OPTIMIZED CLUSTERING OF VPP USING PARTICLE SWARM OPTIMIZATION

S.Y. KIM D.J. KIM I.S. BAE J.O. Kim

e-mail: jokim@hanyang.ac.kr

Hanyang University, Department of Electrical Engineering, Seoul, Korea.

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ABSTRACT

By environmental and technical reasons, the amount of distributed resource will considerably increase in the future power system. As a large number of distributed resource with diverse characteristics have been installed in the distribution system, most engineering and operation concerns are focused on the development of new control approaches and operation. An attractive idea is to aggregate a number of small size generators. This is the concept of Virtual Power Plant (VPP). A VPP is composed of clusters controlled by a management system, and distributed resources form a cluster.

This paper discusses the cluster composition method using Particle Swarm Optimization (PSO) algorithm in optimal approach of economical efficiency. PSO is a population based stochastic optimization technique inspired by social behavior of bird flocking or fish schooling. While the output of thermal units is controlled voluntarily by the owners of distributed resources, the electric power from Photovoltaic (PV) system fluctuates according to weather conditions. For the various distributed resources, such as PV, diesel and Combined Heat and Power (CHP), optimal strategy for clusters composition is organized by comparison of customers' power demand, heat demand and production of distributed resources on time basis.

I. INTRODUCTION

The number of the distributed resources will increase in the future power system due to environmental concerns and energy cost escalation associated with the use of conventional energy sources.

Distributed resources are installed locally close to consumption area and are not intended to be transmitted over long distances. The size of this generation varies from kW to dozens of MW, and this generation can be coupled with heat generation and even cooling systems. Such distributed resources are generally connected to distribution systems. The main technologies for the distributed resources are gas, steam, micro-turbine, hydro turbine, fuel cells, wind turbine and photovoltaic generation [1].

As a large number of distributed resource with diverse characteristics have been installed in the distribution system, most engineering and operation concerns are focused on the development of new control approaches and operation. An attractive idea is to aggregate a number of small size generators. This is the concept of Virtual Power Plant (VPP).

A goal is to couple the decentralized units so that they can be managed and regulated by a Central Power Unit named the Energy Management System (EMS). The EMS can be subdivided into smaller managements systems, called Local Managements System (LMS). The LMSs drive and regulate their Cluster respectively and can take part of the activities of the EMS over. A Cluster is apart from the mean voltage network, in which little to middle-sized consumer are connected. Example of a VPP conception is shown in Figure 1 [2].

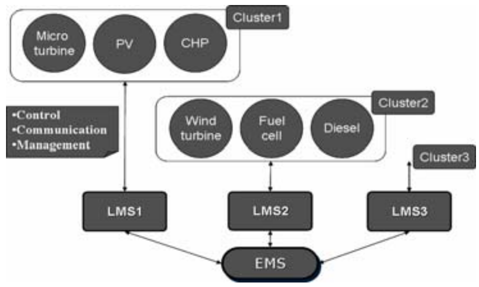

Figure 1. Conception of VPP

The VPP consists of many clusters, which are controlled by many LMSs. This paper discusses how to compose the clusters in the system connected with various distributed resources. If the EMS is composed of only one LMS, all decentralized units should be combined simply into one cluster. It is difficult, however, to determine cluster composition in the VPP consists of two or more clusters. If the clusters are composed considering only regional distance, operation cost of some clusters increase because of the unbalance between (electric or heat) demand and supply. Though the operation cost decrease in the other clusters, total cost of the VPP finally increase.

The clusters should be composed of optimal units considering economic dispatch, characteristic of distributed resources and trade of electric power with grid. An objective function of optimal cluster composition is to minimize total cost of VPP, and a particle swarm optimization technique is used to solve this problem in this paper.

Recently, a new heuristic technique developed by Kennedy and Eberhart in 1995 [3], called particle swarm optimization (PSO). The PSO algorithm has a flexible and well-balanced mechanism to enhance and adapt to the global and local exploration abilities. However, few applications has been done on the optimized system composition, which is the motivation of this paper.

II. SYSTEM DESCRIPTION

A. THE PHOTOVOLTAIC GENERATOR

The PV generator consists of panels, battery, and converter. The scheduling problem of PV is generalized as follows:

$$\text{Minimize} \quad \left| p_{averPV}(t) - p_{PV}(t) \right| \tag{1}$$

$$\text{Subject to} \quad \begin{cases} p_{PV}(t) - p_b(t) - p_u(t) = 0 \\ p_{PV}(t) = f(G_t) \\ -p_b{}^{max} < p_b(t) < p_b{}^{max} \\ 0 \le B_s(t) \le B_s{}^{max} \end{cases} \tag{2}$$

where p_{averPV} is average value of PV power, G_t is radiation, p_b is power charge/discharge to/from battery, and B_s is battery state.

The electric output generated by PV is limited according to the circumstance of PV generation. The main factors that determine the output of PV are PV system efficiency, radiation intensity and temperature of PV panel. Among them, the PV system efficiency is mainly dependent on radiation and temperature. When the two independent variables are recognized, the output of PV at the moment can be predicted.

B. THE ELECTRIC AND HEAT GENERATOR

The electric generator or heat generator is able to produce electric power or heat power, respectively. The production cost of the each generator is given by the well known quadratic function.

$$\begin{aligned} C_e(p) &= \alpha_e + \beta_e \cdot p + \gamma_e \cdot p^2 \\ C_h(h) &= \alpha_h + \beta_h \cdot h + \gamma_h \cdot h^2 \end{aligned} \tag{3}$$

where C is the hourly cost, p and h are the productions of unit, and α , β and γ are positive coefficients of the fuel cost function. These coefficients are dependent on the technology (e.g. fuel cost, efficiency, etc). The production p and h are bounded as follows.

$$\begin{aligned} p^{\min} \le p \le p^{\max} \\ h^{\min} \le h \le h^{\max} \end{aligned} \tag{4}$$

C. THE COMBINED HEAT AND POWER UNIT

The CHP unit is able to produce both heat and electric power. In order to represent the dependency between the electric and heat productions, it is here assumed that the independent variable is the ratio between electric and thermal efficiencies.

$$p_{chp}(h_{chp}) = \eta_{chp} \cdot h_{chp} \tag{5}$$

where h_{chp} is heat flow, p_{chp} is the cogenerated electric power, and η_{chp} is the ratio of electric production to heat production. Similar to the heat/electric generator cost function, the cost function of CHP unit, which includes both heat and electric production, represents in equation (6). Also, the output of CHP unit is also restricted as equation (7).

$$C_{chp} = \alpha_{chp} + \beta_{chp} \cdot h_{chp} + \gamma_{chp} \cdot h_{chp}{}^2 \tag{6}$$

$$h_{chp}{}^{min} \le h_{chp} \le h_{chp}{}^{max} \tag{7}$$

D. EXCHANGE OF ELECTRIC POWER WITH GRID

Under deregulated power market, the spot market uses hourly spot price for electric power. The spot price at the peak load will be higher than that at another load. So, it is assumed that hourly spot price is estimated according to hourly load. The purchasing/selling price of power between VPP and grid is given as follow.

$$C_{grid}(p_{exchange}) = C_{spot} \cdot p_{exchange} \tag{8}$$

where C_{spot} is the hourly spot price of the electric power and $P_{exchange}$ is the amount of exchanged electric power with grid. If the C_{grid} is negative, it represents that the VPP sells electric power to grid and actually obtains a profit. The limitation of exchanged electric power is determined by the capacity of the transformer and transmission line at the network and the conditions of power market.

III. PARTICLE SWARM OPTIMIZATION

The PSO algorithm is a population-based stochastic optimization technique. The potential solutions, called the particles, fly through the search space by following the current optimal particle [6]. Objective function values are used as the fitness values of particles to guide the search process. Each particle records its best individual fitness and position (*pbest*) so far. Moreover, each particle knows the best fitness and position so far in the group (*gbest*) among all individuals.

The basic particle swarm model consists of a group of particles moving about in a physical *n*-dimensional search space. The time-dependent position and velocity of particle are, respectively, denoted with the vectors as follows.

$$X_t^j = \left(x_{1,t}^j, x_{2,t}^j, \Lambda\ , x_{n,t}^j\right) \tag{9}$$

$$V_t^j = \left(v_{1,t}^j, v_{2,t}^j, \Lambda\ , v_{n,t}^j\right) \tag{10}$$

where t is the time step or the number of iteration. The best position of particle j ($p^j best$) and the best position reached by the group (*gbest*) at current iteration t are equations (11) and (12), respectively.

$$X_t^{jp} = \left(x_{1,t}^{jp}, x_{2,t}^{jp}, \Lambda\ , x_{n,t}^{jp}\right) \tag{11}$$

$$X_t^g = \left(x_{1,t}^g, x_{2,t}^g, \Lambda\ , x_{n,t}^g\right) \tag{12}$$

The velocity of individual particle j is updated as equation (13).

$$\begin{aligned} v_{i,t+1}^j &= w_t v_{i,t}^j + c_1 \cdot rand\left(x_{i,t}^{jp} - x_{i,t}^j\right) \\ &\quad + c_2 \cdot rand\left(x_{i,t}^g - x_{i,t}^j\right) \\ i &= 1,2,\Lambda\ , n\ ;\ j = 1,2,\Lambda\ , J \end{aligned} \tag{13}$$

where c_1 and c_2 are positive constants, *rand* is a random number uniformly distributed in the range 0 ~ 1, and w_t is the weight factor and set as inversely proportional with the evolving iterations in w_{min} ~ w_{max} as follow.

$$w_t = w^{max} - \left(w^{max} - w^{min}\right)\left(\frac{t}{maxiter}\right) \tag{14}$$

where *maxiter* is the maximum iterations set by the user.

The second term in the right-hand side of equation (13) represents the adjustment part influenced by the individual's *pbest* position, which is considered as the component of the self-cognition behavior. The adjustment part influenced by the *gbest* position, the third term in equation (13), is considered as the social behavior component.

Based on the updated velocity, the new position of particle j is obtained using equation (15).

$$x_{i,t+1}^j = x_{i,t}^j + v_{i,t+1}^j \tag{15}$$

In each iteration t, all particles use their individual fitness to update the *pbest* and *gbest* values. Searching procedures of the PSO algorithm can be simply described as follows.

Step 1) Generate randomly the initial position and velocity for each particle.

Step 2) Compute the fitness of each particle, and get the *pbest* and *gbest* values at the current iteration.

Step 3) Use equations (13) and (15) to update the velocity and position for each particle.

Step 4) Set the position and velocity at the limit value for any violated particle j.

Step 5) If the maximum iterations are reached, stop; else, go to step 2.

IV. CLUSTER COMPOSITION BY PSO

In the viewpoint of a VPP, operators generally desire that their generators are optimally operated. The power remained after providing for their load offers good chances to be sold on the market. VPP operates in the power market according to the market rules, which can differ from market to market. There are, however, some common aspects in the system operation to minimize the production cost. With cost equations for various resources mentioned above, the optimization problem can be formulated. The objective function is minimization of the sum of all clusters' cost.

$$\min\ C_{total} = C_A + C_B + \Lambda\ + C_N \tag{16}$$

$$\begin{aligned} C_k &= \sum_{i \in k} C_{e,i}(p_i) + \sum_{i \in k} C_{chp,i}(h_{chp,i}) \\ &\quad + \sum_{i \in k} C_{h,i}(h_i) + C_{grid} \\ k &= \{A, B, \Lambda\ , N\} \end{aligned} \tag{17}$$

The cost of each cluster is the sum of the heat/electric fuel cost and the cost/benefit of the electric power exchanged with grid.

The constraints can be divided into two groups. First group is formed by the global constraints, which concern the electric and heat energy balance between VPP generators and loads.

$$\sum_{i \in k} h_i + \sum_{i \in k} h_{chp,i} - h_{demand} \geq 0 \tag{18}$$

$$\sum_{i \in k} p_i + \sum_{i \in k} p_{chp,i} + \sum_{i \in k} p_{u,i} + p_{grid} - p_{demand,i} = 0 \tag{19}$$

The second group of constraints is formed by the local constraints. Each of them is unique for the individual unit only. These constraints are given in equations (2), (3), (6).

To use PSO algorithm in the cluster composition, it is necessary to define particle. According to PSO definition of chapter 3, one particle contains the information of one cluster, and a dimension of particle is the number of units. Each cluster, however, is dependent on the other clusters. When one cluster includes unit A, any other cluster can not include the unit. Therefore, in this paper, one particle is used to express composition of all clusters together. For example, the particle of two-cluster system connected three-unit is as follows.

$$X_t^j = \begin{bmatrix} 1 & 0 & 1 \\ 0 & 1 & 0 \end{bmatrix}$$

where, first cluster consists of first and third units, and second cluster consists of second unit.

To express the particle moving by velocity, it is assumed that components of particle have values from 0 to 1, even though the particle components are integers of 0 or 1 in principle. The position and velocity of particle are positive decimals, which are smaller than 1, and the minimum limit of particle velocity is -1. It is necessarily follows that the position of particle should be rounded off to the nearest integer to calculate operation cost among iteration. Figure 2 shows the flowchart of cluster composition method using PSO algorithm.

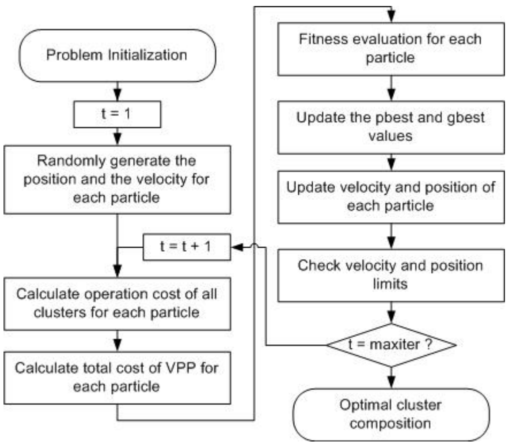

Figure 2. Flowchart of cluster composition algorithm

V. CASE STUDY

The performance of the PSO algorithm is demonstrated by case studies with the distribution network system. Figure 3 depicts the sample system, which consists of electric generators, heat generators, CHP units, and PV units. The dashed and solid lines represent the heat and electric network, respectively.

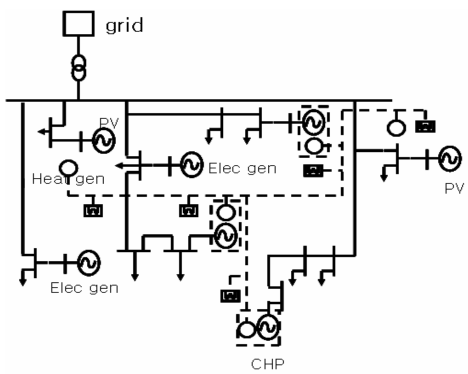

Figure 3. One-line diagram of case study

The number of the electric generators is 2 with a total installed capacity of 1.9 MW, and the number of the heat generators, the CHP units and PV units are 2, 3 and 2, respectively. Its data and capacity are represented in Tables 1 ~ 3.

Table I. Electric and heat generator (kW)

	$p_{\min}$	$p_{\max}$		$h_{\min}$	$h_{\max}$
p_1	**0**	**1200**	h_1	**0**	**800**
p_2	**0**	**700**	h_2	**0**	**500**

Table II. CHP units (kW)

	$h_{chp\min}$	$h_{chp\max 1}$	$\eta_{chp}(kW_e / kW_h)$
h_{chp1}	0	1300	0.577
h_{chp2}	0	500	1
h_{chp3}	0	700	0.8

Table III. Output of PV panel (kWp)

	p_{PV}^{max}
pv_1	200
pv_2	300

The optimal operation of the system during a typical spring day is derived. The electric/heat load curves used in case study are shown in Figure 4. The electric load curve consists of residential, commercial and light industrial load [7]. It is assumed that residential and commercial load have the identical patterns for the heat load. The output electricity generated by PV is determined by the radiation of PV area, and MCS (Monte Carlo Simulation) method is used for obtaining the radiation. All distributed resources are aggregated into a VPP.

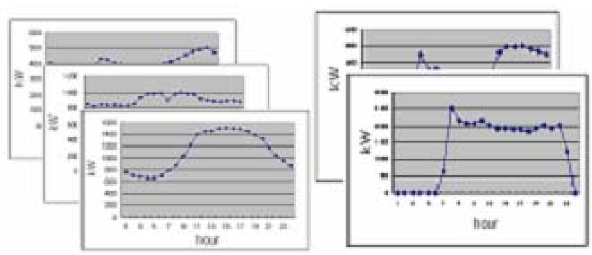

Figure 4. Electric/heat demand curve

When a VPP is divided to three clusters, the cluster composition to optimize total cost is shown at Table 4. Also, Figure 5 depicts the operation costs of all units and purchase cost from grid during 24 hours in this VPP. Cost of almost units decrease in night, while a quantity of purchase power from grid increases in night because of the cheap midnight power price.

Table IV. Optimal composition of 3-cluster VPP

Cluster	Units

1	PV 1, Boiler 2, CHP 2
2	DG 1, DG 2, Boiler 1, CHP 1, CHP 3
3	PV 2

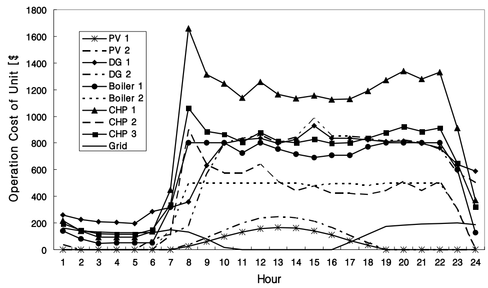

Figure 5. Costs of all units and purchase power in 3-cluster VPP

Operation cost of each cluster in 3-cluster VPP is shown in Table 5 and Figure 6. Though total cost is minimized, cost of each cluster is different with that of the other clusters. The optimization of total cost, namely, does not mean costs of all clusters are identical.

Table V. Cost of each cluster in 3-cluster VPP

	Operation Cost during 1 day
Cluster 1	2134.88 $
Cluster 2	12757.16 $
Cluster 3	184.72 $
Total	15076.76 $

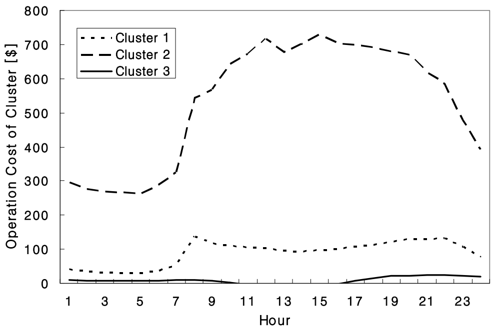

Figure 6. Hourly cost of each cluster in 3-cluster VPP

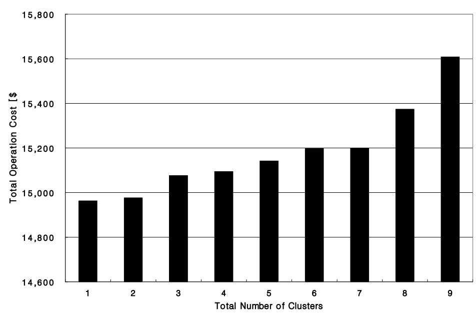

Figure 7. Total cost of n-cluster VPP

Total operation costs of VPPs composed of from 1 to 9 clusters are shown in Figure 7. It is verified in Figure 7 that total cost increases as the number of clusters increases. Operation cost of 9-cluster VPP is most high, in which all units are operated independently by each LMS.

VI. CONCLUSION

A method for the optimal composition of clusters in a VPP has been represented in this paper. It is based on cost functions of the system components. Also, it can be used for the scheduling of the every day operation of VPP including both conventional and unconventional energy sources.

The particle including information about cluster composition moves to the optimal position, and the PSO algorithm is a heuristic approach used to solve that problem. For the applications to find the optimal cluster composition of a VPP, the PSO algorithm is well behaved due to the immunity to the start point, global solution and fast convergence.

There are still many problems for the VPP, such as allowable local distance, voltage level, and the other constraints. In the near future, the number of distributed resources will increase much more and the VPP will be a strategic alternative idea.

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