Electric Power Systems Research 102 (2013) 1–7

Contents lists available at SciVerse ScienceDirect

Electric Power Systems Research

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

Implementing agent-based emissions trading for controlling Virtual Power Plant emissions

Spyros Skarvelis-Kazakos[a,*], Evangelos Rikos[b], Efstathia Kolentini[c], Liana M. Cipcigan[d], Nick Jenkins[d]

[a] School of Engineering, University of Greenwich, Central Avenue, ME4 4TB Chatham Maritime, Kent, United Kingdom
[b] Center for Renewable Energy Sources, 19th km, Marathonos Avenue, 19009 Pikermi, Attica, Greece
[c] National Technical University of Athens, 9 Heroon Polytechniou, Athens, Greece
[d] Institute of Energy, Cardiff University, Queen's Buildings, The Parade, CF24 3AA Cardiff, United Kingdom

ARTICLE INFO

Article history:
Received 15 June 2012
Received in revised form 4 March 2013
Accepted 1 April 2013
Available online 24 April 2013

Keywords:
Virtual Power Plants
Micro-generators
Micro-grids
Carbon emissions
Emissions markets
Multi-agent systems

ABSTRACT

A methodology was developed and tested for controlling the emissions from a group of micro-generators aggregated in a Virtual Power Plant. The methodology is based on the EU Emissions Trading Scheme. A multi-agent system was designed and simulations were performed. The operation of the system was demonstrated experimentally using micro-generation sources installed in two laboratories. Two days of experiments were performed. Results show that system emissions have been controlled with a good accuracy, since only small deviations between desired and actual emissions output were observed. It was found that Virtual Power Plant controllability increases significantly by increasing the number of participating micro-generators.

1. Introduction

Aggregation of Distributed Energy Resources (DER) has been considered as a promising solution for mitigating issues related with DER grid integration, such as network constraints, controllability, or resource intermittency [1–4]. Two aggregation concepts have been proposed [5]: (i) the micro-grids and (ii) the Virtual Power Plants (VPP). Emission Trading Schemes (ETS) have been adopted by several countries as a means to regulate carbon emissions, the most prominent of which is the European Union ETS [6]. This scheme allows the cost-efficient reduction of CO_2 emissions among its participants. Allowances are issued by the regulator, in the form of transferrable Carbon Credits, representing one tonne of CO_2 emissions [6]. The method of "cap and trade" is used, issuing fewer allowances than the participants actually need. Hence, the participants with the lowest cost of emissions reduction are given incentive to balance the emissions of the more costly participants. This results in a cost-efficient way of matching the total emissions to a desired value. The total emissions are controlled by the total amount of Carbon Credits supplied to the participants by the regulator (the European Commission). In this paper, a method for the control of carbon emissions induced by a group of aggregated micro-generators is presented. The purpose of this work was to test this methodology by performing simulations and an experimental demonstration of an agent-based implementation. This methodology is based on the EU ETS scheme, as presented in Section 2. A multi-agent system has been developed for implementing the methodology and is presented in Section 3. The methodology was demonstrated with a simulated and an experimental case study, presented in Sections 4 and 5, respectively. Results are presented in Section 6 and conclusions are given in Section 7.

2. Control methodology

2.1. The Environmental Virtual Power Plant (EVPP)

In [7], the operation of Virtual Power Plants is characterised by two aspects: the Commercial Virtual Power Plants (CVPP) and the Technical Virtual Power Plants (TVPP). This classification was made based on the orientation of aggregation towards markets or power system operation, respectively. Following the CVPP and TVPP classification, the category of Environmental Virtual Power Plants (EVPP) is proposed. The EVPP can also be described as a sub-category of a CVPP, since it operates by simulating the EU Emissions Trading Scheme [6]. Micro-generators are too small to participate

* Corresponding author. Tel.: +44 01634 883125; fax: +44 01634 883153.
E-mail addresses: s.skarvelis-kazakos@gre.ac.uk, sskazakos@yahoo.gr (S. Skarvelis-Kazakos).

0378-7796/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.epsr.2013.04.004

individually in the EU ETS, since there is a lower limit of 20 MW in thermal capacity, which is closer to a typical market participant size [6]. The main benefit of the proposed regulation system is that it enables the participation of micro-generator sources in electricity and emissions markets, potentially increasing their revenue compared to standalone operation. The micro-generation resource is expected to be a sizeable asset, so depending on the size of the aggregator portfolio and the business model, it can bring significant economic benefits to the aggregator as well [5,8].

2.2. EVPP aggregator Carbon Credits

In the EU emissions market, the Carbon Credits allow specific quantities of carbon dioxide equivalent ($CO_{2\text{-}e}$) emissions to be released by the holding party [6]. One Carbon Credit represents one tonne of $CO_{2\text{-}e}$, and it is transferrable, i.e. the market participants can trade Carbon Credits between them [6]. In an EVPP, the Carbon Credits are issued by the EVPP aggregator. The EVPP aggregator creates internal Carbon Credits and distributes them to the micro-generators through the intermediate micro-grid aggregators. The Carbon Credits are received by the micro-generators that participate in the EVPP, who can trade Carbon Credits between them according to their needs, thus creating an emissions market. These internal EVPP Carbon Credits are different from the Carbon Credits in the EU emissions market. The amount of $CO_{2\text{-}e}$ that the internal EVPP Carbon Credits represent (e.g. 1 kg $CO_{2\text{-}e}$ or 1 g $CO_{2\text{-}e}$) depends on the size and emission rates of the generators. The EVPP aggregator is effectively acting as a translator between the EU emissions market Carbon Credits and the internal EVPP Carbon Credits. The EVPP aggregator records and controls the flow of Carbon Credits to and from the micro-generators, but not between them. The micro-generators exchange Carbon Credits between them, autonomously, to match their needs. The concept is illustrated in Fig. 1(i).

2.3. EVPP control policies

The amount of Carbon Credits that are created and fed into the internal market at each trading period is defined by the control policy that is followed by the EVPP aggregator. Three control policies were considered in this work, to reflect the Environmental and Commercial aspects in an EVPP. Technical issues were also considered in terms of micro-generator operational limits. When the EVPP aggregator creates the Carbon Credits, it evaluates the current grid emission factor, or electricity price, or both. It uses fuzzy logic inference techniques (i.e. fuzzification–fuzzy associative matrix–defuzzification) to infer the number of Carbon Credits that it will feed into the internal agent market, based on the indicator that is being assessed.

(i) **Emissions policy [*Goal*:** to reduce the overall emissions resulting from EVPP components/***Indicator***: grid emission factor]. Domestic loads are considered to be included in the EVPP area. As the emission factor of the grid is not taken as constant, the EVPP directs the micro-generators to generate more when the grid emission factor is higher, by supplying more Carbon Credits during these times. Thus, more carbon-intensive grid electricity is displaced and the overall emissions are reduced. Since it is cost-effective for the micro-generators to match their emissions with their Carbon Credits, the overall EVPP output is thus regulated.

(ii) **Cost policy**: [***Goal***: to increase the revenue of the EVPP when it is participating in the wholesale electricity markets/***Indicator***: electricity market price]. The micro-generators are driven to generate more when the electricity price is higher, by supplying more Carbon Credits during these times. The emissions output is proportional to the energy generation. The micro-generators produce more energy and emissions to match the Carbon Credits and this energy is traded by the EVPP.

(iii) **Mixed policy (Cost and Emissions)**: [***Goal***: a multi-objective combination of the above/***Indicator***: grid emission factor *and* electricity market price].

2.4. EVPP operation

The Emissions Trading Scheme was used as the basis to design the EVPP operation. An internal EVPP market is created. An EVPP aggregator, acting as the regulator, distributes Carbon Credits to the micro-generators, through intermediate micro-grid aggregators. The Carbon Credits are essentially unique character strings and they are sent as lists through communication links. The micro-generators trade Carbon Credits to cover their emissions. This process is periodic and has 4 stages [also see Fig. 1(ii)]: (i) the beginning of the trading period, (ii) the trading period, (iii) the end of the trading period and (iv) the penalties allocation. A high-level algorithm of the EVPP operation is presented in Fig. 2. It should be noted that the settling periods between internal EVPP operation and external emissions markets are likely to be different. The EVPP aggregator acquires Carbon Credits from the external emissions market (e.g. once daily) and regulates the internal EVPP Carbon Credits accordingly (e.g. every 15 min).

3. A multi-agent system for the environmental virtual power plant

Intelligent agents are defined as autonomous programmes and multi-agent systems (MAS) are systems which contain more than one agent [10]. A hierarchical structure was used to design the proposed MAS, similar to [3] and [9]. Aggregation was realised at two levels: (i) micro-grid and (ii) EVPP level. The intermediate micro-grid level was introduced to reduce the communicational burden and complexity when large numbers of micro-generators are aggregated by a single entity. The Java Agent DEvelopment framework (JADE), a Java-based platform, was used to develop the MAS [10,11]. It implements standard communication protocols designed by the Foundation for Intelligent Physical Agents (FIPA) [12]. Fuzzy logic techniques were applied for the decision-making processes of the agents, since they are adaptive and allow decisions based on incomparable variables. Agents were developed for each of the proposed entities, as described below:

- **The Environmental Virtual Power Plant (EVPP) Aggregator** agent draws the strategy of the EVPP. It creates and distributes the Carbon Credits to the micro-generators, based on control variables such as the grid emission factor.
- **The Micro-grid Aggregator** agent is a transitional layer between the EVPP and the micro-generators. It does not host any intelligence. Its function is to transfer Carbon Credits and aggregated information.
- **The Micro-generation** agent is responsible for the micro-generation operation. It is located in the micro-generator controller. It has access to the information which influences the micro-generation operation and measurements of the local electrical and thermal demand. Every micro-generator agent is trading Carbon Credits based on its own objectives.

4. Simulated case study

A simulation of the MAS operation was performed, in order to test its behaviour. The agents have been initiated using JADE, as in a practical implementation, but on a single computer. The