A Multi-Agent System Coordination Approach for Resilient Self-Healing Operation of Multiple Microgrids

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***Abstract*—Power networks with multiple microgrids require flexibility and versatil-ity in their coordination tools and decision-making tools from both technical and economical points of view. In particular, the microgrids involve a high penetration of variable energy resources which motivates the need for new coordination and control approaches. In this chapter, some of the literature gaps with respect to the coordination of multiple microgrids are first identified. These gaps suggest that the microgrid integration challenge is not just in the control of an individual microgrid but also in its coordination with others. The chapter then presents a novel multi-agent system coordination approach for the resilient self-healing operation of multi-ple microgrids. An architecture composed of physical agents is presented on a dual platform of JAVA-JADE (environment for developing agents) and MATLAB. The resilience of multiple microgrids is then demonstrated in relation to three types of disturbed operations: (i) highly variable net load, (ii) net load ramp events and (iii) net load changes during high load levels.**

I. INTRODUCTION/MOTIVATION

IN recent years, the "smart grid" vision has come to include a resilient, self-healing property, through microgrids, that allows for healthy regions of the grid to continue to operate while perturbed regions bring themselves back to normal operation (Amin and Wollenberg, 2005); (Colson et al., 2011); (Rieger et al., 2013).

This requires today's power system industry to be innovative as to how to tackle the challenges presented by modern power systems consisting of complex interactions between multiple microgrids (Amin et al.,2013); (Farid and Muzhikyan, 2013); (Kassakian et al., 2011); (Muzhikyan et al., 2013a). These microgrids are defined as electric power systems that: have distributed resources and loads, have the ability to disconnect from and operate in parallel with the main power grid, and are intentionally planned (Bhaskara and Chowdhury, 2012). Utilizing multiple microgrids in a larger region requires robust tools for control and coordination purposes (Ng and El-Shatshat, 2010); (Lasseter, 2011). In particular, the coordination and control of multiple microgrids as semiautonomous power units suggest a decentralized coordination structure which may be rigorously validated and verified while still respecting the socio-economic context in which it operates (Ng and El-Shatshat, 2010).

For example, Figure 1 shows a one-line diagram for an interconnected industrial power-grid composed of two microgrids connected by switched lines to the main power grid. Centralized generators at the top are complemented by distributed solar and wind energy resources at the bottom. Traditional loads are denoted with P+jQ and an arrow while controllable loads are represented by saturated rectangles. Each microgrid may operate independently or connect for an aggregate behavior.

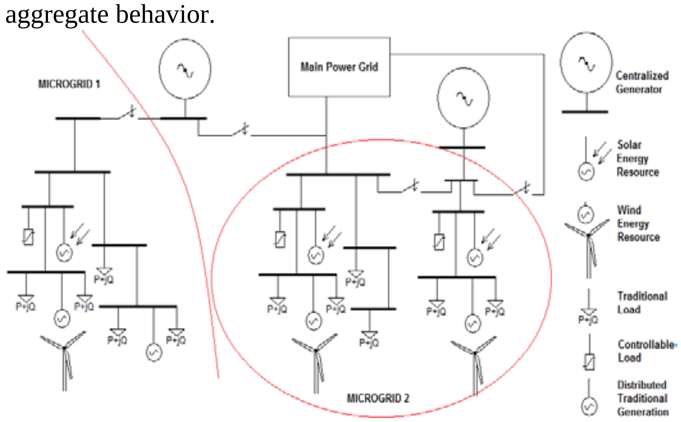

Fig. 1. Multiple microgrids in a power grid

Such behavior has motivated the need for microgrids as semiautonomous power grid units that can autonomously respond to grid events while coordinating their power transmission with other power grid entities. Naturally, this desired resilient self-healing behavior based upon semiautonomous microgrids implies decentralized coordination and control schemes that correspond to each microgrid region.

To address these emerging challenges, this chapter proposes a coordination approach via multi-agent systems (MAS). MAS support the definition of microgrids in that they allow each microgrid to operate autonomously when disconnected, or in a

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coordinated fashion when connected to other microgrids. The justification for MAS is strengthened by the ability to implement agents of increasingly complex and heterogeneous decision-making functionality. Ultimately, each agent may interact and negotiate with other agents to achieve coordinated and semiautonomous behavior (Bellifemine et al., 2007); (Rieger and Zhu, 2013).

This chapter specifically seeks to address these needs by developing a multi-agent system coordination approach for the resilient self-healing operation of multiple microgrids. In order to be directly applicable to the power system industry, specific efforts have been to use methods traditionally found in and recognized by industry. This includes a dynamic model of the physical power system combined with a conventional decision-making approach in each agent. The novelty rests in the holistic behavior of the cyber-physical system as it consists of multiple microgrids being controlled with many interacting agents.

The chapter is divided into five sections, being Section I the introduction and motivation of this research. Section II highlights some of the current gaps in regards to coordination schemes for multiple microgrids systems. Section III contributes the proposed coordination approach. Section IV then provides a case study, which visualize the resilience of the microgrids in relation to three types of disturbed operations: (i) highly variable net load, (ii) net load ramp events and (iii) net load changes during high load levels. The chapter is brought to a close with the discussion and conclusions in Section V.

II. Problem Overview: Coordination and Control of Microgrids

The coordination and control of microgrids is a subject that has received some attention in the literature and remains as a challenge in the power system industry (Gu et al., 2012); (Bhaskara and Chowdhury, 2012). This section discusses the implications of the gaps in regard to coordination schemes for multiple microgrids systems.

A. *Needs of Coordination and Control in Microgrids*

Good coordination and control of microgrids needs to ensure that (Colson and Nehrir, 2009); (Kondoleon et al., 2002):

- New microsources are added to the system without modification of existing equipment.
- The microgrid connects and disconnects itself from the grid rapidly and seamlessly.
- Reactive and active power are independently controlled.
- System imbalances are handled within the microgrids.
- Microgrids can meet the grid's dynamic load requirements.

In order to ensure these tasks, the microgrids use two control methods given by microsources power injections into it (Kondoleon et al., 2002):

1. The first physical control method is the voltage regulation through droop, where, as the reactive current generated by the microsource becomes more capacitive, the local voltage set point is reduced. Conversely, as the current becomes more inductive, the voltage set point is increased.
2. The second physical control method is the frequency regulation through droop (normally presented in isolated mode). When the microgrid separates from the grid, the voltage phase angles at each microsource in the microgrid change, resulting in a reduction in local frequency. This frequency reduction is coupled with a power increase but the microsources have a maximum power rating.

Traditionally, these two control methods are coordinated by an architecture comprised of three main components: a microsource controller, a protection coordinator and an energy manager (Kondoleon et al., 2002); (Lasseter and Piagi, 2004).

The main functions of the Microsource Controller are: to regulate power flow on feeders, to regulate the voltage at the interface of each microsource and to ensure that each microsource rapidly picks up its share of the load when the system islands. The Protection Coordinator must respond to both power system elements and microgrid faults (Kondoleon et al., 2002); (Lasseter and Piagi, 2004). On the other hand, the 3 main functions of the Energy Manager are: 1.) to provide the individual power and voltage set points for each microsource controller, 2.) to ensure that heat and electrical loads are met, 3.) to ensure that the microgrid satisfies operational contracts with the transmission system and maximize the operational efficiency of the microsources (Kondoleon et al., 2002); (Lasseter and Piagi, 2004).

These key functions must be coordinated within a single microgid as well as across multiple microgrid while considering the associated components. This semiautonomous microgrid behavior can be achieved through a hierarchical control structure with three layers. These include a primary and a secondary control, and a tertiary dispatch (Bidram and Davoudi, 2012); (Vandoorn et al., 2011). The first two are often associated with the power system's transient stability while the latter is associated with inter-microgrid coordination.

B. *Primary & Secondary Control for Transient Stability*

The primary and secondary control layers are largely responsible for the real-time transient stability of the power grid and have received significant attention in the industry (Saadat, 2004). Primary control operates on a real-time feedback control principle on the basis of local measurements (Vandoorn et al., 2011).

Secondary control compensates for voltage and frequency deviations that may exist in spite of the primary control. It adjusts set-points dynamically to achieve minimum and stable deviations while the power system transits to new operating points (Bidram and Davoudi, 2012); (Muzhikyan et al., 2013b).

This functionality is particularly important after large disturbances such as generator or load faults. Many approaches to microgrid transient stability control such as turbine governors and automatic voltage regulators have been borrowed from traditional power system (Abdelhalim et al., 2013); (Majumder, 2013). Microgrids, however, pose greater challenges as each generator or load makes up a comparatively large portion of the power flow. As a result, any individual disturbance can have a significantly larger impact on the power system stability. Similarly, further transient stability analysis is required to address disturbances originating within a microgrid that may impact neighboring microgrids under potentially different operational jurisdiction.

C. Secondary & Tertiary Coordination by Multi-Agent Systems

Tertiary coordination refers to the power systems dispatch in order to restore secondary control reserve, manage line congestion, and bring frequency and voltage deviations back to their targets (Vandoorn et al., 2011). The secondary control and tertiary dispatch application to microgrids is limited for two reasons.

First, each individual microgrid may have only a few microsources to be dispatched; so reliability demands often overshadow economic optimization. Second, a multiple microgrid system may not necessarily have a centralized organization that can centrally optimize on its behalf.

In contrast, multi-agent system technology promises to address a number of specific multi-microgrid operational challenges in the power industry (Dimeas and Hatziargyriou, 2005); (Rieger and Zhu, 2013); (Rieger et al., 2013). These include:

- The micro-sources either within a microgrid or across microgrids may have different owners. Decentralized coordination facilitates each owner's unique management interest.
- Each microgrid may operate in a liberalized market and hence should maintain a certain level of "intelligence" as it bids and participates.
- Each microgrid can operate autonomously in the absence of communication systems or cooperatively using potentially any available communication technologies.
- Each microgrid can dynamically and flexibly adapt to the activities occurring in neighboring microgrids and power systems.

Multi-agent systems achieve these challenges for simultaneous, geographically distributed and coordinated decision-making with the control design of each agent. Collectively, they exhibit the following characteristics (Dimeas and Hatziargyriou, 2005); (Colson and Nehrir, 2013):

- Each (virtual software) agent represents a physical entity so as to control its interactions with the rest of the environment.
- Each agent senses changes in the environment and can take action accordingly.
- Each agent can communicate with other agents in the power system with minimal data exchange and computational demands.
- Each agent exhibits a certain level of autonomy over the actions that it takes.
- Each agent has a minimally partial representation of the environment.

III. POPULATION-BASED OPTIMIZATION ALGORITHMS

The proposed multi-agent system coordination approach is built upon a hybrid platform in which a physical layer implemented in MATLAB is controlled by a coordination layer implemented within the Java Agent DEvelopment framework (JADE) (Bellifemine et al., 2007). One particularly interesting feature of this coordination approach is that it takes for study the state-of-industrial-practice rather than the state-of-the academic-literature; thus, the actual markets and operational procedures of industrial power grid organizations were considered in the proposed approach.

This section describes the coordination approach from the bottom up:

1. The differential algebraic equations (DAE) that describe the equations of motion of the physical layer.
2. The model predictive control (MPC) approach used to dispatch each individual microgrid.
3. The heuristics by which the agents decide to coordinate their mutual connection.

Prior to describing the system dynamics and control, it is necessary to further describe the hybrid platform on which the simulations can be implemented. To this effect, the intelligent approach employs two complementary design principles as shown in Figure 2 (Huang et al., 2009). First, the computational platform uses JADE for the virtual modeling & distributed coordination function while it uses an in-house developed MATLAB tool called Reconfigurable Smart Grid Transient Stability Simulator (RSGTSS) for physical modeling and control (Farid, 2012); (Rivera et al., 2014). Second, the intelligent multi-agent architecture employs the concept of "physical agents" (Brennan and Norrie, 2001) in that each physically modeled entity (in MATLAB) has its virtual agent counterpart in JADE.

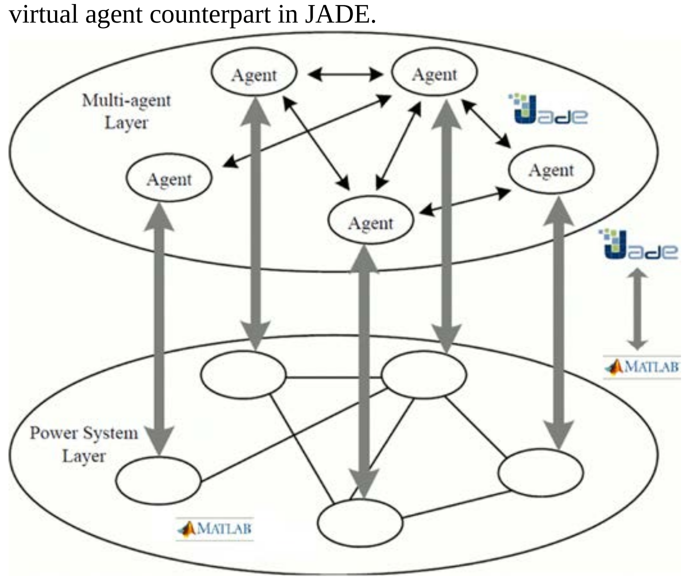

Fig. 2. Architecture Design Principles

The power system itself is modeled to consist of seven physical elements: non- controllable and controllable loads, energy storage units, stochastic and dispatchable generators, buses and branches. These physical elements may be logically aggregated into one or more microgrids. These entities have physical dynamics represented as a set of differential algebraic equations which are implemented in MATLAB. The MATLAB environment provides many in-built functions to facilitate numerical methods including the numerical solution of DAEs. Additionally, the MATLAB environment communicates with a JADE environment (Rivera et al., 2014). The JADE layer serves the dual purpose of control within a given microgrid as well as the coordination between them. The first of these is implemented as a model predictive control while the latter is implemented as heuristic for the mutual connection and disconnection of the microgrids.

Figure 3 shows a UML (Unified Modeling Language) diagram of the JADE architecture, an evolution of the architecture proposed in (Rivera et al., 2014). The power system is modeled to consist of the seven previously mentioned physical elements.

These elements are organized into super-classes called Load-Agent, Generator- Agent, Branch-Agent, Bus-Agent and then further into Energy-Elements and Topology-Elements. The all seven physical agents implement the methods turnOn and turnOff. Additionally, the energy elements can implement the method injectPower. The two classes with stochastic behavior (Non-Controllable-Load-Agent and Stochastic-Generator-Agent) have a method called injectRandomPower which provides the time series data of the injected (positive or negative) power on the network. Each microgrid gains an "awareness" of its component elements using the setupElements method.

In this architecture the microgrid agents send their status (myPowerGrid, set- pointSchedule, reconfigSchedule) to a virtual agent called Facilitator agent. The Facilitator agent acts as the single point of contact between the JADE multi-agent system and the MATLAB-based RSGTSS. The facilitator uses the operations sendAgentCommands and getPowerGridData to update the whole generators status and the network topology. This facilitator uses an interface JAVA-MATLAB through its main() operation, and executes a time domain simulation of the power grid transients under event/disturbances in the power system. As shown in Figure 3, the class MatlabInvocation acts as a communication middleware allowing the agent based architecture to send and receive data to and from the multiple microgrids represented in MATLAB. Further details on the implementation of the platform have been previously reported in (Rivera et al., 2014).

A. Differential algebraic equations and model predictive control approach

The differential algebraic equations that describe the dynamics of the multiple microgrids are presented based upon the models given in (Gomez Exposito et al., 2009). The differential equations describe the dynamics of the dispatchable generators and loads and are simply modeled as either a damped synchronous generator or motor respectively (Gomez Exposito et al., 2009). Each synchronous machine i is described by the equation 1.1:

$$\begin{aligned} \dot{\delta}_i &= \omega_i - \omega_0 \\ \dot{\omega}_i &= \frac{\omega_0}{2H_i}\left[Pm_i - Pe_i(\delta) - D_i\omega_i\right] \end{aligned} \quad (1.1)$$

where δ_i is the machine phase angle, ω_i is the angular frequency, H_i is the mechanical inertia, D_i is the damping, P_{mi} is the dispatchable power applied to the prime mover, and P_{ei} is the electrical power at generator *i* which is a nonlinear function of the machine phase angles. The dynamics of each synchronous machine are coupled by the power flows through the grid topologies, equation 1.2:

$$\mathbf{Pe} = \Re[\mathbf{E}^*\mathbf{YE}] \quad (1.2)$$

where **E** is the system bus voltage and **Y** is the system admittance matrix, detailed formulation is in (Gomez Exposito et al., 2009). The stochastic generators (i.e. solar PV & wind) and non-controllable loads are modeled as static power injections which affect the system admittance matrix (Gomez Exposito et al., 2009). These equations can be thought to apply to each microgrid when they are mutually disconnected or to the aggregation of microgrids when the admittance matrix has been manipulated to reflect their interconnectedness.

The microgrid agents dispatch their dispatchable elements autonomously with the *dispatchMicroGrid* method. In practice, this is implemented by calling an economic dispatch program written in the General Algebraic Modeling System (GAMS), RunGAMS class in Figure 3. In this control approach, each microgrid agent implements its own model predictive control (MPC), as an economic dispatch method, which is able to dispatch the mechanical power setpoints Pm_i for the synchronous machines within its control area. The MPC uses a time horizon of 4 time blocks of 15 second duration and dispatches Pm_i for the first time block in each generator. The MPC formulation is as follow:

$$\min \sum_{t=k}^{K}\sum_{i=1}^{N_G}\left(C_i^F + C_i^G P_{m_{i,t}}^G\right) \quad (1.3)$$

$$\text{s.t.} \sum_{i=1}^{N_G} P_{m_{i,t}}^G = P_{NL_t} \quad (1.4)$$

$$-R_i^{G,\min} \le P_{m_{i,t}}^G - P_{m_{i,t-1}}^G \le R_i^{G,\max} \quad (1.5)$$

$$-P_{m_i}^{G,\min} \le P_{m_{i,t}}^G \le P_{m_i}^{G,\max} \quad (1.6)$$

where the following notations are used:

C_i^F, C_i^G : fixed, and generation (fuel) costs of generator *i*

$P_{m_{i,t}}^G$: power output of generator *i* at time *t*

P_{NL_t} : netload forecast at time *t*

$R_i^{G,\max}, \mathrm{R}_i^{G,\min}$: max/min ramping rate of generator *i*

$P_i^{G,\max}, \mathrm{P}_i^{G,\min}$: max/min power limits of generator *i*

N_G : number of generators

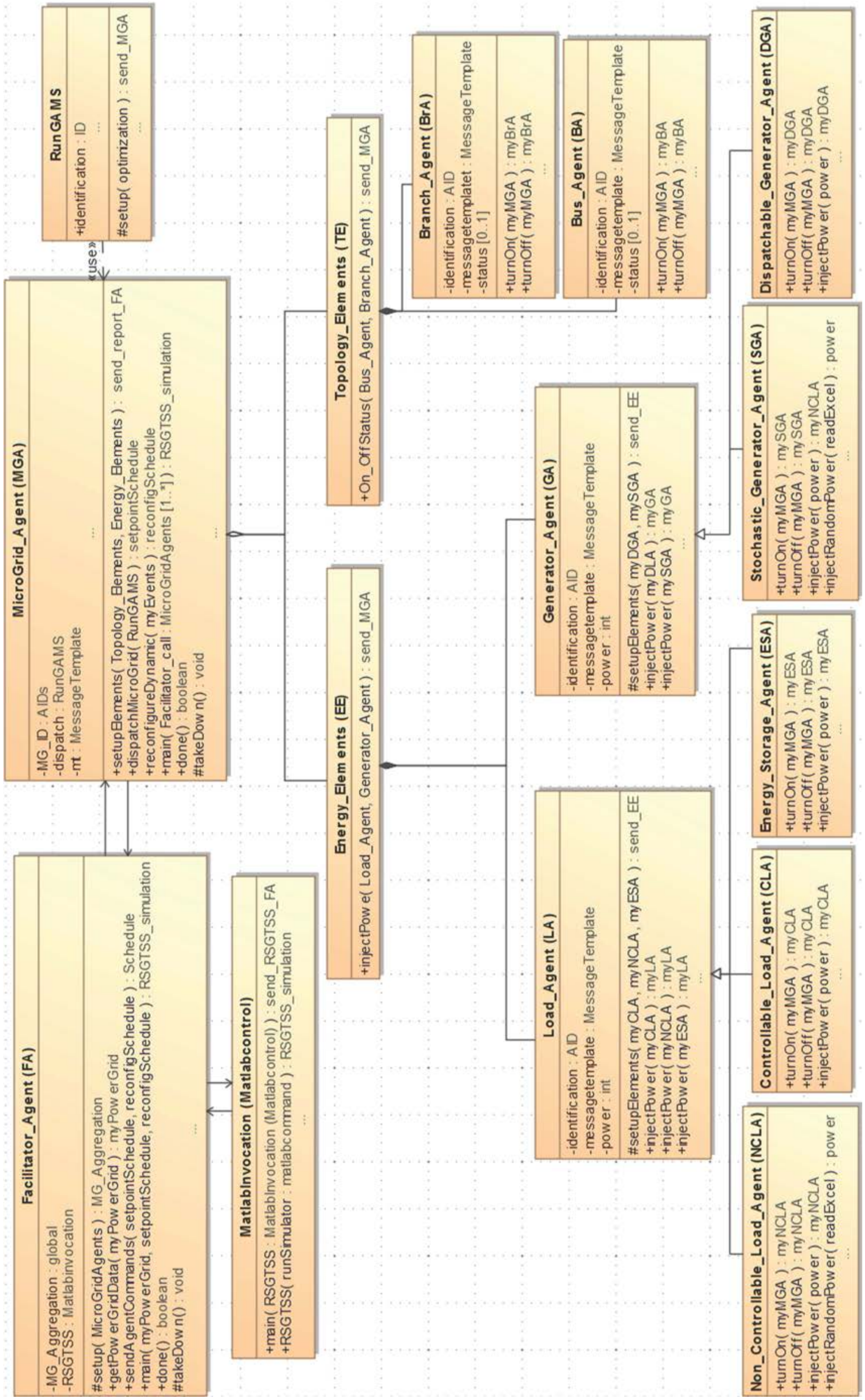

Fig. 3. System infrastructure

B. *Mutual connection coordination by heuristics*

The inter-microgrid coordination is achieved with a heuristic control-action behavior that is able to respond to events/disturbances. In such a way, each agent may interact and negotiate with other agents to achieve a coordinated and semiautonomous behavior. In order to demonstrate the coordination actions and the decentralized decision-making, three kinds of events/disturbances are used: (i) net load high variability time periods, (ii) net load ramp events and (iii) net load changes during high load levels. When these events are forecasted in the microgrids, the agents interact and negotiate with each other to change the topology of the microgrids. Within this approach, the stochastic generators agents and non-controllable loads agents read power-time series data. The data are sent to the microgrid agent who calculates the net load time series (P_{NL}) and evaluates two measures; the relative standard deviation $\bar{\sigma} = \sigma(P_{NL}) / \bar{P}_{NL}$ and the average ramp rate (R) over the four block MPC time horizon. When either measure exceeds a previously determined critical value, a coordination control action $u[t]$ is issued to mutually connect ($u[t]$ =1) or disconnect ($u[t]$ = 0) the microgrids.

$$u[t] = \begin{cases} 1, \bar{\sigma} > \bar{\sigma}_{crit} \\ 1, R > R_{crit} \text{where } R_{crit} = A * \sum_i R_i^{G,\max} \\ 1, P_{NL} > P_{crit} \text{where } \mathrm{P}_{crit} = B * \sum_i P_{m_i}^{G,\max} \\ 0, \text{otherwise} \end{cases} \quad (1.7)$$

Notice that R_{crit} and P_{crit} correspond to Equations 1.5 and 1.6 respectively in the MPC formulation.

In summary, the hybrid platform works along the following operating principle: 1.) The MAS makes decentralized but coordinated decisions under events/disturbances through the MPC and the coordination behavior described by Equation 1.7. 2.) The control signals are sent as reconfigurations and setpoint actions to the MATLAB power grid simulation through the facilitator agent/Matlabcontrol interface. 3.) MATLAB executes a time domain simulation of the power grid transients. 4.) The power system state variables are sent back to the MAS via the facilitator agent/Matlab control interface.

IV. Benefits and Assessment: Impacts of MAS Coordination on Multiple Microgrid Transient Stability

A concept of a power grid composed of multiple interacting microgrids is very much a physical power grid architecture of the future. Nevertheless, MAS present themselves as potential enabling control technology in the absence of already existing comparable conventional technologies. Within the academic literature, the most advanced work in the coordination of multiple microgrids has included power flow analysis physical models that describe the grid's pseudo-steady state behavior. Such analysis does not well address the effects of dynamic reconfigurations or uncoordinated dispatching decisions and can lead to system instabilities (Colson et al., 2011).

Additionally, the recently developed multi-agent power system developments focus exclusively on the multi-agent control system algorithms rather than on their impacts on the power grid behavior itself (Colson and Nehrir, 2013). The proposed agent based application in this work can deal with these drawbacks.

To assess the coordination approach and grasp the application benefits, the six-bus microgrid industrial system depicted in Figure 4 was chosen from Saadat's power systems text (Saadat, 2004) and was used as a template for a three-microgrid power test system. In other words, there are three identical and mutually connected microgrids (MG1, MG2, MG3). They have the potential to (dis)connect at the following bus pairs: MG1.5-MG2.1, MG1.6-MG3.6, MG2.5-MG3.1, where the pairs convention denotes the microgrid number (MG1, MG2, MG3) followed by the original bus number in Figure 4.

This section investigates the resilience of the microgrids in relation to three types of disturbed operations: (i) high net load variability, (ii) net load ramp events and (iii) net load changes during high load levels. Each type of disturbed operation can be seen to correspond to a different part of the power system's dynamics and control. The first corresponds to its internal inertia and damping. The second corresponds to the cumulative ramping constraints in Equation 1.5 and the third corresponds to the cumulative capacity constraints in Equation 1.6. The simulations have a duration of 300 seconds with time blocks of k={0,15,30,45,60,75,90,105,120,135,150,165,180, 195,210,225,240,255,270,285,300} and K=(4x15)+k in Equation 1.3. The MPC optimization program runs at each time block but only the dispatch for the first time block is dispatched.

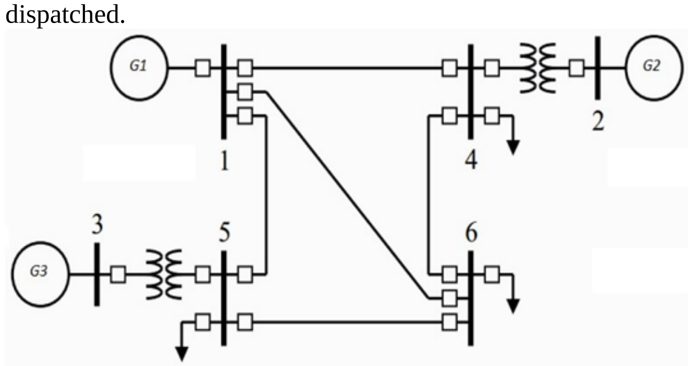

Fig. 4. Microgrid sample

A. *Resilience Towards Net Load Variability*

To understand the impact of net load variability on power system operation, the MAS transient stability platform is tested with different net load relative standard deviations. Figure 5 shows the time domain simulation of the generator angles and speeds for the three unconnected microgrids with a relatively low net load variability in each microgrid.

In this case, the relative standard deviation of the net load is less than 10 % throughout and the net load change period is every 15 seconds. The generators' phase angles find new equilibria in approximately 6.3 seconds after each net load change. Meanwhile, the generators' speeds return to the nominal 60Hz in approximately 7.5 seconds. The oscillations that occur during these times are generally considered acceptable for reliable operation.

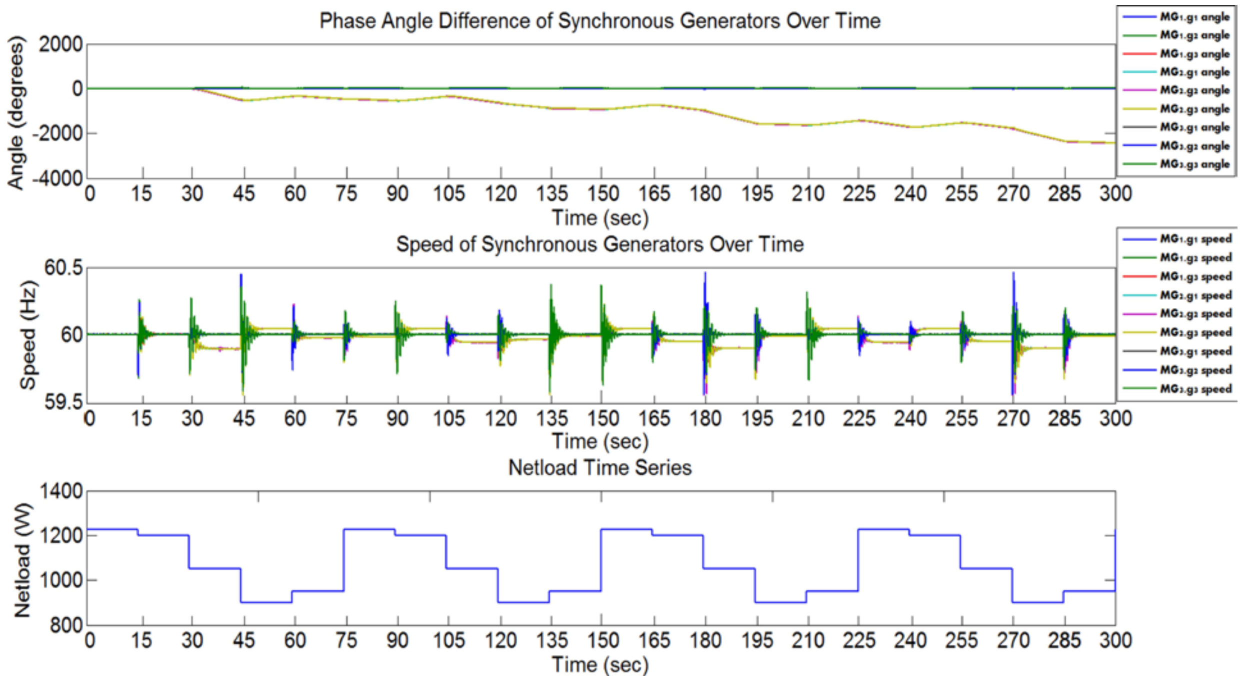

Fig. 5. Autonomous Unconnected Microgrids with Low Net Load Variability

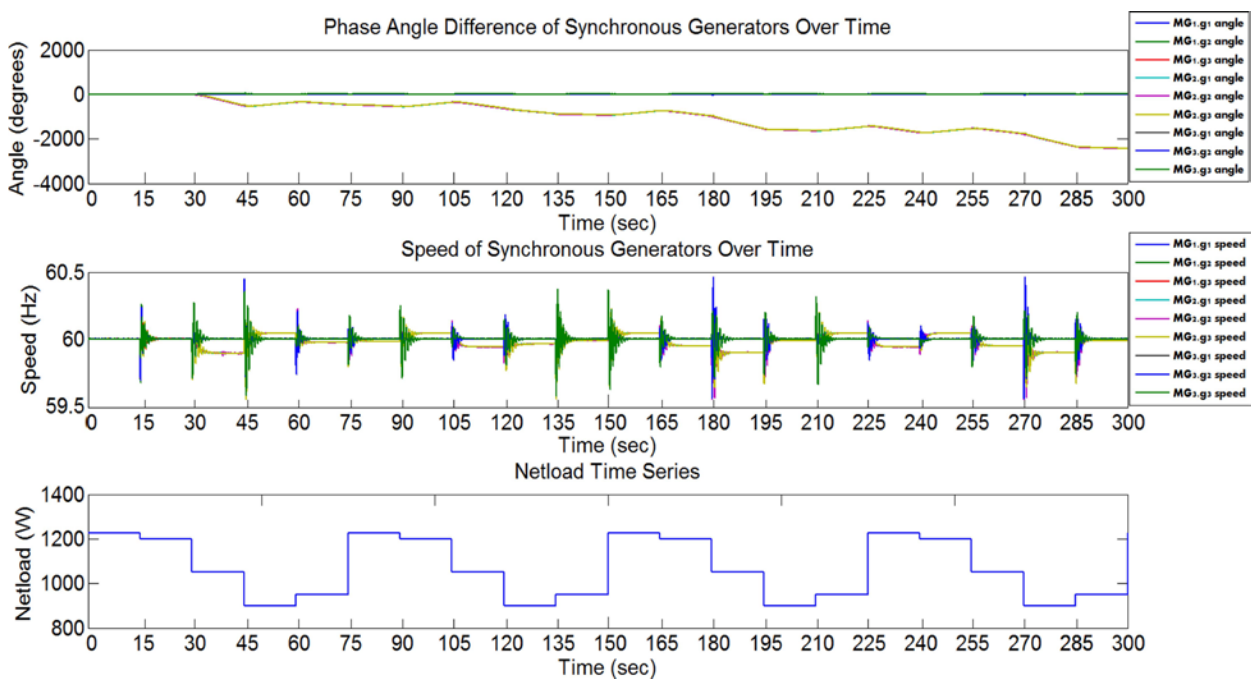

Fig. 6. Autonomous Unconnected Microgrids with High Net Load Variability

In contrast, very different transient behavior is observed once the net load variability is increased. Figure 6, this time shows the time domain simulation of the generator angles and speeds for the same system but with a net load variability greater than 10%. Here, some generator speeds do not always return to the nominal 60Hz and instead settle at lower speeds. As a result, the associated phase angle of these generators continually fall behind in angle relative to the reference bus.

In order to alleviate the shortcomings of this transient behavior, the multi-agent system's coordination strategy seeks to take advantage of the combined inertia of the three microgrids during times of high net load variability. As before, Figure 7 shows the time domain simulation but with the additional markings of C and NC to reflect when the MAS has mutually connected (C) or disconnected (NC) the microgrids. As mentioned in Section 1.3, the MAS decides between a connected and disconnected topology on the basis of Equation 1.7.

Despite having the same net load variability as in Figure 6, Figure 7 shows a greatly improved system response that much more closely resembles that of Figure 5. Intuitively, the energy of the net load variability is "spread-out" amongst the inertias of all of the generators and not just of the local microgrid. In this case, the MAS coordination strategy has successfully allowed for the system phase angles to return to equilibria and the generator speeds to return to the nominal 60Hz.

B. Resilience Towards Net Load Ramping

In order to understand the impact of net load ramping events on power system operation, the MAS transient stability platform is tested with a determined ramp event. Figure 8 shows the time domain simulation of the generator angles and speeds when microgrid 1 experiences a net load ramp event greater than 300W/min (R_{crit}). Here, A=0.6 in Equation 1.7 which means that the microgrid is well within its cumulative ramping capability constraint. In spite of this, the ramp event causes the generator speeds to fall well below the nominal 60Hz and the associated phase angles of these generators continually fall behind in angle relative to reference bus. Interestingly, the simulation shows oscillations in the other microgrids by virtue of the choice of reference bus being in the perturbed microgrid 1.

As in Section 1.4.1, in order to alleviate the shortcomings of this transient behavior, the multi-agent system's coordination strategy seeks to take advantage of the combined inertia of the three microgrids during times of net load ramp events. In this case, the MAS coordination approach detects a forecast of ramp events, through the microgrid agents, and requests the network to change its topology connecting the microgrids, through the line agents that link the microgrids.

As before, Figure 9 shows the time domain simulation with the additional markings of C and NC to reflect when the MAS has mutually connected (C) or disconnected (NC) the microgrids. As mentioned in Section 1.3, the MAS decides between a connected and disconnected topology on the basis of Equation 1.7.

The system oscillates away from the equilibria points when a ramp event occurs and then the system phase angles return to equilibria and the generator speeds return to the nominal 60Hz. These peaks in the oscillations are acceptable for the system, and the recovery is in approximately 7.5 seconds for the phase angles and 8.4 seconds for the speeds after each ramp event. As in Section 1.4.1, the energy of the ramp events are "spread-out" amongst the inertias of all of the generators and not just of the local microgrid. Additionally, while the microgrids are connected as $A \rightarrow 1$ during high netload ramps means that the microgrids could potentially share ramping capability in the situation required.

C. Resilience Towards Net Load Changes during High Load Levels

In order to understand the impact of net load changes during high load levels on power system operation, the MAS transient stability platform is tested with net load levels near to the maximum power generations. Figure 10 shows the time domain simulation of the generator angles and speeds for the three unconnected microgrids with some high level periods in each microgrid. In this case, P_{crit} is 1805 W, correponding to B=0.95 in Equation 1.7. In other words, as the net load approaches the maximum capacities of the dispatchable generators in the microgrid, the microgrid has increasingly less reserve capacity to respond to further deviations. Furthermore, the higher netload values weaken the electrical coupling between the generators, compromising their ability to maintain stability. This indeed occurs in Figure 10 as some generator speeds do not always return to the nominal 60Hz and instead settle at lower or higher speeds. As a result, the associated phase angle of these generators continually fall behind in angle relative to the reference bus.

As in Section 1.4.1, in order to alleviate the shortcomings of this transient behavior, the multi-agent system's coordination strategy seeks to take advantage of the combined inertia of the three microgrids during times of net load changes in high load levels. As before, Figure 11 shows the time domain simulation with the additional markings of C and NC to reflect when the MAS has mutually connected (C) or disconnected (NC) the microgrids. The MAS decides between a connected and disconnected topology on the basis of Equation 1.7.

The system oscillates away from the equilibria points when a net load change occurs and then the system phase angles return to equilibria and the generator speeds return to the nominal 60Hz. These peaks in the oscillations are acceptable for the system, the recovery is in approximately 9 seconds for the phase angles and 8.6 seconds for the speeds after each net load change. As in Section 1.4.1, the energy of the ramp events are "spread-out" amongst the inertias of all of the generators and not just of the local microgrid. Furthermore, the three mutually connected microgrids enhances the system impedance matrix and directly improves the system stability.

V. Discussion and Conclusions

The intelligent multi-agent system approach for the coordination and control of multiple microgrids can now be discussed in regards to its adherence to the requirements identified in Section 1.2. With the proposed approach, each agent can be implemented with increasingly complex decision-making functionality which may be entirely decentralized & autonomous. Alternatively, each agent may interact and negotiate with other agents to achieve a coordinated and semiautonomous behavior. In such a way, each microgrid has a coordination behavior that is able to respond to disturbances in the power system. Here, the JADE platform respects that each microgrid and potentially each microsource can be managed by entirely different organizations. Furthermore, the computational platform is multi-threaded allowing simultaneous decision-making capabilities that occur in geographically distributed locations.

While the power industry has tremendous experience in operating a single large power system, they have comparatively little experience in the operation of that same grid with multiple microgrids together with potentially different controlling entities. For this reason, the MAS control architecture and approach presented here provides a simulation platform with the required flexibility and versatility to address decision-making from technical and economic points of view. This is particularly important when the microgrids involve a high penetration of variable energy resources and thus require new coordination and control approaches. In this chapter, some of the literature gaps with respect to the coordination of multiple microgrids were first identified. These gaps suggest that the industrial microgrid integration challenge is not just in the control of an individual microgrid but also in its coordination with others. The chapter then presented a novel multi-agent system coordination approach for the resilient self-healing operation of multiple microgrids. An architecture composed of physical agents was presented on a dual platform of JADE and MATLAB.

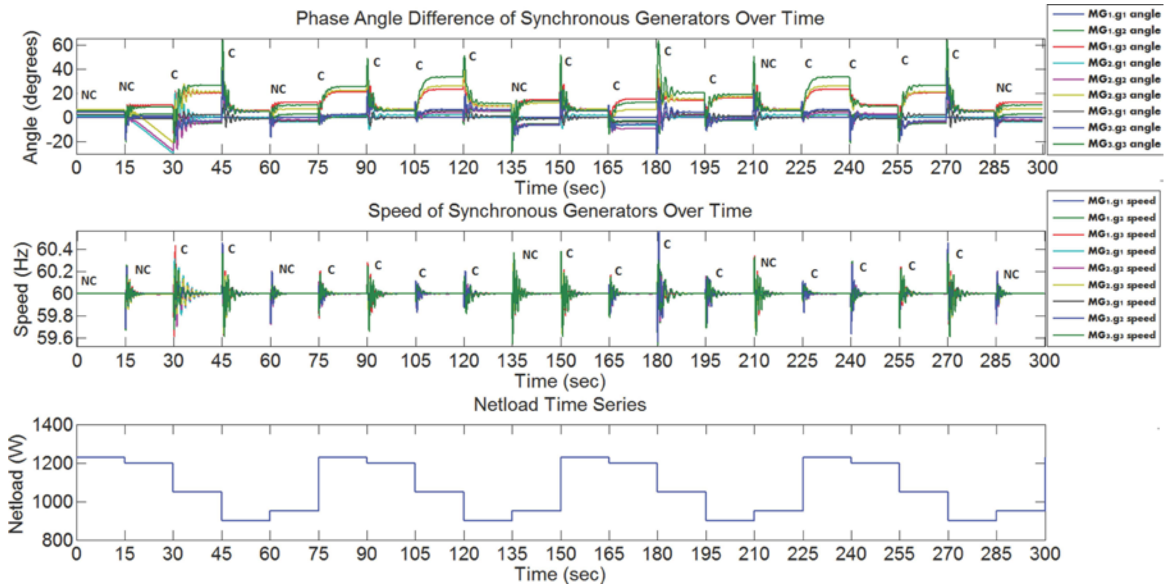

Fig. 7. MAS Coordinated Microgrids with High Net Load Variability

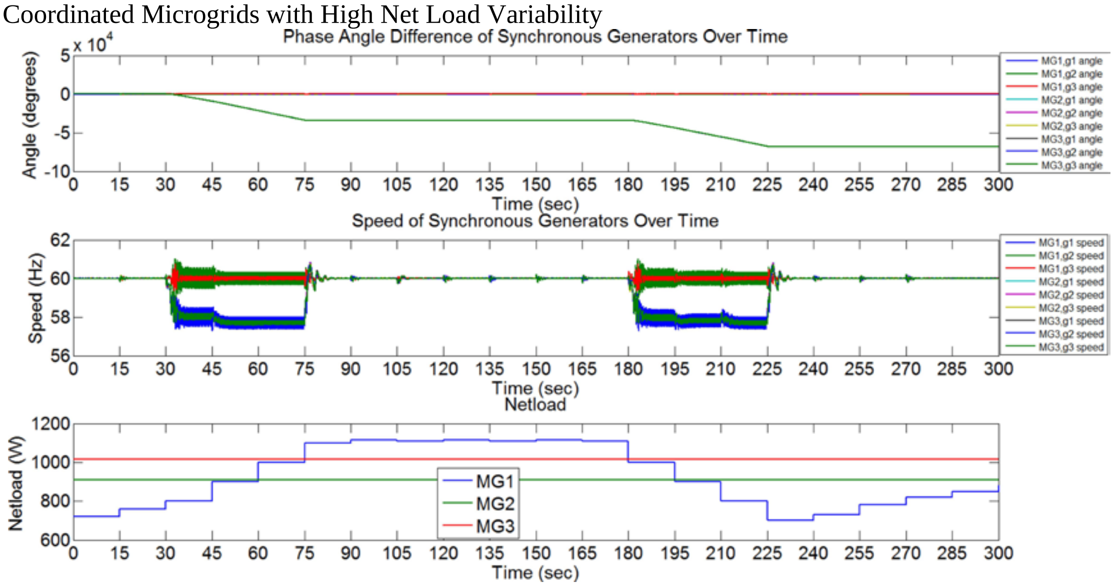

Fig. 8. Autonomous Unconnected Microgrids with Net Load Ramp Events

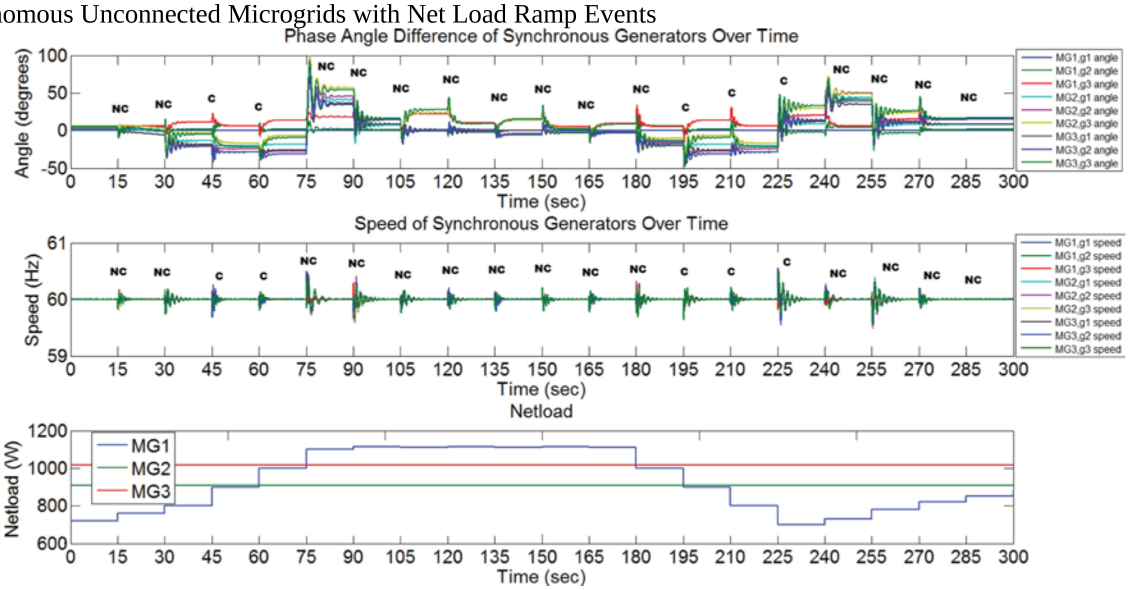

Fig. 9. MAS Coordinated Microgrids with Net Load Ramp Events

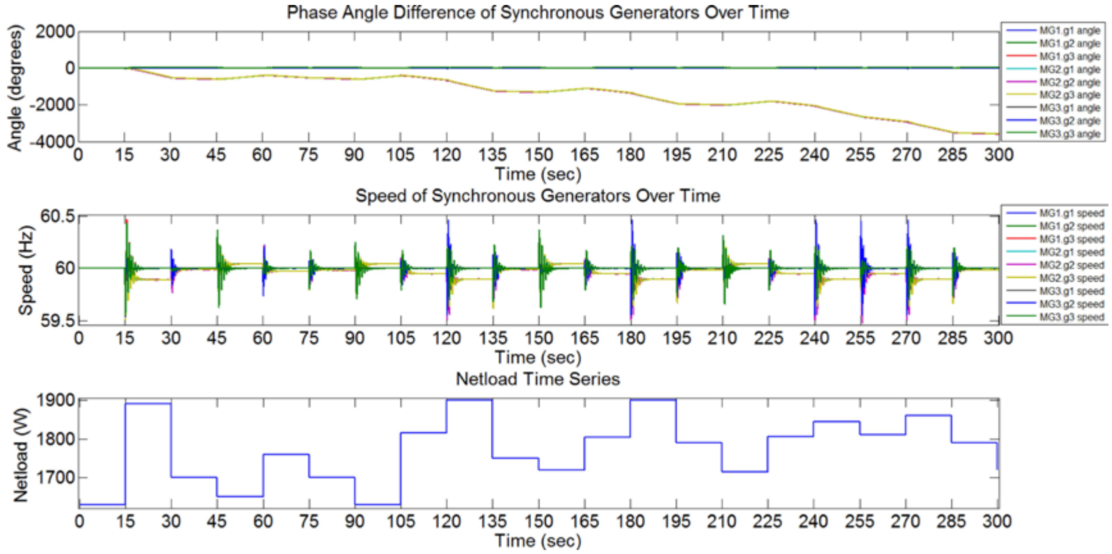

Fig. 10. Autonomous Unconnected Microgrids with High Load Levels

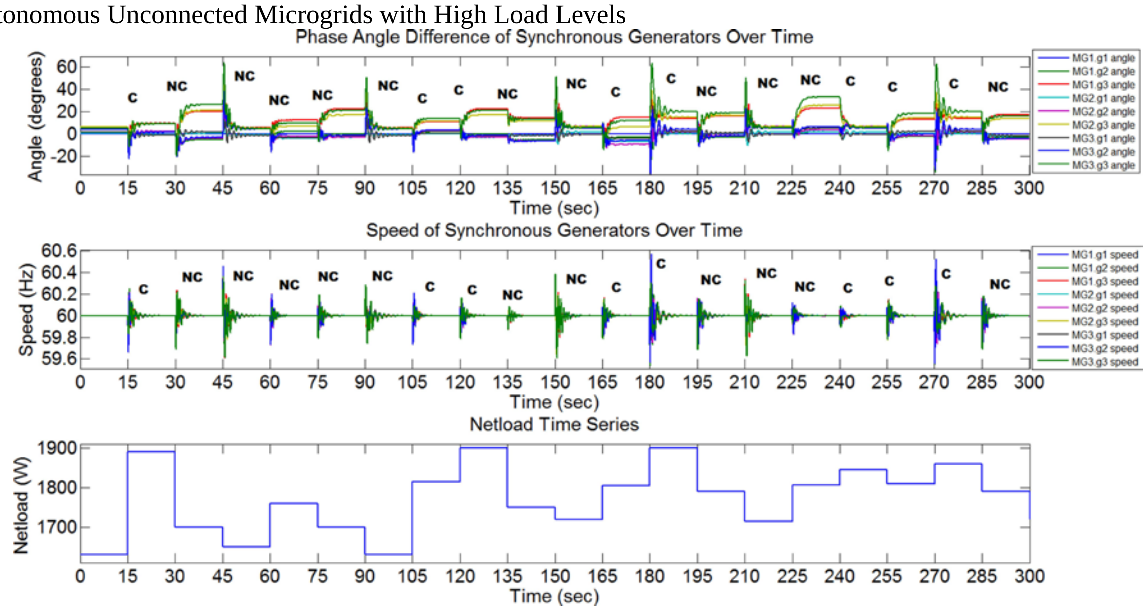

Fig. 11. MAS Coordinated Microgrids with High Load Levels

Thus, the proposed coordination and control approach supports simultaneous, geographically distributed and coordinated decision-making techniques. The main advantages of this agent based approach for resilient self-healing operation of multiple microgrids are: versatile events/disturbances management, fast development, fast computation time and flexible development. This platform allows the time domain simulation of the grid's transient stability while allowing the development of distributed artificial intelligence techniques. The proposed architecture can be seen as an application of the holistic assessment for enterprise control concept being able to integrate decentralized control with economic objectives (Farid, 2013); (Farid and Muzhikyan, 2013). The platform was tested, in order to visualize the resilience of multiple microgrids, on three complementary test cases: (i) highly variable net load, (ii) net load ramp events and (iii) net load changes during high load levels.

Today, power system industry has to be innovative to tackle the many challenges presented by modern power systems consisting of complex interconnections of multiple microgrids. The proposed approach not only enables such complex systems to be simulated, but enables the power system engineers to gain a better understanding and awareness of the operation of the system under study by allowing them to interact with the simulated system. Future work can build upon these purely autonomous decisions with inter-microgrid negotiations that rely on agent's interaction. In this way, this work presents many opportunities for future developments in the domain of resilient self-healing power grids.

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