International Journal of Smart Home
Vol. 10, No. 3, (2016), pp.239-258
http://dx.doi.org/10.14257/ijsh.2016.10.3.24

An Optimal Energy Management Strategy for Thermally Networked Microgrids in Grid-Connected Mode

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Abstract

Networked microgrids (NMGs) are capable of dealing with different load growth scenarios and fluctuations in the electricity market prices in a more efficient way than single microgrids (MGs). A mixed integer linear programming (MILP)-based model for optimal energy management in thermally NMGs with piecewise linearized model for combined heat and power (CHP) generators is proposed in this paper. In order to fulfill the electric load demand, each MG is considered as a distinct entity with the objective to minimize the operation cost. Being in grid-connected mode, this objective can be achieved either by operating the local generations or through trading with the main grid. The thermal load demand can be satisfied by either using the local resources or through trading with other MGs of the NMG with specified lines capacities. The objective is to maximize the usage of more economical units of individual MGs while minimizing the thermal energy waste of the entire network. Case studies with CPLEX in C++ environment have demonstrated the effectiveness and robustness of the proposed strategy for TNMGs in grid-connected mode.

Keywords:_Combined heat and power plants, energy management system, energy optimization, microgrids, networked-microgrids, piecewise linearization_

1. Introduction

The value and importance of MGs to protect the electrical grids from power outages is being increased due to the increased frequency and intensity of events caused by different natural disasters in various parts of the world. MGs have the ability to mitigate power disruption economic impacts [1]. In addition, MGs have an enormous potential to ensure the reliability of service to the end users in an economic way due to the ability of MGs to operate both in grid-connected and islanded modes. Due to the usage of renewable energy sources, MGs are considered more environmentally friendly compared to the conventional power generation systems. These merits of MGs make them an essential part of the modern smart grids. Connecting different MGs to form NMGs is the further developed and application of the concept of MGs [2].

The increased focus on energy efficiency, deployment of renewable energy sources, smart grid technologies, and modern building structures have increased the importance of MGs to a higher level [3]. MGs being deployed in the vicinity of consumers can utilize the waste heat from the generators for district house heating/cooling to improve the overall energy efficiency. Different types of CHP units are becoming integral parts of the modern MGs.

A thermal energy network is required with an MG to distribute the thermal energy produced by the CHP and other thermal energy generation elements. A typical MG would have the following basic elements: CHP generators, renewable energy sources, energy

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ISSN: 1975-4094 IJSH

storage elements, controllable generation units, along with a network for transportation of thermal and electrical energy.

Microgrid management can be seen as an optimization problem, which needs to make decisions regarding the best usage of the generators and storage elements for fulfilling the electrical and thermal load demands [4]. This management of resources is done by an EMS. The architecture of EMS can be either centralized or decentralized. The major task of the EMS is to dispatch the power outputs of the generators and to control the heating and cooling equipment in an efficient and optimized way.

A lot of research can be found in the literature regarding energy management and design for single MG systems [5-7]. A centralized optimal energy management system for microgrids has been proposed by [8] while a decentralized energy management system for microgrids in both grid-connected and islanded modes has been proposed by [9]. Research on multi-agent system-based operation of microgrids has also been a hot topic and is discussed by [10-11]. The role of BESS in the operation of MGs in islanded mode has been discussed by [12] and EMS with distributed energy sources has been analyzed by [13]. Apart from a single MG's EMS, multi-microgrids or networked microgrids' EMS has also been a hot issue for the researcher in the past few decades. Researches related to NMGs can be found in [14-16]. MGs with CHPs are another bright aspect of MGs for efficient use of energy for district heating and cooling in addition to ELD fulfilment. Researches related to overall energy management of MGs with CHPs can be found in [17-20]. Most of the researches in the literature are focused on either single MGs or electrically networked MGs which are commonly known as cooperative MGs or multi-microgrids.

In this paper, a strategy for energy management through thermally networking of MGs has been proposed. The modeled MGs in the TNMG can trade thermal energy to minimize the wastage of thermal energy while making better use of the more efficient CHP, HOB and/or TESS units of individual MGs. The distance between each trading pair is assumed to be different and thermal energy wastage for each pair has been modeled as a function of the distance between them. The amount of thermal energy being traded is limited by the capacity of thermal line connecting each trading pair. If an MG cannot suffice its ELD, it can buy the deficit amount of power from the main grid and in a similar way can sell the surplus amount of power to the main grid. However, the amount of power traded with main grid is limited by the MG's line capacity. Each CHP's cost has been modeled with three piecewise linearized functions in order to incorporate them in the developed MILP based model.

2. Thermally Networked Microgrid Model

2.1. System Model

Figure1 depicts the proposed TNMG-based planning and optimization model. It is assumed that the candidate MGs installed at designated buses would be operated in grid-connected mode. The investments are analyzed on a daily basis. A day is decomposed into 24 periods and load has been assumed to same for each period. Each MG in the modeled TNMG contains the following basic elements: CHP generator, CDG, WM, BESS, HOB, TESS, electrical load, and thermal load. However, the capacity, efficiency, and cost of each identical component of different MGs have been assumed to be different. Each MG uses local CHP,

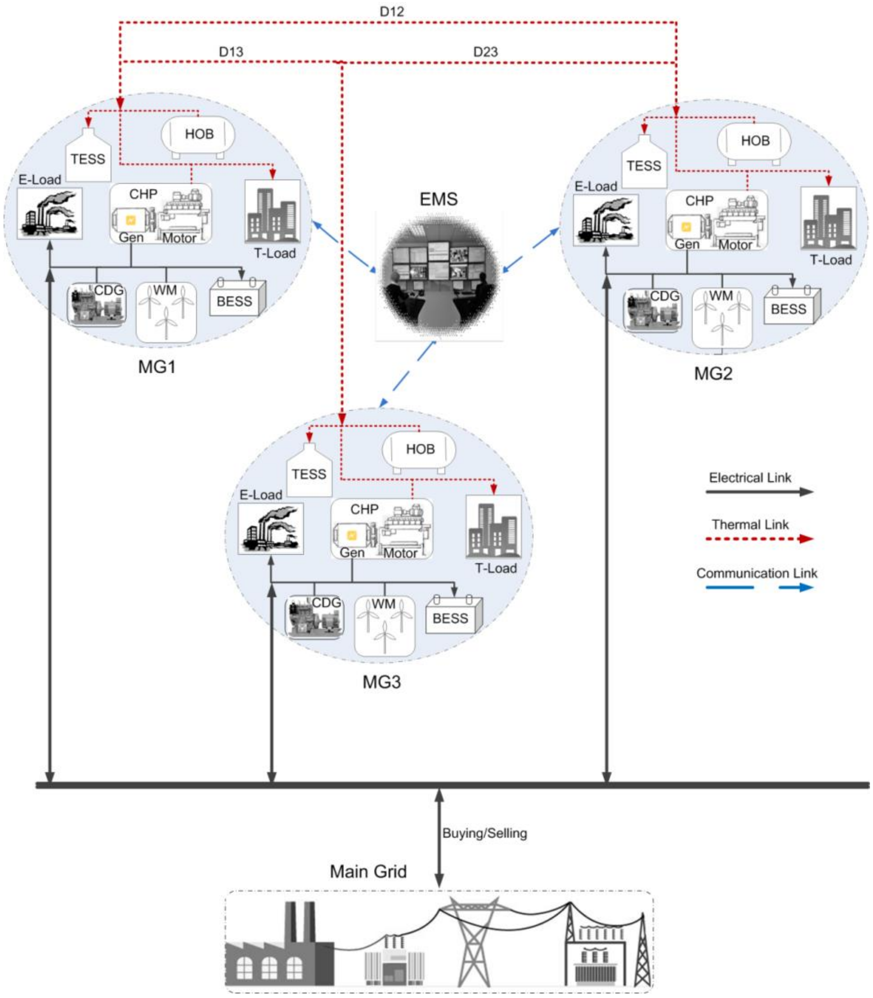

Figure 1. Architecture of Proposed Thermally Networked Microgrids

CDG, and BESS units to fulfil the ELD. However, the deficit amount of power can be bought from the main grid and the surplus amount of power can be sold to the main grid at each interval of time with given line capacities.

The microgrids are assumed to be thermally connected to a thermal network. This way, the thermal loads in each MG would be supplied by several other connected MGs using the common thermal network. Each MG is modeled to send the surplus amount of thermal energy to the other MGs in the network at any time interval while receiving the deficit amount of thermal energy at any other interval from the networked MGs. This configuration would achieve greater thermal stability and controllability along with enhanced redundancy to ensure the supply reliability. This model will ensure the better utilization of cost and efficiency proficient components of individual MGs for minimal wasting of the network's thermal energy while reducing the overall networks operation cost. The amount of thermal energy traded between the MGs is constrained by the capacity of the thermal line connecting the trading pair. A loss factor is assigned to each of the trading pairs, which is a function of distance between them.

A centralized EMS is modeled, which gathers interval-wise information from each MG. The EMS decides the operation of each MG's components and triggers them at each interval of time. An MG with efficient or cheap HOB would be operated to fulfil the TLD of another MG which contains an expensive HOB. A startup cost is associated with each of the CDG and HOB units. The objective of the model is to minimize the operation cost of the entire network while ensuring the thermal and electrical load demands of individual MGs at each interval of time. An MILP based model has been developed to realize the proposed TNMG shown in Figure 1.

2.2. Modeling of Microgrid Elements

This section describes the developed models for piece-wise linearization of CHP cost function, BESS charging /discharging, and TESS charging /discharging. Interval-based loss has been considered for TESS modeling while charging and discharging losses have been incorporated in BESS modeling.

2.2.1. Piece-Wise Linearization of CHP: The relation between cost and power of a CHP generation unit is given by a quadratic equation as shown in equation (1). This equation can be linearized through piece-wise linearization [21]. The function can be decomposed into I number of linear pieces.

$$C^e_{CHP_n}(t) = \alpha.(M^e_{CHP_n}(t))^2 + \beta.M^e_{CHP_n}(t) + \gamma \tag{1}$$

Where, α, β, and γ are the coefficients controlling the cost for per unit production of each CHP generator. The values of these coefficients would be different for different CHP generators. The amount of power produced at any time interval, after linearizing equation (1) can be calculated by using equation (2).

$$M^e_{CHP_n}(t) = M^e_{CHP_{(n,1)}}(t) + M^e_{CHP_{(n,2)}}(t) + \ldots M^e_{CHP_{(n,I)}}(t) \tag{2}$$

Where, I is the maximum number of linearized pieces. The amount of producible power at each linearized interval can be modeled by using following equation.

$$M^e_{CHP_{(n,i)}}(t) \leq \left(B_{(n,i-1)}(t) - E_{(n,i)}(t)\right) \quad \forall \quad i \tag{3}$$

Where, $B_{(n,i)}(t)$ is the beginning point of i[th] interval and $E_{(n,i)}(t)$ is the ending point of the same interval. The relation between the beginning and ending points of each interval are illustrated in Figure 2. The per-unit cost for producing the desired mount of power at any interval t with the linearized model can be calculated by using equation (4).

$$C^{e*}_{CHP_n}(t) = \sum_{i=1}^{I}\left(C^e_{CHP_{(n,i)}}.M^e_{CHP_{(n,i)}}(t)\right)\Big/\sum_{i=1}^{I}\left(M^e_{CHP_{(n,i)}}(t)\right) \tag{4}$$

Where, $C^e_{CHP_{(n,i)}}$ is the slope of line connecting the points $B_{(n,i-1)}$ and $E_{(n,i)}$ as shown in Figure 2. The value of $C^e_{CHP_{(n,i)}}$ at any point $i*$ of the i^{th} interval can be calculated by using equation (5). $B_{(n,i-1)}$ and $E_{(n,i)}$ are the beginning and ending points of the interval i.

$$C^e_{CHP_{(n,i^*)}} = C^e_{CHP_{(n,i)}} + \left(C^e_{CHP_{(n,i+1)}} - C^e_{CHP_{(n,i)}}\right).\left(\frac{M^e_{CHP_{(n,i^*)}} - M^e_{CHP_{(n,i)}}}{M^e_{CHP_{(n,i+1)}} - M^e_{CHP_{(n,i)}}}\right) \tag{5}$$

Each CHP has been linearized with three piece-wise linear functions in the developed model and can be seen in Figure 2.

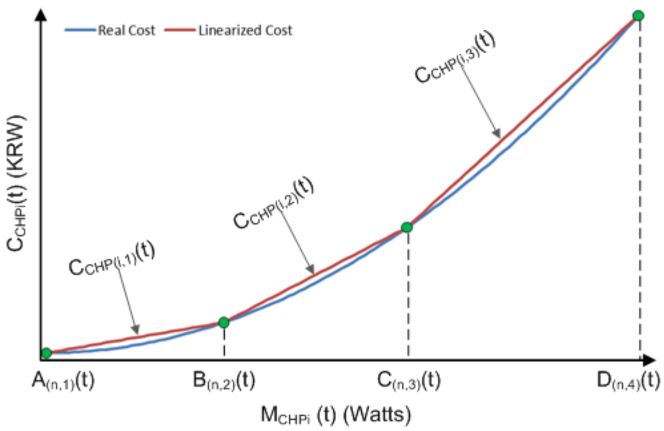

Figure 2. Piecewise Linear Approximation of CHP Generator Cost

2.2.2. Modeling of TESS: The charging, discharging, SOC, capacity, and thermal energy loss per interval has been considered for modeling of each TESS unit. The SOC of n^{th} TESS at any time interval is given by equation (6). Initial value of TESS will be taken instead of $M^h_{SOC_{n-1}}$ for the first step.

$$M^h_{SOC_n}(t) = M^h_{SOC_{n-1}}(t) + M^{h+}_{TESS_n}(t) - M^{h-}_{TESS_n}(t) - M^h_{Loss_n} \quad (6)$$

At any interval *t*, TESS can charge and discharge simultaneously. Thermal energy loss has been assumed to be dependent on the type of TESS material, hence can be assumed to be constant for each interval. The amount of thermal energy at any interval is bounded by the maximum and minimum boundary conditions as given by equation (7).

$$\min\left[M^h_{TESS_n}\right] \le M^h_{SOC_n}(t) \le \max\left[M^h_{TESS_n}\right] \quad (7)$$

The charging and discharging of TESS at each interval is given by equations (8) and (9) respectively. The chargeable amount at any period depends on the maximum capacity, remaining thermal energy from previous period, and amount of energy added at the given period. Dischargeable energy at any period depends upon the amount of energy remained from previous step, added energy at the given period, and minimum amount of thermal energy required to retain by TESS at each period.

$$M^{h+}_{TESS_n}(t) \le \max\left[M^h_{TESS_n}\right] - M^h_{SOC_{n-1}}(t) - M^{h-}_{TESS_n}(t) \quad (8)$$

$$M^{h-}_{TESS_n}(t) \le M^h_{SOC_{n-1}}(t) + M^{h+}_{TESS_n}(t) - \min\left[M^h_{TESS_n}\right] \quad (9)$$

2.2.3. Modeling of BESS: The charging, discharging, SOC, capacity, energy loss for charging, and energy loss for discharging have been considered for the modeling of each BESS unit. The value of SOC at any given time interval is limited by the capacity bounds of the particular BESS. SOC at any given period and capacity bounds for n^{th} BESS unit can be modeled by using equations (10) and (11) respectively.

$$M^e_{SOC_n}(t) = M^e_{SOC_{n-1}}(t) + M^{e+}_{BESS_n}(t).(1 - M^{e+}_{Loss_n}) - \frac{M^{e-}_{BESS_n}(t)}{(1-M^{e-}_{Loss_n})} \quad (10)$$

$$\min\left[M^e_{BESS_n}\right] \le M^e_{SOC_n}(t) \le \max\left[M^e_{BESS_n}\right] \quad (11)$$

The loss factor for BESS has been modeled as a function of the amount of electrical energy charged/discharged to/from the BESS at any given interval of time. The time based energy loss has been assumed to be zero in this study. The chargeable and dischargeable amount of electrical energy to/from the n[th] BESS unit at any period t can be given by equations (12) and (13) respectively.

$$M_{BESS_n}^{e+}(t) \leq \frac{\max\left[M_{BESS_i(t)}^{e}\right] - M_{SOC_{n-1}}^{e}(t)}{(1 - M_{Loss_n}^{e-})} \tag{12}$$

$$M_{BESS_n}^{e-}(t) \leq M_{SOC_{n-1}}^{e}(t).(1 - M_{Loss_n}^{e-}) - \min\left[M_{BESS_n}^{e}\right] \tag{13}$$

The charging and discharging losses have been assumed to be same for this study. However, both depend upon the amount of energy charged or discharged at any given interval of time. BESS cannot charge and discharge simultaneously.

2.3. Problem Formulation

An MILP-based cost minimization model has been developed for the proposed TNMG. The major constraints are the TLD balancing and ELD balancing along with thermal line capacities. Thermal energy can be traded between the networked MGs, and electricity demand can either be fulfilled by the local resources or through trading with the main grid. The modeled BESS can either be used for fulfilling the ELD or for trading with the main grid. Similarly, TESS can be used to fulfil the TLD or for trading thermal energy with other MGs. HOBs are used for satisfying the peak load demand of thermal energy so are the CDGs for electrical energy. The cost for producing electricity from WM has been assumed to be zero and forecasted output values has been used as an input in the developed model.

2.3.1. Objective Function: The objective function for minimizing operation cost of the NMG is given by equation (14). The objective function comprises of cost for CHP units, cost of CDG units, profit of selling electricity to the main grid, cost of HOB units, price for buying electricity from the main grid, startup cost for CDG units, and startup cost for HOB units respectively. Total cost of the network is calculated by summing these terms over the number of MGs in the NMG as given by equation (15). The total daily cost of the NMG is calculated by summing the $C_{MG}(t)$ over the entire intervals and is given by equation (14), which is the objective function.

$$\min \sum_{t=1}^{T}(C_{MG}(t)) \tag{14}$$

$$C_{MG}(t) = \sum_{n=1}^{N} \left\{ \begin{matrix} \left(C_{CHP_n}^{e*}(t).M_{CHP_n}^{e}(t)\right) + \left(C_{CDG_n}^{e}.M_{CDG_n}^{e}(t)\right) - \\ \left(P_{SELL_n}^{e}(t).M_{SELL_n}^{e}(t)\right) + \left(C_{HOB_n}^{h}.M_{HOB_n}^{h}(t)\right) + \\ \left(P_{BUY_n}^{e}(t).M_{BUY_n}^{e}(t)\right) + \left(C_{CDG_n}^{SU}.U_n^{SU}(t)\right) + \\ \left(C_{HOB_n}^{SU}.V_n^{SU}(t)\right) \end{matrix} \right) \tag{15}$$

The startup cost for the CDG units of each MG can be calculated by using equation (16). $U_n^{SU}(t)$ and $U_n(t)$ are the binary variables for n[th] CDG unit at time period t.

$$U_n^{SU}(t) = \left[U_n(t) - U_n(t-1)\right] \geq 0 \tag{16}$$

Similarly the startup cost for each HOB unit can be calculated by using equation (17). The optimization model described in this paper is based on the MILP and can be easily implemented by using commercial solvers like CPLEX [2].

$$V_n^{SU}(t) = \left[V_n(t) - V_n(t-1)\right] \geq 0 \quad (17)$$

2.3.2. Energy Balancing Constraints: For each MG, the total power generation from the local sources along with battery charging/discharging must be balanced with the total of the local ELD and the power traded with the main grid. Therefore, the power balancing equation for each MG can be written by using equation (18). The BESS has been modeled as a load during charging cycle and as a source during the discharging cycle.

$$M_{Load_n}^{e}(t) = \begin{Bmatrix} M_{WM_n}^{e}(t) + M_{CHP_n}^{e}(t) + M_{CDG_n}^{e}(t) + M_{BUY_n}^{e}(\mathrm{t}) \\ - M_{SELL_n}^{e}(\mathrm{t}) + M_{BESS_n}^{e-}(\mathrm{t}) - M_{BESS_n}^{e+}(\mathrm{t}) \end{Bmatrix} \quad (18)$$

The total thermal energy generated from the local sources and the charging/discharging of TESS must be balanced with the total of the local TLD and thermal energy exchanged with other MGs along with the thermal energy lost due to this exchange. Therefore, the thermal load balancing equation for each MG can be written as the equation (19). There is a loss factor associated with the amount of thermal energy received from the other MGs. The loss factor is the function of distance between the two MGs, which exchange the thermal energy.

$$M_{Load_n}^{h}(t) \leq \begin{Bmatrix} M_{CHP_n}^{h}(t) + M_{HOB_n}^{h}(t) + \\ \sum_{\bar{n}=1}^{N} \left\{ \left(\left(1 - M_{Loss_{\bar{n}\to n}}^{h}\right). M_{RECV_{\bar{n}\to n}}^{h}(t) \right) - \left(M_{SEND_{n\to\bar{n}}}^{h}(t) \right) \right\} \\ + M_{TESS_n}^{h-}(t) - M_{TESS_n}^{h+}(t) \qquad \forall\ n \neq \bar{n} \end{Bmatrix} \quad (19)$$

2.3.3. Capacity Constraints: Each of the microgrid components need to operate within the specified limits. Similarly the tradable amount of electricity with the main grid is limited by the line capacity and exchangeable thermal energy between two MGs is also limited by the capacity of thermal line connecting both the MGs. The capacity related constraints for CHPs, CGDs and HOBs are given by equations (20), (21), and (23) respectively.

$$\min\left[M_{CHP_n}^{e}\right] \leq M_{CHP_n}^{e}(t) \leq \max\left[M_{CHP_n}^{e}\right] \quad (20)$$

$$\min\left[M_{CDG_n}^{e}\right]. U_n(t) \leq M_{CDG_n}^{e}(t) \leq \max\left[M_{CDG_n}^{e}\right]. U_n(t) \quad (21)$$

$$\min\left[M_{HOB_n}^{h}\right]. V_n(t) \leq M_{HOB_n}^{h}(t) \leq \max\left[M_{HOB_n}^{h}\right]. V_n(t) \quad (22)$$

The amount of electrical energy which can be bought from the main grid at any time slot is constrained by the capacity of the line connecting the MG with the main grid. Same is the case with the electrical energy sold to the main grid. This can be modeled by using equation (23). The quantity of thermal energy which can be traded with other MGs of the NMG is also constrained by the capacity of the thermal line connecting both the MGs. This constrain can be modeled by using equation (24).

$$M_{BUY_n}^{e}(t),\ M_{SELL_n}^{e}(t) \leq M_{CAP_n}^{e} \quad (23)$$

$$M^{h}_{SEND_{n\to\bar{n}}}(t)\,,\ M^{h}_{RECV_{\bar{n}\to n}}(t) \leq M^{h}_{CAP_{n\to\bar{n}}} \qquad (24)$$

The value of $M^{h}_{CAP_{n\to\bar{n}}}$ for each pair of MGs in the NMG can be computed by using a symmetrical matrix. The self-capacity for MG will be infinite while there will be some positive values for other entries of the matrix.

Each CHP can produce a specific amount of thermal energy and power at any given interval. The amount of thermal energy produced is the function of the power produced by the CHP unit. The ratio between electrical to thermal energy at any time slot for n[th] CHP generator can be given by equation (25). This ratio also needs to be within the maximum and minimum conversion ratio of each CHP and can be given by equation (25). However, in this paper due to the very short time periods, this ratio has been assumed to be constant for the whole period of simulation i.e day-ahead scheduling. However, each CHP of NMG has a different thermal to power conversion ratio. This will enable the NMG to make better use of the more efficient CHP generators by producing more thermal energy and then by sending it to other MGs with less efficient CHP generators.

$$\min[\eta_n] \leq \eta_n(t) \leq \max[\eta_n] \qquad \textit{Where,} \qquad \eta_n = M^{e}_{CHP_n}(t)/M^{h}_{CHP_n}(t) \qquad (25)$$

2.3.4. Thermal Energy Trading: The major contribution of this paper is the design of a strategy for reducing thermal energy wastage by exchanging surplus thermal energy among the TNMGs. Thermal energy is wasted only when all the MGs of NMG produce more thermal energy than their local demands. In each time slot, the MGs with surplus thermal energy send the surplus amount of the energy to those MGs which deficit thermal energy at that time slot. If surplus thermal energy is more than the deficit, TESS can be used to store the energy and used in those time slots where the deficit is greater than the surplus.

Thermal energy is considered as surplus when the amount of thermal energy produced by local CHP, HOB, or though discharging of local TESS is more than the local thermal load demand and charging of TESS. Each MG can send this surplus amount of thermal energy to other MGs and can be realized by using following equation.

$$\sum_{\bar{n}=1}^{N} M^{h}_{SEND_{n\to\bar{n}}}(t) \leq \left\{ \begin{matrix} M^{h}_{CHP_n}(t) + M^{h}_{HOB_n}(t) + M^{h-}_{TESS_n}(t) \\ - M^{h+}_{TESS_n}(t) - M^{h}_{Load_n}(t) \end{matrix} \quad \forall \ n \neq \bar{n} \right\} \qquad (26)$$

Similarly, the deficit can be calculated by comparing the total thermal energy produced by the local sources with the amount of thermal load of that particular MG. The deficit amount of thermal energy for any MG can be realized by using equation (27).

$$\sum_{\bar{n}=1}^{N} M^{h}_{RECV_{\bar{n}\to n}}(t) \leq \left(M^{h}_{LOAD_n}(t) - M^{h}_{SOURCE_n}(t)\right).\left(1 - M^{h}_{Loss_{\bar{n}\to n}}\right) \ \ \forall \ \ n \neq \bar{n} \qquad (27)$$

Where, $M^{h}_{LOAD_n}(t) = M^{h}_{Load_n}(t) + M^{h+}_{TESS_n}(t)$ and

$$M^{h}_{SOURCE_n}(t) = M^{h}_{CHP_n}(t) + M^{h}_{HOB_n}(t) + M^{h-}_{TESS_n}(t)$$

The amount of thermal energy sent and received by MGs of the TNMG at any given interval of time need to be balanced. The amount of energy sent should be equal to the amount of energy received plus the amount of energy lost while receiving that energy. This balancing can be realized by using the following equation.

$$M^{h}_{SEND_{n\to\bar{n}}}(t) = \sum_{\bar{n}=1}^{N} \left(\left(1 + M^{h}_{Loss_{\bar{n}\to n}}\right).\ M^{h}_{RECV_{\bar{n}\to n}}(t) \right) \quad \forall\, n \neq \bar{n} \qquad (28)$$

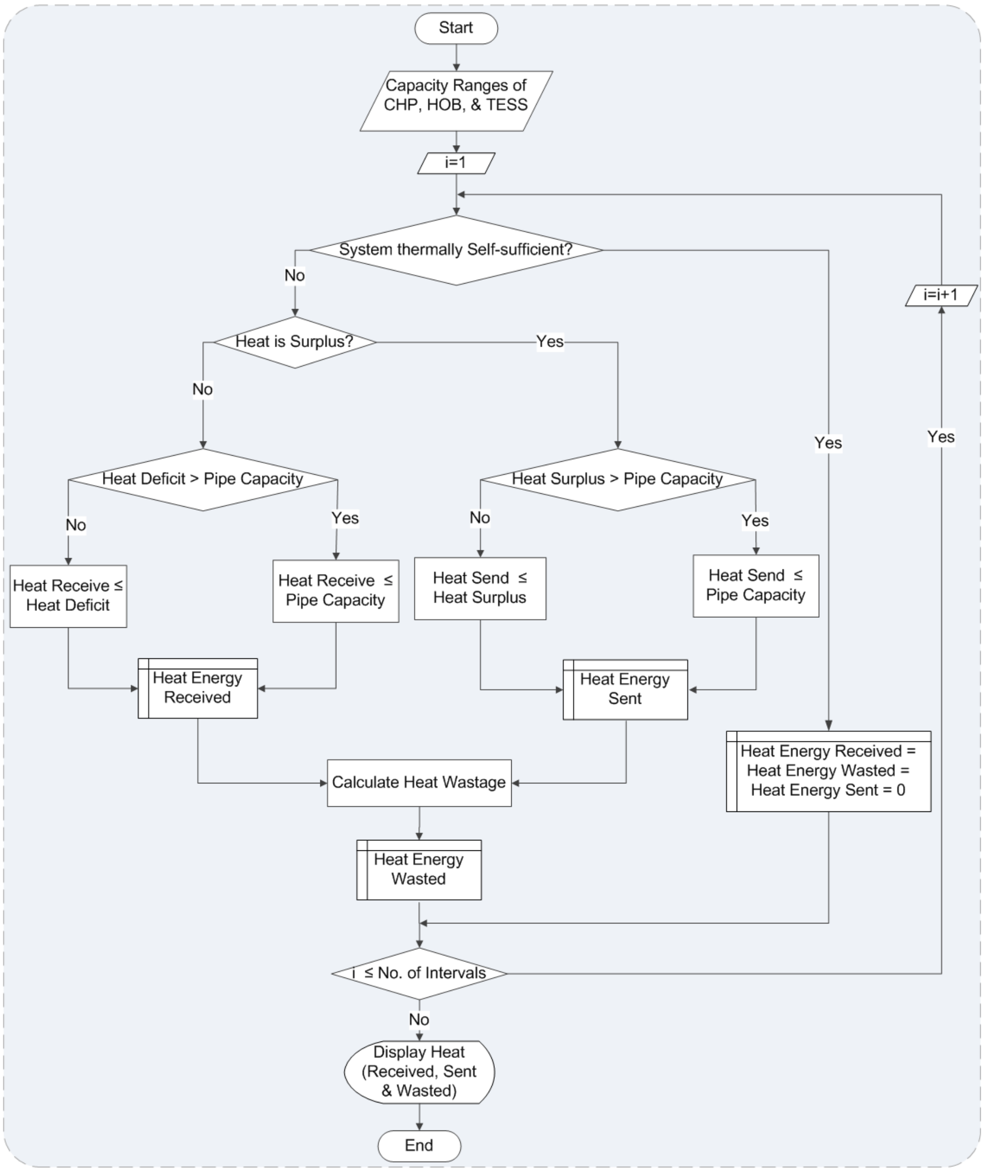

Figure 3. Flow Chart for Trading Thermal Energy

In any time slot, a particular MG can either send or receive thermal energy. However, the thermal energy sent by one MG can be received by many MGs and vice versa. The algorithm for calculating surplus, deficit, and wasted thermal energy is illustrated in figure 3. Thermally self-sufficient MG is defined as the MG whose TLD is equal to the generated thermal energy locally. Wasted energy is defined as the thermal energy which is still remaining after serving local thermal load and sending the deficit amount of other MGs.

The thermal loss can be modeled, if the distance between different MGs of the NMGs along with the loss per unit distance is known. The distance can be modeled in the form of a symmetrical matrix. By using the distance matrix and per unit loss value, another symmetrical matrix containing loss values between each MG pairs in the NMG can be obtained. The diagonal elements of both the matrices will be zero while all other elements will be non- negative.

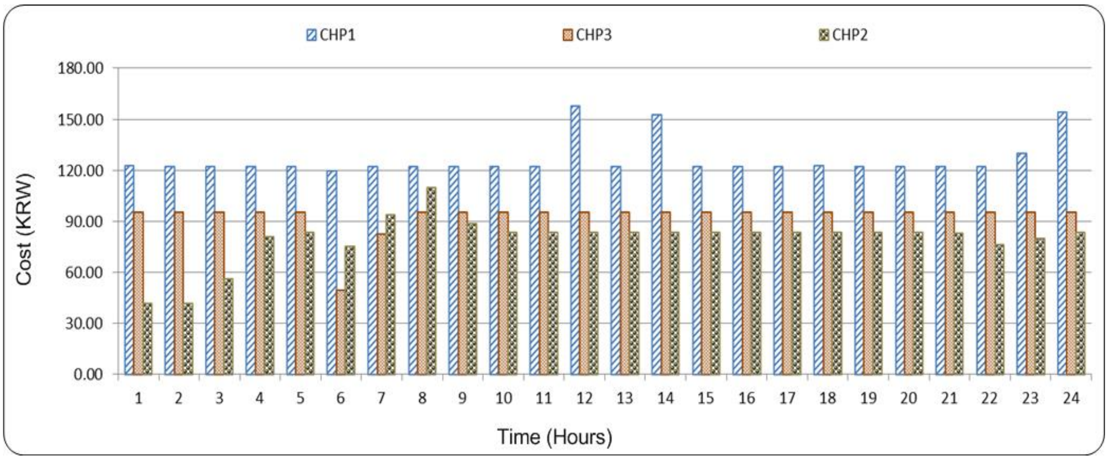

Figure 4. Hourly Per-Unit Generation Cost for CHP Generators in the TNMG

3. Numerical Results

A network of three MGs, namely MG1, MG2, and MG3 has been considered in this study. Each MG contains a CHP, CDG, WM, BESS, HOB, TESS, thermal load, and electrical load. The MGs in the network can trade thermal energy among themselves and each MG can trade power with the main grid. The developed model has been simulated in Visual Studio 2010 by using IBM ILOG CPLEX v12.3. All the prices in this study have been taken in South Korean Won (KRW) and energies in kWh. The selling and buying prices vary hourly, as do the operation costs of each CHP. The hourly buying and selling prices are provided in Appendix 3, table 6. Interval-wise CHP costs of individual MGs are shown in Figure 4.

It can be observed from Figure 4 that CHP1 is the most expensive generator, while CHP2 is the least expensive, and CHP3 is intermediate. The buying and selling prices keep on varying and are at peak during the 10^{th} to 14^{th} intervals. The lowest buying and selling prices can be observed during the 1^{st}, 2^{nd} and 19^{th} to 21^{st} intervals.

3.1. Optimized Results of Electrical Energy

The hourly electrical loads along with WM generations for each MG of the NMG are provided in appendix B. Capacity, minimum/maximum generation limitations, and costs for each element of the NMG are provided in appendix C.

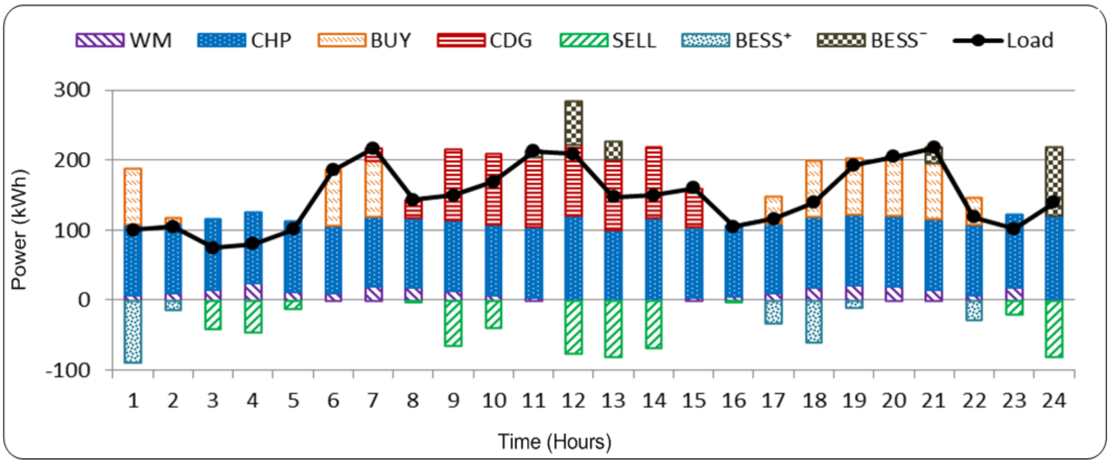

Figure 5. Hourly Electrical Energy Profile of MG1

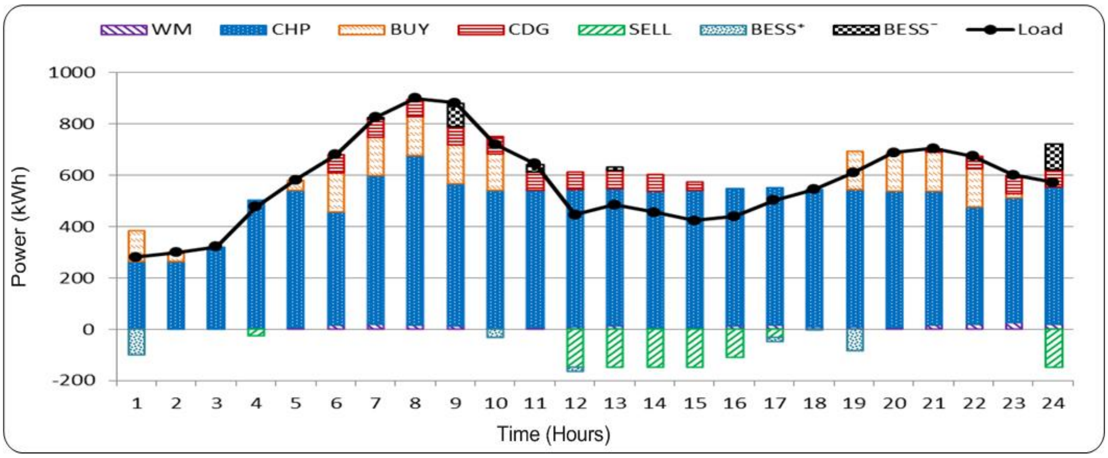

Figure 6. Hourly Electrical Energy Profile of MG2

Electrical energy profile of MG1 is illustrated in Figure 5. It can be observed from figure 5 that MG1 is buying electricity from the main grid during intervals 1, 2, 6, 7, 17, 18, 19, 20, 21, and 22 with the buying price being lower than the generation cost. When the buying price is higher, the MG is either using the CDG units or discharging the BESS to fulfil the energy demand. During the interval 9, 10, 12, 13, and 14, the MG1 is generating electricity by using the CDG unit and is selling that power to the main grid to maximize the profit. When the buying price is lower, MG1 buys electricity from the main grid and charges the BESS. The BESS is either used to fulfill the energy demand during high load intervals or is used for maximizing the profit by selling during the higher selling price intervals. This effect can be observed from intervals, 1, 12, 13, 17, 18, 19, 21, 22, and 24.

A similar type of behavior can be observed in Figure 6, which shows the electrical profile of MG2. The BESS is charged during intervals 1, 10, and19 and the charged energy is either sold to the main grid as in 24th interval or is used to fulfil ELD in high load intervals like 9. During the high load intervals, if buying price is lower than CDG generation cost, electricity is bought from the main grid to the fullest capacity of the line and vice versa for the opposite case. If the ELD cannot by fulfilled due to line capacities or CDG maximum generation limitations, BESS is discharged to fulfill the ELD as in the 9th interval. This effect of using both CDG and buying from the main grid can be observed from intervals 6 to 10 and 22 to 23.

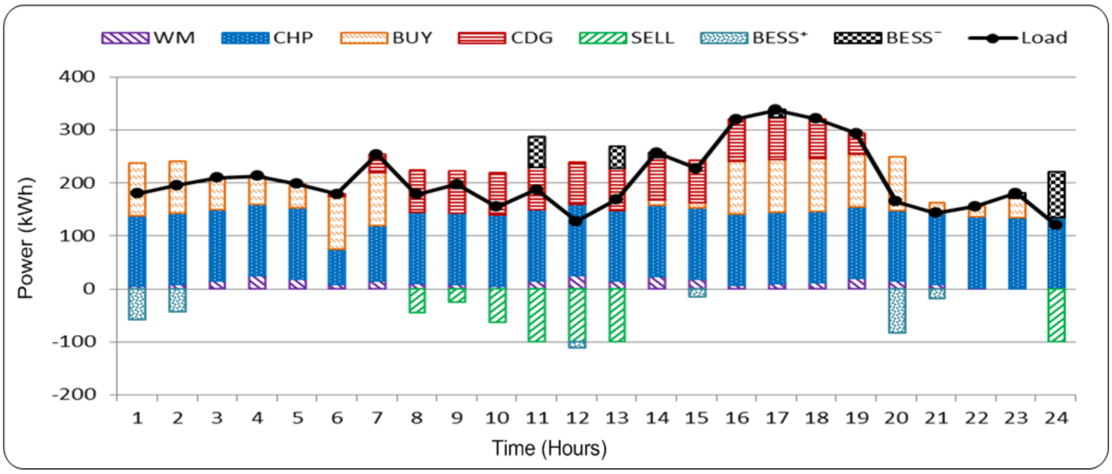

Figure 7. Hourly Electrical Energy Profile of MG3

The electrical energy profile of MG3 is shown in Figure 7. MG3 buys the maximum possible energy from the main grid during the high load periods. The deficit amount after buying is fulfilled either by using the CDG unit or by discharging the BESS, which can be observed from intervals 7 and 16 to 19 in Figure 7. BESS is charged during the low buying price slots and is sold back to the grid during high selling price slots in order to maximize the profit. When the selling price is higher than the generation cost of CDG, CDG is used to generate the power and is sold to the main grid. This effect can be observed in intervals 8 to 13.

3.2. Optimized Results of Thermal Energy

The hourly thermal load of each MG of the NMG is provided in the appendix B. The capacity of each thermal energy generating/storing element of the individual MGs with minimum/maximum generation limitations are provided in appendix C. The optimized results of the thermal energy portion of the TNMG are illustrated in Table 1. The local load is initially fulfilled by the local thermal energy generators or storage elements. At any particular time slot, if an MG has surplus amount of thermal energy, it sends that energy to another MGs with an energy deficit. Some amount of the energy is lost while trading thermal energy between each pair and is proportional to the distance between them. Thermal energy is wasted only when all the MGs generate enough thermal energy to suffice their local loads. In Table 1, the amount of the energy sent or received by each MG has been calculated by using equation (29).

$$M^h_{SEND_n}(t) = \sum_{\bar{n}=1}^{N} M^h_{SEND_{n\to\bar{n}}}(t),\ M^h_{RECV_n}(t) = \sum_{\bar{n}=1}^{N} M^h_{RECV_{\bar{n}\to n}}(t) \quad \forall\, n \neq \bar{n} \quad (29)$$

It can be observed from table 1 that each microgrid becomes thermally self-sufficient at some intervals. MG1 is thermally self-sufficient at interval 19, MG2 at 1 to 4, 7, 11, 13, and MG3 at 22. During intervals 5, 6, and 24 one of the MG in the NMG is sending the thermal energy, while the remaining two are receiving it. While there are several intervals during which two MGs are sending thermal energy, it is received by the third MG. This effect can be observed in intervals 8 to 10, 12, 15 to 18, 20, 21, and 23 in table 1. MG1 and MG2 have not used their HOB units due to the relatively higher per unit generation costs. MG3 has used its HOB during intervals 1 to 5 and 12 to 24. However, during intervals 1 to 5, 18 to 21, and 23, MG3 has sent the thermal energy generated by its HOB to other MGs.

The distance between MG1 and MG2 is assumed to be maximum and minimum for MG1 and MG3. However, the distance between MG2 and MG3 is assumed to be between the other two pairs. It can be observed from Table 1 that the thermal energy trading between MG1 and MG2 is at the minimum due to the maximum thermal energy loss for trading energy for this pair. The effect of becoming frequent thermally self-sufficient in MG2 is also due to relatively larger thermal energy losses for trading energy with MG1 or MG3. The turning on/off of HOB is not frequent in order to minimize the startup costs. A similar effect has been observed for CDGs in the electrical profile of individual MGs.

Before applying the idea of trading thermal energy, each MG has to either use the HOB for fulfilling the deficit amount of thermal energy in each interval or to increase the power generation of local CHP unit. Both of these will increase the operation cost of the NMG. Apart from this increase in operation cost, the remaining amount of thermal energy after serving the local load was wasted by each MG of the NMG. The proposed thermal energy trading algorithm has reduced the wastage of thermal energy by enabling each MG of the NMG to trade the surplus amount of thermal energy in each interval. MGs with cost efficient

Table 1. Optimized Thermal Energy Profile of Individual MGs in the TNMG

Time	MG1						MG2						MG3					
	$M^h_{CHP_1}$	$M^h_{HOB_1}$	$M^h_{SEND_1}$	$M^h_{RECV_1}$	$M^{h+}_{TESS_1}$	$M^{h-}_{TESS_1}$	$M^h_{CHP_2}$	$M^h_{HOB_2}$	$M^h_{SEND_2}$	$M^h_{RECV_2}$	$M^{h+}_{TESS_2}$	$M^{h-}_{TESS_2}$	$M^h_{CHP_3}$	$M^h_{HOB_3}$	$M^h_{SEND_3}$	$M^h_{RECV_3}$	$M^{h+}_{TESS_3}$	$M^{h-}_{TESS_3}$
1	183.0	0.0	0.0	61.9	0.9	0.0	132.0	0.0	0.0	0.0	1.0	0.0	108.9	26.0	64.9	0.0	0.0	0.0
2	182.7	0.0	0.0	72.4	4.1	0.0	132.0	0.0	0.0	0.0	4.0	0.0	108.9	56.0	75.9	0.0	5.0	0.0
3	182.7	0.0	0.0	90.3	5.0	0.0	160.0	0.0	0.0	0.0	19.0	0.0	108.9	65.0	94.7	0.0	10.2	0.0
4	182.7	0.0	0.0	85.7	37.2	7.8	249.6	0.0	0.0	0.0	2.6	0.0	108.9	43.0	89.9	0.0	0.0	0.0
5	182.7	0.0	0.0	80.8	0.0	19.5	268.0	0.0	0.0	0.4	0.0	6.6	108.9	60.0	85.2	0.0	4.8	0.0
6	174.6	0.0	56.6	0.0	5.0	0.0	222.0	0.0	0.0	3.0	5.0	0.0	53.7	0.0	0.0	50.7	17.4	0.0
7	181.8	0.0	73.8	0.0	5.0	0.0	289.6	0.0	0.0	0.0	28.6	0.0	84.6	0.0	0.0	70.4	19.9	0.0
8	182.6	0.0	18.6	0.0	45.0	0.0	331.0	0.0	37.6	0.0	21.4	0.0	108.9	0.0	0.0	52.8	17.7	0.0
9	182.7	0.0	65.8	0.0	0.0	4.1	278.4	0.0	0.4	0.0	0.0	2.0	108.9	0.0	0.0	63.0	2.0	0.0
10	182.7	0.0	49.7	0.0	0.0	0.0	268.0	0.0	25.0	0.0	0.0	12.0	108.9	0.0	0.0	70.7	0.0	1.4
11	182.7	0.0	34.7	0.0	4.1	0.0	268.0	0.0	0.0	0.0	20.0	0.0	108.9	0.0	0.0	33.1	0.0	0.0
12	220.6	0.0	24.6	0.0	0.0	20.0	268.0	0.0	9.9	0.0	0.0	13.9	108.9	1.0	0.0	32.6	0.0	19.4
13	182.7	0.0	17.7	0.0	45.0	0.0	267.8	0.0	0.0	0.0	32.8	0.0	108.9	1.0	0.0	16.9	43.8	0.0
14	214.1	0.0	45.1	0.0	5.0	0.0	268.0	0.0	0.0	82.0	0.0	3.0	108.9	1.0	44.9	0.0	5.0	0.0
15	182.7	0.0	55.7	0.0	5.0	0.0	268.0	0.0	0.0	67.7	11.7	0.0	108.9	1.0	19.4	0.0	2.5	0.0
16	182.7	0.0	57.7	0.0	5.0	0.0	268.0	0.0	0.0	69.0	0.0	1.0	108.9	1.0	18.9	0.0	0.0	0.0
17	182.7	0.0	22.7	0.0	3.1	0.0	268.0	0.0	0.0	46.2	4.2	0.0	108.9	1.0	27.9	0.0	0.0	0.0
18	183.0	0.0	41.9	0.0	0.0	6.9	268.0	0.0	0.0	76.9	0.0	13.1	108.9	3.0	42.4	0.0	0.0	17.5
19	182.7	0.0	0.0	0.0	18.7	0.0	268.0	0.0	0.0	50.3	0.0	8.7	108.9	39.0	53.9	0.0	0.0	0.0
20	182.7	0.0	0.0	65.1	3.9	0.0	265.5	0.0	31.5	0.0	5.0	0.0	108.9	13.0	38.9	0.0	5.0	0.0
21	182.7	0.0	0.0	88.5	0.0	4.8	262.0	0.0	90.0	0.0	5.0	0.0	108.9	36.0	8.9	0.0	27.5	17.5
22	182.7	0.0	0.0	80.1	0.8	0.0	228.0	0.0	90.0	0.0	5.0	0.0	108.9	44.0	0.0	0.0	0.0	0.1
23	189.8	0.0	0.0	89.4	0.0	19.8	245.0	0.0	90.0	0.0	5.0	0.0	108.9	81.0	9.9	0.0	6.1	0.0
24	216.4	0.0	0.0	68.6	5.0	0.0	266.5	0.0	90.0	0.0	5.0	0.0	108.9	36.0	0.0	12.0	3.9	0.0

Figure 8. Hourly Thermal Energy Wastage Before and After Trading in the NMG

HOB units have used their HOBs to fulfil the thermal load demands of other MG having expensive HOBs. This has reduced the usage of expensive thermal energy generators, which has finally reduced the operation of the TNMG.

A comparison of interval-wise collective thermal energy wastage of the NMG is shown in Figure 8. It can be observed that the thermal energy wastage has been remarkably reduced by the proposed algorithm. The majority of energy wastages visible in figure 8 after trading are due to the thermal line losses for trading thermal energy between each pairs. Thermal energy is wasted only when the collective thermal energy of the MGs in TNMG is more than the collective TLD of the network. Such kind of event has been observed in interval 24 and is depicted by Figure 8.

4. Conclusion

A strategy for optimal energy management in TNMGs is proposed. Being in grid-connected mode, the developed system is capable of trading surplus/deficit of electricity with the main grid. The thermal energy balancing can be achieved by either making use of the local resources or through trading with other MGs of the network. The objective is to minimize the operation cost of the entire network while reducing the wastage of thermal energy. Each MG of the NMG contains some basic common elements with different capacities, costs and efficiencies. The network assures the optimal utilization of economical and efficient components of each MG and thus reduces the network's operation cost. Thermal energy is wasted only when the collective TLD of the network is lesser than the combined generation of the network.

Wastage of thermal energy has been minimized by incorporating the proposed strategy for TNMGs in the modeled NMG system. Line capacities of electrical and thermal energy lines have appeared to be bottlenecks in some cases. The storage capacities of BESS and TESS have appeared to play a crucial role in the overall performance of the NMG. The thermal energy wastage after applying the proposed strategy is mainly contributed by the thermal line losses. This loss can be improved if either the MGs of NMG are closely located or he thermal energy loss per kilometer is reduced by using a less conductive (thermally) material.

Appendix A

Nomenclature

Acronyms:

MG	Microgrid.
MILP	Mixed Integer Linear Programming.
NMG	Networked Microgrid.
TNMG	Thermally Networked Microgrid
CHP	Combined Heat and Power.
CDG	Controllable power only Distributed Generator.
BESS	Battery Energy Storage System.
WM	Wind Mill.
HOB	Heat Only Boiler.
TESS	Thermal Energy Storage System.
EMS	Energy Management System.
TLD	Thermal Load Demand.
ELD	Electric Load Demand.
SOC	Status Of Charge.

Identifiers:

e	Electricity .
h	Heat/ Thermal Energy.
e^+	Charging of Electrical Energy.
e^-	Discharging of Electrical Energy.
h^+	Charging of Thermal Energy.
h^-	Discharging of Thermal Energy.
t	Operation Time Interval.
$n, \bar{n}$	Indices for MGs.
d	Distance in kms.
l	loss in percentage.
c	Capacity in kWhs.
i	linearized intervals (pieces).
η	Thermal to Electrical Efficiency
U,V	Binary variables.
C	Cost.
P	Price.
M	Magnitude/ Quantity.

Parameters & Variables:

$C_{MG}(t)$	Operation cost of NMG at time interval t.
$C^{e}_{CHP_n}(t)$	Cost per unit of nth CHP generator at time interval t (original).
$C^{e*}_{CHP_n}(t)$	Cost per unit of nth CHP generator at time interval t (linearized).
$C^{e}_{CDG_n}(t)$	Cost per unit production for nth CDG unit.
$C^{SU}_{CDG_n}$	Startup cost of nth CDG unit.
$C^{h}_{HOB_n}$	Cost per unit production for nth HOB unit.
$C^{SU}_{HOB_n}$	Startup cost of nth HOB unit.
$P^{e}_{BUY_n}(t)$	Price for buying electrical energy at time interval t.
$P^{e}_{SELL_n}(t)$	Price for selling electrical energy at time interval t.
$M^{e}_{WM_n}(t)$	Amount of electrical energy produced by nth wind mill at time interval t.
$M^{e}_{CHP_n}(t)$	Amount of electrical energy produced by nth CHP generator at time interval t.
$M^{e}_{CDG_n}(t)$	Amount of electrical energy produced by nth CDG generator at time interval t.
$M^{e}_{BUY_n}(\mathrm{t})$	Amount of electrical energy bought by nth MG from main grid at time interval t.
$M^{e}_{SELL_n}(\mathrm{t})$	Amount of electrical energy sold by nth MG to main grid at time interval t.
$M^{e-}_{BESS_n}(\mathrm{t})$	Amount of electrical energy discharged from the nth MG's BESS at time interval t.
$M^{e+}_{BESS_n}(\mathrm{t})$	Amount of electrical energy charged to the nth MG's BESS at time interval t.
$M^{h}_{CHP_n}(t)$	Amount of thermal energy produced by nth CHP generator at time interval t.
$M^{h}_{HOB_n}(\mathrm{t})$	Amount of thermal energy produced by nth HOB unit at time interval t.
$M^{h}_{SEND_{n\to\bar{n}}}(\mathrm{t})$	Amount of thermal energy sent by nth MG to the $\bar{n}^{th}$ at time interval t.
$M^{h}_{RECV_{\bar{n}\to n}}(t)$	Amount of thermal energy received by nth MG from $\bar{n}^{th}$ MG at time interval t.
$M^{h}_{Loss_{m\to n}}$	Amount of thermal energy lost while receiving $M^{h}_{RECV_{m\to n}}$.
$M^{h-}_{HESS_n}(\mathrm{t})$	Amount of thermal energy discharged from the nth MG's HES at time interval t.
$M^{h+}_{HESS_n}(\mathrm{t})$	Amount of thermal energy charged to the nth MG's HES at time interval t.
$M^{e}_{Load_n}(t)$	ELD of nth MG at time interval t.
$M^{h}_{Load_n}(t)$	TLD of nth MG at time interval t.
$d_{[m][n]}$	Distance between mth and nth MGs in kms.
$c_{[m][n]}$	Capacity of thermal line connecting mth and nth MGs in kWh.
$l_{[m][n]}$	Loss per km for trading thermal energy between mth and nth MGs in percentage.
$M^{e}_{CAP_n}$	Electrical capacity of line connecting nth MG with the main grid.
$M^{h}_{CAP_{n\to m}}$	Capacity of thermal line connecting nth MG with mth MG.
$M^{e}_{SOC_n}(t)$	SOC of nth MG's BESS at time interval t.
$M^{h}_{SOC_n}(t)$	SOC of nth MG's TESS at time interval t.
$M^{e-}_{Loss_n}$	Amount of electrical energy lost while discharging nth BESS in percentage.
$M^{e+}_{Loss_n}$	Amount of electrical energy lost while charging nth BESS in percentage.
$M^{h}_{Loss_n}$	Amount of thermal energy lost by nth TESS after one time interval in kWh.
$U^{SU}_{n}(t)$	Binary variable for determining startup cost of nth CDG unit.
$V^{SU}_{n}(t)$	Binary variable for determining startup cost of nth HOB unit.
$U_n(t)$	Binary variable for determining on/off status of nth CDG unit.
$V_n(t)$	Binary variable for determining on/off status of nth HOB unit.
η_n	Ratio of electrical to thermal energy of nth CHP unit.
N, M	Total number of MGs in the MG network.
T	Total number of operation intervals.
I	Total number of linearized intervals (pieces) in CHP cost function.

Appendix B

Table 2. Hourly Electrical and Thermal Load of MGs in the NMG

Time	MG1			MG2			MG3		
	$M^e_{Load_1}$	$M^h_{Load_1}$	$M^e_{WM_1}$	$M^e_{Load_2}$	$M^h_{Load_2}$	$M^e_{WM_2}$	$M^e_{Load_3}$	$M^h_{Load_3}$	$M^e_{WM_3}$
1	100	244	8	280	131	0	180	70	4
2	105	251	10	298	128	0	196	84	8
3	75	268	15	320	141	0	210	69	15
4	80	239	25	475	247	4	213	62	25
5	101	283	12	580	275	6	198	79	18
6	186	113	10	679	220	15	179	87	8
7	217	103	20	825	261	20	254	135	15
8	143	119	18	898	272	16	178	144	10
9	150	121	14	881	280	12	197	170	8
10	169	133	8	720	255	4	155	181	5
11	213	144	4	643	248	6	187	142	15
12	209	216	0	445	272	10	128	162	25
13	147	120	0	483	235	12	169	83	14
14	150	164	0	454	353	2	257	60	23
15	160	122	4	423	324	5	227	88	18
16	105	120	6	438	338	12	320	91	6
17	116	157	10	501	310	14	338	82	10
18	139	148	18	544	358	10	321	87	12
19	193	164	22	610	327	8	294	94	20
20	205	244	20	687	229	6	165	78	14
21	218	276	16	703	167	15	143	126	8
22	119	262	8	673	133	20	156	153	2
23	102	299	18	600	150	24	181	174	0
24	139	280	2	571	128	20	121	153	0

Table 3. Distance, Capacity, and Loss per km for Thermal Energy Trading Pairs

MG Pair	MG1 ←→MG2	MG2 ←→MG3	MG1 ←→MG3
Distance (km)	1.3	0.8	0.55
Thermal line Capacity (kWh)	100	110	90
Loss per km	8.5%	8.5%	8.5%

Appendix C

Table 4. Parameters for BESS, TESS, and CHP Units of Individual MGs

Parameters / MGs	BESS			TESS			CHP		
	Capacity (kWh)	Initial Value (kWh)	Charging/ Discharging Loss (%age)	Capacity (kWh)	Initial Value (kWh)	Interval-wise Loss (kWh)	Min. (kWh)	Max. (kWh)	Heat to Power Ratio
MG1	100	0	2	50	5	5	49	168	0.55
MG2	100	0	2	50	5	5	264	880	2.0
MG3	100	0	2	50	5	5	66	220	1.23

Table 5. Parameters for CDG and HOB Units with Line Capacities of Individual MGs

Parameters / MGs	CDG				HOB				Line Capacity (kWh)
	Cost (KRW)	Min. (kWh)	Max. (kWh)	Startup Cost (KRW)	Cost (KRW)	Min. (kWh)	Max. (kWh)	Startup Cost (KRW)	
MG1	120	0	100	139	129	0	100	150	80
MG2	100	0	70	125	142	0	50	168	150
MG3	110	0	80	170	115	0	120	120	100

Table 6. Hourly Buying and Selling Prices for the TNMG

Time	1	2	3		5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
P_{BUY}^{e}	49	55	68	77	88	95	110	130	140	160	171	172	175	150	120	100	75	65	54	49	60	85	110	140
P_{SELL}^{e}	37	43	56	65	76	83	98	118	128	148	159	160	163	138	108	88	63	53	42	37	48	73	98	128

Acknowledgments

This work was supported by the Power Generation & Electricity Delivery Core Technology Program of the Korea Institute of Energy Technology Evaluation and Planning (KETEP), granted financial resource from the Ministry of Trade, Industry & Energy, Republic of Korea. (No. 20141020402350).

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