Multi-Agent System based Voltage Support by Distributed Generation in Smart Distribution Network

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***Abstract*—This paper proposes distributed voltage support method for power distribution network with distributed generation using Multi-Agent System (MAS). A problem of reactive power dispatch in distribution network was considered. Contract-Net-Protocol (CNP) based scheme was used for communication and coordination between agents. A co-simulation based framework including power system simulator and agent environment was developed using socket communication to validate the proposed MAS based approach. For final validation of proposed method, modified IEEE 13 bus system with distributed generation was used. Results show the effectiveness of MAS based distributed approach for voltage support using distributed generation.**

Keywords—Distributed Generation; Multiagent System; Coordination; Voltage Control

I. INTRODUCTION

Today's energy systems are undergoing remarkable changes in the way energy is produced, transmitted and consumed. The operation of traditional electric power systems which is based on production of electric energy in large centralized power plants, usually located away from load centers is facing many challenges due to this transition. Main factors for this transition are use of renewable energy resources, integration of Distributed Generation (DG) into the grid, environmental considerations, increased customer participation and technological development. Further, demand for more and more services to be provided by these energy systems has been resulted in complex energy systems. As time passes there will be more and more renewable and distributed energy resources at the lower level of the system.

However these Distributed Energy Resources make complication for distribution network production, operation and management, where many problems required to be addressed before DG is integrated into the distribution network as per IEEE 1547 series of standards, such as relay protection, energy management, power quality and others [1]. It also brings coordinated voltage control issue. Specially, when the DG is highly penetrated into the distribution network, the coordination issue of the voltage control due to the existence of various types of distributed reactive power sources will become even more serious. The major reason for such problem is that the distribution system was not designed for inclusion of intermittent distributed generation. Thus connection of DG in distribution network can cause local over-voltage and affect the operation of On Load Tap Changer (OLTC) transformer which is used for voltage regulation in existing distribution network. In literature various voltage regulation strategies in distribution network are documented in terms of control structure using many controllable components i.e. OLTC, AVRs, Inverters at DG sites, DG curtailment, and energy storage etc. commonly used control structures are;

- Decentralized control: The control actions are derived locally (at each node) to provide voltage support from DERs. Only local information is used and knowledge of how control action effect the overall system is unknown thus there is no exchange of information [2].
- Decentralized peer-to-peer coordination: Peer-to-peer communication is used by DERs to exchange network information. By exchanging the actions & plans, DERs can coordinate with each other to achieve a system-wide objective. Thus local information along-with neighboring information is used [3].
- Hierarchical control: A hierarchy is constructed according to the structure of the power network. The coordinator at higher level calculates the set points, which are the reference signals for the lower level control. Thus it adds an additional layer of vertical information flow to additional controllers situated above that of the local controllers. The main role of the controllers of the higher level is to ensure concordant behavior between the lower local controllers leading to improved overall global performance [4].
- Centralized Control: The control decision is made only by the coordinator/central controller. Usually, it also collects the complete information from the whole network.

Mostly voltage regulation is performed through a centralized scheme, in which a central computer monitors all the DG units (e.g. wind generator or PV) and adjusts the voltage set-points of these DGs through some optimal

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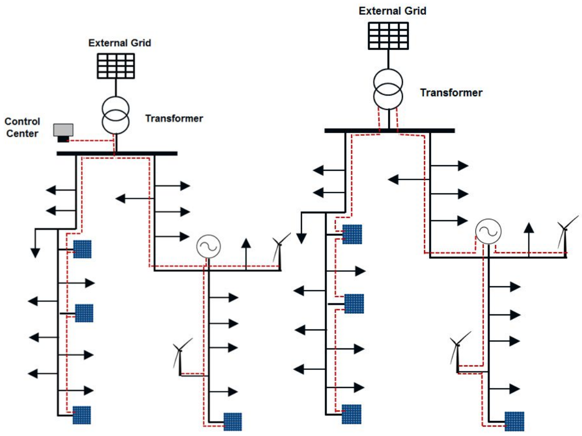
algorithm [5]. However, this centralized regulation algorithm must have the whole network information and thus it needs a large number of devices for data acquisition and communication infrastructure which increases the cost of implementation. On the other hand local control works properly only if there are few DERs in distribution network [6]. Figure 1 shows two control schemes with communication point of view. Figure 1(a) corresponds to a centralized control structure in which decision is made in a central place. Figure 1(b) shows each DER communicates with its neighbours to compute control action.



(a) (b)

Fig. 1. Control Philosophies for DERs(dotted lines shows comunication)

This paper is arranged as follows; Section I provides introduction and some literature review on issues in voltage regulation in distribution network. Section II explains usability of Multi-agents in power system. Simulation platform for Multi-agents and power system is discussed in section III. Section IV describes the voltage control problem and multi-agent based algorithm to solve the problem. Results and discussions are presented in section V with conclusion in section VI.

II. MULTI-AGENTS

A. *Multi-Agent system*

The fundamental element of MAS is “intelligent agent” which has the three main characteristics; reactive, proactive and social abilities [7]. Reactivity means ability of agent to recognize any changes in its environment and react with corresponding actions according to the goal of the agent. Pro-activeness of intelligent agent depicts goal based behaviors. The goal is objective of agent, which is set according to the system wide objective. Social ability of an intelligent agent is the ability to interact with other intelligent agents in its environment. Agents are also specifies by a term called “BDI” (Belief, Desire, Intention). Belief represents knowledge about the environment which it acquires through its sensors. Desires are the goals or design objectives while an intention is the way agents try to achieve their goals. Figure 2 shows an abstract architecture of control agent.

B. *Multi-agent system(MAS) in Power system*

Agent based technology provides an alternative approach for smooth transition of present distribution grid to the smart distribution grid [8]. Major justifications can be:

- Due to the increase complexity and size of the distribution grid, there is need of distributed intelligence and some local solutions, such problems can be tackled by the agent based approach.

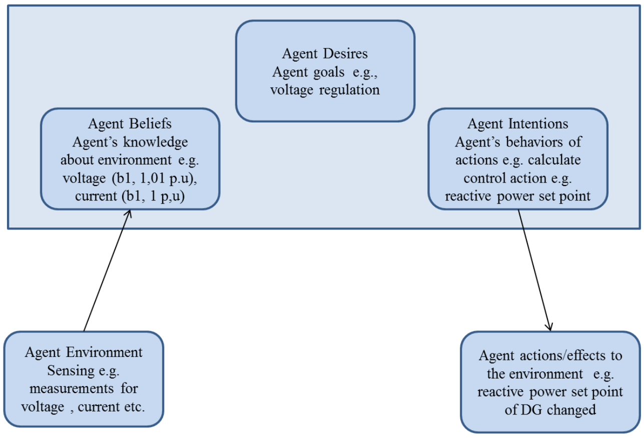


Fig. 2. Abstract agent architecture on the basis of Belief Desire Intention

- Agent based modeling and simulation can be used to test the smart grid design concepts which are related to operation and communication.
- Decentralization, autonomy and active distribution management are the most important features for the smooth modernization of present distribution grid. Any system developed under agent-oriented philosophies contains all the three above mentioned properties, making it a best choice. Also properly modeled agent-based systems can result in flexible, scalable and robust systems [9].

III. SIMULATION PLATEFORM

Current simulation tools do not have the ability to simulate multi-domain system as a whole and it is already established that co-simulation framework of domain specific software is a good option for simulating and experimenting cyber-physical systems to have insight into the system behavior and thorough analysis [10, 11]. Thus a co-simulation framework was developed to test MAS application for voltage regulation in electric distribution network. Java Agent Development framework (JADE) was used for developing agent application and electric grid simulations were carried out using DIgSILENT PowerFactory. PowerFactory provides many methods for coupling with other tools and are discussed in detail in [12, 13]. In this work both the tools were coupled using sockets and master program was written in MATLAB to control the simulation. Figure 3 shows the simulation framework.

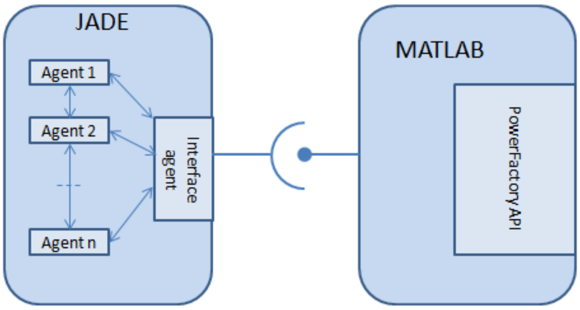


Fig. 3. Interface between JADE & DigSILENT PowerFactory

A. JADE(Java Agent Development)

JADE[1], an open source middleware used for developing Multi-Agent Systems, was originally developed under TILab, formerly CSELT in Italy [14]. This framework facilitates the developing agent based simulations through basic functionalities like agent and behavior classes, inter-agent communication methods. It also provides graphical tool for monitoring, agent execution and communication with debugging function. It is FIPA (Foundation for Intelligent Physical Agents) compliant and supports standards such as FIPA-ACL [15]. Each instance of runtime environment is called a container and many containers make a platform. First container is called main container which hosts Agent Management Services (AMS) and a Directory Facilitator (DF). Container contains various agents and a typical agent consist of a *setup()* method , one or more behaviors and a *takedown()* method. Details can be found in [14].

B. DIgSILENT PowerFactory

DIgSILENT[2] PowerFactory, is a powerful simulation and analysis tool for power system and has many built-in system models and control algorithms [16]. It is capable of doing power flow, qausi-dynamic, RMS simulations with many other analysis tools. It also provides various options for interfacing with other software.

IV. MULTI-AGENT BASED COORDINATED VOLTAGE CONTROL

In this section issues in distribution voltage regulation in the presence of multiple DGs are pointed out first and then proposed solution scheme is introduced.

A. Voltage Regulation

In conventional distribution feeder LTC or VR placed at the substation is used to control the voltage. The objective of voltage regulation is to maintain voltage at all the buses in the system within “normal” limits, which is +/-5% of the rated voltage [17]. In conventional feeder voltage drop on the feeder mainly depends on the load level and by measuring the total load current at the substation enables the voltage regulator to estimate and compensate the voltage drop by adjusting the voltage at the substation end.

However, introduction of Distributed Generation in a distribution feeder affects the voltage profile. This impact mainly depends on the type of DG, amount of power DG supply back to the system and its location in the feeder [18]. Thus when multiple DGs are present in a distribution feeder and supply a considerable part of the load, it becomes difficult for the voltage regulator to use the local current measurements to estimate the accurate voltage drop. Also, sudden disconnection of a DG can result in low voltage limit violation and this voltage condition may cause other DGs to be disconnected by their under-voltage relays. It is mainly because a voltage regulator is a slow acting device (can take more than 5s to move one tap position and corresponds to about 5/8% voltage change). On the other side the DGs use under-voltage/overvoltage protection schemes and are quite sensitive to voltage sags. These protection schemes are usually fast and if voltage level is more than +/-10%, can trip the DG with in 2s [19]. Thus voltage regulator alone cannot provide quick voltage support to restore voltage after a sudden disconnection of DG.

Therefore voltage regulation provided by the LTC needs to be improved for the facilitation of DG integration in distribution network. For this purpose we need a communication link between voltage regulator and DGs, which will enable voltage regulator to collect data from the DGs to estimate voltage across the feeder and allow DGs to provide voltage support. DGs, through proper control of power electronics can be used to provide reactive power support during emergency conditions. The DGs are usually equipped with their own control (local control) to control active and reactive power output. By using these capabilities, a distributed control scheme for voltage regulation using Multi-agent system is proposed in this paper. MAS become a good choice for such kind of problem as local controllers on the regulators and DGs can be improved by the agents that can act as supervisory controllers.

In this paper main focus is on reactive power dispatch scheme by the DG when voltage on a certain node goes out of limit. Voltage support can be provided by the DG by increasing their reactive power outputs in case of violation of lower voltage. Thus the problem can be formulated as;

$$Min\ f(Q) = \sum_{j=1}^{m} Q_j$$

$$\text{s.t.} \quad S_i = f_i(V)\ \textit{power flow at each node i=1....n}$$

$$0.95 \le V_i \le 1.05\ \textit{voltage constraint at each node}$$

$$0 \le Q_j \le Q_j^{\max}\ \textit{var limits for each DG} \qquad (1)$$

The cost of dispatch in this objective function is the total amount of reactive power needed from all DGs. This emergency support by DGs is much faster than the voltage regulator response to an emergency and it is assumed that voltage regulator setting remains unchanged. By linearizing the power flow equations around operating point and using

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[1] http://jade.tilab.com/
[2] http://www.digsilent.de/

the approximation that real power is more sensitive to the change in angle and reactive power to change in voltage we can get the decoupled equations.

$$\begin{bmatrix} Jp_{\vartheta} & Jp_{v} \\ JQ_{\vartheta} & JQ_{v} \end{bmatrix}\begin{bmatrix} \Delta\vartheta \\ \Delta V \end{bmatrix} = \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} \tag{2}$$

The equation system in (2) shows that changes in the voltage magnitude and angle due to small changes in the active and reactive power can be directly calculated from the load flow Jacobian matrix.

Also as the load will not be changed substantially during the control period, equations can be further reduced by setting ΔP to 0, then the sensitivities of the type dV/dQ can be calculated from (2) as

$$\Delta V = J_{Qv}{}^{-1}\Delta Q = S_{vq}\Delta Q \tag{3}$$

DIgSILENT PowerFactory was used to calculate the sensitivities given in (3) using load flow sensitivity feature. Further details on calculating load flow sensitivities in DIgSILENT PowerFactory can be found in [20]. Voltage sensitivities of DG buses was calculated after every step of simulation and forwarded to the corresponding DG agents. Dispatch of reactive power was done according to the sensitivity order of the DGs. The DG with the highest sensitivity was dispatched first to its limit and if it was not able provide the required voltage boost, then the DG with the second highest sensitivity factor was dispatched. Next section provides the details on how reactive power was dispatched using MAS.

B. *Multi-agent based algorithm*

Challenging task in designing multi-agent system is development of strategy that how agents will cooperate and coordinate with each other. Usually a plan is formulated that specifies the actions for agents to achieve their goals [21]. FIPA Contract-Net-Protocol (CNP) is one the mostly used plan for agent interaction. According to this protocol agents take two roles initiator (manager) or contractor. [22]

In this paper two types of agents were considered, Monitoring Agent and Dispatching Agent. Main task of these agents are as follows;

Monitoring Agent: The role of this agent is to monitor the local bus voltage and when voltage violates the normal limits, it will request to the dispatching agents to provide the necessary voltage support with the amount of voltage boost needed. These agents will also act as moderator and will initiate the request for proposal (RFP) and assign bids to the winning bidder on the basis of some criteria. Thus every bus agent can be considered as monitoring agent.

Dispatching Agent: These agents will respond to the RFP by the monitoring agent and will send their proposal containing the cost and maximum limits. All distributed generation units will act as Dispatching Agent.

Figure 4 shows the communication between agents. Spa (socket proxy agent) is responsible for JADE communication with the DIgSILENT Power Factory through MATLAB wrapper. It continuously senses voltage from buses and send it to Bus agent (in this case BusCP). When voltage violates at BusCP, it sends CFP to all the DG agents. All the DG agents reply back with their sensitivities, current reactive power and maximum reactive power capabilities. However, as shown in Fig. 4, DG4 does not participate in this process; it is because this DG does not provide reactive power support. This is accomplished by registering each DG in the directory facilitator agent with its services. Every agent can register itself with the services it provides. Details of steps are given in next section.

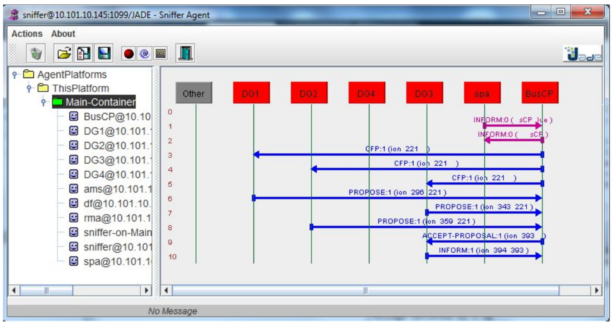

Fig. 4. Agents comunication according to FIPA contract-net-protocol(CNP)

V. TEST RESULTS

In order to evaluate the effectiveness of the proposed MAS based approach modified IEEE 13 Node test feeder network with the DG was taken and is shown in Fig. 5. In test network loads, generations and line parameters were adopted from [23] with some modification. Load and generation characteristics are given in Table 1 and Table 2 respectively.

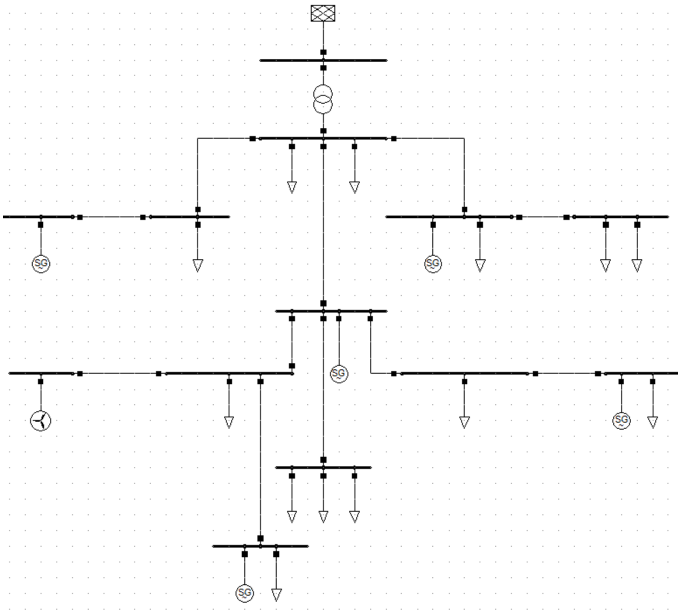

Fig. 5. Modified IEEE 13 Node test feeder

TABLE I. LOAD CHARACTERISTICS

Load	**P [MW]**	**Q [MVAr]**	**Load**	**P [MW]**	**Q [MVAr]**
Ld1	6.93	0.99	Ld7	3	0.01
Ld2	0.57	0.27	Ld8	1	0.1
Ld3	3.52	1.59	Ld9	3.52	1
Ld4	0.34	0.21	Ld10	1	0.1
Ld5	0.35	0.19	Ld11	0.32	0.24
Ld6	0.85	0.25	Ld12	0.54	0.33

TABLE II. GENERATION CHARACTERSTICS

Generator	**P [MW]**	**Qmax [MVAr]**
G1	5	0.426
G2	2.4	0.87
G3	1	0.9
G4	1.5	0.5
G5	2	1
G6	3.5	2.55

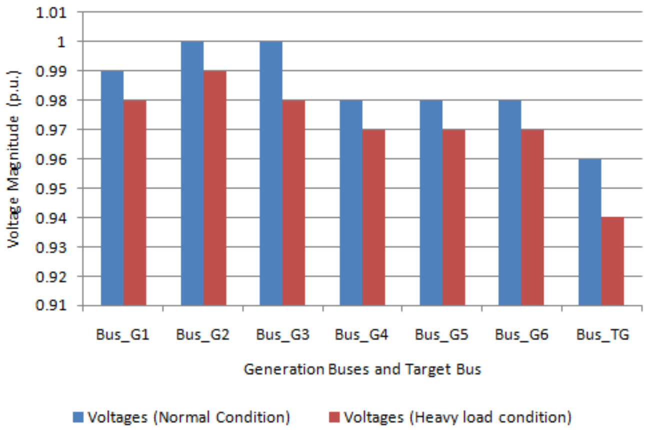

Fig. 6. Generation Bus voltages during normal and heavy load conditions

Figure 6 shows generation bus voltages obtained after calculating load flow during normal network operation and heavy load condition while voltage on target bus (bus12) is 0.9641 which is in permissible range i.e. > 0.94 p.u. After some time with load variation voltage on Bus12 decreases to 0.94 p.u. Bus12 is considered to be the monitored node and selection of the monitoring node is discussed in [24]. After the violation in the bus voltage, monitoring node sends request to the DG agents (dispatching agents) for the required boost in voltage which is ΔV=0.02 p.u. Figure 7 shows the agent communication for reactive power dispatch and explanation of the steps of algorithm is given next.

Step -1 : As soon as voltage at the monitoring node which is bus12 in this case, goes out of limit, it calculates the required voltage boost (ΔV=0.02 p.u , change in voltage with the voltage in normal operating condition).

Step-2: Monitoring agent sends Request-For-Proposal (RFP) message to all the DG agents which have reactive power capability.

Step-3: In this step DG agents receive the RFP and respond with their current reactive power value Q, Qmax and sensitivity factor. Three DGs at bus 6, 8 and 11 were considered to participate in voltage support process. These DG agents respond with the following values;

DG_B6 (0, 0.7, 0.0058)

DG_B8 (0.3, 1, 0.0059)

DG_B11 (0, 3 , 0.0059)

Step-4: Response of all the DGs was examined by the monitoring agent and DG with the highest sensitivity was dispatched first. DG_B8 and DG_B11 have the same sensitivity (0.0059). Priority was given to DG_B11 as voltage is low at bus 11 as compared to bus 8. In order to get the desired voltage boost at Bus12 (ΔV=0.02 p.u), required change in Q should be 3.44 MVar, but Qmax for DG_B11 was 3 thus DG_B11 was dispatched with Q=3 and remaining Q (0.44) was assigned to DG_B8.

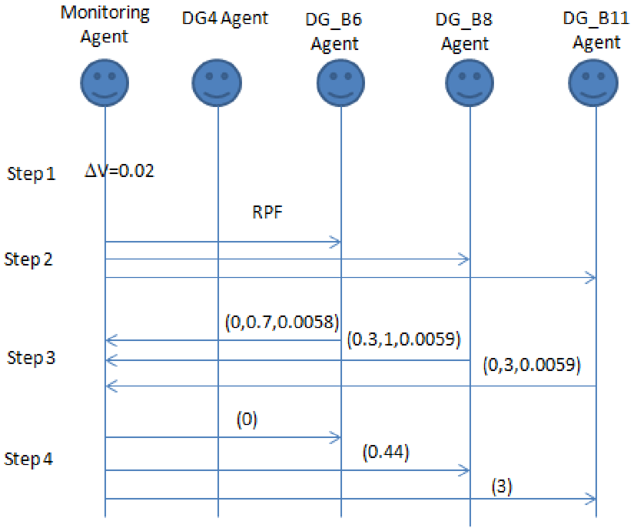

Fig. 7. Dispatch of Reactive power by Agents

Figure 8 shows the voltage magnitude at generation buses and target bus, which is bus12, during normal operation conditions and heavy load conditions. It is clear that voltage at the target bus is above the permissible lower value i.e. > 0.94 after voltage support by the DGs, while voltages at generation buses is also within the range. This shows that MAS approach for distributed voltage support is quite effective.

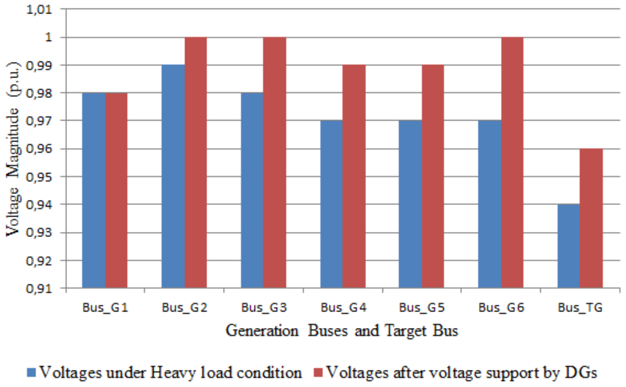

Fig. 8. Bus voltages with voltage support by DGs

VI. CONCLUSIONS

This paper shows that voltage support in distribution network can be implemented using MAS based approach in a distributed manner. A co-simulation framework was used to test the proposed approach. FIPA-contract-net-protocol was used for communication between agents. A case of voltage violation at a specific bus (monitoring node) was considered under heavy load condition. Simulation results show that MAS approach is quite effective for distributed voltage support in a distribution network. This approach can also be used for the light load condition, when voltages are high. Further this method can provide the quick voltage support in system contingencies. However, communication requirements for such an application are required to be analyzed and high communication reliability is needed so that all the DGs can exchange information successfully. Future work would be to investigate the communication effects on the proposed approach.

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