Dynamic coalition formation and adaptation for virtual power stations in smart grids

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ABSTRACT

An agent-based organizational model for a smart energy system is introduced relying on a dynamic coalition formation mechanism for virtual power station (VPS) creation. Following, for VPS maintenance a solution concept is proposed that stems from the existent stability solutions in coalitional games and is introduced in conjunction with a corresponding algorithm, deployed in distributed environments populated by negotiating agents. The algorithm is intended as an open-ended organizational adaptation, concerned with achieving stable configurations that meet the desired functionalities within stochastic scenarios.

Categories and Subject Descriptors

I.2.11 [**Artificial Intelligence**]: Distributed Artificial Intelligence *Coherence and coordination, intelligent agents, multiagent systems*

General Terms

Algorithms, Design

Keywords

virtual power stations, distributed generation, multi-agent systems, coalition formation, emergent organization

1. INTRODUCTION

In recent years, there is an increasing interest in the integration of distributed, small-scale, renewable generation into the power system. An efficient use of distributed energy resources (DER) may increase the flexibility and the resilience of the power system at distribution level. Furthermore, it is possible to reduce the dependence from large-scale, non-renewable, power plants and therefore to contribute to a sensible reduction of CO_2 emissions. According to the US department of Energy, a 5% increase in grid's efficiency is equivalent to the fuel and CO_2 emission of 53 million cars.

The potential allure of the multiagent system paradigm (MAS) to the power industry has been extensively documented so far [1]. To this respect, several management systems have been proposed for the organization of micro-grids [3]. A micro-grids is defined as a subsystem of the distribution grid, formed by generation, storage and load device, interconnected at the electrical and the informational level. Micro-grids can be intended as a systemic approach to realize the emerging potential of distributed generation.

Setting aside from this approach that aims at imposing an architectural control, whether centralized or not, on already predefined micro-grids, our vision is intended at proposing a method for congregating the smart-grid actors to dynamically approximate optimal micro-grid configurations. Thus, the main concern is developing techniques aimed at establishing and adapting a suitable virtual organizational structure. The procedure is designed such that it develops on the concept of integrating DERs in the form of virtual power stations [5]. A virtual power station (VPS) is conceived as a bundle of DERs that are connected through an informational infrastructure and act in a coordinated way as a single entity. The challenging problem related to the implementation of the VPS concept is the distributed control of the DERs, mainly due to the stochastic behaviour of the system and the heterogeneity of the devices involved.

The aim of this work is modelling the coordination of virtual power plants in the sense of coalitional games. Instead of considering centralized architectures [4, 5], we claim that a dynamic, bottom-up, approximation of optimal VPS configurations is more effective to ensure flexibility and robustness to the system.

2. PROBLEM REPRESENTATION

The coalition games we aim to address in our approach are the ones where the coalition formation problem is projected on an underlying network topology, given that the cost for cooperation also plays a major role. This class of games is primarily characterized by non-superadditivity, in the sense that gains resultant from forming coalitions are limited by the actual cost of coalition formation[1] and coordination, thus the grand coalition is seldom the optimal structure. Furthermore, the coalitional game is subject to the dynamism of the environment. The challenge is to develop mechanisms that permit large number of autonomous agents to collectively achieve a desired functionality by permanent adaptive dynamics.

In our scenario, we set to investigate the integration of renewable energy resources to the grid in the form of virtual power stations by means of aggregating the power generating potential of various devices in a novel way in the context of MAS. As system designers, we choose to enable the autonomous agents with the basic coordination primitives, and leave to the agents to self-organize and coordinate as the situation may demand, in a fully distributed manner.

[1]The cost of forming a coalition can be perceived through the negotiation process and information exchange which incur costs.

We model the problem as a dynamic coalition formation game with the following formalization:

Let $M = \langle \mathcal{A}, \beta_i, \mathcal{S}, \Phi, v \rangle$ be a multi-agent system where:

- $\mathcal{A} = \{a_1, a_2, ..., a_n\}$ represents the set of agents of a given portion of the distribution grid. We assume that each stakeholder that is connected to the grid is represented by a software agent that manages the corresponding device (e.g., generators, storage devices, intelligent loads).
- β_i is the forecast amount of electricity for the following day associated with agent a_i. If $\beta_i > 0$, then agent a_i is a *provider*, whilst if $\beta_i < 0$ then agent a_i is a *consumer* (or load). Let $\mathcal{P} \subseteq \mathcal{A}$ denote the set of providers, and $\mathcal{L} \subseteq \mathcal{A}$ the set of consumers. In this work we assume that an agent is either a provider or a load, and therefore $\mathcal{P} \cup \mathcal{L} = \mathcal{A}$, $\mathcal{P} \cap \mathcal{L} = \emptyset$. We will refer onwards generically, to an agent belonging to set $\mathcal{P}$ as PA, and to an agent belonging to set $\mathcal{L}$ as LA.
- $S = \{S_1, S_2, ..., S_m\}$ is the set of coalitions that partition the set $\mathcal{A}$. We assume that all coalitions are disjoint, and therefore:

$$\bigcup_{j=1}^{m} S_j = \mathcal{A}, \quad S_j \cap S_k = \emptyset, \forall\, j \neq k$$

- $\Phi = \{\phi_1, \phi_2, \phi_3\}$ is a set of constraints that must hold for every coalition. In this work, we enforce that the number of members of each coalition does not exceed a predefined value N, which corresponds to the safety limit imposed by technological constraints (ϕ_1). We also want that each coalition is able to supply electricity to all the loads, so as the energetic balance between generation and consumption must be positive (ϕ_2). Finally, each coalition must realise a desired generation profile of electricity that would qualify them as VPS (ϕ_3). Formally:

$$\phi_1 : |S_j| \leq N \quad \forall j \in \{1, ..., m\}$$

$$\phi_2 : \sum_{a_i \in S_j} \beta_i > 0$$

$$\phi_3 : \sum_{a_i \in \mathcal{P}_j} \beta_i = \psi$$

  where $\mathcal{P}_j = \mathcal{P} \cap \mathcal{S}_j$, and ψ represents the desired energetic profile that each coalition wants to achieve.

- $v : \mathcal{S} \rightarrow R$ is a function that for every coalition of the set $\mathcal{S}$ returns its utility value, representing a multi-criterion evaluation of domain specific parameters.

The goal of the coordination problem is obtaining a partitioning of $\mathcal{A}$ into a coalition structure $\mathcal{S}$ that complies with the set of constraints Φ and at the same time maximises the social welfare[2] of the system, without jeopardizing the functionality of any of the coalitions. We leave aside for now what this trade-off implies and further develop on this issue in Sections 5.

[2]For computing the social welfare of the system we mean the typical interpretation of averaging over the utilities of all coalitions.

3. COALITION FORMATION MECHANISM

Our proposed approach is intended as a decentralized and dynamic method. Here coalition formation is achieved by opportunistic aggregation of agents, while maximizing coalitional benefits by means of taking advantage of local resources in the grid. It consists of three phases.

- *Coalition initiation.* To accomplishing this task we have chosen a straightforward approach: the PAs whose energy availability exceeds a predefined threshold value are entitled of establishing themselves as VPS initiators and will do so with a probability p inversly proportional to the number of the agent's PA uncommitted neighbors that are also set to do so.

- *Provider aggregation phase.* This procedure dynamically constructs the organizational structure via a negotiation mechanism, where proposals and requests are handled opportunistically. The initiator PA assumes the role of CA (coordinator agent) for the emergent coalition. The mechanism proceeds in a Contract Net-like fashion with the following steps: CAs send requests to their neighboring PAs indicating the VPS profile that they want to realize, in terms of scale and energetic potential [3]. Based upon these specifications PAs evaluate CAs' offers and select the preferred choice from their candidate set. Eventually, CAs receive offer responses and decide committing PAs.

  The CA's decision is based on calculating an association coefficient that reflects the self-sufficiency of the potential coalition i assuming the joining of actor j. This is denoted as a linear combination of the parameters that apply for this particular case study: security measures (which implies computing contingency analysis - C_j), transmission costs (T_j) and energetic balance (E_j):

$$\varphi_{i,j} = w_1 \cdot C_j + w_2 \cdot T_j + w_3 \cdot E_j \tag{1}$$

  We note that the first two parameters (of negative values) are ought to give an indication of the network's capability of avoiding line overloads and incurred transmission costs. The former gives an indication of the impact that the integration of the LA's load would produce on the system's buses in terms of the percentage of capacity drop. By transmission costs we imply the effect of the power loss in the course of transmission, over the coalition's total power, represented by this ratio. The last parameter represents the percent increase or decrease of the coalition's energetic balance, given the desired state of offer matching demand. Formulating the association coefficient in this manner allows placing more emphasis on the contingency and transmission coefficients at the beginning of the aggregation of actors, while the energetic balance gains more significance proportionally to the number of actors involved. This is obviously a key aspect since one cannot expect attaining a reasonable energetic balance at the very

[3]The constraints imposed on the coalition formation process may vary according to the desired feature of the emerging VPS.

beginning of the coalition formation process. The utility function of the coalition, v, represents the sum of the association coefficients for the coalition members, as shown in Equation 2.

$$v(S_i) = \sum_{j \in S_i} \varphi_{i,j} \tag{2}$$

- *Consumer aggregation phase.*

  Once the VPS energetic potential has been ensured, the only remaining phase requires the aggregation of LAs. This operates in a similar manner. LAs proceed by submitting their forecasted demand to the CAs in their proximity. For each such request, the CAs calculate the corresponding association coefficient. Based on this information, a proposal response is being awarded to the most suitable LAs for joining the coalition, by enclosing its corresponding association coefficient. LAs will conclude the procedure by selecting the coalition whose utility is mostly increased by their commitment. The decision is unequivocally accepted by the CA since it comes as a response to its precedent proposal and it is exclusively addressed to the CA. The LAs' preference for acting in this sense is justified by the fact that the utility of the coalition would have a direct effect on its reliability.

  To be noted that the decision of selecting the best candidate is carried without a complete representation of the environment, but rather based on local and possibly incomplete knowledge. This is the underlying reason for the evolutionary nature of the algorithm that iteratively approximates a solution through refinement steps.

4. COALITION SELF-ADAPTATION

The second important issue we tackle regards the notion of stability that the system is capable to achieve, given the dynamism of the environment. Thus, the problem we are facing in open organizations requires a modification of the coalition structure due to the variations occurring within the system. All actors submit on a daily basis their forecasted profile, which typically does not differ exceedingly from their previous one. Nevertheless these cumulated variations would entail a reorganization of the coalitions for the following forcasted period in order to assure enhanced coordination at the coalition level. Therefore, consequent to calculating the energetic balance of the coalition, it is to be determined the actors that would qualify to be signed-off, or the profile of the actors that would be eligible to be signed-in to the coalition. The association network generated during the coalition formation process, revealing the existing interdependencies within the coalition, plays a key role at this stage. The weakest links signify the actors the coalition is least dependent on, based on which agents are to be proposed for being signed out of a coalition.

With these considerations in mind we seek a notion of equilibrium that intrinsically provides an argumentation scheme, which allows for a reorganization of the coalition structure. Furthermore, the solution concept should reflect the decentralization outlook of our scenario, while minimizing the structural adaptations by providing a minimum set of interaction rules in order of attaining the desired stability properties amongst negotiating agents.

The solution we propose can be directly referenced to game-theoretic approaches on issues of stability and negotiation. For further considerations on notions of stability, their strength, limitations and interrelations we refer the reader to [2]. In our scenario, of utmost importance is the agents' capability to coordinate and reorganize into groups or coalitions by transforming traditional game-theory criterions of stability towards operating in dynamic environments. Moreover, we advocate for reorienting game-theory to accomodate situations where coordination is a more natural operational descriptor of the game rather than simply self-interested settings. As it is emphasized in [2], an equivalent formulation for solution concepts can be in interpreted in terms of objections and counter-objections. More formally, let x be an imputation in a coalition game with transferable payoff $(\mathcal{A}, v)$, we define our argumentation scheme as follows:

- (S, y) is an objection of coalition S to x against T if S excludes i and $e\left(S \cup \{i\}, x\right) > e\left(S, y\right)$
- coalition T counteracts to the objection of coalition S against accepting player i if $e\left(T \cup \{i\}, y\right) / e\left(T, x\right) > 1 + \mu$ or $e\left(T \cup \{i\}, y\right) + e\left(S, y\right) > e\left(T, x\right) + e\left(S \cup \{i\}, x\right) - \tau$.

To correlate the game-theoretic terms introduced above to our setting, we give the interpretation of these terms for our scenario. Specifically, by imputation we mean the distribution of utilities over the coalitions' set, whereas the excess e of each coalition represents the difference between its potential maximum (see Section 2) and its current utility v

We reason that the excess criteria applied for solution concepts such as the kernel and the nucleolus appears to be an appropriate measure of the coalition's efficiency, especially in games where the primary concern lies rather in the performance of the coalition itself. This basis further advocates for argumentation settings where objections are raised by coalitions and not by single players, such as the case of the bargaining set or the kernel. The objection (S, y) may be interpreted as an argument of coalition S for excluding i resulting in imputation y where its excess is being decreased. Our solution models situations where such objections cause unstable outcomes only if coalition T to which the objection has been addressed fails to counterobject by asserting that S's demand is not justified since T's excess under y by accepting i would be larger than it was under x. Such a response would have hold if we simply presumed players to be self-interested and not mind the social welfare of the system. If on the contrary, players are concerned with the overall efficiency of the system, they would consider accepting the greater sacrifice of y in comparison to x only if this would account for an improvement of S that exceeds the deterioration of T's performance by at least the margin τ. Thus, τ is the threshhold gain required in order for justifying the deviation, whereas μ represents S 's tolerance to suboptimal gains.

For applying this solution concept to our setting, we additionally need to take into account the underlying topology and thus restrain the inter-coalition argumentation to the given network structure, representing a particularization of the more generic outline presented herein. When multiple objections are being adressed to one coalition, its decision of considering one would be based on the criteria of maximizing parameter τ, while minimizing parameter μ. Also worth

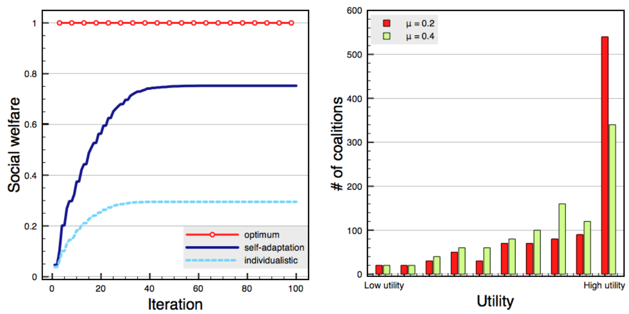

Figure 1: a) Social welfare of the system in number of steps. b) Histogram representation for the utilities of the coalitions

reminding is that the procedure is ought to occur within the domain dependent constraints, that impose maintaining the profile of the coalition within certain limits (see Section 2). Finally, we stress that the aim for our proposed scheme is intended towards an open-ended organizational adaptation concerned with achieving stable configurations in dynamic environments where one-shot optimization procedure are unapplicable.

5. EXPERIMENTAL RESULTS

To begin with, we first evaluate the performance of our algorithm attained through the argumentation scheme introduced. Given the cooperative scenario reflected by our chosen solution concept we have set aside from the Pareto optimal instance[4] where self-interested agents agree to participate in a trade if and only if the contract increases the agent's immediate payoff.

Figure 1(a) points out the average percent increase in social welfare, that the system manages to attain from an initial state to a stable one, achieved during the course of the adaptation phase. A stable configuration of the system is abruptly reached, meaning that the agreements realized earlier improve the social welfare more than the ones performed later. Furthermore, the solution applied is an anytime algorithm that achieves a monotonic improvement of the global (social) welfare of the system

Subsequently we perform a series of experiments to draw more insight to the solution concept introduced. On one hand, our negotiation scheme implies that deviations would only occur if a certain minimum gain τ has been achieved. On the other hand, the extent to which a coalition is willing to decrease its efficiency in detriment of the gain in social welfare is represented by a satisfactory parameter μ. This represents in effect a percentage, which defines what an acceptable performance would be and how tolerant is one coalition towards suboptimal performance. For our simulations we chose an initial value of 0.4 and considered a homogenous population of actors in the system. Although this does not make the objective of our scenario, heterogeneity amongst the actors involved may as well be introduced.

Following, we analyzed the implications of the dependency on this parameter for a better understanding of its functionality. Thus, we have analyzed the stationary states the system falls into as a function of μ. For large values of μ, meaning that coalitions are willing to significantly decrease their utility with respect to the improvement of the global welfare of the system, we encountered an expected global increase in utility, but a considerable variation in the allocation of utilities in the system. Figure 1(b) illustrates a histogram representation of the coalitions' utilities discretised in increasing order of their worth. It can be seen that a 20% increase of μ reduced significantly the number of coalitions operating at high efficiency denoted by the last column of the histogram, while the number of coalitions operating at lower levels of efficiency has been increased. The results emphasized that the best performance of the system was obtained for values of μ in the vicinity of 0.2 . Somewhat surprisingly, what the experiments show is that being willing to accept lower efficiencies in the benefit of the global performance is only advantageous to a certain extent. In actuality, there is a trade-off to be taken into account. Although the overall system utility increases, the ratio between the number of coalitions with low utility and those with high utility is increasing as well. So, for assesing the efficiency of the system not only should we be interested in the global utility, but also in having a uniform distribution of high utilities for the majority of the coalitions.

Future work will further look to a greater extent at the electrical features of the power system and incorporate in a more factual form load-flow computation analyses, that verifies for contingencies and maintains the system within its operational limits.

[4]Represented in the graphs as the individualistic approach.

6. CONCLUSIONS

As a proof of concept our work has introduced a dynamic coalition-based model deployed in distributed environments of negotiating agents. The formation and adaptation mechanism introduced perform an open-ended adaptation of groups of organizational agents, converging towards stable configurations. In particular, we have highlighted the applicability of this approach through the design of a distributed adaptive scheme for the smart electricity grid.

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