# A Holonic Control Architecture
for a Heterogeneous Multi-Objective Smart Micro-Grid

Sylvain Frey*†, Ada Diaconescu*, David Menga† and Isabelle Demeure*
*Télécom ParisTech, CNRS LTCI, Paris, France. Email: {first}.{last}@telecom-paristech.fr
†EDF R&D, Clamart, France. Email: {first}.{last}@edf.fr

***Abstract*—Designing the control infrastructure of future "smart" power grids is a challenging task. Such grids will integrate a wide variety of heterogeneous producers and consumers that are unpredictable and operate at various scales. Smart grids will need to control these in order to attain global objectives at the macro-level, while also taking into account local objectives and private interests at the micro-level. This paper proposes a *holonic control architecture* to help meet these requirements. We show how this architecture can integrate heterogeneous control solutions, including - when applicable - existing state-of-the-art solutions for the smart grid. To better illustrate the utility of this generic architecture we exemplify its use via a proof-of-concept implementation, integrating some basic control solutions. We show how this sample holonic controller can manage a grid simulator in several scenarios. Obtained results support our belief that the proposed architecture can facilitate the development of control solutions addressing the aforementioned challenges.**

***Keywords*-holon; micro-grid; controller integration;**

## I. INTRODUCTION

Over the next decades, the electric grid is expected to undergo massive changes both in its composition and control infrastructure [1] [2] [3]. The increasing introduction of renewable energy sources such as solar panels or wind turbines brings unprecedented volatility and unpredictability in energy production for the grid. This, along with the rise in local storage technologies, can significantly disrupt the current distribution of energy flows. Hence, the grid's control infrastructure must change to deal with the new energy fluctuation patterns. Information Technology (IT) is considered as a necessary extension for transforming power grids into "smart" grids capable of answering such requirements. Most industrial parties and research communities seem to agree that the smart grid's control should be more decentralised (than the traditional one), even if no consensus seems to exist so far concerning a particular control solution [1] [2].

While essential to the viability of modern grids, IT-based control also has the potential to introduce new challenges. Since more and more energy production and storage facilities can be owned privately, the energy market is becoming progressively less centralised. Many actors - including private consumers - can join and define their own power-management *objectives*, such as business profits, bill minimisation or environment preservation. The smart grid's IT infrastructure is a key enabler for such novel objectives, since it enables the independent control of various grid parts - from countries and areas to districts, houses or devices. At the same time, such new facilities can further increase the grid's dynamism and unpredictability, hence making its control even more challenging [3]. Furthermore, they introduce *additional requirements* on the smart grid's overall design. This paper focuses on addressing this last point.

We argue that the multitude of interested parties involved and the diversity of their assets and business objectives are likely to prevent general consensus over a unique control solution for the entire grid. Rather, *heterogeneous control solutions may have to be adopted in different grid sections* as better suited to their particular settings and goals. We also highlight the fact that the pursuit of *private goals in various smart grid parts (micro-level) may often prove incompatible with the global goals of the overall grid (macro-level).* Finally, smart grids are developing in parallel with adjacent socio-technical systems such as smart appliances, houses and cities, which feature their own constraints and objectives. *Integrating such smart technologies within the smart grid will be a likely source of further management conflicts.*

The ad-hoc integration of *heterogeneous multi-objective control solutions* for the grid, entangled with other smart systems, may jeopardise the very benefits that motivated the current transition towards distributed power systems. Hence, great care must be taken when designing the smart grid's general *integration infrastructure*, to prevent global disasters from emerging out of local self-interested decisions. Composition of disparate, local control solutions into coherent organisations, ensuring a fair balance between micro and macro objectives, is a key step of the design process.

In this paper, we capitalise on our Software Engineering (SE) experience in building integration solutions for scalable, heterogeneous, multi-objective self-* systems. Previous work [4] proposed a *generic architecture and methodology* for designing adaptive controllers for such systems. It was complemented by a catalogue of *integration design patterns* [5], defining re-usable solutions to common integration problems related to system control. In this paper we introduce a holonic structure within this approach and refine it for the smart micro-grid domain. **The main contributions include**:

- identifying **requirements** on grid controller design that highlight the need for an **integration-driven approach**;
- showing how state-of-the-art control applications for the smart grid mostly follow **three generic integration patterns** [5] (with several variants);
- proposing a **holonic integration architecture** for the smart grid that enables the recursive composition of various instances of the three patterns identified before;
- highlighting the key role that **state information**, **goal-oriented exchanges** and **conflict resolution** play in the holonic integration of such mixed control organisations.

We **exemplify** the proposed integration architecture via a **proof-of-concept implementation**. We show how two simplified control organisations, which follow two different patterns, can be integrated into a multi-level, multi-objective micro-grid, via state information, goal exchanges and conflict resolution. **Experimental results** from several power management scenarios run on a distributed smart grid simulator indicate the viability of the approach. We believe that this contribution lays a good foundation for developing smart grid control systems that can address the important issues identified beforehand.

The content of this paper is as follows. Part II introduces a simplified grid model, insisting on management goals and integration requirements. Part III describes the integration architecture, defining holon-related concepts, goal expression and conflicts. It then presents the three generic power management patterns and their qualitative evaluation. Part IV focuses on related work showing how it conforms to the generic architecture and patterns. Part V presents the proof-of-concept implementation and discusses results.

## II. REQUIREMENTS FOR SMART GRID MANAGEMENT

### A. *A simplified grid model*

In this paper an electrical network is seen as a tree; in reality, several such trees can be interconnected. Leaves represent end-user producers (e.g. power plant or solar panel), consumers (e.g. city lights or washing machine) or both (e.g. batteries). The term *prosumer* designates such endpoints and the associated term *prosumption* means either production or consumption. By convention, a positive prosumption represents a production and a negative one a consumption.

Internal tree nodes, or *aggregators*, delimit hierarchical sub-networks. For instance, a house electricity meter defines the house's local network, which is itself nested in a district network, which is part of a city network and so on. From the point of view of its parent, a sub-network can be seen as a single prosumer featuring a total prosumption that equals the sum of the individual prosumptions of its child prosumers. For instance, let us consider a house where at some instant a solar panel produces $300W$ while a TV set and an oven consume $100W$ and $250W$ respectively. From the perspective of the parent district network, the house is equivalent to a single prosumer prosuming $P_{house} = 300W - 100W - 250W = -50W$ - i.e. a consumer at the moment. The same applies to the district network, whose total prosumption as seen from its own parent network equals the sum of every house prosumption.

Whenever a grid's prosumption is not null the parent network must compensate for the difference (e.g. in the house example the district provides $50W$). If available, this amount of power may come from a local source, like the production of another house, or from the district's parent network. Otherwise, a *blackout* may occur and damage connected prosumers. The *load* of a grid is defined as the ratio between its total productions and consumptions. A *high* load corresponds to a lack of production or an over-consumption. A *low* load indicates the opposite: a low consumption or an over-production. Consequently, load adjustments can rely on both production and consumption control.

### B. *Power management in the grid*

Power management in the smart grid aims to maintain appropriate load levels in every grid part (or sub-network) and to avoid blackouts. *A priori*, energy producers try to maximise sale profits whereas consumers to minimise their electricity bill. There is a high variety of possible regulations in energy markets, stipulating prosumer rights, electricity prices and control modalities. This paper does not assume any specific pricing system or market regulation. Instead, we suppose that an administrative authority is in charge of each grid sub-network, at each granularity (e.g. house grid and district grid). Such authority will have a prosumption objective for their grid, in the form of a viability interval $[p^{min}, p^{max}]$, which they can change over time. Such intervals are chosen arbitrarily in the paper to ensure the necessary flexibility for embracing a wide range of realistic administrative goals later on.

Traditional power grids consisted of a large majority of consumers supplied by a few large producers. Load control used to be quite centralised, adjusting production to consumption estimates at a regional or national level. With the progressive introduction of renewable energy sources, particularly solar panels, and the development of low-cost batteries, every end-user may also become a producer.

This paper focuses on low-tension small-scale electrical networks, or *micro-grids*. The typical example is that of a district grid regrouping a few dozens houses, each featuring variable prosumption profiles. Electric appliances provide services such as heating or entertainment. Private users are arguably self-interested and concerned with goals such as comfort and local power management. These are translated into heating or entertainment services or into a bill reduction. This means that the grid must cater for conflicting interests which must be balanced, since maintaining a warm home may interfere with load peak or bill reductions.

### C. *Requirements for smart grid controllers*

Smart grids must comply with numerous requirements, including quality of service, efficiency, reliability, robustness and extensibility, to only mention a few. To clearly delineate the relevance of our contribution, we focus on the subset of controller requirements that demand the use of integration-oriented architectural styles for the future smart grids:

***Multi-authority and multi-level:*** Several administrative authorities interact within the smart grid, each one defining their objectives over a grid part. Each authority's part (e.g. house grid) is connected to parts of other authorities (e.g. other house grids) and may be included in larger parts of higher authorities (e.g. district grid). Authorities may be selfish, and the smart grid must cater for all their interests, in a fair manner. From a control perspective, this implies splitting the grid into multiple levels, each managed by a different controller. Controllers must then be integrated to ensure the coherence of the overall system (cf. III.B). This paper focuses on residential micro-grids, where relevant authorities include private customers and a district administrator.

***Multi-objective:*** The authorities controlling the grid may want to define additional objectives, which may interfere with power management. In this paper, we consider the case of balancing domestic services with power management at the house and district levels. Here, grid controllers must be able to follow conflicting objectives, such as *"maintain temperature"* and *"reduce consumption"*. These objectives may vary in time, depending on user preferences. Additional conflicts may appear between administrative entities, for instance when the comfort objective of private users threatens the load-peak reduction objective of a grid administrator.

***Heterogeneity:*** Electric devices, and prosumers in general, are widely diverse. Different devices in dissimilar contexts require specific controllers, which must also consider user preferences. Moreover, the multi-level requirement implies a high diversity of managed grid scales, goals and characteristics (e.g. voltages, intensities). Finally, the way of dealing with multi-objectives may differ depending on the authorities involved. For instance, *collaborative* controllers would be suitable for managing a house and its appliances, since under the sole authority of the home owner. The owner's objectives should not be overridden by higher grid authorities, except for extreme contexts such as blackout threats. Conversely, *competitive* controllers would be better suited to handle administrative conflicts among home owners, and with the district manager.

***Scalability:*** Modern grids include significant numbers of prosumers, making the scaling of control algorithms a pending challenge. Additionally considering heterogeneity and dynamism exacerbates this challenge. Indeed, the hierarchical nature of the grid (cf. "multi-level" requirement) already equips architects with a divide-and-conquer approach (a SE classic), splitting the grid into nested management levels. Yet, even at the scale of a city, thousands of houses with millions of devices can raise important scalability concerns.

***Incremental change:*** The power grid is a massive asset that has been constructed progressively and has been running for decades. Any changes introduced in the future will have to be progressive, so as not to disturb or jeopardise a working system that provides an essential service. Therefore, replacing large parts of the grid at once (either network or controllers) seems unrealistic and probably non-recommended. Indeed, progressive evolution involving intermediate, stable forms, seems to characterise many complex systems [6] [7].

A notable constraint is the smart grid's business model: smart houses, *a fortiori* smart cities, will not be constructed at once while ignoring existing assets. Instead, *smart grid-enabled* appliances are likely to come into the market progressively, replacing existing systems, until smart houses, districts and cities can start emerging. This means that smart grid controllers requiring large numbers of prosumers will become viable only once such numbers are available. Similarly, smart grid-enabled prosumers relying on third-party controllers will only be useful once such controllers are installed.

Based on these considerations we argue that no single control design can address all these requirements across the entire smart-grid (cf. III.E). A **mixed solution integrating several heterogeneous controllers** is needed instead, which raises additional integration requirements. First, there is a need for ***standard taxonomies and protocols*** to allow:

- integration of heterogeneous, third-party appliances and controllers (cf. "incremental change" requirement);
- self-adaptation of controllers to changes in their micro-level environments and neighbouring controllers;
- macro-level self-organisation for grid-wide goals based on heterogeneous, self-interested controllers.

Significant standardisation efforts are already supported by entities such as the National Institute of Standards and Technology (NIST), OASIS Energy Market Information Exchange (EMIX) and Energy Interoperation technical committees. These aspects go beyond the scope of this paper.

***Flexible micro-macro integration:*** A smart grid must ensure a balance between individual (micro) and collective (macro) objectives, based on user specifications and grid regulations. Since these can change over time, smart grid solutions must be flexible enough to rebalance objectives at runtime. Hence, the capability of a macro-level controller to override micro-level objectives, and vice-versa, should be an adaptable parameter of the management system.

***Meta-management feedback:*** The trade-off between micro and macro objectives is a meta-management goal in itself, since it dictates the conflict-resolution strategy and hence the system behaviour. Administrators should receive continuous feedback on their management decisions, in both collaborative and competitive situations.

## III. INTEGRATION ARCHITECTURE PROPOSAL

### A. Architecture Overview

In previous work we proposed a methodology for designing large-scale, multi-objective, adaptive control systems - starting from the definition of goals from an administrator's perspective, then translating and splitting goals gradually down to the lowest-level managed resources [4]. We also showed how goal conflicts could be identified and where conflict resolution mechanisms should be placed in the system to address them. Management goals were defined via a triplet $(V, S, T)$ where $V$ is a domain-specific *viability zone*, $S$ an *evaluation scope* of managed resources, and $T$ a *period* over which the goal applies. Then, management *conflicts* correspond to *scope intersections* - i.e. managed resources following different goals. Hence, the projection of goal scopes on system resources allows the identification of conflict zones where it is necessary to inject specific integration logic for conflict resolution.

We have proposed a catalogue of *integration patterns* for conflict resolution in self-managed systems [5]. Patterns are expressed in terms of *organisations* of controllers. They specify abstract *roles* - implemented by concrete controllers; and *messages* - exchanged among role players. In this paper we propose to apply three of these patterns (or organisations): ***hierarchy*, *stigmergy*** and ***collaboration***. We also propose ***a holonic architecture for recursively integrating various instances of these patterns***, representing grid levels of increasing scales. We identify the generic integration mechanisms for having any of the patterns represent one role in a higher-level pattern (cf. III.B).

Individually, each *power management organisation* captures invariant structures of state-of-the-art smart grid management systems proposed in the domain (cf. IV). When combined, the resulting organisations are meant to be sufficiently generic to allow standardisation and favour reusability (cf. "heterogeneity" and "incremental change" requirements) and expressive enough to help design controllers that answer specific smart grid constraints (cf. "multi-level", "multi-objective" and "scalability" requirements).

The purpose of this contribution is to facilitate the design of heterogeneous multi-objective power-management solutions for scalable smart-grids. It provides a reusable base for experimenting with a wide variety of concrete solutions, combining various types of controllers. We believe this process is essential for addressing all the smart-grid requirements identified above.

### B. Holonic Architecture

We adopt the view by which smart grids should be constructed as holonic systems, or holarchies [Fig. 1] [8]. By definition, a *holon* is simultaneously a *whole* with respect to its composing parts, and a *part* of an enclosing (holonic) structure [9]. This hierarchical organisation style is readily applicable to smart grids, where each grid level (e.g. a house grid) represents both a self-reliant whole for the hierarchical level below (e.g. house appliances), and a dependent part for the hierarchical level above (e.g. district grid).

We propose applying an integration architecture that allows constructing smart grids in this manner [4]. As a *whole*, a grid level (holon) is implemented via a semi-autonomous *organisation* that follows one of the patterns (cf. III.D). As a *part*, it represents a mere *role* in a higher-level organisation from which it receives control directives. To integrate in this architecture, both as a whole and as a part, a holon must:

- *provide* its supra-organisation with an *aggregated description of its internal state*, based on the individual states of its parts (accuracy can vary, discussed below);
- *receive directives* or *goals* from its supra-organisation;
- *resolve conflicts* between a new goal and existing goals;
- *translate* accepted goals from supra-organisation semantics into internal parts semantics; here, goals may also be *split* into sub-goals.

In the proposed architecture, these functions belong to a special-purpose Goal Management layer (or membrane) [4]. This is a logical component: it can be designed as an actual layer "around" the holon, or distributed across the holon's parts; or both. The concrete solution will depend on the requirements and integrated patterns of each application.

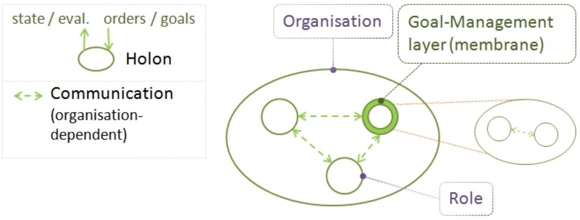

Figure 1. Holonic control architecture for the smart micro-grid.

In this paper we consider only the two bottom levels of such a holarchy, including house and district grids. However, we believe that the proposed architecture would also apply at higher grid levels, based on the same principles. In addition, since the holonic structure separates the grid into decoupled sub-grids it also favours grid reliability and robustness. This is because possible failures and blackouts can be isolated into localised parts of the whole, where self-healing solutions may be applicable [10]. Finally, a holonic structure may also help with self-protection and privacy concerns. Here, the state information a holon provides to its supra-organisation can depend on the business context (e.g. collaboration or competition) and may even change during runtime (e.g. threat detection). For instance, if privacy is an important concern (e.g. between house and district managers) the holon may simply respond to orders (e.g. to reduce or increment consumption) by accepting or declining them, with no further justification that may give away its

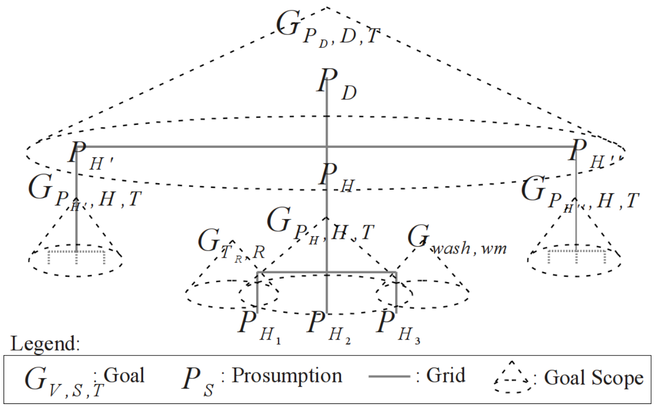

Figure 2. Holonic scopes and goals in the smart micro-grid.

internal state. In a more trusted environment, a holon may provide minimal state information, in an aggregate form (like exemplified in the paper). Finally, in a trusted context, like within a household, devices may freely share information with the house manager, via secured protocols. Yet, while highly relevant, these aspects are beyond the paper's scope.

### C. Goal Formalisation in the Smart Grid Domain

Let us consider a given house $H$ including several prosumers and one aggregator. At the district level, $H$'s aggregator is equivalent to a prosumer with a prosumption $p_H = \sum p_{H_i}$ for all prosumptions $p_{H_i}$ in the house. Let the prosumption objective for house $H$ for period $T$ be: $G_{p_H,H,T} : \forall t \in T, p_H(t) \in [p_H^{min}, p_H^{max}]$. Here, the goal's *viability constraint* is formulated as a target interval $[p_H^{min}, p_H^{max}]$. $H$ is the *evaluation scope* of the goal, meaning that goal fulfilment depends on the behaviours of prosumers inside house $H$ (i.e. prosumptions $p_{H_i}$). $T$ is the *time scope* indicating the periods over which the goal should be pursued. More sophisticated viability constraints are beyond the paper's scope. The way domain $[p_H^{min}, p_H^{max}]$ is determined is discussed later in the paper. For now, let us assume these values are set at runtime by a house power manager, taking into account user preferences (e.g. maximum monthly bill), external constraints (e.g. electricity tariffs) and requests (e.g. reduction order from a district manager).

Goal $G_{p_H,H,T}$ is not the only one in the house. A prosumer may have several goals, depending on its nature:

- for an electric heater, goal $G_{T_R,R}$ aims to maintain a temperature of at least $22°C$ in room $R$ at all times;
- for a washing machine $wm$, goal $G_{wash,wm,[20:00,21:00]}$ aims to run a $40°C$, $1$ hour cycle at $20:00$;
- for a lamp, goal $G_{light,R,[\forall presence]}$ aims to light room $R$ whenever a resident is present.

These extra goals are *conflicting* with the house's power objective $G_{p_H,H,T}$ since they all imply electricity consumption and their evaluation scopes ($R$ and $wm$) are included in the house scope ($H$). For instance, maintaining $25°C$ in every room while not consuming more than $10kW$ may not be possible. Hence, *conflict resolution*, i.e. the ability to detect incompatible goals and find a trade-off among them [5] [4], will be necessary in this management system.

The actual conflict resolution method will depend on runtime context and user preferences. For instance, some users may prefer sacrificing comfort in favour of energy savings in most situations, but they may want to ensure comfortable conditions in particular circumstances, like a visit or a cold, whatever the cost. User preferences may be selective in regard to different equipments and services. For example, dimmed lighting may be acceptable but temperature should never drop below a comfort threshold in certain rooms.

At the district level, goal formalisation is quite similar. Suppose the district grid $D$ has a prosumption objective $p_D$: $G_{p_D,D,T} : \forall t \in T, p_D(t) \in [p_D^{min}, p_D^{max}]$. As before, fulfilling this goal depends directly on the behaviour of houses in district $D$, and by transitivity, on end-user goals and appliance prosumptions. The district goal is said to be *conflicting directly* with house objectives $G_{p_H,H,T}$ and *conflicting indirectly* with appliance objectives. Here, goals pursued by devices (micro-level) may conflict with goals pursued by a house or a district manager (macro-level).

Conceptually, we can already intuit how a holonic approach can apply to this smart grid example. A smart appliance, like a heater, is both an autonomous whole (maintaining a temperature) and a part in a supra-organisation (participating to the house's prosumption goal). Similarly, the house is both a whole (with its prosumption goal) and a part in the district organisation (with a higher-level goal). Let us now see how each holon can be designed both as a whole (internal organisation) and as a part (role in supra-organisation); and what capabilities enable its double nature.

### D. Power Management Organisations

An organisation aims to attain one or several (macro-) goals in the presence of internal managers or controllers that pursue their own (micro-) goals. Within its scope, an organisation defines: abstract *roles* that concrete managers should implement; and integration *messages* that should:

- enable inter-manager exchanges, including monitoring or exposing of manager states, behaviours or goals;
- enable administrators to observe the organisation's state, acknowledge unpredicted conflict situations and provide resolution directives.

Based on this model, we can describe an abstract power management organisation as follows. It has one *Power Manager* role (optional) and a set of *Prosumer* roles (at least one) [Fig. **??**]. The manager in the Power Manager role pursues a power goal for a grid section (e.g. house or district); managers in Prosumer roles follow power goals for corresponding grid sub-sections (appliances or houses). A Power Manager has a coordination role with respect to Prosumers in the same organisation. Its precise authority and method varies for each integration pattern. In the holonic architecture, house managers play both a *Prosumer* role (part) for the district organisation and a *Power Manager* role (whole) for their house grid. Their dual nature makes them suitable for integrating power organisations that operate at the district and at house levels.

Various types of messages may be exchanged within an organisation, as follows; each kind of organisation may or may not use all message types (as shown later):

***Prosumption Packets:*** model prosumption profiles. They may contain any of the following prosumption information:

- time - e.g. (earliest) start and (latest) end dates;
- current measures and future estimates - e.g. minimum, mean, maximum prosumption over the packet duration;
- dependencies between packets, in a Gantt fashion, to allow more flexible behaviours - e.g. a washing machine splitting its cycle into several successive steps.

***Statuses:*** allow Prosumer controllers to indicate whether or not they are likely to accept profile changes on advertised packets. A Prosumer can display either a *Flexible* or a *Non-Flexible* status to mark packets that a Power Manager can or can not reconfigure, respectively. More advanced statuses can advertise reconfiguration capabilities by proposing alternative prosumption profiles (e.g. a washing machine showing its deadline and the range of possible execution times; or a heater showing a "comfort" and an "economy" profile).

***Orders:*** enable a Power Manager to ask its Prosumers to: *Reduce* their prosumption; *Raise* it; or follow *Any* prosumption profile. Orders may also define the precise prosumption levels expected (e.g. in response to a flexible Packet advertised via the Status). Priorities are included to indicate the Order's urgency (or authority); they are to be compared with the priority of Prosumer Statuses indicating their prosumption criticality. Orders may be addressed to an individual Prosumer or to a group of Prosumers (e.g. defined by their status); or broadcasted to the entire organisation.

***Negotiations:*** allow Prosumers to exchange information in a peer-to-peer fashion, for implementing decentralised decision algorithms (e.g. synchronisation, trading or agreement-related messages). Initiatives like FIPA aim to classify and standardise agent conversations and favour integration between heterogeneous agents [11]. Similar efforts are under way in the smart grid domain (cf. II.C).

Several flavours of power management organisations can be constructed on this basis - role and message types - resulting in different integration patterns and their variants.

***Hierarchy pattern:*** relies on a central orchestrator to ensure the organisation's macro-objectives. It addresses power management as a classic scheduling problem, where Prosumers provide *Prosumption Packets* and associated *Statuses* and the Power Manager schedules them via direct *Orders*. Such orders can start, stop, shift or scale (up/down) the Prosumers' advertised packets. A Prosumer's *Non-Flexible* Status may exempt it from obeying such orders, in case users specify goals that take priority over power control. Yet, if the number of *Flexible* Prosumers is insufficient for the Power Manager to attain its goal, the user should be warned that its choices jeopardise its global power objective.

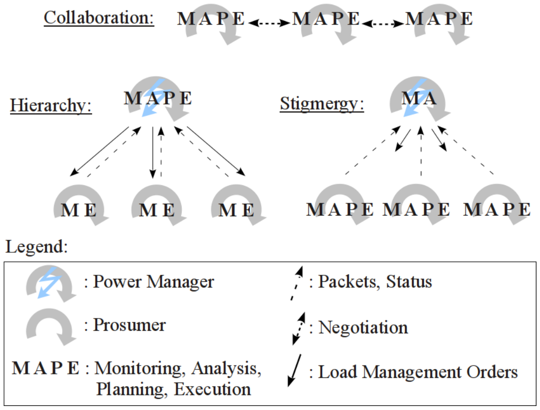

Figure 3. The three pattern: hierarchy, stigmergy and collaboration.

***Stigmergy pattern:*** relies on control decentralisation; and on choreography based on global information, which is formed and accessible via a shared environment. Here, information from all Prosumers are aggregated, including Prosumption Packets and Statuses. The prosumption aggregate is compared to the organisation's global objective and an estimate of the managed grid's state is broadcasted back to Prosumers - e.g. grid load too high, too low or just right. Each Prosumer reacts individually by adjusting its prosumption to the extent to which its Status permits it (i.e. Flexible). To avoid that concomitant Prosumer reactions cause overshoots and oscillations, only a subset of Prosumers are allowed to react to aggregate estimations; this is typically based on a probabilistic method. To achieve the correct behaviour, the overall number of Prosumers and an estimate of their overall flexibility is also aggregated and broadcasted, allowing each Prosumer to determine a suitable probability of reaction. In practice, the information collection, aggregation and broadcasting can itself be achieved in a centralised or decentralised fashion. When centralised, a Power Manager can play the necessary monitoring and analysis role. Decentralised solutions based on gossip among Prosumers can provide a viable alternative.

***Collaboration pattern:*** also relies on decentralised control, but delegates all management to Prosumers. All forms of centralised coordination are excluded - i.e. only direct inter-Prosumer communication and *no* Power Manager, as in most multi-agent or game theory approaches (cf. IV).

### *E. Qualitative comparison and evaluation*

From an architectural perspective, the three organisations can be compared based on the way in which the Monitoring, Analysis, Planning and Execution (MAPE) functions [12] are assigned to organisation roles. The Hierarchy concentrates Analysis and Planning into the Power Manager, limiting Prosumers to Monitoring and Execution. Conversely, the Stigmergy limits the Power Manager role (when available) to Monitoring and Analysis, delegating Planning and Execution to the Prosumers. The Collaboration pushes all MAPE functions in the Prosumers. Let us now compare these organisations based on their ability to reach management goals and address the key requirements identified (cf. II.C).

***Hierarchy pattern:*** this is a classic centralised organisation that allows fine global control. The *Power Manager* can compute precise estimates of the managed grid's state and of its reconfiguration possibilities, and can issue individual scheduling orders to adjust load levels. Precision of control is only limited by the amount of information available to the Power Manager and by the effectiveness of its scheduling logic. In cases where the energy scheduling problem has at least one solution (because Flexible Prosumers are available in sufficient numbers) the Power Manager should find it.

However, this type of organisation may raise scalability issues when the number and dynamism of prosumers rises, since scheduling computations may become costly. Indeed, the more the scheduler takes into account local Prosumer goals and complicated profiles, the more intricate and costly its algorithm becomes. Also, since centralised, this pattern is best suited to cases that involve a single authority.

***Stigmergy pattern:*** this is a decentralised organisation that should ensure good scalability and facilitate heterogeneity, since newcomers only need to be able to read and react to broadcasted information aggregates. Yet, as indicated above, additional de-synchronisation mechanisms must be injected in this case to prevent over-reactions or oscillation issues, which require, in turn, collecting and broadcasting additional information [13] [14]. When relying on probabilistic behaviours, this approach may require a large number of participants in order to provide statistically reliable results at the organisation level. This constraint may become inconvenient in cases where a smart grid is developed from scratch (cf. ”incremental change” requirement). Since heavily relying on the collaboration of all parties involved, this pattern is also best applicable to cases where a single authority specifies all the goals.

***Collaboration pattern:*** this is another decentralised organisation that should also feature good scalability characteristics. Certainly, the exact properties of this kind of organisation will highly depend on the concrete implementation variant adopted. In the absence of a higher-level controller, each participant (Prosumer) can more readily pursue its own goals. Hence, this organisation represents a good choice when several authorities specify goals that can be conflicting and cause competition within the organisation.

This qualitative analysis indicates that each type of organisation is best suited for a different application context; and that none of them can address all the requirements identified as important for smart grid controllers. Therefore, a different organisation type should be selected for controlling each part of the grid. These heterogeneous controllers should be integrated, as proposed here, into a global controller that can in this way address all the requirements combined.

## IV. RELATED WORK

This section shows how examples of control solutions identified in the literature fit the three presented patterns. We only present a few notable examples with no further analysis of their features, since these were discussed in subsection III.E. The patterns can also be identified in other applications domains which are out of the paper's scope. The purpose here is to show that available control solutions generally follow one of the organisation types analysed above, with the associated advantages and inconveniences. The holonic architecture we propose is complementary to these approaches, as it facilitates their integration into global controllers, capable of featuring suitable characteristics in different parts of the managed system (or smart grid).

***Hierarch pattern:*** NiceGrid project controls residential storages and heat pumps in a district, allowing it to go into “island mode” for a limited period of time each day, cutting consumption completely from the parent grid [15]. This kind of controller provides good control of the district prosumption on demand of the parent grid, yet its influence is limited to specific devices in limited numbers. Furthermore, data privacy is a pending concern each time appliance control is deported out of its owner's reach. [16] [17] try to bring *Hierarch*-like solutions into houses, centralising control of smart appliances into a house-level loop. Appliances provide profiles and user preferences to the hierarch which in turn computes optimal prosumption scheduling and executes it. Since appliance profiles are hard to establish it is unsure how such central hierarchs would apply to very different house configurations, and how tolerant they would be to configuration variations (appliance churn).

***Stigmergy pattern:*** Recently, a new class of grid control architecture have emerged, that fit into the *stigmergy* pattern. These proposals aim to provide ultra-large scale control of individual appliances via the use of global shared state and probabilistic control. [13] relies on users setting flexibility preferences for their appliances via a color code. [14] relies on the ability of thermal storages (heaters, fridges, air conditioners...) to switch on or off rapidly at certain points of their thermodynamic cycle without comfort degradation. Both of these solutions scale up nicely while allowing massive appliance variety and runtime variability, be it the result of changing user preferences, device churn or partial failures in the grid. A significant drawback of such extreme scalability is the incompatibility of these solutions with small scales. For instance, allowing a single house to go into “island mode” and act as if disconnected from the district grid is not a possibility these solutions address.

***Collaboration pattern:*** The collaboration pattern is extremely generic and encompasses any smart grid management system where Prosumers negotiate their behaviour in a peer-to-peer fashion. Well-known multi-agent algorithms such as Contract Net Protocol [18], auction markets [19] or general agent games [20] have been proposed in the domain. Standardisation efforts for agent controllers in the grid, such as [21], have been based on the FIPA standard [11].

## V. PROOF-OF-CONCEPT IMPLEMENTATION

### A. Simulator

A proof-of-concept smart micro-grid simulator was developed during this work - MisTiGriD[1]. Its purpose is two-fold. For the scope of this paper, it helps illustrate the proposed holonic architecture via a concrete implementation, integrating two types of organisations and providing experimental results. For the future work, it offers a reusable platform for designing and experimenting with various combinations of control organisations and algorithms. MisTiGriD includes:

- a simplified electricity grid model, allowing to develop simulated appliances with arbitrary prosumption profiles (e.g. heaters, lamps, solar panels or batteries) and to deploy them on a house grid. Separate house simulators can be remotely connected to form a distributed district grid deployed across several physical machines.
- a simplified heat transfer model, allowing to create thermal objects such as rooms, heaters and external atmosphere. Some temperatures may be controlled directly - e.g., by switching heaters on and off, or by adjusting the external temperature.
- support for instrumentation of simulated components - e.g., every prosumption, temperature and state variation is monitored and persisted.
- an implementation of the proposed management architecture via a particular combination of integration patterns and management resources, as detailed below.
- a graphical user interface (GUI) that enables experimenters to interact with the simulation at runtime - deploy new appliances, change management preferences or emulate user behaviour (e.g. switch appliances on and off, open/close doors, change management goals).

The simulator relies on technologies such as the OSGi dynamic service platform and Akka middleware[2]. Additional information is available on the project web page.

### B. Sample Implementation of a Smart Micro-Grid

This section describes the most significant behaviours of simulated appliances and managers. The implementation does not cover each aspect of the micro-grid model or of the global architecture presented in the paper. Its purpose is to provide a simplified yet relevant proof-of-concept implementation that can show how integrated controllers can reach multiple goals (micro and macro) in a district-size grid.

*House Management:* The power management organisation within each house follows the Stigmergy pattern, with a centralised monitor and analysis function (Power Manager). A hierarchy-based solution, not presented here, was also tested with success. The house-level organisation is based on a shared discrete schedule, similar to a *black board*, onto which Prosumers publish Prosumption Packets containing:

- prosumption *start* and *end* dates;
- *maximum* prosumption during the interval;
- packet status - either *Flexible* or *Non-Flexible*.

The house Power Manager computes, for every time slot, whether or not the house prosumption objective is fulfilled, and updates the schedule with load information on time slots - either *high load* or *normal load*. In turn, Flexible Prosumers may react to high load levels, as described next.

*Smart Lamps:* model consumer appliances that feature sporadic on/off behaviours, such as actual lights, vacuum cleaners, TV sets or hot plates. When switched on, a smart lamp may consume at full or reduced power - 100W or 30W in the simulation. This enables a lamp's manager to reduce its consumption in case of high load; such reduction attempt is ignored in case the user set the lamp in "comfort" mode. "Eco-friendy" lamps advertise Flexible Consumption Packets when consuming at full power and Non-Flexible Packets otherwise; "comfort" lamps are always Non-Flexible.

*Smart Heaters:* model thermostatic appliances such as electric heaters, air conditioners or hot water tanks. Power management for these prosumers consists in anticipating or delaying heating and cooling periods in order to shift power consumption cycles [14]. Such management does not reduce quality of service, since target temperature intervals are still respected. To avoid oscillating behaviours, cycle shifts are followed by "refractory periods" during which the heater is Non-Flexible; otherwise the heater appears Flexible.

*District Management:* an organisation based on the Hierarchy pattern was implemented for the district. Here, house Power Managers represent district Prosumers. They aggregate the Prosumption Packets from their appliances into two district-level Prosumption Packets, advertising the *flexible* and *non-flexible* parts of the overall house prosumption. The district Power Manager monitors the district grid's state via a global schedule similar to the one used in houses and sends orders to house managers - either *reduce load* or *any load*. House managers accepting an order reduce their maximum prosumption limit (e.g. 800W to 200W in the following scenarios), this new viability domain affecting in turn the house's internal power management.

In short, this sample implementation integrates a Stigmergy organisation (house holon) with a Hirerarchy (district holon). The House Manager provides the necessary functions for making the transition between: the house as a whole - with its internal Stigmergy organisation; and the

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[1] available online at http://perso.telecom-paristech.fr/∼sfrey/

[2] cf. http://www.osgi.org and http://akka.io

house as a part of the district - playing a Prosumer role in the Hierarchy. Namely, the House Manager uses internal device information to provide an aggregate state to its supra-organisation, as if it represented the state of a single part. In the other direction, the House Manager receives orders from its supra-organisation (as if it was a single part), decides to accept them or not (depending on internal conflicts), and translates them for its internal organisation (as changes in the house goal in this case).

Other integration scenarios can also be envisaged. For instance, if the house was also organised as a Hierarchy, external orders from the District Manager would simply be translated into internal orders for Device Managers. A house organised as a completely decentralised Stigmergy or as a Collaboration would have to create and provide aggregate states in a decentralised manner; also, devices would have to react individually to external orders and coordinate their actions so as to ensure the desired effect at the house level.

### C. Scenarios and Results

The purpose of the presented experiments is to show how control solutions can be recursively integrated by having an entire organisation (whole) represent one part in a higher-level organisation. Obtained results indicate the viability of this (holonic) integration approach. They are *not* meant to validate any of the control solutions presented, either individually or composed; nor to evaluate their performance.

The **House Grid Scenario** features a house composed of 6 rooms, containing 6 heaters and 5 lamps (simulated as described above). Fig. **??** shows the house Power Manager objective, the sum of lamp consumptions, and the total house consumption. House consumption includes all heaters and lamps, averaged over a short sliding window for visibility reasons. This scenario consists of three consecutive phases:

***Phase 1:*** the house Power Manager pursues a constant house objective that imposes a maximum consumption of 800W. Heaters pursue constant temperature goals in their rooms. In the middle of phase 1 (about 100 s), residents trigger several *non-flexible* lamp consumptions. The heaters compensate for the load increase (as described above) so the house consumption goal is not overshoot.

***Phase 2:*** only heaters are consuming. The house Power Manager lowers the maximum house consumption objective from 800W to 200W, in reaction to a district signal (cf. next scenario). The 6 heaters, each one consuming 200W, manage to schedule themselves collaboratively so that their total consumption meets the goal with limited error. All returns to normal when the house goal is reset to 800W.

***Phase 3:*** features an *inflexible* lamp consumption, as in phase 1. Also, a simulated cold wave forces heaters through more frequent heating cycles. Since the user does not allow heaters to reduce their temperature or lamps to degrade their quality of service, the total house consumption increases abruptly. This is consistent with the user's preferences, which prioritised comfort over energy savings/bill.

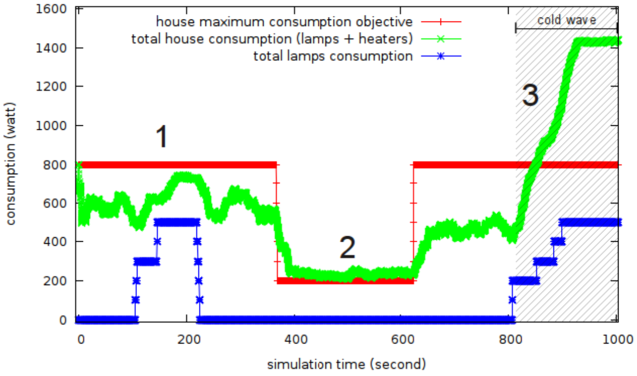

Figure 4. House scenarios.

The **District Grid Scenario** could be very similar to the one run at the house level, due to the smart grid's holonic architecture. Indeed, in this case, flexible houses would compensate for high-consuming neighbours (phase 1 above), global loads would adapt to changes in the district's maximum consumption goal (phase 2), and excessive consumption would occur when a majority of houses would go into comfort mode (phase 3). Fig. **??** shows another type of scenario, where the district administrator tests the range of possible system responses. Starting from a district goal with overly-high maximum consumption, the administrator decreases this value step-by-step. Results show how houses are able to adapt their consumptions in response to district goal reductions, until the limit becomes too small for the heaters to follow - i.e. from 800s onwards the houses, and implicitly the heaters, can no longer schedule themselves to further reduce their consumptions. The simulation was run with 8 houses similar to the one described above.

A prompt and regular adaptation reaction from the district grid, even if measured under constant conditions, is a good result for a district administrator. It indicates that the district is likely to feature several specific constants, such as minimum and maximum prosumption plateaux within which the district's load can adapt. This in turn will help implement district power management policies with respect to the higher grid levels - region and country. The district's flexible response suggests that there is room for adaptability making precise prosumption targets achievable at the district scale. More importantly, this means that house-level power management, although not under the direct control of the district manager, may contribute to achieving the district administrator's objectives. This was precisely the overall aim of the integration architecture proposed in the paper.

## VI. CONCLUSIONS & FUTURE WORK

This paper presented a holonic architecture for smart-grid control, which enables the recursive integration of

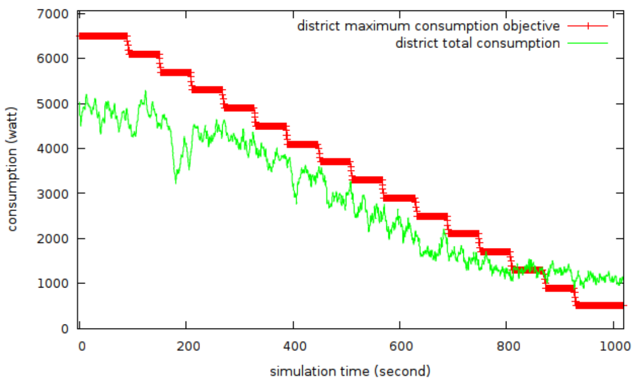

Figure 5. District scenario.

heterogeneous control solutions implemented at different grid scales. The purpose of this contribution was to address a number of stringent requirements that we identified for the future grid, including multiple authorities, conflicting objectives, heterogeneity of control solutions and scalability. We have identified three main integration patterns that seem to characterise state-of-the-art control solutions in the domain; and showed how such solutions can be integrated via exchanges of state information, goals and conflict resolution.

We experimented with a proof-of-concept implementation of two of the patterns, integrated together and run on a distributed smart grid simulator. The obtained results indicated the viability of the approach, including most notably:

- the ability to achieve multiple objectives, both individual (micro-) and global (macro-), by integrating heterogeneous appliances and controllers into organisations operating at two grid levels - house and district;
- the ability for administrators to dynamically tune the priorities of their objectives, in order to rebalance results at the micro and macro levels;
- the ability for several administrators to specify and pursue their conflicting interests at various grid levels while maintaining the coherence of the macro-level, where critical economic interests lie.

Future work will focus on studying the behaviour of the presented approach and simulator in additional control scenarios at larger grid scales. This will include the introduction of new types of prosumers such as local producers and storage facilities. In addition to experimenting with different combinations of concrete organisations and algorithms, we can explore the possibility of having organisations self-adapt to contextual changes, swapping between integration patterns that are best suited in each case.

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