Cost and Emission Optimization in Power Plant Using the Single Echelon Economic Dispatch Model (SEED)

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Abstract. The electricity supply chain system consists of power plants, transmission and distribution. Differences in power plant characteristics cause differences in fuel costs and emissions. Inaccuracies in scheduling the plant have an impact on the surge in fuel use. This becomes the basis for the optimization of power plant scheduling. Optimization on the generator side is usually using the economic dispatch model. However, the Economic Dispatch Model does not consider optimization on the transmission network. Optimization on the transmission network is needed because there are losses in the transmission network. Losses will be even greater when the distance between the power plant and the customer is getting farther away. So if distance can be minimized, fuel costs can be reduced. Minimizing the distance for shipping goods can use the transportation model, but the transportation model cannot be used for electricity distribution. This is because there are differences between goods and electricity. Therefore, this study proposes the Single Echelon Economic Dispatch (SEED) model. This model is a combination of the economic dispatch model and the transportation model. This model is able to do simultaneous optimization between the generator side and the transmission side. The model is applied to the Mahakam system in East Kalimantan, using all PLN's power plants. Load consists of two types, namely low load and peak load. As a result, in peak load and low load conditions, the P11 power plant produces the biggest losses and emissions. This is because electricity production in P11 has to go through a longer path compared to other plants. The P11 is also a power plant that requires the highest fuel costs

1. Introduction

The electric power interconnection system is a system where Power plants located in various locations are connected to all customers in various regions. This interconnection causes a group of power plants to act as a group of suppliers. If all the power plants have the same characteristics, the allocation of the burden of each power plant is easy [1], [2]. In fact, the power plant has different characteristics. This difference causes differences in total costs and emissions so that the total production of each power plant must be calculated in advance to reduce the impact on increasing costs and emissions [3], [4].

One model used to schedule and determine the amount that must be produced by each plant is Economic Dispatch. This model is able to perform optimization on the generator side so that it can get scheduling with a minimum total fuel cost.

However, the economic dispatch model does not consider the distribution side. The distribution side is important because of losses during electricity delivery [5], [6]. Losses are the partial loss of...
electricity sent from source to destination, where the farther the distance from the power plant to the customer, the greater the losses that occur.

Increased losses can lead to higher fuel costs and emissions. This is because the power plant must produce more electricity than the total demand [7], [8]. This is done to cover losses. Increasing the amount of production which causes an increase in costs and emissions. Based on this, losses must be managed.

Loss management by optimizing the shipping path can be done on the transmission network. A set of power plants must be determined to precisely supply which set of power plants. So that we get a minimum total distance. Thus it can produce smaller losses [9].

Allocating shipping lines usually uses a transportation model. Many transportation models are applied to various real problems. This is because this model is simple and easy to use. Various problems are solved by the transportation model including, the allocation of labor, the selection of factory locations, the selection of supplier locations, the distribution of goods, and others. This model is simple because it only requires data on production capacity in a source, demand capacity for a destination, and transportation costs from source to destination.

However, the transportation model cannot be used for electricity allocation and distribution. This is because there are differences between the nature of electricity and manufactured goods. There are 2 main differences between electricity and manufactured goods. First, electricity cannot be stored. Second, electricity must always be available.

Therefore, this study proposes a new model called the Single Echelon Economic Dispatch (SEED). This model combines the advantages of the transportation model and the economic dispatch model so that the combined optimization between the production side and the distribution side is obtained. This model is able to make detailed electricity generation and distribution scheduling allocations with minimal total costs.

2. Literature Review

2.1. Single Echelon Transportation Model
The transportation model manages the delivery of goods from a collection of sources to a set of destinations. This model is introduced by (Hitchcock, 1941). In this case, commodities can be sent from various sources to various destinations. The mechanism is illustrated in the following figure:
Constraints:  
\[ \sum_{j} X_{ij} \leq S_i \quad \forall i \]  
\[ \sum_{i} X_{ij} \geq D_j \quad \forall j \]  
\[ X_{ij} \geq 0 \quad \forall i, j \]  

where 
\( S_i \): Supply capacity at source i  
\( D_j \): Demand at point j.  
\( C_{ij} \): Shipping costs from source i to destination j.  
\( X_{ij} \): Number of items sent from source i to destination j.

The main difference between transportation for goods and transportation for electricity is the balance between supply and demand. In the transportation model for goods, suppliers are allowed to send goods greater than demand. (Equation 3), but in transportation for electricity, suppliers must send goods as large as demand or called equilibrium. This point of equilibrium is called the Balanced Transportation Problem (BTP). Variations in BTP can be seen in Figure 2 (Sabbagh, Ghafari, & Mousavi, 2015). The difference between the two also occurs at the supplier's capacity limits.

| Model BTP-1: | Model BTP-2: | Model BTP-3: |
|-------------|-------------|-------------|
| \[ \text{Min } z = \sum_{i=1}^{m} \sum_{j=1}^{n} c_{ij} \cdot x_{ij} \] | \[ \text{Min } z = \sum_{i=1}^{m} \sum_{j=1}^{n} c_{ij} \cdot x_{ij} \] | \[ \text{Min } z = \sum_{i=1}^{m} \sum_{j=1}^{n} c_{ij} \cdot x_{ij} \] |
| Subject to \[ \sum_{j=1}^{m} x_{ij} \geq s_i, (i = 1 \ldots m) \] | Subject to \[ \sum_{i=1}^{m} x_{ij} \leq s_i, (i = 1 \ldots m) \] | Subject to \[ \sum_{i=1}^{m} x_{ij} = s_i, (i = 1 \ldots m) \] |
| \[ \sum_{i=1}^{n} x_{ij} \leq d_j, (j = 1 \ldots n) \] | \[ \sum_{i=1}^{m} x_{ij} \geq d_j, (j = 1 \ldots n) \] | \[ \sum_{i=1}^{m} x_{ij} = d_j, (j = 1 \ldots n) \] |
| \[ x_{ij} \geq 0 \] | \[ x_{ij} \geq 0 \] | \[ x_{ij} \geq 0 \] |

\( c_{ij} \): shipping costs from source i to destination j  
\( x_{ij} \): the number of items sent from source i to destination j  
\( s_i \): the maximum amount of supply of resources i  
\( d_j \): demand at destination j.

2.2. Economic Dispatch Model
Economic dispatch was introduced since 1928. There are 3 researchers who are considered as the originator of the economic principle of the generator (Estrada, 1930; Stahl, 1931; Wilstam, 1928). The initial economic dispatch is called the classic Economic dispatch model. This model uses the concept of the base load method and the best point load method. How it works, sort generator units based on
the highest efficiency level. Furthermore, generator scheduling is given to the generating unit with the highest level of efficiency, and so on until the last generating unit.

When there are differences in the characteristics of each plant, the base load technique becomes less effective. Therefore, a new technique emerged known as equal incremental cost. The main concern of this technique is the characteristics of each different generator. The way it works, the meeting point of all generators is searched, and the optimal allocation is made based on this meeting point. This equal incremental cost technique is still used today. This technique was introduced by (Steinberg & Smith, 1933). The advantage of this technique is that it can provide a low total cost for all the plants involved in the system. However, this initial model still has shortcomings, namely the losses in the transmission network have not been considered. One of the causes of losses in transmission networks is the length of the transmission network. The longer the transmission distance, the greater losses will occur. These losses will ultimately affect the total cost of fuel because the plant must produce more electricity than the demand for compensation losses. Furthermore, Economic dispatch that considers losses in the network is introduced by (George et al., 1949). The Economic Dispatch formula is as follows:

\[
F_i = a_i P_i^2 + b_i P_i + c_i
\]

\[
P_{i,\text{min}} \leq P_i \leq P_{i,\text{max}}
\]

3. Proposed Model

3.1. Single Echelon Transportation Model

Transportation Model has advantages in the field of distribution. The use of this model causes the total shipping costs to be minimal. While the Economic Dispatch model has an advantage in the field of generator loading allocation or generator scheduling. The use of economic dispatch models is able to create a power plant scheduling that results in minimal fuel costs. Combining the advantages of these two models provides several advantages. First, the development of a new transportation model called the Single Echelon Economic Dispatch (SEED). Second, the combined optimization between the generator side and the distribution side. Conceptually, the development of the SEED model can be seen in the following figure:

![Figure 3. Conceptual Model for Single Echelon Economic Dispatch (SEED) development](image_url)
transportation is commonly used in people or goods while ED is used in electricity. The nature of the two objects is different. The main requirement for electricity is in the form of an equation between the supply side and the demand side. Therefore, as another approach used is the Balanced Transportation Problem as shown in Figure 2.

Three types of BTP as shown in Figure 2 are variations of the transportation model application for real cases. The three variations have the same objective function, namely minimization of costs (min z). While the difference between the three is the model limitation. Cost is the sum of the shipping costs per unit from each source i to destination j denoted by multiplied by the number of items sent from source i to destination j denoted by $x_{ij}$.

The characteristics of the three variations of BTP are used as a reference for the development of the SEED model. Development is carried out by combining several boundaries so that new variations of BTP emerge. Furthermore, a merger with the Economic Dispatch model was obtained to obtain the SEED model. The result of merging BTP with economic dispatch as in figure 4.

| Single Echelon Transportation Problem (Modification BTP) | Economic Dispatch (Equations 2.1 – 2.3) | Proposed Model (Single Echelon Economic Dispatch, SEED) |
|--------------------------------------------------------|------------------------------------------|-------------------------------------------------------|
| Min $z = \sum_{i=1}^{m} \sum_{j=1}^{n} c_{ij} \cdot x_{ij}$ | $F_i = a_i P_i^2 + b_i P_i + c_i$ | Minimize $F_i = \sum_{i=1}^{m} \sum_{j=1}^{n} a_i P_{ij}^2 + b_i P_{ij} + c_i$ |
| Subject to $\sum_{i=1}^{n} x_{ij} \geq s_{\text{min}} \cdot (i = 1 \ldots m)$ | $P_{i\min} \leq P_i \leq P_{i\max}$ | $\sum_{i=1}^{m} \sum_{j=1}^{n} a_i P_{ij}^2 + b_i P_{ij} + c_i$ |
| $\sum_{j=1}^{m} x_{ij} \leq s_{\text{max}} \cdot (i = 1 \ldots m)$ | $P_i = D_i$ | $\sum_j P_{ij} \geq P_{i\min}$ |
| $\sum_{i=1}^{n} x_{ij} = d_j \cdot (i = 1 \ldots n)$ | $\sum_j P_{ij} \leq P_{i\max}$ | $\sum_i P_{ij} = L_j + P_{\text{ij}} \cdot (j = 1 \ldots J)$ |
| | $P_{ij} \geq 0$ | $P_{ij} \geq 0$ |

Figure 4. Development mechanism of the proposed model

The SEED model has the objective function of minimizing fuel costs as well as in the economic dispatch model. While the difference between them lies in the coverage of the model. This can be seen from the notation used. The basic model of economic dispatch uses notation $P_i$, which means the amount of electricity produced at the generator i. Whereas the SEED model uses notation $P_{ij}$ which means the amount of electricity produced by the generator i sent to destination j. If this scope is included in the objective function, then this model is prepared to be able to complete 2 tasks, namely production optimization tasks, and simultaneous distribution optimization tasks. As a guarantee of a feasible solution, the SEED model is also equipped with 3 constraints.

4. Experiment and Results
This chapter discusses experiments using the SEED model. Divided into basic models, supply and demand data, and transmission data

4.1. Basic Model
There are 2 types of objectives that can be used in the SEED model, namely minimizing fuel costs (Rp) and minimizing emissions (kg), as shown in the following formula:

$$\text{Minimize } F_i = \sum_{i=1}^{K} \sum_{j=1}^{J} a_i P_{ij}^2 + b_i P_{ij} + c_i$$

(7)
\[
\min F_i = \sum_{i=1}^{K} \sum_{j=1}^{J} d_{ij} P_{ij}^2 + e_i P_{ij} + f c_i
\]

Constraint,
Limit of Power Plant:
\[
\sum_{j} P_{ij} \geq P_{i \text{min}}
\]
\[
\sum_{j} P_{ij} \leq P_{i \text{max}}
\]

Power Balance Constraint
\[
\sum_{i} P_{ij} = L_j + P_{kij} \quad (j = 1, \ldots, J)
\]

Non-negativity constraint
\[
P_{ij} \geq 0
\]

Where,
\(F_i\) : Total fuel costs (Rp)
\(E_i\) : Total emissions \(CO_2\)
\(a_i, b_i, c_i\) : coefficient of fuel cost curve for i-generations.
\(d_{ij}, e_i, f_i\) : \(CO_2\) emission curve coefficient for i-generations
\(P_{ij}\) : The amount of electricity produced by the generator \(i\) sent to the customer \(j\) (MW)
\(P_{i \text{min}}\) : Lower limit of i-generator production (MW)
\(P_{i \text{max}}\) : Upper limit of i-generator production (MW)
\(L_j\) : Demand for customers \(j\) (MW)
\(P_{kij}\) : Losses on the transmission network between \(i\) and \(j\) (MW)

4.2. Data of Experiments

The proposed model is used in the Mahakam interconnection system in East Kalimantan. This system has 11 power plants (P1 to P11) located in various locations. While demand is in 4 cities, namely Samarinda, Bontang, Balikpapan and Tenggarong. Demand for these 4 cities is divided into 12 locations (L1 to L12) as shown in the following table:

| Table 1. The distance between the Power plant and location |
|-----------------------------------------------------------|
| P | L1  | L2  | L3  | L4  | L5  | L6  | L7  | L8  | L9  | L10 | L11 | L12 |
|---|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 1 | 1.0 | 21.5| 16.8| 25.1| 37.1| 44.3| 123.9| 72.4| 100.5| 113.9| 113.9| 135.1|
| 2 | 16.8| 37.3| 1.0 | 9.3 | 21.3| 28.5| 108.1| 56.6| 84.7 | 98.1 | 98.1 | 119.3|
| 3 | 25.1| 45.6| 9.3 | 1.0 | 13.0| 20.2| 99.8 | 48.3| 76.4 | 89.8 | 89.8 | 111.0|
| 4 | 113.9| 134.4| 98.1| 89.8| 101.8| 109.0| 188.6| 137.1| 14.4 | 14.4 | 1.0  | 22.2 |
| 5 | 135.1| 155.6| 119.3| 111.0| 123.0| 130.2| 209.8| 158.3| 35.6 | 35.6 | 22.2 | 1.0  |
| 6 | 72.4 | 92.9 | 56.6 | 48.3 | 36.3 | 29.1 | 52.5 | 1.0  | 123.7| 137.1| 137.1| 158.3|
| 7 | 1.0  | 21.5 | 16.8 | 25.1 | 37.1 | 44.3 | 123.9| 72.4 | 100.5| 113.9| 113.9| 135.1|
| 8 | 123.9| 144.4| 108.1| 99.8| 87.8 | 80.6 | 1.0  | 52.5 | 175.2| 188.6| 188.6| 209.8|
| 9 | 123.9| 144.4| 108.1| 99.8| 87.8 | 80.6 | 1.0  | 52.5 | 175.2| 188.6| 188.6| 209.8|
| 10| 123.9| 144.4| 108.1| 99.8| 87.8 | 80.6 | 1.0  | 52.5 | 175.2| 188.6| 188.6| 209.8|
| 11| 111.6| 132.1| 95.8 | 87.5| 99.5 | 106.7| 186.3| 134.8| 12.1 | 25.5 | 25.5 | 46.7 |
Each interconnected power plant has characteristics like the following table:

|   | Limit of Power Plant | Constanta of cost function |
|---|---------------------|-----------------------------|
|   | L Pimin  | Pimax  | a   | b   | c    |   |
| 1 | 23.5    | 14.0   | 32.0 | -256.0 | 1,200.0 |
| 2 | 16.0    | 5.0    | -1.1 | 263.9  | 250.0   |
| 3 | 3.1     | 2.0    | 17.0 | 49.9   | 150.0   |
| 4 | 3.6     | 2.0    | 32.0 | 256.0  | 256.0   |
| 5 | 7.8     | 6.0    | 5.3  | -2.6   | 230.0   |
| 6 | 14.2    | 5.0    | 32.0 | -256.0 | 2,000.0 |
| 7 | 65.0    | 5.0    | 32.0 | -256.0 | 3,500.0 |
| 8 | 10.0    | 7.0    | 57.8 | 3.0    | 157.0   |
| 9 | 2.4     | 1.6    | 17.0 | 49.9   | 200.0   |
| 10| 1.0     | 0.0    | 17.0 | 49.9   | 500.0   |
| 11| 200.0   | 20.0   | 32.0 | -256.0 | 3,000.0 |

The experiment is divided into two conditions. First, the allocation of power plant loading at low loads. Second, the allocation of the power plant loading at peak load. In low load conditions, the demand is 194.8 MW, while the total production of all plants is 195.22 MW. There is a difference between the amount of supply and demand as much as 0.36 MW. This difference is used to anticipate losses that occur along the transmission network to keep energy equilibrium continues (Equation 11). The power plant with the biggest losses is P11 (192 KW). This is because electricity produced by the P11 generator must go through the longest transmission line, which is 1,063.9 km. The total emissions generated by the system are 96.59 kg, with the largest emissions in P11 (29.91 kg). The total fuel cost in this low load condition is Rp 215,377.36.

At peak load, demand increases to 343.4 MW, while the total production of all power plants is 345.76 MW. There is a difference between the amount of supply and the amount of demand of 2.36 MW. This difference is used to anticipate losses that occur along the transmission network to keep energy equilibrium continues (Equation 11). The biggest power plant with Losses is P11 (115.34 MW). This Losses is caused by the electricity produced by the P11 power plant having to go through the longest transmission line, which is 3,671.6 km. The total emissions generated by the system are 185.59 kg, with the largest emissions in P11 (115.34 kg). The total fuel cost at peak load conditions is Rp. 1,374,744.5

5. Conclusions

The transportation model was successfully developed for applications in the case of electricity production and distribution. Development is done by combining transportation models with the Economic Dispatch model. This combined model is called the Single Echelon Economic Dispatch (SEED).

The output of the SEED model is in the form of electricity distribution in detail. SEED is also able to calculate the electric distance from a power plant to a customer. During low loads and peak loads, P11 is the plant plant with the farthest distance and the largest losses. P11 is also the power plant with the largest emissions.
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References

[1] R. P. Parouha and K. N. Das, “A novel hybrid optimizer for solving Economic Load Dispatch problem,” Int. J. Electr. Power Energy Syst., vol. 78, pp. 108–126, 2016.

[2] Wahyuda, B. Santosa, and A. Rusdiansyah, “Load allocation of power plant using multi echelon economic dispatch,” in AIP Conference Proceedings, 2017, vol. 1902.

[3] A. Y. Abdelaziz, E. S. Ali, and S. M. A. Elazim, “Combined economic and emission dispatch solution using Flower Pollination Algorithm,” Int. J. Electr. Power Energy Syst., vol. 80, pp. 264–274, 2016.

[4] Wahyuda, B. Santosa, and A. Rusdiansyah, “Cost analysis of an electricity supply chain using modification of price based dynamic economic dispatch in wheeling transaction scheme,” IOP Conf. Ser. Mater. Sci. Eng., 2018.

[5] I. Gani, Wahyuda, B. Santosa, and A. Rusdiansyah, “Analysis of costs and emissions on the addition of production capacity of the power plant using multi echelon economic dispatch Analysis of Costs and Emissions on The Addition of Production Capacity of The Power Plant Using Multi Echelon Economic Dispatch,” in AIP Conference Proceedings, 2019, vol. 060016, no. June.

[6] D. Zou, S. Li, Z. Li, and X. Kong, “A new global particle swarm optimization for the economic emission dispatch with or without transmission losses,” Energy Convers. Manag., vol. 139, pp. 45–70, 2017.

[7] I. Gani, Wahyuda, B. Santosa, and Muliaati, “Multi Echelon Distribution Model for Electric Market Deregulation Collaboration Strategy in East Kalimantan Multi Echelon Distribution Model for Electric Market Deregulation Collaboration Strategy in East Kalimantan,” in IOP Conference Series: Materials Science and Engineering, 2019.

[8] M. B. Nappu and A. Arief, “Network Losses-based Economic Redispatch for Optimal Energy Pricing in a Congested Power System,” Energy Procedia, vol. 100, no. September, pp. 311–314, 2016.

[9] T. Soares, F. Pereira, H. Morais, and Z. Vale, “Cost allocation model for distribution networks considering high penetration of distributed energy resources,” Electr. Power Syst. Res., vol. 124, pp. 120–132, 2015.