated topics only or in its preliminary phase. There are also few work proposing holonic control of the grid. These control schemes vary from homogeneous recursive control to heterogeneous multi-objective control (Table 1). In a holonic architecture for the power grid, every prosumer component (e.g. a household) can be seen as a holon [11]. Holons can cluster together to form bigger holons (e.g. a neighborhood community) in a higher aggregation level. This bottom-up aggregation continues to finally form the whole smart grid. In this approach, the homogeneous control is recursively implemented in each level. However, customers and producers may have different interests and objectives in different scales and layers of the grid, preventing the system to work with a unique control scheme. Another common drawback of the proposed MAS approaches for the control of the energy grid is that they only consider electricity and ignore the fact that energy networks are interconnected.

[1] https://www.dawis.wiwi.uni-due.de/en/.

Table 1. Design and control of Holonic architectures proposed for power grid.

	Holonic design	Control approach
Nageri et al. [11]	Households Neighborhood District, …	Homogeneous Recursive Service oriented
Frey et al. [12]	Micro-Grids	Heterogeneous Multi-objective
Ounnar et al. [13]	Resource holon Energy holon Service holon	Homogeneous Multi criteria decision making
Pahwa et al. [14]	Substation network Feeder network Neighborhood network	Homogeneous Collaborative

We are trying to address the aforementioned issues by our Holonic Micro-Grid control architecture which has two layers, namely (i) *Physical Layer* and (ii) *Aggregation layer*. Depending on different interests, Holons of each layer can be competitive or collaborative. The coalition between holons can be formed by means of communication and energy profile matching. Besides, in our Holonic Multi-agent control system for the network of Micro-Grids we utilize the concept of unified Energy Agent. By so doing, not only can we model the various physical components of the grid regardless of the type of energy carrier, but also the aggregation layer which forms a network of Holonic interconnected Micro-Grids.

3 Proposed Holonic MAS Control of Micro-grids

The general scheme of the proposed two-layer Holonic control architecture is depicted in Fig. 1. In the following, the physical layer and the aggregation layer of the architecture are introduced.

3.1 Physical Layer

In the lowest layer, there are physical components that are controlled by Energy Agent interface. This unified Energy Agent is basically a specialized autonomous software system that is developed to economically manage the energy consumption, production, conversion and storage to smoothly integrate and run the potential ability of all entities (physical components) of the real world Micro-Grid system. A physical component could be as simple as a water boiler with only electricity consumption, or as complicated as a Combined Heat and Power (CHP) unit, with a natural gas consumption and electricity production. Therefore, in our model, all of the entities (holons) in the physical layer are identified by their energy profiles. This is also true for upper layer holons, as their energy profiles are the accumulation of the profiles of their sub-holons.

Electric vehicle (EV) is an example of physical components that is modeled in [8] with the help of an Energy Agent. As shown in Fig. 2, this basic EV model has three

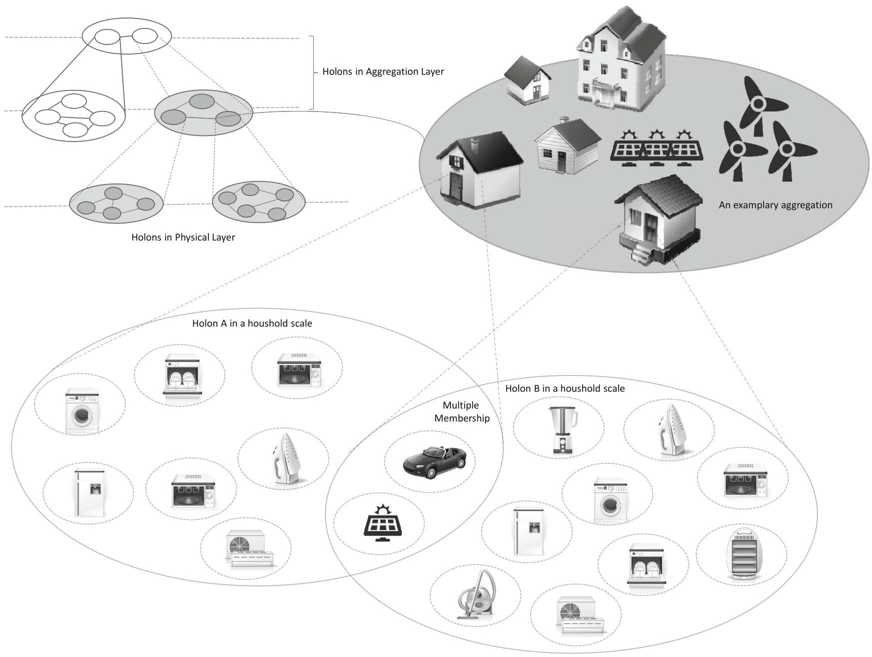

Fig. 1. Holonic architecture of micro-grids

possible system states, namely *Charge*, *Discharge* and *Idle*. The possible transition of these states and the step size, along with the state of the charge (SoC) and full charge capacity of the EV battery are also modelled.

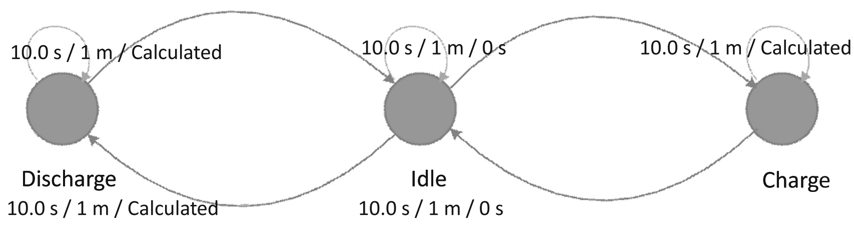

Fig. 2. Electric Vehicle (EV) basic model, system states and transitions [15]

3.2 Aggregation Layer

The second layer is composed of the aggregations of the components in the lowest layer. These aggregations are formed with the help of Energy Option Model (EOM) which provides the technical detailed information about the behavior and flexibility of the investigated system. Various possible use-cases of EOM are shown in Fig. 3. This layer is initially composed of all the (possible) combinations of existing generation and consumption units within certain Micro-Grid boundaries. Considering possible collaboration opportunities, there are different levels of aggregations in this layer. The collaboration between a single wind turbine and a storage unit is one example of the aggregations in this layer. As stated before, each entity can also have a holonic structure. Specifically, for the example mentioned above, the storage unit itself could be the result of Electric Vehicles (EVs) battery aggregation [15].

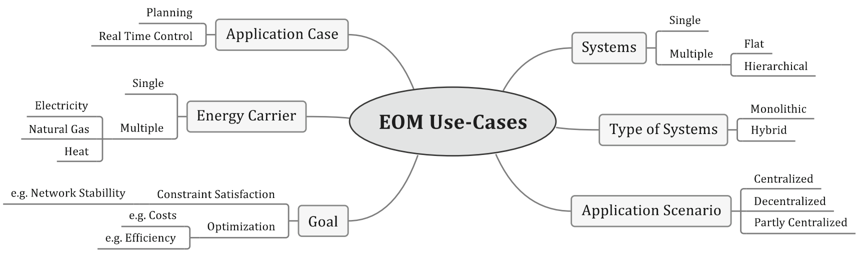

Fig. 3. Possible use-cases of EOM

The last level of aggregation is formed by the coalition of multiple Micro-Grids. Micro-Grids with various energy profiles could join together in order to exchange the power or any other energy carrier to which they are connected. The coalition could be formed based on different criteria such as economic interests, environmental, and/or reliability concerns.

3.3 Coalition Formation

Depending on being competitive or collaborative, different sorts of coalitions can be formed. Micro-grid holons with a positive energy profile are considered as *sellers*, and the one with the negative energy profile as *buyers*. An example of the collaborative power exchange between a group of Micro-Grids is the coalitions formed to decrease the power loss. Authors in [16] formulate the energy exchange between the Micro-Grids as a cooperative game. In their energy exchange model, in a set of Micro-Grids, a coalition is a group of cooperative seller and buyer Micro-Grids. The aim is to minimize the power loss during the local power exchange between a seller and a buyer, plus the power losses during the distribution from the main grid to the participated Micro-Grids. They used auction theory and matching games to optimize the problem. The collaboration between Micro-Grids is also possible and beneficial based on the fact that the Micro-grids in different locations probably have different energy profiles during the day. As the peak hours in the Micro-Grids situated in a residential area differ from the peak hours in the Micro-Grids of a commercial area [17], their energy profiles to some extent could be complementary.

As mentioned before, the aggregation between holons in our architecture could happen in each aggregation level, from the physical components aggregation to Micro-Grids coalitions. Depending on being collaborative or competitive, various matching algorithms can be used to form Holonic aggregations. To form an aggregation, first, the mapping process between the holons should be performed. The rating mechanism embedded in our Holonic model (Sect. 3.4) helps the individual holons to join or leave a holonic aggregation. This process is recursively done, whenever an energy request command is broadcasted from an upper Holon to its sub-holons.

3.4 Characteristics

Some of the most beneficial features of Holonic structures are the *Autonomy* within the boundaries of holons, *Multiple Membership*, and *Dynamic Reorganization* of holons. We also consider a *Rating Mechanism* to distinguish various energy profiles of each Holon based on their quality of service (priority and reliability degree). In the following each feature is explained in more detail.

Autonomy in Holarchy. Holons of the aggregation layer are homogenous in the sense that they have the same inherited control mechanism, but at the same time autonomous by freedom to have multiple and conflicting objectives, leaving or joining various holons. The holons of individual Micro-Grids might be competitive, aiming to maximize their utility, and/or collaborative in the sense of satisfying common general objectives. With our two layered Holarchy, the coordination is performed by broadcasting the control decisions from a super-holon to its sub-holons, whereas autonomous operation of the Holons existing in each layer is guaranteed.

Profile Rating. Considering various degrees of priorities and reliability, the energy needed or delivered by Holons are categorized based on their (accumulative) criticality or reliability. This categorization or, as we call it, rating mechanism could happen to each Holon, regardless of its position or scale. If the energy profile of each Holon is categorized, it may provide the potential for collaboration and resource sharing. As, for instance, the coalition between a Holon with the critical energy demand and another Holon with the high reliable energy supply is more likely to be formed.

Multiple Memberships. The multiple memberships might happen as a means of providing the other holons with various services, such as back-up reserve. In Fig. 1, a set of solar panels in a household would join a Holon from another household to use the storage services provided by an EV battery. Another example of these multiple memberships could be found in shopping malls equipped with back-up micro-generators. These rather expensive generation facilities are used in order to provide a reliable source of energy in case of any failure in the main grid. In fact, these facilities are idle most of the time, making the owner Holon to be present in multiple bigger holons.

Dynamic Reorganization. In each Holon of the Micro-Grid aggregation level, there is an agent representing the certain Micro-Grid. When a Micro-Grid Holon wants to enter a coalition, it receives the energy requests from the other Micro-Grids and broadcast it to its subordinated parts. Accordingly, the energy profiles of the holons in the aggregation layer are refined. This is done by means of recursively changing the existing aggregations or forming new aggregations in the way that the energy request is satisfied.

4 Conclusion and Future Work

Micro-Grids, as solutions for a better utilization of distributed renewable energy resources, are of a paramount interest in recent years. The main motivation to invest on having groups of distributed generators and storage facilities near actual loads are basically reliability issues, better resource allocation, and environmental concerns. In this paper, the concepts of a two-layered Holonic architecture for a network of Micro-Grids are introduced. We modelled our proposed Holonic Micro-Grids by the help of the unified Energy Agent and Energy Option Model (EOM), which principally enables us to aggregate and utilize the operational flexibility of any type of energy conversion process. Our control architecture consists of two layers, namely physical layer and aggregation layer. Recursive and bottom-up features of this approach enables us to model energy management of Micro-Grids in a decentralized manner, considering the comprehensive integration of prosumers in the future smarter grid. We devised a procedure in which groups of prosumers may form a coalition based on the complementarity of their energy profile. For the next steps of our work, first, the communication between the Holons in order to find proper matches of energy profiles should be described and then, the detailed negotiation mechanism between the holons to satisfy the optimum local goals as well as the general objectives of the upper layer holons ought to be described.

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