Load Flow Allocation to Improve the Fairness of MW-Mile Method

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***Abstract*—In a deregulated power system, an appropriate wheeling cost is required to provide valuable economic information to market participants, such as generation and transmission companies. The load flow method is used in power wheeling to determine the condition of the existing system after the wheeling participant is added to the system. In the load flow method, it can be seen how much power is generated from a generator. However, the power flow method cannot determine wheeling generator allocation to the power flow in each transmission network. For this reason, power tracing will be used to determine the wheeling generator allocation. Power tracing is also a solution that could improve the fairness of determining wheeling costs. This paper discusses the power tracing method to determine load flow allocation for wheeling generators using the genetic algorithm (GA) method. GA is one of the optimization techniques, where in power tracing with GA, the load flow allocations (LFA) problem will be assumed as an optimization problem. Calculation with tracing and without tracing will be compared to demonstrate the benefits of the proposed technique. Experimental results showed that the MW-mile method with LFA yielded more expensive wheeling costs than the conventional method. The cost is more expensive due to the absence of cost reduction as in the conventional MW-mile method, and wheeling users pay wheeling costs based on the transmission usage. Although wheeling costs are high, the LFA method provides a fair price because wheeling users pay a fee based on the actual usage. In the future, another power tracing may be used to help determine wheeling costs.**

***Keywords*—Power Wheeling, MW-Mile, Load Flow Allocation, Tracing, Genetic Algorithm.**

I. Introduction

Wheeling has become a solution for industries that intend to transmit electricity through their generation but do not have a transmission line. Wheeling is also very beneficial in increasing the penetration of renewable energy, which is growing rapidly since one of the characteristics of renewable energy depends on the location [1]. Therefore, it takes a transmission line to transmit electrical energy, and power wheeling can solve this problem. Wheeling is defined as the delivery of electrical energy from the seller to the buyer via a third-party transmission line [2]. Power wheeling can also be defined as utilizing transmission and distribution network facilities to distribute electricity by third parties [3].

The problem that often arises in power wheeling is determining the fair price of wheeling for the transmission owner and the industry that wants to join wheeling. Discussions related to wheeling have undergone much development. Fairness of wheeling costs became a major topic in many discussions. Wheeling costs are expected to reflect costs according to their contribution, both in terms of transmission network owners and wheeling actors [4]. Due to fairness, if one side assumes the price of wheeling is unfair, then the wheeling scheme will not occur, or the transmission provider may refuse to lend their transmission lines to the industry. Several methods have been used to determine the cost of wheeling. These methods can be grouped into the embedded price, incremental cost, and marginal cost [5].

Embedded cost calculates the cost of wheeling on the transmission network due to its general use. Embedded cost includes the cost of capital and the average cost of maintenance and operations in addition to the cost of production. Embedded cost consists of a postage stamp, contract path, boundary flow, line to line method, or MW-Mile [5]. MW-Mile is a better method than other embedded methods (postage stamp method, contract path method) since it considers the changes in power flow that occur due to the addition of new plants. Meanwhile, in other methods, changes in power flow will be ignored [6]. In some applications, the length of the transmission line can also be expressed in kilometers. MW-Mile method is the first method of determining the transmission network's cost that considers the actual cost of using a transmission network based on direct current (DC) power flow calculations.

On the calculation of wheeling costs, especially on the MW-Mile method, the system's condition will be recognized by the power flow method after the wheeling generator is added. However, the power flow method cannot determine the allocation of the generator to each line. In addition, the nonlinear nature of power flow determines which generator's power flow becomes difficult. As a result, power tracing is used to solve this issue.

In [7], a genetic algorithm (GA) was used to help calculate wheeling costs. It was used to obtain optimal power flow (OPF). The OPF and GA results were used to calculate wheeling costs. The MW-Mile and MVA-mile methods were used in this research to calculate the cost of wheeling. Reference [8] used Kirschen method to determine generator contributions to individual costumer, while MW-Mile method was used to determine the power wheeling cost.

The proportional sharing principle method is well-known in [9]. It was assumed that the sum of the incoming and outgoing currents of the branch was zero. Based on the calculation of topological distribution factors, this technique approximated Kirchhoff's law to determine the allocation of generators and loads on the transmission line. This method was applied to both

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DC and AC power flows. In [10], the proportional sharing principle method was used to help determine wheeling cost. Furthermore, the tracing method used to trace the flow of electricity and the MVA-KM method and MW-Mile method was compared.

The power flow tracing technique based on a directed circuit was proposed [11]. This method computed individual generators' contributions and loads to line flows and the actual power transfer, which is essential to transmission open access. The power flow tracing method based on a directed circuit used the power sharing principle based on the generation of the path. Reference [12] proposed a transmission loss and load flow allocation (LFA) with a GA. A GA determined losses in every transmission and the generator's contribution to the system's load.

This paper used a GA to trace or determine the wheeling generator's allocation to the load flow in each transmission line. Therefore, the LFA problem was the objective function. In calculating the MW-Mile, the wheeling participant only paid power flow in the transmission line due to their wheeling generator contribution, which was expected to improve the fairness for the MW-Mile method. This paper is organized as follows: Section II explains the load flow allocation method, MW-Mile method, and optimal power flow (OPF). Section III presents the results and discussion. The last section, which is Section IV, is a conclusion.

II. Methods

This section is intended to describe OPF, MW-Mile method, and the proposed method LFA with a GA.

A. Optimal Power Flow

In the interconnection power system, cost optimizations are done by adjusting each generator's active power and reactive power to minimize operating costs. This method is called OPF. OPF can provide an appropriate network conditions approach with restrictions on the network. It determines the variable values of voltage, power, phase angle, power flow, and losses on the network. OPF is a power flow calculation that considers generation cost [13]. It is used in the wheeling scheme to determine system conditions after the wheeling generator or wheeling load is added. OPF uses all variable controls to minimize operating costs for the power system. OPF method has limitations for active and reactive power, a constraint for transmission, and constraints in grid bus. The objective function in OPF is shown in (1) and (2) [14].

$$F(P_g) = \sum_{i=1}^{Ng} \alpha_i + \beta_i P_{gi} + \gamma_i P_{gi}^2 \quad (1)$$

$$Ft = \sum_{i=1}^{n} F(P_g) \quad (2)$$

with Ft is the total cost function. The equation for active and reactive power in every bus is (3) and (4).

$$P_i = V_i \sum_{j=1}^{N_b} |V_j| \, |Y_{ij}| \cos(\theta_i - \theta_j + \Psi_{ij}) \quad (3)$$

$$Q_i = V_i \sum_{j=1}^{N_b} |V_j| \, |Y_{ij}| \cos(\theta_i - \theta_j + \Psi_{ij}). \quad (4)$$

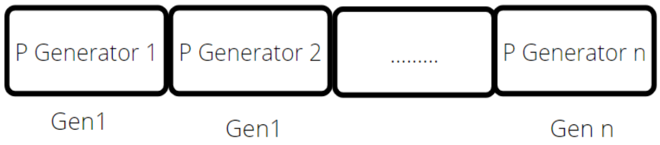

Fig. 1 Chromosome illustration.

Constraint in OPF for active and reactive power in power plant, the limitation for ampacity in transmission, and voltage in grid bus are shown in (5)–(8) as follows

- constraint voltage in bus

$$V_i^{min} \le V_i \le V_i^{max} \quad i = 1 \ldots n_b \quad (5)$$

- constraint active power in power plant

$$P_{gi}^{min} \le P_{gi} \le P_{gi}^{max} \quad i = 1 \ldots n_b \quad (6)$$

- constraint reactive power in power plant

$$Q_{gi}^{min} \le Q_{gi} \le Q_{gi}^{max} \quad i = 1 \ldots n_b \quad (7)$$

- constraint power flow in transmission

$$S_l \le S_l^{max} \quad (8)$$

where P_{gi} is active power from the generator in bus i, Q_{gi} is reactive power from the generator in bus i, and V_i is voltage in bus i.

B. Load Flow Allocation

Tracing is a solution that could improve the transparency of the transmission system's operation. Transparency in transmission system operation considered the electricity pool in the United Kingdom [9]. In this case, transmission line was assumed lossless, and losses was about 2% if generation was charged to area suppliers via a uniform pro-rata charge. An electricity tracing method would allow suppliers and generators to be charged for the actual number of losses caused, thereby encouraging efficiency. The OPF method results could determine how much the wheeling generator generates electrical energy. However, OPF cannot determine the contribution of each generator to the power flow. Therefore, power flow tracing in the power wheeling scheme was used to determine the contribution of the wheeling generator to the transmission line's power flow. As a result, the wheeling costs were expected to be more equitable.

GA is a stochastic method that applies biological processes to solve the optimization problem. GA allows individuals to develop under specific rules to achieve a condition that optimizes fitness or minimizes cost. This paper uses GA to solve the LFA problem. In a GA, the first step is to encode the candidate solution in a chromosome representation. Chromosomes are matrices with values for their elements in numbers generated randomly. Each individual on a chromosome is called a gene, and a collection of several chromosomes is called a population. Each gene on a chromosome will contain the contribution value of each

TABLE I
GENERATOR DATA

Bus	Cost Function	P (min)	P (max)
1	$10 + 14P + 20P^2$	50	100
2	$40 + 50P + 70P^2$	30	73
5	$50 + 60P + 90P^2$	30	90

TABLE II
BUS DATA SCENARIO 1

Bus	Generator (MVA)		Load (MVA)	
	P (MW)	*Q (MVar)*	*P (MW)*	*Q (MVar)*
1	98	50	-	-
2	70	50	50	20
3	-	-	50	20
4	-	-	70	50
5	88	50	20	10

generator on a bus. Therefore, the number of genes on a chromosome depends on the number of generators in the scenario. Fig. 1 shows an illustration of chromosomes for power tracing with a GA.

The algorithm proposes an objective value based on the fitness's quality. The GA will terminate the process when the fitness is 1. Thus, GA will find the optimized value for the LFA problem [12].

$$(H) = \sum_{i=1}^{n} \Delta P_{j-k}^{Gi} \quad (9)$$

where:

$$\Delta P_{j-k}^{Gi} = \sum P_{j-k}^{Gi(tr)} - P_{j-k} \quad (10)$$

$$Fitness = \frac{1}{1+H}. \quad (11)$$

P_{j-k} is obtained from the OPF solution. $P_{j-k}^{Gi(tr)}$ is the result of power flow tracing with a GA for generator i on the bus j-k. Each generator is assumed to contribute to every transmission line in this method. The number of genes depends on the number of generators because genes represent the generator on the system. Before running GA, it is necessary to create a chromosome representation. The value of the results of the fitness calculation will determine the quality of the chromosomes. A good fitness has a value close to 1 and will stop when the fitness value reaches 1. As in (10) and (11), the fitness value will be 1 if the sum of $P_{j-k}^{Gi(tr)}$ equals to P_{j-k}

The operation of the GA consists of: selection, crossover and mutation. Selection is an operation to ensure that the representative of a chromosome received in the next generation has better quality or depends on its fitness value. In the natural selection model, chromosomes with better fitness have a better chance of survival than the next generation. Chromosomes that survive are likely to be paired with other chromosomes. Thus, the selection method used is a roulette wheel.

A crossover is an operation where chromosomes that have been selected will be crossed over so that a new chromosome will appear. *Pc* is the crossover rate or the probability of crossing over. It is the ratio of chromosomes expected to be crossed in every generation to the total number of chromosomes in the population. For example, if the crossover rate is set to 50%, 50% of the chromosomes will cross over, determined by the mutation rate parameter [12]. A mutation is a process of changing the value of a chromosome. This mutation replaces the missing chromosomes from the population due to selection, and the values used will be randomly generated.

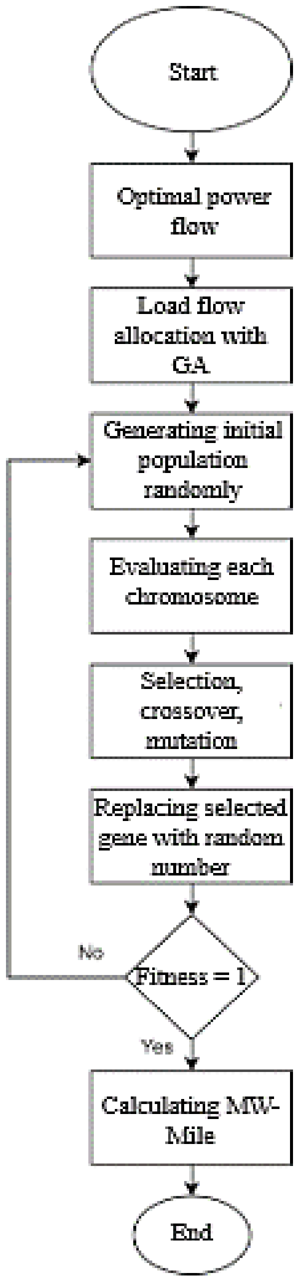

Fig. 2 Flowchart of the research stage.

C. MW-Mile Method

The MW-Mile method for transmission pricing is widely used because it measures the actual usage of transmission lines. Transmission length, transmission capacity, and power flow in the system are all factors to consider when calculating transmission costs using this method [5]. This method is

TABLE III
POWER FLOW IN 5 BUS TEST SYSTEM

From Bus	To Bus	Before Wheeling Scheme		After Wheeling Scheme	
		MW	*MVar*	*MW*	*MVar*
1	2	26.3	0.0	32.4	2.9
1	3	53.7	7.7	67.6	7.6
2	4	4.8	9.3	45.0	26.9
2	5	7.0	5.7	0.20	2.9
2	3	12.0	0.6	13.5	7.7
3	4	1.7	7.2	14.1	0.2
4	5	3.0	4.5	10.9	11.5

TABLE IV
LOAD FLOW ALLOCATION RESULT

From Bus	To Bus	G1 (MW)	G2 (MW)	G3 (MW)	Total (MW)
1	2	8.0	11.0	13.4	32.4
1	3	40.6	16.0	11.0	67.6
2	4	36.0	5.0	4.0	45.0
2	5	0.0	0.0	0.2	0.2
2	3	3.5	5.0	5.0	13.5
3	4	1.0	11.0	2.1	14.1
4	5	2.0	5.9	3.0	10.9

TABLE V
MW-MILE CALCULATION

From Bus	To Bus	PLFA (MW)	P_i^k (MW)	MW-Mile Rp (Million/Day)	MW-Mile with LFA Rp (Million/Day)
1	2	11.0	6.2	1.2	2.20
1	3	16.0	13.8	2.8	3.20
2	4	5.0	40.3	8.1	1.00
2	5	0.0	-6.8	-1.4	0.00
2	3	5.0	1.5	0.3	1.00
3	4	11.0	12.3	2.5	2.20
4	5	5.9	7.9	1.6	1.18

complicated because any changes in the transmission network necessitate a recalculation of flow in all lines. MW-Mile aims to fix the problems in the rolled-in-embedded technique. The distance between the recipient points does not influence the wheeling transaction's calculation of the transmission system's usage [6]. However, the change in power flow on the system caused by wheeling transactions is considered for determining wheeling price. MW-Mile method for power wheeling cost allocated the user who wants to use the transmission line, *Ck* is calculated using [15]:

$$C_k = \sum_{i=1}^{n} \frac{L_i \times F_i \times P_i^k}{P_i^c} \quad (12)$$

where L_i is the length of transmission i, F_i cost per mile for transmission i, and F_i is determined by transmission provider. P_i^c is transmission capacity in line i, and P_i^k power flow in transmission line i by user k (MW). P_i^k in the proposed method will use the result from LFA with a GA. Fig. 2 shows a flowchart for the research stage.

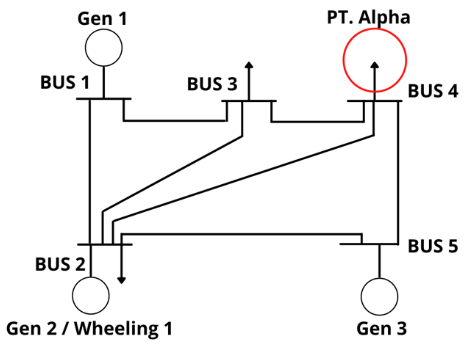

Fig. 3 Test system of 5-bus test.

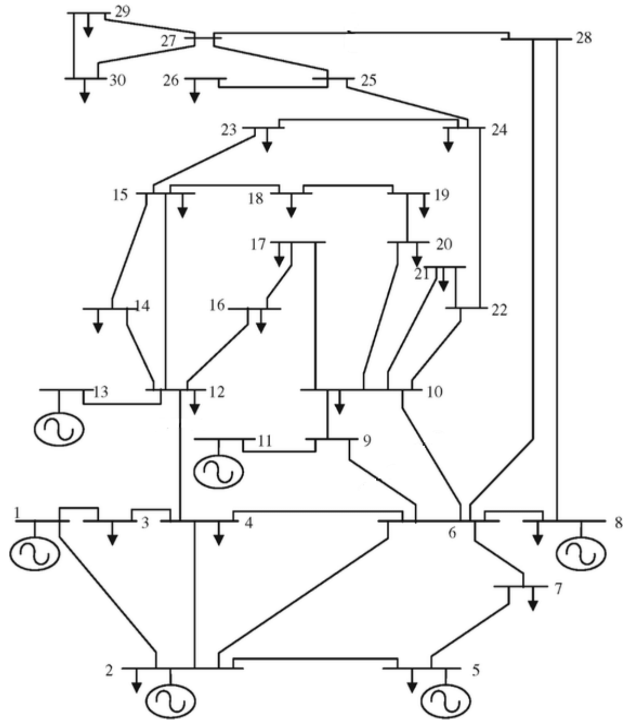

Fig. 4 Test system of 30-bus.

TABLE VI
COMPARISON OF THE MW-MILE METHOD

Method	Conventional MW-Mile	MW-Mile with LFA
Wheeling cost Rp (million)/month	10.78	15.1

III. RESULT AND DISCUSSION

This section discusses how to improve the MW-Mile method using LFA. The 5-bus test system and 30-bus test system were used to test the proposed method.

A. The 5-Bus Test System

The single line diagram for the 5-bus test system is shown in Fig. 3. In this scenario, a single-wheeling user was simulated and compared to the proposed and conventional MW-Mile methods. PT. Alpha in bus 4 intended to fulfill their electrical energy by building a new power plant in bus 2. There was no

TABLE VII
MW-MILE CALCULATION FOR 30 BUS

From Bus	To Bus	PLFA (MW)	P_i^k (MW)	MW-Mile Rp (Million/Day)	MW-Mile with LFA Rp (Million/Day)
1	2	1.0	-1.4	-0.02	0.01
1	3	27.2	-1.4	-0.01	0.16
2	4	45.0	-2.6	-0.04	0.65
3	4	0.0	-1.4	-0.01	0.00
2	5	4.9	3.9	0.09	0.12
2	6	1.0	-7.7	-0.23	0.03
4	6	1.1	6.2	0.18	0.03
5	7	12.4	-3.9	-0.09	0.29
6	7	13.6	-3.9	-0.02	0.06
6	8	4.1	35.2	0.08	0.01
6	9	4.0	8.5	0.08	0.04
9	11	10.4	0.0	0.00	0.08
9	10	29.0	8.5	0.07	0.25
4	12	2.4	2.2	0.02	0.02
12	13	7.0	0.0	0.00	0.05
12	14	7.0	2.8	0.02	0.04
12	16	1.0	-0.6	-0.01	0.01
14	15	5.5	2.8	0.02	0.03
16	17	7.5	-0.6	-0.01	0.07
15	18	1.6	-1.1	-0.02	0.02
18	19	9.0	-1.1	-0.01	0.04
19	20	1.2	1.1	0.02	0.02
10	20	2.0	1.1	0.02	0.03
10	17	0.0	-0.6	-0.01	0.00
10	21	3.2	0.5	0.01	0.05
10	22	10.0	6.3	0.01	0.02
21	22	0.0	-0.5	-0.01	0.00
15	23	2.0	3.9	0.08	0.04
22	24	1.0	6.8	0.20	0.03
23	24	0.0	-3.9	-0.07	0.00
24	25	0.0	-10.7	-0.15	0.00
25	26	0.0	0.0	0.00	0.00
25	27	4.0	-10.7	-0.41	0.15
28	27	24.2	49.3	0.09	0.05
27	29	0.0	3.2	0.01	0.00
27	30	12.8	56.8	0.10	0.02
29	30	0.0	-3.2	-0.28	0.00
8	28	14.8	22.9	1.82	1.17
6	28	18.7	26.4	2.11	1.49

additional load in bus 4, so load in bus 4 was 70 MW, and the wheeling transaction of 70 MW from bus 2 to bus 4. The transmission owner or regulator set cost Rp/mile was Rp1,000,000/day for cost function generator and generator capability shown in Table I.

After the wheeling generator was added, power flow on the system was calculated using the OPF method. The power flow calculation was performed before and after the wheeling user was added to the system to the wheeling user's impact on power flow in the system. The OPF method determined the power flow in the system while taking into account the system's constraints. Bus data for OPF calculation is shown in Table II.

Calculations of OPF before and after wheeling load added to the system is shown in Table III. The implementation of wheeling on bus 4 caused the power flow in the system to change. The additional load on bus 4 resulted in additional power requirements on the transmission line around bus 4, as in the branch from bus 3 to bus 4 had an increase in power flow of 12.3 MW. The load on the system has the characteristics that the nearest power plant will meet their electrical energy needs because it has an optimal distance to minimize losses on the transmission line. As a result, the power flow on the transmission line from bus 2 to bus 5 was reduced by 6.8 MW. This reduction was due to the load on bus 2, which was met by the nearest power plant, i.e., the wheeling generator. This decrease in power flow on bus 2 to bus 5 reduced wheeling costs in the conventional MW-Mile method.

TABLE VIII
MW-MILE CALCULATION OF 30 BUS TEST SYSTEM

No.	Method	Wheeling Cost Rp (Million)/Day	Wheeling Cost Rp (Million)/Month
1.	Conventional MW-Mile	3.7	109.8
2.	MW-Mile with LFA	5.1	152.7

Since the OPF method could not determine generator allocation to the load flow in the transmission line, LFA was used in this scenario to determine generator allocation to the power flow. In the LFA method, every generator was assumed to contribute to power flow in every transmission line. The value of a gene in the GA depended on the number of generators in the system. Since the system after the wheeling generator had three generators, the gene's value amounted to 3 genes. Gene 2 was used to calculate the MW-Mile method for the wheeling calculation, and the other results were ignored.

The population was set at 1,000, the crossover rate was 50%, and the mutation rate was 50%; the experimental approach chose these values. The number of populations did not affect the calculation because iteration stopped before 1,000 when GA already found the solution. However, an error might occur if iteration was more than the generation set, and the result will be shown from the last GA iteration. GA found the optimal value randomly, so gene 1 to gene 2 were chosen randomly in the GA calculation. GA calculation stopped until gene 1 to gene 3 equaled the power flow result on the transmission network.

Table IV shows the result of LFA of a 5-bus test system using GA. GA iteration stopped if the fitness function was equal to 1. The sum of genes 1 to 3 was the same as with the power flow from the OPF. This result demonstrated that GA could generate a satisfactory and appropriate solution to the LFA problem. Results from G2 were used to calculate the MW-Mile. However, this algorithm takes a long time if there are more generators in the system. After the LFA was calculated, the wheeling price was calculated with the MW-Mile method.

On Table V, value of PLFA is wheeling generator allocation from power tracing with GA and P_i^k is the change for power flow in transmission *i* by user *k*. P_i^k is determined by the OPF study. In the conventional MW-Mile method, when the power flow in the transmission line is reduced due to the wheeling scheme, it reduces the wheeling costs. In bus 2 to bus 5, the value of P_i^k is -6.8 MW because there was a reduction in power flow after the wheeling scheme was implemented. In the MW-Mile method using the LFA method, the wheeling user paid a wheeling fee based on the allocation of the wheeling generator on the transmission line.

Table VI shows MW-Mile calculation with the conventional MW-Mile method and MW-Mile with LFA. In the conventional MW-Mile method, the wheeling user will be charged a fee based on changes in power flow caused by the wheeling scheme. Therefore, in the 5-bus system scenario, the wheeling costs were smaller. Wheeling costs were reduced since there was a reduction in power flow of 6.8 MW, which reduced wheeling costs. In the proposed method, the wheeling calculation used a different approach. Wheeling becomes more expensive than the conventional method because there is no cost reduction, and wheeling users will pay a wheeling fee based on the allocation of the wheeling generator to the power flow in the transmission line.

B. The 30-Bus Test System

In this research, the 30-bus test system was used to test the proposed method on a more extensive system. Fig. 4 displays the single line diagram for the 30-bus test system which is used in this scenario [16]. Load bus in bus 30 (60 MW) intended to build a power plant to fulfill their electrical energy in bus 6. Therefore, a transaction of 60 MW from bus 6 to bus 30 was carried out. OPF method was performed to calculate power flow in the system after the wheeling user was added to the system.

There were seven generators in the system in calculating LFA with a GA in this 30-bus scenario. Consequently, the gene in the GA was set to seven genes. For chromosomes in GA, the fewer chromosome values are set, the more iterations in GA will be. Since GA was used to help determine the cost of wheeling in this scenario, in power tracing with the GA, the value of the gene representing the wheeling generator was used for wheeling calculation. At the same time, the other gene values were ignored. In Table VII, PLFA is the wheeling generator allocation resulting from the GA.

The value of P_i^k in Table VII illustrates how the power flow to the system changes due to the wheeling scenario. The wheeling load in this scenario was located on bus 30, so the power flow in the system was more significant in the transmission to bus 30. There was a 56.8 MW change in the power flow in the transmission line from bus 27 to bus 30. The negative notation on P_i^k value in Table VII indicates a reduction in power flow due to the wheeling scheme. In the conventional MW-Mile method, it will reduce the wheeling costs. When calculating MW-Miles with power tracing, wheeling users will be charged a wheeling fee based on the wheeling generator allocation to the system. Therefore, there will be no reduction in wheeling costs.

Table VIII shows that the implementation of LFA with GA to help determine the cost of wheeling with the MW-Mile method in the larger systems makes the cost of wheeling with the conventional MW-Mile method lower than the proposed method. The wheeling cost is lower because the conventional MW-Mile method has a cost reduction due to a reduction in power flow caused by the wheeling scenario. In the proposed method, the wheeling user paid a wheeling fee based on the use of the transmission line.

IV. CONCLUSION

This paper presents LFA techniques with GA to improve the fairness of the MW-Mile method for power wheeling cost calculations. To validate the proposed technique, simulations were run on five buses to test the method on a smaller system and thirty buses to test the method on the larger system. The simulation results demonstrated that the GA could solve LFA

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problems, and the main advantages of GA included no complicated mathematical derivations and straightforward tracing. Furthermore, LFA enabled wheeling users to determine the wheeling charge based on their transmission usage. This method described the actual use and gave wheeling charges in a fair manner. Even though GA took longer to compute, the results given in this paper are promising. In the future, this research can be carried out by reducing the processing time required to get an equitable result. Furthermore, other power flow tracing approaches may be used in the future to help determine the value of the generator allocation and give a better calculation in determining wheeling cost.

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