Allocation of Transmission Loss for Determination of Locational Spot pricing

Chang-Seok You*, Kyung-Il Min, Jong-Gi Lee*** and Young-Hyun Moon†**

Abstract - The deregulation problem has recently attracted attentions in a competitive electric power market, where the cost must be earmarked fairly and precisely for the customers and the Independent Power Producers (IPPs) as well. Transmission loss is an one of several important factors that determines power transmission cost. Because the cost caused by transmission losses is about 3~5 %, it is important to allocate transmission losses into each bus in a power system. This paper presents the new algorithm to allocate transmission losses based on an integration method using the loss sensitivity. It provides the buswise incremental transmission losses through the calculation of load ratios considering the transaction strategy of an overall system. The performance of the proposed algorithm is evaluated by the case studies carried out on the WSCC 9-bus and IEEE 14-bus systems.

Keywords: Deregulation, Loss Sensitivity, Spot Pricing, Transaction Strategy, Transmission Loss Allocation

1. Introduction

The Deregulation problem in a modern competitive power market has been embossed as an important issue in many countries. Under the deregulation environment, the traditional integrated electric power system is divided into generation, transmission, and distribution groups [1], [2]. The main objective of the deregulation is to provide a reasonable choice to consumers with the cost, which is down through competition. The power system industry in South Korea has been operated by the traditional monopoly public enterprise. However, the re-structure of power industry is now required imperatively due to the difficulties of effective control (by the government) resulting from its growing scale.

The precise calculation for the cost of transmission service acceptable to the every partner is becoming an important issue in a deregulated power open market. Moreover, the cost by transmission losses ranges in about 3 to 5% of total generation cost. Therefore, it cannot be negligible for the accurate calculation for the cost of transmission service [3]-[5].

Generally, the power losses were treated by the slack bus in a power system as an additional load [3], [4]. However, the cost generated by transmission losses should be allocated fairly to each associated transmission network user (TNU) in the present competitive model. Unfortunately, it is so complicated to allocate the cost of transmission losses accurately to each TNU of the power system because a power-flow equation is nonlinear [6]-[10].

Until now, several methods for the loss allocation have been reported in the literature [1]-[7], [9]-[14]. However, there has been no scheme to allocate transmission losses exactly reflecting the environment of a real power system to the knowledge of the authors.

This paper presents the novel transmission loss allocation algorithm by using the loss sensitivity. And, it provides the incremental transmission losses [11], [12]-[14] through the calculation of load ratios considering the transaction strategy based on the bilateral contract market in an overall system. The previous method reported in [11] (by the same authors) calculates the loss sensitivity by using the loss ratio parameter of the power at each bus with respect to the total power in all buses without considering the power flow of an entire system. Because a power market system is operated by the transaction through arbitrary contracts between electric power producers and consumers, the effective transmission loss allocation (to each bus) suitable to a real power market system can be obtained by the transaction strategy considering the power flow.

In this paper, the loss allocation is carried out by integrating the incremental transmission loss, with respect to the load parameter λ, which provides the average loss sensitivity. The performance of the proposed method is compared with that of the previous method in [11] by the several case studies.

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2. Proposed Algorithm

2.1 Organization of a transaction strategy

The currents in a power system flow so that the power losses of an entire system are minimized. The transaction strategy may be change allocation of system loss and the total sum of allocated losses should be greater than actual system loss; otherwise, system operator encounter a serious problem. However, the following theorem gets rid of such worry about the loss allocation based on the transaction strategy. Theorem: The total summation (P_{Loss}^{TS}) of the losses allocated to each bus is always greater than the actual system loss(P_{Loss}). That is,

$$P_{Loss}^{TS} \geq P_{Loss} \tag{1}$$

The mathematical relationship between P_{Loss}^{TS} and P_{Loss} in (1) is theoretically proved with the DC power flow. In this study, it is assumed that this analysis can be applied approximately to the AC power flow.

-Proof-

Consider a DC circuit. The total system losses (TSL) can be expressed as

$$\text{TSL} = \frac{1}{2}\sum R_k I_k^2$$
$$\text{subject to } \sum_{k \in S_{Ni}} I_k = 0 \; (i = 1, 2, \cdots N) \tag{2}$$

where S_{Ni} is the set of all lines connected with node i. And, line k is connected between the nodes i and j (Note that $I_k = I_{ij}$.).

Then, the Lagrangean function with (2) is given by

$$L = \frac{1}{2}\sum R_k I_k^2 - \sum \gamma_i \left(\sum_{k \in S_{Ni}} I_k \right) \tag{3}$$

The optimal conditions of (3) are given by

$$\begin{cases} \dfrac{\partial L}{\partial I_k} = R_k I_k - (\gamma_i - \gamma_j) = 0 \\ \rightarrow R_k I_k = \gamma_i - \gamma_j \text{ (KVL)} \end{cases} \tag{4.a}$$

$$\left\{ \frac{\partial L}{\partial \gamma_i} = \sum_{k \in S_{Ni}} I_k = 0 \text{ (KCL)}. \right. \tag{4.b}$$

Let the Lagrangean multipliers to be node voltages, i.e. ,

$$\gamma_i = V_i, \gamma_j = V_j$$

Then one can easily find that (4.a) just represents the KVL for branch k, i.e.

$$R_k I_k = V_i - V_j$$

Because two optimal conditions $(\partial L / \partial I_k = 0, \partial L / \partial \gamma_i = 0)$ in (4) satisfy the Kirchhoff's voltage (KVL) and current (KCL) laws, it can be said that the currents flow so that the power losses of the entire system are minimized. The DC power flows are dertermined by using the analogy between the DC circuits and the DC power flow networks. The minimum loss principle should be equally applied to the DC power flows. The proof is therefore completed.

As mentioned before, the transactions in the deregulated power market are formed by the arbitrary contract (or power flow) between suppliers and demanders. In this organized transaction strategy, the total summation of the losses allocated to each bus is greater than the total system losses obtained by the OPF. Therefore, it is necessary to make the policy that the excess profit compensating the difference between theses two variables should be taken by the power suppliers.

2.2 Calculation of buswise loss allocation

The loss sensitivity is used for the calculation of the transmission losses in each bus. At first, the transmission loss allocated to bus i is calculated by integrating the incremental power losses, dPLoss,bus, by the variation of power as

$$P_{Loss,bus(i)} = \int dP_{Loss,bus(i)}. \tag{5}$$

Then, the dPLoss,bus can be expressed as

$$dP_{Loss,bus(i)} = \frac{\partial P_{Loss}}{\partial P_i} dP_i + \frac{\partial P_{Loss}}{\partial Q_i} dQ_i. \tag{6}$$

The combination of (5) and (6) gives

$$P_{Loss,bus(i)} = \int_{(0,0)}^{(P^0,Q^0)} \left(\frac{\partial P_{Loss}(\boldsymbol{P},\boldsymbol{Q})}{\partial P_i} dP_i + \frac{\partial P_{Loss}(\boldsymbol{P},\boldsymbol{Q})}{\partial Q_i} dQ_i \right) \tag{7}$$

where P and Q are the real and reactive bus injection power vectors, respectively. Note that the integral in (7) is a path-dependent integral in which path c may be determined by the past load / generation profile.

It can be conjectured that the total system loss should be path-independent since the total loss is completely determined by the present states of a system. However, the loss portion at each bus is obviously dependent on the trajectories of the previous states. In case of a real-time application, it is possible to evaluate the bus-wise losses by considering the actual load and generation trajectories. In this study, the bus-wise losses are calculated under the assumption that all loads and generations are proportionally changed. To deal with this problem, a load parameter λ is introduced to represent the load level of a power system. The λ varies from 0 to 1 where 'λ=0' means 'no load' and 'λ=1' means 'full load condition'.

By using the λ, the variables in (7) can be represented by

$$\mathbf{P} = \mathbf{P}^0\lambda, \mathbf{Q} = \mathbf{Q}^0\lambda, dP_i = P_i^0 d\lambda, dQ_i = Q_i^0 d\lambda. \quad (8)$$

By taking the values in (8) into (7), the loss at bus i is represented by

$$P_{Loss,bus(i)} = \int_0^1 \left(\frac{\partial P_{Loss}(\lambda)}{\partial P_i} + \tan\theta_i \frac{\partial P_{Loss}(\lambda)}{\partial Q_i} \right) P_i^0 d\lambda, \quad (9)$$

where θ_i is the power factor angle of the injection power at bus i.

2.3 Loss sensitivity reflecting Transaction strategy

The slack bus in a power system accounts for the losses of entire system. In order to calculate the loss sensitivity at a generator bus, it is required to increase the small amount of ΔP_L in the all load buses. Then, the total increments by the powers ΔP_L at the load buses should be the same as the increments of the generation and the system losses should be covered by the slack bus. Thereafter, the loss sensitivity can be calculated by

$$\frac{\partial P_{Loss}(\lambda)}{\partial P_i} = \frac{\partial P_{slack}(\Delta P_L)}{\partial P_{Gi}} \quad (10)$$

where $P_{slack}(\Delta P_L)$ is the power at the slack bus calculated after increasing ΔP_L in the load buses connected to the generator bus i. The applied ΔP_L should be shared in each load bus by the ratio of the powers flowing into the load buses with respect to the power from the generator bus. This ratio is called the load ratio.

As an example, the arbitrary power flow in the five-bus system is shown in Fig. 1. The load ratio at bus 1 in Fig. 1 can be expressed as

$$\begin{cases} P_{G1} \to P_{L4} : 20/30 = 0.67 \\ \quad\;\; \to P_{L5} : 10/30 = 0.33 \\ \dfrac{\Delta P_{L4}}{\Delta P_{G1}} = 0.67 \\ \dfrac{\Delta P_{L5}}{\Delta P_{G1}} = 0.33 \end{cases} \quad (11)$$

where ΔPLj/ΔPGi *is the load ratio.*

Here we will define the power transaction vector $\alpha^{(i)}$ with respect to the power increase in Generation bus i

$$\alpha^{(i)} = \left[\alpha_1^{(i)}, \alpha_2^{(i)} \ldots \alpha_n^{(i)}\right]^T \text{ with } \alpha_j^{(i)} = \frac{\Delta P_{Lj}}{\Delta P_{Gi}}$$

Thereafter, the loss sensitivity of the five-bus power system in Fig. 1 can be calculated by increasing ΔP_L with the load ratios at buses 4 and 5 connected to the slack bus. It is important to note that the power flow is considered to be equal to the transaction strategy among the partner of a power market system. Therefore, it is so important to organize the appropriate transaction strategy in the system to allocate the transmission losses to each bus reasonably.

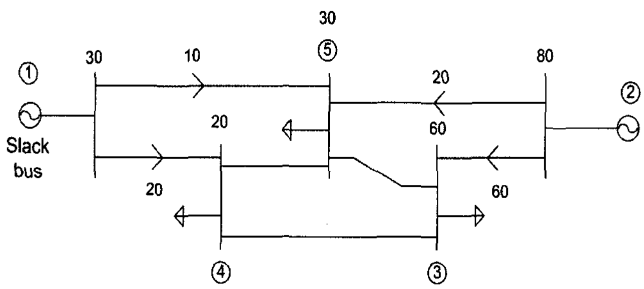

Fig. 1. The bilateral contract of the 5-bus system

The power transactions should be reflected into the calculation of real power loss sensitivity. This study adopts the following procedures. The equation of the Newton-Raphson method is expressed as given by

$$\begin{bmatrix} \Delta \boldsymbol{P}_G - \Delta \boldsymbol{P}_L \\ -\Delta \boldsymbol{Q}_L \end{bmatrix} = \boldsymbol{J} \begin{bmatrix} \Delta \boldsymbol{\theta} \\ \Delta \boldsymbol{V} \end{bmatrix} \quad (12)$$

where

- J is the jacobian matrix.
- Subscripts G and L denotes the generator bus and the load bus, respectively.

Here, $\begin{bmatrix} \Delta \boldsymbol{P}_G - \Delta \boldsymbol{P}_L \\ -\Delta \boldsymbol{Q}_L \end{bmatrix}$ is the mismatch vector. Then, the mismatch vector can be rewritten as

$$\begin{cases} \Delta \boldsymbol{P}_G - \Delta \boldsymbol{P}_L = \left[\boldsymbol{u}_i - \boldsymbol{\alpha}^{(i)} \right] \Delta \boldsymbol{P}_{Gi} \\ -\Delta \boldsymbol{Q}_L = -\boldsymbol{\beta} \Delta \boldsymbol{P}_{Gi} \end{cases} \tag{13}$$

where

- u is the unit vector with 1 for its ith component.
- $\boldsymbol{\alpha}^{(i)} = \left[\alpha_1^{(i)}, \alpha_2^{(i)}, \cdots, \alpha_n^{(i)} \right]^T$ with $\alpha_j^{(i)} = \Delta P_{Lj} / \Delta P_{Gi}$
- β = [tanθ1α1, tanθ2α2, ..., tanθnαn]T.

By using (12) and (13), we can calculate the injection changes in the slack bus as follows

$$\Delta P_S = \left[\left(\frac{\partial \boldsymbol{P}_s}{\partial \theta} \right)^T, \left(\frac{\partial \boldsymbol{P}_s}{\partial V} \right)^T \right] \begin{bmatrix} \Delta \boldsymbol{\theta} \\ \Delta \boldsymbol{V} \end{bmatrix}$$
$$= \left[\left(\frac{\partial \boldsymbol{P}_s}{\partial \theta} \right)^T, \left(\frac{\partial \boldsymbol{P}_s}{\partial V} \right)^T \right] \boldsymbol{J}^{-1} \begin{bmatrix} \left(\boldsymbol{u}_i - \boldsymbol{\alpha}^{(i)} \right) \Delta \boldsymbol{P}_{Gi} \\ -\beta \Delta \boldsymbol{P}_{Gi} \end{bmatrix} \tag{14}$$

where Ps is the real injection power to the slack bus.

And, the transmission loss change can be given by

$$\Delta \boldsymbol{P}_{Loss} = \sum_{i=1}^{N} (\Delta \boldsymbol{P}_{Gi} - \Delta \boldsymbol{P}_{Li}) = \Delta \boldsymbol{P}_{G} - \sum \Delta \boldsymbol{P}_{Li} + \Delta \boldsymbol{P}_s = \Delta \boldsymbol{P}_s \tag{15}$$

By using (14) and (15), we can express the transaction-based marginal loss sensitivity at load level λ in a generator bus.

$$K_{Gi}(\lambda) = \frac{\partial P_{Loss}(\lambda)}{\partial P_{Gi}} = \left[\left(\frac{\partial P_s(\lambda)}{\partial \theta} \right)^T, \left(\frac{\partial P_s(\lambda)}{\partial V} \right)^T \right] \boldsymbol{J}^{-1}(\lambda) \begin{bmatrix} \boldsymbol{u}_i - \boldsymbol{\alpha}^{(i)} \\ -\boldsymbol{\beta} \end{bmatrix} \tag{16}$$

By substituting the (16) to (9), the power losses allocated to each bus can be now computed. Then the average loss sensitivity can be given by

$$K_{Gi}^{AV} = \frac{P_{Loss\ i}^{allocated}}{P_{Gi}} = \int_0^1 K_{Gi}(\lambda) d\lambda \tag{17}$$

Eq.(17) looks somewhat strange since the average sensitivity is calculated after the loss allocation determined. However, the average loss sensitivity is very important to the market participants and is required to be announced.

3. Case Studies

*The proposed algorithm is now applied to the WSCC 9-*bus and the IEEE 14-bus systems. Its performance is compared to that of the previous algorithm [11], which did not use the integration method with the load level parameter λ. The simulation case studies are carried out with the C++ software, and the steps taken in the simulation to implement the proposed algorithm are shown in Fig. 2.

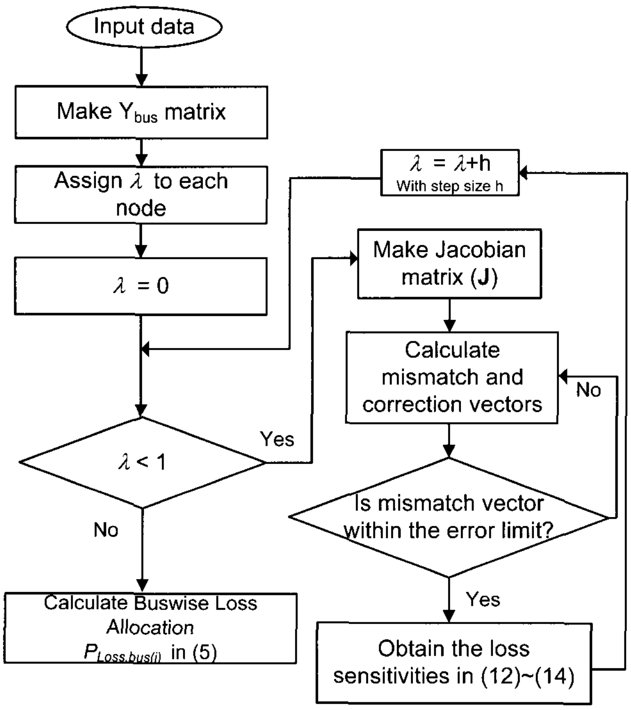

Fig. 2. Flow chart for the steps taken in the simulation

3.1 Test in the WSCC 9-Bus System

Several tests are carried out in the WSCC 9-bus system in Fig. 3 with a typical transaction in Table 1.

The test results are given to provide marginal and average sensitivities with the corresponding loss allocations in Table 2. The performances of the proposed method (method A) and conventional method in [11] (without using the integration by the load level parameter λ) are compared.

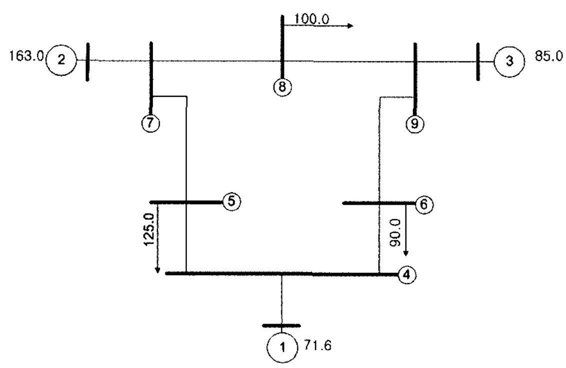

Fig. 3. WSCC 9-bus system

It is clearly shown from the results in Table 2 that loss allocation by the marginal sensitivity almost doubles that by the average sensitivity as expected, and that the total summation of the transmission losses allocated to each bus (for the all cases) is greater than the actual power loss calculated by the Flow Algorithm. Also, the proposed method shows a nice performance, providing the sum of allocated losses pretty close to the actual losses.

Table 1. Bilateral Contracts Between Generators and Loads in the WSCC 9-Bus System (%)

P-Q buses \ P-V buses	1	2	3
4	0	0	0
5	55.7	52.5	0
6	44.3	0	71.0
7	0	0	0
8	0	47.5	29.0
9	0	0	0

Here, it is noted that the above table provides the transaction matrix α

$$\alpha = \begin{bmatrix} 0.0 & 0.0 & 0.0 \\ 0.557 & 0.525 & 0.0 \\ 0.443 & 0.0 & 0.710 \\ 0.0 & 0.0 & 0.0 \\ 0.0 & 0.475 & 0.290 \\ 0.0 & 0.0 & 0.0 \end{bmatrix}$$

Table 2. Loss Sensitivities and Buswise-Allocated Losses (P [pu])

Bus No.	Loss Sensitivity		Loss Allocation	
	S_M† at full load	S_{Avg}††	Conventional by S_M†	Proposed by S_{Avg}††
1	0.00872	0.00392	0.624301	0.280621
2	-0.01074	-0.00547	-1.750757	-0.891636
3	-0.00284	-0.00159	-0.241737	-0.135658
4	-	-	0.000000	0.000000
5	0.05029	0.02409	6.286880	3.012090
6	0.05070	0.02472	4.563200	2.224691
7	-	-	0.000000	0.000000
8	0.01039	0.00496	1.039655	0.496346
9	-	-	0.000000	0.000000
Total	-	-	**10.521542**	**4.986455**
Total loss by the power flow calculation			**4.641021**	

† Marginal Sensitivity

†† Average Sensitivity

3.2 Test in the *IEEE 14*-Bus System

The performance of the proposed algorithm is evaluated by the test in the IEEE 14-bus system in Fig. 4. The bilateral contracts between generators and loads in the IEEE 14-bus system are given in Table III. As same in the previous test, Table 3 shows a typical bilateral transactions by the PF calculation.

The test results are given in Table IV. The same conclusions can be obtained as given in the previous test case.

Here it is noted that, in any case, the total sum of allocated losses is greater more than that the actual system loss obtained by power-flow calculation.

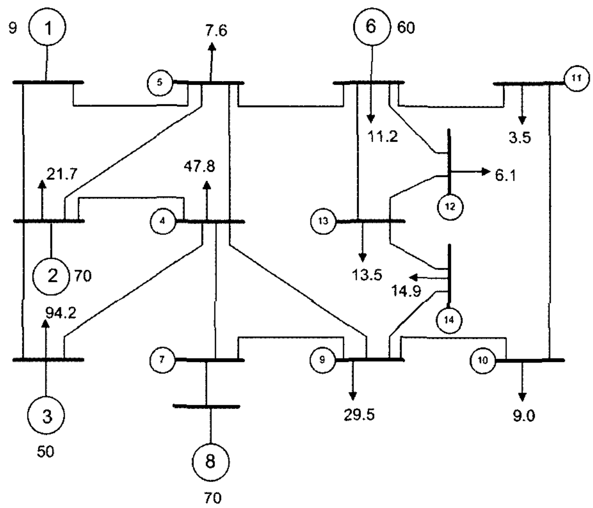

Fig. 4. IEEE 14-bus system

Table 3. Bilateral Contracts Between Generators and Loads in the IEEE 14-Bus System (%)

P-Q buses \ *P-V* buses	1 $(\alpha^{(1)})$	2 $(\alpha^{(2)})$	3 $(\alpha^{(3)})$	6 $(\alpha^{(6)})$	8 $(\alpha^{(8)})$
2	42.5	32.0	0	0	0
3	0	39.0	100.0	0	25.0
4	0	19.0	0	18.0	18.0
5	57.5	10.0	0	0	0
6	0	0	0	20.0	0
7	0	0	0	0	0
9	0	0	0	0	41.0
10	0	0	0	10.0	6.0
11	0	0	0	6.0	0
12	0	0	0	10.0	0
13	0	0	0	23.0	0
14	0	0	0	13.0	10.0

Table 4. Loss Sensitivities and Buswise-Allocated Losses (P [pu])

Bus / No.	Loss Sensitivity		Loss Allocation	
	$S_M^{\dagger}$ at full load	$S_{Avg}^{\dagger\dagger}$	Conventional by $S_M^{\dagger}$	Proposed By $S_{Avg}^{\dagger\dagger}$
1	0.002686	-0.000075	0.024178	-0.000673
2	0.012093	0.003439	0.846477	0.240701
3	0.025650	0.008602	1.282505	0.430081
4	0.003118	0.001724	0.149028	0.082401
5	-0.004319	-0.001263	-0.032825	-0.009602
6	0.0169297	0.006744	1.015782	0.404663
7	-	-	0.000000	0.000000
8	0.020247	0.007694	1.417347	0.538615
9	0.002252	0.001654	0.066438	0.048789
10	0.000136	0.001132	0.001227	0.010190
11	0.004863	0.002804	0.017020	0.009815
12	0.007813	0.004276	0.047661	0.026081
13	0.013689	0.007102	0.184807	0.095873
14	0.032058	0.015753	0.477669	0.234722
Total	-	-	**5.497313**	**2.111655**
Total loss by the power flow calculation			**1.733637**	

4. Conclusions

The proposed algorithm in this paper presents the new method, which can apply to electric power market system to use a transaction strategy not considered in the existing transmission losses allocation algorithm by loss sensitivity. As applied arbitrary transaction strategies, the allocated transmission losses of each bus are calculated. As a result, we can prove that whatever calculated by any transaction strategy, the total of the allocated transmission losses of each bus is more than the total loss of AC power-flow algorithm and as transaction strategy is more and more optimal, the total of the allocated transmission losses of each bus is the most adjacent with the total loss of AC power-flow algorithm. And, we presented the reasonable scheme in which an excess profit of the total of the allocated transmission losses of each bus about the total loss of AC power-flow algorithm is taken by power suppliers.

In this paper, the allocated transmission losses of each bus is calculated by the method of integrating loss sensitivities using by the load level parameter λ which is a linear curve increasing from 0 to 1. However, in the real power system, power demand should not increase linearly. Namely, power demand could present variously as time. Therefore, in order that this algorithm is more adjacent with the real situation of power systems, in future, we need the study that is about the algorithm calculating as changing the increasing pattern of load parameter λ in each bus.

Acknowledgements

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