Cellular Automata Model with Game Theory for Power Management of Hybrid Renewable Energy Smart Grids

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Abstract. In recent years, control of smart grids that match electricity demand in different sites and forms with supply has been considered as one of the most difficult aspect of smart energy grids design. In this paper we present a Cellular Automata (CA) based approach combined with Game Theory for the enhancement of Power Management Strategies (PMSs) of multiple Hybrid Renewable Energy Systems (HYRES) that form a smart grid for the exchange of energy. More specifically, taking advantage of the local interactions of HYRES we coupled CA principles with Public Goods Game (PGG) for modeling. The presented CA model focuses on providing valuable feedback for PMSs of the understudy HYRES connected in a grid. In this manner, a flexible network based HYRES design is considered and applied to specific HYRESs located in Olvio, near Xanthi, Greece, part of SYSTEMS SUNLIGHT facilities. The proposed model can be applied to the understudy HYRESs grid management to enhance and optimize its PMS based on the provided energy prediction scenarios.

Keywords: Cellular Automata, Game Theory, Modeling, Power Management Strategy, Hybrid Renewable Energy System, Smart Energy Grids.

1 Introduction

The applying control of smart grids that match electricity demand in different sites and forms with supply has been considered as one of the most difficult aspects of smart energy grids design [1]. On the other hand, a new type of Renewable Energy Systems (RES) is becoming all the more popular as a response to the continuously growing need for green energy [2]. That is the *Hybrid Renewable Energy Systems* (HYRES). Such a hybrid energy system usually consists of two or more renewable energy sources used together to provide increased system efficiency as well as greater balance in energy supply. This combination offers the advantage of exploiting

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different types of green energy without completely depending on the availability of a single one. Therefore, hybrid systems present a better balance in energy production than the conventional systems, which make use of a single technology and tend to be more inconsistent. However, despite the advantages that the adoption of HYRES may have, there are still some weak spots. Research and development efforts are required for: improving their performance, establishing techniques for accurately predicting their output reliably and integrating them with other conventional generating sources. Moreover, the cooperation between the different discrete systems does not often occur in the most efficient way. For example, storage of the excess energy supply does not always occur in the most effective way and thus the system usually depends on conventional fuels. The optimized management of the various co-operating subsystems is the key point towards achieving the best possible green energy utilization and system efficiency.

In this context, the term "cooperation" is leading to game theory, which is defined as the analysis of mathematical prototypes of collaboration and antagonism between intelligent rational decision-makers [3]. Moreover, taking into consideration the technological advances in smart grids design, *Cellular Automata* (CA) concept can be considered as a wise choice to model them. More specifically, smart energy grids are designed with greater number of HYRESs, which are found in a more mesh or grid-like regular structure and the resulting distribution of the electricity produced and stored is becoming more complex. In regards to the aforementioned Game Theory, one of the most suitable for our case study examples is the *Public Goods Game* (PGG) [4-8], because there are systems that compete for the overall produced energy, which are affected by the decisions made and the resulting consumption.

As a result, a model was produced using game theory concepts, and more specifically PGG, on CA lattice, to simulate the impact of the conflict of many nodes of a smart energy grid demanding electricity. Additionally, this model will also be easily coupled with an autonomous HYRES, where its estimations can be used by a central control unit in order to create in real time the proper Power Management Strategies (PMSs) for the efficient smart energy grid utilization that can lead to the overall optimization. For doing so, a generic network model is also described for the representation of the hybrid power generation systems taken into consideration in this work. In order to test the efficiency of the proposed model an already implemented HYRES which locate at premises of Systems SUNLIGHT at Xanthi Greece is considered. The architecture of the smart grid into consideration and the systems which are connected to the smart grid are illustrated in Fig. 1. Each system serves its own AC load (1kW), the power is produced using a PV rated at 2.7kW, 5.4kW and 15kW respectively. Lead-acid battery (BAT) arrays of 2000Ah, 2000Ah and 3000Ah are also utilized to provide the necessary power to the systems during night time and when the available renewable power is not enough to serve the demanded loads. As a backup option each system has a diesel generator (DG) of 1.1kW. Furthermore two of them (System 2, System 3) are equipped with wind generators (WG), 3kWp each. At System 3 there is a 4kW Polymer Electrolyte Membrane (PEM) electrolyser (EL) that generates hydrogen from the excess of energy and stores it at 30bar pressure cylinders. Finally System 3 has a 4kW PEM Fuel Cell (FC) system that produces power when required using the stored hydrogen. Within each standalone system DC and AC busses are established where each device is connected to them through appropriate power converters (Fig. 1). The specific system combines different renewable technologies, has some storing capabilities and also includes a conventional energy generator as a backup unit. The current HYRES system supplies a part of SYSTEMS SUNLIGHT facilities with electricity, without the interference of any other power plant.

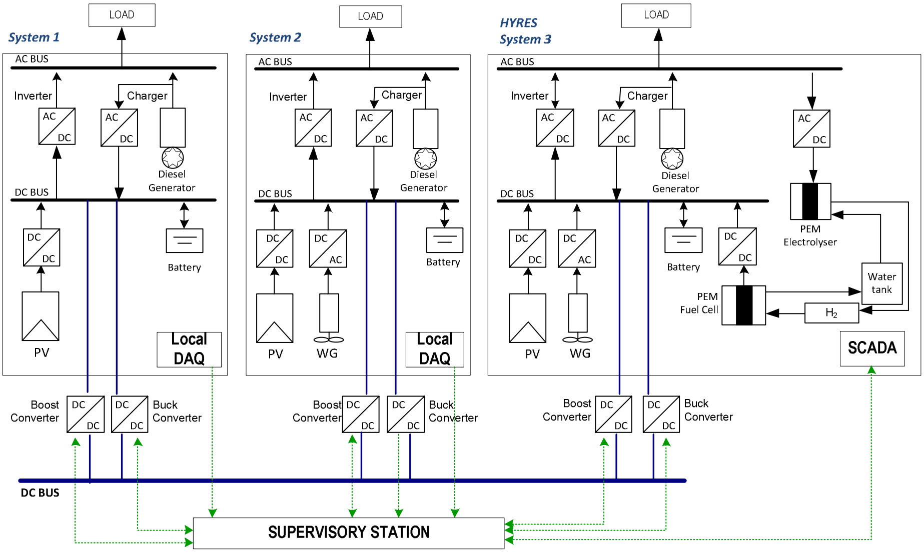

Fig. 1. System topology, architecture of the smart grid node and information flow among the systems, the converters and the supervisory station

2 The Proposed Cellular Automaton Model Using Public Goods Game Concepts

In order to apprehend the dynamics between cooperation and competition for power management and electricity demand in the context of smart grids, mathematical tools are needed as mentioned in Section 1. Game theory provides mathematical tools to model, structure and analyze interactive scenarios. It can be defined as the study of mathematical models of conflict and cooperation between intelligent rational decision-makers. Among other well-known game theory paradigms we will focus on the Public Goods Game (PGG) [4], which presents the interactions of individuals constituting a group. For instance, some individuals are awarded with an equal amount of money. Afterwards, the individuals are facing a challenge; to invest in total or a part of the initial amount awarded into a common pot, being aware that the common pot raised, will be multiplied and divided equally to all of them, regardless the contribution each one made. In the case that everyone invests the entire initial amount, everyone will get a greater amount of the money invested. Still, each one is tempted to "free-ride" on the investments made by other members of the group, since this way there is no risk for his initial capital. Assuming that all players follow this "rational" strategy, the initial capital will remain static [5].

From a theoretical point of view, players participate in a PGG in groups of n players. The game is elapsed t rounds. On every round of the game, a player i obtains an award w and faces the dilemma on how to divide it. He must choose between an investment c_i, to a public good, the common pot, and private utilization, $w - c_i$. The total amount invested by the n members of a society is multiplied by β, $\beta < n$, and equally distributed to the n members [4]. Denoting $m = \beta / n$, $m < 1$, the payoff of player i at each round as a function of the contribution to the public good is illustrated by equation (1). Finally, at the beginning of the next round, the obtained award w for a player i, will be equal to the payoff π_i gained by the player at the previous round.

$$\pi_i = w - c_i + m \sum_{i=1}^{n} c_i \tag{1}$$

In PGG, the public good or environment is depicted by the multiplication factor β, that in the case of remaining constant during the game, the public good cannot be totally consumed by players that adopt "wrong" strategies. The amounts that are chosen by the players for investment have an impact on the production of the common good that will be equally divided among them [7].

Common sense dictates that in a society that is donating itself with a public good, every individual constituting it will be highly tempted to become a free rider, meaning to give in little or nothing at all, with consequences to the welfare of the community and at the same time receiving the rewards everyone else receives. The fact that the phenomenon of free riders will cause the community to provide its members with less rewards, is also predicted by economic theory [6]. Moreover, supremacy of asocial, defecting strategies is prognosticated by traditional and evolutionary game theory. On the other hand, a permanent and strong willingness to cooperate in societies is significant [5]. It becomes impressive to differentiate from theoretical prognostications, granted the significant obstacles to establish and maintain cooperative behavior in large groups. However, the progress in theory and experiments has demonstrated some methods that are capable of encouraging cooperation. Many modifications of the classic PGG have been proposed, including spatial PGG, and PGG in which the players are separated in groups [8]. In spatially extended systems cooperators can have great advantages when they form clusters that reduce exploitation through defectors [5]. As a result the use of Cellular Automata (CA) comes into hand, taking advantage of their ability to successfully depict local interactions and incorporate inhomogeneities in their local rule.

CA can be considered models of physical systems, where space and time are discrete and interactions are local. In general, a CA requires:

1. A regular lattice of cells covering a portion of a d–dimensional space;
2. A set $\mathbf{C}(\vec{r},t) = \{C_1(\vec{r},t), C_2(\vec{r},t), \ldots, C_m(\vec{r},t)\}$ of variables attached to each site $\vec{r}$ of the lattice, giving the local state of each cell at the specific time value t;
3. A rule $\boldsymbol{R}=\{R_1, R_2, \ldots, R_m\}$ which specifies the time evolution of the states $\boldsymbol{C}(\vec{r},t)$ in the following way: $C_j(\vec{r},t+1) = R_j(\boldsymbol{C}(\vec{r},t), \ldots, \boldsymbol{C}(\vec{r}+\vec{\delta}_q,t))$, where $\vec{r}+\vec{\delta}_k$ designate the cells which belong to a given neighbourhood of cell $\vec{r}$.

In the above definition, the rule ***R*** is identical for all sites and it is applied simultaneously to each of them, leading to synchronous dynamics. However, spatial (or even temporal) inhomogeneities can be introduced. Furthermore, in the above definition, the new state of a particular cell r at time t+1 is only a function of the previous state of the specific cell and of the cells which belong to its designated neighbourhood. The neighbourhood of cell $\vec{r}$ is the spatial region in which a cell needs to search in its vicinity. For 2–d CA, two types of neighbourhood are usually considered: namely, von Neumann neighbourhood, which consists of a central cell (the one which is to be updated) and its four geographical neighbours north, west, south and east and Moore neighbourhood which contains, in addition, second nearest neighbours northeast, northwest, southeast and southwest, i.e. a total of nine cells, whereas the von Neumann neighbourhood comprises of only five cells. CA have sufficient expressive dynamics to represent phenomena of arbitrary complexity [9] and at the same time can be simulated exactly by digital computers, because of their intrinsic discreteness, i.e. the topology of the simulated object is reproduced in the simulating device [10]. The CA approach is consistent with the modern notion of unified space–time. In computer science, space corresponds to memory and time to processing unit. In CA, memory (CA cell state) and processing unit (CA local rule) are inseparably related to a CA cell. Furthermore, they can easily handle complicated boundary and initial conditions, inhomogeneities and anisotropies [11].

As mentioned above, a hot ongoing research topic is the conflict and the cooperation for the shared power resources between different or same Hybrid Renewable Energy Systems (HYRESs) of a smart energy grid. Consequently, a model is proposed here, to simulate the conflict between autonomous HYRESs and to estimate its impact over the entire smart grid's performance. The CA rules that will apply on that situation are considered to be in accordance with the PGG described earlier. The CA cells are regarded as the HYRESs of a smart energy grid and it is assumed, for sake of simplicity that they are identical, thus they are represented as PGG players placed in CA cells in a square grid. The HYRESs are, usually consisting of Photovoltaic Arrays, Wind Generators, Polymer Electrolyte Membrane (PEM) Fuel Cells, Battery Arrays, Diesel Generators, etc. In a real energy grid system, each HYRES could be different depending on the varying electricity priorities of the corresponding buildings that serve like households, schools, medical clinics, etc. As a result, the reward of every CA cell will simulate the accessibility to "pool of power/ produced and stored electricity" of the smart grid for approximately the same period of time for an HYRES according to its needs for electricity demand. That means that the public good will be assumed to be the total amount of electricity produced by all available HYRESs for a time period. Moreover, the investment of a player placed in a CA cell in every round will correspond to the amount of electricity resources that the HYRES does not need and can be stored by fuel cell and used from other HYRESs. As the amount of "pool of power/ produced and stored electricity" accessibility by a HYRES is modeled as the payoff of every player, the available common good through time depends on the payoffs of the players.

The players/cells of the proposed model are placed in a square CA grid. Each CA cell will interact with his neighbors, as they constitute a community of a PGG. Furthermore, the type of the neighborhood and the boundary conditions can be altered in order to depict different smart energy networking grids. Without loss of generality, the neighborhood type selected was Moore, the boundary conditions are selected to be periodic, for sake of clarity, and the grid is 5×5, in order to simulate a system of 25 players competing over a "pool of power/ produced and stored electricity". However, the model is not restricted by these options. As mentioned before, other smart grids can be easily simulated by using a larger grid and different neighborhood's radius.

Another parameter of the CA model is the time steps, namely the game rounds, here empirically chosen equal to 100. Furthermore, the multiplication factor β is set to 10, a value lower than the amount of HYRESs connected to the grid, n=25, in order to keep the "social dilemma". The multiplication factor can be altered to a constant or dependent by time value to simulate different system circumstances. The gain of every player (i,j) on round t for the configuration described above is given by Equation (2).

$$\begin{aligned} \mathrm{sd}Gain^{t}_{(i,j)} = \frac{\beta}{n}(&Investment_{(i-1,j)} + Investment_{(i,j-1)} + \\ &Investment_{(i+1,j)} + Investment_{(i,j+1)} + \\ &Investment_{(i-1,j-1)} + Investment_{(i-1,j+1)} + \\ &Investment_{(i+1,j-1)} + Investment_{(i+1,j+1)} + \\ &Investment_{(i,j)}) \end{aligned} \tag{2}$$

Moreover, the payoff of every player i on round t, is given by Equation (3).

$$\begin{aligned} &Payoff^{t}_{(i,j)} = Payoff^{t-1}_{(i,j)} - Investment_{(i,j)} + sdGain^{t}_{(i,j)} \\ &\text{where } Investment_{(i,j)} = (produced\_power)_{(i,j)} - (power\_consumption)_{(i,j)} \end{aligned} \tag{3}$$

Furthermore, the amount of the investment of every player is determined by the strategy it adopts. Players with investment value 0 are defectors and represent HYRESs that need an excessive amount of energy due to increased electricity demands. Also, players choosing investment value 1, namely cooperators, represent HYRESs that need a very small amount of energy and do not interfere significantly with the others' needs. Moreover, every player can choose intermediate values to invest, simulating the proportional need of energy.

Finally, the total payoff of a single HYRES at the end of the last round will be the sum of the rewards obtained for all previous rounds. As the payoff of each player on one round represents the ability to access the same amount of produced and stored electricity of the system for a period of time, the total payoff of the group will represent the available utilization of the produced and stored electricity that is corresponding to the energy performance in terms of electricity demand and service of the smart energy grid.

3 Efficient Representation of Energy Management Strategies

In this section we will review the representation of PMSs as described in [12] where the microgrid was seen as a graph and the flow of power and hydrogen within was described through flowsheets. More specifically, each device in the microgrid is seen as a node of a graph and its connection as an edge in Fig. 2.

Table 1. Microgrid parameters

PV (66.64W rated power)	217
WG (1kW rated power)	3
BAT	3000Ah
EL	5000W
BF	8bar, ~1m3
FT	20bar, ~220m3

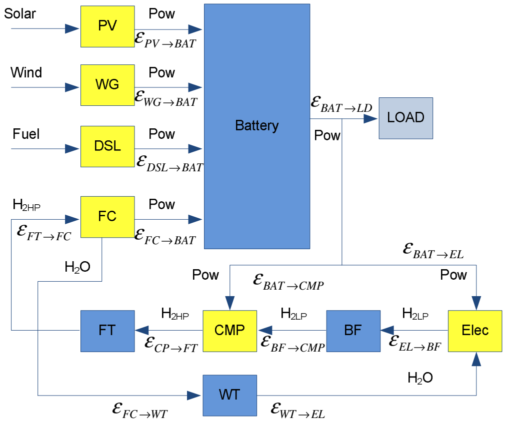

Fig. 2. Network diagram of the standalone microgrid [1]. The parameters of the system are given in Table 1.

In our system the flows between the nodes can be in various states like electrical energy (POW) or hydrogen in high pressure (H2P) and hence the input to each node for each state *j* is given by:

$$F_n^{In,j}(t) = SF_n^j(t) + \sum_{l=1}^{N} \varepsilon_{l\to n}(t) F_{l\to n}^{Out,j}(t) \tag{4}$$

where $F_n^{In,j}(t)$ is the input to node n at the instant *t*, $SF_n^j(t)$ are external inputs, $F_{l\to n}^{Out,j}$ are the outputs of the other nodes, $\varepsilon_{l\to n}(t)$ are binary variables that determine the connection of a specific edge and *N* is the number of nodes in the graph. For example in the case of the battery, equation (4) can be written as:

$$\begin{aligned} F_{BAT}^{In,POW}(t) &= \sum_{l=1}^{N}\left(\varepsilon_{l\to BAT}(t) F_{l\to BAT}^{Out,POW}(t)\right) \\ &= \varepsilon_{FC\to BAT}(t) F_{FC\to BAT}^{Out,POW}(t) + \varepsilon_{RES\to BAT}(t) F_{RES\to BAT}^{Out,POW}(t) + \varepsilon_{DSL\to BAT}(t) F_{DSL\to BAT}^{Out,POW}(t) \end{aligned} \tag{5}$$

where $F_{RES\to BAT}^{Out,POW} = F_{PV\to BAT}^{Out,POW} + F_{WG\to BAT}^{Out,POW}$.

The binary variables that determine the connection can be defined as

$$\varepsilon_{l\to n}(t) = L\left(\varepsilon_{l\to n}^{Avl}(t), \varepsilon_{l\to n}^{Req}(t), \varepsilon_{l\to n}^{Gen}(t)\right) \tag{6}$$

where L is a logical operator (like AND, OR, …) and $\varepsilon_{l\to n}^{Avl}(t), \varepsilon_{l\to n}^{Req}(t), \varepsilon_{l\to n}^{Gen}(t)$ are three binary variables that determine the availability, the requirement and other general conditions necessary to activate the connection l to n. In general the activation of a connection (from node l to n) depends on logical propositions c_i that can be described by binary variables ρ_i. For example, for the activation of the FC in order to supply power to the battery we have $c_{FC\to BAT}$. There is a requirement for energy to be delivered to the battery which it terms of the ρ variables can be written as:

$$\rho_{FC\to BAT}^{SOC(t)} = \left[SOC(t) < Str_{FC\to BAT}^{SOC(t)}(t) \right] \tag{7}$$

where the numerical variable $Str_{FC\to BAT}^{SOC(t)}(t)$ defines the lack of available energy in the battery and SOC is the state of charge. In case there is a hysteresis zone (as it is usually the case in such systems) then (7) can be written as:

$$\begin{aligned} \rho_{FC\to BAT}^{SOC(t)} = & \left[SOC(t) < Lo_{FC\to BAT}^{SOC(t)}(t) \right] \vee \\ & \left[\left[Str_{FC\to BAT}^{SOC(t)}(t) < SOC(t) < Stp_{FC\to BAT}^{SOC(t)}(t) \right] \wedge \left[\varepsilon_{FC\to BAT}\left(t^{-}\right) = 1 \right] \right] \end{aligned} \tag{8}$$

where $Stp_{FC\to BAT}^{SOC(t)}(t)$ is the upper limit of the hysteresis zone and t^{-} is the previous observation instant.

Using this approach it is possible to systematically represent any PMS for a microgrid and to create many other PMSs by simple altering some variables in these tables. Also the aforementioned approach can be easily extended to a networked environment where each node will be an autonomous station. The objective is to optimally exchange energy between the involved nodes and to avoid the utilization of diesel generator while protecting the accumulators within each node. In order to implement such approach a new set of zones are defined, the request and surplus zones, that are modelled using the same principles as the hysteresis zones of each subsystem.

4 Flexible PMS Representation

In the following we use the energy scenarios presented in Section 2 and combine it with the PMS representation of Section 3. The objective is to study the SOC of the systems in the case of isolated operation and in the case of energy exchange. A three days period of time is selected during July. The request and the surplus zones are set between 50V to 52V and 54V to 56V respectively. The response of the systems is shown at Fig. 3.

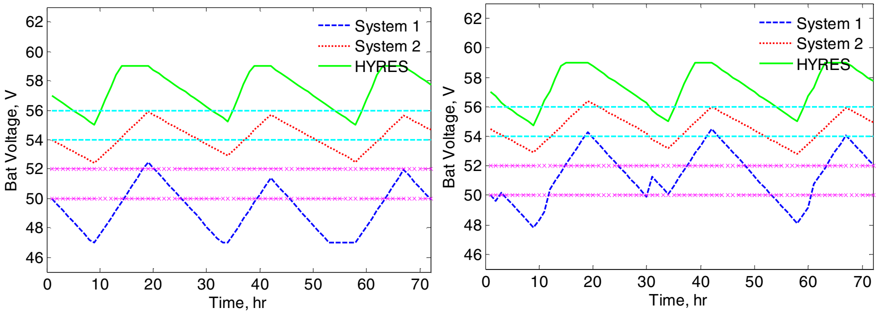

Fig. 3. (a) Battery voltage when systems are isolated. (b) Battery voltage response when systems exchange energy.

In the first case (Fig. 3a) we can observe that System 1 needs power and when the battery voltage drops below 47V the diesel generator is enabled at the nighttime of the 3rd day (between 52nd -58th hour). At the same time it is observed that system HYRES has an excess of energy which is transformed into hydrogen since the exchange of energy is not allowed. On the second case (Fig. 3b), where energy is allowed to be exchanged between the system, it is observed that HYRES provides energy to System 1 and thus, the use of energy is avoided. When the systems operated isolated, System 3 requests power for 64 sampling periods whereas in case of energy exchange System 3 requests power for 17 sampling periods. This clearly shows that the available energy is used in a better way and that the diesel generator is not used. Also it is observed that the depth of discharged of System 3 is reduced, which signifies that the overall lifetime of its accumulators is protected. Finally the amount of energy that cannot be absorbed by the network is also reduced from 38KWh to 24KWh which is also beneficial for the overall network performance. As far as the hydrogen storage is concerned in the first case the electrolyzer operates for 23hrs whereas in the second cease for 16 hrs. Although energy is distributed to the network, a smaller amount of hydrogen continues to be produced and stored at the final tanks for future usage.

5 Conclusions

In this paper, a Cellular Automata (CA) based approach combined with Game Theory for the enhancement of Power Management Strategies (PMSs) of multiple Hybrid Renewable Energy Systems (HYRES) that form a smart grid for the exchange of energy was presented. The presented CA model focuses on providing valuable feedback for PMSs of the understudy HYRES connected in a grid. In this manner, a flexible network based HYRES design is considered and applied to a specific HYRES located in Olvio, near Xanthi, Greece, part of SYSTEMS SUNLIGHT facilities. The proposed model can be applied to the understudy HYRES grid managing to enhance and optimize its PMS based on the provided energy prediction scenarios.

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