A Multi-Agent Approach for Decentralized Voltage Regulation in Micro Grids by Considering Distributed Generators

Fenghui Ren and Jun Yan

School of Computing and Information Technology,
University of Wollongong, Australia
`fren@uow.edu.au, jyan@uow.edu.au`

Abstract. Distributed generators (DGs) are considered as significant components to modern micro grids because they can provide instant and renewable electric power to consumers without using transmission networks. However, the use of DGs may affect the use of voltage regulators in a micro grid because the DGs are usually privately owned and cannot be centrally managed. In this paper, an innovative multi-agent approach is proposed to perform automatic and decentralized control of distributed electric components in micro grids for the voltage regulation purpose. Autonomous software agents are employed to make local optimal decisions on voltage regulation by considering multiple objectives and local information; and agent-based communication and collaboration are employed toward a global voltage regulation through dynamic task allocation. The proposed approach contains three layers for representing the physical micro grid, the multi-agent system and the human-computer interface, and is implemented by using three Java-based packages, i.e. InterPSS, JADE and JUNG respectively.

Keywords: Distributed generators, voltage regulation, micro grid, multiagent system

1 Introduction

Maintaining consistent and stable voltage levels in a micro grid (MG) is very important because under-voltage can cause overheating of induction motors, and over-voltage can cause equipment damage [Farag *et al.*2012,Ufa *et al.*2022]. Voltage regulation is a procedure to keep voltages within normal limits, which is usually ±5% of the rated voltage [Trip *et al.*2018]. Usually, through collecting sensor readings from predefined measurement points, a Load Tap Changer (LTC) or a Voltage Regulator (VR) can estimate the status of a grid, and perform corresponding operations to regulate voltages [Deshmukh *et al.*2012,Li *et al.*2010]. However, such regulation mechanisms are no longer suitable after the connection of distributed generators (DGs) to the grid.

In recent years, DGs emerge as alternative power resources and are considered as one of the most significant technologies in power grid systems [Basak *et al.*2012] [León *et al.*2022,Ufa *et al.*2022]. In general, by comparison with conventional bulk generations, DGs are smaller scale and located closer to loads. However, the usage of DGs bring both benefits and trouble to existing MGs. On one hand, DGs can supply power to consumers in a MG without needing a transmission network, so as to significantly decrease power loss, voltage drop and cost [Basak *et al.*2012]. Some DGs use renewable energy and contribute to the carbon emission deduction as well. On the other hand, most DGs can only provide intermittent power to a MG due to the intermittent nature of energy resources such as wind and sun [Ramchurn *et al.*2011,Wang *et al.*2022]. Also, most DGs are privately owned and a utility can not centrally control all DGs in a MG. Therefore, with an increasing level of DGs penetrations, a MG may behave quite differently from conventional operations. For example, a DG located in downstream will mislead the reading of a LTC or VR because of the LTC and the VR does not know of the existence of the DG, then the LTC or VR will definitely perform incorrect operations [Basak *et al.*2012,Farag *et al.*2012] and the voltage level of the MG will be impacted. Also, because the power output from a DG using renewable energy to a MG can suddenly have a significant change due to weather or the DG owners' reasons, the voltage level on a DG and its affected area may also change a lot in a short time. However, because LTC or VR can not provide fast enough voltage regulation, DGs may not able to ride through emergency conditions due to voltage drops and automatically be disconnected from the MG [Wang *et al.*2022]. Due to the sudden loss of a DG's power, consequential voltage instability may result more disconnects of other DGs, and such a chain reaction may eventually catastrophic power outage in a MG [Wang *et al.*2022].

Several approaches were proposed to address the above challenge in recent years. In [Shaheen and El-Sehiemy2020], an enhanced grey wolf algorithm (EGWA) is proposed to solve the optimal allocation of capacitor banks, the distributed generations, and the voltage regulators, which can increase the efficiency to detect and resume the issues caused by the voltage drop. However, as the DGs may change the behaviour of a MG, the predefined optimal allocation may not work effectively after the connection/disconnection of DGs. In [Deshmukh *et al.*2012], voltage regulation problem was formulated as an optimization problem on reactive power dispatching by considering DGs, and was solved through a large amount of calculation. Although technologies, such as distributed computing [Yu *et al.*2012], adaptive computing [Li *et al.*2010] and fuzzy control [Spatti *et al.*2010] were employed to increase the efficiency of voltage regulation, the lack of interactions between electrical components still limits dispatching efficiency by considering the dynamics of a MG and the uncertainties of DGs. In [Wang *et al.*2019], a two-layer co-planning method was used to optimize the placement of DG and battery energy storage towards the voltage regulation. However, the construction and running costs of battery energy storage are too high which stops to apply the solutions in the real-world MGs. In [Farag *et al.*2012], a Multi-Agent System (MAS) for voltage regulation and reactive power dispatching are introduced. However, the MAS employed a central controller to manage the regulation by using global information. Therefore, such centralized mechanisms can not handle the voltage regulation in a MG when private DGs are connected [Rogers *et al.*2012]. Even through some decentralized MASs were also proposed to overcome such a limitation [Fakham *et al.*2011], practical issues such as how to minimize the regulation cost and time, how to effectively organise regulation through communication, and how to properly design and implement such as MAS were not properly discussed. The network self-organization approach was also combined with the MAS to handle the distributed voltage regulation issue for a large distribution network [Al Faiya *et al.*2021], issues such as asynchronous agent communication and incidences handling are still not resolved properly. The multi-agent reinforcement learning approaches [Wang *et al.*2021,Wang *et al.*2020] were also proposed to perform the active voltage control to relieve power congestion and improve voltage quality. However, issues such as lack of training data and the uncertainties of real-world scenarios limit the usage of the solutions in real-world applications.

Theoretically, voltage levels are impacted by power delivered through it. If power injected to a MG can be quickly modified, then voltages will be adjusted in a short period accordingly. Conventional bulk generations are impractical due to their large scales, but such a problem does not exist for DGs. Therefore, adjusting DGs power outputs is considered as a matter for a fast voltage regulation. Furthermore, in order to perform more efficient regulation, DGs need to collaborate with other devices. Because of private ownership of DGs, the conventional centralised-based approaches can not efficiently coordinate all the electrical devices due to their limitations of flexibility, communication, cooperation, and decision making [Razavi *et al.*2019]. Therefore, in this paper, an innovative decentralised coordinated voltage regulation approach is proposed by considering the connection of DGs in a MG. Autonomous agents are proposed to automatically and adaptive control all electrical devices in a MG, and each agent can make local optimal regulation through using local information and devices. Furthermore, the proposed coordination approach will enable the dynamic collaboration of agents in voltage regulation, which will approximate the voltage regulation of the whole MG to its optimization. Multiple objectives and constraints such as regulation time and cost are considered. A detail introduction of the MAS design and implementation is also given in this paper.

The organization of this paper is as follows. Section 2 introduces the principle and the objectives of voltage regulation by considering DGs, and Section 3 introduces our multi-agent approach to this decentralized voltage regulation. Section 4 demonstrates the performance of the proposed approach through a case study. Finally, the conclusion and future work are given in Section 5.

2 Voltage Regulation Considering DGs

2.1 Principle

Traditionally, all DGs are required to work in a power factor control model [Wang *et al.*2020], where the power factor ($PF = P/Q$) indicates the ratio between active power output (P) and reactive power output (Q).

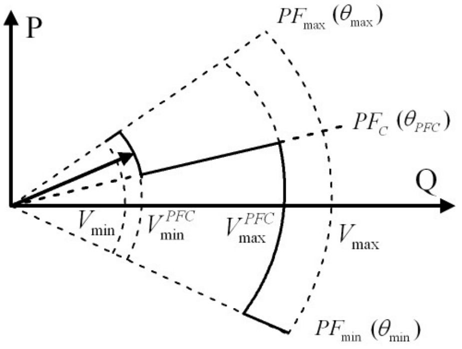

Fig. 1. Vector diagram of a DG's voltage.

As shown in Figure 1, when DGs work in a power factor control model, a constant PF is maintained. However, if a DG's voltage approaches statutory limits, i.e. V_{min} or V_{max}, the DG can deactivate the power factor control model and regulate its voltage through adjusting its power output. Basically, in order to keep P at a requested level, a DG will increase Q when its voltage drops to the lower threshold V_{min}^{PFC}, so as to increase its voltage. On the other hand, if its voltage reaches its upper threshold V_{max}^{PFC}, the DG will decrease Q, which leads to a decrement of its voltage. Therefore, based on the Jacobian matrix of the Newton power flow [Yu *et al.*2012], the linear relationship between a DG's changes on its power output and voltage is displayed in Formula (4):

$$\Delta V = \Lambda_{VQ} \cdot \Delta Q + \Lambda_{VP} \cdot \Delta P. \tag{1}$$

where ΔP and ΔQ are a DG's changes on active and reactive power, ΔV is DG's corresponding voltage change, and Λ_{VP} and Λ_{VQ} are the correlations between changes of voltage, active and reactive power, respectively.

The correlation between changes of P and Q is shown as the Jacobian matrix of the Newton power flow in Formula (2) [Yu *et al.*2012].

$$\begin{pmatrix} \Delta\theta \\ \Delta V \end{pmatrix} = \begin{pmatrix} \Lambda_{\theta P} & \Lambda_{\theta Q} \\ \Lambda_{VP} & \lambda_{VQ} \end{pmatrix} \begin{pmatrix} \Delta P \\ \Delta Q \end{pmatrix} \tag{2}$$

with

$$\Lambda = \begin{pmatrix} \Lambda_{\theta P} & \Lambda_{\theta Q} \\ \Lambda_{VP} & \lambda_{VQ} \end{pmatrix}, \tag{3}$$

where ΔP and ΔQ are a DG's changes on active and reactive power, $\Delta\theta$ and ΔV are the DG's corresponding changes on PF ($PF = th(\theta)$) and voltage, respectively. Then a linear relationship between a DG's changes on its power output and voltage is displayed in Formula (4):

$$\Delta V = \Lambda_{VQ} \cdot \Delta Q + \Lambda_{VP} \cdot \Delta P. \tag{4}$$

Usually, in order to minimize impacts to a MG, active power output will not be changed, i.e. $\Delta P = 0$, and a DG will only adjust its reactive power output during a voltage regulation.

2.2 Objectives and Constraints

In this paper, three objectives for a voltage regulation are set by considering DGs, which are the time objective, the cost objective, and the population objective.

Time objective: In order to get a fast regulation on voltage to protect DGs in emergency situations, total time spent on the regulation should be minimized, i.e.

$$\min \sum_i t(\varDelta v_i), \tag{5}$$

where $t(\varDelta v_i)$ is the time spent on regulating i's voltage, and $\varDelta v_i$ is the minimum voltage change for node i getting back to normal.

Cost objective: A MG may connect multiple DGs, and costs of the DGs on voltage regulations will also be different by considering their motor types, resources and locations. We also want to minimize the total cost, i.e.

$$\min \sum_i \varDelta Q_i \cdot c_i, \tag{6}$$

where c_i is DG i's cost of adjusting a unit reactive power, and $\varDelta Q_i$ is the amount of reactive power modified.

Population objective: In case multiple voltage fluctuations occur, voltage regulations should recover problem nodes as much as possible to their normal limits, i.e.

$$\max_i \{0.85\ \textit{(p.u.)} \leq v_i \leq 1.05\ \textit{(p.u.)}\}, \tag{7}$$

where v_i is the voltage of the ith problem node.

The fulfillment of the objectives should not lead to violation of operating other components; hence, several constraints are reinforced.

Current limit: For each electrical component i, current through it should be not greater than its limit, i.e.

$$\forall i, |I_i| \leq |I_i^{max}|. \tag{8}$$

where I_i is current on component i, and I_i^{max} is component i's limit on current.

Voltage limit: The voltage regulation should not cause any new voltage fluctuation to other components, i.e.

$$\forall i, 0.95\ \textit{(p.u.)} \leq v_i \leq 1.05\ \textit{(p.u.)}. \tag{9}$$

Reactive power output limit: An DG's reactive power output should not exceed its surplus capability, i.e.

$$\forall i, |Q_i| \leq |Q_i^{max}|. \tag{10}$$

where Q_i is DG i's reactive power output, and Q_i^{max} is DG i's limit on reactive power output.

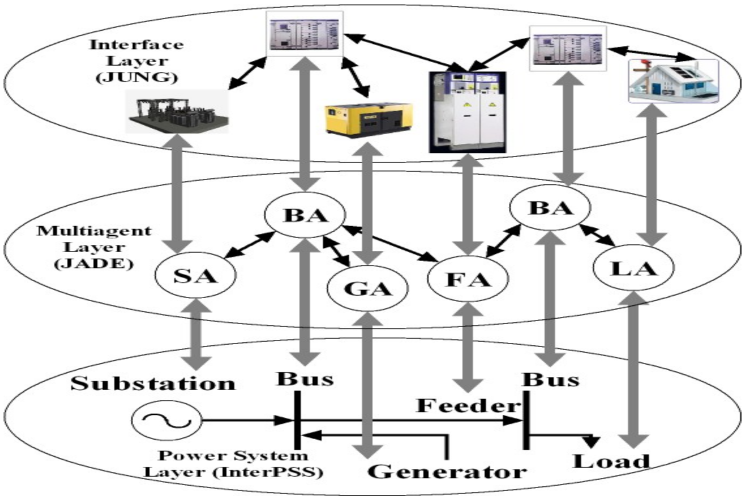

Fig. 2. A three-layer view of the proposed approach.

3 A Multi-Agent Based Voltage Regulation

3.1 Principle

In order to fulfill the above objectives by considering all requested constraints, a multi-agent approach is introduced in this section. As shown in Figure 2, the proposed approach contains three layers, i.e. a power system layer, a multi-agent layer and a interface layer. First, the power system layer locates in the bottom and presents a MG. In this paper, we consider five key electrical components for voltage regulation purposes, i.e. *substation* (controlling LTC), *feeder* (controlling VR), *busbar*, *load* and *DG*. Second, the multi-agent layer locates in the middle and presents a MAS to dominate communications, decision-makings, and collaborations between the electrical components. Five types of agents are proposed in this layer to control the five identified electrical components correspondingly, i.e. *substation agent*, *feeder agent*, *bus agent*, *load agent* and *DG agent*. Third, the interface layer locates on the top and visualizes the whole system.

By comparison with conventional centralized voltage regulations, the proposed approach has the following advantages. (i) A *decentralized management* is employed by the proposed MAS, which means that there is no central controller, and agents work automatically based on information they receive from corresponding electrical components and neighboring agents. No agent will preset the global information. (ii) Agents are represented as nodes in a peer-to-peer network, and can communicate with their neighboring agents. Non-adjacent agents can communicate and share information through in-between agents. And (iii) there is no dependency relationship between agents, and the MAS size is scalable. Agents act as a "plug and operate" component. In the following subsections, characteristics of proposed agents will be introduced firstly, then three mechanisms will be introduced to dynamically control the agents in distributed voltage regulation. Finally, implementation of the proposed MAS will be also briefly introduced.

3.2 Agent Design

We propose five agents as follows. Characteristics of the proposed five agents are introduced below.

Substation Agent (*SA*): A *SA* represents a secondary substation, and monitors current, voltage and power output of the substation. During a normal operation, the *SA* continuously exchanges information with neighboring agents, and operates a LTC under requests to perform a conventional voltage regulation. The response time and cost of a *SA* are two crucial factors for its neighboring agents to decide whether the *SA* should be requested to involve in a regulation process.

Feeder Agent (*FA*): A *FA* represents a physical feeder which delivers power to downstream components, and monitors current and voltage drop on the feeder through communicating with upstream and downstream agents. A *FA* checks cables transmission abilities to decide whether required power can be delivered. In case a *FA* is requested to join in a voltage regulation process, it will operate corresponding VRs to fulfill the request. Usually, a *FA* can provide a faster regulation than a *SA*, but a slower regulation than a GA. A *FA*'s regulation cost is impacted by the distance between its VRs and problem nodes.

Bus Agent (*BA*): A *BA* represents a physical bus-bar that conducts power between electrical components. A *BA* records information on connected electrical components, such as current and voltage. During a voltage regulation, a *BA* can make its local decisions on a local regulation plan in order to reach its local objectives. Usually, once a *BA* receives a regulation request from a neighboring agent, the *BA* will firstly search for a local solution by using only local resources. If the local resources cannot fulfil the regulation request, the *BA* and then will request help from its upstream agents. For a secondary *BA*, it will contact a *SA* to perform conventional regulation through operating a LTC.

Generator Agent (*GA*): A *GA* represents a DG. During normal operations, a *GA* monitors current, voltage and power output of a DG, and maintains the DG's power factor. During a voltage regulation process, a *GA* deactivates the DG's power factor control model and provides voltage supports to a MG through adjusting the DG's reactive power output. Also, a *GA* should ensure that the DG's reactive power output does not exceed its limit. Usually, a DG is ranked by considering its response time, cost and effect on a voltage regulation, and a *GA* also makes individual decisions on how to respond to neighboring agents regulation requests by considering the DG's capacity.

Load Agent (LA): A *LA* represents a load in a MG. A *LA* monitors current and voltage level of the load, and reports to its upstream *BA* once a voltage fluctuation is detected. Each *LA* is assigned a priority to indicate the significance of the load. Usually, a *LA* with a high priority is handled earlier than a *LA* with a low priority during voltage regulation. Once a regulation plan is determined, a LA will confirm with its upstream agent for execution.

3.3 Mechanism Design

In order to efficiently manage electrical components to perform distributed voltage regulations by considering the existence of DGs, three novel mechanisms are proposed to control agents and to regulate voltage during three typical operations on electrical components, ie. the connection, the disconnection, and the voltage fluctuation. All mechanisms employ decentralized designs, and are independent on a MG or agent types.

Connection Mechanism When a new electrical component i needs to be connected to a MG, a corresponding agent a_i will be firstly generated to represent the new component. Let a_i be represented by a seven-tuple $a_i =< AID_i, I_i^{max}, T_i^{max}, Q_i^{max}, V_i^t, C_i^t, P_i^t >$ (where AID_i is a_i's ID, $I_i^{max}, T_i^{max}, Q_i^{max}, V_i^t, C_i^t, P_i^t$ indicates a_i's max current, max regulation time, max reactive power, voltage, regulation cost and priority, respectively), and the nine-tuple $n_{i,j} =< AID_j, I_{i,j}^{max}, Q_{i,j}^{max}, T_{i,j}^{max}, I_{i,j}^t, Q_{i,j}^t, C_{i,j}^t, \Lambda_{i,j}^t, P_i^t >$ be a_i's record on its neighboring agent a_j. Then the connection process is as follows:
Step 1: a_i is created to represent the electrical component i, and is initialized according to component i's features.
Step 2: a_i sends a connection request with information $< AID_i, I_i^{max}, Q_i^{max}, T_i^{max}, C_i^t, P_i^t >$ to a_j, and waits for a_j's response. If component i cannot provide reactive power, then $Q_i^{max} = 0$, $T_i^{max} = +\inf$, and $C_i^t = +\inf$.
Step 3: a_j receives a_i's connection request. If the connection is not allowed, a_j denies the request, and the procedure goes to **Step (v)**. Otherwise, the procedure goes to **Step (iv)**.
Step 4: Firstly, a_j creates a new neighboring agent record according to information sent by a_i, i.e. $n_{j,i} =< AID_i, \min(I_i^{max}, I_j^{max}), Q_i^{max}, T_i^{max}, 0, 0, (C_i^t + L_{j,i}), 0, P_i^t >$ (where $L_{j,i}$ indicates a cost of power loss on a cable between components i and j), and adds $n_{j,i}$ to its neighboring agents set, i.e., $\mathbf{N_j} \leftarrow \{n_{j,i}\} \cap \mathbf{N_j}$. Secondly, a_j informs other existing neighboring agents about its update on reactive power supply, cost and priority by sending $(Q_i^{max}, T_i^{max}, (C_i^t + L_{j,i}), P_i^t)$. Thirdly, a_j's neighboring agents update their records on a_j, i.e., $Q_{k,j}^{max} \leftarrow (Q_{k,j}^{max} + Q_i^{max})$, $T_{k,j}^{max} \leftarrow \min(T_{k,j}^{max}, T_i^{max})$, $C_{k,j}^t \leftarrow \min(C_{k,j}^t, (C_i^t + L_{j,i} + L_{k,j}))$, and $P_{k,j}^t \leftarrow \max(P_{k,j}^t, P_i^t)$. Lastly, a_j's neighboring agents inform their updates to their neighboring agents, and concurrently, a_j replies a_i with an agreement.
Step 5: If a_i receives an agreement from a_j, a_i creates a new neighboring agent record according to information sent by a_j, i.e. $n_{i,j} =< AID_j, \min(I_i^{max}, I_j^{max})$, $\sum_k Q_{j,k}^{max}$, $\min(\min_k\{T_{j,k}^{max}\}, T_j^{max}), 0, 0$, $(\min(\min_k\{C_{j,k}^t\}, C_j^t) + L_{i,j})$, $0, \max(\max_k\{P_{j,k}^t\}, P_j^t) >$, and adds $n_{i,j}$ to its neighboring agents set, i.e. $\mathbf{N_i} \leftarrow \{n_{i,j}\} \cap \mathbf{N_i}$. After that, a_i connects to the MG. Otherwise, if a disagreement is received, the procedure is terminated.

Disconnection Mechanism An existing electrical component may also need to be disconnected from a MG. Suppose that agent a_i wants to disconnect from a MG, and agent a_j is its upstream component, then the disconnection process is given as follows:

Step 1: a_i sends a disconnection request to a_j, and waits for a_j's response.

Step 2: a_j receives the request, and then activates the *voltage regulation mechanism* to re-dispatch reactive power without considering a_i. If a_j fails to reallocate reactive power, then the disconnection is not allowed and the procedure goes to **Step 4**. Otherwise, the procedure goes to **Step 3**.

Step 3: Firstly, a_j deletes the record of a_i from its neighboring agents set, i.e. $\mathbf{N_j} \leftarrow \mathbf{N_j}/n_{j,i}$. Secondly, a_j informs other existing neighboring agents about its update on reactive power supply, cost and priority by sending (Q_i^{max}, $\min(\min_k\{T_{j,k}^{max}\}, T_j^{max})$, $\min(\min_k\{C_{j,k}^t\}, C_j^t)$, $\max(\max_k \{P_{j,k}^t\}, P_j^t)$) (where $k \in \mathbf{N_j}, k \neq i$). Thirdly, a_j's neighboring agents update their records on a_j, i.e., $Q_{k,j}^{max} \leftarrow (Q_{k,j}^{max} - Q_i^{max})$, $T_{k,j}^{max} \leftarrow \min\ (\min_k\{T_{j,k}^{max}\}, T_j^{max})$, $C_{k,j}^t \leftarrow \min(\ \min_k\{C_{j,k}^t\}, C_j^t)$, and $P_{k,j}^t \leftarrow \max(\max_k\{P_{j,k}^t\}, P_j^t)$. Lastly, a_j's neighboring agents inform their updates to their neighboring agents, and concurrently, a_j replies a_i with an agreement on disconnection.

Step 4: If a_i receives an agreement from a_j, a_i will delete the record of a_j from its neighboring agents set, i.e. $\mathbf{N_i} \leftarrow \mathbf{N_i}/n_{i,j}$, and then a_i disconnects from components j. Otherwise, a_i should keep the connection with a_j, and seeks for another disconnection from the MG in future.

Distributed Voltage Regulation Mechanism If any voltage fluctuation happens on any electrical component, this mechanism will be activated automatically to regulate voltages by considering all the objectives and constraints mentioned in subsection 3.1. Basically, a decentralized design is employed in this mechanism. Agents make local reasoning and decision making on their regulation plans based on their local information, which includes the calculation of regulation solutions, reactive power resource selections, and reactive power dispatching. A recursive strategy is employed during the regulation when multiple agents are involved. The regulation process is introduced as follows.

Step 1: Let a_k be the agent which firstly notices a voltage fluctuation, i.e. its voltage is beyond its limit ±5% (p.u.), and V_k^t be the voltage value. Then a_k firstly calculates the difference between its existing voltage and its target voltage using Formula (11). In this paper, the target voltage is set to 0.85 (p.u.) for any existing voltage lower than 0.85 (p.u.), and is set to 1.05 (p.u.) for any existing voltage higher than 1.05 (p.u.).

$$\varDelta V_k^t = \begin{cases} 0.85 - V_k^t, & \text{if } V_k^t < 0.85, \\ 1.05 - V_k^t, & \text{if } V_k^t > 1.05. \end{cases} \tag{11}$$

Step 2: In order to choose a right adjustment for a voltage regulation, a_k makes a combined consideration on different factors, i.e. regulation speed, cost and effectiveness. Let a_i be a_k's *ith* neighboring agent, and a_k firstly evaluates a_i by using Formula (12).

$$E(a_k, a_i) = \frac{1/T^{max}_{k,i}}{\sum_j 1/T^{max}_{k,j}} \cdot W^s_k + \frac{1/C^t_{k,i}}{\sum_j 1/C^t_{k,j}} \cdot W^c_k + \frac{\Lambda^t_{k,i}}{\sum_j \Lambda^t_{k,j}} \cdot W^e_k, \tag{12}$$

where W^s_k, W^c_k, and W^e_k are a_k's preferences on the speed, cost and effectiveness of the regulation respectively, and $W^s_k + W^c_k + W^e_k = 1$.

Then, a_k ranks all neighboring agents as $\mathbf{N^r_k}$, i.e. $\forall a_i, a_j \in \mathbf{N^r_k}, a_i \geq a_j \Rightarrow E(a_k, a_i) \geq E(a_k, a_j)$. Let a_i be a next agent in $\mathbf{N^r_k}$, then a_k calculates a voltage change that a_i should provide by considering a line's loss as $\Delta V^t_{k,i} = \Delta V^t_k + L_{k,i}$. Also, a_k calculates a possible change on a_i's reactive power output in order to cover $\Delta V^t_{k,i}$ according to Formula (4) under an assumption that $\Delta P = 0$, i.e. $\Delta Q^t_{k,i} = \Delta V^t_{k,i}/\Lambda^t_{k,i}$. If a_k believes that a_i can afford such a modification, i.e. $\Delta Q^t_{k,i} + Q^t_{k,i} \leq Q^{max}_{k,i}$, a_k will send the voltage change request $req^t_{k,i} = \Delta V^t_{k,i}$ to a_i. Otherwise, the voltage change request will be updated by considering a_i's maximum reactive power output as $req^t_{k,i} = \Delta V^{u,t}_{k,i} = \Lambda^t_{k,i} \cdot (Q^{max}_{k,i} - Q^t_{k,i})$, and leave the remaining voltage change, i.e. $\Delta V^{r,t}_{k,i} = \Delta V^t_{k,i} - \Delta V^{u,t}_{k,i}$, to a next neighboring agent in $\mathbf{N^r_k}$.

Step 3: Once a_i receives a_k's regulation request, the request will be inserted into a_i's request queue, i.e. $\mathbf{req_i}$, by considering a_k's priority and time when the request was received. Let $req^t_{k,i}$ and $req^t_{j,i}$ be two requests in $\mathbf{req_i}$, then $req^t_{k,i}$ is in front of $req^t_{j,i}$ iff $R(i, req^t_{k,i}) > R(i, req_{j,i})$, where $R(i, req_{k,i})$ is defined in Formula (13).

$$R(i, req_{k,i}) = \frac{1/(t_k - t_1)}{\sum_k 1/(t_k - t_1)} \cdot W^t_i + \frac{P^t_{i,k}}{\sum_k P^t_{i,k}} \cdot W^p_i, \tag{13}$$

where t_k is time when the request $req^t_{k,i}$ was received, and $P^t_{i,k}$ is a_i's record on a_k's priority. W^t and W^p are a_i's weighting on time and priority, respectively. Each time when a_k receives a new request, queue $\mathbf{req_i}$ will be updated.

Let us assume that a_i already completes all requests in front of $req^t_{k,i}$, and starts to process request $req^t_{k,i}$. If a_i represents an electrical component which can adjust reactive power directly (i.e. a DG, a feeder or a substation), then a_i can make a decision on the request $req^t_{k,i}$ without contacting other agents. In order to do that, a_i firstly calculates its remaining supply ability to a_k as $Q^{r,t}_{i,k} = Q^{max}_i - \sum_k Q^t_{i,k}$, and replies to a_k to indicate the actual amount that a_i can supply, i.e. $rsp_{i,k} = \min(Q^{r,t}_{i,k}, |req^t_{k,i}|)$. However, if a_i cannot adjust reactive power directly, a_i needs to contact its neighboring agents for a_k's request. To do that, a_i needs to employ *voltage regulation mechanism* again by seeking $req^t_{k,i}$ change on its voltage. Obviously, such a recursive procedure will be repeated until an electrical component, which can adjust reactive power directly, is reached.

Step 4: Suppose that a_i receives a response from a neighboring agent a_j, i.e. $rsp^t_{j,i}$. If a_i's request can be fully satisfied by a_j, i.e. $rsp^t_{j,i} = req^t_{i,j}$, then a_i will respond $rsp^t_{i,k} \leftarrow rep^t_{j,i}$ to a_k directly. Otherwise, a_i will seek for the remaining voltage $\Delta V^{r,t}_{i,m} \leftarrow (\Delta V^t_{k,i} - rsp^t_{j,i} \cdot \Lambda^t_{i,j})$ from its next neighboring agent by sending a request $req^t_{i,m} = \Delta V^{r,t}_{i,m}/\Lambda^t_{i,m}$. Such a procedure will be repeated until

a_i's request is fully satisfied by its neighboring agents or no more neighboring agent can be contacted. Finally, a_i responds to a_k by combing all the responses from neighboring agents, i.e. $rsp^t_{i,k} = \sum_j rsp^t_{j,i}$. Then a_i is ready for executing operations and waits for a_k's confirmation. However, if a_i receives a cancellation request from a_k before operations can be executed, a_i will cancel the regulation and forward the cancellation to related neighboring agents.

Step 5: Once a_k receives a_i's response, a_k will reply to a_i with a confirmation for executing. If a_k's request can be fully satisfied by a_i, i.e. $rsp^t_{i,k} = req^t_{k,i}$, then the regulation is complete. Otherwise, a_k will seek for the remaining voltage change $\Delta V^{r,t}_{k,m} \leftarrow (\Delta V^t_{k,i} - rsp^t_{i,k} \cdot \Lambda^t_{k,i})$ from its next neighboring agent by sending a request $req^t_{k,m} = \Delta V^{r,t}_{k,m}/\Lambda^t_{k,m}$. Then the steps **(ii)-(iv)** will be repeated until a_k's original request is fully satisfied by its neighboring agents cumulatively. Because conventional LTC and VR are involved in the procedure and represented by SAs or FAs, we assume that a_i's original request on voltage change can be satisfied eventually.

Step 6: a_i receives a_k's confirmation, and forwards the confirmation to related neighboring agents. The agents, which receive the confirmation, start to adjust their reactive power as promised.

3.4 System Development

As shown in Figure 2, our MAS solution contains three layers and we employ three well-known Java-based packages, i.e. InterPSS (Internet technology based Power System Simulator), JADE (Java Agent Development Framework), and JUNG (Java Universal Network/Graph Framework), for the development of each layer, respectively. InterPSS is an open-source Java-based development project to enhance power system design, analysis, diagnosis and operation [Zhou *et al.*2019]. We employ InterPSS for the development of the power system layer. JADE is a free agent development framework, and the communication among agents in JADE is carried out according to FIPA-specified Agent Communication Language (ACL) [KS2019]. We employ JADE on top of InterPSS to develop the middle layer to monitor and control electrical components. JUNG (Java Universal Network/Graph Framework) is a free software library that provides a common and extendable language for modeling, analysis, and visualization of data that can be represented as a graph or network [Team2016]. We employ JUNG on the top of InterPSS and JADE to visualize the whole system.

4 Simulation

In this section, we demonstrate the performance of the proposed MAS through a case study. In Figure 3, a MG is firstly output by using InterPSS. The MG contains one substation, two feeders, five buses, six loads, and one generator. The limits of reactive power flow for the substation, buses and feeders are set to 500 MVar. The maximum reactive power supply for the substation is set to 300 MVar, and the MG is also connected to a 100 MVar DG. It is also assumed

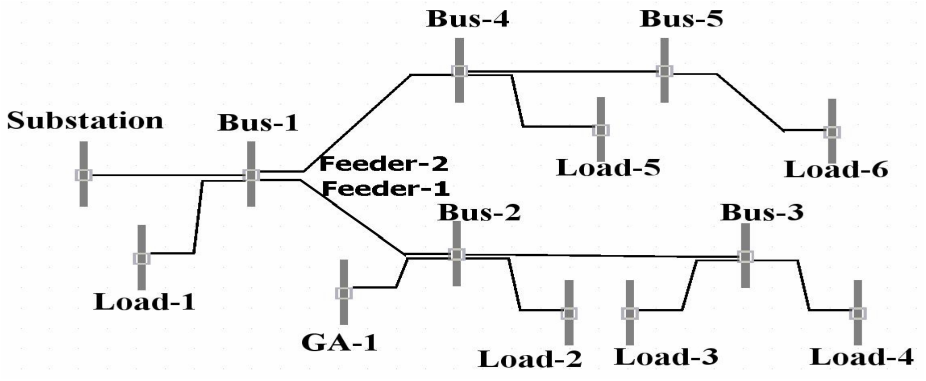

Fig. 3. An InterPSS output showing a power micro grid.

that the DG's response time on a voltage regulation is much shorter than a LTC or VR, and we set those two response times to 0.1 p.u./sec and 0.02 p.u./sec, respectively. The cost of voltage regulations is depended on the type of control devices, and the distance between a problem node and a control device.

We set the cost for adjusting 1 MVar as \$20 through a LTC and VR, and as \$10 through a DG. The delivery of 1 MVar through 1 km is assumed to be \$1, and the distance between any two electrical components is assumed to be 1 km. In Figure 4, the multi-agent simulation of the MG using JADE and JUNG is illustrated. The graph illustrates reactive power dispatching in the MG at a certain moment. Information about reactive power such as direction, amount and price are displayed in the simulation.

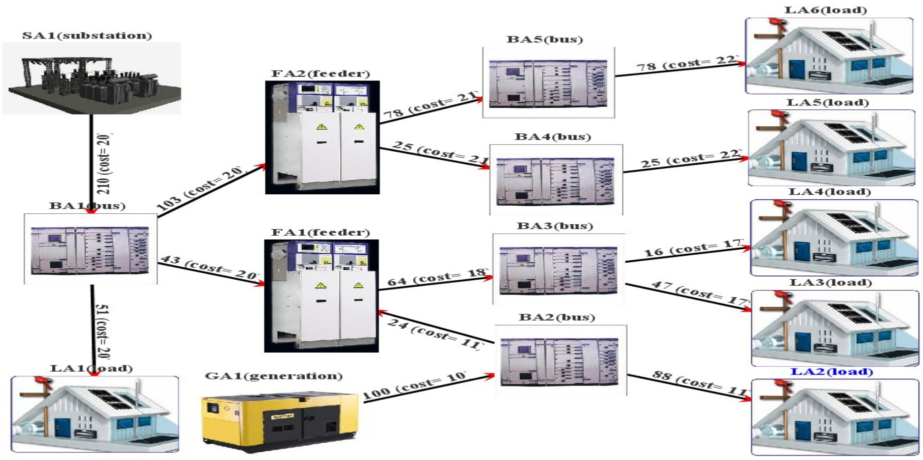

Fig. 4. A multi-agent simulation of a micro grid.

In order to show continuous adjustments on reactive power, Agent *BA1*'s historical records on reactive power adjusting through neighboring agents are displayed in Figure 5. The negative power indicates the power input from the upper-stream Agent *SA1*, and the positive power values indicate the power outputs to the downstream Agents *LA1*, *FA1*, and *FA2*. All agents will apply the mechanisms introduced in Section 3.3 to automatically balance the power inputs and outputs dynamically by considering the three objectives. Through the communication and collaboration of all agents, the voltage level of the MG can be regulated automatically through adjusting the reactive power of each associated agent accordingly. Due to the page limit, the historical records of other agents are not presented in this paper.

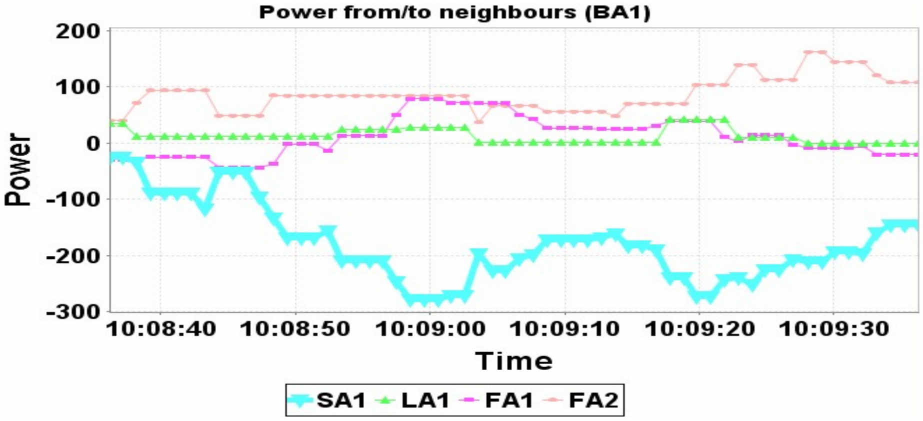

Fig. 5. The historical records of *BA1*.

In order to test the proposed mechanisms, another generator, i.e. DG2 (rated at 50 MVar), is proposed to connect the MG through *BA5*. In Figure 6, communications between agents during DG2's connection, and a voltage regulation through *GA2* are displayed. Explanations are given below.

(**Messages 1-2**): *GA2* sends a request to *BA5* for connection, and *BA5* agrees with the connection. (**Messages 3-16**): *BA5* informs its updates (i.e., limit, cost and sensitivity) to its neighboring agents, i.e. *FA2* and *LA6*. Then *FA2* further informs its neighboring agents, i.e. *BA1* and *BA4*, about its update. Such a procedure is executed by other agents recursively, and eventually all agents receive update notices from their neighboring agents. (**Messages 17-20**): *LA5* sends a voltage regulation request to *BA4*, and *BA4* forwards such a request to *FA2*. Because *BA5* already informed *FA2* that a faster, cheaper, and more efficient voltage regulation service can be provide after *GA2*'s connection, through comparison with the voltage regulation service provided by *BA1* (i.e. provided by *SA1* through adjusting LTC actually), *FA2* decides to contact *BA5* firstly, and then *BA5* forwards the request to *GA2*. (**Messages 21-24**): *GA2* agrees

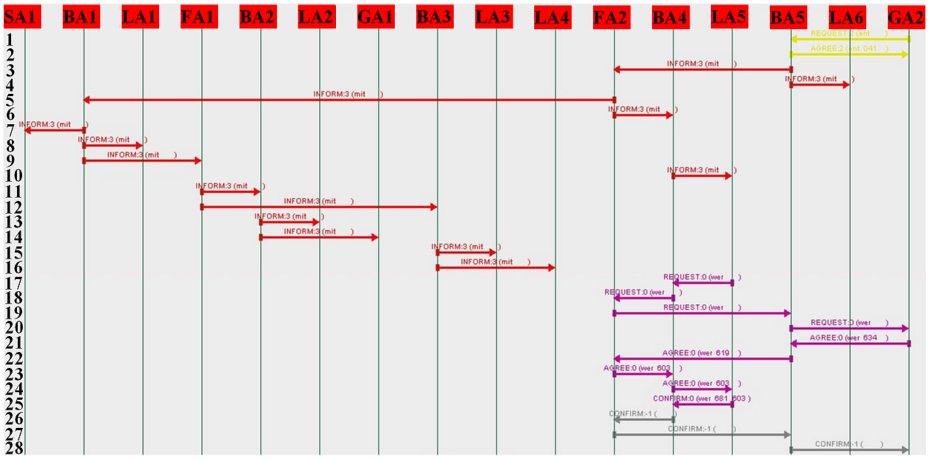

Fig. 6. Communications between agents during component connection and voltage regulation

with *BA5*'s request to provide a voltage regulation through adjusting its reactive power output. *GA2* replies an agreement to *BA5*'s request, and waits for *BA5*'s confirmation for executing. Then *BA5* forwards the agreement to *FA2*. Eventually, the agreement is received by the original requester, i.e. *LA5*. All involved agents, i.e. *GA2*, *BA5*, *FA2*, and *BA4*, are waiting for *LA5*'s confirmation for executing. (**Messages 25-28**): *LA5* confirms with *BA4* that it is ready for the execution, and such a confirmation is eventually forwarded to *GA2* through *BA4*, *FA2* and *BA5*. Then *GA2* adjusts its reactive power output, and *LA5*'s voltage is regulated.

The above case study demonstrated that the proposed MAS solution can effectively manage a MG with DGs, and perform distributed voltage regulations by using of local information and agent communication. The proposed agents can make decentralized decisions to control corresponding electrical components and perform self-adaptive voltage regulation services. The procedures, i.e. selecting reactive power resources by considering their limits, costs and sensitivities, planing reactive power dispatching by considering the dynamics of neighboring agents, and executing of voltage regulation plans, have demonstrated the good performance of the proposed agents.

5 Conclusion and Future Work

The DG is considered to be a significant technologies in power grids, and provides supplemental electric energy to modern MGs without using transmission networks. However, the uncertainty and dynamics of DGs can make conventional voltage regulations become deactivated. In this paper, a decentralized multi-agent approach for dynamic and distributed voltage regulation by considering the DGs was proposed. The proposed approach not only provides sufficient autonomy for an individual agent to make local optimal decisions on local voltage regulation by using local information, but also supports dynamic agent collaborations for searching a global voltage regulation solution by using agent communication, dynamic task allocation and team forming. Multiple objectives and constraints are considered by the proposed agents during their distributed voltage regulations, and agents can dynamically adjust their regulation plans according to environmental changes. Development of the proposed approach by using InterPSS, JADE and JUNG was introduced, and the good performance of the proposed approach on voltage regulation in a simulated MG was also demonstrated.

Future work of this research will focus on comprehensive systemic testing and evaluation through using large scale MGs and numerous DGs with different energy resources and supply capabilities.

References

[Al Faiya *et al.*2021] Badr Al Faiya, Dimitrios Athanasiadis, Minjiang Chen, Stephen McArthur, Ivana Kockar, Haowei Lu, and Francisco De Leon. A self-organizing multi-agent system for distributed voltage regulation. *IEEE Transactions on Smart Grid*, 12(5):4102–4112, 2021.

[Basak *et al.*2012] P. Basak, S. Chowdhury, S. Halder nee Dey, and SP Chowdhury. A Literature Review on Integration of Distributed Energy Resources in the Perspective of Control, Protection and Stability of Microgrid. *Renewable and Sustainable Energy Reviews*, 16(8):5545–5556, 2012.

[Deshmukh *et al.*2012] S. Deshmukh, B. Natarajan, and A. Pahwa. Voltage/VAR Control in Distribution Networks via Reactive Power Injection Through Distributed Generators. *IEEE Trans. on Smart Grid*, 3(3):1226–1234, 2012.

[Fakham *et al.*2011] H. Fakham, F. Colas, and X. Guillaud. Real-time Simulation of Multi-Agent System for Decentralized Voltage Regulation in Distribution Network. In *IEEE Power and Energy Society General Meeting*, pages 1–7, 2011.

[Farag *et al.*2012] HEZ Farag, E.F. El-Saadany, and R. Seethapathy. A Two Ways Communication-Based Distributed Control for Voltage Regulation in Smart Distribution Feeders. *IEEE Trans. on Smart Grid*, 3(1):271–281, 2012.

[KS2019] Gayathri Devi KS. Hybrid genetic algorithm and particle swarm optimization algorithm for optimal power flow in power system. *J. Comput. Mech. Power Syst. Control*, 2:31–37, 2019.

[León *et al.*2022] Leonardo F León, Maximiliano Martinez, Leonardo J Ontiveros, and Pedro E Mercado. Devices and control strategies for voltage regulation under influence of photovoltaic distributed generation. a review. *IEEE Latin America Transactions*, 20(5):731–745, 2022.

[Li *et al.*2010] H. Li, F. Li, Y. Xu, D.T. Rizy, and J.D. Kueck. Adaptive Voltage Control with Distributed Energy Resources: Algorithm, Theoretical Analysis, Simulation, and Field Test Verification. *IEEE Trans. on Power Systems*, 25(3):1638–1647, 2010.

[Ramchurn *et al.*2011] S.D. Ramchurn, P. Vytelingum, A. Rogers, and N.R. Jennings. Agent-Based Homeostatic Control for Green Energy in the Smart Grid. *ACM Trans. on Intelligent Systems and Technology*, 2(4):35, 2011.

[Razavi *et al.*2019] Seyed-Ehsan Razavi, Ehsan Rahimi, Mohammad Sadegh Javadi, Ali Esmaeel Nezhad, Mohamed Lotfi, Miadreza Shafie-khah, and João PS Catalão. Impact of distributed generation on protection and voltage regulation of distribution systems: A review. *Renewable and Sustainable Energy Reviews*, 105:157–167, 2019.

[Rogers *et al.*2012] A. Rogers, SD Ramchurn, and NR Jennings. Delivering the Smart Grid: Challenges for Autonomous Agents and Multi-Agent Systems Research. In *Proc. of the 26th AAAI Conf. on Artificial Intelligence*, pages 2166–2172, 2012.

[Shaheen and El-Sehiemy2020] Abdullah M Shaheen and Ragab A El-Sehiemy. Optimal coordinated allocation of distributed generation units/capacitor banks/voltage regulators by egwa. *IEEE Systems Journal*, 15(1):257–264, 2020.

[Spatti *et al.*2010] D.H. Spatti, I.N. da Silva, W.F. Usida, and R.A. Flauzino. Real-Time Voltage Regulation in Power Distribution System Using Fuzzy Control. *IEEE Trans. on Power Delivery*, 25(2):1112–1123, 2010.

[Team2016] JUNG Development Team. Java universal network/graph framework, 2016.

[Trip *et al.*2018] Sebastian Trip, Michele Cucuzzella, Xiaodong Cheng, and Jacquelien Scherpen. Distributed averaging control for voltage regulation and current sharing in dc microgrids. *IEEE Control Systems Letters*, 3(1):174–179, 2018.

[Ufa *et al.*2022] RA Ufa, YY Malkova, VE Rudnik, MV Andreev, and VA Borisov. A review on distributed generation impacts on electric power system. *International Journal of Hydrogen Energy*, 47(47):20347–20361, 2022.

[Wang *et al.*2019] Licheng Wang, Ruifeng Yan, and Tapan Kumar Saha. Voltage regulation challenges with unbalanced pv integration in low voltage distribution systems and the corresponding solution. *Applied Energy*, 256:113927, 2019.

[Wang *et al.*2020] Shengyi Wang, Jiajun Duan, Di Shi, Chunlei Xu, Haifeng Li, Ruisheng Diao, and Zhiwei Wang. A data-driven multi-agent autonomous voltage control framework using deep reinforcement learning. *IEEE Transactions on Power Systems*, 35(6):4644–4654, 2020.

[Wang *et al.*2021] Jianhong Wang, Wangkun Xu, Yunjie Gu, Wenbin Song, and Tim C Green. Multi-agent reinforcement learning for active voltage control on power distribution networks. *Advances in Neural Information Processing Systems*, 34:3271–3284, 2021.

[Wang *et al.*2022] Rui Wang, Dazhong Ma, Ming-Jia Li, Qiuye Sun, Huaguang Zhang, and Peng Wang. Accurate current sharing and voltage regulation in hybrid wind/solar systems: an adaptive dynamic programming approach. *IEEE Transactions on Consumer Electronics*, 68(3):261–272, 2022.

[Yu *et al.*2012] L. Yu, D. Czarkowski, and F. de León. Optimal Distributed Voltage Regulation for Secondary Networks with DGs. *IEEE Trans. on Smart Grid*, 3(2):959–967, 2012.

[Zhou *et al.*2019] Mike Zhou, Jianfeng Yan, and Donghao Feng. Digital twin framework and its application to power grid online analysis. *CSEE Journal of Power and Energy Systems*, 5(3):391–398, 2019.