Effects of Smart Grid Communication Networks in Distributed Generation Dispatch

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Abstract

One of the key aspects in the development of smart grids is the design of bidirectional, real time communication networks in all the fields of the power grid, from the generation to distribution, and including the customer interaction. Because of that, new control and dispatch strategies need to be developed in order to deal with the different issues that are induced by the communication network, such as delays and packet dropouts. This work overviews the smart grid communication network architecture with some of the main characteristics and elements, and the degrading effects of wired and wireless communication networks in an optimal evolutionary dispatch technique are illustrated, using a novel simulation tool that includes the power system dynamics and the communication network infrastructure. Besides, a delay compensation method that solves the delayed dispatch problem is developed for centralized dispatch control.

1 Introduction

The electrical power grid has evolved during the 20th century, and it has benefited from many innovations and improvements over the last decades. However, in some aspects its basic design has little changed from the 1880s [1], and it has become a very large, complex, and inefficient system, with many issues that must be solved. One of the main problems that has arisen are the blackouts, and as a result, utilities need to have better visibility into their operations beyond what can be sensed in a control center. This has led to the implementation of the supervisory control and data acquisition (SCADA) in order to monitor and control the power grid. However, large grids are more difficult to control, because they are divided into many subparts with only basic communications between them, and controlling them is becoming a harder task with current SCADA systems.

With the advances in communication and measurement technologies, the vision of a reliable, efficient, and cost-effective power grid has become reachable and many efforts in the design and implementation of the future power grid have been done. In [2], the future power system architecture is introduced, based on

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the increase of communication infrastructure, distributed generation, and different decentralized control strategies. However, new challenges have arisen due to the effects of the inclusion of renewable resources into grid, such as photovoltaic (PV) cells and wind turbines, which will be commonly used in the future [3].

One of the greatest challenges for future electricity grids lies in the demand side response [4]. This demand response includes the customers into the power generation process, and can provide many advantages such as increasing awareness of energy usage, more efficient operation of markets, mitigates market power, enhances reliability, and in combination with certain new technologies, can support the use of renewable energy resources, distributed generation, and advanced metering [5]. The use of these distributed and renewable generators introduce new variables into the power system, and the correct dispatch of these units, taking into account different constraints of each generator (e.g., cost, availability, power capacity) is a fundamental problem that needs to be solved. Common centralized control techniques are not feasible for this kind of problems, because of the high quantity of information, and the impossibility to obtain an accurate model of the power system. For this reason, resource allocation strategies are implemented, in order to dynamically allocate the power resources in the dispatch of DG. In [6] a control strategy is used to optimally allocate the power resources based on an evolutionary game theoretical approach called replicator dynamics (RD). This strategy models how natural selection affects the amount of individuals in different habitats of an environment according to a fitness value that they can obtain in each habitat. The amount of individuals in each habitat changes as a result of the interaction the total population. At the end, the population evolves until it maximizes the social welfare. This strategy has been widely used in order to solve resource allocation problems [7–9] and in [6] the dispatch problem has been solved. However, no communication effects have been considered in these approaches. This is why we want to illustrate the effects of the communication networks in the dispatch problem, taking into account the RD strategy for different communication protocols, using a novel simulation tool, that integrates the networked control system simulator Truetime, and a power system simulator, PSAT.

In order to deal with the challenges presented above, the future power system, the so called *Smart Grid* has to be smart enough to monitor and control the grid taking into account the variations in the demand side, as well as the inclusion of intermittent and uncertain renewable distributed generation, all of these through real-time bidirectional communication networks. For this reason, a whole novel communication architecture has to be developed and new control strategies need to be implemented in all the layers of the smart grid, in such a way delays and packet dropouts induced by the communication infrastructure are considered. There is not a strong theory dedicated to the solution of these kind of problems, but the developments in networked control systems (NCS) may be very useful in order to deal with the effects of the communication network for the power system. For this reason, an adequate simulation tool is necessary, in such a way the power system dynamics and the communication network architecture can be integrated.

This work overviews the smart grid communication network architecture with some of the main characteristics and devices, as well as the different kind of networks that should be used for each stage of the grid, beginning with the customer side network to the distribution and generation networks in Section 2. Section 3 presents an optimal dispatch strategy that can be used with the inclusion of renewable resources, and Section 4 illustrates the effects of the communication networks for the dispatch problem due to the delays and packet dropouts, using a simulation tool that combines the communication constraints with the power systems dynamics. In Section 5 a delay compensation strategy is implemented based on a nonlinear observer for delayed systems, in order to solve the problems induced by the communication network delays. A discussion is presented in Section 6, and some conclusions and future directions are briefly discussed in Section 7.

2 Smart Grids Communication Architecture

The Smart Grid is a complex system of systems that integrates communication networks technologies with the electrical power grid, in order to make the generation and distribution of electricity more efficient and cost-effective. The Smart Grid is expected to affect all fields of the current electrical grid system, with the use of applications and tools that enable real-time decision making, based on multiple data acquisition and customers interaction [1]. Therefore, an Advanced Metering Infrastructure (AMI) is being developed, in order to install smart meters on consumer premises for demand response and communication systems to connect the meters to distribution control centers, in such a way that the optimal decisions on how and when to produce and consume electricity can be made [10].

The smart meters are advanced systems that include communication infrastructure and control devices. They are able to measure the energy consumption of a customer and they can read the values of voltage, phase angle and frequency, and communicate that information to the data collector. Besides, the bidirectional communication of data enables the ability to collect information from the power grid, as real-time pricing (RTP) and diagnostics of the grid, in such a way that customers can choose when to connect or disconnect from the grid, or when to turn on a home distributed generator, or plug-in a hybrid electrical vehicle (PHEV). Therefore, smart meters can be used to control all home appliances and devices of the customer, and they can communicate with other meters in their reach [11].

A particular characteristic of the smart meters is the time period between each data measurement due to the elevate quantity of data that needs to be managed at the central controller. Such measurements (provided by smart meters) may be required as often as once every 15 minutes to support energy management applications [12], and to ease the data collection. For this reason, designing an effective bidirectional, real-time communication network architecture for data collection and processing is a key to the successful implementation of the smart grid.

Figure 1 illustrates a general smart grid architecture, that includes the electrical grid system and the communication networks distribution. In this figure, different kind of networks that may be used for each part of the power system can be seen, from generation to customers, taking into account the distributed generation (e.g., renewable resources) and a microgrid structure. This architecture includes Home Area Networks (HANs), Building Area Networks (BANs) and Industrial Area Networks (IANs), which communicate the appliances and devices within a home, a building or an industry. There is also a Neighbor Area Network (NAN), which is a network of multiple HANs that sends the metering data to the data collector, and delivers them through a Wide Area Network (WAN) to the Energy Service Provider and to the distribution central control [13]. WANs are the largest networks in the smart grids, and are commonly used for communication between several microgrids and different widely distributed central controllers and generators. All these infrastructure allow us to see the smart grid as an interconnection of various microgrids and distributed controllers [14], in such a way that the smart meters data of each microgrid are delivered in real-time, and the control decisions have to be executed considering all the interconnected microgrids (only the microgrids that are not in island mode).

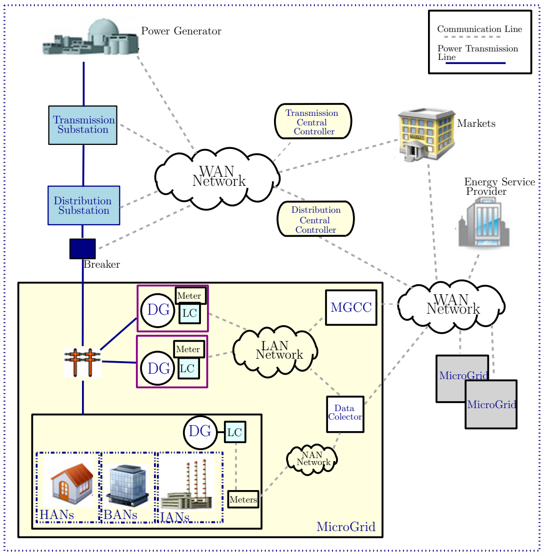

Figure 1: Smart grid communication architecture.

A single microgrid is composed of distributed generators (or distributed energy resources), buildings (i.e, homes, industries), and controllers (Figure 1). Distributed generators can be located closer to the point of consumption (e.g., home PV or wind turbines), or they can be connected directly into the grid (e.g., PV, wind, bio mass, tidal, microturbines). Each generator has a smart meter that sends the power and voltage information to the MGCC (micro grid central controller), and local controllers (LC) that receives the information about how much power has to be dispatched, and ensures to generate that power. The correct control of the dispatched power in a microgrid is a very important research area in the future power system architecture. Next we will focus in the dispatch of distributed generators, using an optimal resource allocation technique.

3 Dispatch of Distributed Generators

One of the main challenges that the smart grid deals with, is the increase of distributed generation and the way how the power is dispatched for these units in order to supply the demand [15]. The dispatch problem must consider technical and commercial aspects of each generator, including the different problems that arise due to the inclusion of renewable resources into the grid [16]. These kind of energy resources present a lot of uncertainties because of their dependence on the weather, and robust dispatch strategies have to be developed. There are some strategies that can solve the dispatch problem, such as particle swarm optimization (PSO) [17], genetic algorithms [18], and neural networks [19], just to name a few. However, we are going to focus in the strategy illustrated in [6], in order to analyze the effects of the communication networks in an optimal dispatch strategy, including the intermittence of the generators. The strategy is based on the replicator dynamics (RD), which is an evolutionary algorithm based on natural selection, in which individuals of a population look for nutrients in an environment, and evolve according to their mutual interaction and relative fitness value [20]. In this model, each individual has N pure strategies, which correspond to choosing which habitat to live. The number of individuals is constant, and corresponds to $\sum_{i=1}^{N} p_i = P_d$, for $P_d > 0$.

The fitness value $f_i(p_i)$, indicates the goodness of the individuals playing strategy i (placed in habitat i), and the average fitness is given by

$$\bar{f} = \frac{1}{P_d} \sum_{j=1}^{N} p_j f_j\left(p_j\right) \tag{1}$$

With this concepts, the general model of the replicator dynamics is described by

$$\dot{p}_i = p_i(f_i(p_i) - \bar{f}) \tag{2}$$

The analogy between the power dispatch problem and the RD is based on the problem described in [6], where the total number of generators in the system is N, and the i^{th} strategy corresponds to choosing one of the generators. p_i is the amount of power assigned to the generator i, and P_d is the power demanded in the microgrid. In [6], the fitness value associated to each generator is given by

$$f_i\left(p_i\right) = D \frac{1}{c_i} \left(1 - \frac{p_i}{P_{nom_i}}\right) \tag{3}$$

due to the power dispatched depends on the generation cost $c_i > 0$ and the maximum power $Pnom_i > 0$ of each generator. We have added the binary valued $D \in \{0, 1\}$ that indicates whether or not a generator is active (turned on) or disconnected from the system, in such a way that intermittencies of DGs can be considered.

In [6], the authors show that this strategy is optimal in order to dynamically solve the power dispatch problem for some DGs in a microgrid, but no communication effects were considered. Next, we will show through a novel simulation tool how the communication network affects the performance of the system with this optimal strategy, and a possible solution is introduced.

4 Effects of the Communication Networks in the Dispatch Problem

The inclusion of the communication networks in all the power system architecture offers many improvements such as monitoring, control and resource management. However, the insertion of the network may have degrading effects on the control strategies performance due to the communication constraints and limitations, such as time delays and packet dropouts. Some stability and control analysis for power systems have been developed that take into account the delays that can be introduced in the system due to the network [21, 22]. However, there are not power dispatch techniques that consider communication issues, and it is still an open research area. For this reason, we want to illustrate these kind of effects in a microgrid with some distributed generators, using the smart grid communication architecture described in Section 2, and the optimal dispatch strategy described in Section 3 based on the replicator dynamics.

The communication network is designed based on [12] where the smart meter data, containing the information of fitness and current dispatched power from each local controller (LC), are delivered to the MGCC each *15 minutes* through the network. With all the information from each generator stored in the MGCC, the average fitness $\bar{f}$ is calculated, and sent back to the local controllers also through the communication network, in such a way that the new amount of power that needs to be dispatched for each generator is calculated depending on the load demand and the generator capability. This exchanging process is executed during ten seconds in order to assure the convergence of the algorithm with a low amount of data transmissions.

Next, a novel simulation tool for smart grid systems is introduced, and some simulations for a microgrid with the communication infrastructure are presented.

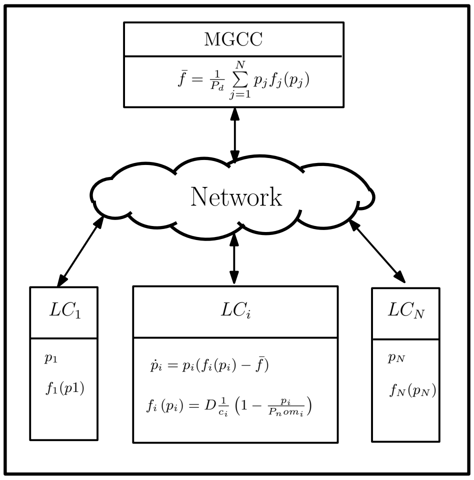

Figure 2: Agent Scheme for the Replicator Dynamics strategy. Figure adapted from [6].

4.1 Simulation Results

In order to design new control strategies for smart grids that includes the models of the different elements of the power grid (e.g., generators, PMUs, renewable sources), with the communication network interaction, a simulation tool has been developed. This tool is Matlab/Simulink based, and is the combination of Truetime [23] and PSAT toolboxes, which are used for simulating networked control systems and power systems, respectively. PSAT is a powerful free simulator that works under plain code environment and do not work directly with simulink blocks. However, we have modified the main code and improve the simulation environment in such a way that PSAT simulink simulations can be performed. With this, the Truetime toolbox can works directly with PSAT, and smart grid simulations may be developed for different kind of networks and communication protocols .

The problem we want to illustrate, is based on the microgrid scheme presented in Figure 2 for four distributed generators, each one with storage and communication capabilities. To avoid an excessive penetration of distributed generation in the microgrid and to assume that power flow constraints are respected, the IEEE 13 node test feeder is used as a microgrid reference model, and the nominal powers and placement of the power controllable generators presented in [6] are chosen. Also, we have chosen the same values used in [6] for the fixed nominal powers of the DGs, $P_{nom} = [P_{nom_1}, ..., P_{nom_4}] = [172, 47, 66, 106]$ kW, and the cost factor for each generator, i.e., $c = [1\ 0.8\ 0.3\ 0.4]$

To simulate the demanded power from the microgrid, a typical hourly demand profile in Colombia is defined with the microgrid capacity as the maximum load at rush hour [6]. This demanded power is assumed to be constant during all the negotiation states (i.e., each 15 minutes), for a period of one hour. Besides, in order to observe a most real behavior of the microgrid, we consider intermittencies in some of the generators, that can be caused due to interaction of an user (turning on or off a generator) or because of the kind of generator (can be a PV or a wind turbine, which depend on the weather). The intermittencies are presented when generator four is turned off at 6:15h and turned back on at 11:15, and when generator three is turned off at 16:15h and it is never turned back on in that period of time. Besides, we want to illustrate the effects of different communication networks protocols and structures in the dispatch algorithms, and the way that delays and packet dropouts affects the performance of the control strategy depending on the type of network.

The simulations are made during a day period $24h$, where one of the generators is turned off at 6:15h and turned back on at 11:15h. First, we considered the case where the communication between the LC and MGCC is direct, without taking into account the network architecture. Figure 3 shows the results.

It can be seen that the system with the RD strategy has an appropriate performance for a non networked environment. Despite the variations due to the intermittent generator, the total demanded power is fully covered during all day.

Other tests are developed where the communication network is included. We consider different kinds of networks in order to illustrate the effects of using various protocols, and wired and wireless structures.

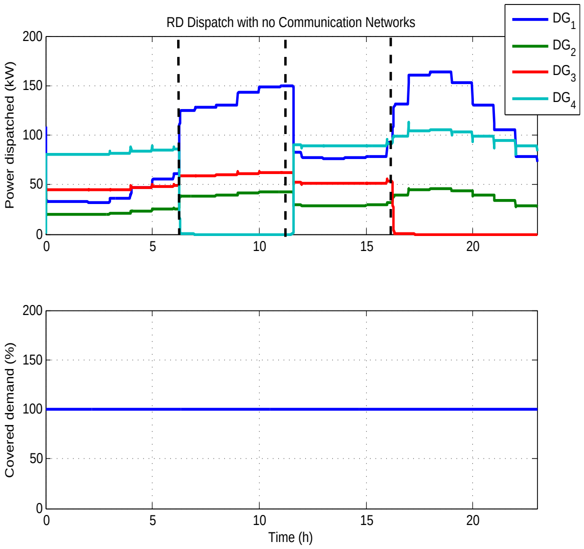

Figure 3: Power dispatched using RD without communications infrastructure.

There is not a specific standard of communication networks for smart grids. However, in [13] some of the main developments in protocols and communication structures for smart grids are presented, and we focus in four of them, which are included in the Truetime simulator, and are widely used in industrial applications. We have chosen two wired structures, such as Switched Ethernet, CAN, and two wireless structures, WiFi and Zigbee. In the wired networks, *Switched Ethernet* is a very promising alternative for real-time industrial application due to the elimination of uncertainties in Ethernet, because there will never be any collisions on the network segments. Each node has a dedicated path and the data transmission of all nodes can be made at the same time. In [24], a novel Switched Ethernet architecture is introduced for power systems monitoring. Another network is based on *CSMA/AMP* (Carrier Sense Multiple Access with Arbitration on Message Priority) with CAN (Controller Area Network) standard. This protocol is used for communicating distributed nodes without a computer host, but data transmission is not simultaneously. Each message has a specific priority according to which it gains access to the bus in case of simultaneous transmission [25]. On the other hand, wireless communication networks are very promising in the smart grid development, due to the great amount of devices that will need to be monitored and controlled in the future power system, and a total wired architecture will not be feasible. Two of the main wireless standards that have been considered for smart grids are the ZigBee and WiFi. Zigbee is low in cost, power, data rate, and complexity, and easy for deployment and implementation [26], and with WiFi, they could be used for smart meter interfaces in the home and local area network [27].

For our simulations, we use the four network protocols introduced above, with the fifteen minutes data recollection. Each fifteen minutes the algorithm is executed with a sampling period $h = 100ms$, during ten seconds in order to ensure the convergence of the RD. h is selected in such a way the replicator can achieve an steady state, with a low computational cost.

We have developed two different experiments, in order to make evident the impacts of delays and packet dropouts. First, we induce the delays τ_i due to the communication network, for $i = 1, \dots 4$. The communication between each ones of the nodes have different delays value due to the distribution of the generators, the different distances and the uncertain that may be produced by the communication architecture. These delays have random behavior and change each time the data are transmitted, i.e., each fifteen minutes.

Figure 4 illustrates the covered demand for different time delays ranges, with the WiFi communication network. It can be observed that the RD strategy is not optimal under delay conditions, and as long as the delays are increased, the dispatched power presents bigger variations and oscillations. Also, the simulation is performed for the different protocols mentioned above, and Figure 5 shows how for an average time delay of 2 seg and for wired and wireless schemes, the behavior is practically de same.

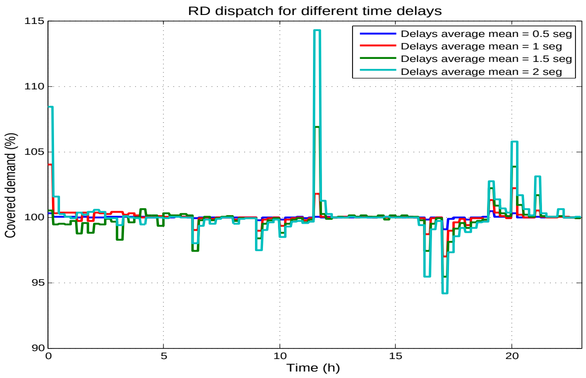

Figure 4: Power dispatched using RD with the communication structure considering a multiple random delays for the WiFi standard .

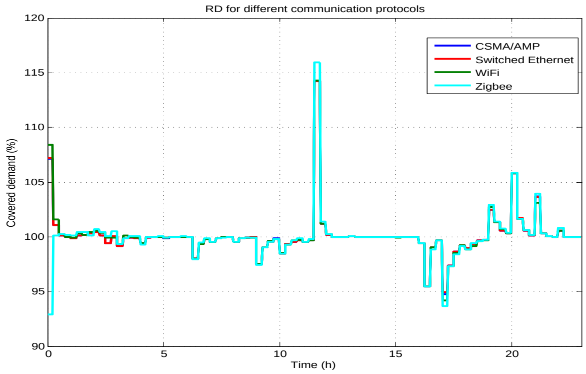

Figure 5: Power dispatched using RD with the communication structure considering different communication protocols .

On the other hand, packet dropouts also have degrading effects in the microgrid, and they may appear when there are node failures or message collisions. We have simulated the RD dispatch strategy with the delays presented above (i.e., average time delay of 2 seconds), and different percentage of data loss, each one with 10%, 20%, 40%, and 70%. These values have been chosen arbitrarily in such a way that extreme conditions can be considered, either for low and very high data losses. Figure 6 shows the behavior of the dispatch strategy with data loss for two of the protocols mentioned above, the WiFi and Switched Ethernet.

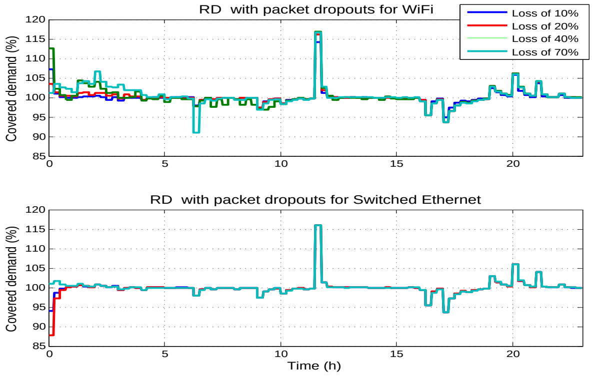

Figure 6: Power dispatched using RD with the communication structure considering a different percentages of packet dropouts.

The impacts of communication networks are evident, and it is necessary to develop control strategies that can deal with this issues. However, the interest of this paper lies mainly in the delay effects in the RD strategy. For that reason we will present some stability analysis for the replicator dynamics presented above based on some simulation results. For the packet dropouts case, there is still too much work, and we do not explore this area yet.

4.2 Delayed Replicator Dynamics

The delayed replicator dynamics proposed is based in the scheme of Figure 7, where each delay is produced due to the communication network. The whole system can be divided in two subsystems H_1 and H_2 described by

$$\begin{aligned} H_1 &= \begin{cases} \dot{x}_i = x_i(f_i - u_1(t - \tau_{2i})) \\ y_1 = x \cdot f \end{cases} \\ H_2 &= \begin{cases} y_{2i} = \sum_{j=1}^{N} u_{2j}\left(t - \tau_{1j}\right) \end{cases} \end{aligned} \tag{4}$$

each one with $i = 1, 2, \ldots, N$. τ_1 and τ_2 are vectors with different time varying delays, and each output y_{2i} corresponds to the calculation of $\bar{f}$ with delayed inputs.

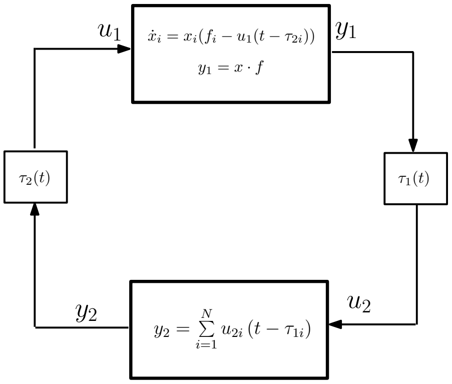

Figure 7: Feedback Interconnection scheme

Some simulations have been developed considering the interconnection structure of Figure 7, for the IEEE 13 node test feeder with four DGs with the characteristics presented above. Here we considered that $x_i = \frac{1}{Pd} p_i$ in order o obtain the portion of the demanded power Pd that is supplied by each generator. Figure 8 shows different simulations of the system for different constant time delays.

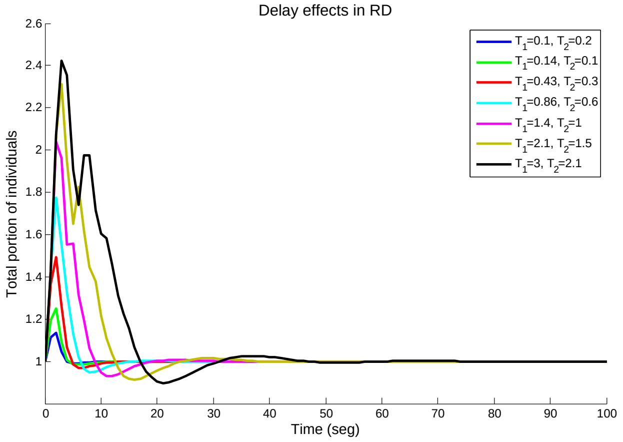

Figure 8: Total portion of individuals for different time delays

It can be observed that the delayed system always reach its steady state for any time delay. However, the steady state time increases as the sum of τ_1 and τ_2 increases. For time varying delays, the results are very similar, and the steady state time is proportional to $\max_{i=1,2,\ldots,N}(\tau_{1i}) + \max_{i=1,2,\ldots,N}(\tau_{2i})$

These results show that for the delayed RD that solves the dispatch problem presented above, the system is asymptotically stable independent of the delays, for all the $x(t_0)$ in the simplex.

In order to demonstrate the asymptotically stability of the interconnected delayed system, some passivity concepts for feedback interconnected systems can be used, based on $\mathcal{L}_2$ gain stability.

Chopra et. al. [28] demonstrated that the delayed feedback interconnected system in Figure 9, is asymptotically stable independent of the delays if for the nondelayed system of Figure 10, there exists storage functions such that

$$V(x_n) \leq \frac{1}{2}\left({\gamma_n}^2\|u_n\|^2 - \|y_n\|^2\right)$$

and each $\mathcal{L}_2$ gain is $\gamma_n = 1$, for $n = 1, 2$.

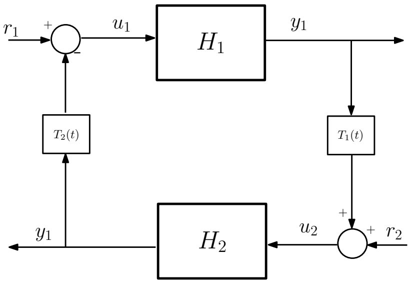

Figure 9: Feedback Interconnection of two dissipative delayed systems

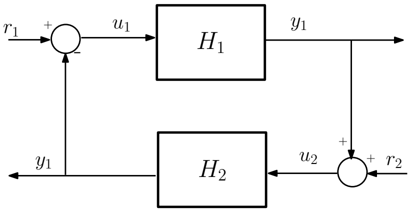

Figure 10: Feedback Interconnection of two dissipative systems

For our case of study, the two subsystems are given by Equation 4, where $y_1 = u_2$ and $y_2 = -u_1$, and the inputs r_1 and r_2 are 0. However, to show that the origin is stable, the system has to be described in terms of the error $e_x = x - x*$, where $x*$ are the equilibrium points of the systems, and the new subsystems are now of the form

$$H_1 = \begin{cases} \dot{e}_x = (e_x + x^*)\, f - (e_x + x^*)\, \bar{f} \\ y_1 = (e_x + x^*)\, f \end{cases} \tag{5}$$

$$H_2 = \left\{ y_2 = -\bar{f} \right.$$

Next, it can be said that

$$V(e_x) = V_1(e_x) + V_2(e_x)$$

, then, the total condition for $\mathcal{L}_2$ stability is

$$V(e_x) \leqslant \frac{1}{2}\left(\left({\gamma_1}^2 - 1\right)\|u_1\|^2 - \left({\gamma_2}^2 - 1\right)\|u_2\|^2\right)$$

.

So, if γ_1,and γ_2 are 1, then $V(e_x) \leqslant 0$.

A storage function that fits with that condition is

$$V\left(e_x\right) = -\min_{k=1,2,\ldots,N}\left(e_{xk}\right)$$

which is positive defined $V > 0$, and it is zero only when all the errors are zero $V(0) = 0$. Therefore, the derivative of $V(e_x)$ is given by

$$\dot{V}\left(e_x\right) = -\left(e_{xk} + x_k*\right)\left(f_k - \bar{f}\right)$$

where the term f_k is always bigger than $\bar{f}$ when the error is the most negative one. Hence, the condition $\dot{V} \leqslant 0$ is true for this storage function. Therefore, the origin is asymptotically stable for any initial condition inside the simplex.

The main problem lies in the fact that with the inclusion of the smart grid structure, the exchange of information between H_1 and H_2(MGCC) has to be low, due to the high quantity of data that has to be managed for the MGCC. This can be observed in Figure 4, where the negotiation time was approximately 10 seconds, and the system was not able to achieve the steady state for some time delays.

In order to correct this problem, a nonlinear delay state observer is introduced in the next section.

5 State Observer for Delayed Nonlinear Systems

As it was pointed before, time delays can affect the behavior of a system, and, it is necessary to develop new strategies. For the dispatch problem, it have been shown that the system is asymptotically stable indecently of the delays. However, these delays makes that the trajectories of the system get out of the simplex, due to the the average fitness $\bar{f}$ does not correspond to the optimal one but it gets closer to it during time until the optimal $\bar{f}$ is found. A solution is presented in order to make the steady state time very small, obtaining a closer value to the optimal of the average fitness $\bar{f}$. For that reason, an estimation of the state variables has to be made, considering the time delays produced by the communication network, and a more accurate average fitness value can be obtained. In [29] an observer for nonlinear systems with delayed output measurements is presented, considering bounded variable delays, and the instantaneous knowledge of its value. This observer considers systems of the type

$$\begin{aligned} \dot{x}(t) &= f\left(x(t) + gx(t)u(t)\right) \qquad && t \geqslant -\Delta \\ \bar{y} &= h\left(x(t-\delta(t))\right) \qquad && t \geqslant 0 \quad \delta(t) \in [0, \Delta] \end{aligned} \tag{6}$$

where $x(t) \in \Re^n$ is the state of the system, $u(t) \in \Re^n$ is the input, $\bar{y}(t) \in \Re$ is the measured output, $\delta(t)$ is the varying delay measurement, bounded by some $\Delta > 0$.

In order to obtain the state observation, it is necessary to define the drift-observability map in Equation 7, where the $\mathrm{Ł}_{\varphi}^{k}\lambda$ is the k-times repeated Lie derivative of the function $\lambda(x)$ with respect to the vector field φ.

$$z = \Phi(x) = \begin{bmatrix} h(x) \\ L_f h(x) \\ \vdots \\ L_f^{n-1} h(x) \end{bmatrix} \tag{7}$$

With this, the jacobian of z is obtained, $Q(x) = J(\Phi(x))$. If the system is globally drift observable, $Q(x)$ is non-singular, which is a very important characteristic in order to design the observer.

The proposed observer is then given by

$$\dot{\hat{x}} = f\left(\hat{x}(t)\right) + g(\hat{x}(t))u(t) + Q^{-1}\left(\hat{x}(t)\right) K \left(\bar{y}(t) - h\left(\hat{x}(t - \hat{\delta}(t))\right)\right) \tag{8}$$

where K is a suitable gain, and $\hat{\delta}(t)$ is an approximation of the time delay, due to the impossibility to obtain the exact measurement of the delays in a communication network.

For our problem, we have kept the structure defined in Figure 2, but the average fitness will be calculated considering the observed states, using the observer for nonlinear delayed systems presented above.

The observer in [29] only considers a single output, and we need the observation of all the states to obtain the average fitness value. For that reason, the K gain in Equation (8) is now considered as a gain vector, and $\hat{\delta}(t)$ is a vector that contain the estimate measurement of the time delays for each state. Then the new drift-observability map is now described by

$$z = \Phi(x) = \begin{bmatrix} h_i(x) \\ L_f h_i(x) \\ \vdots \\ L_f^{n-1} h_i(x) \end{bmatrix} \tag{9}$$

for h_i being any state output of the system.

Figure 11 illustrates the utility of the state observer for the $24h$ demand profile and the characteristics of the DGs simulated above, with fixed delays of 3, 2.26, 1.5 and 1 seconds only in the communication between the LCs and the MGCC (i.e., $\tau_2 = 0$).

It can be seen that the inclusion of the state estimation makes the system stable and the total demand is covered correctly. This is because the $\bar{f}$ is calculated with the delay estimated inputs, and it is closer to the optimal one.

6 Discussion

It is clear that the communication networks induce degrading effects into the performance of any system. For our case of study, the selected optimal strategy is greatly affected by the microgrid dispatch

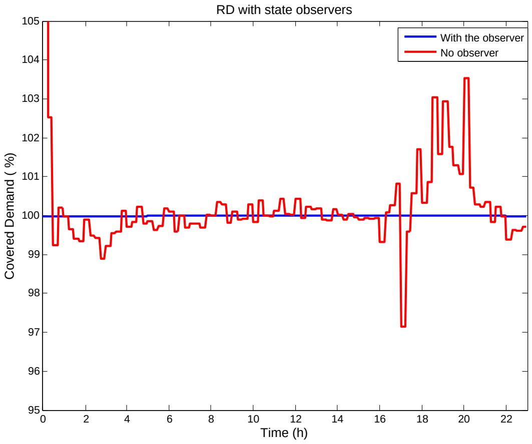

Figure 11: Behavior of the system considering the state observer

architecture proposed in Figure 2. It can be observed in Figure 4 that the good performance of the system obtained with the non-networked environments (Figure 3) is degraded with the inclusion of the communication network. This may be produced mainly because of two factors: a) the *quantization* of the $\bar{f}$ parameter when the fitness data and the power measure of each one of the generators is sent thorough the network to the MGCC, and b) the random delays induced by the communication architecture. The combination of these two factors in the RD produce a great impact in the power dispatch, because when the local controller is about to calculate its fitness and the new power according to the average fitness of the four generators, the $\bar{f}$ value that each local controller receives is not the value necessary to optimally allocate the resources, provoking that the dispatched powers may be out from the simplex of the RD. In Section 4.2 it have been shown that for any initial $p_i(0)$ inside the simplex, the system is asymptotically stable independent of the delays, but it may be out of the simplex until the steady state is finally achieved. Hence, the oscillations in the covered demand observed in Figure 4 are produced when the steady state time is bigger than the negotiation time. The intermittence of the generators make this problem even worst. When one of the generators is turned off or on, the drastic change produce an increase in the error of the dispatched power, and the replicator values can get even further of the simplex. This can be observed in the higher peaks of the covered demand in the Figure 4 that occurs when one of the generators is turned on. Figure 5 shows the dispatched power of the microgrid when the communication is made thought different kinds of networks, either wired and wireless. It can be seen that there is not a significan difference in the behavior of the system for the four networks, because the differences in the communication protocols are not relevant (i.e., very small time differences) for these kind of problems. However, for high speed systems, an small variation may provoke different behaviors.

In the packet dropout simulations (Figure 6), the main characteristic of Switched Ethernet can be seen, i.e., there are not data collisions. For this reason, even when we set a data loss of 70%, the performance of the system is almost the same. For the WiFi protocol, the packet dropouts effects are significant, and increase the impact produced by the delays. This is because when the intermittency occurs, the RD needs to reallocate all the resources abruptly, and more data need to be transmitted in order to achieve the steady state. The data loss produce that the steady state is not achieve by the RD. Therefore, the Switched Ethernet protocol offers a very good performance in the presence of packet dropouts, and its a good choice in order to design a communication infrastructure in a microgrid. However, the wireless schemes are necessary when there are many devices that need to be connected, and in such cases a wired architecture is not feasible.

In order to deal with the delay effects produced by the communication network, the proposed state observer is a very feasible option, due to the capability to observe delayed states for multiple outputs and variable delays. Besides, the error margin in the delay estimation is high, and it is a great advantage due to the impossibility to obtain the exact instantaneous delay measurement at any time. However, as the number of states increases, the calculus of z becomes more difficult, and the computational cost increases considerably. Besides, one of the main objectives of using the microgrid replicator dynamics structure, is that the MGCC made small mathematical operations to obtain the $\bar{f}$ value.

Clearly, there is a huge room to improve dispatch strategies that includes the communication networks constraints. We have started with the compensation of time delays. However, it is still an open research area, and Networked Control Systems theories might be helpful in order to design controllers that can deal with delays and packet dropouts, based in estimation and delay compensations (e.g., [30], [31], [32], [33]).

7 Conclusions

The communication architecture for the smart grid is the key for the future of the power system. However, the inclusion of customer interaction and renewable generators introduce new challenges and problems such as load balance of the grid, connection and disconnection of generators, real-time control, data management, just to name a few. For this reason the current dispatch and control strategies has to be reevaluated, and the network effects has to be considered.

The dispatch strategy based on RD is optimal for un-networked environments in order to solve resource allocation problems. However, the induced delays and packet dropouts cause a degrading effect on the performance of the dispatch technique, provoking over demand and under demand effects. Besides, from the point of view of networking, the choice of correct communication protocols is a fundamental issue in the design of smart grids, and new protocols that reduce the delays and data loss need to be design, thinking in large scale and widely distributed systems. Another solution could be the increase of the negotiation time between the MGCC and the LC. However, that implies that the MGCC has to deal with a high amount of data, which is not good because it not only deals with the DGs information, but also with the information of other microgrids. The proposed delayed nonlinear system estimator is a feasible option in order to correct the effects produced by the delays in the system. However, as the number of distributed generators increases, the estimation becomes more difficult. For that reason, the future research may try to analyze the local replicator dynamics with delay effects, and a new decentralized microgrid structure may be proposed. On the other hand the proposed simulation tool is very useful in the design of controllers and dispatch strategies for smart grids. The combination of Truetime and PSAT allows the implementation of smart grids easily in the simulink environment, taking into account the different communication protocols and devices, and the models of power grids elements. Besides, it is very useful in the simulation of dispatch and control strategies of distributed power systems, and it can be used to choose the more adequate communication protocols and networks for a physical problem.

The design of the smart grid is still a novel research area, and there are still many unsolved problems and rising challenges that need to be considered for the future of the power systems.

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