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Optimal cost allocation algorithm of transmission losses to bilateral contracts

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ABSTRACT

One of the trends in electricity reform is the involvement of bilateral contracts that will participate in electricity business development. Bilateral agreements require fair transmission loss costs compared with the integrated power system. This paper proposes a new algorithm in determining the optimal allocation of transmission loss costs for bilateral contracts based on the direct method in economic load dispatch. The calculation for an optimal power flow applies fast decoupled methods. At the same time, the determination of a fair allocation of transmission losses uses the decomposition method. The simulation results of the optimal allocation of power flow provide comparable results with previous studies. This method produces a fair allocation of optimal transmission loss costs for both integrated and bilateral parties. The proportion allocation of the transmission lines loss incurred by the integrated system and bilateral contracts reflects a fair allocation of R. 852.589 and R. 805.193, respectively.

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1. INTRODUCTION

One of the trends in electricity reform is the involvement of bilateral contracts that will participate in electricity business development as in [1]. In the era of openness, the interaction between various stakeholders in electricity service will result in a new agreement in determining the efficiency parameters of the power system. The components of the transmission network losses and the fair allocation of the transmission loss factors for the respective parties will affect an efficiency improvement of the power system discussed in [2]. Bilateral parties to the contract will use the same transmission network to realize their transactions, where the power generated is equal to the active power received by the load [3, 4]. Electricity business development tends to transform into an electric power system that involves bilateral contracts to participate in electricity development studied by [5, 6]. So that related parties can distribute electricity to their loads with broad areas by utilizing available transmission network. The impact on vast service areas will pay transmission line loss to the integrated system as in [7]. However, the presence of bilateral contracts in an integrated system will cause the problem of fair cost allocation of transmission losses for all parties.

The fundamental characteristic of the deregulated electricity market is the transparency of the allocation of costs due to transmission losses. The transmission line is a crucial component of the deregulated market, so the loss of the transmission line must be a concern and under the conditions of the bilateral contract. The optimal transmission loss formulates cost allocation to related parties. Increased efficiency on the generator side has been widely studied, especially in the operation of generator-based limits [8]. In the deregulated market that is more competitive and sustainable, the calculation of the allocation of transmission losses needs to involve all components of the power system as in [9]. In general, the operation of the generating system must consider a merit order or generator scheduling. Therefore the objective function of the economic load dispatch is to minimize fuel costs under optimal load flow conditions studied by [10, 11].

The solution to the economic load dispatch problems represented by quadratic fuel cost functions has been studied by [12]. Fuel consumption in power plants is affected by the load, and the fuel cost curve tends to decrease with increasing load or electricity generation [13]. The generator supplies electricity to the load through the transmission line. The effect of transmission line loss has been discussed widely by [14-16]. Transmission losses are distinguished based on current flow due to conductor resistance and load current that commonly uses superposition techniques [17-19]. In a deregulated power system, it is essential to allocate losses fairly to market participants. Each party is responsible for transmission losses incurred by its expenses. Bilateral parties to the contract must bear transmission losses because the generator capacity is equal to the total load [20]. Based on studies conducted by [21] have analyzed the complex power flows from the generator to the transmission network using the voltage superposition method. While the optimization method for transmission line loss using the direct method of economic dispatch studied by [22, 23] has successfully solved the issues of optimal loss allocation from the transmission line.

The economy of the power system has widely elaborated in reducing the related cost of transmission line losses. Cost allocation is a function of transmission losses, and generator limits make the economic load dispatch problem more complicated. Efforts done by [24, 25] provide accurate solutions to deliver electric power economically. Economic dispatch modeling involving inequality and equality constraints has also been successfully demonstrated by [26-28]. The use of the models in power flow optimization done by [29, 30] has accurately solved the optimal losses in the transmission lines using direct and fast-decoupled methods. The power flow from the generator to the load defines the contribution of complex and active powers. The studies done by [31-33] have formulated the allocation loss on each transmission line using decomposition techniques. This method can allocate the power losses on each transmission line for both integrated and bilateral contracts load. Optimal allocation of losses from transmission lines obtained by the fast decouple method is a solution to convergent power flow for both bilateral contracts and non-bilateral contracts as in [34, 35]. The convergent solution of power flow in the power system forms the base case.

Furthermore, studies done by [36–38] has succeeded in determining power loss in transmission line loss in economic dispatch problems through the B-Loss Matrix approach. The application of load balancing components, generator limits, and transmission loss as a constraint factor will ease the problem of economic load dispatch [39]. Therefore, the fuel cost and optimal allocation of transmission line loss can calculate the optimal cost allocation of transmission line loss for a bilateral contract. This paper proposes a fair separation of optimal allocation of transmission losses and optimal energy costs based on fuel costs. The method represents a new algorithm on the optimal allocation of transmission losses and the costs of transmission loss for each bilateral contract. The optimal allocation of transmission line losses will provide an optimal cost allocation of transmission losses for bilateral parties. The direct method to solve the economic dispatch problem will determine an optimal solution for cost allocation for both parties. The superposition technique calculates the current distribution of the transmission line for an integrated system and bilateral parties. The decomposition technique expresses the power loss allocation of both integrated and bilateral parties. The proposed algorithm of optimal energy costs allocation is validated using the Game Theory technique to determine the convergent transmission loss allocations.

2. RESEARCH METHOD

2.1. Problem formulation

A grid-based power system consisting of generators and transmission lines connected to the load is an integrated power system. Based on the market mechanism, the bilateral contract generator supplies there's loads through the transmission lines of the integrated system. One important issue that gets the attention of the experts is to determine the costs of direct losses for the parties to the bilateral contract. The contract between an integrated system and bilateral agreements must meet the requirements that the power generated by a bilateral party is equal to its total load. Therefore, the transmission losses are supported by the integrated system. The power flow to the power loads must represent the optimal transmission losses, which can ultimately determine the fair allocation of the transmission losses between the integrated system and the bilateral contract. Figure 1 depicts the approach for determining the optimal.

Figure 1 shows that the input of the optimization process consists of a transmission network, generators of an integrated and bilateral contract, and integrated and bilateral contract loads. Furthermore, the optimal power flow formulates the power loss allocation in the transmission lines using superposition and decomposition techniques and the B-Loss matrix approach. The results of the transmission loss costs for the bilateral contract transactions are determined based on the optimal economic dispatch and transmission loss allocation.

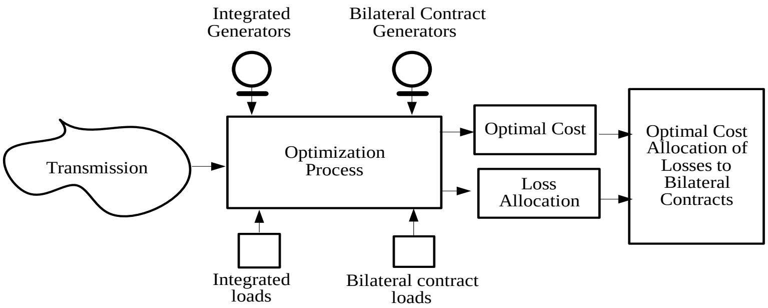

Figure 1. The approach of optimal allocation of transmission line loss cost for bilateral contrats

2.2. Optional cost allocation modeling

Electricity losses are power losses in the transmission network, so the generators must supply these losses besides the loads connected to the power system. In the concept of bilateral contracts, bilateral generators do not provide transmission losses. Therefore, the integrated generators compensate for the transmission losses, and the fuel cost of integrated generators affects the costs of transmission loss. The fuel costs function of the power plant is modeled in quadratic form, as expressed by in (1). In (2), (3), and (4) are the constraints of power systems. In (2) and (3) show the balance of active power of the generator, load demand, power losses, and the active power limit of the generator. In (4) represents a constraint for the active power limits of the generator.
Objective function:

$$B(P) = \sum_{i=1}^{n} a_i + b_i P_i + c_i P_i^2 \tag{1}$$

subject to:

$$\sum_{i=1}^{n} P_i - P_D^{\#} - P_{loss} = 0 \tag{2}$$

$$P_D^{\#} = \sum_{j=1}^{m} P_j^{bl} - P_D \tag{3}$$

$$P_i^{min} \leq P_i \leq P_i^{max} \tag{4}$$

based on the direct method studied by [15], the optimal condition of the active power of the generator is given by (5). The value of Lambda in (6) is obtained from the calculation of the optimal power flow using the direct method.

$$P_i = \frac{\lambda - b_i}{2a_i} \tag{5}$$

$$\lambda = \frac{P_D^{\#} + P_{loss} + \sum_{i=1}^{n} \frac{b_i}{2c_i}}{\sum_{i=1}^{n} \frac{1}{2c_i}} \tag{6}$$

The fast-decoupled method defines the convergence of the power flow of real transmission losses based on the optimal economic dispatch. The loss calculations with the new algorithm start with an initial step of $P_{loss} = 0$. While (4) calculates the optimal power flow according to the generator limits as a function of λ and P_i^{op}. In (7) calculates the number of marginal fuel costs for each power plant.

$$\lambda_i = b_i + 2c_i P_i^{op} \tag{7}$$

Determination of value P_i^{op} is done by the procedure as follows;
- If $P_i \geq P_i^{max}$, then $P_i^{op} = P_i^{max}$
- If $P_i \leq P_i^{max}$, then $P_i^{op} = P_i^{min}$

- If $P_i^{min} \leq P_i \leq P_i^{max}$, then $P_i^{op} = P_i^{min}$

The optimal fuel cost for transmission losses is determined based on the marginal system cost. In (8) formulates the marginal cost of a power system;

$$\rho = \frac{\sum_{i=1}^{n} \lambda_i P_i^{op}}{\sum_{i=1}^{n} P_i^{op}} \quad (8)$$

2.3. Allocation of optimal transmission line losses for bilateral contracts

Based on studies conducted by [31], (9) defines the complex power of a generator passing through the j-k line. Whereas the flow of the generator current from Bus i is received by the load on Bus j and obtained through (10).

$$S_{jk}^{Gi} = V_j F_{jk}^{*} \left(I_i^{Gi}\right)^{*} \quad (9)$$

$$I_j^{Di} = V_j^{Gi} y_j^{\mathrm{D}} \quad (10)$$

The complex power and active power of generator i flowing to the load on Bus j are obtained through (11) and (12). Hence the total active power of generator i distributed to loads is obtained through (13). So that the transmission loss allocation from generator i is obtained, which is formulated through (14). Then the transmission loss caused by a load on the Bus i is calculated by (15).

$$Sd_j^{Gi} = V_j \left(I_i^{Di}\right)^{*} \quad (11)$$

$$Pd_j^{Gi} = Real \left(S_j^{Di}\right) \quad (12)$$

$$Pg_i^{D} = \sum_{i=1}^{n} Pd_j^{Gi} \quad (13)$$

$$Pr_i^{G} = Pg_i^{D} - Pg_i \quad (14)$$

$$Pr_i^{D} = Pg_i^{G} - Pd_i \quad (15)$$

Finally, the allocation of transmission losses for bilateral contracts is calculated based on the pro-rata method and is derived by (16). Determination of the amount of optimal loss costs (lco) is obtained through (8) and (16) as formulated in (17).

$$P_i^{loss} = \frac{Pr_i^{G} + Pr_i^{D}}{2} \quad (16)$$

$$lco_i = \rho P_i^{loss} \quad (17)$$

2.4. Algorithm

As mentioned in the problem formulation that the optimal power flow will provide the optimal allocation of transmission loss; hence the optimal fuel cost can be derived. The optimization methodology is derived based on the mathematical formulation described in section 2. Power flow optimization as an economic dispatch problem is calculated using the direct method to obtain the optimal fuel costs represented in (8). Then the base case is determined from the calculation results of power flow using the fast-decoupled method. Therefore, the allocation of transmission losses can be calculated based on the power sent by the generator and the energy received by the loads, as stated in (16). The procedures undertaken to produce optimal cost allocation from transmission line losses for bilateral contracts are as the following stages:

- Input all data of power system configuration and fuel cost parameter.
- Determine Economics dispatch through (6) and (7).
- Calculate the optimal transmission line loss using the fast-decoupled method.
- If the power loss difference is higher than ε (convergence value), then update the transmission loss in (6) and return to stage 2. If the power loss difference is small from ε then continue to stage 5.
- Calculate the optimal fuel cost through (8).
- Determine the base case from the optimal power flow results that resulted from the fast-decoupled method. The fast decouple method is based on economic dispatch problems.
- Calculate the allocation of transmission losses for all bilateral contracts through (10) to (16).
- Calculate the optimal cost allocation of transmission line loss through (17).
- Results of optimal cost allocation of transmission losses to a bilateral contract are determined.
- Finish.

3. RESULTS AND ANALYSIS

To implement the optimization method of optimal allocating costs from the transmission line losses to bilateral contracts, the 6-Bus power system was used in this paper. A single line diagram of the 6-Bus power system is shown in Figure 2. From Figure 2, the case study of this power system consists of 3-station power plants, 4-loads, and 7-transmission lines. Table 1 shows the transmission lines data. Three bilateral contracts are accommodated to enter the power system, and the others are under the integrated system. Table 2 depicts the load data from the power system for the three bilateral contract transactions. The total load power of the bilateral contract is equal to the total generator power of 200 MW. Table 3 shows data of the fuel cost parameter and the generator active power limits.

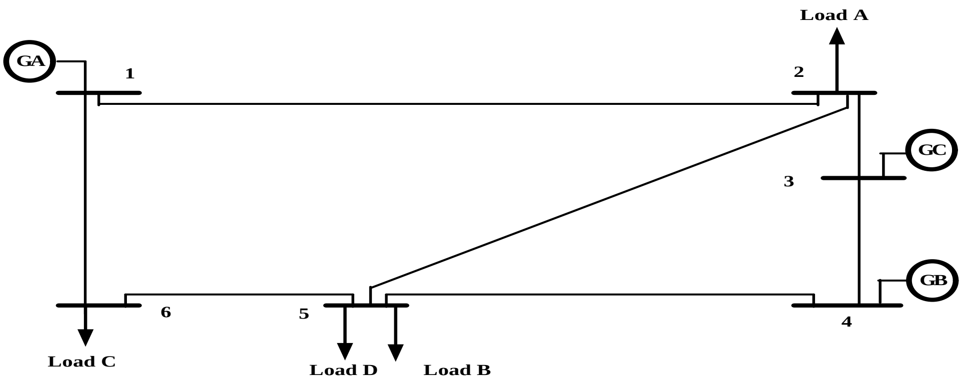

Figure 2. The 6-Bus power system

Table 1. Parameters of branch of 6-buss system [21]

From Bus i	To Bus j	R (Ω)	X (Ω)	B (Ω)
1	2	2.0	10	0
1	6	3.0	11	0
2	3	0.5	4	0
2	5	2.0	8	0
3	4	0.5	3	0
4	5	2.0	8	0
5	6	1.5	6	0

Table 2. Load data of power system [21]

Type	Transaction number	User	Supplier	Load quantity	
				P (MW)	Q (MVAR)
Integrated	-	Load A	GA, GB, GC	110	50
	-	Load D	GA, GB, GC	100	40
Bilateral contract	T1	Load A	GA	20	20
	T2	Load B	GB	80	35
	T3	Load C	GA	100	50

Table 3. Fuel cost parameter and active power limit of generator

Gen	a	b	c	P_{min} (MW)	P_{max} (MW)
GA	200	860	0.45	5	60
GB	400	630	2.95	5	40
GC	130	518	1.05	20	180

3.1. Assessment result

Table 4 shows the base case of the optimization results involving the entire power system configuration. Table 4 shows that the transmission line loss is 1.967+j 8.421 MVA and was noticeable also by [21]. The total integrated load is 210 MW and the bilateral contract load is 200 MW. By applying the economic dispatch method, Table 5 shows the marginal cost for each bus in a bilateral contract. The simulation results show that the marginal cost of the power system is 842.79 R/kWh. Simulation results that represent the optimal solution for transmission loss allocation are as the basis for allocating the loss costs both the integrated system and bilateral contracts. The optimal conditions of power flow involving fuel cost parameters produce the optimal allocation value of transmission loss and transmission loss costs, as shown in Table 6. From Table 6, T3 Transaction bears the highest transmission loss expense among the three transactions. This cost is caused by the most significant transaction power contribution (100 MW) compared to deals with T1 and T2 in Table 2. Whereas the load of transmission line loss costs borne by the integrated system R 852.589 is slightly higher than the cost incurred by bilateral transactions.

Table 4. Base case from optimal power flow

Bus	V(pu)	sv (rad)	Pg (MW)	Pd (MW)	Qg (MVar)	Qd (MVar)
1	1.000	0.000	131.5	0.0	74.1	0.0
2	0.993	-0.007	0.0	130.0	0.0	70.0
3	1.000	0.004	160.5	0.0	70.7	0.0
4	1.000	0.003	120.0	0.0	58.6	0.0
5	0.986	-0.016	0.0	180.0	0.0	75.0
6	0.985	-0.017	0.0	100.0	0.0	50.0
Loss	= 1.967 + j 8.421		412.0	410.0	203.4	195.0

Table 5. Optimal economic dispatch

Generator	Mar. Cost (R)	Pmin (MW)	Popt (MW)	Pmax (MW)
GA	870.35	5.00	11.50	60.00
GB	786.00	5.00	40.00	40.00
GC	854.98	20.00	160.47	180.00
Total	842.79		211.50	

Table 6. Optimal allocation of transmission line loss and transmission line loss cost

Transaction	Transmission Loss Alocation			lco (Thousands R)
	Generator (MW)	Load (MW)	Average (MW)	
T1	0.099	0.095	0.097	81.854
T2	0.360	0.382	0.371	312.771
T3	0.494	0.480	0.487	410.567
SubTotal	0.953	0.958	0.955	805.193
Integrated	1.014	1.009	1.017	852.589
Total	1.967	1.967	1.967	1657.782

3.2. Discussion

The calculation of cost allocation is using a mathematical approach based on the optimal economic load dispatch method. Fuel cost parameters significantly influence the allocation of optimal transmission losses for bilateral contracts to compensate for transmission line losses. Parties involved in bilateral contract transactions need an optimal cost allocation from transmission line losses. So that fair allocation of transmission line loss will be treated for each party under market mechanisms. The integrated system bears the optimal loss of transmission network to meet the load requirements in bilateral contracts. This optimization model also meets the minimum and maximum active power limits of generators, so that each generator will operate within its capacity limit range. The composition for each generator, as illustrated in Table 5, shows that only the GB generator operates at maximum capacity. This composition is under the criteria for fuel cost parameters (a, b, c). The proposed algorithm of optimal allocation of transmission line loss cost (Ico) for bilateral transactions simulated the optimal allocation of power flow, which provided comparable results with previous studies.

The simulation results show that the parties bear the total loss of the transmission line of 1,967 MW as shown in Table 6 to the bilateral contract transaction and the integrated system. The total allocation of power losses as a base case is in line with the results of a study by [21]. Table 6 shows that the active power losses allocated to the integrated system and bilateral contract are respective 1.014 MW and 0.953 MW that reflects a fairness allocation. However, the cost allocated to the bilateral contract is 4.4% less than it cost assigned to the integrated system. It provides a very reasonable proportion because the total generator capacity of the integrated system and bilateral contracts are 210 MW and 200 MW, respectively. Therefore, this optimization model has represented a new algorithm in determining the optimal allocation of loss costs for bilateral contracts.

4. CONCLUSION

This paper proposes a new algorithm in the allocation of transmission loss costs for an integrated system and bilateral contracts. The algorithm provides a reliable algorithm that defines lost coss allocation in the economic load dispatch problem. An optimization algorithm is a mathematical derivation based on the optimization of economic dispatch problems using the direct method. This method can produce optimal fuel costs. Accurate optimal power flow can be difined through fast decouple methods based on the optimal power generation. Furthermore, the application of the decomposition method results in a fair allocation of transmission line losses.

The proposed lco algorithm has been tested in determining the optimal allocation of power flow in bilateral transactions through simulations that in line with previous studies. From the simulation results, it can be seen that this method produces a fair allocation of optimal transmission loss costs. The allocation of transmission losses incurred by the integrated system and bilateral contracts reflects a fairness allocation of respective 1.014 MW and 0.953 MW. Meanwhile, the costs of transmission losses incurred by the integrated system and bilateral contracts amounted to R 852.589 and R 805.193, respectively.

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