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Electrical energy management in unbalanced distribution networks using virtual power plant concept

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ABSTRACT

This paper integrates different developed optimization algorithms based on modification of the big bang big crunch method for virtual power plant realization. The proposed algorithms aim to manage the electrical energy in unbalanced distribution networks in order to minimize the purchased energy from the grid. This goal is achieved through the optimal placement of renewable based distributed generators, optimal scheduling of the controllable loads and optimal operation of energy storage elements. The proposed algorithms are implemented in MATLAB environment and tested on the IEEE 37-node feeder. The results show great reduction in the purchased energy from the grid and the subsequent discussions emphasize the significance of using the virtual power plant concept in managing the electrical energy.

1. Introduction

Virtual power plant (VPP) is a recent rapidly growing concept that has many definitions; all these definitions agree upon the fact that VPP is an aggregation of distributed generation (DG, small generating units connected to the distribution network) units of different technologies in order to operate as a single power plant that has the ability to control the aggregated units and to manage the electrical energy flow between these units in order to obtain better operation of the system [1–6]. From the authors perspective VPP can be viewed as “A concourse of dispatchable and non dispatchable DGs, energy storage elements and controllable loads accompanied by information and communication technologies to form a single imaginary power plant that plans, monitors the operation, and coordinates the power flows between its component to minimize the generation costs, minimize the production of greenhouse gases, maximize the profits, and enhance the trade inside the electricity market”.

VPP consists of the three main components, distributed energy resources (DER), energy storage elements (ESEs) and information and communication systems. DER can be either distributed generators or controllable loads connected to the network, ESEs can store energy during off-peak periods and feed it during the peak periods and the information and communication systems manages the operation of other VPP components through communication technologies in bidirectional ways.

The optimal VPP operation aims at enhancing its operation and minimizing the cost of its produced energy. VPP optimization methodology depends on the power system under study; either if it is new or existing. For a newly-established power system, VPP has the ability to choose the capacity and location of the DG units and ESEs, and the locations of the loads to be controlled and the appropriate control strategies and schedules. On the other hand for existing power systems, these options are limited as the location and size of the DG units and ESEs, and the locations of the controllable loads are pre-determined. The studies slanted toward the optimization of the VPP operation [7–23] can be categorized into three groups:

1) DG units’ optimal sizing and siting [7–15]: Researchers investigated various optimization techniques to determine the optimal location and size of DG in order to reduce power loss and improve the voltage profile of the power system. Similarly, VPP optimization can be carried out through optimal placing of stochastic DG units (wind and photovoltaic). Other studies were performed to select the optimal capacity of a conventional power plant used in collaboration with DG units as well as purchasing energy from the electricity market to supply the required VPP energy.

   The optimization methods used for optimal sizing and siting of DG units could be analytical [7–9], numerical [10–12] and heuristic [13–15].

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2) ESEs optimal sizing and siting [16–20]: Optimal sizing and siting of ESEs helps in reducing power loss, improving voltage profiles, and in optimizing the generation of stochastic DGs.
3) Optimal load control scheduling [21–23]: The VPP has the authority to control or even to interrupt the loads according to their importance in order to optimize its operation.

This paper presents three optimization algorithms based on modification of the big bang big crunch (BB–BC) method [24] for optimal placement of renewable based DGs, optimal sizing of ESEs and optimal load control scheduling. The proposed algorithms are integrated together in order to minimize the energy purchased from the grid which realize the VPP concept. The proposed algorithms are implemented in MATLAB and tested on the IEEE 37-node feeder. The results emphasize the significance of using the virtual power plant concept in managing the electrical energy.

2. Problem statement

The optimization problem under study can be stated as:

GIVEN: the input data comprise the distribution feeder structure, feeder loads values, load types, and available renewable based DGs power schedule.

Objective functions: the objective function is to minimize the annual energy purchased from grid using Eq. (1)

$$\text{Minimize} \sum_{h=1}^{96} P_{sub,h} \times 90 \tag{1}$$

Where: $P_{sub,h}$ is the active power purchased from substation at certain hour h. The 96 value represents the total number of hours of the typical day model of the four seasons (4×24 h), the 90 value represents the number of repetition of the typical day model of the four seasons (3 months for each season $\times$ 30 days per season).

REQUIRED: to determine exactly the required (optimal) renewable based DG power schedule and location, optimal load control schedule and optimal size and operation schedule of the ESEs for the sake of minimizing the energy purchased from substation without violating the following system constraints:

- Voltage limits: voltage at each bus should be within a permissible range usually:

$$0.95\ \text{p.u.} \leq V \leq 1.05\ \text{p.u.} \tag{2}$$

- Lines thermal limit (line Ampacity): it represents the maximum current that the line can withstand at certain DG penetration, exceeding this value leads to melting of the line.

$$I_{flow} \leq I_{Thermal} \tag{3}$$

- Power balance: the sum of input power should be equal to the sum of output active power in addition to the active power loss. The input power may include the DG active power, the ESEs power and the active power supplied by the utility. The active output power is the sum of loads active power.

$$P_{sub} + P_{ESE} + \sum P_{DG} = \sum P_{loads} + P_{loss} \tag{4}$$

ASSUMPTIONS: The following assumptions are made.

- All the renewable DG units are working at a unity power factor.
- All buses in the system under study are subjected to the same meteorological conditions.
- All loads participating in the load control program may be subjected to 10% reduction at any hour of the day.
- All loads are scaled by multiplying them by load scaling factor obtained from the modeling strategy presented in Section 3.
- Load control interval is exactly one hour (i.e. each load is controlled once per day).
- Controlling multiple loads at the same time interval is permitted.
- The energy can be fed back to the substation (i.e. grid).
- Any day model for each season starts at 12:00 pm

APPROACH: apply the modified BB–BC method to solve the optimization problem and find the optimal location and power schedule of DGs, optimal load control schedule and optimal charging and discharging schedule of ESEs in order to minimize the energy purchased from substation.

3. VPP components modeling

3.1. Renewable based DGs and load modeling

The model presented in Ref. [25] is used. This model considers the stochastic nature and dependence of renewable based DG and system demand. This probabilistic model is based on Monte Carlo method and diagonal band copula according to three years of historical meteorological and system demand data. The results of this model are the most likelihood values of the PV power, wind power and system demand for the 96 h represent the four season's typical day model.

3.2. Energy storage elements modeling

ESE model is described using Eqs. (5) and (6) subjected to the constraints from Eqs. (7) to (10)

$$Discharge: \ E(t+1) = E(t) + P(t).\Delta t/\eta_d, \ p(t) = -ve \tag{5}$$

$$Charge: \ E(t+1) = E(t) + P(t).\Delta t.\eta_c, \ p(t) = +ve \tag{6}$$

Subjected to power limits:

$$0 \leq P(t).\eta_c \leq P_{\max} \tag{7}$$

$$-P_{\max} \leq P(t)/\eta_d \leq 0 \tag{8}$$

Stored energy limits:

$$0 \leq E(t) \leq E_{\max} \tag{9}$$

Starting and ending limits:

$$E(0) = E_{final} \tag{10}$$

Where $E(t)$ is the energy stored in the ESE at time t. $P(t)$ is the power of the ESE output at time t. Δt is the time duration of each interval and equals to 1 h. η_d and η_c are the discharge and charge efficiency respectively. $P_{\max}$ is the maximum discharging or charging rates. $E_{\max}$ is the maximum energy stored in the ESE respectively. For the energy balance of the ESE, the final stored energy inside the ESE (E_{final}) at the end of period of study is set to be the same as initial stored energy inside the ESE ($E(0)$).

4. Methodology

The electrical energy is managed within the VPP to achieve the required objective using the following procedure:

1 Optimal allocation of RES in order to achieve the required objective (i.e. minimize the energy purchased from grid).
2 Determination of the optimal load control schedule required to minimize the purchased energy while the RES are connected to their optimal locations.
3 Determination of the optimal power schedule of the RES, considering them dispatchable, required to minimize the purchased energy.