Multi-agent System for Voltage Control in Distribution Systems

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***Abstract*—This study proposes the simulation of the multi-agent system that performs voltage control in distribution systems. The multi-agent system is a natural approach to smart grid, because it combines the advances in computing, distributed systems and artificial intelligence to provide more features on real-time monitoring of demand and consumption of electricity, management of large-scale distributed generators, among others, from a distributed control over the grid. From this perspective, a framework that simulates the multi-agent systems to control capacitor banks in distribution system, which is a basic control in distribution system. In order to accomplish this, a framework that comprises distributed computing, communication and fuzzy decision making is proposed in this study.**

***Index Terms*—Smart grids, reactive power control, voltage control, distributed artificial intelligence, multi-agent systems.**

I. Introduction

THE power distribution systems are undergoing to radical change in concept and design. The attempt to reduce the usage of highly polluting energy sources, the search for energy efficiency, the new generation schemes are demanding the research groups for new technological solutions. One of the requirements for such modern distribution system is the presence of active data communication in the distribution network.

The new layer of information allows the efficient management of the system, by making it more reliable and visible to the system operators. It will also allow tasks such as system reconfiguration, detailed monitoring of demand and consumption, loss reduction, among others benefits. In a smart grid, data are received from different equipments which are dispersed over the power system. It can be sent through the layer of information to other system equipment. These measurements subsidize the new features expected for this generation of electrical networks. For instance, algorithms, methodologies and computational methods, are needed to obtain the domain over the distributed characteristic of smart grids and then, to implement the controls and new network features.

With this challenge in mind, this paper proposes the real-time control of distribution system based on distributed multi-agent systems. As mentioned earlier, many controls are expected for smart distribution systems. And for most of them the automatic execution of specific tasks are expected. In order to address one of these features, this research work investigates the management of capacitor banks for voltage regulation by agents. The proposed approach differs from classical voltage control strategies from the operational point-of-view. Various voltage control methods that applies optimization and methods based on concepts of artificial intelligence such as fuzzy logic do not consider the communication and the application of decentralized actions. For example, in [1], the dynamic programming and fuzzy systems has been proposed for voltage control. [2] has proposed a hybrid method that combines neural network and fuzzy dynamic programming; in [3] a fuzzy system with simulated annealing optimized solution has been proposed; finally, in [4] reactive power are used in coordination of capacitors.

The main contribution of this paper, is a distributed algorithm performed by the multi-agent system that models and simulates the operation of distribution system. The specific action simulated by this system is to perform voltage regulation. The fuzzy system is used for decision making about the selection of the required capacitor banks. This approach is significantly different from the classical local voltage control, because in this case the communication enables the decision making of capacitors banks in real-time and takes into account the whole system condition through communication of the parts of the system monitored by agents.

The basic idea is to let the multi-agent systems to manage the information collected by measurements that are scattered in the network and to provide a control action. In the present problem, the action is to switch on or off capacitor banks to keep the voltage of the system within its limits. The decision to whether apply or not the switching procedure is given to the fuzzy inference system according to the degree of sensitivity aimed in the control. The multi-agent system is able to manage such control actions that are related to the many features expected to be present in real smart-grids.

This paper is organized as follows: Section II provides a description of multi-agent systems, Section III introduces the fuzzy inference system used in this work, Section IV describes the working of the multi-agent system with fuzzy inference system developed in this research work and discuss some simulation results. In Section V the simulation of the proposed multi-agent system is described and in Section VI the conclusions are drawn.

II. Multi-agent Systems

An agent is an entity that perceives and acts upon the environment in order to achieve some objectives [5]. The agent can be considered as a specific type of software or a robot in case the environment is the physical environment. The main feature of an agent is the autonomous working without any direct interference.

An intelligent agent has the characteristics of an intelligent system: a knowledge base that will support the resolution of a problem, for which it has been modeled, and the search and handling methods of the database that will serve to provide the decision-making according to the data entry.

An agent has two components that allow the interaction with its environment They are the sensors and the actuator. The sensors are the tools for an agent to perceive the environment, and the actuators are the parts of the agent that perform the action from the result of decision making process, calculated from the state of agent and the search made on the knowledge base.

The sensors might be (depending on the agent and the type of application for which it has been designed) based on computer vision, sonar, meters, etc. For actuators, legs or arms could be the mechanical functions, among others. Similarly, there are problems which application of intelligent systems is more favorable when brought to the application of agents, i.e., not only a single computational entity that centralizes the process of data collection, decision making or both. However, working in distributed intelligent systems is a change on the paradigm that requires different theoretical considerations and a range of new techniques for implementing and obtaining satisfactory results.

The area which is related with the application of intelligent systems in distributed environments is called distributed artificial intelligence. It is based on concepts of artificial intelligence, computer science, social sciences, economics, organization and management to support its theory [6].The multi-agent system are systems where agents in a distributed computing environment performs distributed artificial intelligence techniques [7], [8]. Theoretical work in power systems can be found in [9], [10]. However, only after the society and industry interest in efficient power delivery systems the application of multi-agent system are being considered for real deployment [11].

In the next section, the Fuzzy Inference System used to provide the decision to control the bank of capacitors is introduced.

III. Fuzzy Inference System

The fuzzy inference system used in this work is the same defined by Mamdani [12], which is composed of "If-then" clauses composed of the following steps:

1) Definition of a set of fuzzy rules
2) Fuzzification of the inputs using the input membership functions;
3) Mapping of fuzzy input to fuzzy output according to fuzzy rules and find the consequence output distribution;
4) Deffuzification of the output distribution.

The fuzzy system has been implemented according to diagram of the Figure 1 and it applies operations of union and intersection of sets as been proposed by Zadeh [13], by means of maximum and minimum operators (that is why the inference system is also called Max-Min inference system). During the fuzzification the inputs are processed by intersection of fuzzy memberships of each input variables in the linguistic terms defined for each of them. This process results in a membership degree used in the activation of each rule. In other words, for the $k-th$ rule, a coefficient of activation D_k is calculated where the index k of the fuzzy set are the linguistic terms that form the rule k. This process transforms the quantitative information to qualitative information and is considered as a generalization process with

$$\begin{aligned} D^k &= T[\mu_{A_1^k}(x_1), \mu_{A_2^k}(x_2), \ldots, \mu_{A_p^k}(x_p)] \\ &= \min[\mu_{A_1^k}(x_1), \mu_{A_2^k}(x_2), \ldots, \mu_{A_p^k}(x_p)] \end{aligned} \quad (1)$$

The deffuzification used in this work, which is to obtain crisp values that corresponds to a physical action in the system, applied the center of mass method to the output distribution.

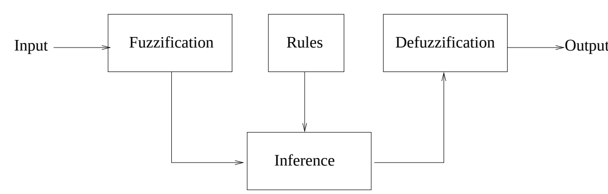

Figure 1. Fuzzy inference system [12]

A. Fuzzy variables and membership function

The fuzzy system is based on three variables and 20 fuzzy rules. The variables are: Voltage deviation ΔV and the last voltage (V) received from the measurement agent. The variable CB (capacitor banks) is represent the output of the inference system and shows the settings of the capacitor banks.

1) Input: The voltage variable V has been divided in four fuzzy subsets in a universe of discourse of [0.8 0.11] (p.u.). The subsets are represented by:

- low-critical (LC):[0.8 0.8 0.9 0.92] - Trapezoidal shaped membership function
- precarious (P): [0.9 0.925 0.95] - Triangular shaped membership function
- adequate (A):[0.93 1 1.05] - Triangular shaped membership function
- high-critical (HC): [1.03 1.05 1.1 1.1] - trapezoidal shaped membership function

The membership function for voltage variable is shown in Figure 2.

The voltage deviation ΔV has been divided in five fuzzy subsets in a universe of discourse of [-0.1 0.1]. The subsets has been defined after some tests to identify the best average performance:

- negative (N): [-0.1 -0.1 -0.02 -0.04] - Trapezoidal shaped membership function

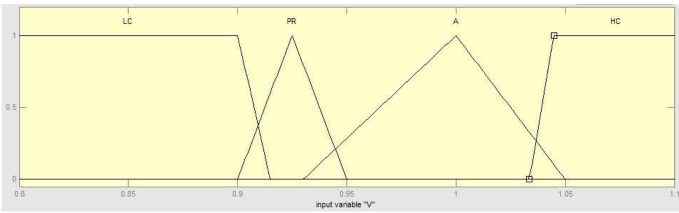

Figure 2. Membership function of Voltage variable

- low-negative (LN):[-0.03 -0.0015 -.0018 0] - Trapezoidal shaped membership function
- zero (ZE):[-0.01 0 0.01] - Trapezoidal shaped membership function
- low-positive (LP): [0 0.0022 0.025 0.05] - Triangular shaped membership function
- positive (P): [0.04 0.06 0.1 0.1] - Trapezoidal shaped membership function

The membership function for voltage deviation (ΔV) is shown in Figure 3.

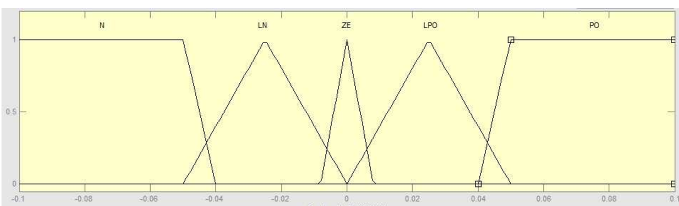

Figure 3. Membership function of Voltage deviation (ΔV)

2) Output: The variable CB has been divided in four fuzzy subsets in a universe of discourse of [0 1] in pu. The subsets has been defined as in the following:

- zero (ZE): [0 0 0.075 0.09] - trapezoidal shaped membership function
- low (L): [0.05 0.13 0.18 0.2] - trapezoidal shaped membership function - medium (M): [0.18 0.22 0.7 0.8] - trapezoidal shaped membership function - Up (U): [0.7 0.8 1 1] - trapezoidal shaped membership function.

The membership function for capacitor banks (CB) is shown in Figure 4. In Table II, the linguistic rules related to voltage deviation are shown. The voltage limits have been set according to the resolution number 505 of ANEEL - Brazilian Electricity Regulatory Agency [14].

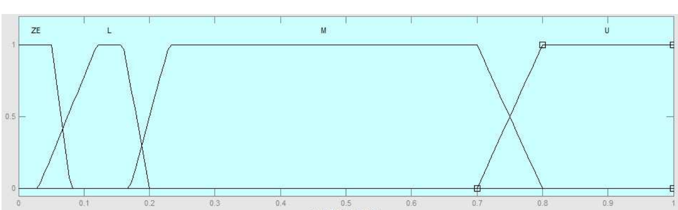

Figure 4. Membership function of Capacitor bank

Finally, the numerical value of fuzzy decision is obtained. 3 capacitors of 600 kvar have been considered. The linguistic variables will determine whether they will be used and the amount as well as shown in Table III.

Table I
LINGUISTIC RULES FOR VOLTAGE VARIABLES

Rules	
Low-critical	$V < 0.9$ p.u.
Precarious	0.9 p.u. $<= V < 0.93$ p.u.
Adequate	0.93 p.u. $<= V <= 1.05$ p.u.
High-critical	$V > 1.05$ p.u.

Table II
LINGUIST RULES FOR ΔV

Rules	
Negative	$\Delta V < -0.05$
Low-negative	$-0.05 \leq \Delta V < 0$
Zero	$\Delta V = 0.0$
Low-positive	$0 < \Delta V \leq 0.05$
Positive	$\Delta V > 0.05$

Table III
USAGE OF CAPACITOR BANKS

Capacitor banks	
Large	1800 KVAR
Medium	1200 KVAR
Small	600 KVAR
Zero	Off

Table IV
FUZZY RULES AND THE CORRESPONDING DECISION. EACH OUTPUT DEFINES THE AMOUNT OF CAPACITOR BANKS. LC - LOW CRITICAL, PR - PRECARIOUS, A-ADEQUATE, HC - HIGH CRITICAL, LN - LOW NEGATIVE, N - NEGATIVE, ZE - ZERO, PO - POSITIVE, LPO - LOW POSITIVE

AND		V			
		LC	PR	A	HC
ΔV	LN	M	M	S	ZE
	N	L	L	M	ZE
	ZE	S	S	ZE	ZE
	PO	S	S	ZE	ZE
	LPO	M	M	ZE	ZE

IV. MULTI AGENT SYSTEM AND FUZZY INFERENCE FOR VOLTAGE CONTROL

One key characteristic of smart grids that allows the development of new control and monitoring features of the system is the presence of data transmission between system equipment. For example, the smart meters should transmit voltage, current and power demand measurements to a control center which will allow functionality such as system reconfiguration, auto-recovery, control actions on capacitor devices or other switching actions.

This work proposes the use of two agents for the voltage control using capacitor banks, as a mean to test the multi-agent structure, however it is possible to expand and have many agents controlling different buses with different type of control. One agent is in the load bus and periodically send voltage measurements to the distribution control center. In the control center, there is an agent which task is to receive the data and send it to a fuzzy system that will decide whether the capacitor banks is needed and how it is switched on. In Figure 5, the flow of actions performed by the master agent is shown.

The master agent collects the data acquired by the measurement agent and performs the decision making and then, send the action to the measurement agent. This type of action aims two objectives: 1) to separate the computation and the decision making of the action and 2) to implement global controls, i.e., controls that depends on data from other regions, otherwise only local control without communication would be used.

For each agent, various parameters must be defined. For example, the time interval in which the data will be collected by the agent must be carefully defined. If this interval is short, the amount of data might result too large to be processed, or if applied to the controllers may result in oscillations on the voltage. If the interval is too long, the efficiency to solve the problem might result low.

Another data that must be defined in the beginning of the process is the position of the measurement agent. The positioning affects the distribution of information and the ability to implement the control actions. The agent could have been located in some branch of the system or with some loads represented by a leaf in a graph model of the problem. The determination of the best position becomes a planning problem. However, this paper will consider that the position of the agent is already defined. In a simplified way, the master agent calculates the deviation between two measurements obtained in different time instants. Based on the last voltage measurement and from the voltage deviation the agent submit the information to the fuzzy decision making. The fuzzy decision making send back the command to perform. In Figure 6 the flowchart of the actions of the measurement agent is shown.

V. Simulation of Multi-agent System

The multi-agent system and the fuzzy inference system has been developed in Java programming language. The framework for the development of multi-agent systems JADE (Java Agent DEvelopment) [15] which provides various pre-defined tools and functions have been used. JADE is well known to the multi-agent developers, and it has been also used in power systems area [10].

The JADE framework has allowed to distribute the computational task over network of workstations. The multi thread programming is easily ported and with the standardized access to the network of computers, the execution of each agent in different computers, therefore simulating the smart grid environment with communication capable devices of the distribution system which are scattered on the system.

The computers where the agents have been executed are connected by standard ethernet network, which simulates the decentralized environment. Communication tests with message passing between agents and the execution of the decision making have been carried successfully.

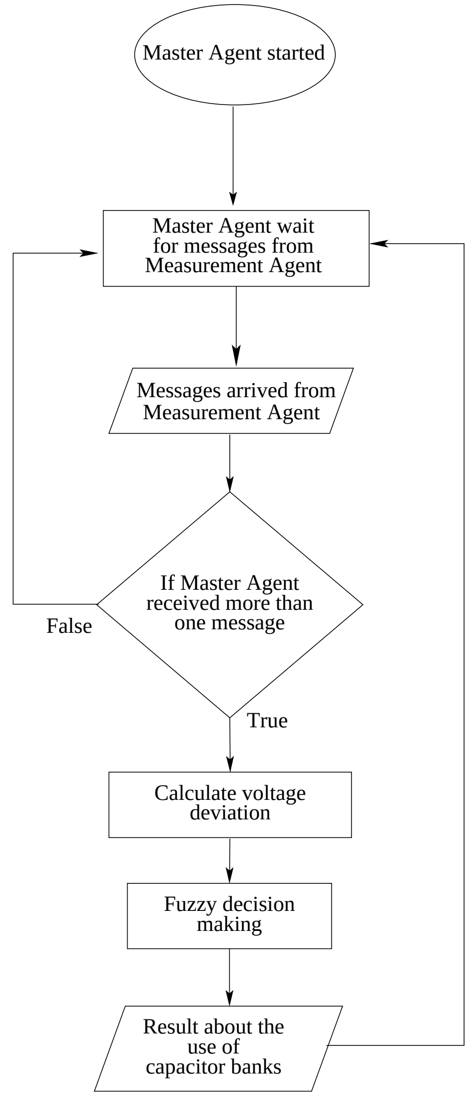

Figure 5. Flowchart of the voltage control by multi-agent system. The perspective is from the master agent

Tests have been carried out with a customized 14 bus system. The system is a meshed system. The topology is shown in Figure 8 and its characteristics are shown in Table V and Table VI. In Figure 8, the measurements agents have been placed in bus 5 and in bus 14. A generation of the measurements based on regular power flow has been implemented. The Measurement Agent collects the measurement and send it to the Master agent to fuzzy inference. The sequence of these actions are depicted in Figure 7. The result of these simulations are shown in Table VII. For these conditions, the inference system suggested to switch-on “small” amount of capacitor banks, which means 600 kvar.

VI. Conclusion

In this research work a multi-agent framework for distribution system control has been proposed. The multi-agent system has many similarities with all characteristics that are expected in smart distribution systems. It was verified that

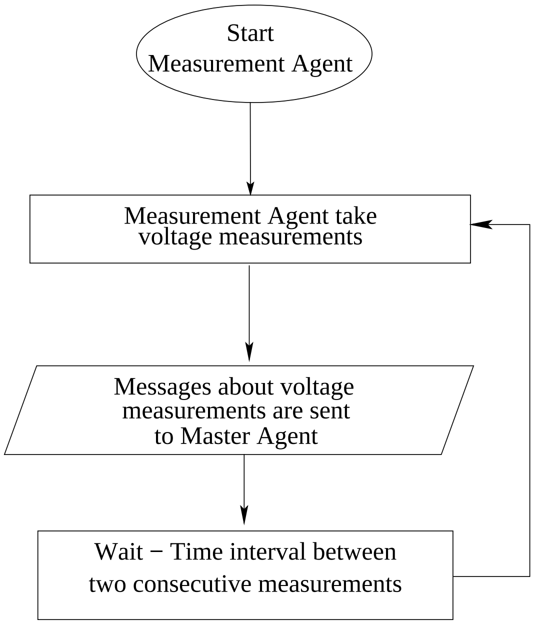

Figure 6. State diagram of measurement agent

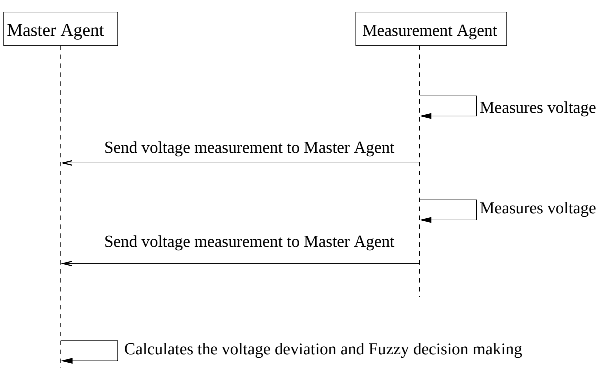

Figure 7. Sequence diagram of multi-agent implementation

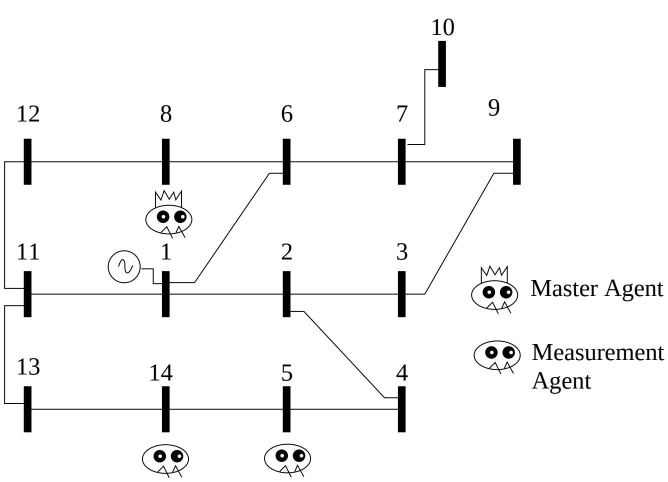

Figure 8. 14-bus test system

Table V
BUS DATA OF THE 14-BUS SYSTEM

Bus	P[MW]	Q[Mvar]
1	0.0	0.0
2	2.0	1.6
3	3.0	1.5
4	2.0	0.8
5	1.5	1.2
6	4.0	2.7
7	5.0	3.0
8	1.0	0.9
9	0.6	0.1
10	4.5	2.0
11	1.0	0.9
12	1.0	0.7
13	1.0	0.9
14	2.1	1.0

Table VI
LINE DATA DATA OF THE 14-BUS SYSTEM

From	to	R (%)	X(%)
1	2	0.75	10.0
2	3	8.0	11.0
2	4	9.0	18.0
4	5	4.0	4.0
1	6	11.0	11.0
6	7	8.0	11.0
6	8	11.0	11.0
7	9	11.0	11.0
7	10	8.0	11.0
1	11	11.0	11.0
11	12	9.0	12.0
11	13	8.0	11.0
13	14	4.0	4.0
3	9	4.0	4.0
8	12	4.0	4.0
5	14	9.0	12.0

simulation of such system with the addition of fuzzy controlled actions, such as the voltage control applied in this work seems feasible. An important question that needs to be answered is how to deal efficiently with many data that will be circulating in such system. Therefore a next stage is testing the system with a large number of agents performing different tasks and reporting to different master agents. This type of management is a challenge even for simulation purposes.

ACKNOWLEDGMENTS

The authors would like to thank the São Paulo Research Foundation (FAPESP) and Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), Brazil, for the financial support.

Table VII
TEST RESULTS FOR ALLOCATION OF MEASUREMENT AGENTS IN BUS 5 AND BUS 14

Test Results			
Load	**Voltage (V) in t_1**	**Voltage (V) in t_2**	**Fuzzy Decision**
5	0.9452	0.9408	Low
5	0.9408	0.9407	Low
14	0.9413	0.9360	Low
14	0.9360	0.9359	Low

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