A Control Framework for the Smart Grid for Voltage Support Using Agent-Based Technologies

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***Abstract*— The introduction of remotely controlled network devices is transforming the way the power system is operated and studied. The ability to provide real and reactive power support can be achieved at the end-user level. In this paper, a framework and algorithm to coordinate this type of end-user control is presented. The algorithm is based on a layered architecture that would follow a chain of command from the top layer (transmission grid) to the bottom layer (distribution grid). At the distribution grid layer, certain local problems can be solved without the intervention of the top layers. A reactive load control optimization algorithm to improve the voltage profile in distribution grid is presented. The framework presented in this paper integrates agent-based technologies to manage the data and control actions required to operate this type of architecture.**

***Index Terms*— reactive power resources, voltage control, distributed control, intelligent agents, incident command system**

I. INTRODUCTION

Today, the power grid is transforming and evolving into a faster-acting, potentially more controllable grid than in the past. This so-called “Smart Grid” will incorporate new digital and intelligent devices to replace the old analog devices in the power network. These new devices would allow remote control and operation, providing an opportunity for new control schemes and algorithms.

Many proponents of the Smart Grid think that controlling end-user devices, such as loads, will help the power grid during stress and abnormal situations. For example, the Grid Friendly Appliance controller developed at Pacific Northwest National Laboratory (PNNL) [1] will sense grid conditions by monitoring the frequency of the system and providing automatic load demand response in times of disruption to improve the frequency of the grid. This controller will be installed in certain appliances to turn them off or reduce the loading for a few minutes or even a few seconds to allow the grid to stabilize. Projects like this have the potential to transform the way the power grid is operated and analyzed

Currently, the grid is operated in a centralized manner. For example, the system protection against faults utilizes relays that are constantly monitoring the grid to detect abnormal conditions, and they initiate corrective action when it is needed. This protection implements local controls that are part of the SCADA supervisory scheme, which is a centralized framework.

This paper extends the ideas presented in [2] and [3] for using real and reactive load as a resource to mitigate certain problems in the power grid. It would integrate the centralized structure of protective relays into the proposed control framework. In [2], a scheme that uses intelligent agents is implemented to relieve line overloads by controlling certain loads in the grid. Also, a decentralized optimization algorithm was presented to minimize power losses in the distribution network. In [3], a scheme to control reactive power to maintain a healthy voltage profile is presented. The algorithm would be implemented using an intelligent control scheme following a chain-of-command structure called Incident Command System (ICS). The work presented in this paper combines both intelligent frameworks into a more effective scheme that would allow control at the different levels of the power grid. The paper also presents an optimization algorithm to control reactive resources in the distribution system by using the proposed framework with the incorporation of intelligent agents.

This paper is organized as follows. Section II presents the ICS framework. The details of the proposed control algorithm are presented in Section III of the paper. In Section IV an optimization algorithm to control reactive load in the distribution network is presented. In Section V of the paper, an agent-based simulation and test-bed are presented. Finally, conclusions and future work are presented in Section VI.

II. INTELLIGENT CONTROL FRAMEWORK

Members of a chain of command structure such as the Incident Command System (ICS) follow a line of authority and responsibility. The ICS is a “systematic tool used for the command, control, and coordination of an emergency response” [4]. This system is used by firefighters and other emergency personnel for efficiently handling the emergency scenarios they face daily. From the widespread successful uses of this system, it has proven to be effective for dealing with emergencies and with large numbers of responders who may not all work together normally but have the same goals for the incident. Interestingly, a similar framework is needed for the intelligent control of power system devices to respond efficiently when the power system is in crisis. In the ICS, each individual reports to only one supervisor. The individuals

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work in groups, and the group members report to a particular supervisor or officer who in turn reports to another specific officer. The functional unit with the highest authority is called command. Below command may be different sections, branches, functional groups, and geographical divisions [4]. The resources which actually perform the task are at the lowest level in the chain of command.

For the power system events of interest in this paper, the individual end-user real and reactive-power-controllable devices are the resources. Similar to the personnel resources in the ICS, end-user devices do not normally work together, but they have the same goal in a crisis.

Figure 1 shows the power grid as it is currently configured. A central EMS supervises conditions over the bulk transmission system. The transmission system meets the distribution system at the feeder relays, each of which serve a set of downstream relays (Control Relays). The downstream relays control the delivery of power to various loads, which, as the smart grid continues to grow, will increasingly be regulated by a controller.

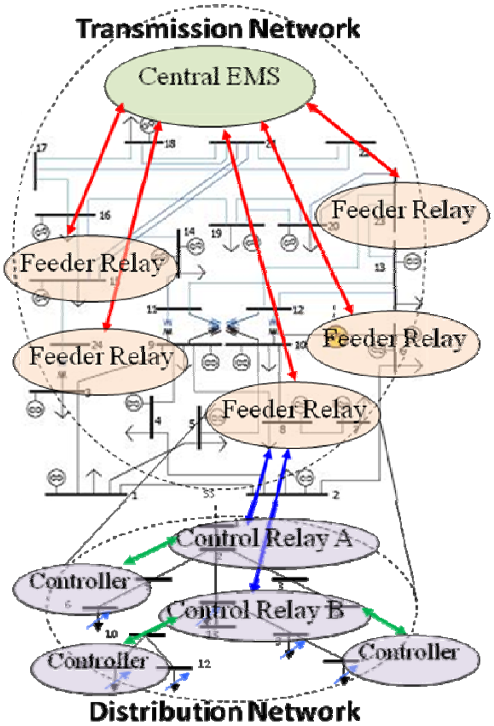

Figure 1. Transmission-distribution block diagram

In keeping with the ICS model, let us divide the nodes shown in Figure 1 into distinct supervisor-employee groupings called realms. Each realm consists of a top layer and a bottom layer. Each device in the top layer of a realm can supervise and control the activity of a set of devices in the bottom layer of the realm. The top-level devices in each realm do not communicate directly with any devices lower in the hierarchy than the bottom-level devices in their realm. Instead, if control actions need to be taken further down in the hierarchy, the bottom-level devices of the realm, which are also the top-level devices of the next lower realm, will send the appropriate control signals downstream. This pattern of delegation is at the heart of the ICS model, and it provides a convenient way to segregate and secure communications on the smart grid.

In order to manage the information and control commands, the ICS command structure can be implemented using a multi-agent system architecture. The feeder relay will have an agent that manages the data and the control actions needed in the corresponding layer of the framework. The layered architecture can be implemented to allow two-way communications. In this type of vertical layer behaviors architecture, the flow of information comes from the bottom layers (get data) and from the top layers (control commands). Thus, the information goes in two different directions [5]. One way to coordinate this system is to implement a centralized multi-agent planning technique. In this technique, there is usually one coordinating agent that received the information of other agents and plans/coordinates the individual actions of the bottom layer agents [5]. Then, since all the agents would have a single or specific task, the coordination of the system is rather straightforward. Another technique for coordinating this system involves a competitive negotiation in which each agent has a specific goal, and the degree of cooperation of individual agents is not known in advance. An example of this type of competitive negotiation is presented in [6-10] in which a set of agents is formed to coordinate a response to a problem while other agents coordinate a response to the same problem.

One of the main problems with the layered architecture is that if a direct communication link is lost from the central coordinating agent to the bottom agents, then the task cannot be performed. In order to solve this issue, the control algorithm would need to have a contingency response to this type of problem. In the ICS command structure presented in this paper, the coordinating agent could be the Central EMS and the bottom layer agents could be the feeder relays and other relays connected to the Central EMS (Figure 1). In Section III of the paper, an algorithm that addresses these issues is presented. The algorithm complements the ICS model presented in paper [3] and is able to handle different control situations.

Note that this organization is flexible enough to handle problems in a decentralized way instead of always through a central top-level controller. For example, if a top-level device on any of the lower realms detects a local problem, and if that device is suitably equipped to formulate a response, it can initiate correction of the problem by coordinating the devices beneath it. Such a situation would not need to rely on the Central EMS to send the control messages. Thus, potential applications of the framework extend beyond voltage control and could also benefit from the use of intelligent agents as in [2]. In general, such a scheme can be used to enact any corrective and preventative controls.

III. CONTROL ALGORITHM AND ARCHITECTURE

The control algorithms that will be implemented using the proposed hierarchical arrangement of realms would have to be flexible enough to handle problems in a decentralized way instead of always in a centralized top-down manner. In order to do this, the algorithm should be robust enough to handle situations locally while ensuring that the local actions don’t affect other areas of the power grid.

A. *The Central Control Scheme*

To understand better this type of control involving realms and layers, consider the following algorithm.

1) The Central EMS detects a problem somewhere on the system. Based on the information and data received from the relays, it computes an aggregate response that would mitigate the problem. It formulates action requests and sends them through the hierarchy, where they are received by the feeder relays.
2) Once the request is received by the feeder relays, they must verify that the aggregated request can be performed. The feeder relays would verify the request by communicating to the downstream controllers and verifying that the aggregate response requested by the Central EMS can be performed.
   Thus to verify the request the feeder relay agent computes a set of response actions that would allow it to fulfill the aggregated request. This is because the relay now needs to coordinate locally how the aggregate power requested from the Central EMS would be control at the specified moment in time in the distribution network.
3) After the feeder relay verifies that the control action can be performed and computes a set of responses for the controllers within its purview, it sends a message to the Central EMS agreeing to do the requested control action. If a local controller can't perform the requested command, then the feeder relay should formulate a new local response. If a local solution within the distribution network can't be found, then the Central EMS should be notified by the feeder relay and a new set of responses should be computed by the Central EMS.
4) At this point, if all of the feeder relays agree on the requested control, the Central EMS sends a command to the feeder relay confirming that the control action is going to be performed. Even if all of the feeder relays agree, the Central EMS will still have one last opportunity of cancel the control action, if, for example, it will affect other areas of the power network.
5) Once the confirmation from the Central EMS is received by the feeder relay, it will perform the control action by sending the commands to the controllers and relays to which they are connected.
6) Each controller then controls the loads under its supervision to meet the requests.
7) Once the control action is performed, the feeder relay will send a message to the Central EMS indicating that the control actions were completed. By doing this, the Central EMS will have a log of the control actions that are being performed in the power grid, which will allow various steps to be retraced if necessary.

With this type of control algorithm, the actions are not performed until after there is verification from the top to the bottom layers that the algorithm can be performed without major consequences. There must be verification that the devices can be controlled and that the control of the devices is not going to create more problems to the power grid.

B. *The Local Control Scheme*

In the previous section, the algorithm was initiated from the very top of the command system (i.e. the Central EMS). However, there are going to be cases where the action would be initiated locally, say, from the feeder relays. For this type of scenario, the following algorithm will be implemented.

1) The feeder relay detects a problem for which it has the authority to initiate a local response.
2) After verifying that the control is not going to have a negative impact in the rest of the power grid (a task to be considered in a future paper) it will formulate control action requests and send them through the hierarchy where they are received by the load controllers.
3) Once the control action is performed, the feeder relay will send a message to the Central EMS indicating that the control actions were performed. By doing this, the Central EMS will have a log of the control actions that are being performed in the power grid.
4) At this point the Central EMS can determine if the control action will affect other regions of the power grid. If there is a negative effect in other regions of the grid, then a solution involving coordination with other regions need to be formulated and computed.

It is again important to notice that the Central EMS would have a log of all of the control actions that are being performed by the feeder relays. The purpose of this log is to have a record of what is happening in the grid. For this matter, the operators would know at any time what is being done in the grid and, if one of the control actions creates a problem or can't be performed at a certain moment, they would consult the log and reverse the offending control actions.

IV. REACTIVE RESOURCES FOR VOLTAGE SUPPORT

The work presented in [3] investigates the integration of end-user reactive-power-controllable devices, such as solar panels and pluggable hybrid electric vehicles (PHEVs), to provide voltage support to the grid. In the previous work [3], it was demonstrated that, by controlling the reactive power of certain buses in the transmission network, the voltage profile through the grid can be maintained within the desired magnitude. However, in order to be able to control the reactive loads in the transmission network, the same analysis has to be performed in the distribution network. In the distribution network, the loads are served by different feeders and circuits. Therefore, the analysis is different from how the transmission network is analyzed. Therefore, the analysis is different from how the transmission network is analyzed, because the system is primary radial. In this section, a strategy for identifying optimal control strategies on the distribution network for maintaining suitable voltage profiles is described.

A. *The Voltage Problem Formulation*

The voltage control problem studied here has the following mathematical formulation:

$$\min \quad \sum_{k=1}^{N}\left(V_k(x,u)-V_{k\,spec}\right)^2$$

$$\text{s.t.} \quad \begin{array}{l} \mathrm{DPF}(x,u) \\ 0 \le u \le (u)^{\max} \end{array} \tag{1}$$

where *DPF* are the distribution power-flow constraints. The power flow constraints are equality constraints describing the voltage and current relationship at each branch and node. For each voltage and current equation there is a real and imaginary equation describing the governing behavior of voltages and currents in a distribution network.

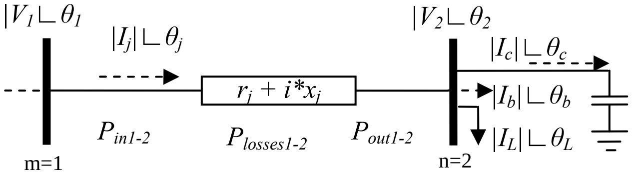

Figure 2. Branch diagram in a distribution feeder

The DPF equality constraints for the bus voltages are:

$$\mathrm{Re}\left[\left(|V_m|\angle\theta_m\right)=\left(|V_n|\angle\theta_n\right)+\left((r+i*x)*\left(|I_j|\angle\theta_j\right)\right)\right] \tag{2}$$

$$\mathrm{Im}\left[\left(|V_m|\angle\theta_m\right)=\left(|V_n|\angle\theta_n\right)+\left((r+i*x)*\left(|I_j|\angle\theta_j\right)\right)\right] \tag{3}$$

Equations (2) and (3) may be rewritten as

$$\begin{array}{l}\left(|V_m|\cdot\cos\theta_m\right)= \\ \left(|V_n|\cdot\cos\theta_n\right)-\left(|I_j|\cdot\cos\theta_j\right)\cdot(r)+\left(|I_j|\cdot\sin\theta_j\right)\cdot(x)\end{array} \tag{4}$$

$$\begin{array}{l}\left(|V_m|\cdot\sin\theta_m\right)= \\ \left(|V_n|\cdot\sin\theta_n\right)-\left(|I_j|\cdot\cos\theta_j\right)\cdot(x)-\left(|I_j|\cdot\sin\theta_j\right)\cdot(r)\end{array} \tag{5}$$

The DPF equality constraints for the line currents are:

$$\mathrm{Re}\left[|I_j|\angle\theta_j=|I_L|\angle\theta_L+|I_b|\angle\theta_b\right] \tag{6}$$

$$\mathrm{Im}\left[|I_j|\angle\theta_j=|I_L|\angle\theta_L+|I_b|\angle\theta_b\right] \tag{7}$$

$$|I_L|\angle\theta_L=\frac{|S_{Load}|}{|V_n|}\angle\left(\theta_{Load}-\theta_n\right)=$$

where: (8)

$$\left(\frac{S_{Load}}{V_n}\right)^*=\left(\frac{P_{Load}+i\cdot Q_{Load}}{|V_n|\cos\theta_n+i\cdot|V_n|\sin\theta_n}\right)^*$$

In this problem, the reactive load will be controlled and can be represented as:

$$Q_{Load}=Q_{LoadOld}-\Delta Q_{Load} \tag{9}$$

ΔQ_{Load} will be calculated in the optimization problem.

Equations (6) and (7) may be rewritten as

$$|I_j|\cdot\cos\theta_j=|I_L|\cdot\cos\theta_L+|I_b|\cdot\cos\theta_b \tag{10}$$

$$|I_j|\cdot\sin\theta_j=|I_L|\cdot\sin\theta_L+|I_b|\cdot\sin\theta_b \tag{11}$$

After some algebra if equation (8), (9) and (10) are substituted into (10) and (11) the resulting load currents components with it corresponding real and imaginary part will be:

$$\begin{array}{l}|I_L|\cdot\cos\theta_L+i\cdot|I_L|\cdot\sin\theta_L= \\ \dfrac{P_{Load}\cdot|V_n|\cos\theta_n+Q_{LoadOld}\cdot|V_n|\sin\theta_n-\Delta Q_{Load}\cdot|V_n|\sin\theta_n}{\left(|V_n|\right)^2}+ \\ i\cdot\left(\dfrac{P_{Load}\cdot|V_n|\sin\theta_n-Q_{LoadOld}\cdot|V_n|\cos\theta_n+\Delta Q_{Load}\cdot|V_n|\cos\theta_n}{\left(|V_n|\right)^2}\right)\end{array} \tag{12}$$

For this problem, the inequality constraints are simply the maximum and minimum values the bus voltages can have and the maximum branch currents passing through the feeder. In this case, the cost function of the equations penalized the voltage inequality constraint for the buses in which we want the voltage to be above a certain value, typically above 0.9 p.u. value. The proposed optimization problem can be solved using many optimization techniques, including for example, the Lagrangian approach. This type of problem can be formulated as a constrained nonlinear optimization problem as follows:

$$\begin{array}{ll}\text{minimize} & f(x,u) \\ \text{subject to} & g(x,u)=0 \\ & h(x,u)\le 0\end{array} \tag{13}$$

where $\boldsymbol{x}$ is the vector of unknown variables, $\boldsymbol{u}$ is the vector of control parameters, $f(x,u)$ is the objective function, $g(x,u)$ and $h(x,u)$ represent the equality and inequality constraints, respectively.

Next, the problem is converted to an unconstrained minimization problem using the following Lagrange function [12] for this problem as:

$$L(x,u,\lambda,\beta)=f(x,u)+\lambda^T g(x,u)+\beta^T(u)^2 \tag{14}$$

or equivalently,

$$\begin{array}{l}L(x,u,\lambda,\beta)=f(x,u)+\lambda^T g(x,u)+ \\ \beta^T_{\min}(0-u)^2+\beta^T_{\max}\left(u-(u)^{\max}\right)^2\end{array} \tag{15}$$

where $\boldsymbol{\lambda}$ is the vector of Lagrange multipliers related to the equality constraints and $\boldsymbol{\beta}$ is the vector of penalties that are applied when the control variables are outside their minimum and maximum values. In this case, the controllable parameter is the ΔQ_{Load} (controllable reactive load). For this paper, the optimization problem was solved using the Newton approach.

B. Ten- and Thirty-Four-Bus Reactive Load Control Examples

The optimization algorithm was tested on a 10-bus feeder and a 34-bus feeder. In both cases, the loads were modeled as constant PQ devices. The 10-bus system is shown in Figure 3. In the 10-bus system, the reactive loads to be controlled are located at buses 4, 5, 7, 8, 9 and 10. The results are presented in Table 1 and 2. It can be seen that the voltages in the system were increased through the control actions, and that all controllable reactive loads participated in the action. There are still voltages below the voltage target of 0.9 pu because is the best solution that can be achieved for the 10-bus system.

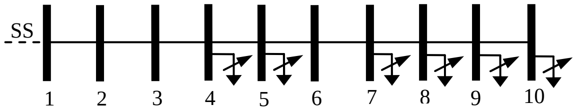

Figure 3 Ten-Bus feeder at substation SS

Table 1 Reactive Load kVARs for 9-bus system

Case	Controllable Load (kVARr)	Initial Load (kVARs)	Final Load (kVARs)
CV1: Bus 4	646	446	-200
CV1: Bus 5	1,940	1840	-100
CV1: Bus 7	210	110	-100
CV1: Bus 8	160	60	-100
CV1: Bus 9	330	130	-200
CV1: Bus 10	400	200	-200

Table 2 Bus Voltage for 10-bus system

Case	Initial Volts (pu)	Final Volts (pu)
CV1: Bus 5	0.889	0.91879
CV1: Bus 7	0.85875	0.89384
CV1: Bus 8	0.83756	0.87613

In the second scenario, the algorithm was tested on a modified IEEE 34-bus distribution system (Figure 4). In this case (CV2 in Table 3 and 4) the loads to be controlled are located at buses 17, 20, 22, 23, 25, 27, 29 and 30 respectively. In this case the voltages were initially below 0.9 p.u. from bus 17 to bus 34.

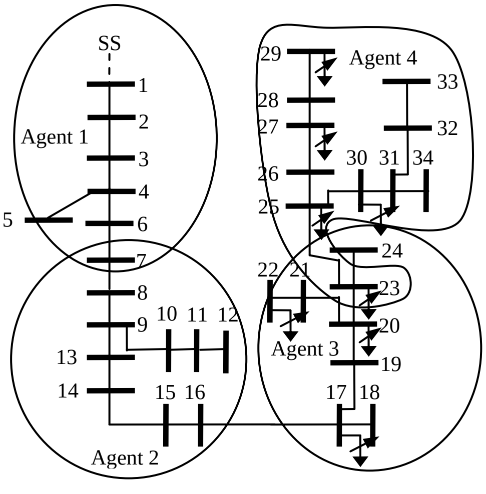

Figure 4 IEEE Modified 34 Bus feeder connected to substation SS

The results from this algorithm (Table 3 and 4) show that using the algorithm can effectively find the amount of reactive load to be controlled. This fact is more visible in Table 4 for the case when only the voltage profile target was set to be at 0.9 pu. For this case the total amount of controllable reactive load was 519 kVARs but only 415.9 kVARs was used to satisfy the desire set voltage. When the voltage profile target was 0.91 pu, all of the controllable 519 kVARs of reactive load was used.

Table 3 Reactive Load kVARs for 34-bus system

Case	Control Load (kVARs)	Initial Load (kVARs)	Final Load (kVARs) 0.91 pu case	Final Load (kVARs) 0.9 pu case
CV2: Bus 17	7	2	-5	-5
CV2: Bus 20	13	3	-10	3
CV2: Bus 22	95	75	-20	-20
CV2: Bus 23	31	1	-30	1
CV2: Bus 25	27	7	-20	-20
CV2: Bus 27	205	105	-100	-40.912
CV2: Bus 29	46	16	-30	-30
CV2: Bus 30	95	55	-40	-40

Table 4 Bus Voltage for 34-bus system

Case	Initial Volts (pu)	Final Volts (pu) 0.91 pu case	Final Volts (pu) 0.9 pu case
CV2: Bus 19	0.85946	0.91088	0.90151
CV2: Bus 20	0.85945	0.91088	0.9015
CV2: Bus 21	0.85945	0.91087	0.9015
CV2: Bus 22	0.85829	0.9102	0.90082
CV2: Bus 23	0.85783	0.91017	0.90061
CV2: Bus 24	0.85783	0.91017	0.9006
CV2: Bus 25	0.85592	0.90928	0.89956
CV2: Bus 26	0.85588	0.90927	0.89954
CV2: Bus 27	0.85567	0.90921	0.89945
CV2: Bus 28	0.85554	0.90916	0.8994
CV2: Bus 29	0.85554	0.90916	0.8994
CV2: Bus 30	0.8556	0.90905	0.89933
CV2: Bus 31	0.85539	0.90885	0.89913
CV2: Bus 32	0.85537	0.90884	0.89912
CV2: Bus 33	0.85527	0.90875	0.89902
CV2: Bus 34	0.85537	0.90884	0.89911

V. AGENT SIMULATION AND TESTBED IMPLEMENTATION

In order to test the algorithm in a realistic setting, a simulation testbed was created. We describe the testbed here. The testbed includes agents simulated using JADE (Java Agent Development Framework) [5, 13 and 14]. JADE is a JAVA framework for developing FIPA (foundation for intelligent physical agents) compliant agent applications and is one of the most widespread agent-oriented and completely distributed middleware systems to create agents [5]. In the work presented in [2] a similar framework was created but worked only on a single computer. The testbed created here can have agents running in different computers and can communicate between them as long as they are connected to the same computer network. This will allow for a distributed implementation of the agents just as will occur in a real power system. In the real system, an agent would be housed in a control device, such as an intelligent relay. Therefore, each JADE-based agent models an agent that would be placed in an actual system control device.

The agents were modeled using the JADE platform, while the power network itself, including its loads, generators, and transmission lines, were modeled using Matlab. A connection between the agents and Matlab was established so that the agents could be informed of the state of the power system. For example, changes to the power system were modeled and solved in Matlab, and the resulting changes in system parameters, such as voltages and currents, were communicated to the JADE-based agents. Furthermore, the optimizations algorithms were run and solved in Matlab. Agents could request an optimization from Matlab to evaluate control alternatives.

Now the implementation of the algorithm on this testbed is described. The system was designed to emulate the ICS architecture described in Section II. Figure 5 shows the testbed in detail. Computer A simulates the transmission network and associated transmission-level agents. Similarly, computer B simulates the distribution network and its associated agents. The ICS control algorithm presented in Section III-A was coded and executed on these computers to solve the reactive resources optimization problem described in Section IV.

The control algorithm was implemented as follows:

1) The Matlab-based power system model is recalculated based on new system conditions. These power model changes are then communicated to the agents housed in the Central EMS and downstream feeder relays and controllers, which are modeled using JADE.
2) The Central EMS detects a low voltage problem somewhere on the system. Based on the information and data received from the feeder relays (FR), it computes an aggregate response that would mitigate the problem by performing a transmission-level optimization problem that is similar to the one presented in Section IV.A but applied to a transmission network. See [3] for the details of this algorithm. For this case the equality constraints are the transmission network equations. After a Solution of the optimization is obtained the Central EMS agent will send the resulting requested load to be controlled through the hierarchy, where they are received by the feeder relays.
3) Once the request is received by the FRs, each FR will verify that the aggregated request can be performed. It does this by surveying the equipment downstream from it. Keep in mind that a transmission network bus usually consists of many substations, each of which aggregates many distribution networks. Therefore, the FR sees a multi-level network beneath it. We identify the top of these levels by the Top Feeder Relay, or TFR. Thus, each distribution network feeder will have a top feeder relay (TFR) that will be coordinating the controller relays (CR) of the feeder (Figure 6). Note here that there could be multiple TFRs per FR.
4) The FR relays would verify the request by communicating to the TFR. The FR relay at this point knows how much load the TFR can control, but that doesn't mean that all of the reactive load can or should be controlled, because changes to one set of devices could have a harmful impact on other devices. Then, after this, the TFR will perform the voltage problem optimization to determine the amount of reactive load it can control. If a CR can't perform the requested command, then the TFR should formulate a new local response. After a solution is obtained, a command is sent to the FR indicating the amount of load that the particular TFR can control.

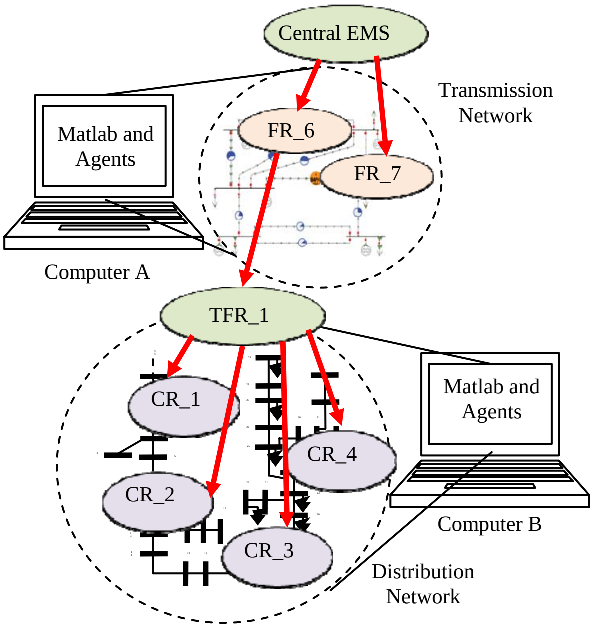

Figure 5 Agent and Simulation Test-Bed

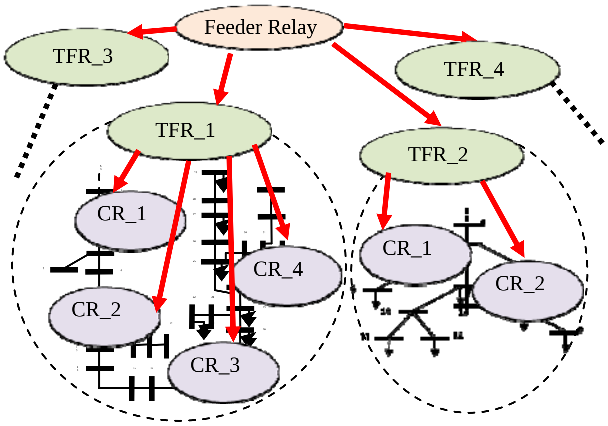

Figure 6 Feeder Relays and Top Feeder Relay Agents in the Distribution Network

5) Once the FR receives the controllable loads from all of the TFRs, it verifies that the aggregated request by the Central EMS agent can be performed.
6) After the FR verifies that the control action can be performed because all of the requested aggregated load can be controlled, it will send a message to the Central EMS agreeing to do the requested control action. If the FR can't provide the control requested

by the Central EMS, the algorithm proceeds to step 11.

7) At this point, the Central EMS sends a command to the FR confirming that the control action is going to be performed.
8) Once the confirmation from the Central EMS is received by the FR, it will send the control command to the TFRs, which will then send the specific commands to the connected CRs.
9) Each controller then sends a command to the load controllers under its supervision to meet the requests.
10) Once the control action is performed, the TFRs send a message to the FR indicating the control has been performed. Subsequently, the FR then sends a message to the Central EMS indicating that the control actions were performed. The algorithm then stops.
11) For the case identified in step 6 when the FR can't control the requested aggregated load, the FR reports the amount of available load that is controllable. Then, the Central EMS will send a cancel command to the FR. Then the FR will send a cancel command to the TFRs. At this point the Central EMS will try to find a new solution, and the algorithm will start again.

A. Agent Simulation Case Study

In this section, an example to test the simulation is presented. The example presented in this case is a 7-bus transmission network with a low voltage of 0.94pu at bus 6 and 0.99 pu at bus seven. The set-point value of their respective buses is 0.95 pu and 0.99 pu. Thus, a reactive support optimization algorithm was performed by the Central EMS agent, and the following amount of load was identified o be controlled: 3.52 MVARs for bus 6 and 17.083 MVARs for bus 7.

For this simulation, only the integration between the feeder relay at bus 6 (FR_6) and the top feeder relay 1 (TFR_1) was performed. The TFR_1 is responsible for the same 34 bus system presented in Section IV-B. Again the same simulation was performed for the 34-bus feeder and the results were the same. For this case, the voltage of the buses has to be improved to 0.9 pu. In this distribution network, there are four agents (Figure 4). The first is responsible for buses 1 through 7 but no load is controlled. The second is responsible for buses 7 through 16 but no load is controlled. The third is controlling loads at buses 17, 20, 22 and 23 connected to those same buses and is responsible for buses 16 through 24. The fourth is controlling loads at buses 25, 27, 29 and 30 connected to those same buses and is responsible for buses 23 through 34, excluding 24. Once a solution for the reactive loads was obtained, the TFR sent the amount of load to be controlled to those relay controller agents. The results in Table 3 show that not every one of the available controllable loads needed to be used to satisfy the constraint. In other words, because of operational constraint in the distribution grid, not all of the available load can be used as requested by the FR. This is because there are cases in which setting voltages above certain values could affect the behavior of other devices such as tap-transformers or capacitors. Thus, using the algorithm to effectively determine the amount of load to be controlled is important, because it ensures that operating constraints are obeyed.

The other TFR agents that are interacting with FR_6 in Figure 6 were assumed to be connected to a distribution network feeder but in this case only one TFR was connected to a simulated distribution network. However, this test-bed can easily be extended to include other TFR agents if desired.

In the transmission network simulation, other feeder relays could have the same set up as the one presented in Figure 5. Thus the applications could be extended to test or interact with bigger simulations. An interesting point is that the computers used to model the agents could be connected to real load control devices and thus should be able to model the effect of control strategies devised by the optimization algorithms.

In this paper the control of the reactive load is assume to be always possible and no real time control is presented. In the future, real time control is going to be implemented by controlling a reactive load (a battery providing reactive power by using an inverter). By doing this the proposed algorithm will need to be modified to incorporate the effect of having real time control to inject reactive power into a real distribution network. Also the effect of loss of communication will need to be incorporated in the analysis to test the resiliency of the algorithm to such failures.

Finally it is important to notice that the interaction between the transmission and the distribution layer is the responsibility of the feeder relay at the bus where the distribution network starts. In this paper only two distribution feeders where tested, where one was simulated in detail (34-bus distribution feeder) and the other distribution feeder was assumed to be always controllable and was modeled as a constant PQ load. This is the ideal case when the requested controllable load is equal to the amount that is available to be control. In the future the algorithm will handle many distribution feeders. The interaction between the feeder relay and the TFR will need to be revised. An algorithm to determine the amount of load to be controlled among the TFRs will need to be developed to handle the case when there is more controllable load than the requested amount. The algorithm should determine how the feeder relay will send control commands to the TFRs.

The proposed framework is the first step in designing an algorithm to provide local control of different resources in the power grid.

VI. CONCLUSION

This paper presented a control algorithm framework that could be implemented in the Smart Grid. The framework is based on a hierarchical structure in which each action follows a chain of command from the top layer (Control Center) to the bottom layers (distribution network and loads).

A key component of the control algorithm framework is a reactive load control optimization algorithm to improve the voltage profile in distribution networks. This algorithm complements the strategy described in [3] for the transmission network. The unified control algorithm framework, encompassing both the transmission and distribution networks and their associated agents, was implemented in software and tested on two different small systems, where it was found to provide effective voltage control.

In future work, the control framework will be applied to larger transmission and distribution power networks to see if it is similarly effective. Also, the impact on the transmission network of autonomous control in the distribution network is going to be studied more thoroughly. This impact is potentially important, because actions taken locally could impact conditions more broadly. Therefore, whether local control should be done autonomously or with intervention from the Control Center must be evaluated. The future work will strive to make this determination. Finally, the framework will be integrated with actual devices in a laboratory testbed to demonstrate its practical implementation for real utility systems.

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