Optimal microgrid controller design of a hybrid microgrid for Khun Pae village in Thailand

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Abstract

This paper presented the allocation of available local distributed energy resources with the aim of maximizing the use of renewable energy resources for Khun Pae Village in Chiang Mai, Thailand, which is considered a microgrid. As a reference, a microgrid simulation was done by HOMER Pro with black box code utilization. This method integrates a new optimal microgrid controller dispatching design using a Modified Heuristic into the existing HOMER scheme to find the minimized Net Present Cost (NPC) and Cost of Energy (COE). The results showed that the NPC and COE based on the Modified Heuristic technique provided lower costs than those obtained from HOMER Pro Load Following. It was also shown that the proposed optimization technique provides smoother and lower operating costs as well as annual throughput to extend battery lifetime.

Keywords: Distributed energy resources, Renewable energy, Microgrid controller, Net Present Cost, Cost of Energy, HOMER Pro Load Following, Modified Heuristic

1. Introduction

Globally, electricity consumption per capita has increased by 40 percent since 1990. Along with this growing demand for renewable energy, there are still over 1.3 billion people in remote areas who either do not have access to reliable sources of electricity or who are not connected to a power grid at all. For this reason, a new approach is needed for the grid of the future to accommodate this issue. This means a grid that can support remote mining and industrial sites and communities in addition to managing the peaks and troughs of energy demand. Further, it must be a grid that can support the need for a greener planet.

The next promising evolution of the conventional grid is Microgrid (MG) solution, which can safely integrate the maximum possible renewable energy into small scale power networks and choose the optimal microgrid controller design with Battery Energy Storage System (BESS) optimization to meet the lowest long-term energy costs, grid stability and the best outcome for the environment.

Examples of such studies include S.C. Bhattacharyya [1], who investigated and reviewed alternative methodologies for analyzing the off-grid electricity supply. They found different methodologies for electrification in off-grid areas and indicated the strengths and weaknesses of each approach. This study, however, did not include the optimal microgrid controller dispatching design with combined hydro, solar and BESS.

O. Erdinc and M. Uzunoglu [2] introduced optimization techniques for MG planning. Several sizing

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methodologies including available software as well as potential different optimization techniques were examined in the context of this paper. They found that HOMER (Hybrid Optimization Model for Multiple Energy Resources) was the black box code utilization and introduced optimization techniques for microgrid planning.

A.T.D. Perera, R.A. Attalage, K.K.C.K. Perera and V.P.C. Dassanyake [3] presented a new optimization method that was a combination of multi-criterion and multi-objective optimization on a standalone renewable energy system using HOMER without considering the optimal MG controller dispatching design with combined hydro, solar and BESS.

W. Margaret Amutha and V. Rajini [4] investigated the cost-benefit and technical analysis of rural electrification alternatives in southern India using simulation software. They showed that a hybrid combination of solar, wind, hydro and BESS is a cost-effective, sustainable, and economically as well as environmentally viable alternative to grid extension. However, this study focused only on the results of comparing conventional grid extension-related costs and did not include the optimal MG controller dispatching design with combined hydro, solar and BESS.

S. Salahi, F. Adabi and S. Babak Mozafari [5] designed and simulated a Hybrid MG for Bisheh Village, Iran. They analyzed a sensitivity analysis to investigate the effects of problem uncertainties such as interest rate and purchasing price by using simulation software. This study did not include the optimal microgrid controller dispatching design with combined hydro, solar and BESS.

The main purpose of this paper is to study an optimal MG controller design with energy storage optimization considering renewable energy grid integration. To achieve this objective, a remote village called Khun Pae in Chiang Mai Province, Thailand was considered. Electricity production and cost comparison based on various combinations of renewable energy grid integration were calculated using developed simulation software. The new proposed dispatching Modified Heuristic is used to achieve optimally considering economical and technical issues in order to supply the predicted mid-term and long-term loads. Net Present Cost (NPC) and Cost of Energy (COE) results are compared with conventional HOMER Pro Load Following.

2. Smart Microgrid Khun Pae Village

In accordance with the Thai government's policy to promote clean energy to supply power to the distribution system, the Provincial Electricity Authority (PEA) has devised a power development plan aiming to develop a secure and smart distribution system to support the application of distributed renewable energy resources. Microgrid is one of the projects in PEA's network development plan. PEA identified the development of a microgrid at Khun Pae Village, Chiang Mai Province project, as shown in Fig. 1. Khun Pae Village is located at 18° 18’ 31’’ N, 98° 29’ 06’’ E, roughly 35 km away from Hod substation. It covers a residential area of 1.08 km2, a farming area of 19.02 km2 and a concession area of 36.10 km2. This village has an average temperature of 25 ℃ throughout the year, annual average wind speed of 3.01 m/s, annual average solar radiation of 4 to 6 kWh/m^2/day and annual flow the river average of 0.35 m3/day from May to October in the rainy season. With this statistical data, the village has significant potential for the utilization of renewable sources. It consists of 735 households with 3,818 people.

The load profile data is taken from the PEA record. The primary load demand is approximately 69.85 kW peak. The demand has been estimated for two different modes, comprising normal and water-saving modes. The average daily load of Khun Pae village is shown in Fig. 2.

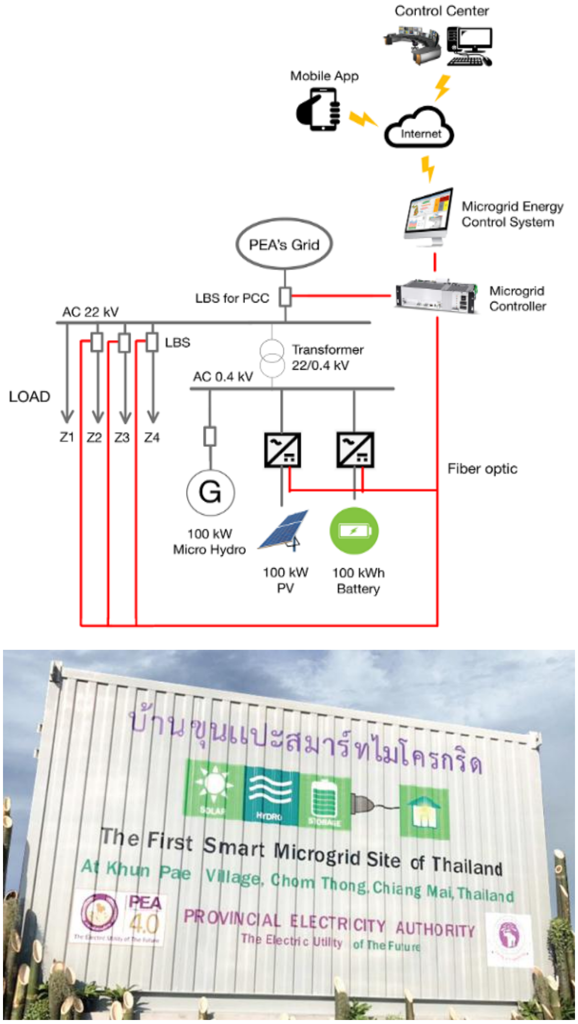

Fig. 1. Single line diagram of a microgrid at Khun Pae

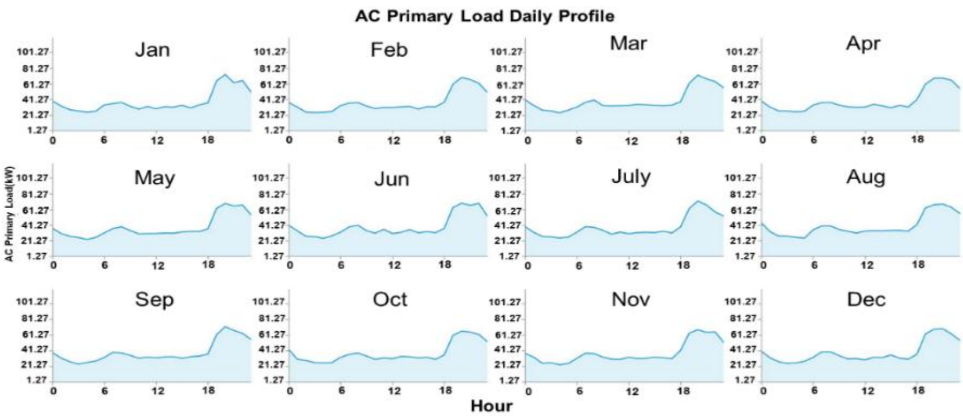

Fig. 2. Average daily load in Khun Pae village

A grid-connected hybrid energy system for Khun Pae village was optimally designed with regard to the potential of micro-hydro, solar PV energy and BESS [6]. The MG function was designed to operate both grid connecting and islanding modes. In grid connecting mode, the micro-hydro, solar PV and BESS can supply AC primary load with the main grid in PQ control mode. In island mode, the MG controller can disconnect the load break switch at PCC connection and supply all AC primary load zones with hydro, PV and BESS mode. If the power in BESS is less than 60 %, the loads for zone 3 and zone 4 will be disconnected. On the other hand, if the power in BESS is less than 40 %, the disconnection of the loads from zone 2 will be required, as shown in Fig. 3.

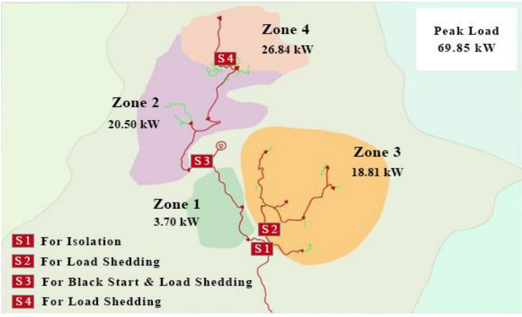

Fig. 3. Load zoning under microgrid controller

3. Khun Pae Microgrid Configuration Design

A simulation was done by using HOMER Software, which was developed by the U.S. NREL. To perform a sensitivity analysis on the price of purchasing power from the main grid, a tariff rate of 0.106 $/kWh (the average electricity price of Thailand) was applied. Also, a sensitivity analysis was performed based on various parameters such as interest rate, grid prices, wind speed, solar radiation, and air temperature. The obtained results were compared against each other. The simulation identified the optimal hybrid microgrid configuration with a connection to the main grid, as shown in Fig. 4. In addition, the use of renewable natural resources and BESS inside the microgrid was more economical than purchasing power from the main grid [7].

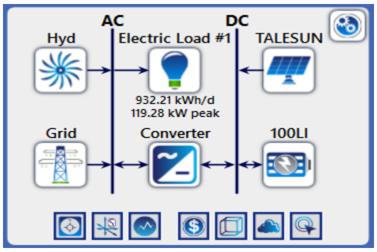

Fig. 4. Overall diagram of the hybrid microgrid connected to the main grid

After examining each design, the simulation software selected the one that could meet the load with the system constraints. The various combinations of renewable energy for Khun Pae Village were compared and evaluated with a conventional option based on Net Present Cost (NPC) and Cost of Energy (COE). The NPC (life-cycle cost) of a component is defined as the present value of all the costs of installing and operating the component over the project lifetime minus the present value of all the revenue that it earns over the project lifetime. The annualized value total NPC using the following equation is given below.

$$C_{ann,tot} = CRF\left(i, R_{proj}\right) \cdot C_{\mathrm{NPC},tot} \tag{1}$$

where,

$C_{ann,tot}$ = The Total Annualized Cost [$/year]

$C_{\mathrm{NPC},tot}$ = The Total Net Present Cost [$]

i = The Annual Real Discount Rate [%]

R_{proj} = The Project Life Time [year]

$CRF\left(i, R_{proj}\right)$ = A Function Returning the Capital Recovery Factor

The simulation software defines the levelized cost of energy as the average cost per kWh of useful electrical energy produced by the system. The simulation software divides the annualized cost of producing electricity by the total useful electric energy production using the equation below.

$$COE = \frac{C_{ann,tot}}{E_{served,ACprim} + E_{served,DCprim} + E_{served,def} + E_{grid,sales}} \quad (2)$$

where,

$C_{ann,tot}$ = The Total Annualized Cost [$/year]

$E_{served,ACprim}$ = The AC Primary Load Served [kWh/yr]

$E_{served,DCprim}$ = The DC Primary Load Served [kWh/yr]

$E_{served,def}$ = The Deferrable Load Served [kWh/yr]

$E_{grid,sales}$ = The Energy Sold to the Grid [kWh/yr]

4. Optimal Microgrid Controller Dispatching Design by Simulation Software

4.1. Proposed modified heuristic optimization technique [9]

The proposed Modified Heuristic makes use of the last time step for the production of Solar PV power output each day. The concept of this method aims to manage energy efficiency by detecting the last time step for the production of Solar PV power output and the SOC of BESS. As the night time (PV power output = 0) only energy from hydro and battery is available, the battery should have the full SOC in this time step by filling energy to BESS from the hydropower output in the previous time step. The time step in the Modified Heuristic has two conditions, as follows: (1) The time step is the last time step for the production of Solar PV power output (2) the SOC of BESS in the time step is less than 100%. The simulation software uses the following equation to calculate the Solar PV power output.

$$P_{PV} = Y_{PV} f_{PV} \left(\frac{\overline{G_T}}{\overline{G_{T,STC}}} \right) \left[1 + \alpha_P \left(T_c - T_{c,STC} \right) \right] \quad (3)$$

Y_{PV} = The Rated Capacity of the PV Array, Meaning Its Power Output under Standard Test Conditions [kW]

f_{PV} = The PV Derating Factor [%]

$\overline{G_T}$ = The Solar Radiation Incident on the PV Array in the Current Time Step [kW/m^2]

$\overline{G_{T,STC}}$ = The Incident Radiation at Standard Test Conditions [1 kW/m^2]

α_P = The Temperature Coefficient of Power [%/ ℃]

T_c = The PV Cell Temperature in the Current Time Step [℃]

$T_{c,STC}$ = The PV Cell Temperature under Standard Test Conditions [25 ℃]

Another important equation that affects the energy production of Solar PV is finding the incident angle of the light from the sun relative to the surface of the Solar PV.

$$\cos\theta = \sin\delta\sin\phi\cos\beta - \sin\delta\cos\phi\sin\beta\cos\gamma + \cos\delta\cos\phi\cos\beta\cos\omega + \cos\delta\sin\phi\sin\beta\cos\gamma\cos\omega + \cos\delta\sin\beta\sin\gamma\sin\omega \tag{4}$$

θ = The Angle of Incidence [°]
β = The Slope of the Surface [°]
γ = The Azimuth of the Surface [°]
ϕ = The Latitude [°]
δ = The Solar Declination [°]
ω = The Hour Angle [°]

The SOC of the BESS can be considered as follows

$$SOC(i) = \begin{cases} SOC(i-1) + \left(\left(E_{batt,charge} \times \eta_{batt,c} \right) \times \dfrac{100}{Q_{\max}} \right) & \text{Normal} \\ SOC(i-1) + \left(\left(E_{PV,i} + \left(E_{hyd,i} - E_{prim,AC,i} \right) \times eff_{inv} \right) \times \eta_{batt,c} \times \dfrac{100}{Q_{\max}} \right) & \text{Modified Heuristic} \end{cases} \tag{5}$$

$SOC(i)$ = State of Charge in ith Time Step (%)
$E_{batt,charge}$ = Energy Charge to Battery [kWh]
$Q_{\max}$ = The Total Capacity of the Storage Bank [kWh]
$\eta_{batt,c}$ = Battery Charge Efficiency [%]
$E_{PV,i}$ = Solar PV Power Output in ith Time Step [kWh]
$E_{Hyd,i}$ = Hydro Power Output in ith Time Step [kWh]

The overall flowchart of the proposed Modified Heuristic optimization technique is shown in Fig. 5.

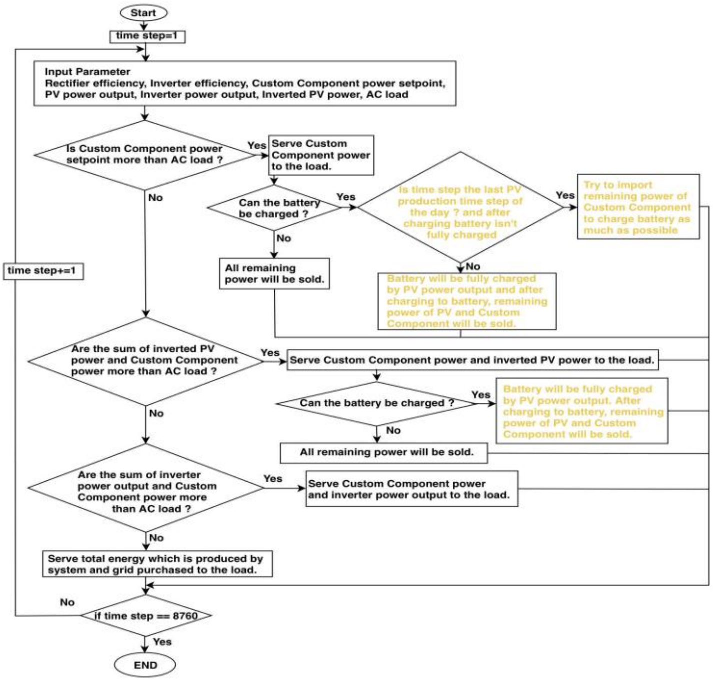

Fig. 5. Flowchart of the proposed modified Heuristic optimization technique

The monthly average value of electric energy generation in a year for these studies is shown in Fig. 6. The state of charge of the BESS is shown in Fig. 7.

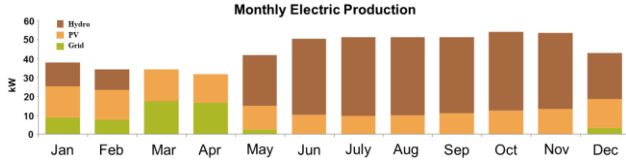

Fig. 6. Monthly value of electric energy generation

The diagram shows the monthly value of electric production in a year. The proportions of power generation from solar PV, micro-hydro and main grid purchase are 29.40 %, 59.70 %, and 10.80 %, respectively. The solar PV power output is 17.90 kW or equivalent to 430 kWh/day, while the total production is 157,052 kWh/year. It can generate a maximum output of 96.30 kW and its levelized cost is 0.0727 $/kWh. The micro hydropower plant can generate the maximum output of 55.60 kW and the average output is 36.30 kW. The micro hydropower plant cannot operate in March and April (summer season). The annual electrical production is 318,418 kWh/year and its levelized cost is 0.0477 $/kWh. The main grid purchased energy amounting to about 57,848 kWh/year and energy sales of around 182,901 kWh/year. The state of charge of the BESS is shown in Fig. 7.

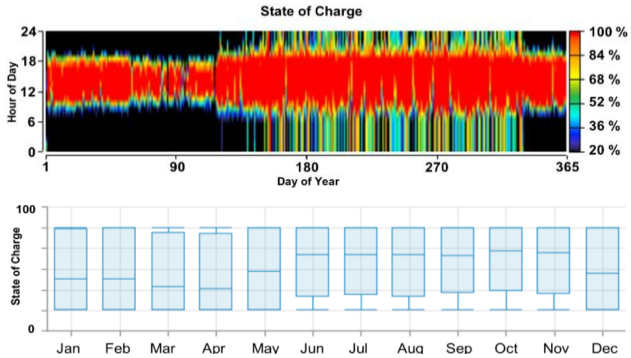

Fig. 7. State of charge (SOC) of BESS

The BESS has energy-in, energy-out and annual throughput of approximately 24,773 kWh/year, 22,353 kWh/year and 23,562 kWh/year, respectively. The power generation from all sources in a day of August normal and water-saving modes is shown in Fig. 8 and Fig. 9, respectively.

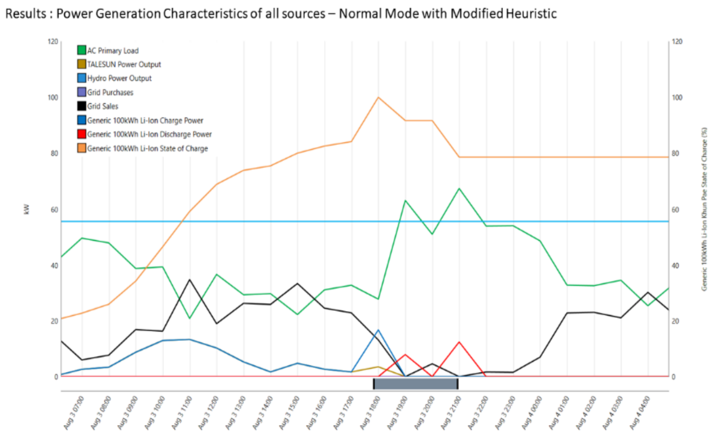

Fig. 8. Power generation characteristics of all sources – normal mode with Modified Heuristic

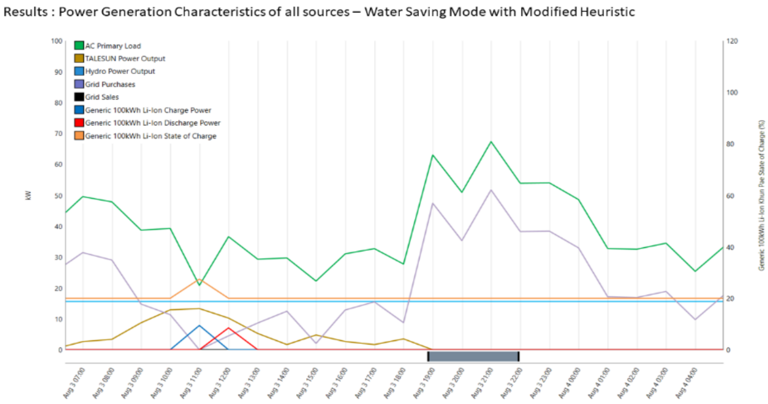

Fig. 9. Power generation characteristics of all sources – water-saving mode with Modified Heuristic

5. Case Study and Results

The modified heuristic method expands opportunities for full charging of the BESS. On August 3 at 6 pm, the BESS was not fully charged by the residual Solar PV power. However, this hour was the last time for Solar PV production this day. The system had the residual water power 27.82 kW and the SOC of BESS was at 84.11 %. The modified heuristic decided to deliver the residual water power to charge the battery as much as possible to store renewable energy while maintaining a low level of losses. On August 3 at 6 pm, the BESS was charged with 3.52 kW from Solar PV and 13.21 kW from Hydropower, and 13.14 kW was sold to the grid. The SOC of the BESS was increased from 84.11 % to 100 %. Therefore, this method can store more power at battery than the common Heuristic and Dynamic Programing methods, as shown in Fig. 10, 11 and 12, respectively.

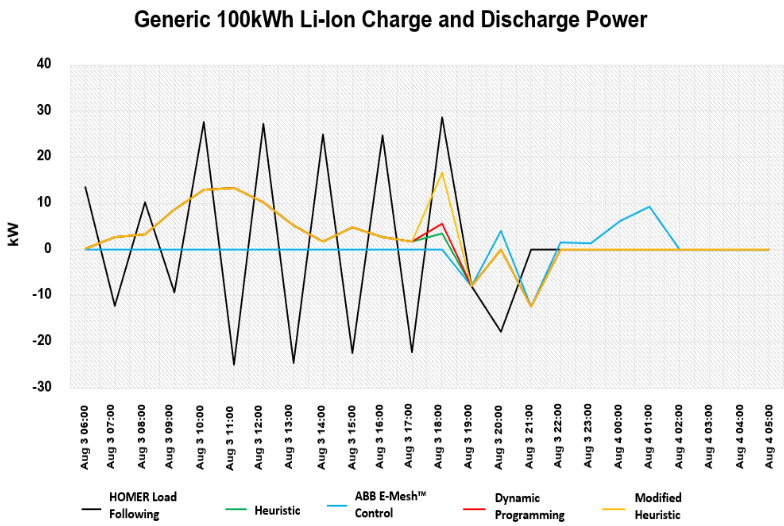

Fig. 10. Comparison of the dispatched optimization methods for charged and discharged power

By comparing the dispatched optimization of all methods for charging and discharging power, as shown in Fig. 10 for August 3 at 6.00 pm, HOMER Pro Load Following controller commanded that energy was charged to the BESS and discharged for sale to the grid or to serve the load. Modified Heuristic chose to charge the battery more than Dynamic Programming and Heuristic did while the ABB E-mesh control started to discharge for serving load after August 3 at 6.00 pm.

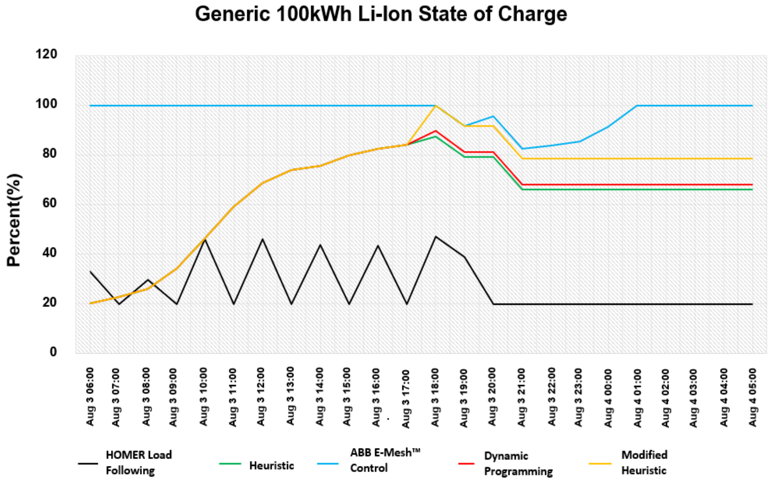

Fig. 11. Comparison of the dispatched optimization methods for state of charge (SOC)

The time-dependent state of charge (SOC) is shown in Fig. 11. On August 3 at 6.00 pm, the SOC of BESS for Modified Heuristic and ABB E-mesh control was kept higher than 80%, followed by Dynamic Programming, Heuristic and HOMER Pro Load Following, respectively.

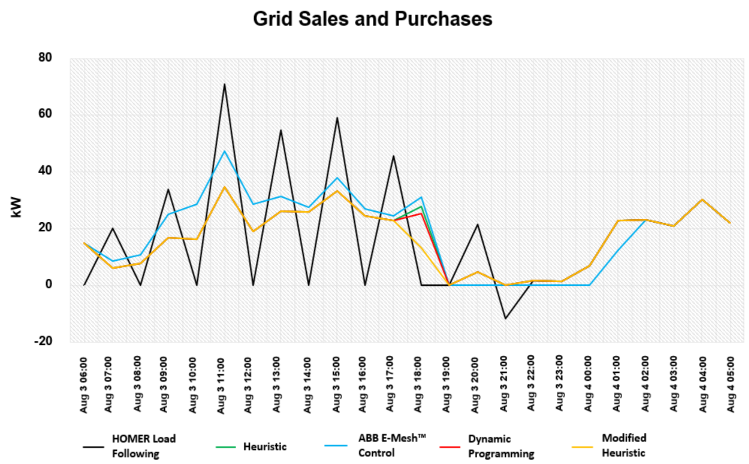

Fig. 12. Comparison of the dispatched optimization methods for grid sales and purchases

Based on the grid sales and purchases for each period shown in Fig. 12, Heuristic, Dynamic Programming, and ABB E-mesh control offered a similar result; That is, they tried to sell energy to the grid in many time slots. For HOMER Load Following, the SOC value was observed to be zero from 8 pm, but energy was sold to the grid most of the time. The optimal microgrid controller dispatching design for a single tariff by HOMER Pro Load Following, Heuristic, ABB E-Mesh™ Control [10], Dynamic Programing and Modified Heuristic is shown in Table 1.

Table 1. Comparative results for the optimal microgrid controller dispatching design with a single tariff

Type of Dispatching	Normal Mode				Water-Saving Mode			
	NPC ($)	Diff (%)	COE ($)	Diff ($)	NPC ($)	Diff (%)	COE ($)	Diff ($)
HOMER Load Following (Reference case)	956,734.50	-	0.1041	-	1,063,233.00	-	0.1267	-
Heuristic	946,152.40	-1.11	0.1025	-1.54	1,056,776.00	-0.61	0.1254	-1.03
ABB E-Mesh™ Control	965,176.80	0.88	0.1050	0.86	1,081,219.00	1.69	0.1287	1.58
Dynamic Programming	946,176.00	-1.10	0.1025	-1.54	1,056,798.00	-0.61	0.1254	-1.03
Modified Heuristic	946,162.80	-1.10	0.1025	-1.54	1,056,820.00	-0.60	0.1254	-1.03

The analysis was extended to include two tariffs (peak and off-peak periods) with different rates of power purchase from power sale to the main grid. The prices for power exchange are shown in Table 2. The results of NPC and COE are shown in Table 3.

Table 2. The prices for exchange power with PEA's grid

Consumption Time	Purchase Rate from the Main Grid ($/kWh)	Sale Rate to the Main Grid ($/kWh)
Off-peak (22:00-09:00)	0.070	0.088
Normal (Single tariff)	0.106	0.088
On-peak (09:00-22:00)	0.150	0.088

Table 3. Comparative results for optimal microgrid controller dispatching design with two tariffs (Normal Mode)

Type of Dispatching	Single Tariff		Two Tariffs	
	NPC ($)	COE ($)	NPC ($)	COE ($)
HOMER Load Following (Reference case)	956,734.50	0.1041	950,230.90	0.1032
Heuristic	946,152.40	0.1025	938,629.90	0.1017
ABB E-Mesh™ Control	965,176.80	0.1050	959,677.50	0.1044
Dynamic Programming	946,176.00	0.1025	938,639.60	0.1017
Modified Heuristic	946,162.80	0.1025	938,651.60	0.1017

The simulation results in Table 3 show that the NPC of Heuristic, Modified Heuristic, and Dynamic Programming are similar. The NPC obtained from Heuristic for single and dual tariff is slightly lower than the others. The results of HOMER Pro Load Following and ABB E-Mesh™ Control are more expensive than the proposed Heuristic, Modified Heuristic, and Dynamic Programming dispatch strategy. However, Heuristic not only offers the lowest-cost NPC in both normal mode and water-saving mode, but also provides the lowest NPC in both single tariff and two tariffs. The introduction of two tariffs tends to decrease NPC and COE for all dispatch strategies.

Table 4. Comparative results for optimal MG controller dispatching design with energy in/out and losses of BESS (Normal Mode)

Type of Dispatching	Energy In (kWh/yr.)	Diff (%)	Energy Out (kWh/yr.)	Diff (%)	Losses (kWh/yr.)	Diff (%)	Annual Throughput (kWh/yr.)	Diff (%)
HOMER Load Following (Reference case)	50,201	-	45,238	-	5,023	-	47,685	-
Heuristic	24,753	-50.69	22,334	-50.63	2,478	-50.67	23,542	-50.63
ABB E-Mesh™ Control	25,038	-50.12	22,591	-50.06	2,507	-50.09	23,813	-50.06
Dynamic Programming	24,766	-50.67	22,346	-50.60	2,480	-50.63	23,555	-50.60
Modified Heuristic	24,773	-50.65	22,353	-50.59	2,480	-50.63	23,562	-50.59

The results in Table 4 show the energy in, energy out and losses for each method. The results reveal that the proposed Heuristic, Modified Heuristic, and Dynamic Programming and ABB E-Mesh™ Control can provide lower energy in/out, losses and annual throughput than HOMER Pro Load Following. It is obvious that the proposed optimization techniques provide smoother and lower annual throughput in order to extend battery life time.

6. Conclusion

This paper presents a heuristic-based methodology to maximize the use of local distributed energy resources, including renewable energy. The microgrid at Khun Pae Village in Chiang Mai, Thailand was used as a case study in the simulations. It can be seen from the optimal microgrid controller dispatching design by the simulation software that all dispatches result in slightly different Net Present Cost (NPC) and Cost of Energy (COE) for these case studies. Because HOMER Pro is a black box code utilization, this paper proposes a new optimal microgrid controller dispatching design using the modified heuristic technique integrated into the existing simulation software scheme to find the minimum NPC and COE. The results show that NPC and COE based on the modified heuristic enable lower costs than those obtained from HOMER Pro Load Following. In addition, the proposed optimization techniques obviously provide smoother and lower operating costs to supply the predicted mid-term and long-term loads for the village and annual throughput to extend battery life time. Furthermore, the obtained results of two tariffs analysis reveal that the two tariffs rates offer lower NPC (life cycle cost) when compared with a single tariff. Future research should focus on possible optimization techniques and multiple tariff rates to find lower NPC and COE.

Conflict of Interest

In Thailand, many areas still lack sufficient power generation, thus affecting the reliability and quality of the distribution grid system. This study presents an optimization technique to enhance the available locally distributed energy resources and maximize the use of renewable energy resources. Khun Pae Village in Chiang Mai, Thailand was employed as the testbed location. Electricity production and cost comparison based on various combinations of renewable energy grid integrations are calculated using the simulation software. The new proposed dispatching could be used to achieve optimal results considering economical and technical issues in order to supply the predicted mid-term and long-term loads. Therefore, the authors declare that there is no conflict of interest regarding the publication of this article.

Author Contributions

Praditpong Suksirithawornkul and Assoc. Prof. Dr. Suttichai Premrudeepreechacharn conceived, planned the optimization techniques and carried out the simulations. Tirapong Kasirawat contributed to sample preparation data. Assoc. Prof. Dr. Somporn Sirisumrannukul contributed to the interpretation of the results. All authors provided critical feedback and helped shape the research, analysis and manuscript. Praditpong Suksirithawornkul took the lead in writing the manuscript.

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