Energy Conversion and Management 88 (2014) 573–581

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

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

M.S. Rahman [a,*], M.A. Mahmud [b], H.R. Pota [a], M.J. Hossain [c]

[a] School of Engineering & Information Technology, The University of New South Wales, Canberra, ACT 2610, Australia
[b] School of Software and Electrical Engineering, Swinburne University of Technology, Hawthorn, VIC 3122, Australia
[c] Griffith School of Engineering, Griffith University, Gold Coast, QLD 4222, Australia

ARTICLE INFO

Article history:
Received 15 June 2014
Accepted 1 September 2014
Available online 20 September 2014

Keywords:
Multi-agent system
Smart distribution network
Reactive power
Voltage stability
PI control
DSTATCOM

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.

* Corresponding author. Tel.: +61 2 6268 8015.
E-mail address: md.rahman3@student.adfa.edu.au (M.S. Rahman).

http://dx.doi.org/10.1016/j.enconman.2014.09.002
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]

$$P_L = P_0\left(\frac{V}{V_0}\right)^{\alpha}$$
$$Q_L = Q_0\left(\frac{V}{V_0}\right)^{\beta} \qquad (1)$$

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,