Scalable Multi-Agent System for Real-Time Electric Power Management

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***Abstract*-- A scalable multi-agent paradigm is presented for control of distributed energy resources to achieve higher reliability, higher power quality, and more efficient (optimum) power generation and consumption A dynamic hybrid multi-agent system is proposed in this paper as a means to achieve scalability for control of a large network of power generation, transmission, load, and compensation sources. Example ancillary agents are developed for system stability and harmonic and reactive current compensation.**

***Index Terms*—compensation, distributed generation, harmonics, intelligent multi-agents, reactive power, stability.**

I. INTRODUCTION

THE electric power industry in the 21st Century will see dramatic changes in both its physical infrastructure and its control and communication infrastructure. These changes are the result of mainly three factors: 1) the push toward a deregulated industry, 2) the development of more efficient and/or less polluting energy resources that are cost competitive with traditional power generation sources, and 3) the continued electrification and integration of information technology into most facets of our everyday lives has resulted in a need for a better reliability and improved power quality than the existing power grid can supply [1].

As a result, a shift will take place from a relatively few large, concentrated generation centers and the transmission of electricity over mostly a high voltage ac grid to a more diverse and dispersed generation infrastructure that includes renewable or sustainable energy sources. Power electronics and their associated control will be a critical component for interfacing these new distributed energy resources (DER) and providing new ancillary services that can improve the reliability, stability, and quality of the electric grid.

This change in a physical infrastructure combined with a trend toward deregulation of the electric power industry will result in new control and information technology challenges that have yet to be addressed. In some cases, distributed power generation will provide the opportunity for generation and consumption to be co-located at places where it is needed. However, distributed energy resources bring several problems related to connection to the electric grid, central control of large numbers of small generators, and coordination of these distributed resources. The control and interchange of system information will take place among hundreds or even thousands of distributed generation centers instead of just among a handful of large utilities. Also, the energy market will be much more dynamic with a need for real-time price structure and information exchange [2]. The stability and reliability of power systems becomes intractable if large numbers of generators and resources connected to the grid have no synergy, no coordination, or no intercommunication.

In addition, more than just real power will be for sale in future electricity markets because ancillary services will also be available to improve the reliability and quality of the delivered electricity or to reduce system operation costs. Power electronics have not only made grid connection of distributed energy resources possible, but this technology also provides great opportunities to make the distributed resources significantly more useful and valuable to the grid other than as just a real power source, by enhancing grid stability and reliability. Power electronics-based grid interface systems have the ability for reactive power generation/compensation, power flow control, harmonic compensation, voltage regulation, dynamic control over the frequency and voltage output, and real-time control/connection of DER [3].

A multi-agent paradigm is ideal for control of distributed energy resources to achieve higher reliability, higher power quality, and more efficient (optimum) power generation and consumption [4], [5]. In the context of the electric power industry, large-scale and real-time response are just two of the challenging requirements for implementing a multi-agent system that can control power flow and power electronics interfaces in a dynamic way. The scale of the power system can be anywhere from thousands to tens of thousands of nodes with an array of interconnections between the nodes. Some of the parameters that will have to be passed between agents include average values of voltage, current, real power, non-active (reactive) power, or perhaps even the real-time voltage and current waveforms.

Because multi-agent systems process data locally and only transfer results to an integration center, computation time is largely reduced, and the network bandwidth is very much reduced compared to that of a central control. Multi-agent systems also allow scalability such as when new resources, loads, or interconnections are added to the system and extensibility such as performing new tasks or communicating a new set of data that becomes available.

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II. SCALABLE MULTI-AGENT APPROACH

An agent is defined here as an information processor. In this framework, an agent is a software entity that performs autonomous actions based on information. Agents may rely on other agents to acquire or share information to achieve their goals. Agents can also be recursive in that a collection of agents can be considered an agent if they posses information together as a set.

In the past few years, multi-agent techniques have found their place in many distributed systems such as distributed problem solving, distributed information fusion, distributed scientific computing, and also DER management [6]-[10]. However, these earlier applications, especially in the area of power, tended to neglect the size of the application domain while focusing only on functional properties like agent negotiation, collaboration, and communication. In the context of the electric power industry, the scale of the power system can be anywhere from thousands to tens of thousands of nodes with an array of interconnections between the nodes.

Therefore, in order to translate multi-agent techniques to practical systems, scalability issues become significant. The scalability of a multi-agent system depends on whether the worst-case performance of the system is bounded by a polynomial function of the load [11]. A dynamic hybrid multi-agent system is proposed in this paper as a means to achieve scalability. In this hybrid architecture, besides connecting to their parents and children, each agent can also connect to their siblings. Peer agents can communicate and collaborate with each other. Peer agents will dynamically select a leader to establish the real connection with their parents. The hybrid structure is illustrated in Fig. 1.

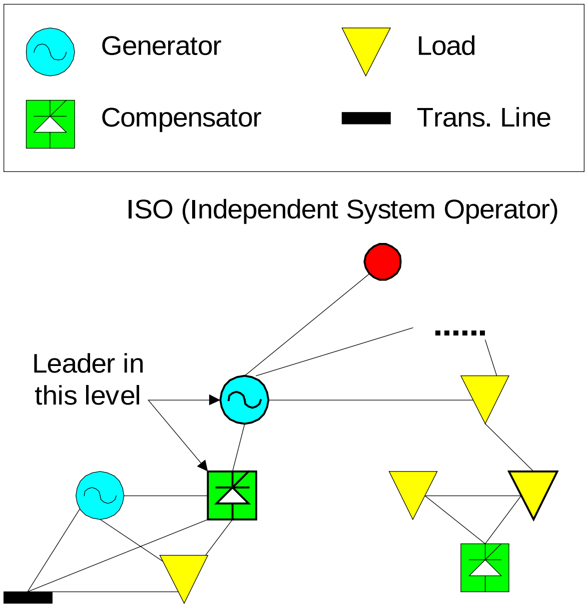

Fig. 1. Hybrid multi-agent architecture for scalability.

In the multi-agent paradigm, two kinds of agents are identified: the *traditional agents* and the *ancillary agents*. Traditional agents model the behavior of generator, load, and transmission lines, while the ancillary agents model a compensator, different weather conditions, or other elements needed for power transmission planning.

Each agent is a hybrid entity of four attributes: A = {Identification, Method, Knowledge, Interface}. *Identification* is used to identify with which modality (e.g. generator, load, transmission line, compensator, etc.) this agent is associated. *Method* is the embedded coalition formation algorithm, discussed later in this paper. *Knowledge* includes the apriori information (e.g. values of parameters like voltage, current, etc.) of its neighbors and the accumulated derived knowledge from the coalition formation process. *Interface* provides the interface functions for agents to access the knowledge base of each other and also for agent communication (knowledge exchange).

In a large distributed system such as the U.S. power grid, communication from one or several agents will be interrupted at times. Under these adverse conditions, the remaining agents will need to be able to make decisions that do not jeopardize grid stability or reliability. Fault-tolerant agents that can make decisions in the absence of data from one of their neighboring agents is required. Although the data from a particular agent may be missing, many times this data can be inferred from the load flow and voltage information from neighboring agents. Therefore, through agent collaboration, fault detection can be achieved.

III. COMPENSATOR AGENTS FOR STABILITY

Agents can be developed for power electronic compensators that can provide an array of services such as reactive power generation, power flow control, harmonic compensation, voltage regulation, or dynamic control over the frequency and voltage. These converters can be integrated with generation resources, loads, or act as a stand-alone system. A large set of decision criteria is necessary for the agents such that they can make control decisions that will ultimately improve the power quality and reliability of the electric grid. The following shows one example of the many ways a compensator could be used.

Compensators combined with a system stabilization algorithm can be used for power flow control between multiple resources. In order to transmit a certain amount of real power from Point 1 to Point 2 (P_{12}) as shown in Fig. 2, the phase angle difference δ_{12} between Point 1 voltage V_1 and Point 2 voltage V_2 has to be precisely controlled and monitored according to the following well-known formula:

$$P_{12} = \frac{V_1 V_2}{X_{12}} \sin \delta_{12} \tag{1}$$

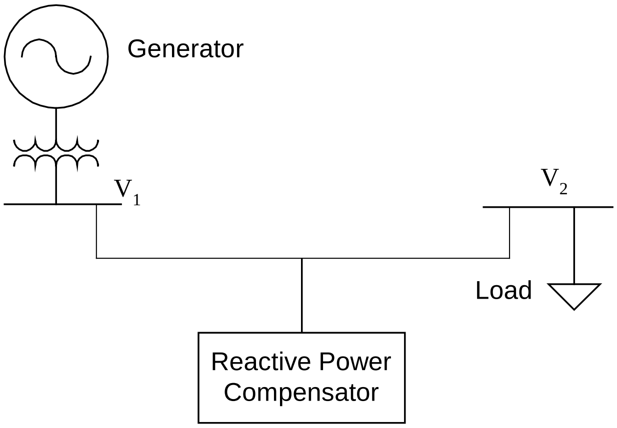

Fig 2. Two-bus system with reactive power compensator at midpoint.

Equation (1) gives a power versus angle curve (P/δ), which has its maximum value at δ_{12} = 90 degrees. However, any more power than this maximum value that is demanded by Point 2 causes the system to become unstable and/or collapse. However, if a third distributed resource (or agent) is located at the midpoint between Point 1 and Point 2, and this resource is capable of providing reactive power to hold its voltage constant at the value V, the P/δ curve becomes

$$P_{12} = \frac{2V^2}{X'_{12}} \sin\frac{\delta_{12}}{2} \tag{2}$$

assuming $V_1 = V_2$, and X'_{12} is the sum of the transmission line, transformer, and transient reactances between Points 1 and 2. As a result, the maximum power that can be transmitted from Point 1 to Point 2 is doubled. In other words, system transient stability can be greatly improved by providing ancillary services such as reactive power from DER. This provides two significant opportunities for system stability improvement: (1) an increase in the transient stability margin for a given power transfer or (2) an increase in the possible power transfer while maintaining transient stability.

IV. COMPENSATOR AGENTS FOR NON-ACTIVE POWER

Non-active power can be thought of as the useless power that causes increased line current and losses, greater generation requirements for utilities, and other effects/burdens to power systems and connected/related equipment. Agent-controlled power electronic compensators can be used to mitigate and/or eliminate much of the non-active power found in distribution systems such that generation resources are able to supply a larger real power demand. Another benefit in the application of power electronics compensators is that they can be controlled by agents such that loads receive high-quality voltage waveforms [12], [13]. A shunt compensator to minimize the useless power/current can be configured as shown in Fig. 3.

The idea of non-active current/power is formulated as follows:

$$i_p(t) = \frac{P(t)}{V_p^2(t)} v_p(t), \tag{3}$$

$$i_q(t) = i(t) - i_p(t), \tag{4}$$

where

$$V_p(t) = \sqrt{\frac{1}{T_C}\int_{t-T_C}^{t} v_p^2(\tau)\,d\tau}. \tag{5}$$

$i_p(t)$ is the active current and $i_q(t)$ is the non-active current. $P(t)$ is the average active power over the interval $[t-T_c, t]$. $V_p(t)$ is the rms value of the voltage, $v_p(t)$ over the same interval $[t-Tc, t]$, which is expressed by (5). In terms of compensators, $v_p(t)$ is the reference voltage that can be the voltage itself, $v_p(t) = v(t)$, or it could be the fundamental component of $v(t)$, where $v(t) = v_f(t) + v_h(t)$ and $v_p(t) = v_f(t)$, or something else depending on compensation objectives.

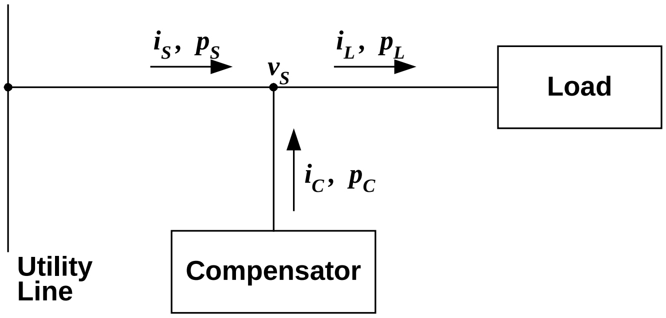

Fig. 3. A shunt compensator configuration.

These definitions, (3), (4), and (5), are valid for single-phase and poly-phase circuits and are valid regardless of whether the voltage and current waveforms are sinusoidal or non-sinusoidal, periodic or non-periodic, and balanced or unbalanced. The given definitions also have great flexibility to meet all compensation objectives [14]. Table I shows some of the choices for v_p and T_c for particular compensation objectives.

TABLE I
RESULTING SOURCE CURRENT FOR VARIOUS COMPENSATION OBJECTIVES

Compensation Objectives	v_P	T_C	**Resulting Source Current**
Single-phase reactive current	v_S	$T/2$ or T	Unity PF and sinusoidal if v_S sinusoidal
Single-phase reactive and harmonic current	v_{Sf}	$T/2$ or T	Unity PF and sinusoidal regardless of the distortion of v_S
Non-periodic and transient currents	v_{Sf}	nT	Smoothed sinewave with unity PF
Instantaneous reactive power	v_S	$T_C \rightarrow 0$	Instantaneously unity PF for polyphase systems

V. CONCLUSIONS

Because of the deregulation of the electric power industry and the proliferation of new generation sources and ancilliary services that are now part of this changing industry, a scalable multi-agent system for real-time electric power management has been presented. A dynamic hybrid architecture has been chosen for this system to enable rapid communication and control responses. Novel ancillary agent compensators have been identified for system stability and for reactive and harmonic power mitigation.

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BIOGRAPHIES

Leon M. Tolbert (S 1989 – M 1991 – SM 1998) received the B.E.E., M.S., and Ph.D. in Electrical Engineering from the Georgia Institute of Technology, Atlanta, Georgia

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