Canonical Coalitional Games vs. Coalition Formation Games for Power Exchange Management of Networked Microgrids

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Abstract. The concept of networked microgrids, which refers to a cluster of microgrids connected with each other, has emerged in the literature as a consequence of the increasing development of renewable energy. Energy management systems have been developed for planning, monitoring and controlling the power exchange into networked microgrids. Their main components are optimization algorithms for power exchange management. Several optimization algorithms based on coalition formation games were proposed to minimize distribution and transformation power loss of networked microgrids. Unlike these approaches, this paper proposes a non-lineal model based on canonical coalitional game for power exchange management of networked microgrids. To show the performance of the proposed model, results of the model and results of an algorithm based on coalition formation games recently reported in the literature are compared with. The main conclusion of this work is, when the objective is to minimize total power losses, the problem of power exchange management of networked microgrids should be modelled as a canonical coalition games and not as coalition formation games.

1 Introduction

Electrical microgrids integrate renewable energy sources as solar panels or wind turbines, controllable distributed generators as fuel cells or micro turbines and battery energy storage systems to meet local loads demand [1].

With the increasing development of renewable energy, the concept of multi-microgrids [2] or networked microgrids [3] has emerged in the literature, which refers to a cluster of microgrids connected with each other. The aim of networked microgrids is to achieve resilience and stability through power exchange among them and smooth the incorporation of distributed generation into power systems [4].

The intermittent nature of wind and solar power could cause energy deficit or excess at different times of the day. This poses new challenges to the power exchange management of networked microgrids [5].

Responding to these challenges, Energy Management Systems (EMS) have been developed for planning, monitoring and controlling the power exchange into networked microgrids. The three classical management system architectures, centralized, decentralized and hybrid, where proposed to design EMS for networked microgrids. A summary of these EMS architectures and a discussion of their strengths and weaknesses can be found in recent literature [6].

Main components of EMS for networked microgrids are optimization algorithms for power exchange management [7]. Several optimization algorithms based on coalition formation games, also known as coalition structure formation, were proposed to minimize distribution and transformation power loss of networked microgrids connected to a macro station.

A coalition structure of a set of microgrids MG = {1, …, N} is defined as the set of disjoint coalitions $\Pi = \{S_1, S_2, \dots, S_n\}$. The number of coalition structure that can be formed is exponential in the number of microgrids N, and, more importantly, it is huge even relative to the number of coalitions 2^N.The size of Π_N is the number of partitions of a set of size N, which is known as a Bell number BN. This number can be shown to satisfy $(N/4)^{N/2} \leq BN < N^N$. This implies that the direct enumeration approach will take super-polynomial time [8]. So, heuristic based algorithms were proposed for finding good coalition structures. Particularly, a coalition formation algorithm based on merge and split rules that uses the Pareto order concept for merging or splitting decisions was proposed [9]. Based on this last algorithm, different approaches, which use distance threshold between microgrids and/or pricing mechanism to limits the number of coalition structures to be analysed, have been proposed for power exchange management of networked microgrids [5] [10–13]. The main drawback of these algorithms is that, a value function verifying the superadditivity property could be defined by considering total power losses by transmission and transformation due to energy exchanged between microgrids and with the macro station to meet the power balance of a coalition. The superadditivity property of the value function guarantees that grand coalition is the best coalition structure.

Some approaches based on the grand coalition (canonical coalitional games) were proposed in the literature. But, unlike this work, they are focused on different network topology; apply a lineal model for computing power losses instead of the conventional AC Optimal Power Flow (ACOPF) non-lineal model [4]; are focused on both the contractual aspects of the electricity market [14] or the battery usage aspects [15] without considering transmission and transformation power losses; or are limited to only consider the energy exchange between two microgrids [16].

This paper proposes a non-lineal model based on canonical coalitional game for power exchange management of networked microgrids interconnected with the main grid through a macro station. To show the performance of the proposed model, results of the model and results of an algorithm based on coalition formation games recently reported in the literature are compared with.

The remainder of this paper is structured as follows: Section 2 presents the networked microgrids topology in which the work is focused; Section 3 presents the canonical coalitional game based model for power exchange management proposed in this work; Section 4 presents a comparative analysis of results of both the proposed canonical coalitional games based model and the coalition formation games based algorithm recently reported in the literature. Finally, Section 5 presents conclusions and future work.

2 Topology of networked microgrids

A distributed network composed of a set of microgrids MG={1, …, N} and a macro station MS connected to the main grid through a transformer is considered (Figure 1). The main grid operates at high voltage, while energy can be exchanged between microgrids at medium voltage. A Central Controller CC coordinates the energy power transmission of a microgrid. Central controllers are interconnected and each knows the generation and demand forecasts of the microgrid that it coordinates.

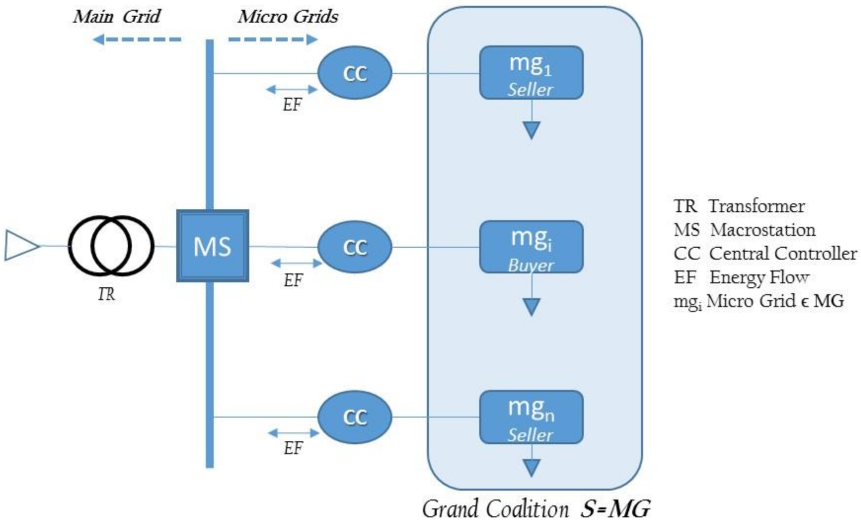

Fig. 1. Topology of a set of networked microgrids.

For a given time period, usually of one hour, a power production forecast P_i and a load demand forecast D_i for each microgrid i∈MG are generated. Based on these forecasts, the power surplus ($Q_i = P_i - D_i > 0$) or the power deficit ($Q_i = P_i - D_i < 0$) is calculated, which defines the state Q_i of microgrid i∈MG. The state of networked microgrid set MG for the time period is defined as $Q = \{Q_1, \ldots, Q_N\}$.

3 Canonical coalitional games based model

Grand coalition S involves all microgrids i∈MG. Microgrids with power surplus ($Q_i > 0$) define the seller set MGS and microgrids with power deficit ($Q_i < 0$) define the buyer set MGB. So, grand coalition S = MGS ∪ MGB = MG.

Definition1: for a given state $Q = \{Q_1,, \ldots, Q_N\}$ of networked microgrid set MG, a power exchange strategy defines the power that microgrids i∈MGS and microgrids j∈MGB exchanges between them and with macro station m∈MS to meet the power balance of grand coalition S.

Definition 2: when microgrids exchange energy between them only transmission power loss should be considered and, when the macro station intervenes, transmission and transformation power loss should be considered.

Definition 3: an optimum power exchange strategy minimizes transmission and transformation power losses of grand coalition S.

Definition 4: when microgrid i∈MGS delivers power K_{im} to macro station m∈MS, power loss by transmission and transformation P_{im}^{loss} is given by Equations 1.a and 1.b. [10]

$$P_{im}^{loss} = RU_{im} * K_{im}^2 + \beta * K_{im} \quad (1.a)$$

$$RU_{im} = \frac{R_{im}}{U_{im}^2} \quad (1.b)$$

Where, R_{im} is the resistance of distribution line, β is the power lost fraction by power transformation at macro station and U_{im} is the tension over distribution line.

Definition 5: when microgrid j∈MGB receives power P_{mj} from macro station m∈MS, power loss by transmission and transformation P_{mj}^{loss} is given by Equations 2.a and 2.b. [10]

$$P_{mj}^{loss} = RU_{mj} * K_{mj}^2 + \beta * K_{mj} \quad (2.a)$$

$$RU_{mj} = \frac{R_{mj}}{U_{mj}^2} \quad (2.b)$$

Where, K_{mj} is the power that macro station m∈MS delivers to ensure microgrid j∈MGB receives power P_{mj}. It is given by Equations 3.a and 3.b. [10]

$$K_{mj} = P_{mj}^{loss} + P_{mj} \tag{3.a}$$

$$K_{mj} = RU_{mj} * K_{mj}^2 + \beta * K_{mj} + P_{mj} \tag{3.b}$$

Parameters, variables and sets .

S: coalition of microgrids S ⊆ MG

MGS ⊆ S: set of microgrids seller with power surplus (Qi> 0) that participate of grand coalition S.

MGB ⊆ S: set of microgrids buyer with power deficit (Qi < 0) that participate of grand coalition S.

MGB ⋃ MGS = S.

MGB ⋂ MGS = Ø.

MS = {m}: set of macro station.

P_{ij}: Power received by microgrid j∈MGB from microgrid i∈MGS.

K_{ij}: Power delivered from microgrid i∈MGS to microgrid j∈MGB.

P_{im}: Power received by macro station m∈MS from microgrid i∈MGS.

K_{im}: Power delivered from microgrid i∈MGS to macro station m∈MS.

P_{mj} : Power received by microgrid j∈MGB from m∈MS.

K_{mj}: Power delivered from macro station m∈MS to microgrid j∈MGB.

Qi: power offered by microgrid i∈MGS (Qi = Qi).

Qj: power required by microgrid j∈MGB (Qj = - Qj).

RU: resistance of distribution line divided by square tension over distribution line.

β: fraction of power lost by transformation at macro station m∈MS.

Objective Function.

The objective function u({S}) is defined as total power losses by transmission and transformation due to the power exchanged among microgrids and the power exchanged with macro station m∈MS to meet the power balance of coalition S (Equation 4).

$$Min\, u(\{S\}) = \sum_{i \neq j \in S}[RU_{ij} * K_{ij}^2] + \sum_{i \in S}[RU_{im} * K_{im}^2] + \sum_{j \in S}[RU_{mj} * K_{mj}^2] + \beta * (\sum_{i \in MGS} K_{im} + \sum_{j \in MGB} K_{mj}) \tag{4}$$

Constrains.

Power received by microgrid j∈MGB from microgrid i∈MGS (Equation 5).

$$P_{ij} = K_{ij} - RU_{ij} * K_{ij}^2 \quad \forall\, i \in MGS,\ \forall\, j \in MGB \tag{5}$$

Power received by macro station m∈MS from microgrid i∈MGS (Equation 6).

$$P_{im} = K_{im} - RU_{im} * K_{im}^2 - \beta * K_{im} \quad \forall\, i \in MGS,\ \forall\, m \in MS \tag{6}$$

Power received by microgrid j∈MGB from macro station m∈MS (Equation 7).

$$P_{mj} = K_{mj} - RU_{mj} * K_{mj}^2 - \beta * K_{mj} \quad \forall\, j \in MGB,\ \forall\, m \in MS \tag{7}$$

Power balance of microgrid i∈MGS (Equation 8).

$$K_{im} + \sum_{j \in MGB} K_{ij} = Q_i \quad \forall\, i \in MGS \tag{8}$$

Power balance of microgrid j∈MGB (Equation 9).

$$P_{mj} + \sum_{i \in S} P_{ij} = Q_j \quad \forall\, j \in MGB \tag{9}$$

The optimization model could be used for generating the optimum power exchange strategy of any coalition S ⊆ MG.

Definition 6: the function value v(S) of coalition S is v(S) = min u({S}).

It should be noted that any collation S = S'⋃{i} verifies v(S) ≤ min u({S'}) + v({i}). So, value function v(S) verifies the superadditivity property. This property ensures that function value v(S) of grand coalition S = MG will be smaller that the function value v(S') of any coalition S'⊂MG.

Definition 7: an individual coalition S involves a single microgrid that exchanges its power surplus or deficit with the main grid through the macro station.

When microgrid i∈MGS delivers power K_{im} = Qi to macro station m∈MS, power loss by transmission and transformation P_{im}^{loss} is defined by Equation 1 and, when microgrid j∈MGB receives power P_{mj} = - Qi from macro station m∈MS, power loss by transmission and transformation P_{mj}^{loss} is defined by Equation 2. So, the corresponding value functions of individual coalitions {i} and {j} are defined by Equations 10 and 11.

$$v(\{i\}) = u(\{i\}) = P_{im}^{loss} \tag{10}$$

$$v(\{i\}) = u(\{j\}) = P_{mj}^{loss} \tag{11}$$

4 Canonical Coalitional Games vs. Coalition Formation Games

The comparative analysis was performed for a 12-MG and a 24-MG networks recently reported in the literature [5]. Parameters values in both scenarios are: resistance of distribution lines R =0.2 Ω/km; power lost fraction by power transformation at macro station β = 0.03; tension over distribution line between microgrids U_{ij}=25kv and between a microgrid and the macro station U_{im}=50kv. Only active power exchange is considered.

For a given time period, the state reported for the12-MG network, existing connections and microgrid locations are reported in Figure 2. Seller set MGS = {3, 5, 6, 8, 10, 12} and buyer set MGB = {1, 2, 4, 7, 9, 11}.

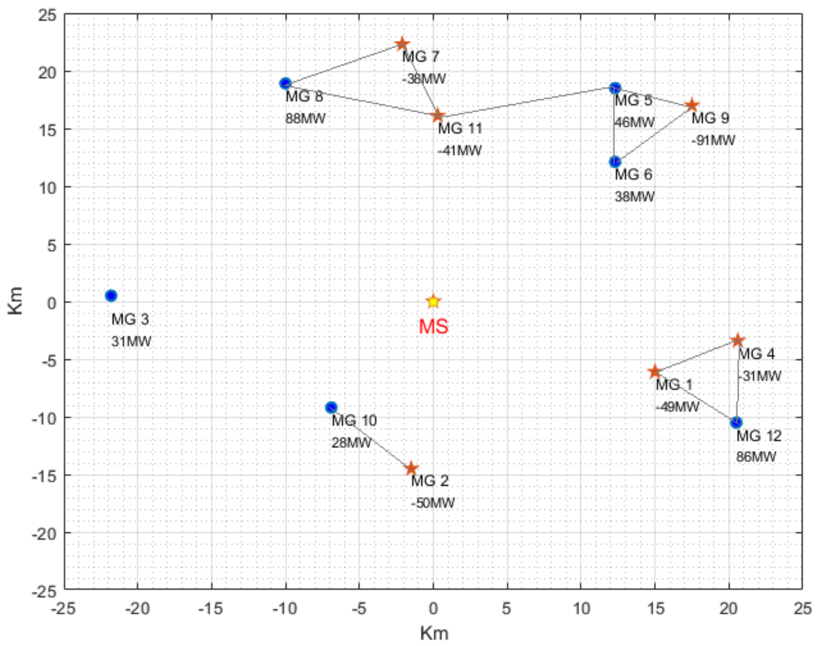

Fig. 2. Location for the12-MG network [km], reported states *Q [MW]*, and existing connections.

Figure 3 shows the state reported for 24-MG network, existing connections and microgrid locations. Seller set is MGS={4, 7, 8, 12, 13, 15, 18, 19, 21, 22, 23, 24} and buyer set MGB={ 1, 2, 3, 5, 6, 9, 10, 11, 14, 16, 17, 20}.

For both cases, 12-MG and 24-MG networks, it is was assumed that microgrids separated by a distance less than 14,5 km are connected with electric lines and are capable to power exchange between them and all microgrid are connected with the macro station [5].

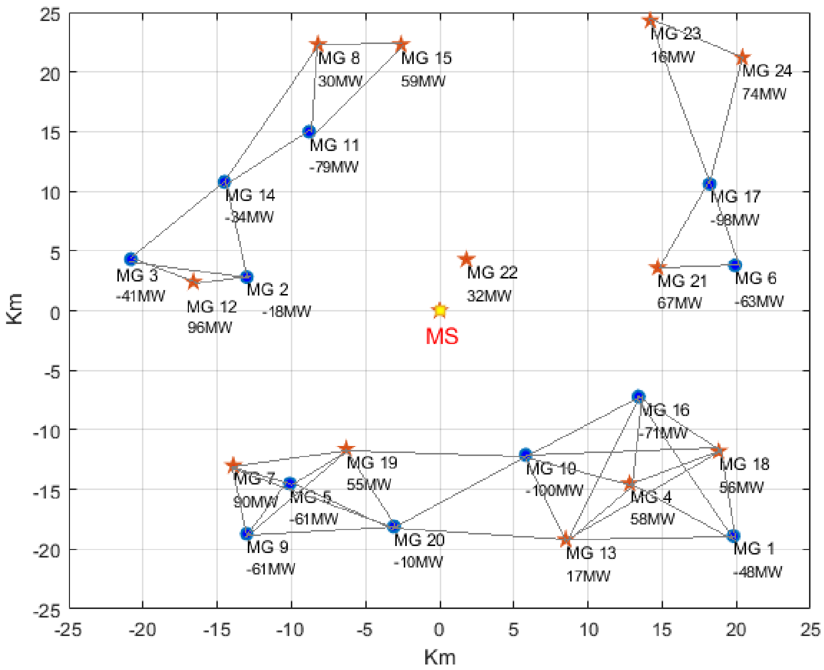

Fig. 3. Location for the24-MG network [km], reported states Q [MW], and existing connections.

4.1 Results of the Canonical Coalitional Games based model

Results obtained for 12-MG network by using the canonical coalitional games based model proposed in this work are summarized on Table 1. D is the power delivered from either microgrid i∈MGS or macro station m∈MS. R is the power received by either microgrid j∈MGB or macro station m∈MS. L is the transmission and transformation loss. The total loss for 12-MG network is v(S) = 29 MW.

Table 1. Results of the canonical coalitional games based model for the 12-MG network.

D	Delivered	j∈MGB																					
L	Loss	1			2			4			7			9			11			Kim			
R	Received	D	L	R	D	L	R	D	L	R	D	L	R	D	L	R	D	L	R	D	L	R	Ki =Qi
i∈MGS	3																			31,0	2,6	28,4	31,0
	5													39,9	2,8	37,1	6,1	0,1	6,0	0,0	0,0	0,0	46,0
	6													31,3	2,2	29,1	6,7	0,2	6,5	0,0	0,0	0,0	38,0
	8										33,3	3,0	30,2				25,0	2,1	22,9	29,7	2,4	27,3	88,0
	10				25,8	1,6	24,2													2,2	0,1	2,1	28,0
	12	36,7	3,0	33,7				30,1	2,1	28,1										19,2	1,3	17,9	86,0
	Pmj	16,2	0,8	15,3	27,5	1,7	25,8	3,0	0,1	2,9	8,1	0,4	7,8	27,0	2,2	24,8	5,9	0,2	5,7	Total Loss			29,0
	Pj =Qj	49,0			50,0			31,0			38,0			91,0			41,0			v(S)			MW

Results obtained for 24-MG network by using the canonical coalitional games based model are summarized on Table 2. The total loss for 24-MG network is *v(S)* = 53.8 MW.

The proposed model was solved by using LINGO 17.0 x64. The run time for both cases was less than 1 second running on a PC, Intel i7, 32Gb RAM.

Table 2. Results of the canonical coalitional games based model for the 24-MG network.

D	Delivered	j∈MGB																	
L	Loss	1			2			3			5			6			9		
R	Received	D	L	R	D	L	R	D	L	R	D	L	R	D	L	R	D	L	R
i∈MGS	4	15,5	0,6	14,9															
	7										38,2	1,9	36,3				35,9	2,4	33,5
	8																		
	12				18,4	0,4	18,0	39,1	2,3	36,9									
	13	2,8	0,0	2,8															
	15																		
	18	20,1	0,9	19,1															
	19										20,0	0,6	19,4				15,2	0,7	14,5
	21													35,3	2,1	33,3			
	22																		
	23																		
	24																		
	Pmj	11,9	0,7	11,2				4,3	0,2	4,1	5,5	0,2	5,3	32,4	2,7	29,7	13,8	0,8	13,0
	Pj =Qj			48			18			41			61			63			61

D	Delivered	j∈MGB																					
L	Loss	10			11			14			16			17			20			Kim			
R	Received	D	L	R	D	L	R	D	L	R	D	L	R	D	L	R	D	L	R	D	L	R	Ki =Qi
i∈MGS	4	24,2	1,4	22,8							18,2	0,8	17,5										58
	7																7,2	0,2	7,0	8,8	0,4	8,4	90
	8				23,5	1,3	22,2	6,5	0,2	6,3													30
	12							22,0	1,3	20,6										16,5	0,9	15,6	96
	13	11,3	0,3	11,0							2,9	0,0	2,8										17
	15				34,6	3,7	30,9													24,4	1,8	22,6	59
	18	14,9	0,9	14,0							21,0	1,0	20,0										56
	19	16,7	1,1	15,6													3,1	0,0	3,0				55
	21										9,6	0,3	9,3	22,1	1,2	20,8							67
	22																			32,0	1,3	30,7	32
	23													16,0	1,2	14,8							16
	24													41,5	6,0	35,5				32,5	3,5	29,0	74
	Pmj	39,4	2,8	36,5	27,7	1,9	25,8	7,4	0,3	7,1	22,7	1,3	21,4	29,1	2,3	26,8				Total Loss			53,8
	Pj =Qj			100			79			34			71			98			10	v(S)			MW

Tables 1 and 2 show for each MG into the set of seller, the power they send, the loss produced by transmission and the power that will be received by the MG into the set of buyers. For example, for the 12-MG network scenario, the MG12 places D=36.7 MW of power at MG1's disposal. MG1 receives R=33.7 MW of power because the transmission losses are L=3 MW. MG1 buys the availability of power to the macro station of R=15.3 MW. Due to the fact that L=0.8 MW of transmission and transformation losses are produced, the macro station must supply D=16.2 MW. MG12, after commercializing with MG4, sells its surplus to the D=19.2 MW macro station, but due to transformation and transmission losses, the macro station receives L=17.9 MW.

4.2 Results of the Coalition Formation Game based algorithm

Coalition structures $\Pi = \{S_1, S_2, \dots, S_n\}$ reported in literature [5] as those obtained by using an heuristic coalition formation algorithm based on merge and split rules, the Pareto order concept, distance threshold between microgrids and a pricing mechanism, are evaluated. The minimum loss of each coalition $S_i \in \Pi$ was obtained by using the canonical coalitional games based model. Results obtained for both the 12-MG and 24-MG networks are summarized on Tables 3 and 4.

Table 3. Losses of the coalition structure *Π_{12MG} = {CI, CII, CIII, CIV, MG3}* reported for the 12-MG network [5]

				Coalitional Loss [MW]
12-MG	Coalition I	*mg8, mg7, mg11*	V(CI)	12,89
	Coalition II	*mg10, mg2*	V(CII)	4,8
	Coalition III	*mg5, mg6, mg9*	V(CIII)	11,68
	Coalition IV	*mg1, mg4, mg12*	V(CIV)	10,54
	Individual Coalition	*mg3*	V(mg3)	0,93
	Total Losses [MW]		V(Π_{12MG})	**40,84**

Table 4. Losses of the coalition structure *Π_{24MG} = {I, II, III, IV, V, VI, MG10, MG22}* reported for the 24-MG network [5]

				Coalitional Loss [MW]
24-MG	Coalition I	*mg8, mg15, mg11*	V(CI)	8,83
	Coalition II	*mg14, mg3, mg12, mg2*	V(CII)	5,34
	Coalition III	*mg7, mg5, mg19, mg9, mg20*	V(CIII)	7,74
	Coalition IV	*mg16, mg18, mg4, mg13, mg1*	V(CIV)	8,35
	Coalition V	*mg21, mg6*	V(CV)	6,1
	Coalition VI	*mg23, mg24, mg17*	V(CVI)	16,95
	Individual Coalition	*mg10*	V(mg10)	18,7
	Individual Coalition	*mg22*	V(mg22)	1,34
	Total Losses [MW]		V(Π_{24MG})	**73,35**

The literature reports run times of 1.06 seconds for executing the heuristic coalition formation algorithm running on an Intel Processor 5Y70 CPU 1.3 GHz environment.

4.3 Results analysis

The minimum power loss obtained for Coalition I = {MG8, MG7, MG11} (Table 3) by using the model based on canonical coalitional games is v(Coalition I) = 12.89 MW, which is close to the 11.20 MW reported in the literature. This difference is due transmission and transformation losses of Coalition I produced by the sale to the macro station of its power surplus (10.2% of the 88 MW of power surplus of MG8) are not accounted for.

Comparing the total power loss value reported in Table 1 (29 MW) with that reported in Table 3 (40.84 MW) for the 12-MG network, it can be seen that the model based on canonical coalition games allowed to obtain an energy exchange strategy that reduces power loss by 29%.
A similar analysis of total power loss value reported in Table 2 (53.8 MW) and that reported in Table 4 (73.35 MW) for the 24-MG network yields a power loss reduction of 26%.

5 Conclusion and future work

A non-lineal model based on canonical coalitional game for power exchange management of networked microgrids interconnected with the main grid through a macro station was presented.
The model was used for generating the power exchange strategy that minimizes the power loss for two scenarios recently reported in the literature: 12-MG network and a 24-MG network. The performance of the proposed model was assessed by comparing, for each scenario, power loss values obtained for the grand coalition with that obtained by summing the power loss of each coalition in the coalition structure reported in literature. The power loss reduction obtained for each scenario shows the good performance of the proposed model when comparing with a recently proposed coalition formation game based algorithm. In other words, results shows that, even though heuristics algorithms can find good coalition structure different of the grand coalition, the grand coalition is the best. So, taken into account that running times of both approaches are similar, investing time and effort in looking for these good structures is not justified.
As conclusion of this work, the following issues must be emphasizes:

- Coalition structure games were developed for modelling coalition games which value function does not verify the superadditivity property. But, as it is shown in this work, transmission and transformation power losses of networked microgrids define a value function that verifies the superadditivity property. So, the problem of to define a power exchange strategy for networked microgrids that minimizes total power losses must be modelled as a canonical coalition games.
- The proposed model is not only better in terms of power loss reduction when compared with those based on coalition structure formation, but also, it has the value of being independent of distance thresholds between microgrids and/or pricing mechanisms.
- Even though the benefit distribution is a central issue of coalitional games for which different fairness criteria, such as egalitarian fair, Shapley value, core, nucleolus and proportional division were proposed, the scope of this work was limited to analyse the canonical coalition games versus the coalition structure games as modelling strategy of the problem of power exchange management of networked microgrids.

Future works will be focused on to develop a planning and execution monitoring model for a hybrid EMS architecture.

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