Grid-Independent Cooperative Microgrid Networks with High Renewable Penetration

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***Abstract*—Microgrids (MG) with renewable energy resources have shown competitive operational advantages for smart grid integration. In the wake of events such as the July 2012 India blackout, recent interest has been directed to the deployment of MGs in grid-independent (islanded) settings. In this paper we develop an autonomous distributed framework for cooperation amongst a set of grid-independent microgrids to improve the overall microgrid network (MGN) reliability. We further develop an enhanced distributed algorithm to support the proposed system. This work adopts a game theoretic approach via coalition formation games (CFG) formulation for static and dynamic MGNs. We consider MGNs with variable renewable distributed energy resources (DER) penetration levels and variable wind generation percentage of the total renewable generation mix. Main results show cooperation gains for cooperative MGN, study the effects of rate policies, and show how the proposed system performs under different renewable DER penetration levels and wind generation percentages.**

I. Introduction

Microgrids (MG) are now a widely acceptable smaller scale power networks that are capable of supplying local controllable loads and utilizing distributed energy resources (DERs) as well as energy storage technologies. MGs not only help alleviate power demand on the grid, but also could save power losses along transmission and distribution line as generation is in more proximity to the load. Microgrids proved to be valuable in their resilience and reliability specially during blackouts and major grid instabilities.

MGs and the emerging nanogrids are being positioned to represent modulator building blocks for future smart grid distribution. Many industries are already implementing projects for remote areas where the power delivery solely depends on MGs and DERs [1], [2]. In such setups connectivity to the grid might be available or not based on proximity to urban infrastructure and the amount of investment required to establish the connectivity. Interestingly, it is expected that consumers will be tempted in the future to shift to off-grid power distribution alternatives.

MGs with increasing penetration levels of renewable DERs face challenges as a result of the intermittent nature of these resources. The main challenges are scheduling and stability analysis due to resources variability and uncertainty. Different approaches exist to address the variable and uncertain nature of these resources, but it still requires incorporating energy storage technologies to bridge the energy gap associated with renewable DERs [3].

Different storage technologies being deployed in various parts of the smart grid where they enable solutions such as frequency and voltage regulation, load shifting and shaving. Benefits of utilizing storage technologies extend to applications such as better harnessing intermittent renewables such as wind [4], in addition to the importance of storage for solving mismatch problems in microgrids with DERs [5].

Power availability and reliability of isolated deployments of grid-independent MGs, particularly MGs with intermittent DERs, could be improved by promoting coordinated operation between the different MGs. A Microgrid Network (MGN) is composed of a group of microgrids that are capable of interacting with each other on the physical and cyber levels. An MGN operates either in integrated mode; in which the MGN is connected to the grid to supplement demand and absorb surplus; or in independent mode, where the MGN is isolated from the grid.

MGNs provide an opportunity for researchers to consider new power delivery design schemes. Previous research in this arena looked at various interactions between microgrids. Different optimization control techniques have been employed to coordinate resources between MGs [6], [7], [8]. Moreover, researchers have considered different hierarchies for interconnecting MGs [9], [7]. Matamoros *et al.* [10] considered power trading between islanded MGs as an optimization problem. Meanwhile, Saad *et al.*[11] and Wei *et al.* [12] looked at cooperation between microgrids with grid connectivity using coalition formation game theory.

Most of the work referenced above proposed sharing internal information of local MG parameters to help facilitate the coordination between MGs. Also most of the results were shown for a grid connected MGN with a limited network size.

We present a general system model to coordinate between microgrids in a grid-independent microgrid network. The proposed model extends the work presented by Saad [11] and Wei [12] for grid connected MGs. Moreover, we develop an enhanced distributed algorithm for solving the CFG. We further extend our attention to the resulting dynamics of the proposed model, and the effect of incentives in enhancing desired dynamics. As a case study, we show the benefits of the proposed system model in improving the reliability of MGNs with high penetration levels of renewable DERs and high wind generation percentages.

The contributions of this work are summarized as follows; develop a system model for autonomous cooperative MGN

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operating in grid-independent mode. Design a distributed algorithm for the cooperative MGN controllers in the aforementioned system model, and showcase the benefits of the model for MGN with high DER penetration levels.

This paper is organized as follows. A quick review of coalition formation game formulation is presented in section II-A, then we introduce and discuss the proposed system model in section III. Simulation results and their discussion are presented in section IV.

II. Cooperative Microgrid Networks: Coalition Formation Game Theory

This paper considers cooperation between MGs using a cooperative game theoretic based approach. Coalition Formation Games (CFGs) provide a suitable framework to study cooperation in networks, and help answer questions such as which coalitions will emerge and how do the structure of the formation change in response to variations in number and strength of players.

A. Coalition Formation Games (CFG)

A set of N players seek to strengthen their position in a game by forming coalitions. A coalition worth in a game is quantified by a quantity denoted as coalition value v; hence, a coalition game is uniquely defined by (N, v). CFG deal with two notions of rationality: individual rationality (i.e. players seek the best payoff) and collective rationality (i.e. only stable groups will emerge for which the coalition value is the best).

For a coalition game with transferable utility (TU) and N players [13], [14], [15], the coalition value function $v : 2^N \rightarrow \mathbb{R}$ assigns a value for each $S \subseteq N$ with $v(\varnothing) = 0$. The coalition value function v describes the maximum collective payoff a set of players gain by forming a coalition.

Lets define an imputation as a game outcome (possible solution), which is a payoff distribution vector $x = \{x_1, x_2, ..., x_n\}$ among N players, that satisfies group rationality $\sum_i^N x_i = v(N)$ and individual rationality $x_i \geq v(i)$, for all players. A good payoff vector is one that is stable; in which members have no incentive to leave a coalition and seek other coalitions with better payoff, and fair; where the payoff vector is distributed amongst coalition members in away that relates to members contribution to the coalition value. In cooperative games the core solution concept is defined as the set C of stable payoff distribution vectors (imputations) that satisfies group and individual rationality.

To arrive at solutions for a coalition formation game means to find a stable structure that lies in the core. This is generally a complex problem, since an N number of agents have 2^N possible coalition structures. One approach to arrive at the optimal structure is to evaluate the utility of all possible structures in an exhaustive search and select the structure with the best coalition value. This approach is of an exponential complexity [16].

Algorithmic approaches [17][14][18] have been favoured to arrive at solutions with a much lower complexity. Apt *et al* formalized preference relations between partitions(Pareto Order), and described an algorithmic approach that utilizes progressive merge and split rules based on the Pareto Order [14]. Interested readers are encouraged to refer to [14], [18] for detailed elaboration. In the following Pareto order definition a collection refers to a coalition formation structure where coalitions are disjoint.

Definition 1 (Pareto Order)**.** [14], [11] Let the same players $\mathcal{N}$ be formed in two collections of disjoint coalitions, collection $\mathcal{C}$ and collection $\mathcal{K}$ and let the payoff of a player j in a coalition $C_j \in (C)$ be defined as $\phi_j(C_j)$. Collection $\mathcal{C}$ is preferred over $\mathcal{K}$ by Pareto order, if and only if the payoff of at least one player j under $\mathcal{C}$ is better than the payoff under $\mathcal{K}$ for all players where $j \in \{1, \ldots, N\}$.

III. System Model

Assume a distribution environment with N microgrids, as shown in figure 1. Each MG is parameterized by location, power requirements, where a positive value implies surplus (producer) and negative value indicates shortage (consumer), and power rates (unit price of power exchanged between a consumer and a producer MG pair).

In the proposed cooperative MGN each MG has an internal controller to balance its demand and supply, and an external controller to coordinate the network of interconnected MGs. The model utilizes a global energy storage (GS) for the MGN to facilitate the coordination of power exchange and to ensure the balance of the MGN. We also include different power rate policies in the system model to allow for the study of the effect of rates as incentives for cooperation.

The proposed MGN can work in two modes; a non-cooperative mode where each MG interacts with the storage to supply or consume power. And a cooperative mode where MGs self-organize into coalitions such that consumer and producer MGs in a coalition coordinate power exchange within the coalition, the resulting coalition may interact with the storage in the case of net power surplus or shortage.

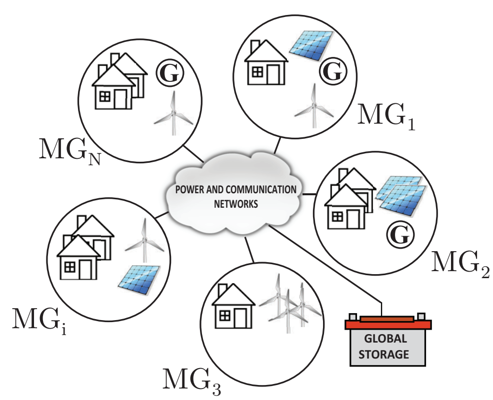

Fig. 1. A schematic of a grid-independent cooperative microgrid network

Let a cooperative MGN initialize with N MGs where each MG is classified, according to its power requirements at time t, to be either a consumer or producer. Consequently let S_{cons}

represent the subset of consumer MGs and S_{prod} be the subset of producer MGs. Let $\mathcal{P}$ be defined as the amount of power exchanged during cooperation, and define P_i as the power requirements of MG_i. The cooperative coalition formation game of N MGs is defined as $(N, v), v : 2^N \to \mathbb{R}, \forall S \subseteq N$.

For every coalition S, given an order $\tau \in \Gamma$, where Γ is the set of all different orderings of consumers in $S_{cons} \in S$. We define the utility of coalition S as a function of the overall cost of power, described in equation (1). The overall cost depends on rates and amounts of power exchanged. The rates R_1, R_2 and R_3 are the power rates for power exchange in-between MGs, between consumer MGs and the storage, and between producer MGs and the storage, respectively. Power exchange between consumer MGs and the storage is denoted by $\mathcal{P}_{is}$, similarly power exchange between producer MGs and storage is denoted as $\mathcal{P}_{js}$. The minimum utility under all orderings $u(S, \tau)$ is the value v of coalition S.

$$\begin{aligned} u(S,\tau) = \quad & \textstyle\sum_{\substack{i \in S_{cons} \\ j \in S_{prod}}} R_1 \mathcal{P}_{ij} + \\ & \textstyle\sum_{i \in S_{cons}} R_2 \mathcal{P}_{is} + \sum_{j \in S_{prod}} R_3 \mathcal{P}_{js} \end{aligned} \tag{1}$$

$$v(S) = \min_{\tau \in \Gamma} u(S, \tau) \tag{2}$$

Dynamics of the proposed cooperative MGN are affected by amounts of power exchanged, rates and losses. Amounts of power exchange are found as a solution of the aforementioned game. Losses over distribution lines are calculated according to $P_{ij}^{loss} = R_{ij} I_i^2 + \beta \mathcal{P}_i = \frac{\mathcal{P}_i^2 R_{ij}}{U_1^2}$, where R_{ij} is the resistance of the corresponding distribution line and is a function of distance between MGs and line resistance. I_i is the current in the distribution line during the power exchange of amount $\mathcal{P}_i$. The dynamics of equations (1) and loss equation result in two forces, one guiding the coalition formation towards a one big group (the grand coalition), and one pushing towards the non cooperative case where each coalition is composed of one MG (singleton coalitions).

In this work we adopt an algorithmic approach to arrive at a stable coalition structure. We propose the Distributed Merge-Swap Algorithm (DiMSA) outlined in algorithm 1. In the algorithm description, let $S(MG_i)$, where,$|S(MG_i)| \geq 1$ be defined as the coalition S containing MG_i as one of its members. The algorithm initializes with N singleton coalitions. Without loss of generality we adopt a proportional payoff distribution formula among MGs in a coalition.

where the relation $\triangleright$ is defined as the Pareto order, and ϕ is the individual payoff of MG_i. The swap step is further defined as follows:

$$\text{SWAP}(cons(i), prod(m), cons(w)) = \\ \begin{cases} S(prod(m), cons(w)) \to S(prod(m)), \{cons(w)\} \\ S(prod(m)) \cup cons(i) \to S(prod(m), cons(i)) \end{cases} \tag{3}$$

For our cooperative MGN, we next lay the assumptions underlying the system model;

- **Connectivity**; all MGs have full communication and power line connectivity, and are allowed to exchange power over the power network. The model relies on MGs coordinating with minimum information exchange.
- **Storage**; the storage is accessible by all MGs, and is able to support multiple power transactions simultaneously. Further, storage is assumed to be of unlimited capacity.
- **MGs**; MGs are assumed to be rational players. we also assume that an MG prioritizes its internal power demand before interacting with other MGs or the storage.

Algorithm 1 Distributed Cooperative MGN Formation Algorithm (DiMSA), executed by the MNCC at $MG_i, \forall i \in \{1, \ldots, N\}$

```
INITIALIZE S_i^(0) = {MG_i, Storage}, ∀i ∈ {1,...,N}
for iteration It := 1 → NoItr do
  for cons(i) := {i := 1, → No.ofConsumers} do
    Enumerate preferred producer list based on losses
    if the most preferred producer could meet the power needs of cons(i) then
      if S(cons(i), prod(m)) ▷ {S(prod(m)), cons(i)} then
        Join: cons(i) ∪ S(prod(m)) → S(prod(m), cons(i))
        Continue to next cons(i)
    else if cons_i needs not met by the most preferred producer then
      Index := rank of the least preferred attached producer
      for m := 1 → Index − 1 do
        if prod(m) max load is attached to the consumer then
          Continue to next prod(m)
        else
          Find list of consumers attached to prod(m) → list
          for w := 1 → length(list) do
            if (cons(i) ∪ prod(m) ▷ cons(w) ∪ prod(m)) and
            (φ^future(cons(j)) ▷ φ^current(cons(i))) based on (1)
            then
              SWAP(cons(i), prod(m), cons(w))
```

A. Cooperation Measures

To evaluate the benefits of coordination for cooperative MGN, it is insightful to define a gain measure. We define cooperative gain CG as the normalized difference between non-cooperative (cost$^{non-coop}$) and cooperative (cost^{coop}) power cost as expressed in equation (4). Non-cooperative power cost cost$^{non-coop}$ is calculated based on N individual MGs that interact directly with the storage as shown in (5), and the cooperative power cost is based on the value of the cooperative coalition formation game.

$$\text{CG} = \frac{\text{cost}^{non-coop} - \text{cost}^{coop}}{\text{cost}^{non-coop}} \tag{4}$$

$$\text{cost}^{non-coop} = \sum_{i \in S_{cons}} R_2 P_{is} + \sum_{j \in S_{prod}} R_3 P_{js} \tag{5}$$

As we include the energy storage to facilitate the interaction between the individual MGs in an MGN, it is valuable to introduce a quantifying measure for how dependent would the distributed cooperation be on the storage. System design could benefit from this measure to plan necessary limits of storage capacity needed to support the cooperative MGN. This is specially interesting with the case of intermittent renewable DERs. Let the storage dependency ratio (SDR) be defined by equation (6), it is clear from this definition that the SDR for the non-cooperative MGN is equal to 1.

$$\text{SDR} = \frac{\max\{\sum_i \mathcal{P}_{is}, \sum_j \mathcal{P}_{js}\}}{\max\{\sum_i P_{is}, \sum_j P_{js}\}} \tag{6}$$

IV. Numerical Results and Discussion

The numerical results in this section divide into two parts; static MGN and dynamic MGNs with varying penetration levels of renewable DERs.

A. Static MGN: measures and performance

In this section we seek to provide further insight into the dynamics of cooperation and the DiMSA algorithm performance. All quantities with no loss of generality are in per unit bases. N MGs are randomly divided into two subsets of consumers and producers with corresponding random energy requirements of values between $[0-100]$. MGs are randomly placed on a grid of 10x10, with the GS placed at the center. Power losses are calculated based on a line resistance of $R = 0.1$ and line voltage $U_1 = 1$. For representative results the various measures are averaged over a large number of iterations 10000.

Results are shown in figure 2 for a fixed rate policy $R_1 = 1, R_2 = 2, R_3 = 1$, where interestingly cooperation gain showed to be robust to the size of the network at a around 50% . This result hints that the algorithm is always able to arrive at an optimal coalition structure. In addition result exhibit a substantial cooperation gain for cooperative MGN over non-cooperative MGN. SDR results show a similar behaviour. Further, results show that the algorithm run time increase vs. N follows a polynomial function of second order.

To study the effect of power rate policy on the dynamics of the cooperative MGN, we fix $R_3 = 2$ and set $N = 20$ while we vary R_1, R_2. Results are shown in figure 3. It is clear that cooperation is strongly discouraged for high values of R_1 in the region where R_2 is lower than R_1 and R_3.

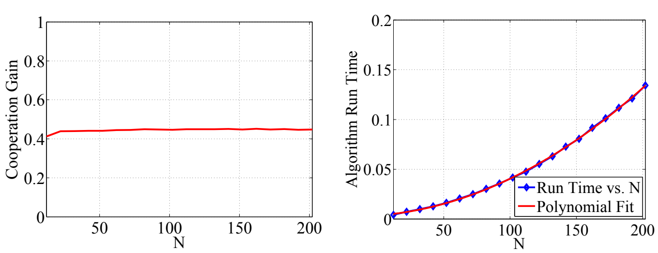

Fig. 2. Cooperative gain and algorithm run time vs. N.

B. Dynamic MGN with renewable DERs

The simulation setup considers an MGN of $N = 10$ MGs, each containing a random number of loads, wind turbines, PVs and diesel generators. The DER resources are assigned randomly to satisfy a renewable DER penetration level. Further, we guide the assignment of renewable DER resources by specifying the energy mix percentages between wind and PV. The community of the MGN is designed such that there is an overall balance between load and generation.

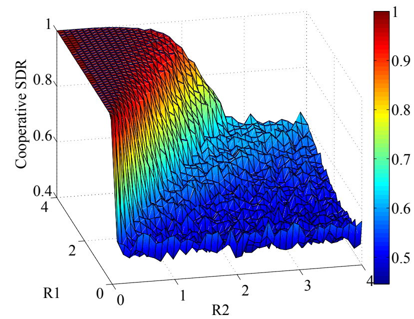

Fig. 3. SDR for fixed $R_3 = 2, N = 20$ and variable R_1, R_2.

For the preassigned duration of the simulation, we generate the corresponding load and power generating resources profiles with a one hour sample period. We use home load and PV generation profiles that are based on data generated by [19], [20] using EnergyPlus Simulation software [21].

As for wind generation profiles, we rely on equation (7) to calculate the power output of a wind turbine [22].

$$P = k * C_p * \rho * \frac{1}{2} * A * V^3 \tag{7}$$

where, P = power output (kW), C_p = maximum power coefficient $[0.25 - 0.45]$, ρ = air density (lb/ft^3) A = rotor swept area (ft^2), V = wind speed (mph) and $k = 0.000133$ which is a constant to yield the power in kilowatts. In this work, we consider the specifications of $5kW$ wind turbine with a diameter of $5(m)$. Further, wind speed is calculated by sampling a two-parameter Weibull probability density model [23], which is described using equation (8)

$$f(x) = (k/\lambda) * (x/\lambda)^{(k-1)} * \exp(-(x/\lambda)^k) \tag{8}$$

where k,$\lambda 0$ are the shape and scale parameters of the Weibull distribution respectively. The Weibull shape and scale parameters here are set at $k = 1.94$ and $\lambda = 4.48$.

We next study the time evolution of the MGN using the proposed cooperative MGN and DiMSA algorithm. In case 1, we consider 100% renewable DER penetration, with a wind generation percentage of 80% and 20% PV, results shown in figures 4 show that the proposed cooperative MGN can support very high levels of renewable DER penetration with reasonable storage capacity, and the figures describe the involved cooperation dynamics.

In case 2, we study the average performance of the proposed system with fixed wind generation percentage at 80%, and varying renewable DER penetration level between $[0-100\%]$. Results in figure 5 show that as the penetration level increases the capacity of required storage increases, as well as the SDR ratio. We renewable DER penetration level at 60% for case 3 and vary wind generation percentage of the DER mix between $[0 - 100\%]$. Interestingly, the results in figure 6 show that increased percentages of wind energy could actually help cooperation and relief the dependency on the storage. Moreover, the required storage capacity is reduced as well with increased wind generation percentages.

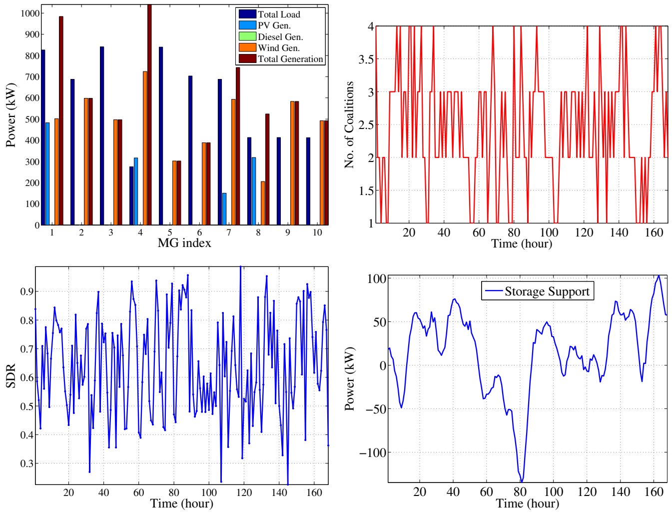

Fig. 4. Case1: DER penetration $= 100\%$, and wind generation at $= 80\%$

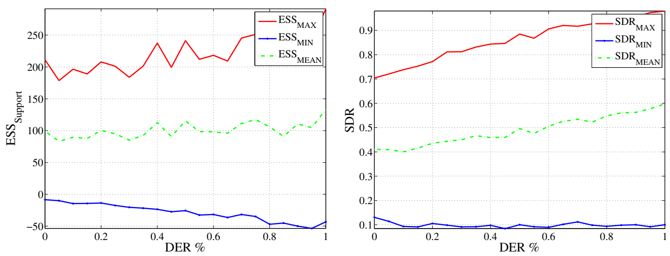

Fig. 5. Case2: storage support and SDR vs. DER penetration.

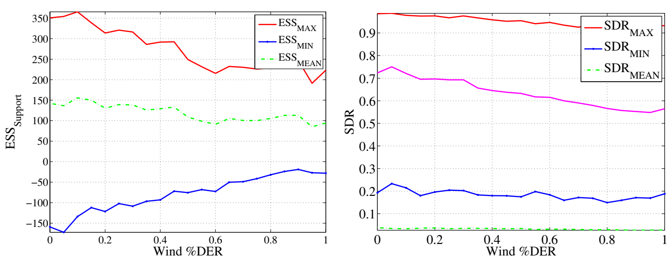

Fig. 6. Case3: storage support and SDR vs. wind generation percentage.

V. Conclusions

This work proposes an autonomous cooperative framework for grid-independent microgrid networks, and formulates an enhanced distributed algorithm (DiMSA) for the proposed framework. The model is based on coalition formation games that accounts for power rate policies and transmission line losses. We study the ability of proposed global storage to facilitate cooperation amongst the MGs within the network. The objective of proposed system is to improve individual MG demand-supply balance by cooperation, as well as to best utilize renewable DER by exchanging surplus with cooperating MGs.

Numerical results demonstrate the benefits of employing this cooperative model specially for high penetration levels of renewable DERs, and provide insights into the dynamics of cooperation, dependency on the storage, and capacity limits of the storage needed for different penetration levels and different wind generation percentages.

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