Voltage Regulation Based on Fuzzy Multi-Agent Control Scheme in Smart Grids

A. Sajadi, H. E. Farag, P. Biczel, and E. F. El-Saadany

***Abstract*—Trend of reconfiguration of power system is leading to smart grids which are absolutely best possible solution for future power systems. Future smart grids, including Distributed Generation (DG) units, encounter a broad range of challenges like metering, management, and control. In this paper, architecture for fuzzy multi-agent based control for voltage regulation in smart grid is proposed. To investigate the effectiveness of the proposed architecture, a simulation model in MATLAB/Simulink is done. The simulation results show how proposed system can regulate voltage in smart distribution feeders.**

***Index Terms*—Smart Grids, Voltage Regulation, Fuzzy Logic, Multi-Agent Systems.**

I. INTRODUCTION

DISTRIBUTED Generation (DG) technology with reconfiguration of power industry has made a revolution in Power system's body in 21st Century. Magnificent advantages of DG units, for instance generating electricity and heat at the same time and compatibility with environment have resulted to intensify their development. Consequently, this technology, particularly the units based on renewable energies such as Solar, Wind, and Fuel Cells, will play a key role in near future in the energy generation system of urban areas. Generated electricity energy by DG units is the best option from economical point of view in order to provide necessary energy to meet consumption in systems according to limited capacity of transmission and distribution networks [1]. The future energy generation systems will be based on integration of DG units and existing conventional facilities which is called "Smart Grids" [2] and can operate in whether islanded mode or connected mode. However, increasing penetration of the DG units in distribution networks brings up new challenges in monitoring, metering, and controlling of networks which it leads to more complex power systems. As well, new complex control techniques are necessary to be implemented to endure flexibility and reliability of power systems [2-3]. In conventional power systems, this is accomplished by Supervisory Control and Data Acquisition (SCADA) [4,5]. Current trend of monitoring and controlling of power systems operations is moving towards the use of an automated agent technology, which is known as multi-agent based systems [6]. A multi-agent based system is the combination of several agents working in collaboration together to achieve the overall goal of the system [6,7,8]. Therefore a very well organized infrastructure consisting of hardware and software protocols is very essential to exchange the system status and control signals. In overall system, each control unit is known as an agent and it interacts with other agents belonging to system via well defined communication language [6].

During recent years, some works [9-16] have been done to show how distributed control can contribute in distribution networks. Objective of this research is considering integration of previous works in this work to design and implement a fuzzy multi-agent based control for voltage regulation. In order to reach this goal, proper model for fuzzy agents will be proposed. The rest of the paper is organized into six sections. Section II presents the proposed fuzzy multi-agent based system. Section III presents the study results; it includes modeling the proposed controller by a simulation in MATLAB Simulink™ on 16-bus distribution feeders. It illustrates how proposed control scheme can regulate the voltage at load buses. Case results showing impacts of proposed controller on optimization of tap changer performance are presented and discussed. Finally at section VI conclusion and recommendation close the paper.

II. THE PROPOSED FUZZY MULTI-AGENT BASED SYSTEM

Fuzzy multi-agent based system is integrity of artificial intelligence with agent based control scheme. In this system each local control unit is known as an agent which is independent functional module operating on its own data and its operation can be affected by received messages from other agents. As well it can sends message to other agents. Overall goal of multi-agent system is to disassemble a complex system into some partial systems [6]. The co-operation between agents based on the exchanged messaged through a communication infrastructure can solve convoluted problems. According to this theory we propose a multi-agent based distributed control system for voltage regulation in smart distribution grids. Therefore, what system comprises are LTC (on-load tap changer) agent, DG agents, load agents, and communication between them. Fig. 1 illustrates an overall view on the proposed system.

A. Interior Structure of Agents

Proposed interior structure of each agent is based on the principle of fuzzy controller theory. Therefore, it should basically be consisting of fuzzifier, interference engine, and defuzzifier [17]. Fig. 2 illustrates diagram of overall proposed interior architecture for agents.

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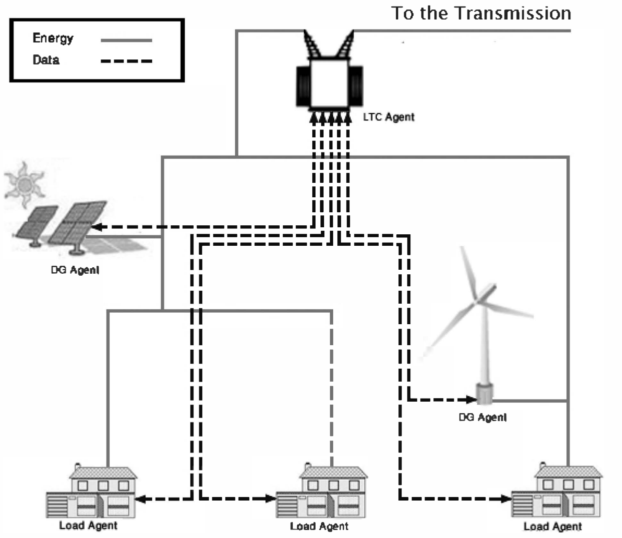

Fig. 1. Proposed system overview

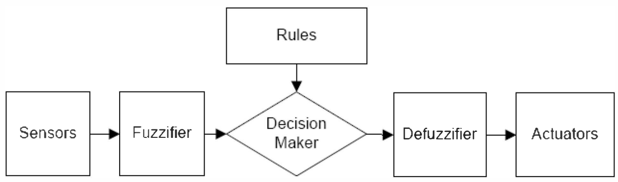

Fig. 2. Proposed interior structure of a single agent

As it is shown, the control agent fuzzifies received data via local measurement sensors and messages from other agents by converting the crisp values into linguistic label(s). The interference engine of the fuzzy control agent represents the decision maker. This inference engine is based on predefined rules that have been extracted to achieve the objective(s) of each agent and avoid any conflict between the cooperated agents. The output of the agent which can be in the form of setting a local actuator or sending a message to another agent(s) will be defuzzified to a crisp value.

In the proposed system, interference engine is computing by AND-ing the if- and then- clauses. The example follows:

"If *voltage deviation* is **Zero (Z)** and *permission* is **Negative (N)** and *average tap operation* is **High (H)** then *reply* is **Accept (A)**."

Also, "Center of Gravity" method is applied for defuzzification:

$$y = \frac{\sum_{i=1}^{N} x_i . \mu(x_i)}{\sum_{i=1}^{N} \mu(x_i)}$$

where x the value of the universe of discourse related to the output variable sampled at N points, and $\mu(x_i)$ is the respective degree of membership, which is formed by taking the union of all the contributions of fuzzy rules [18].

All the membership functions are shown on fig. 3.

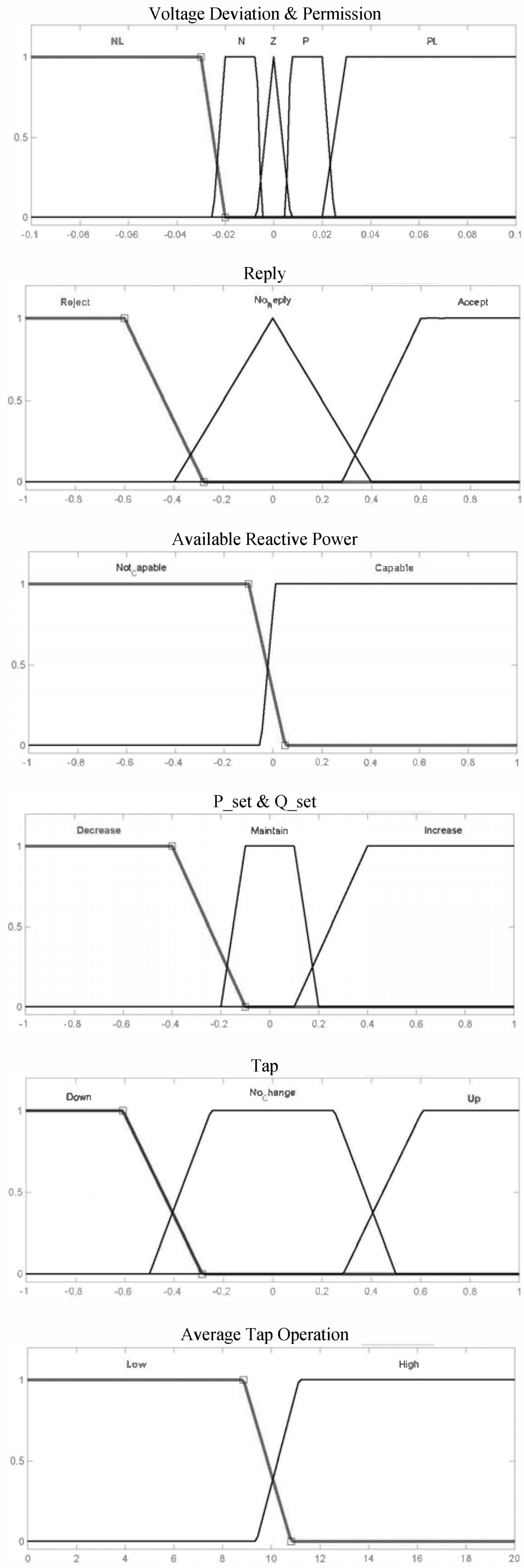

Fig. 3. Membership functions of proposed system

B. LTC Agent

Tap changer agent has two goals: the first one is keeping voltage of feeders in standard voltage range by changing transformer tap. The other one is minimizing number of tap changing operations to prevent excessive tap operation. The LTC agent has 3 inputs. The inputs and their defined fuzzy values are:

- Voltage Deviation: Negative Large (NL), Negative (N), Zero (Z), Positive (P), Positive Large (PL);
- Permission: Negative Large (NL), Negative (N), Zero (Z), Positive (P), Positive Large (PL);
- Average tap operation: High (H), Low (L).

The outputs and their defined fuzzy values are:

- Tap: Up (U), No Change (N), Down (D);
- Reply: Accept (A), Reject (R); No Reply (N).

The rules used in LTC decision maker are shown in table 1.

TABLE I
RULE BASE FOR FUZZY ALGORITHM FOR LTC

Average tap operation: H (Tap)					
Per. /V. dev.	NL	N	Z	P	PL
NL	D	D	N	N	U
N	D	D	N	N	U
Z	D	N	N	N	U
P	D	N	N	U	U
PL	D	N	N	U	U
Average tap operation: L (Tap)					
Per. /V. dev.	NL	N	Z	P	PL
NL	D	D	D	U	U
N	D	D	N	U	U
Z	D	N	N	N	U
P	D	D	N	U	U
PL	D	D	U	U	U

Average tap operation: H (Reply)					
Per. /V. dev.	NL	N	Z	P	PL
NL	R	R	A	A	A
N	R	R	A	A	A
Z	N	N	N	N	N
P	A	A	A	R	R
PL	A	A	A	R	R
Average tap operation: L (Reply)					
Per. /V. dev.	NL	N	Z	P	PL
NL	R	R	R	A	A
N	R	R	R	A	A
Z	N	N	N	N	N
P	A	A	R	R	R
PL	A	A	R	R	R

This agent receives measured voltage deviations from load agents. Then it chooses highest absolute value of deviation as most critical case to make decision based on, in either cases of overvoltage or undervoltage [19]. For instance, if there are Positive and Positive Large messages received from two load points, it will make decision based on Positive Large. Also, it receives permission messages from DG agents. The permission message represents voltage deviation at DG units coupling point to the grid. Furthermore, according to recorded data and tap operations history, LTC agent estimates tap changer operation for upcoming assumed time interval. This estimation can be offline or online depends on available data. In this paper, we consider predicted tap changer operation is given data.

If there is no permission message, tap changer performs in same way as a traditional voltage regulator does. It means if overvoltage or undervoltage happens, tap goes up or down. But in presence of permission messages, scenario is different than before. Let us assume a permission message is received; if average tap operation is low, it will be rejected to keep generation of DG unit at maximum point and tap will operate. But if average tap operation is high, reply will be accepted permission. It means the DG agent has to regulate this voltage deviation by its own.

TABLE II
RULE BASE FOR FUZZY ALGORITHM FOR DG

Permission					
Rep. /V. dev.	NL	N	Z	P	PL
A	Z	Z	Z	Z	Z
R	Z	Z	Z	Z	Z
N	NL	N	Z	P	PL
Available Q: C (Q_set)					
Per. /V. dev.	NL	N	Z	P	PL
A	I	I	M	D	D
R	M	M	M	M	M
N	M	M	M	M	M
Available Q: N (P_set)					
Per. /V. dev.	NL	N	Z	P	PL
A	M	M	M	M	M
R	D	D	M	I	I
N	M	M	M	M	M

C. DG Agent

As the LTC agent, DG agent has two goals. First, is to keep voltage of its feeder in standard voltage range. Second one is keeping generation of DG unit maximum. The DG agent has 3 inputs. The inputs and their defined fuzzy values are:

- Voltage Deviation: Negative Large (NL), Negative (N), Zero (Z), Positive (P), Positive Large (PL);
- Reply: Accept (A), Reject (R); No Reply (N);
- Available Q: Capable (C), Not Capable (N).

The outputs and their defined fuzzy values are:

- Permission: Negative Large (NL), Negative (N), Zero (Z), Positive (P), Positive Large (PL);
- Q_set: Increase (I), Maintain (M), Decrease (D);
- P_set: Increase (I), Maintain (M), Decrease (D).

The rules used in DG decision maker are shown in table 2. Level of deviation from maximum and minimum allowed voltage in the bus [19] at DG unit connection point will be sensed by local measurement, if there is any. A module determines available reactive power of DG using following approach:

$$Q_{g\_av} = \sqrt{S_{nom}^2 - (P_g^2)} - Q_g^2$$

where S_{nom} is nominal total power of DG unit, P_g generating active power by DG unit, Q_g is generating reactive power by DG unit, and Q_{g_av} total possible reactive power by DG unit.

First we assume there is voltage deviation, so a permission message will be sent to tap changer. If reply is rejected permission, then operation point of DG unit will be maintained and it will continue generating without any modification in settings. Otherwise, by using dQ/dV sensitivity factor, it can realize if DG controller can regulate voltage by modification of reactive power level or should curtail its generated real power using dP/dV sensitivity factor.

D. Load Agent

The main task of load agent is measurement of bus voltage at load point. Its other task is to control the status of loads based on predefined priority to manage critical and-critical loads. In this paper just the first task is assigned to the load agent. Therefore, after getting information from the sensor, compares it with maximum and minimum allowed voltage in the bus [19], to detect deviations from reference value, either overvoltage or undervoltage.

$$\Delta V_{\max} = (V_m - V_{\max})$$

$$\Delta V_{\min} = (V_{\min} - V_m)$$

In case of the normal operation, both of these two values should be positive. In case of overvoltage, V_{max} will be positive and in case of undervoltage, V_{min} will be positive. In either case, deviation should be converted to linguistic labels by fuzzification. On the other hand, there is no executive task for this agent. So, load agent has just 1 output which its defined fuzzy values are:

- Voltage Deviation: Negative Large (NL), Negative (N), Zero (Z), Positive (P), Positive Large (PL);

Because of absence of decision maker in this agent, there is no need to any rule.

III. Simulation Results and Discussion

The 16-bus distribution feeders [20] shown in fig. 4 has been used to investigate the performance of the proposed fuzzy multi-agent based distributed voltage control approach. The test system has been implemented in MATLAB Simulink™.

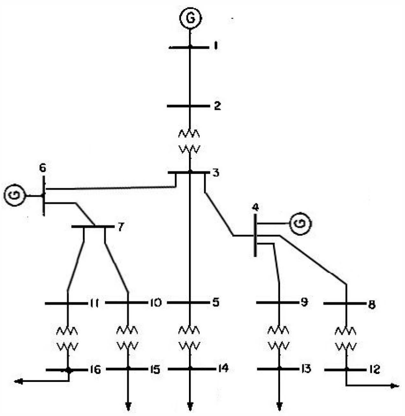

Fig. 4 Case studies system model

The test system includes two DG units and a LTC transformer in substation. A 69/13.8 kV transformer with 32 taps is modified as LTC transformer. One of the DG units is dispatchable and it is modeled as a 1.5 MVA synchronous machine connected to bus 6. The other one is renewable-energy unpredictable source and it is modeled as a 6 MVA DFIG wind turbine connected to bus 4.

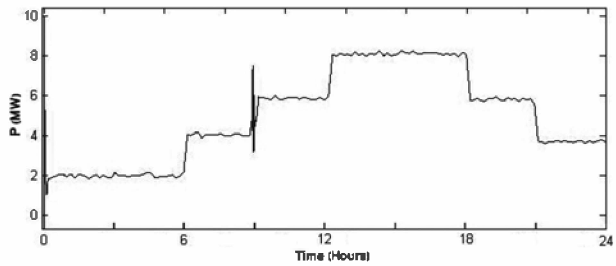

Fig 5. Load profile over 24 hours

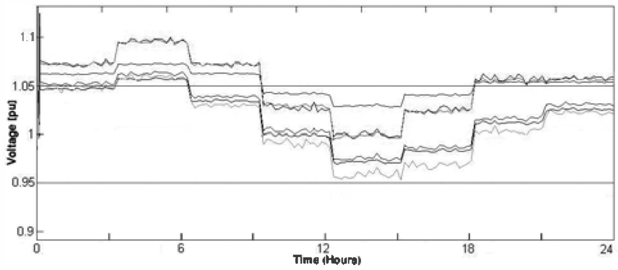

Fig. 6. Voltage profiles at load buses before applying proposed method

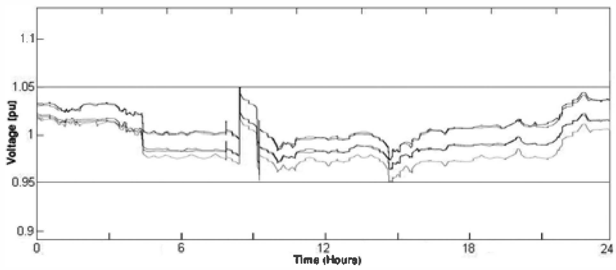

Fig. 7. Voltage profiles at load buses after applying proposed method

Fig. 5 shows the test system load profile over 24 hours. The minimum value for load is 2 MW and its maximum is considered 8 MW. In addition, at 6:00, 9:00, and 12:00 consumption increases and at 18:00 and 21:00 it decreases.

Fig. 6 shows the voltage profile at different load buses when the LTC performing based on the traditional local control and the DG units are operate in constant PQ mode.

As shown in the figure, when the system works with traditional control techniques, three load buses have overvoltage condition during first 9 hours. Moreover, voltage profiles at load points are following proportionally load profile. It means exactly at same times with load variation, we can see the voltage variation as well.

Fig. 7 illustrates the capability of proposed control method in voltage regulation at load points over 24 hours. As is shown, voltage at all the buses is kept within standard range and neither overvoltage nor undervoltage is recorded.

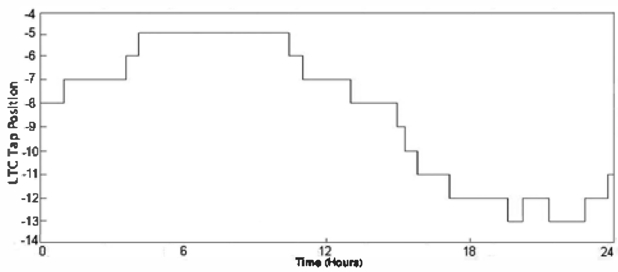

Fig. 8. LTC tap changer operation during 24 hours.

Fig. 8 shows the LTC operation along the 24 hours. As shown in the fig. 15 tap operations are performed to keep voltage magnitude within allowed standard limits.

IV. Conclusion

This paper discussed the design and implementation of the fuzzy multi-agent based control system for voltage regulation in smart distribution grids. The proposed system consists of LTC agent, DG agents, and load agents. As the fuzzy decision maker has implemented, they are called fuzzy agents. A simulation has been done to show the effectiveness of the proposed multi-agent control structure. The results are the evidence of capability and superiority of the proposed multi-agent control structure in acceptable regulating the voltage by keeping voltage within standard range during 24 hours. Distributed measurements by placing sensors at load points and communication with LTC were applied. Also the collaboration between agents optimized performance of the tap changer.

Future work is based on another scenario which tap changer agent after rejecting request message, sends a negotiation message to other DG agents to regulate voltage of target point by changing level of reactive power injection or consumption of them. In this case, active power generation will be kept in maximum level.

In sum, this work aims at demonstrating capability of fuzzy multi-agent based control system in a smart grid located at a distribution level.

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