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Distributed multi-agent scheme for reactive power management with renewable energy

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ABSTRACT

This paper presents a new distributed multi-agent scheme for reactive power management in smart coordinated distribution networks with renewable energy sources (RESs) to enhance the dynamic voltage stability, which is mainly based on controlling distributed static synchronous compensators (DSTATCOMs). The proposed control scheme is incorporated in a multi-agent framework where the intelligent agents simultaneously coordinate with each other and represent various physical models to provide information and energy flow among different physical processes. The reactive power is estimated from the topology of distribution networks and with this information, necessary control actions are performed through the proposed proportional integral (PI) controller. The performance of the proposed scheme is evaluated on a 8-bus distribution network under various operating conditions. The performance of the proposed scheme is validated through simulation results and these results are compared to that of conventional PI-based DSTATCOM control scheme. From simulation results, it is found that the distributed MAS provides excellence performance for improving voltage profiles by managing reactive power in a smarter way.

1. Introduction

Energy distribution networks are usually passive networks in which both real and reactive power always flow from medium to lower voltage levels. In recent years, the integration of renewable energy sources (RESs) has attracted a great deal of interest due to potential environmental and economic factors. The integration of RESs into the distribution networks adds new dynamic elements due to the variabilities and inherent uncertainties in the operation of RESs. The integration of wind energy generation poses a major challenge to the power industry due to the intermittent nature of wind [1]. Presently, 30 percent of the installed wind power is still being produced by induction generator (IG)-based wind turbines (WTs) which are directly connected to the grid as distributed generation (DG) and operate at an almost fixed-speed [2]. Therefore, it is extremely important to export some reactive power to the systems to maintain voltage profile since the IG requires a source of reactive power for its operation. The lack of reactive power support can reduce the energy transfer capability from the source to the load [3,4]. Therefore, it is essential to manage the reactive power in an efficient way in order to maintain the dynamic voltage stability of distribution networks and this can be achieved by using an intelligent control scheme in a distributed multi-agent system (MAS) framework.

The reactive power control plays an important role in maintaining the voltage profile within specified limits and can be achieved through the dynamic compensating devices. Traditionally, shunt capacitors have been employed for reactive power compensation [5] but, in the case of variable loads and a high penetration of RESs, a fixed capacitor bank may often lead to either over or under compensation. Moreover, it cannot ensure dynamic voltage recovery during low voltage (LV) conditions due to the drop in VAr supports [6]. With the growing energy ratings obtained by solid-state devices, the static synchronous compensator (STATCOM) has emerged as one of the new generation of power electronic-based shunt flexible AC transmission system (FACTS) devices [7–9]. STATCOMs connected to distribution networks are commonly known as distribution or distributed STATCOMs (DSTATCOMs) and are widely used to regulate the line voltage at the point of common coupling (PCC) by providing appropriate reactive power support.

A variety of control approaches is proposed for reactive power control with most of those involves traditional control techniques.

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0196-8904/

There are a few MAS-based approaches for energy management with RESs discussed in [10–15] and recent research studies indicate that a few agent-based techniques have been used for reactive power management. A multi-agent approach for reactive power management with coordinated voltage control strategy is proposed in [16–18] using a set of multi-objective functions. A paradigm of distributed agent-based reactive power control scheme with shunt compensation using PI controller is discussed in [19–21] for voltage regulation. In [22,23], a multi-agent based coordinated approach for secondary voltage control with reactive power management using STATCOM is provided. Also, a few more studies based on reactive power management using multi-agent frameworks can be found in [24].

Though all approaches [10–23] so far discussed in this paper are surely functional, but there is no clear indication about the estimation of reactive power. However, the estimation of reactive power is a key issue which cannot be neglected as it is essential for initiating the control actions [25]. Moreover, the approaches [10–23] do not exploit how the controller will respond for estimating reactive power by adopting to changes in the operating conditions of the system and tuning the PI controller gain based on this estimated information. This is the motivation for using a distributed MAS in which an agent-based control method ensures fast and desired responses through communication to maintain voltage stability with proper estimation of reactive power under various operating conditions.

The main focus of this paper is to design a distributed multi-agent scheme for reactive power management with wind power generation to maintain dynamic voltage stability. It is mainly based on designing a PI controller for a DSTATCOM to control both the DC-link voltage and reactive current. In this MAS, each intelligent agent represents a specific physical device model with a particular definition which performs a set of specific tasks to enhance the voltage stability. When a disturbance, e.g., fault, occurs in a distribution system, the agents estimate the required amount of reactive power for the system and use this information to determine the control objectives for the DSTATCOM controller. In this paper, the gains of the proposed agent-based PI controller are tuned using the well-known Ziegler–Nichols (Z–N) method where the gain parameters can be adjusted to track the reference values. The chosen control objectives are the DC-link capacitor voltage and reactive power. The performance of the designed scheme is demonstrated on an 8-bus test distribution network under various operating conditions, such as faults, different wind energy penetration levels and change in wind speeds, to ensure dynamic voltage stability within the energy distribution network.

The rest of the paper is organized as follows: Section 2 presents the distributed MAS architecture for distribution systems; Individual activity of each intelligent agent is presented in Section 3; Section 4 discusses the performance evaluation through simulation results; and finally, the paper is concluded with a brief remark in Section 5.

2. Distributed multi-agent framework for reactive power management

The MAS is a group of multiple interacting distributed intelligent agents within an environment. The autonomous agents can act in response to physical events in the surrounding environment by exerting independent control actions over the physical models. This MAS provides an effective platform for modeling autonomous decision-making entities for power grid operation [26,27]. In power systems, physical devices, such as DG units, control equipments, loads and transformers, are installed in a distributed manner throughout the entire network which is well suited for MAS. A general architecture of an agent-based distribution energy system is shown in Fig. 1. In this figure, the DS stands for the distribution substation, V_S and V_R are the sending end and receiving end voltage, respectively, $P$and Q the real and reactive power, respectively, which are flowing through the distribution network to the customer, i.e., the quantities supplied from the DS, and P_L and Q_L the real and reactive power consumed by loads, respectively. In distributed multi-agent framework as shown in Fig. 1, different nodes within the physical models of the power system are considered as different agents. These agents simultaneously work together to flexibly estimate the necessary information by gathering all local measurements and share those information with each other within the MAS environment to implement the control actions over the physical devices.

In the distributed MAS as shown in Fig. 1, the Dynamic Node (DN) agent captures the information of the DG unit connected to DSs, whereas the ZIP (Z-impedance, I-constant current, P-constant power) Node (ZIPN) agent gathers real and reactive power load information. The Root Node (RN) agent comprises of PMUs for monitoring, measuring and estimating purposes and finally, the agent embedded within the DSTATCOM control equipment is considered as the control agent which uses a PI controller to meet the desired control objectives. In this distributed multi-agent framework, the group of node agents associated with the physical device model are represented as an individual subsystem. Each subsystem is connected physically with each other as well as through communication provided by agents. In this paper, it is assumed that the smart distribution system already has necessary communication network superimposed on the physical network layer which is also valid for practical implementation as a practical system has high-speed wireless or fiber optic communication facilities. As the designed distributed MAS is the collection of several intelligent agents, each agent is individually responsible for performing some specific or a set of specific tasks. The details of all agents along with their activities have been discussed in the following section with an aim to enhance the voltage stability of distribution networks with proper reactive power management.

3. Individual role of intelligent agents

3.1. Activities of DN agent

In this paper, the DN agent is designed to capture the dynamics of the generators connected to the power systems. The generators are considered as wind farm-based IGs, the characteristics of which change depending on the intermittent nature of wind. Dynamic models of such wind farm-based generators are essential in order to adapt their changing characteristics using DN agent which provide its generated information to the RN agent for an actual wind energy generation count. The wind farm model considered in this paper is the fixed speed wind turbine (FSWT) model connected to the IG and their relevant modeling can be found in [28–30].

3.2. Activities of ZIPN agent

The ZIPN agent is designed to collect the aggregated load data and share this information with RN agents. The static load model is considered to represent this agent which can be described by the following equations [31]

$$\begin{aligned} P_L &= P_0\left(\frac{V}{V_0}\right)^{\alpha} \\ Q_L &= Q_0\left(\frac{V}{V_0}\right)^{\beta} \end{aligned} \tag{1}$$

where P_0 and Q_0 are the real and reactive power consumed at the reference voltage V_0, respectively. The exponents α and β depend on the type of loads, e.g., $\alpha = \beta = 0$ for constant power load models,

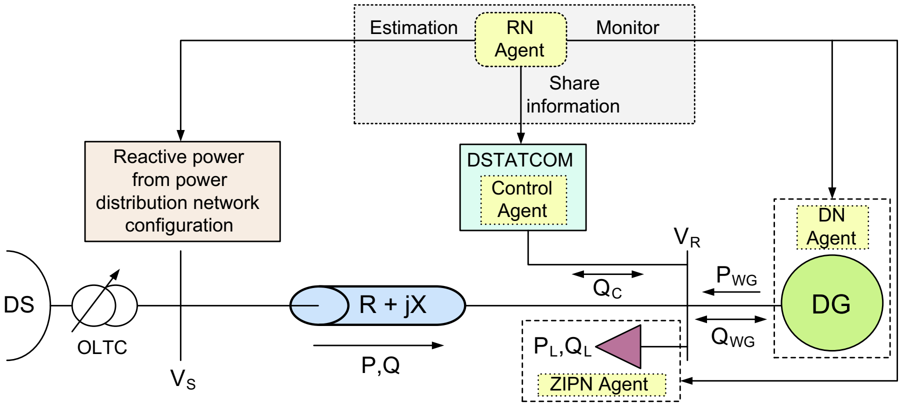

Fig. 1. Distributed multi-agent framework for distribution systems.

$\alpha = \beta = 1$ for constant current load models, and $\alpha = \beta = 2$ for constant impedance load models. The real and reactive power characteristics of composite ZIP load models are given by [32]

$$\begin{aligned} P_L &= P_0\left[a_p\left(\frac{V}{V_0}\right)^2 + b_p\left(\frac{V}{V_0}\right) + c_p\right] \\ Q_L &= Q_0\left[a_q\left(\frac{V}{V_0}\right)^2 + b_q\left(\frac{V}{V_0}\right) + c_q\right] \end{aligned} \tag{2}$$

where the coefficients a_p, b_p, c_p, a_q, b_q and c_q are the parameters of the model which define the proportion of each component, respectively.

3.3. Activities of RN agent

The RN agent monitors the overall network condition based on the information obtained from the DN agent as well as ZIPN agents and process all these local information. The RN agent is also responsible for estimating required amount of reactive power for maintaining the voltage stability of the distribution network. Finally, it shares this information with the DSTATCOM controller agent for controlling the reactive power to ensure the voltage stability. The RN agent mainly performs two major activities-dynamic adaptability and reactive power estimation. In the following, these activities are discussed in details.

3.3.1. Activity 1: dynamic adaptability

To check the actual wind energy penetration into the grid, the RN agent continuously monitors the present wind energy (P_{WG}) by taking information from DN agents. If the present wind energy penetration (P_{WG}) from the DN agent is the same as the nominal wind energy (P_{WG}^0) extracted from the wind turbine, the RN agent uses this information to estimate the reactive power since this parameter has changed due to change in wind energy penetration level. If the wind energy penetration level changes, i.e., there is a new wind energy penetration (P'_{WG}), it can be dynamically adapted by comparing the present wind power generation with the nominal one according to the following logic.

$$\begin{aligned} &P_{WG} = P_{WG}^{\circ}(\text{for normal operation}) \\ &\text{if } P_{WG} > P_{WG}^{\circ} \text{ and } P_{WG} < P_{WG}^{\circ}(P_{WG}^{\circ} \pm \% \text{ penetration level change}) \\ &P'_{WG} = P_{WG}(\text{for new penetration level}) \\ &\text{else } P_{WG} = P_{WG}^{\circ} \end{aligned}$$

where P_{WG}^0 is the initial wind energy generation extracted from the wind turbine. Based on the actual wind energy integration, RN agent estimates the reactive power and shares this information to the controller agent to implement the control action.

3.3.2. Activity 2: reactive power estimation

The reactive power estimator within the RN agent is designed in such a way that the RN agent can assess the situation on the basis of the measurements from sensing devices, i.e., PMUs, and information from other entities, such as DN and ZIPN agents and send the proper data to the DSTATCOM control agent.

If the sending end bus voltage of the system shown in Fig. 1 is considered as the base voltage with phase angle assumed to be zero, the voltage variation formula (per unit) for a distribution network with DG can be written as [25,33]

$$\Delta V = RP + XQ = R(P_{WG} - P_L) + X(\pm Q_{WG} - Q_L \pm Q_C) \tag{3}$$

This equation is commonly known as the voltage variation formula, where P_{WG} is the active power supplied by a DG unit which is always positive, Q_{WG} the reactive power supplied by a DG unit which can be positive or negative depending on the type of DG, and Q_C the reactive power of the compensator which can be positive or negative.

In Eq. (16), it can be seen that the compensator, i.e., DSTATCOM, may either supply or absorb reactive power to ensure dynamic voltage stability. Since an IG based FSWT is considered as DG, in such case, the DG unit absorbs reactive power and Eq. (3) can be written as

$$\Delta V = R(P_{WG} - P_L) + X(-Q_{WG} - Q_L \pm Q_C) \tag{4}$$

The RN agent first monitors the system voltage of the network and if it determines that it is within the specified limits of ±6 percent, shares this information with the DSTATCOM controller agent which will not take any action. However, when the voltage profile exceeds the permissible limits, the RN agent estimates the necessary reactive power using Eq. (3) and sends this information to the DSTATCOM controller agent to take the necessary action to avoid violation of the voltage profiles. The proposed control scheme is discussed in the following subsection.

3.4. Activities of control agent

3.4.1. DSTATCOM model

The structure of a six-pulse pulse width modulation (PWM) generator-based DSTATCOM connected to the PCC of a distribution network is shown in Fig. 2. In order to design a DSTATCOM controller, a dynamic model of it can be obtained by applying the electrical network theory to Fig. 2 as

$$\begin{aligned} \dot{i}_a &= -\tfrac{R}{L} i_a + \tfrac{1}{L}(v_a - e_a) \\ \dot{i}_b &= -\tfrac{R}{L} i_b + \tfrac{1}{L}(v_b - e_b) \\ \dot{i}_c &= -\tfrac{R}{L} i_c + \tfrac{1}{L}(v_c - e_c) \end{aligned} \tag{5}$$

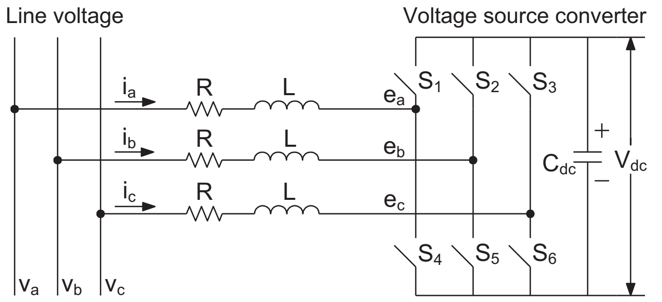

Fig. 2. DSTATCOM connected to distribution system.

where, R is the inverter and transformer conduction losses, L the equivalent inductance of the transformer and filter; i_a, i_b and i_c are AC currents of DSTATCOM; v_a, v_b and v_c are line voltages; and e_a, e_b and e_c are the inverter output voltage. As the DSTATCOM model presented by the above equations is time-variant for a balanced three-phase system, it can be transformed into a synchronously rotating time-invariant dq-frame through the park transformation as [7]

$$\begin{aligned} \dot{I}_d &= -\tfrac{R}{L}I_d + \omega I_q + \tfrac{1}{L}(V_d - E_d) \\ \dot{I}_q &= -\omega I_d - \tfrac{R}{L}I_q + \tfrac{1}{L}(V_q - E_q) \end{aligned} \tag{6}$$

where I_d and I_q are the dq-frame AC currents, V_d and V_q the dq-frame line voltages, $\omega = \frac{d\theta}{dt}$ the angular frequency and it is considered that the system of reference dq-frame rotates at the same speed and θ the angle through which the d-axis leads the magnetic axis of phase-a winding which is obtained using the phase-locked loop (PLL) technique as presented in [34].

Since a PWM technique is used in the DSTATCOM and harmonics produced by the inverter are neglected, the equations relating AC-side and DC-side can be written as

$$\begin{aligned} E_d &= M_d v_{dc} \\ E_q &= M_q v_{dc} \end{aligned} \tag{7}$$

where $M_d = M\cos\alpha$ and $M_q = M\sin\alpha$ are the input switching signals, v_{dc} the voltage across the capacitor (C_{dc}), M the modulation index, and α the switching function of DSTATCOM that describes its turn-on and turn-off capabilities, with M and α the control variables of the DSTATCOM which can be written as

$$\begin{aligned} M &= \frac{\sqrt{E_d^2 + E_q^2}}{v_{dc}} \\ \alpha &= tan^{-1}\left(\frac{E_q}{E_d}\right) \end{aligned} \tag{8}$$

The power balance equation for the inverter can be written as

$$P = v_{dc}C_{dc}\frac{dv_{dc}}{dt} \tag{9}$$

Now Eq. (9) can be simplified as

$$\dot{v}_{dc} = \frac{1}{C}(M_d I_d + M_q I_q) \tag{10}$$

where $C = \frac{2}{3}C_{dc}$. Therefore, the set of complete nonlinear mathematical equations of DSTATCOM due to switching functions can be written as

$$\begin{aligned} \dot{I}_d &= -\tfrac{R}{L}I_d + \omega I_q + \tfrac{1}{L}(V_d - M_d v_{dc}) \\ \dot{I}_q &= -\omega I_d - \tfrac{R}{L}I_q + \tfrac{1}{L}(V_q - M_q v_{dc}) \\ \dot{v}_{dc} &= \tfrac{1}{C}(M_d I_d + M_q I_q) \end{aligned} \tag{11}$$

The real and reactive power equations can be written as

$$\begin{aligned} P &= \tfrac{3}{2}(E_d I_d + E_q I_q) \\ Q &= \tfrac{3}{2}(E_d I_q - E_q I_d) \end{aligned} \tag{12}$$

Now if θ is chosen as zero, then

$$E_q = 0, \quad \text{and} \quad Q = \frac{3}{2}E_d I_q \tag{13}$$

Therefore, to control the current I_q, it is sufficient to control reactive power Q which is compensated by regulating the DC voltage v_{dc}. If the estimated reactive power is considered as a reference power Q_{ref}, to improve the voltage profile of a distribution network, the reference current can be calculated from Eq. (13) as

$$I_{qref} = \frac{2}{3}\frac{Q_{ref}}{E_d} \tag{14}$$

From Eq. (24), it is seen that I_{qref} can be zero only when Q_{ref} is zero which means that, when the amount of reactive power required from a DSTATCOM is zero, the controller agent will not take any control action. Using the reference current from Eq. (14), the reference DC voltage v_{dcref} can be written as

$$v_{dcref} = V_d + RI_{qref} + \omega LI_{qref} \tag{15}$$

3.4.2. Controller design algorithm

In this paper, the control agent is used to track the reference output and the reference value is calculated from the reactive power estimated by the RN agent so they can be automatically updated according to changes in system conditions. The detailed block diagram of a PI controller for controlling DSTATCOMs is shown in Fig. 3. The DC bus voltage and reactive power are measured and compared with the reference values while the d-axis and q-axis currents are obtained from the errors through the DC voltage and reactive power control loops, with the current control loop taking the current command and generating appropriate firing pulses. To compensate the coupling effect of the dq-axes currents, a factor of L is cross-linked in the current control loop. In the control block diagram as shown in Fig. 3, a remarkable point is that the DC bus voltage (v_{dc}) and reactive power (Q) are totally decoupled due to the abc-to-dq transformation.

In a traditional DSTATCOM, the value of I_{qref} can be found from the measured voltage (V_m) and reference voltage (V_{ref}) through a PI control scheme shown in Fig. 4 whereas, it is obtained from reactive power control loop using Q_{ref} in the proposed MAS-based scheme. This reference value (Q_{ref}) make the proposed MAS-based control scheme different from the conventional control scheme.

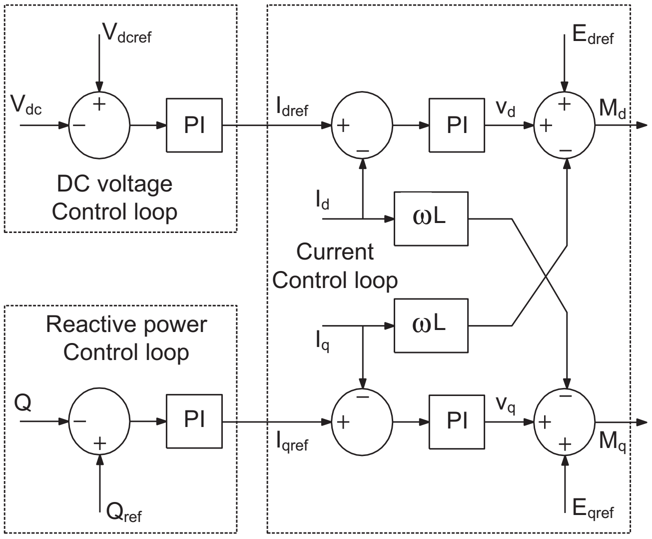

Fig. 3. dq-frame PI control block diagram of DSTATCOM.

The typical equation of the agent-based PI controller is given as [35,36]

$$u(t) = K_p\left[e(t) + \frac{1}{T_i}\int_0^t e(\tau)d\tau\right] \tag{16}$$

where K_p and T_i are the parameters of the PI controller.

In terms of the Laplace transformation, Eq. (16) can be written as

$$U(s) = K_p\left[1 + \frac{1}{T_i s}\right]E(s) = \left[K_p + \frac{K_i}{s}\right]E(s) \tag{17}$$

where $e(t)$ is the system error, $K_i = \frac{K_p}{T_i}$, and $u(t)$ is the controller output. The controller gains need to be selected in such a way that the error is minimized very quickly.

Since the performance of the DSTATCOM depends on the proper tuning of controller parameters, the gains of the PI controller are tuned using Z–N tuning method which is a widely used practical method to tune the controller parameters [37–39]. The parameter tuning according to this method can be demonstrated by the following steps

- Considering $T_i = \infty$ and increasing K_p from 0 to the critical gain (K_{cr}) where the closed-loop system becomes marginally stable, i.e., the output exhibits sustained oscillations.
- The corresponding period of oscillation T_{cr} with a crossover frequency ω_{cr} is determined at the critical gain.
- The recommended values of K_p and T_i are found to be $K_p = 0.4\,K_{\mathrm{cr}}$ and $T_i = 0.8T_{\mathrm{cr}}$.

Thus, the gain of the PI controller can be written as

$$G_{\mathrm{PI}}(s) = 0.4K_{\mathrm{cr}}\left[1 + \frac{1}{0.8T_{\mathrm{cr}}}\right] \tag{18}$$

In the control agent, this PI controller is used to maintain the dynamic voltage profile of distribution networks with RESs. The flow-chart which reflects the whole design procedure is shown in Fig. 5. The performance of the proposed scheme is evaluated in the following section.

4. Performance evaluation of distributed MAS

In order to evaluate the effectiveness of the proposed distributed MAS approach, a 8-bus distribution network as shown in Fig. 6 is considered. It operates at 25 kV/50 Hz and includes IG-based wind farm units connected at bus-3 and bus-5 with nominal capacities of 6 MW. A DS with rating of 1000 MVA, 120 kV is connected at bus-1 and electrical loads at bus-7 and bus-8. The total real and reactive power loads on the system are $P_L = 5.5$ MW and $Q_L = 1.2$ MVAr, respectively. The system data are also given in the Appendix of this paper. Bus-2 is the PCC at which all DG units, the DS and loads are connected through transformer and distribution lines. In this system, the RESs have excess active power which can be exported to the main grid after supplying the loads connected to the distribution network. In fact, in this operating condition, it is essential to provide additional reactive power to the system since the induction generator consumes reactive power. To maintain the voltage profile within the specified level, a DSTATCOM is connected at bus-2 to support this reactive power.

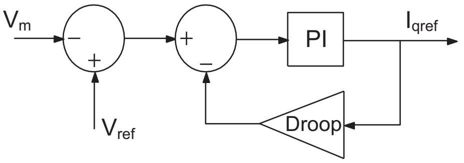

Fig. 4. PI control block diagram for obtaining I_{qref} value in conventional DSTATCOM.

When a large fault, for example, a three-phase short-circuit fault occurs, the transfer of energy from DG units to the distribution system is considerably hampered and the voltage profile of the system is adversely affected. In fact, if the fault persists for a long time, the system undergoes voltage instability. In such a situation, it is essential to maintain the specified voltage profile at the PCC for the stable operation of the distribution network. This can be achieved by the reactive power being either absorbed from or released to the system through the DSTATCOM at the time required. The designed scheme undertakes these tasks efficiently whose performance is evaluated by applying three-phase short-circuit faults at PCC under different cases. In this paper the following three cases are considered:

- performance evaluation for fault at PCC with nominal wind power capacity;
- performance evaluation for fault at PCC with increased wind power penetration;
- performance evaluation for change in wind speed;

Finally, the performance of the distributed MAS is validated by a comparison with a conventional PI-based DSTATCOM without MAS connected at the PCC.

4.1. Case-1: performance evaluation for fault at PCC with nominal wind power capacity

During the normal operation of a distribution energy network, the agents do not take any action other than continuously monitoring activities. When a three-phase short-circuit fault occurs at the PCC, as the generator does not supply any power to the system until the fault is cleared, the DS needs to do so in order to meet the load demand. The amount of active power supplied by the DS is the difference between the load demand and power supplied by the wind farm units. If the amount of reactive power supplied by the DS is higher than the load requirement, it is essential for the excess to be absorbed by the DSTATCOM; otherwise, the DSTATCOM will supply reactive power to the distribution system.

The following fault sequence is considered to evaluate the performance of the proposed scheme for a fault applied at bus-2:

- fault occurs at $t = 5$ s; and
- fault is cleared at $t = 5.1$ s (6-cycle fault).

Under normal operating conditions with a nominal wind energy generation, i.e., up to $t = 5.0$ s, the agent-based DSTATCOM supplies reactive power to maintain the specified voltage profile at the PCC. As a matter of fact, during the fault condition, the DS supplies both real and reactive powers, with the former sufficient but the latter insufficient to meet the load demand. In such a case, the post-fault voltage is different from the pre-fault steady-state voltage if the DSTATCOM is unable to provide some extra reactive power. Consequently, sometimes the system voltage will fluctuate and it can take a few seconds to a few minutes for it to settle down to its steady-state value or the system may even become unstable. The extra amount of power required is estimated by the RN agent which shares this information with the controller agent to manage the reactive power through DSTATCOM. As a result, a similar pre-fault and post-fault steady-state can easily be obtained.

The reactive power support provided by the agent-based DSTATCOM is shown in Fig. 7 (green solid line) in which it can be seen that the DSTATCOM supplies some reactive power during the pre-fault condition. Then, when a fault occurs at $t = 5.0$ s at the PCC, as the reactive power provided by the main DS is not sufficient, the MAS-based DSTATCOM supplies additional reactive power during the faulted condition which is also seen from

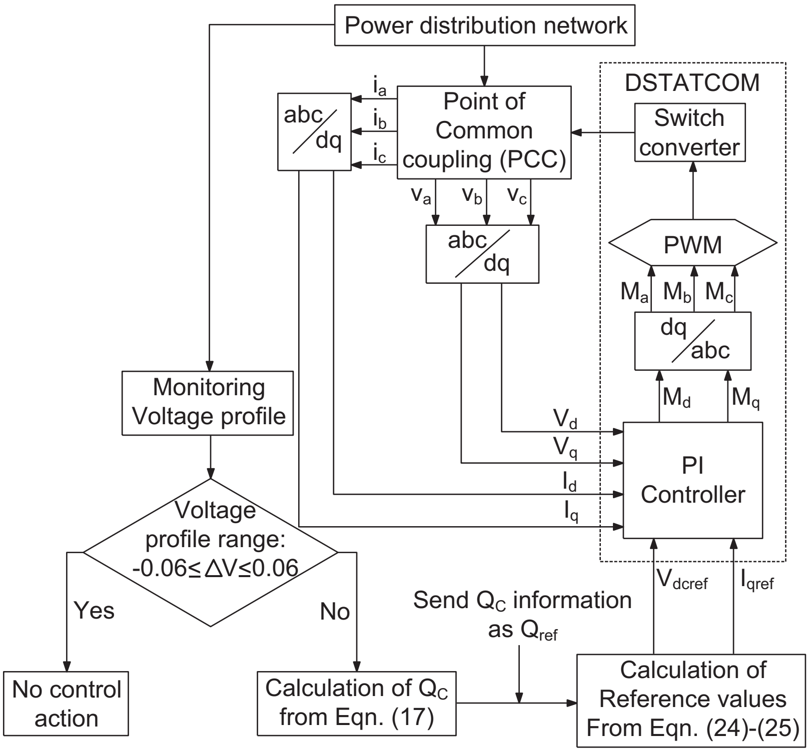

Fig. 5. DSTATCOM controller for reactive power control.

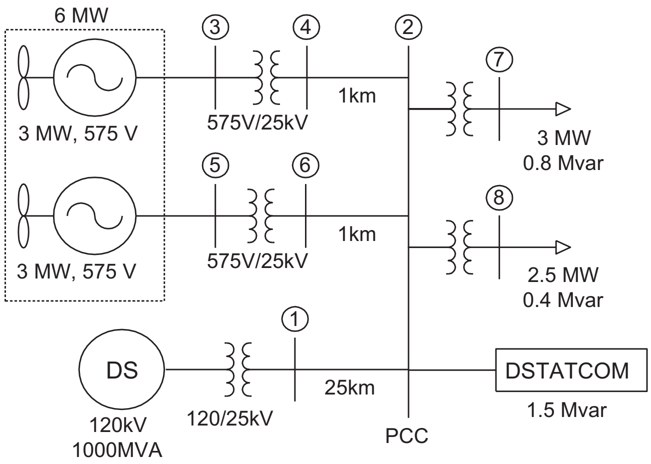

Fig. 6. Single-line diagram of 8-bus distribution network with DG units.

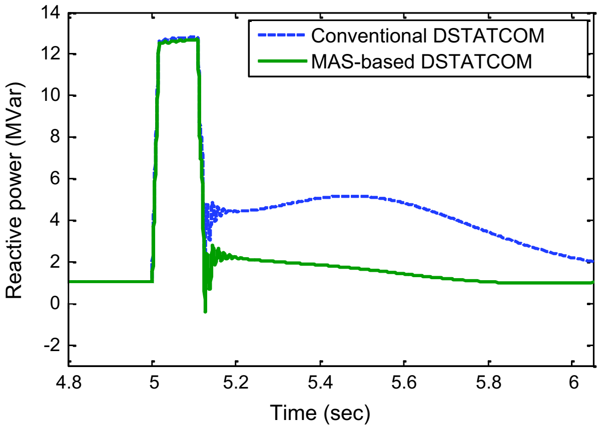

Fig. 7. Reactive power for nominal wind energy (green solid line presents proposed MAS-based approach and blue dashed line presents conventional approach). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 6. The corresponding voltage profile at the PCC in Fig. 8 (green solid line) shows that it is stable during the pre-fault and post-fault periods. All operations are performed in a smarter way based on the information exchanged by the various agents.

Now, if a conventional PI-based DSTACOM without any communication and coordination is placed at the PCC, it can be seen that it supplies the required amount of reactive power to the system until $t = 5.0$ s and settles down much more slowly as compared to the agent-based DSTATCOM controller during the post-fault condition, as shown in Fig. 7(blue dashed line). The voltage profile of the system is also shown in Fig. 8(blue dashed line) in which it can be seen that the post-fault voltage recovers more slowly using conventional DSTATCOM than that using the agent-based DSTATCOM controller due to the lack of information exchange among the physical components of the distribution system. From Figs. 7 and 8, it is clear that the proposed MAS approach with DSTATCOM performs better than the conventional DSTATCOM.

The difference between the conventional and proposed controller can be also seen from the bode diagram of the system response. Figs. 9 and 10 present the bode plots of log gain and phase against frequency for the proposed MAS-based DSTATCOM controller and conventional DSTATCOM controller without MAS, respectively. The gain margin of the proposed approach is found 96.1 dB and that of conventional approach is 55.5 dB, which determines that the MAS-based DSTATCOM is more robust and perform much better than the conventional PI-based DSTATCOM.

The PI controller gains, i.e., values of K_p and K_i along with the voltage recovery times for both proposed and conventional control approaches are shown in Table 1.

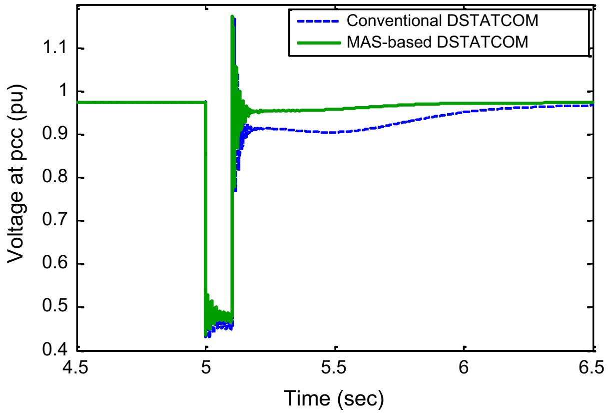

Fig. 8. Voltage profile at PCC for nominal wind energy (green solid line presents proposed MAS-based approach and blue dashed line presents conventional approach). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

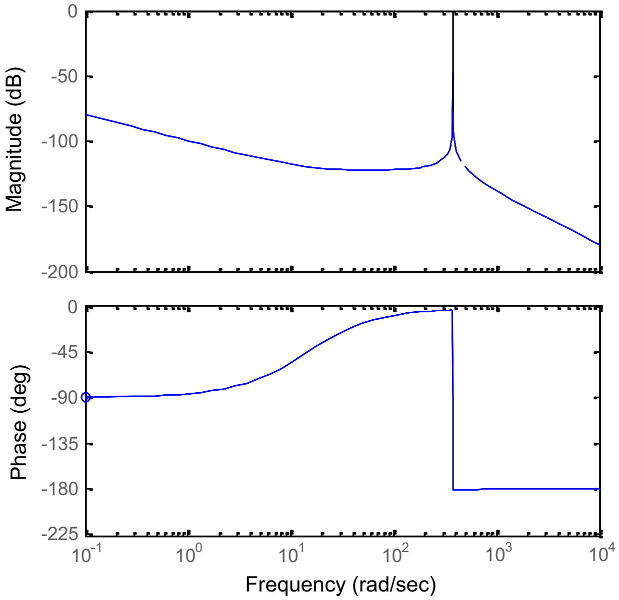

Fig. 9. Bode diagram for MAS-based DSTATCOM control.

4.2. Case-2: performance evaluation for fault at PCC with increased wind energy penetration

The same analysis is conducted for a three-phase fault at 5 s at bus-2 for an increased wind energy penetration level. Since the voltage stability of a distribution system with a large amount of wind energy penetration has recently become a major concern, the impact of growing wind generation on transient voltage stability is dynamically evaluated by increasing the penetration level from 6 MW to 7 MW, i.e., by 16.7 percent. Therefore, a new estimation of the reactive power is required each time the system operating condition changes which can be dynamically achieved by the RN agent taking information from the other agents.

Now if the wind power penetration is increased by 16.7 percent, the RN agent obtains this information from the DN agent and also estimates the reactive power for this operating condition. Once this information is obtained, the RN agent shares it with the controller agent which acts to control the reactive power through the DSTATCOM. It is shown in Fig. 11(green solid line) that the MAS-based DSTATCOM supplies some reactive power for the new operating condition of the system for which the voltage profile at the PCC is shown in Fig. 12(green solid line). It can be seen that it is improved due to the correct regulation of the reactive power and DC voltage across the capacitor. The proposed approach is also compared with the conventional approach with DSTATCOM for this new operating condition.

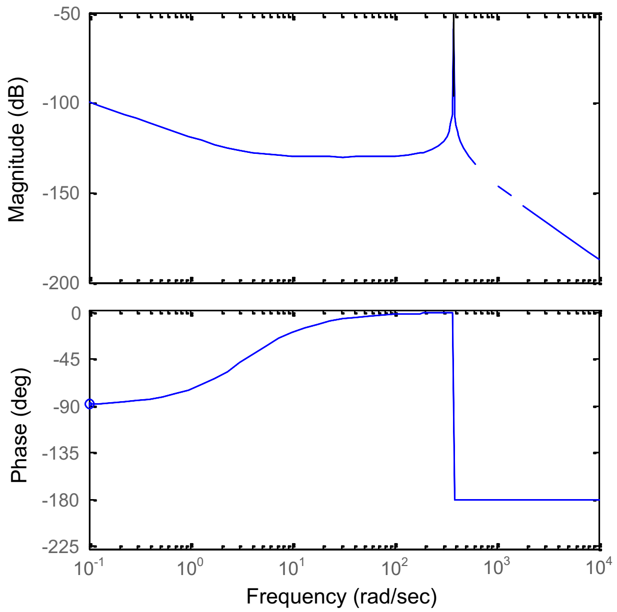

Fig. 10. Bode diagram for conventional DSTATCOM control.

Table 1
PI gains and voltage recovery times of both control approaches.

Parameters	Conventional approach	Proposed approach
K_p1	0.0001	0.0040
K_p2	0.300	0.710
K_i1	0.020	0.029
K_i2	10.0	7.0
Voltage recovery times (sec)	0.9	1.5

4.3. Case-3: performance evaluation for change in wind speed

When the IG is subjected to sudden rise in speed, both active and reactive powers increases consequently. To ensure a stable

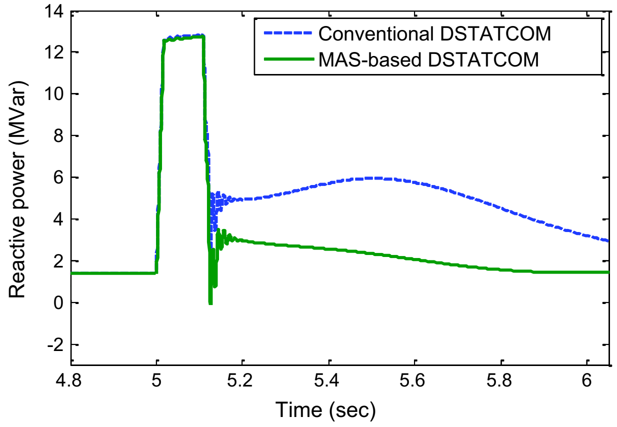

Fig. 11. Reactive power for increasing wind energy (green solid line presents proposed MAS-based approach and blue dashed line presents conventional approach). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

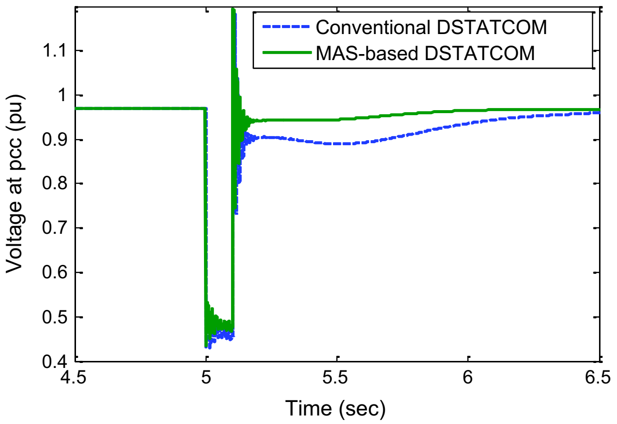

Fig. 12. Voltage profile at PCC for increasing wind energy (green solid line presents proposed MAS-based approach and blue dashed line presents conventional approach). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

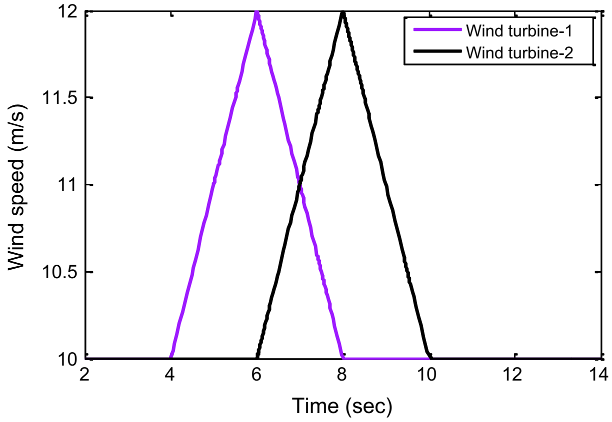

Fig. 13. Wind speed variation.

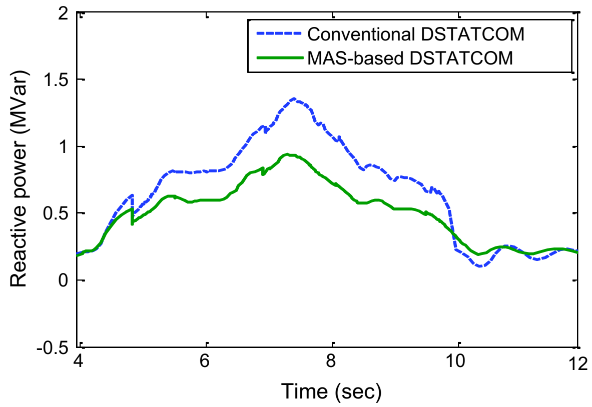

Fig. 14. Reactive power support for change in wind speed (green solid line presents proposed MAS-based approach and blue dashed line presents conventional approach). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

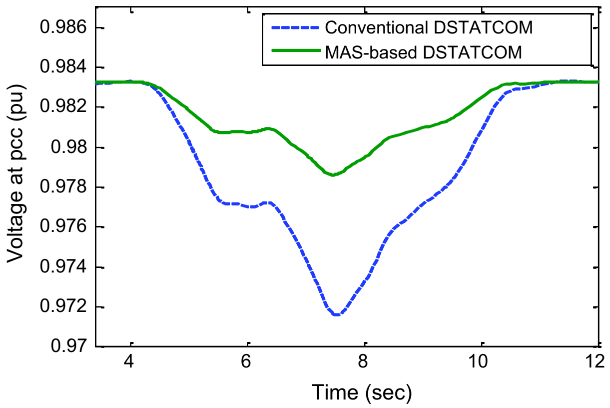

Fig. 15. Voltage profile at PCC for change in wind speed (green solid line presents proposed MAS-based approach and blue dashed line presents conventional approach). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

response to this sudden change in speed variations, an adequate reactive power supports need to be provided which can be achieved by the proposed approach. A simulation is conducted in which the initial wind speed applied to each WT is 10 m/s. For WT1, wind speed is 10 m/s for 4 s and after that wind speed ramped to 12 ms during 2 s. The wind speed is again ramped down to 10 m/s during 2 s and the WT2 has the same speed characteristics with 2 s time delay. The applied wind speed variation with time used in this case study is shown in Fig. 13. The deigned MAS-based DSTATCOM controller increases the reactive power supply to keep the stable voltage profile which can be seen in Figs. 14 and 15(green solid line), respectively, and it can be seen that the proposed scheme performs much better than conventional DSTATCOM by maintaining a good voltage profile.

From the above case studies, it is obvious that the designed distributed multi-agent scheme enhances the dynamic voltage stability of distribution networks with RESs by controlling reactive power in a more superior and smarter way than the conventional approach under various operating conditions.

5. Conclusion

The designed distributed multi-agent infrastructure for reactive power management maintains the voltage profiles of distribution networks with RESs under various operating conditions. To implement this scheme, the designed agent-based controller with a DSTATCOM model gathers information of the reactive power estimation to meet the control objectives. Different scenarios are considered to investigate the effectiveness of the designed scheme and from the simulation results, it is clear that the designed scheme provides consistently better performances under major disturbances as compared to the conventional approach in terms of damping, settling time, oscillations and overshoots, thereby reflecting its superiority. Although the proposed methodology is discussed for FSWTs, it is applicable to any other generators connected to distribution networks. Future work will deal with the consideration of different types of RESs and the design of nonlinear controller within the multi-agent platform.

Appendix A

The total system components of distribution system used for simulations are given below:

Network parameter:

Base voltage = 25 kV, frequency = 50 Hz.

Wind farm-based induction generator parameters (WT1 and WT2):

Power = 3 MW, voltage = 575 V, wind speed = 10 m/s, stator resistance, $R_s = 0.004843$ pu, stator reactance, $X_{ls} = 0.1248$ pu, rotor resistance, $R_r = 0.004377$ pu, rotor reactance, $X_{lr} = 0.1791$ pu.

Transmission line parameters:

Line-1 and Line-2 = 1 km, $r1 = 0.1153\ \Omega/\text{km}$, $r0 = 0.413\ \Omega/\text{km}$, $l1 = 1.05$ mH/km, $l0 = 3.32$ mH/km, Line-3 = 25 km, $r1 = 0.1153\ \Omega/\text{km}$, $r0 = 0.413\ \Omega/\text{km}$, $l1 = 1.05$ mH/km, $l0 = 3.32$ mH/km.

Load parameters:

Load-1 = 3 MW, 0.8 MVAr

Load-2 = 2.5 MW, 0.4 MVAr

DSTATCOM parameters:

Capacity = 1.5 MVA, $V_{DC} = 4$ kV, $C_{DC} = 375\ \mu\text{F}$, $Z_{converter} = 0.007 + j0.22$ pu.

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