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 more flexibility and versatility 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 paper, 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 their coordination with others. The paper then presents a novel multi-agent system coordination approach for the resilient self-healing operation of multiple microgrids. An architecture composed of physical agents is presented on a dual platform of JAVA-JADE (environment for developing agents) and MATLAB. It is then demonstrated to visualize the resilience of multiple microgrids in relation to two types of disturbed operations: (i) highly variable net load, and (ii) net load ramp events.

I. INTRODUCTION

With steadily increasing penetration of variable energy resources (VERs) into the power grid, the concept of microgrids has gained importance [1]–[3]. Microgrids play an important role in utilizing renewables locally and bringing robustness to the electric grid.

Utilizing multiple microgrids in a larger region requires robust tools for control and coordination purposes [4], [5]. In particular, the coordination and control of multiple microgrids as semi-autonomous 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 [4].

For example, Figure 1 shows an interconnected power-grid that has been divided into multiple microgrids which may coordinate their power flows but also mutually disconnect and operate autonomously. The “smart grid” vision has come to include a resilient, self-healing property that allows for healthy regions of the grid to continue to operate while perturbed regions bring themselves back to normal operation [6].

Such behavior has motivated the need for microgrids as semi-autonomous 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 semi-autonomous microgrids implies decentralized coordination and control schemes that correspond to each microgrid region.

To address these emerging challenges, this paper proposes a coordination architecture via multi-agent systems (MAS). The reason for using MAS theory is that each agent can be implemented with increasingly complex decision-making functionality which may be entirely decentralized and autonomous. Alternatively, each agent may interact and negotiate with other agents to achieve coordinated and semi-autonomous behavior [7].

This paper specifically seeks to address these needs by developing a multi-agent system coordination approach for the resilient self-healing operation of multiple microgrids. It proceeds as follows. 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, to visualise the resilience of the microgrids in relation to two types of disturbed operations: (i) highly variable net load, and (ii) net load ramp events. The paper is brought to a close in Section V.

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Fig. 1. Semiautonomous microgrids
II. BACKGROUND: COORDINATION AND CONTROL OF MICROGRIDS

The coordination and control of microgrids is a subject that has received some attention in the literature [8], [9]. This section discusses the implications of the gaps in regards 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 [10], [11]:

- 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 [10]:

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 [10], [12].

The main functions of the Microsource Controller are: regulate power flow on feeders, regulate the voltage at the interface of each microsource and 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 [10], [12].

The main functions of the Energy Manager are: to provide the individual power and voltage set points for each microsource controller, ensure that heat and electrical loads are met, ensure that the microgrid satisfies operational contracts with the transmission system and maximize the operational efficiency of the microsources [10], [12].

These key functions must be coordinated within a single microgrid as well as across multiple microgrid while considering the associated components. This semi-autonomous 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 [13], [14]. 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 literature [15]. Primary control operates on a real-time feedback control principle on the basis of local measurements [14].

Secondary control compensates for voltage and frequency deviations that may exist in spite of the primary control. It adjusts setpoints dynamically to achieve minimum and stable deviations while the power system transits to new operating points [13]. 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 systems [16], [17]. 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 and 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 [14].

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 promise to address a number of specific multi-microgrid operational challenges [18]. 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 [18], [19]:

• 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. Multi-Agent System Coordination Approach for Resilient Self-Healing Operation

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) [7]. 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 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.

The power system itself is modeled to consist of seven physical elements: dispatchable and stochastic generators, controllable and non-controllable loads, energy storage units, 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. The Matlab environment can communicate up to a JAVA-JADE environment through a software interface called Matlabcontrol [20]. The JAVA-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 2 shows a UML diagram of JAVA-JADE architecture and further details on the implementation of the platform have been previously reported in [21]. In this platform the physical agents send their status (on-off, set points and reconfigurations) to a virtual agent, called facilitator. This facilitator uses the interface JADE-MATLAB and executes a time domain simulation of the power grid transients under event/disturbances in the power system. In order to get the time domain simulation, Matlab uses a power flow tool (MATPOWER [22]) and power stability simulation tool (RSGSTT: Reconfigurable Smart Grid Transient Stability Simulator [21], [23]).

Next, the differential algebraic equations that describe the dynamics of the multiple microgrids are presented based upon the models presented in [24]. 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 [24]. Each synchronous machine $i$ is described by:

\[ \delta_i = \omega_i - \omega_0 \]
\[ \dot{\omega}_i = \frac{\omega_0}{2H_i} \left[ -P_m^i - P_c^i(\delta_i) - D_i \delta_i \right] \]

where $\delta$ is the machine phase angle, $\omega$ is the angular frequency, $H$ is the mechanical inertia, $D$ is the damping, $P_m$ is the dispatchable power applied to the prime mover, and $P_c$ is the electrical power at that generator 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:

\[ P_e = \Re[\mathbf{E}' \mathbf{Y} \mathbf{E}] \]

where $\mathbf{E}$ is the system bus voltage and $\mathbf{Y}$ is the system admittance matrix, detailed formulation is in [24]. The stochastic generators (i.e. solar PV & wind) and non-controllable loads are modeled as static power injections which affect the system admittance matrix [24]. 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.

In this control approach, each microgrid agent implements its own model predictive control which is able to dispatch the mechanical power setpoints $P_m$ for the synchronous machines within its control area. The formulation of which is as follows:

\[ \min \sum_{i=1}^{K} \sum_{t=1}^{N_G} (C^F_i + C^G_i P_{m_i,t}^G + C^U_i + C^D_i) \]
\[ \text{s.t. } \sum_{i=1}^{N_G} P_{m_i,t}^G = P_{NL,t} \]
\[ -P_{m_i}^G, \text{max} \leq P_{m_i}^G \leq P_{m_i}^G, \text{min} \leq P_{m_i}^G \leq P_{m_i}^G, \text{max} \]
where the following notations are used:

\[ C_{i}^{F}, C_{i}^{G}, C_{i}^{U}, C_{i}^{D} \] fixed, generation (fuel), startup and shutdown costs of generator \( i \)

\[ P_{m_{i,t}} \] power output of generator \( i \) at time \( t \)

\[ P_{NL,t} \] net load forecast at time \( t \)

\[ P_{m_{i},G,max}, P_{m_{i},G,min} \] max/min power limits of generator \( i \)

\[ R_{i}^{G,\max} \] maximum ramping rate of generator \( i \)

\[ N_{G} \] number of generators

In this case, the MPC uses a horizon time of \( K=4 \) with each time block \( k=15 \) seconds. The optimization program runs at each time block but only the dispatch for the first time block is dispatched to the synchronous machines.

Finally, the inter-microgrid coordination is achieved with a heuristic control-action behavior that is able to respond to events/disturbances. In order to demonstrate the coordination actions and the decentralized decision-making, two kinds of events/disturbances are used: a.) net load high variability time periods and b.) net load ramp events. 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 generator and load agents have power-time series data for a duration of 5 minutes with a resolution of 15 seconds. The data is sent to the microgrid agent who calculates the net load time series \( (P_{NL}) \) and evaluates two measures; the relative standard deviation \( \sigma_{NL} = \sigma(P_{NL})/P_{NL} \) 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 or disconnect the microgrids.

\[
u[t] = \begin{cases} 
1, & \sigma > \sigma_{crit} \\
0, & \text{otherwise}.
\end{cases} \quad (7)
\]

\[
u[t] = \begin{cases} 
1, & R > R_{crit} \\
0, & \text{otherwise}.
\end{cases} \quad (8)
\]

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 Equations 7 and 8) 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. CASE STUDY: IMPACTS OF MAS COORDINATION ON MULTIPLE MICROGRID TRANSIENT STABILITY

To test the coordination architecture, the six-bus microgrid system depicted in Figure 3 was chosen from Saadat’s power systems text [15] and was used as a template for a three-microgrid power test system, that is to say, three mutually connected microgrids with the same topology within them. The three microgrids have the potential to (dis)connect at the following bus pairs: 1.5-2.1, 1.6-3.6, 2.5-3.1, where the two digit numbering convention denotes the microgrid number followed by the original bus number in Figure 3.
This section investigates the resilience of the microgrids in relation to two types of disturbed operations: (i) highly variable net load, and (ii) net load ramp events. Each is taken in turn with simulations of 300 seconds duration.

A. Resilience Towards Net Load Variability

To understand the impact of net load variability on power system operation, Figure 4 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 ($\sigma(P_{NL})/\bar{P}_{NL}$) is less than 10% throughout. 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.

In contrast, very different transient behavior is observed once the net load variability is increased. Figure 5, this time shows the time domain simulation of the generator angles and speeds when microgrid 1 experiences a net load ramp event greater than 300W/min. 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. 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 IV-A, 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 6 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 III, the MAS decides between a connected and disconnected topology on the basis of Equation 7.

Despite having the same net load variability as in Figure 5, Figure 6 shows a greatly improved system response that much more closely resembles that of Figure 4. 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 phase angles to return to the nominal 60Hz.

B. Resilience Towards Net Load Ramping

To understand the impact of ramp events on power system operation, Figure 7 shows the time domain simulation of the generator angles and speeds when microgrid 1 experiences a net load ramp event greater than 300W/min. Here, the ramp event causes the generator speeds to fall well below the nominal 60Hz and the associated phase angle of these generator 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 IV-A, 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
to integrate decentralized control with economic objectives. This work presents many opportunities for future developments in the domain of resilient self-healing power grids.

**REFERENCES**


