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A CONFORMING METHOD FOR REGIONAL MARGINAL LOSS SURPLUS ALLOCATION

by

XIAOLONG WANG

A THESIS

Presented to the Faculty of the Graduate School of the

MISSOURI UNIVERSITY OF SCIENCE AND TECHNOLOGY

In Partial Fulfillment of the Requirements for the Degree

MASTER OF SCIENCE IN ELECTRICAL ENGINEERING

2013

Approved by

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ABSTRACT

The marginal transmission loss model is used in electricity markets across the United States to measure a resource’s marginal contribution to system loss. This model prices loss into the locational marginal price as a marginal loss component. Marginal loss pricing will render a net revenue surplus within an energy balanced system. This marginal loss surplus (MLS) is typically allocated back to scheduling coordinators in proportion to the measured demand on a system-wide basis. However, when the system experiences heterogeneous loss across different regions, the system-wide allocation method fails to recognize the regional differences in actual loss costs. As a result, it may create subsidies between regions. This thesis proposes a conforming regional allocation method to extend the allocation method from system-wide to regions. A non-conforming regional allocation method was used to compare with the conforming regional allocation on the impact of MLS allocation in different regions. This study demonstrates that the proposed method precisely conforms to the system-wide allocation method within each region. More specifically, this study computes the MLS contribution of each region based on the conforming regional allocation method, it then compares with each region's MLS based on a system-wide allocation method. This study found that the proposed conforming regional allocation method does provide fair allocation across different regions and can thus be applied across United States' electricity markets.

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I thank my family for all of their support and encouragement. My mother Jianyun Nie, my father Ping Wang, they provide me endless love and support.

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ANHM	Anaheim
AZUA	Azusa
BANN	Banning
CA ISO	California ISO
CORO	City of Corona
CWRP	Corporate Wetlands Restoration Partnership
CWRS	California Waste Recovery Systems
DCOPF	DC Optimal Power Flow
ERCOT	Electric Reliability Council of Texas
FERC	Federal Energy Regulatory Commission
ISO	Independent System
ISO-NE	New England ISO
LMP	Locational Marginal Pricing
MCC	Marginal Cost of Congestion
MCL	Marginal Cost of Losses
MCL	Marginal Cost of Losses
MW	Megawatt
MISO	Midwest ISO
MLS	Marginal Loss Surplus
MW	Megawatt
NCPA	Northern California Power Agency
NP26	Northern of Path 26
NYISO	New York ISO
OPF	Optimal Power Flow
PASA	Pasadena
PG&E	Pacific Gas and Electric Company
Pnode	Pricing Nodes
PSTN	Port of Stockton

PTOs	Participating Transmission Owners
RTO	Regional Transmission Organization
RVSN	RADVision
SC	Scheduling Coordinators
SCE	Southern California Edison
SDG&E	San Diego Gas & Electric
SMD	Standard Market Design
SMEC	System Marginal Energy Cost
SP26	Southern of Path 26
SPP	Southwest Power Pool
VERN	Vernon

1. INTRODUCTION

1.1. ELECTRICITY MARKET IN THE UNITED STATES

1.1.1. ISOs and RTOs. In North America, two-thirds of electricity consumers and more than 50 percent of Canada's population are served by Independent System Operators (ISOs) and Regional Transmission Organizations (RTOs) respectively [1]. ISO/RTOs were created by the Federal Energy Regulatory Commission (FERC) to handle the challenges associated with operating multiple, interconnected, independent power supply companies. ISO/RTOs themselves are independent, revenue-neutral entities charged with, among other responsibilities, operating a robust, reliable, wholesale power system that balances the need for higher transmission reliability with the need for lower costs. Their responsibilities also include developing effective processes, tools, and methods for improving competitive electricity markets across North America.

Before ISO/RTOs, the power from generator belongs to different utilities, and those utilities provide the local power (see Figure 1.1).

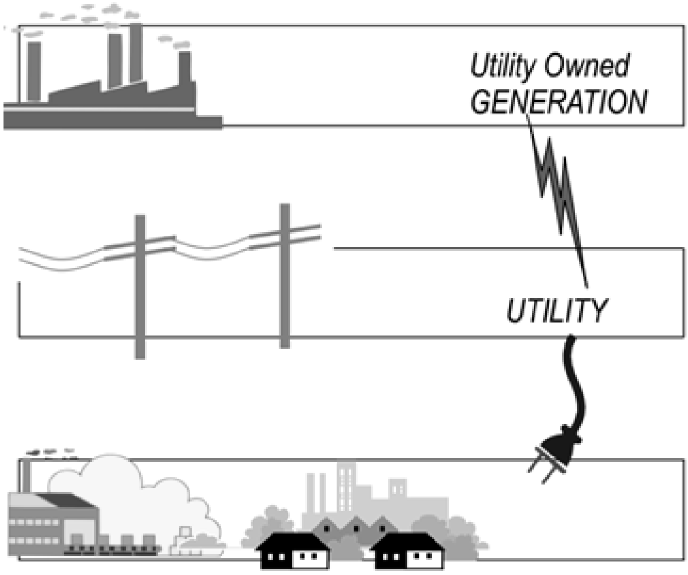


Figure 1.1. System Operations before ISO/RTOs [2]

The California ISO network is an example of this electricity market. This network delivers wholesale electricity to local utilities for distribution to 30 million Californians (see Figure 1.2).

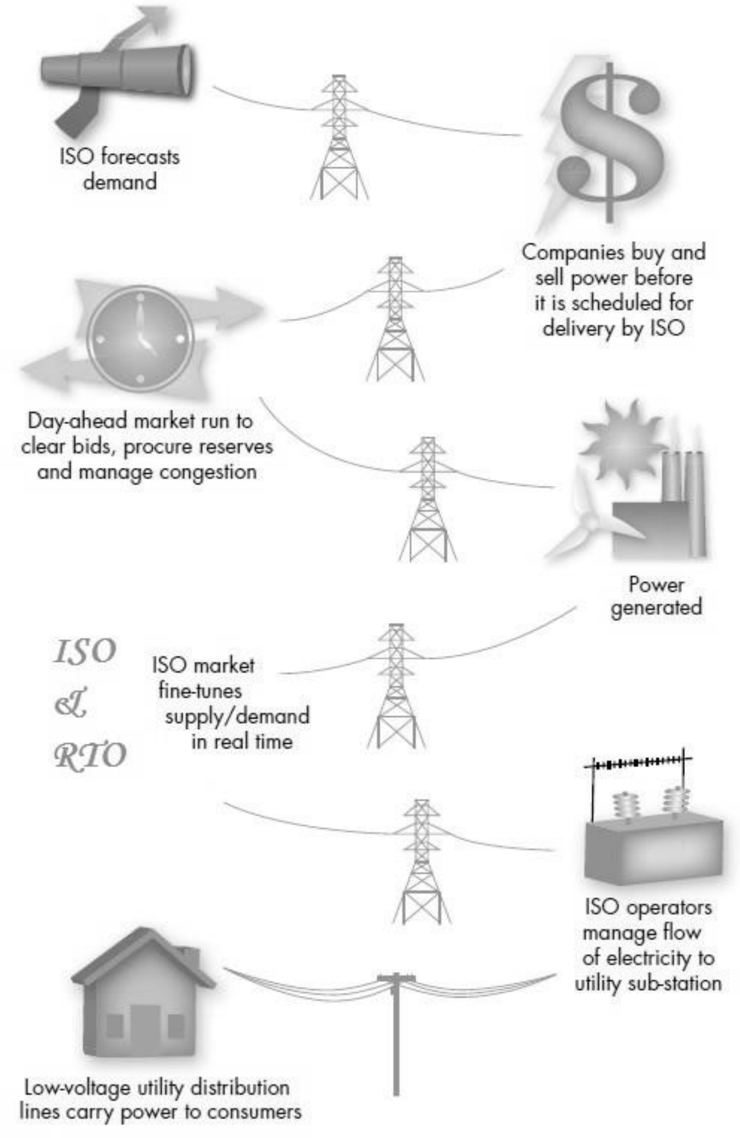
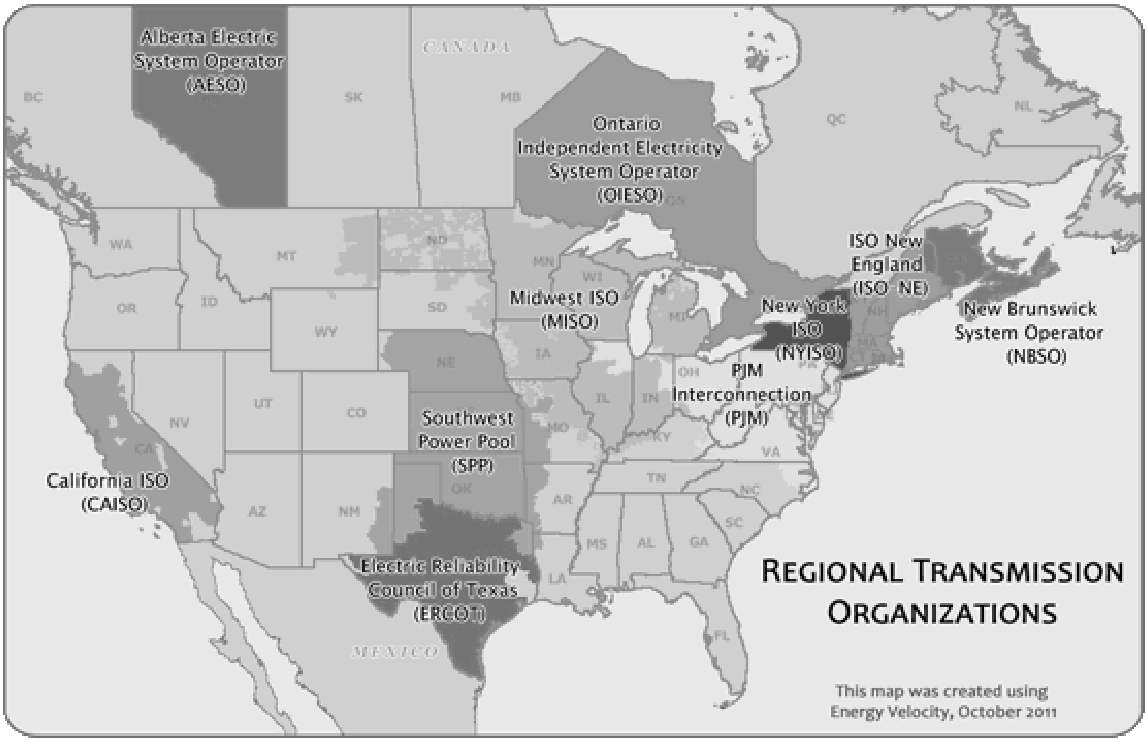


Figure 1.2. System Operations in California ISO [3]

In this thesis, most examples and analyses are based on the California ISO. These methodologies, however, could be applied to other ISO/RTOs.

1.1.2. Wholesale Market Design. A standard market design (SMD) proposed by FERC in April 2003 has been adopted by United States' wholesale power markets [4]. This proposed market design includes three parts. 1. Central oversight by an independent market operator. 2. A two-settlement system with a day-ahead market and a real-time market. 3. Management of grid congestion by means of locational marginal pricing (LMP).

FERC's SMD have been implemented (or are scheduled for implementation) in the United States' energy regions. These regions include the Midwest (MISO), New England (ISO-NE), New York (NYISO), the Mid-Atlantic States (PJM), California (CAISO), the Southwest (SPP), and Texas (ERCOT) (see Figure 1.3).



This map was created using Energy Velocity, October 2011

Figure 1.3. ISO/RTOs Operating Regions [5]

1.2. LOCATIONAL MARGINAL PRICING

Locational marginal pricing methodology is the dominant approach used in power markets to calculate electricity prices and manage transmission congestion. LMPs help accurately represent both the system's physical constraints as well as economic realities. The purpose for using LMP in electricity market is to enhance greater competitive of electricity market and to more accurately reflect the cost of congestion and the price of transmission [6] [7].

The LMP is the cost required to serve the next Megawatt (MW) of load at a specific location using the lowest production cost of all available generators, while still maintaining all transmission within limits. It reflects the value of power at a specific location at the time that power is delivered. LMPs are computed for each node and market period in both day-ahead and real-time markets.

The day-ahead market is a forward market. In this market, hourly LMPs are calculated for the next operating day based on generator offers, demand bids, and scheduled bilateral transactions. The real-time market is a spot market. In this market the current LMPs are calculated at five-minute intervals based on actual grid operating conditions.

LMPs are used in market settlement processes to determine not only generator payments but also load charges by multiplying the amount of energy produced or consumed at that location. LMPs are also used in ancillary service calculations to both price transmission and manage congestion [8].

In ISO/ RTO operating regions, LMPs are calculated at a large number of locations, known as nodes. These nodes represent places on the system where either generator injects power into the system or where demand (or load) draws power from the system. Each pricing node (*pnode*) is related to either one or more electrical buses on the power grid (see Figure 1.4).

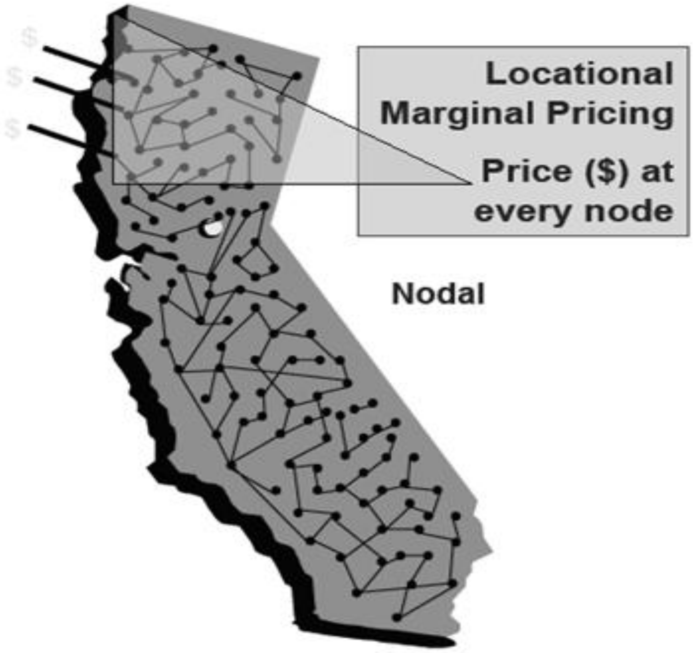


Figure 1.4. California Simplified Node Map[9]

The LMP at each node comprised of three components. 1. The system marginal energy cost (SMEC). 2. The marginal cost of congestion (MCC). 3. The marginal cost of losses (MCL).

$$LMP(\$/MW) = SMEC + MCC + MCL \tag{1}$$

where SMEC is the component of the LMP that reflects the marginal cost of providing energy from a designated reference location. A distributed reference bus is used to weight the pricing nodes throughout the system. MCC is the component of the LMP at a node that accounts for the costs of congestion (as measured between that node and a reference bus). It is calculated by using both the cost of marginal units controlling constraints and the sensitivity on each bus. MCL is the component of the LMP at a *pnode* that accounts for the marginal real power losses as measured between that node and a reference bus (i.e., energy lost as it travels over the wires). The MCL is calculated by using penalty factors. These factors are discussed in Section 2.

1.2.1. System Marginal Energy Cost. The system marginal energy cost is defined as the cost to serve the next increment of demand at the specific location or node that can be produced from the least expensive generating unit in the system that still has available capacity. It is calculated in both day-ahead and real-time markets, while ignoring both congestion and loss. If the system marginal energy cost were the only component in the LMP, then the lowest-priced electricity would reach all locations and prices would be the same across the entire grid.

1.2.2. Marginal Cost of Congestion. When the transmission network is congested (heavy use of the transmission system in an area), the next increment of energy cannot be delivered from the least expensive unit on the system. This is because it would cause overloading on the transmission system or violate a transmission operating criteria, such as voltage profile requirements. The congestion component is calculated at a node as the difference between the energy component of the price and the cost of providing the additional, more expensive, energy that can be delivered at that location.

The congestion component is analogous to a taxi ride for megawatts of electricity. When the traffic is light, either the fare is expected to be consistent and predictable. corresponding to a period with either little or no congestion on the grid. Similarly, heavy traffic results in a higher fare comparable to a time of congestion on the transmission system [10].

1.2.3. Marginal Cost of Loss. All transmission systems experience electrical losses as electricity is sent over transmission lines. These losses account for a small percentage of electricity from generators. Nodal prices are adjusted to account for the marginal cost of losses. Transmission losses are nonlinear functions of both the generators and the loads within the system. Before an LMP-based market was adopted, losses were treated as a static component of load. Both the physical nature and the location of power system losses were ignored. FERC views the marginal loss pricing mechanism as preferable to the average loss model. The marginal loss model more accurately models the physical reality of power system losses, permitting increased efficiency and more optimal asset utilization [11].

The marginal cost of loss is created by the marginal loss modeling set by the ISO/RTOs. It can be used to reward generators or load that reduce loss, meanwhile punishing those that increase loss in the power system. A separate marginal loss price is charged to load and credited to generator for every location on the power grid. It can be either positive or negative with respect to the reference bus. If an increase in load at a bus would decrease losses, then the marginal loss component of the LMP of that bus would be negative. If an increase of load at a bus would increase losses, then the marginal loss component of the LMP at that bus would be positive. If an increase in generator at a bus would result in an increase in losses, the marginal loss component of that bus would be negative. If an increase in generator at a bus results in a decrease of system losses, then the marginal loss component of LMP at that bus would be positive. Total network losses are determined by using a linearized approximation model based on the loss sensitivities to location-specific changes in power injection and withdrawal.

1.3. MARGINAL LOSS

Incorporating the marginal cost of losses into LMPs is necessary to not only ensure least-cost dispatch and establish nodal prices that accurately reflect the cost of supplying the load at each node [12]. Marginal losses rise exponentially with transmission system flows. They exceed average losses (roughly by a factor of two, as shown in Section 2) and result in an over-collection of loss revenues. As a revenue-neutral entity, an ISO is responsible for allocating the over-collection to the Participating Transmission Owners (PTOs). The marginal loss surplus (MLS) eventually returns to the entities that considered as demand (both internal loads and exports).

A reasonable method for allocating the residual should meet the following basic principles [13].

- Avoid allocating any credits for the loss surplus to criteria that can be impacted by market participant actions so that the credit does not distort incentives. Do not tie the credit to market participant’s schedules.
- Allocate the surplus to market participants based on the contribution of marginal loss.

Currently, ISOs will typically collect the MLS and hold it to refund at a later time. The MLS is allocated proportionally based on measured demand within each region. This method, known as the system-wide demand ratio MLS allocation method (as shown in

Section 3), has been approved by FERC. This method, however, is considered both unfair and unjust by market participants. It fails to recognize the significant differences in transmission losses for different regions within the ISO control area. For example, there are two regions in the whole electric system. If each one has fifty percent of the total measured demand, eventually, 50/50 of MLS will be distributed to each region by the system-wide allocation method. These transmission losses, however, are determined not only by measured demand but also by the transmission line's voltage. Because low voltage tends to incur more loss when compared to high voltage. MLS should be allocated to market participants based on marginal loss. If one region has more low voltage transmission lines, then more loss will be created, thus the region with more lower voltage transmission lines should get more MLS than the region with higher voltage transmission lines.

1.4. WORK SUMMARY

In Section 2, LMP and MLS models have been discussed mathematically in the DCOPF model. The relation that the system marginal loss doubles the system marginal loss is verified within those models.

In Section 3, the thesis proposes a conforming regional MLS allocation method that can reflect both regional differences and their impacts on ISO marginal loss charges. This method acts as one possible alternative method that could distribute MLS based on its actual contributions in each region and thus maximize fairness. It also conforms to the system-wide demand ratio MLS principle.

Simultaneously, a non-conforming regional MLS method is proposed to allocate loss residual when heterogeneous loss exists in different regions. This method introduces a new principle that treats the loads and the exports differently within the exporting region. In a non-conforming regional MLS method, the MLS regional allocation does not conform to the system-wide demand ratio MLS principle.

In Section 4, the conforming regional MLS allocation method is compared to the non-conforming regional MLS allocation method. This comparison suggests the conforming regional MLS method is a more preferable solution when distributing MLS.

In Section 5, three marginal loss surplus allocation methods are discussed by a large-scale example from California ISO. The impact of both the direction and magnitude of the inter-region flow to MLS in not only the exporting region but also the importing region is discussed illustrating the difference between these three methods.

2. DC OPTIMAL POWER FLOW MODEL CONSIDERING LOSSES

The core of FERC proposed Standard Market Design is locational based marginal pricing for electrical energy by which the energy prices and the associated transmission usage chargers are to be determined based on marginal costs in order to promote economic efficiency [14]. One of the main challenging issues in implementing LMP methodology is the pricing of marginal transmission losses, which requires accurate analysis of transmission losses and incorporating the effects of marginal losses into the optimal generator scheduling programs.

2.1. TRANSMISSION LOSSES

Transmission losses are always involved as energy consumed during the process of moving power from generator to load because of the resistance of each element in the transmission system. These losses cause unwanted but inevitable heating of transmission lines, cables and transformers, and they manifest as additional electrical load, requiring the generators to produce additional power to compensate the losses. Transmission and distribution losses are a small percentage of total energy use. For example, California average system losses for transmission and distribution ranged from 5.4 percent to 6.9 percent during 2002 to 2008 based on Energy Commission data as shown in Figure 2.1.

Utility specific losses will vary based on the individual transmission and distribution system. For example, losses within the northern California area tend to be higher since the transmission system is composed of longer and lower voltage transmission lines, which cause more losses (the main reason for proposing regional marginal loss surplus allocation, discuss in Section 3). The location of a generator with respect to the grid and with respect to load affects the amount of line losses that occur.

Losses vary greatly as a function of network configuration, generator locations and outputs, and customer locations and demands. Transmission losses are a function of the square of the line flows through the circuit or transformer windings (I^2R), hence, transmission losses during heavy loading period are often much higher than under average loading condition.

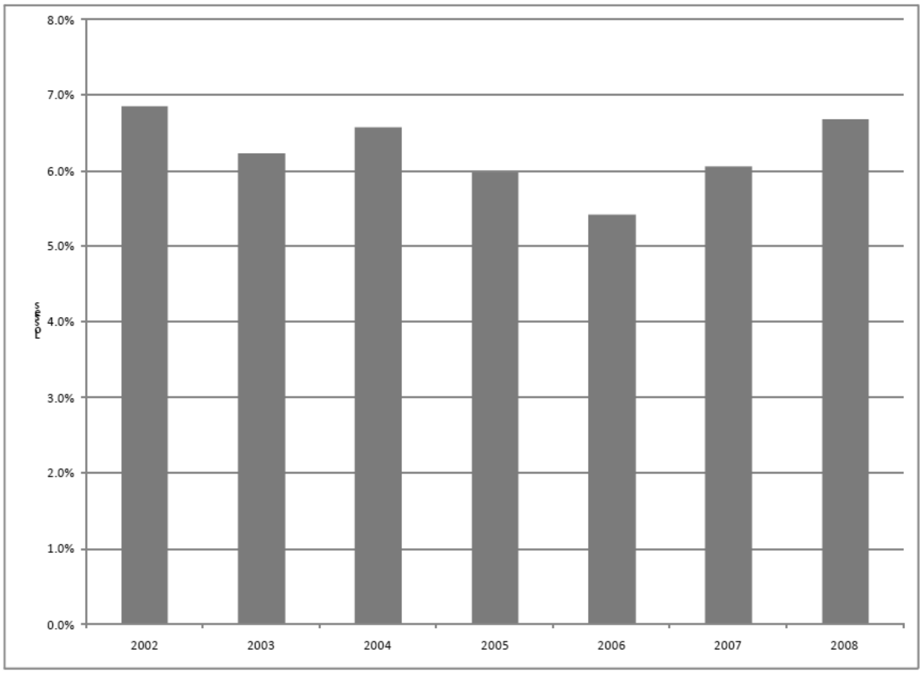


Figure 2.1. California Average Historical Transmission and Distribution Losses [15]

2.2. LOSS FACTOR AND DELIVERY FACTOR

Transmission losses are priced at each bus according to marginal loss factors. The marginal loss factors represent the percentage increase in system losses caused by a small increase in power injection or withdrawal. In marginal loss price, the key considerations are the marginal loss factor and the marginal delivery factor. Mathematically, they can be written as

$$LF_i = 1 - DF_i = \frac{\partial Loss}{\partial P_i} \tag{2}$$

where

LF_i is the marginal loss factor at node i;

DF_i is marginal delivery factor at node i;

$Loss$ is the system average loss function of power injections;

P_i is net injection at node i.

The loss factor and delivery factor can be calculated in (3) and (4), based on definition of loss factor.

$$Loss = \sum_{k=1}^{m} F_k{}^2 \times R_k \tag{3}$$

$$\begin{aligned}\frac{\partial Loss}{\partial P_i} &= \frac{\partial}{\partial P_i}(\sum_{k=1}^{m} F_k{}^2 \times R_k) \\ &= \sum_{k=1}^{m} R_k \times 2F_k \times \frac{\partial F_k}{\partial P_i}\end{aligned} \tag{4}$$

where
m is the number of lines in the system;
F_k is the line flow at line k;
R_k is the resistance at line k.

A line flow can be considered as an aggregation of all power resources in the linear dc network. Generator is a positive source and load is a negative source [16]. Line flow can be written as

$$\begin{aligned}F_k &= \sum_{j=1}^{n} GSF_{k,j} \times (G_j - D_j) \\ &= \sum_{j=1}^{n} GSF_{k,j} \times P_j\end{aligned} \tag{5}$$

where
n the number of nodes is in the system;
G_j is the generator dispatch at node j;
D_j is the demand at node j;
$GSF_{k,j}$ is the shift factor of node j to line k.
From equation (4) and (5), LF can be written as

$$\begin{aligned}\frac{\partial Loss}{\partial P_i} &= \sum_{k=1}^{m} R_k \times 2F_k \times \frac{\partial F_k}{\partial P_i} \\ &= \sum_{k=1}^{m} R_k \times 2(\sum_{j=1}^{n} GSF_{k,j} \times P_j) \times \frac{\partial(\sum_{j=1}^{n} GSF_{k,j} \times P_j)}{\partial P_i} \\ &= \sum_{k=1}^{m} R_k \times 2(\sum_{j=1}^{n} GSF_{k,j} \times P_j) \times GSF_{k,i}\end{aligned} \tag{6}$$

Loss factor may be positive or negative, depending on whether an increase of injection at the bus may increase or reduce the total system loss. For example, in a simple three bus system, with B as reference bus (see Figure 2.2), Bus A generates 1000 MW of power, Bus B and Bus C have load 475 MW and 450 MW respectively. The loss on line A-B is 25 MW, the loss on line A-C is 50MW. If there is a hypothetical injection increase at Bus A, the increased injection will be absorbed by the reference bus B or two load buses proportionally, the line flows will increase and then the system loss will increase, in this case, the loss factor at bus A is positive. If the hypothetical injection increase at Bus B, the increased injection will be absorbed by reference Bus B or the two load buses proportionally, and it will reduce the flow on line A-B, the line flows as well as the system loss will reduce, thus, the loss factor at bus B is negative.

According to (2), the delivery factor is less than 1 when the loss factor is positive and will be greater than 1 when loss factor is negative.

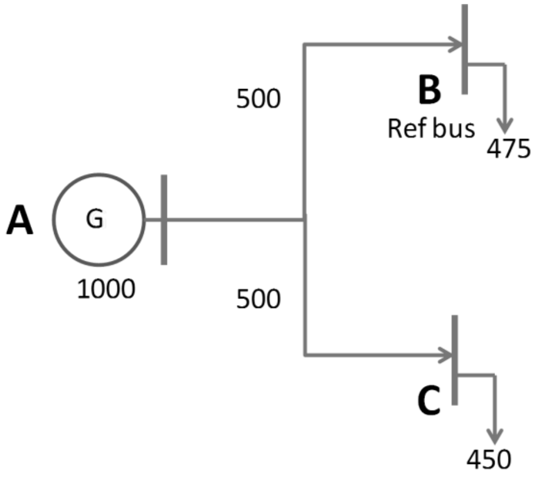


Figure 2.2. Three-Bus System

2.3. MARGINAL LOSS VERSUS AVERAGE LOSS

In 1.3, we have mentioned that marginal loss (injection multiplied by marginal loss factor) is twice the average loss (also referred to as actual loss) [16] [17] [18] [19]. The proof of this fact in dc model is given as follows:

$$Loss^{marg} = \sum_{i=1}^{n} \left(\frac{\partial Loss}{\partial P_i} \times P_i \right) \tag{7}$$

According to (3)-(6)

$$\begin{aligned} Loss^{marg} &= \sum_{i=1}^{n}((\sum_{k=1}^{m} R_k \times 2(\sum_{j=1}^{n} GSF_{k,j} \times P_j) \times GSF_{k,i}) \times P_i) \\ &= \sum_{i=1}^{n}(\sum_{k=1}^{m} R_k \times 2 \times F_k \times GSF_{k,i} \times P_i) \\ &= 2 \cdot \sum_{k=1}^{m}(R_k \times F_k{}^2) \\ &= 2 \cdot Loss \end{aligned} \tag{8}$$

where

$Loss^{marg}$ is the marginal loss

From (8), we can apparently see the net injection multiplied by loss factor doubles the system loss.

The ratio of marginal loss and average loss in California ISO from December 2011 to November 2012 is all around 2 (see in Figure 2.3). The data were taken from California ISO's market database and were run by 'Marginal Loss Surplus Allocation' SAS program. The result confirms that marginal loss is roughly twice as much as the average loss.

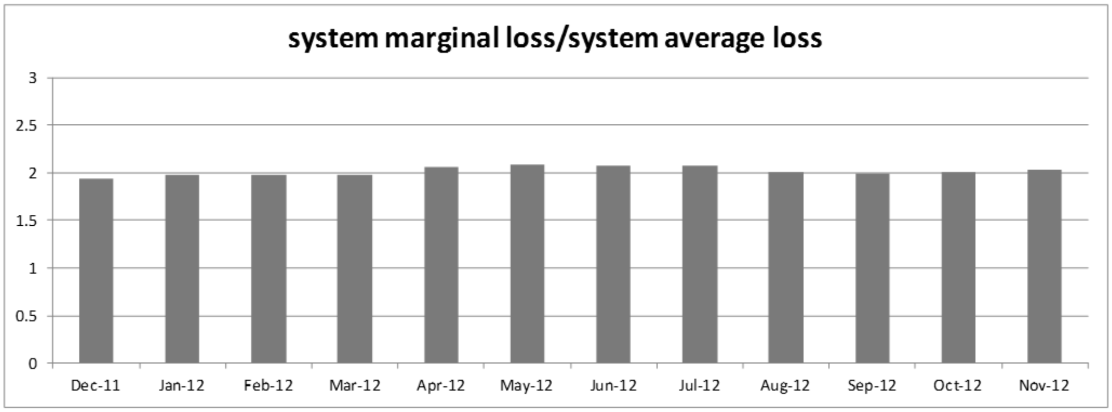


Figure 2.3. Ratio of Marginal Loss and Average Loss

The ratio of marginal loss and average loss is approximately equal the ratio of marginal loss cost and average loss cost. According (1), the LMP at reference bus is the system energy price, which is the same throughout the system. One year's the marginal loss cost and average loss cost in California ISO is shown in Figure 2.4, which clearly represent their doubled relationship.

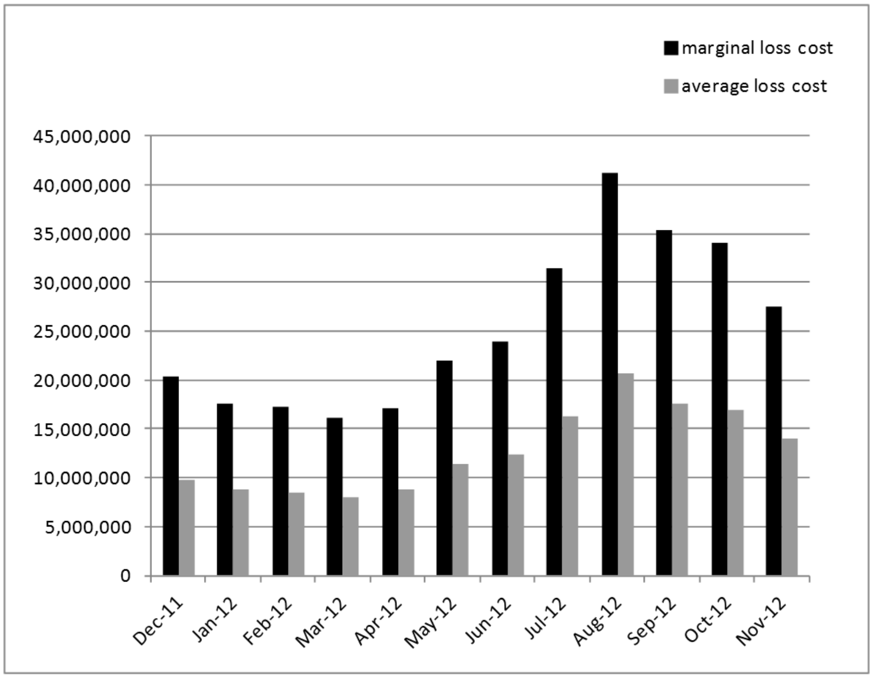


Figure 2.4. Marginal Loss Cost and Average Loss Cost

2.4. DC OPTIMAL POWER FLOW ALGORITHM WITH MARGINAL LOSS

Transmission losses are essentially important in determining the optimal scheduling of generator resources. The generator scheduling process involves two fundamental tasks:

- Optimal combination of generator resources that satisfies system load and required operating reserves subject to operational constraints.
- Optimal utilization of generator resources such that the total system energy production costs is minimized.

2.4.1. Loss Penalty Factor. In the traditional optimal generator scheduling programs, the effects of incremental transmission losses are usually considered through the use of loss penalty factors associated with individual generator facilities. Loss penalty factor that can be used to include the effect of losses in dispatch [20][17]. These loss penalty factors are used to obtain the equivalent generator production costs. Thus, the marginal losses are included in the total cost minimization of system operation.

Loss penalty factor associates loss factor and delivery factor, mathematically, it is written as:

$$\begin{aligned} PF_i &= \frac{1}{1-\frac{\partial Loss}{\partial P_i}} \\ &= \frac{1}{1-LF_i} = \frac{1}{DF_i} \end{aligned} \tag{9}$$

where

PF_i is loss penalty factor at node i.

If an increase of injection results an increase of system loss, the penalty factor will be greater than 1, the units looks less attractive to dispatch. If an increase of injection results a decrease of system loss, the penalty factor will be less than 1, the unit looks more attractive to dispatch [16]. In the marginal loss model, the marginal impact of generator dispatch on loss is taking into consideration by the market optimization. For example, if a generator incurs 1% of loss by injecting at its location and being balanced by the slack bus withdraw, then $\frac{\partial Loss}{\partial P_i} = 0.01$, according to (9) $PF_i = 1.01$, which means in the market optimization, the resource needs to generate 1.01 MW in order to meet 1 MW of load at the slack bus.

2.4.2. DC Optimal Power Flow Model. As shown in (2), loss factor at node i is affected by the net injection P_i, which is the generator dispatch G_i minus load D_i. Conversely generator dispatch may also depend on loss factors since different generators may be penalized differently based on their loss factors.

P_i is unknown before performing any dispatch. The method to solve this is to have an estimation of dispatch to obtain an estimated LF at each bus first. Then, the new dispatch results can be obtained by using the estimated loss factors. This process is named iterative DC optimal power flow (DCOPF) approach. In this approach, the simple basis is to keep updating DF_i and P_{loss} in $(i+1)th$ iteration by using the dispatch results from $l\,th$ iteration until the convergence reaches the stop criteria. The LMPs can be obtained from the last iteration [16].

In a nodal market, the ISO typically clears the market by an optimal power flow (OPF) to minimize the total system bid cost as well as meeting demand and satisfying transmission flow limits and other operational constraints. Contingencies can also be included in the optimal power flow, and the resulting model is called a security constrained OPF. For discussion simplicity, the DCOPF model discussed above is used in this thesis [16][21]. There are more sophisticated marginal loss models discussed in [21][22]. The marginal loss allocation (MLS) method proposed in this paper is applicable to any OPF based marginal loss model independent of the OPF model itself and the algorithm to solve the OPF. A simplified DC OPF model is as follows:

$$\min_p \sum_{i=1}^{n} C_i \times G_i \tag{10}$$

$s.t.$

$$\sum_{i=1}^{n} \frac{(G_i - D_i)}{PF_i^{est}} = Loss^{est} \tag{11}$$

$$\sum_{i=1}^{n} SF_{l,i}(G_i - D_i) \le FL_l^{\max}, \forall l = 1, 2, \cdots, m_{cstr} \tag{12}$$

$$P_i^{\min} \le P_i \le P_i^{\max}, \forall i = 1, 2, \cdots, n \tag{13}$$

where

(11) is the energy balance constraint

(12) is the transmission constraint

C_i is the generator bid cost at node i;

PF_i^{est} is the loss penalty factor at Bus i from previous iteration;

$Loss^{est}$ is the loss from previous iteration;

$SF_{l,i}$ is the shift factor of node i to constraint l;

$FL_l^{\max}$ is the transmission constraint l 's flow limit;

m_{cstr} is the number of transmission constraints in the system.

$P_i^{\min}$ is generator i 's minimum generator level;

$P_i^{\max}$ is generator i 's maximum generator level.

$Loss^{est}$ is used to offset the doubled system loss caused by the marginal loss factor and marginal delivery factor.

After obtaining the optimal solution of generator dispatch, the LMP at any Bus can be calculated with Lagrangian function. The Lagrangian function for OPF can be written as

$$\psi = (\sum_{i=1}^{n} C_i \times G_i) - \lambda(\sum_{i=1}^{n} \frac{(G_i - D_i)}{PF_i^{est}} - Loss^{est}) - \sum_{l=1}^{m} \mu_l (\sum_{i=1}^{n} SF_{l,i}(G_i - D_i) - FL_l^{\max}) \quad (14)$$

where

ψ is the Lagrangian function;

λ is the Lagrangian multiplier for the power balance constraint, and is also called the system energy component;

μ_l is the Lagrangian multiplier for the $l-th$ transmission constraint.

In (14)

At a location j, its LMP is determined by

$$LMP_j = \frac{\partial \psi}{\partial D_j} = \lambda + \sum_{i=1}^{m} \mu_l \cdot SF_{l,j} + \lambda(\frac{1}{PF_j} - 1) \quad (15)$$

From (15), LMP at location j consists of three components: system marginal energy cost, marginal cost of congestion, and marginal cost of losses. This is consistent with (1). The LMP formulation can be written as (16)-(19).

$$LMP_j = LMP^{energy} + LMP_j^{cong} + LMP_j^{loss} \quad (16)$$

$$LMP^{energy} = \lambda \quad (17)$$

$$LMP_j^{cong} = \sum_{i=1}^{m} \mu_l \cdot SF_{l,j} \quad (18)$$

$$LMP_j^{loss} = \lambda(\frac{1}{PF_j} - 1) \quad (19)$$

The total revenue from collecting the marginal loss component from all power supply and demand is

$$\sum_{j=1}^{n} \lambda\left(\frac{1}{PF_j}-1\right)(D_i - G_i) \tag{20}$$

If we assume loss is paid at the system-wide energy component λ, then the system marginal loss is

$$\sum_{i=1}^{n} \left(\frac{1}{PF_i}-1\right)(D_i - G_i) \tag{21}$$

On the other hand, the system average loss cost is

$$\sum_{j=1}^{n} \lambda(G_i - D_i) \tag{22}$$

with the system average loss equal to

$$\sum_{j=1}^{n} (G_i - D_i) \tag{23}$$

Because marginal loss revenue is higher than the average loss cost, the difference between them is the marginal loss surplus:

$$\begin{aligned} MLS &= \sum_{j=1}^{n} \lambda\left(\frac{1}{PF_j}-1\right)(D_i - G_i) - \sum_{j=1}^{n} \lambda(G_i - D_i) \\ &= \sum_{j=1}^{n} \lambda \frac{1}{PF_j}(D_i - G_i) \end{aligned} \tag{24}$$

where

MLS is marginal loss surplus

Equation (14)-(24) provide means to calculate LMP of each node and MLS for the simple six-bus example as Figure 2.5, where the generator, load and power flow have been converted to p.u. values with the MVA basis equal to 10,000.

In this example, we assume the four branches that connect G1, G2, D1 and D2 to the system have resistors. There is no congestion in the system. The loss on each transmission line is shown adjacent to the impedance. So the difference between an LMP and the energy component (LMP^{energy}) is equal to the loss component. The average loss function is written as follows

$$Loss = 0.05 \cdot P_{G1}{}^2 + 0.04 \cdot P_{G2}{}^2 + 0.2 \cdot P_{D1}{}^2 + 0.1 \cdot P_{D2}{}^2 \tag{25}$$

where

P_{G1}, P_{G2} is the power flow of generator 1and generator 2

P_{D1}, P_{D2} is the power flow of load 1and load 2

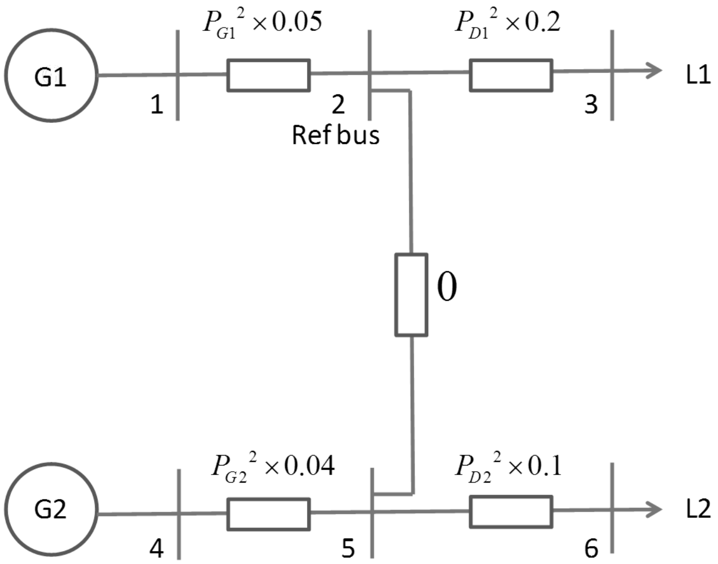


Figure 2.5. Simple Six-Bus System

Generator G1's bid is \$40/MWh up to 10,000 MW, and G2's bid is \$20 up to 4,000 MW.

Load D1 is 5,000MW, and D2 is 5,000MW. $P_{D1} = P_{D2} = \dfrac{5000}{10000} = 0.5$

The need for the system is slightly more than 10,000 MW due to the line loss. The least cost solution for this system is to dispatch all the power from G2 which has a lower bid, the rest of demand should be met by the power of G1. Thus $P_{G2} = \dfrac{4000}{10000} = 0.4$

In a balance energy system

$$\begin{aligned} 0 &= P_{G1} + P_{G2} - P_{D1} - P_{D2} - Loss \\ &= P_{G1} + P_{G2} - P_{D1} - P_{D2} - (0.05 \cdot P_{G1}{}^2 + 0.04 \cdot P_{G2}{}^2 + 0.2 \cdot P_{D1}{}^2 + 0.1 \cdot P_{D2}{}^2) \end{aligned} \tag{26}$$

Thus $P_{G1} = 0.7063$

Because there is no congestion in the system, $LMP_j^{cong} = \sum_{i=1}^{m} \mu_l \cdot SF_{l,j} = 0$, (15) can be written as

$$LMP_j = \frac{\partial \psi}{\partial D_j} = \frac{\lambda}{PF_j} \tag{27}$$

G1 supply the rest of the demand and loss in the system except all the contribution of output from G2, hence the LMP at Bus 1 should be same as it bid \$40/MWh [23]. Bus 2 is the reference bus, its LMP should be $LMP^{energy} = \lambda$. $LMP_1 = \$40/MWh, P_1 = P_{G1}$.

According to (9), (27)

$$\begin{aligned} LMP_1 &= \frac{\lambda}{PF_j} \\ &= \lambda \cdot (1 - \frac{\partial Loss}{\partial P_1}) \\ &= \lambda \cdot (1 - \frac{\partial (0.05 \cdot P_1^2)}{\partial P_1}) \\ &= \lambda \cdot (1 - 2 \cdot 0.05 \cdot P_1) \end{aligned} \tag{28}$$

$P_{G1} = 0.7063$

Thus, $\lambda = \$43.04/MWh$ that is the energy component.

LMP on each bus can be calculated by using the same method, the difference between generators and load in (28) is $P_G = P_j$ and $P_D = -P_j$

Each bus's generator and load (p.u.) can be obtained by applying energy balance equation (26).

Based on (9), (28), each bus’s loss factor, delivery factor, and penalty factor can be obtained respectively.

According to (16)-(19), energy component, congestion component, and loss component of LMP can be calculated for each bus. Hence, the above data of each bus can be summarized as Table 2.1.

Table 2.1. Simple Six-Bus System Parameters

Elements	Bus #					
	1	2	3	4	5	6
Generator p.u.	0.7063	0	0	0.4	0	0
Load p.u.	0	0	0.5	0	0	0.5
Loss Factor	0.0706	0	-0.2000	0.0360	0	-0.0999
Delivery Factor	0.9294	1	1.2	0.9640	1	1.0999
Penalty Factor	1.0760	1	0.8333	1.0374	1	0.9092
Energy Component($)	43.04	43.04	43.04	43.04	43.04	43.04
Congestion Component($)	0	0	0	0	0	0
Loss Component($)	-3.04	0	8.61	-1.55	0	4.3
LMP ($)	40	43.04	51.65	41.49	43.04	47.34

The power flow in each branch can be summarized as Table 2.2

Table 2.2. Simple Six-Bus System Power Flow

Flow Direction	Power Flow (p.u.)
1->2	0.7063
2->3	0.55
2->5	0.1314
4->5	0.4
5->6	0.525

Figure 2.5 and the data in Table 2.1,Table 2.2 will be used again in Section 3.

Apply data in Table 2.1 to equation (20)-(24)

The system marginal loss revenue is

$$\begin{aligned} MCL &= \sum_{j=1}^{n} \lambda\left(\frac{1}{PF_j} - 1\right)(D_i - G_i) \\ &= \$91540.041 \end{aligned} \tag{29}$$

The system marginal loss equal to

$$\begin{aligned} Loss_{m\mathrm{ar}} &= \sum_{i=1}^{n} \left(\frac{1}{PF_i} - 1\right)(D_i - G_i) \\ &= 2126.8597MW \end{aligned} \tag{30}$$

The system average loss cost is

$$\begin{aligned} CL &= \sum_{j=1}^{n} \lambda(G_i - D_i) \\ &= \$45,751.52 \end{aligned} \tag{31}$$

The system average loss equal to

$$\begin{aligned} Loss_{ave} &= \sum_{j=1}^{n} (G_i - D_i) \\ &= 1,063MW \end{aligned} \tag{32}$$

From (30) and (31), the ratio of marginal loss and average loss is

$$\begin{aligned} Ratio_{avg}^{m\mathrm{arg}} &= \frac{Loss_{mar}}{Loss_{ave}} \\ &= 2 \end{aligned} \tag{33}$$

Once again it proves that system marginal loss is roundly double system average loss.

The marginal loss surplus:

$$\begin{aligned} MLS &= \sum_{j=1}^{n} \lambda\left(\frac{1}{PF_j} - 1\right)(D_i - G_i) - \sum_{j=1}^{n} \lambda(G_i - D_i) \\ &= \$45,788.521 \end{aligned} \tag{34}$$

The over-collection is due to pricing losses at the margin. System marginal loss cost is almost double system average loss cost. System average loss cost is close to marginal loss surplus. The MLS should change with system average loss. For example, two months average loss and MLS data in California ISO's 'Market Performance Metric Catalog' 2012 report in shown in Figure 2.6. The left label is marginal loss surplus data based on Million dollars, corresponding to the clustered columns. The right label is the average losses data based on MW, corresponding to line with marks.

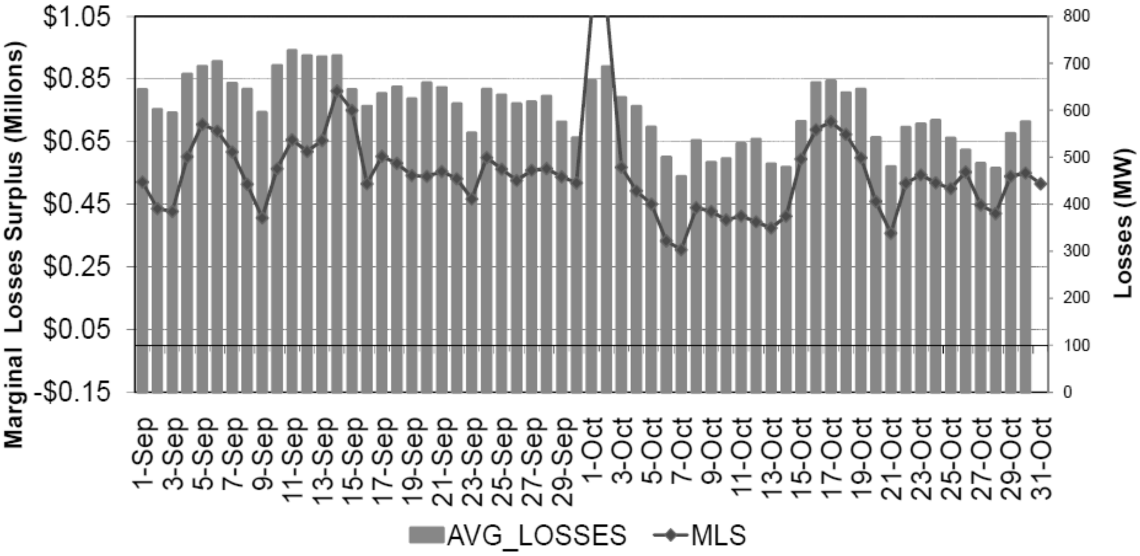


Figure 2.6. Daily Marginal Losses Surplus Credit Allocation [24]

In Figure 2.6, the loss in each day varied because of each day's load is different. The MLS follows the changing trend of system average loss, which illustrates that average loss is a determinable factor that affects the amount of MLS. According to the double relationship between marginal loss and average loss, the MLS in each day has a direction proportional function relationship with average loss on that day.

In order to keep neutrally, ISO need to redistribute MLS back to market participants. Three methods of MLS allocation are introduced and discussed in Section 3 to make sure a fair approach is chosen to deal with marginal loss surplus allocation.

2.5. CONCLUSION

A marginal transmission loss model is used in the United States' electricity markets to account for a resource's marginal contribution to system loss. This model inserts loss into the locational marginal price as a marginal loss component. Loss factor, delivery factor and penalty factor has been discussed theoretically to verify the fact that marginal loss doubles the average loss. LMP and MLS models have been discussed mathematically in the DCOPF model and a six-bus example. For an energy balanced system, marginal loss pricing will render a marginal loss surplus. To maintain marginal price signals which reflect locational price differences in marginal loss costs, the ISO is responsible for distributing marginal loss surplus back to market participants. This process is discussed in Section 3.

3. MARGINAL LOSS SURPLUS ALLOCATION

As discussed in Sections 1 and 2, adoption of full LMP can reflect the marginal cost of transmission losses as well as grid congestion. In order to keep revenue neutrality and maintain marginal price signals which reflect locational price differences in marginal loss costs, the ISO needs to credits back the MLS to stakeholders.

3.1. SYSTEM-WIDE DEMAND RATIO MLS ALLOCATION METHOD

Several methods can be used to allocate MLS. The most widely way is to allocate MLS back to scheduling coordinators (SC) or transmission owners on an hourly basis proportional to their measured demand. The measure demand includes both internal demand plus real-time exports to neighboring balancing area [25]. This method is known as the system-wide demand ratio MLS allocation method (or system-wide method).

This method relies on a simple principle: losses associated with every line whose flow enters a given bus are transferred to the lines whose flows leave the bus proportionally to the flows of those lines.

The system-wide method is

$$MLS_i = \frac{D_i^{md}}{\sum_{i=1}^{n} D_i^{md}} \cdot MLS, \forall i = 1, 2, \cdots n \tag{35}$$

where

D_i^{md} is the measured demand at location i;

MLS is the total marginal loss surplus in the whole system;

MLS_i is the marginal loss surplus in at location i.

For example in Figure 3.1, the whole system is separated by region A and region B. There is an inter-region flow between region A and region B, the power flow is assumed going from A to B. Generator and import has been omitted.

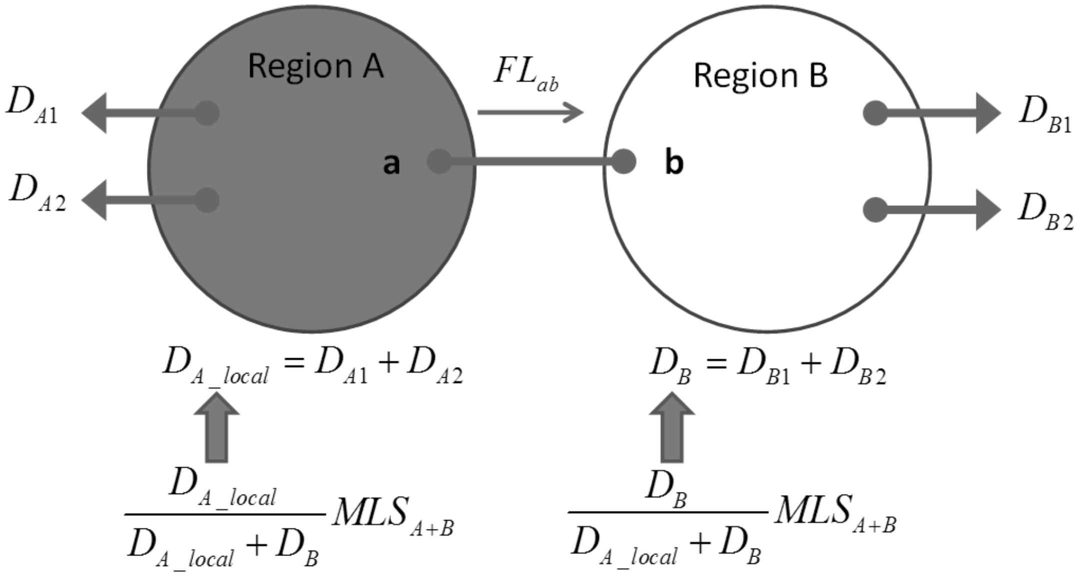


Figure 3.1. System-wide Demand Ratio MLS Allocation Illustration

where

D_{A1}, D_{A2} is different measured demand in region A;

D_{A_local} is region A's total measured demand (not include FL_{ab}), and $D_{A\_local} = D_{A1} + D_{A2}$;

D_{B1}, D_{B2} is different measured demand in region B;

D_B is region B's total measured demand, and $D_B = D_{B1} + D_{B2}$;

FL_{ab} is the power flow from region A to region B;

MLS_{A+B} is the total marginal loss surplus for both region A and region B.

In this case, D_{A1}, D_{A2}, D_{B1}, D_{B2} are the simple symbolize of different market participants in each region.

According to (35), the marginal loss surplus allocation (MLSA) for region A can be summarized as Table 3.1.

Table 3.1. MLSA in Region A - System-wide Method

Region A demand	MLSA
D_{Ai}	$\dfrac{D_{Ai}}{D_{A\_local} + D_B} MLS_{A+B}$
D_A	$\dfrac{D_{A\_local}}{D_{A\_local} + D_B} MLS_{A+B}$

Similarly, MLSA for region B can be summarized as Table 3.2

Table 3.2. MLSA in Region B - System-wide Method

Region B demand	MLSA
D_{Bj}	$\dfrac{D_{Bj}}{D_{A\_local} + D_B} MLS_{A+B}$
D_B	$\dfrac{D_B}{D_{A\_local} + D_B} MLS_{A+B}$

The system-wide method has been accepted by FERC and is widely used. California ISO has adopted this method since September 21, 2006 [25].

There are several advantages of using the system-wide method to allocate MLS [25]:

- Consistent with the results of a power flow
- Depend on the amount of energy consumed
- Depend on the relative location in the transmission net-work
- Avoid volatility
- Maintain appropriate economic marginal signals
- Easy to understand
- Simple to implement

3.2. ARGUMENTS AGAIST THE SYSTEM-WIDE METHOD

MLS is allocated based on measured demand in the system-wide demand ratio allocation method. Several arguments exist within this method. One argument is that MLS should be allocated based on the marginal loss payment. It should not be based on measured demand. FERC, however, stated that “the method for disbursing the amounts of any over collections should not directly reimburse customers for their marginal loss payments; as such a reimbursement would interfere with the goal of basing prices on marginal losses and would undermine LMP price signals to investors and load” [12]. Therefore, this topic is not discussed in this thesis.

Another argument is that this method ignores the case when there are significant differences in transmission lines’ voltage for different regions, which may have incurred loss and charged for loss nonuniformly. Therefore, it is unfair to allocate the losses caused by transmission lines into different regions on a demand ratio basis. For example, both northern California and southern California electric utility services are illustrated in (Figure 3.2). Each is connected by a set of three 500 kV power lines, known as ‘Path26’ (Figure 3.3). These lines begin at the large Vincent substation and terminate at the massive Midway substation [26].

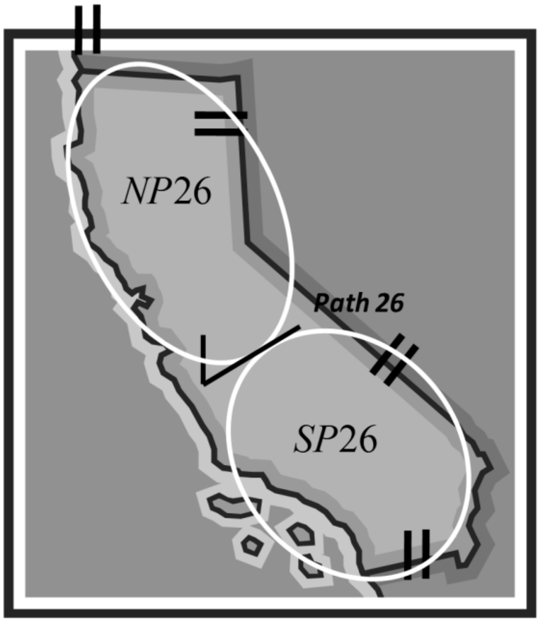


Figure 3.2. NP26 Region and SP26 Region in California ISO [27]

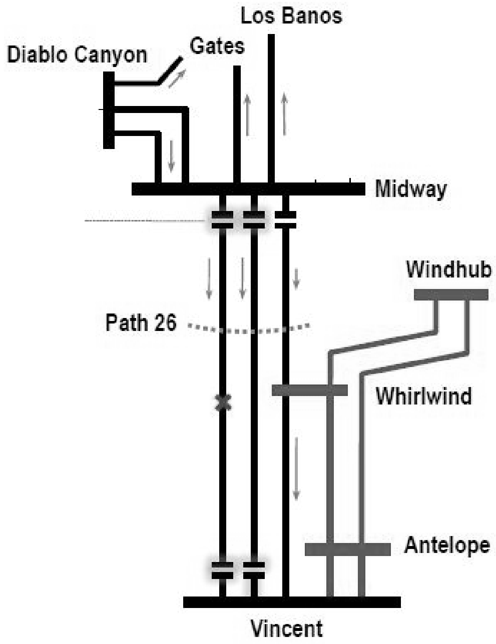


Figure 3.3. Path 26 (Midway-Vincent) [28]

The main eclectic utilities in North California under California ISO control area are:

- Pacific Gas and Electric Company (PGAE)
- Corporate Wetlands Restoration Partnership (CWRP)
- Northern California Power Agency (NCPA)
- Port of Stockton (PSTN)

Within it, PG&E (based in San Francisco) is considered to be the biggest eclectic utility in northern California as shown in Figure 3.4.

The main eclectic utilities in South California are:

- Southern California Edison (SCE)
- San Diego Gas & Electric (SDG&E)
- Anaheim (ANHM)
- Azusa (AZUA)
- Banning (BANN)
- City of Corona (CORO)
- California Waste Recovery Systems (CWRS)

- Pasadena (PASA)
- RADVision (RVSN)
- Vernon (VERN)

SCE (based in Rosemead) and SDG&E (based in San Diego) are the two largest eclectic utility in southern California as shown in Figure 3.4.

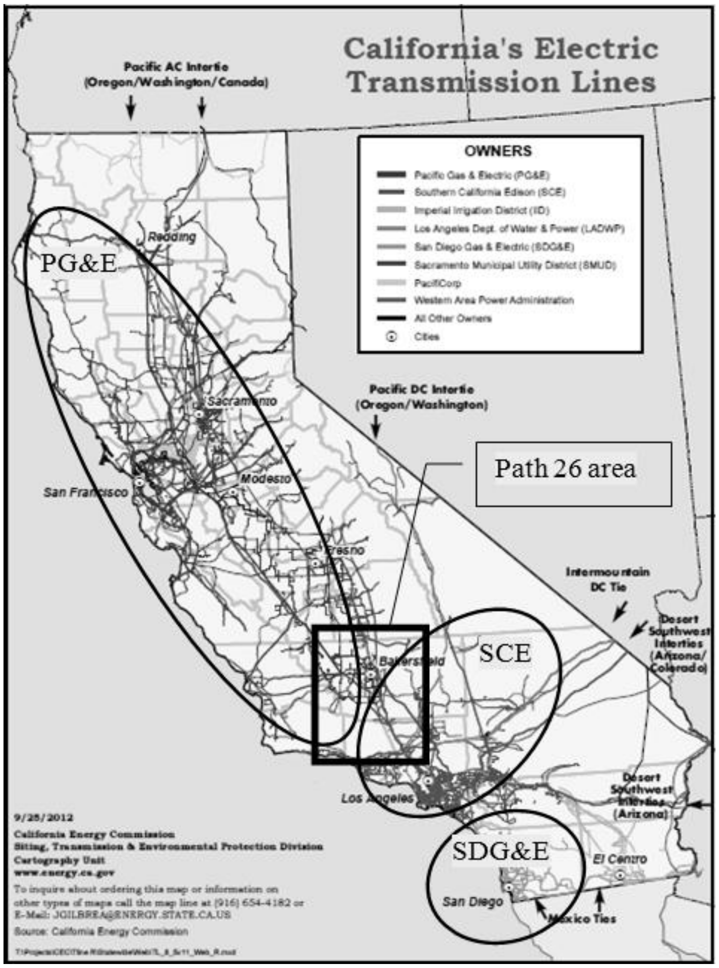


Figure 3.4. California's Electric Transmission Lines [29]

The average voltage from the transmission lines in northern California is generally lower than that in southern California. 'This lower average voltage' in means northern California incurs more transmission loss, which in turn, contributes more marginal loss to the entire California power system. Applying the system-wide demand ratio MLS allocation fails to recognize the significant differences in transmission losses for different regions within the California ISO control area. These losses may create subsides between different regions. Hence, the market participants in northern California can express dissatisfaction with the system-wide method.

3.3. COMFORMING REGIONAL MLS ALLOCATION METHOD

A conforming regional MLS allocation method (conforming regional method) is discussed in this thesis to resolve MLS allocation and improve the system-wide method shortages [12]. This method's process is very simple, and can be summarized in the following steps: 1. Divide the entire system into regions. 2. Apply the system-wide method into each region. 3. Adjust the inter-region MLS properly.

Transmission losses incurred in one region cannot be attributed to demand in that region alone. Thus both the actual and marginal loss costs in each region must be considered to reflect the impact of demand in one region on the losses in the other region. More specifically, a share of the transmission loss costs within the exporting region is deemed to be caused by demand in the corresponding importing region. It should therefore be allocated to the other region accordingly [18].

In this thesis, the amount of transmission loss costs in each region incurred to serve demand in the other region was estimated based on both the direction and magnitude of the inter-region flow. A portion of the actual loss and marginal loss costs in the region on the exporting side of the inter-region flow was allocated to the region on the importing side of the inter-region flow. For example, if Path 26 flows in Figure 3.2 and Figure 3.3 in the N-S direction, some of the losses in the northern California are incurred to serve demand in southern California. Therefore, a portion of the loss costs in the northern region were allocated to the southern region. This allocation applies to both actual losses and marginal losses. The difference between the adjusted marginal costs and the actual loss costs in each region is the adjusted MLS.

Both contribution and feature of the proposed approach are to separate regions in the MLS allocation while precisely maintaining the existing the system-wide method in each region. The system-wide method is the demand ratio share. The conforming regional method is independent of the system-wide method, hence is widely applicable.

The conforming MLS allocation method assumes two principles:

P1. There is a system-wide MLS allocation method (the demand ratio method).

P2. MLS incurred in a region will be allocated in the region according to the system-wide MLS method.

The conforming method is as follows:

1. Cut the tie lines between regions in the middle.
2. Represent each exporting flow of a region by an export schedule that equals the average power flow of the tie line with LMP equal to the average LMP of the two end points of the tie line. Represent each importing flow of a region by an import schedule that equals the average power flow of the tie line with LMP equal to the average LMP of the two end points of the tie line.
3. Calculate and allocate the MLS in each region using the system-wide allocation method.
4. The MLS allocated to the inter-region export will be redistributed to the corresponding importing region using the system-wide allocation method [30].

The formula of the conforming regional method can be written as:

$$MLS_i^{\mathrm{ex}} = \frac{D_i^{\mathrm{ex}}}{\sum_{i=1}^{n} D_i^{ex}} \cdot \left(MLS^{ex} \cdot \frac{\sum_{i=1}^{n} D_i^{ex}}{\sum_{i=1}^{n} D_i^{ex} + E^{\mathrm{int}er}}\right), \forall i = 1, 2, \cdots n \tag{36}$$

$$MLS_j^{im} = \frac{D_j^{im}}{\sum_{i=j}^{n} D_j^{im}} \cdot \left(MLS^{im} + MLS^{ex} \cdot \frac{E^{\mathrm{int}er}}{\sum_{i=1}^{n} D_i^{ex} + E^{\mathrm{int}er}}\right), \forall j = 1, 2, \cdots n \tag{37}$$

Where

MLS^{ex} is the total marginal loss surplus in exporting region;

MLS^{im} is the total marginal loss surplus in importing region.

MLS_i^{ex} is the marginal loss surplus in exporting region at location i;

MLS_j^{im} is the marginal loss surplus in importing region at location j;

D_i^{ex} is the measured demand in exporting region at location i (not include E^{inter});

D_j^{im} is the measured demand in importing region at location j;

E^{inter} is the inter flow from exporting region to importing region.

Apply the conforming regional method on the example of Figure 3.1, it can be illustrated in Figure 3.5.

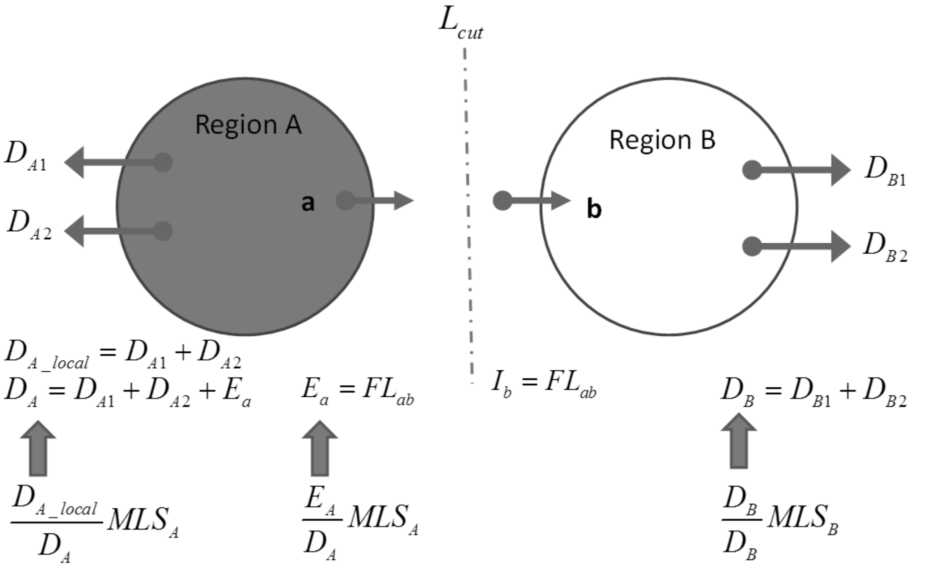


Figure 3.5. Conforming Regional Marginal Loss Allocation Illustration

where

E_a is the export from region A to region B;

I_b is the import from region A to region B;

D_A is the total demand for region A (include FL_{ab}) , and $D_A = D_{A1} + D_{A2} + E_a$,

MLS_A, MLS_B is marginal loss surplus for region A and region B after regional calculating;

First, the whole system is separated by tie line L_{cut} into two regions: region A and region B. Each region is treated as self balance system.

Second, the average inter-region flow FL_{ab} from a to b is obtained by calculating the simple average of the ab flow at the end and the b end. For tie line ab, region A is the exporting region, and region B is the importing region. After the tie line is cut, region A has an export $E_a = FL_{ab}$ at a, and its LMP is $\frac{1}{2}(LMP_a + LMP_b)$, and region B has an import $I_b = FL_{ab}$ at b, and its LMP is $\frac{1}{2}(LMP_a + LMP_b)$. Thus, FL_{ab} acts as a demand for region A and a supply for region B separately.

Third, we apply the system-wide demand ratio MLS in each of the regions, because region A and region B are completely separated now, and each of them is treated as a self balanced system. Then, for example, region A will receive $\frac{D_{A\_local}}{D_A} MLS_A$, D_{A1} in region A will receive $\frac{D_{A1}}{D_A} \cdot MLS_A$ in region A. Export E_a will also receive its share of MLS in region A, $\frac{E_A}{D_A} \cdot MLS_A$.

Last, because E_a is actually a demand from region B, its share of MLS received in region A will be transferred to region B and redistributed in region B. Region B's adjusted total MLS is $MLS_{B-adj} = MLS_B + \frac{E_a}{D_a} \cdot MLS_A$, including both its only MLS, MLS_B, and the MLS transferred from E_a into region B: $\frac{E_a}{D_a} \cdot MLS_A$. As a result, the demand D_{B1} in region B will receive MLS: $\frac{D_{B1}}{D_B} \cdot MLS_{B-adj}$. Table 3.3, and Table 3.4 shows the MLSA for region A and region B

Table 3.3. MLSA in Region A - Conforming Regional Method

Region A demand	MLSA
D_{Ai}	$\frac{D_{Ai}}{D_A} MLS_A$
D_A	$\frac{D_{A\_local}}{D_A} MLS_A$

Table 3.4. MLSA in Region B - Conforming Regional Method

Region B demand	MLSA
D_{Bj}	$\frac{D_{Bj}}{D_B} \cdot (MLS_B + \frac{E_a}{D_a} \cdot MLS_A)$
D_B	$MLS_B + \frac{E_a}{D_a} \cdot MLS_A$

3.4. NON-CONFORMING REGIONAL MLS ALLOCATION METHOD

In the conforming region MLS allocation method, the fraction of losses in one region should be allocated to other regions. Both the direction and magnitude of the inter-region flow are important factors affect this. For example, for an N-S Path 26 flow, suppose the source of power serving the southern region load is deemed far from the grid backbone (see Figure 3.2). In this instance the source will contribute significantly to northern region losses. However, if it is deemed to be either at or close to the grid backbone (such as the Midway substation), its contribution to northern region losses is negligible. The conforming regional method, however assumes losses for flow from generator to export on the inter-region tie line has the same impact as losses from generator to load. Additionally, this method ignores the real case: both generator and export tend to be near the grid backbone. Therefore the flow from generator to export on an inter-region tie line should have lower losses. The differences between the conforming regional method and the non-conforming regional method are illustrated in Figure 3.6 and Figure 3.7 respectively. Region A is the exporting region. Region B is the importing region. The inter-region flow in the conforming regional method is between bus 2 and bus 4. In contrast, the inter-region flow on the non-conforming method is between bus 1 and bus 3. The inter-region flow is more close to generators in the conforming regional method than the non-conforming regional method.

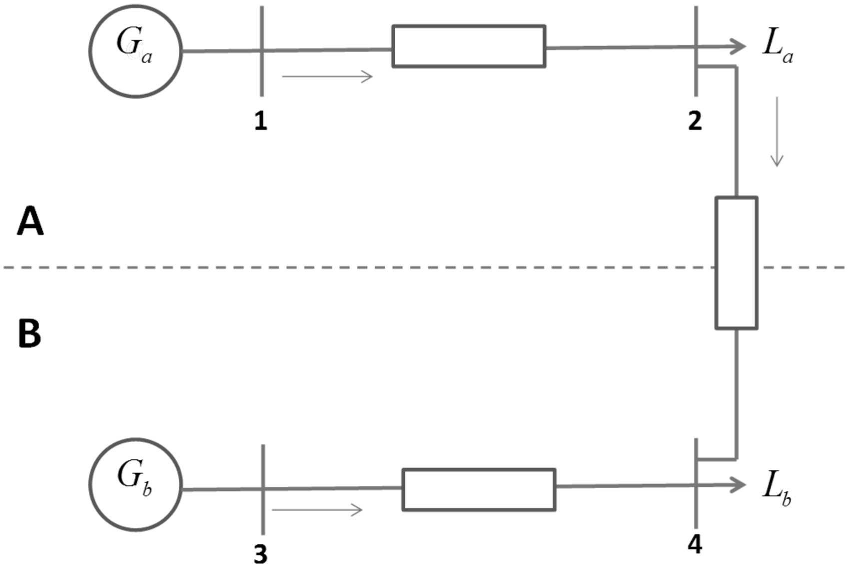


Figure 3.6. The Conforming Regional Method Base System

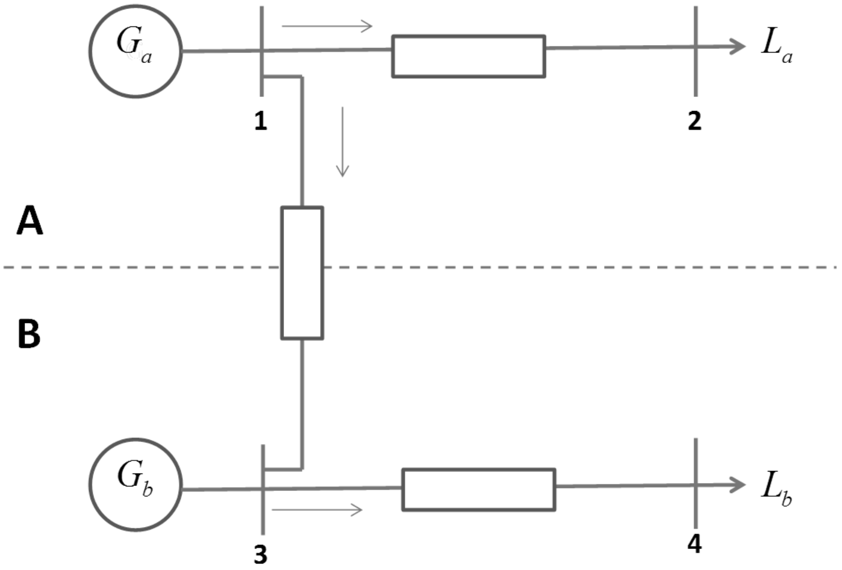


Figure 3.7. The Non-Conforming Regional Method Base System

To continue allocate MLS regionally and avoid above concerns, another regional method is proposed. This method treats the inter-region flow differently from other demands in the exporting region. Because this type of method does not conform to the system allocation method for the inter-region flow, it is referred as the non-conforming MLS allocation method (non-conforming regional method).

In addition to two principles previously discussed, the non-conforming regional method assumes a third principle:

P3. The inter-region export will be allocated MLS per the cost to serve it [31].

The non-conforming method is as follows:

1. Cut the tie lines between regions in the middle.
2. Calculate the ratio of exporting region’s total load & loss over the sum of its total load, loss and inter region’s flows. Represent the exporting region's total generator's flow by multiplying this ratio. Keep exporting region's loads, importing region's generators and loads unchanged.
3. Calculate and allocate the MLS in each region, without including the inter-region's flow.
4. Calculate both the remaining generator and its total cost in the exporting region.
5. Redistribute the total cost of the exporting region's remaining generator to the corresponding importing region.

The formula of the non-conforming method is:

$$
\begin{aligned}
MLS_i^{\mathrm{ex}} &= \frac{D_i^{\mathrm{ex}}}{\sum_{i=1}^{n} D_i^{ex}} \cdot \left(\sum_{i=1}^{n} LMP_i^{l} \cdot D_i^{ex} - \sum_{i=1}^{n} LMP_i^{g} \cdot G_i^{ex} \cdot \frac{\sum_{i=1}^{n} G_i^{ex} - E^{\mathrm{int}er}}{\sum_{i=1}^{n} G_i^{ex}}\right) \\
&= MLS_i^{\mathrm{ex}} + LMP_{E^{\mathrm{int}er}} \cdot E^{\mathrm{int}er} - LMP_{E^{\mathrm{int}er}} \cdot E^{\mathrm{int}er} \qquad (38) \\
&= \frac{D_i^{\mathrm{ex}}}{\sum_{i=1}^{n} D_i^{ex}} \cdot \left(MLS^{ex} - LMP_{E^{\mathrm{int}er}} \cdot E^{\mathrm{int}er} + \sum_{i=1}^{n} LMP_i^{g} \cdot G_i^{ex} \cdot \frac{E^{\mathrm{int}er}}{\sum_{i=1}^{n} G_i^{ex}}\right), \forall i = 1, 2, \cdots n
\end{aligned}
$$

$$MLS_j^{im} = \frac{D_j^{im}}{\sum_{i=j}^{n} D_j^{im}} \cdot \left(MLS^{im} + LMP_{E^{\mathrm{inter}}} \cdot E^{\mathrm{inter}} - \sum_{i=1}^{n} LMP_i^{g} \cdot G_i^{ex} \cdot \frac{E^{\mathrm{inter}}}{\sum_{i=1}^{n} G_i^{ex}}\right) \tag{39}$$

$$\forall j = 1, 2, \cdots n$$

where

G_i^{ex} is the generator in exporting region at location i ;

LMP_i^{l} is the LMP for the measured demand at location i;

LMP_i^{g} is the LMP for the generator at location i;

$LMP_{E^{\mathrm{inter}}}$ is the LMP for the inter-region flow between exporting region and importing region.

Continue using Figure 3.1 and Figure 3.5’s two regions' example, the non-conforming method can be illustrated by Figure 3.8.

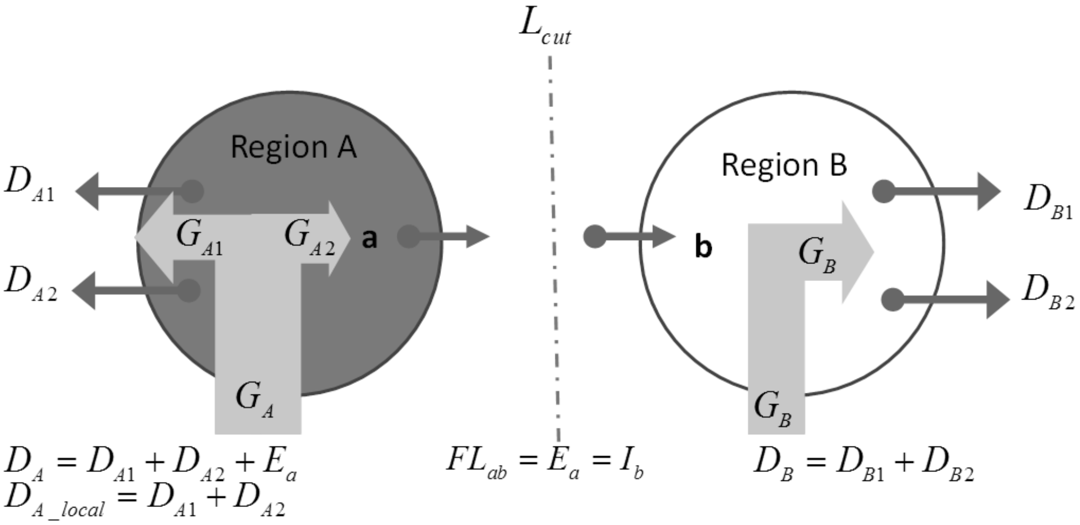


Figure 3.8. Non-Conforming Regional Marginal Loss Allocation Illustration

where

G_{A1}, G_{A2} is different supply (generator &import) in region A;

G_A is region A's total supply, and $G_A = G_{A1} + G_{A2}$;

G_B is region A's total supply.

In the context of Figure 3.8, we would first use generator in exporting region A to serve measured demand and losses in region A, generator in A is used pro-rata for this, for example, if E_a represents 10% of total demand in region A, then it is assumed that 10% of generator from each generator and import G_{A2} is used to serve E_a, the rest G_{A1} is used to serve the measured demand and loss in region A. Total demand in region A is $D_A = D_{A\_local} + E_a$, hence the ratio of G_{A1} is $\frac{D_{A\_local}}{D_A}$, G_{A2} is $\frac{E_a}{D_A}$. Any remaining generator in region A would be used to serve measured demand and losses in B. All generator in region B is used to serve measured demand and losses in B since B must import energy.

Then, the MLS in each region need to be calculated by using the load in the region and the generator ascribed to serving load and losses in the region. The MLS incurred by serving Ea with pro-rata generator in region A is allocated to E_a, and redistributed in region B.

According to (38) (39),

Region A's MLS is $MLS_A - LMP_{E_a} \cdot E_a + \sum_{i=1}^{2} LMP_i^g \cdot G_i \cdot \frac{E_a}{G_A}$,

Region B's MLS is $MLS_B + LMP_{E_a} \cdot E_a - \sum_{i=1}^{2} LMP_i^g \cdot G_i \cdot \frac{E_a}{G_A}$

The results can be summarized as Table 3.5

Table 3.5. MLSA in Region A - Non-Conforming Regional Method

Region A demand	MLSA
D_{Ai}	$\frac{D_{Ai}}{D_A}(MLS_A - LMP_{E_a} \cdot E_a + \sum_{i=1}^{2} LMP_i^g \cdot G_i \cdot \frac{E_a}{G_A})$
D_A	$MLS_A - LMP_{E_a} \cdot E_a + \sum_{i=1}^{2} LMP_i^g \cdot G_i \cdot \frac{E_a}{G_A}$

MLSA for region B can be summarized as Table 3.6

Table 3.6. MLSA in Region B - Non-conforming Regional Method

Region B demand	MLSA
D_{Bj}	$\frac{D_{Bj}}{D_B} \cdot (MLS_B + LMP_{E_a} \cdot E_a - \sum_{i=1}^{2} LMP_i \cdot G_i \cdot \frac{E_a}{G_A})$
D_B	$MLS_B + LMP_{E_a} \cdot E_a - \sum_{i=1}^{2} LMP_i \cdot G_i \cdot \frac{E_a}{G_A}$

3.5. ARGUMENTS AGAIST NON-CONFORMING REGIONAL METHOD

The non-conforming regional method introduces a new principle that stresses the losses from generator to the inter-region flow have different impact as losses from generator to load. It is based on the fact that both generator and export tend to be near the grid backbone, which should incur lower losses. The non-conforming regional method, therefore, treats the exporting region’s flow from generator to inter region’s export and load differently.

The primary concern regarding the non-conforming regional method is that this method is based on the cost causation principle rather than the demand ratio principle. If the inter-region flow is treated differently, both other loads and exports will be treated differently; both will be based on the same principle. In this method, however, only the inter-region flow is treated differently. It is based on cost causation principle, other demands are still based on demand ratio principle. The demand ratio principle has already been approved by FERC. Whether this inconsistency of the non-conforming regional method will also be approved is a question.

3.6. SUMMARY

The system-wide method, the conforming regional method, and the non-conforming regional method have each been proposed in this section. One argument about the system-wide method is that this method fails to recognize the loss differences in different regions. Both the conforming regional method and the non-conforming method act as alternative solutions. The argument on the non-conforming regional method shows that this method is based on cost causation basis rather than a demand ratio basis. In contrast, the conforming regional method is an extension of the system-wide method and always consistent with demand ratio basis.

4. COMPARASION OF THREE MLS ALLOCATION METHODS

The system-wide method ignores the significant differences in transmission loss across various regions. As a solution, the conforming regional method is proposed to distribute MLS when the system has heterogeneous loss in different regions. Meanwhile, a non-conforming method is proposed to further separate the losses for flow from generator to export on the inter-region tie line and losses from generator to load.

According to (36)-(39), the key difference between the conforming method and the non-conforming method is how much MLS that will be allocated to inter region E^{inter}.

The MLS that the conforming method allocates to E^{inter} is

$$MLS_{adjust}^{con} = MLS^{ex} \cdot \frac{E^{\text{inter}}}{\sum_{i=1}^{n} D_i^{ex} + E^{\text{inter}}} \tag{40}$$

Because MLS^{ex} and $\frac{E^{\text{inter}}}{\sum_{i=1}^{n} D_i^{ex} + E^{\text{inter}}}$ are both positive value, MLS_{adjust}^{con} is always a positive value in the conforming regional method.

The MLS allocated to E^{inter} by the non-conforming method is

$$\begin{aligned} MLS_{adjust}^{non} &= LMP_{E^{\text{inter}}} \cdot E^{\text{inter}} - \sum_{i=1}^{n} LMP_i^{g} \cdot G_i^{ex} \cdot \frac{E^{\text{inter}}}{\sum_{i=1}^{n} G_i^{ex}} \\ &= E^{\text{inter}} \cdot (LMP_{E^{\text{inter}}} - \sum_{i=1}^{n} LMP_i^{g} \cdot G_i^{ex} \cdot \frac{1}{\sum_{i=1}^{n} G_i^{ex}}) \\ &= E^{\text{inter}} \cdot (LMP_{E^{\text{inter}}} - LMP_{avg}^{g}) \end{aligned} \tag{41}$$

where

LMP_{avg}^{g} is the average LMP of generators and imports in the exporting region.

Because $E^{\text{inter}} \geq 0$, $(LMP_{E^{\text{inter}}} - LMP_{avg}^{g})$ is determined by the LMP of inter region's flow and average LMP for all generators and imports in exporting region, if $(LMP_{E^{\text{inter}}} - LMP_{avg}^{g}) \geq 0$, MLS_{adjust}^{non} will be non-negative, if $(LMP_{E^{\text{inter}}} - LMP_{avg}^{g}) \leq 0$,

MLS_{adjust}^{non} will be non-positive. According to (28), $LMP_i = \lambda \cdot (1 - \frac{\partial Loss}{\partial P_i})$, $\frac{\partial Loss}{\partial P_i}$ is always a positive value for generators and imports, is always negative value for loads and exports. Hence, the inter-region flow is an export for exporting region, the LMP for it is larger than λ (LMP at reference bus). Whereas, the LMPs for all the generators and import in exporting region is lower than λ. $(LMP_{E^{\text{int}er}} - LMP_{avg}^{g}) \geq 0$, MLS_{adjust}^{non} is also a positive value in the non-conforming regional method.

MLS_{adjust}^{con} and MLS_{adjust}^{non} are values of MLS transferred from exporting region to importing region by the conforming regional method and the non-conforming method respectively. A discussion of which method transfer more MLS to importing region is shown in (42)-(45)

In a energy balance system

$$\sum Demand = \sum Generation - \sum Loss \tag{42}$$

According to (24)

$$MLS^{ex} = \sum_{i=1}^{n} D_i^{ex} \cdot LMP_{avg}^{l} + E^{\text{int}er} \cdot LMP_{E^{\text{int}er}} - (\sum_{i=1}^{n} D_i^{ex} + E^{\text{int}er} + Loss^{ex}) \cdot LMP_{avg}^{g} \tag{43}$$

where

LMP_{avg}^{l} is the average value of loads in exporting region.

Because $\sum_{i=1}^{n} D_i^{ex} \cdot LMP_{avg}^{l} \gg E^{\text{int}er} \cdot LMP_{E^{\text{int}er}}$

$$LMP_{avg}^{l} \approx \frac{\sum_{i=1}^{n} D_i^{ex} \cdot LMP_{avg}^{l} + E^{\text{int}er} \cdot LMP_{E^{\text{int}er}}}{(\sum_{i=1}^{n} D_i^{ex} + E^{\text{int}er})}$$

(43) can be written as

$$\begin{aligned} MLS^{ex} &= (\sum_{i=1}^{n} D_i^{ex} + E^{\text{int}er}) \cdot LMP_{avg}^{l} - (\sum_{i=1}^{n} D_i^{ex} + E^{\text{int}er} + Loss^{ex}) \cdot LMP_{avg}^{g} \\ &= (\sum_{i=1}^{n} D_i^{ex} + E^{\text{int}er}) \cdot (LMP_{avg}^{l} - LMP_{avg}^{g}) - Loss^{ex} \cdot LMP_{avg}^{g} \end{aligned} \tag{44}$$

According to (45), (40) can be written as

$$\begin{aligned} MLS_{adjust}^{con} &= E^{\text{int}er} \cdot \frac{((\sum_{i=1}^{n} D_i^{ex} + E^{\text{int}er}) \cdot (LMP_{avg}^{l} - LMP_{avg}^{g}) - Loss^{ex} \cdot LMP_{avg}^{g})}{\sum_{i=1}^{n} D_i^{ex} + E^{\text{int}er}} \\ &= E^{\text{int}er} \cdot (LMP_{avg}^{l} - LMP_{avg}^{g} - \frac{Loss^{ex} \cdot LMP_{avg}^{g}}{\sum_{i=1}^{n} D_i^{ex} + E^{\text{int}er}}) \\ &= E^{\text{int}er} \cdot (LMP_{avg}^{l} - LMP_{avg}^{g} - \partial \cdot LMP_{avg}^{g}) \end{aligned} \tag{45}$$

Where

∂ is the value of total loss over total demand of exporting region

The difference between MLS_{adjust}^{con} and MLS_{adjust}^{non} can be obtain, use (46) minus (41)

$$\begin{aligned} MLS^{differ} &= MLS_{adjust}^{con} - MLS_{adjust}^{non} \\ &= E^{\text{int}er} \cdot (LMP_{avg}^{l} - LMP_{avg}^{g} - \partial \cdot LMP_{avg}^{g}) - E^{\text{int}er} \cdot (LMP_{E^{\text{int}er}} - LMP_{avg}^{g}) \\ &= E^{\text{int}er} \cdot (LMP_{avg}^{l} - LMP_{E^{\text{int}er}} - \partial \cdot LMP_{avg}^{g}) \end{aligned} \tag{46}$$

$E^{\text{int}er}$ is always a positive value, hence whether the conforming regional method or the non-conforming regional method transfer more MLS to the importing region depends on the value of $(LMP_{avg}^{l} - LMP_{E^{\text{int}er}} - \partial \cdot LMP_{avg}^{g})$, if it is positive, the conforming regional method will transfer more MLS to the importing region than the non-conforming regional method, if it is negative, the conforming regional method will transfer less MLS than the non-conforming regional method to the importing region. Therefore the magnitude of $(LMP_{avg}^{l} - \partial \cdot LMP_{avg}^{g})$ and $LMP_{E^{\text{int}er}}$ are the key factors that determine the value of MLS^{differ}.

4.1. SIX-BUS EXAMPLE

The simple six-bus example in Figure 2.5 is referred in Figure 4.1 as an example to evaluate three MLS allocation methods and above conclusion. The LMP and power flow for each bus has already recorded in Table 2.1 and Table 2.2. The load and power flow have been converted to p.u. values with the MWA equal to 10,000. The system can be divided into two regions A and B, the inter-region flow is 0.1314 on A-B tie line. The energy component LMP^{EN} is \$43.04. There is no congestion in the system. The loss component LMP^{Loss} is equal to the difference between an LMP and the energy component.

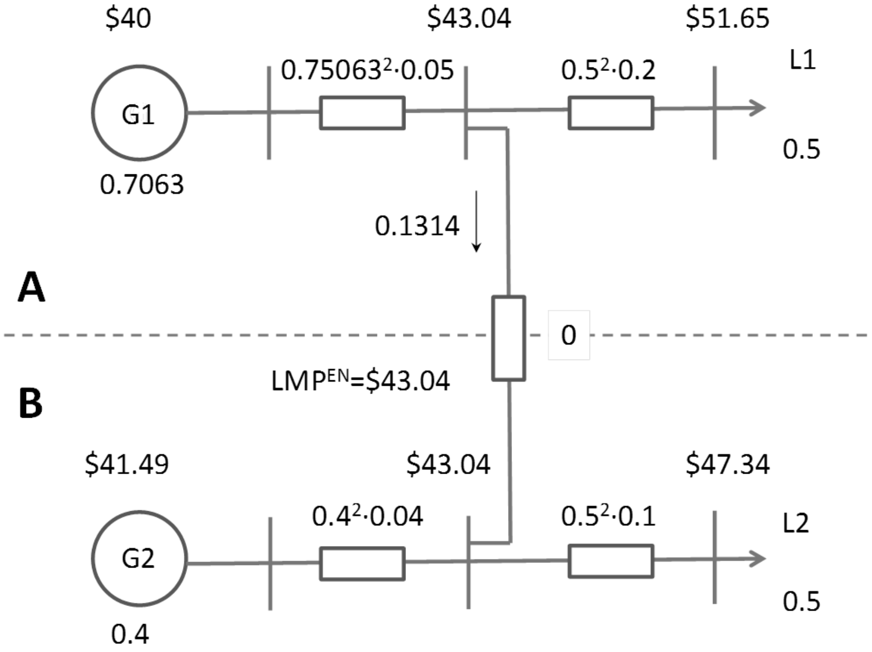


Figure 4.1. Simple Two Region System

The MLS allocation results using the system-wide method, the conforming regional method, and the non-conforming regional method are listed in Table 4.1, Table 4.2, and Table 4.3 respectively.

In the system-wide method (Table 4.1), each region has 50% of the total measured demand, the MLS is allocated 50/50 between region A and region B.

Table 4.1. MLS Allocation - System-wide Method

Region	Resource	Schedule	Price	Total MLS	MLS allocation
A	G1	-7063	40	46470	23235 (50%)
	D1	5000	51.65		
B	G2	-4000	41.49		23235 (50%)
	D2	5000	47.34		

In the conforming regional method (Table 4.2), the exporting region A has incurred about 70% of the total MLS, while region B has incurred 30% of the total MLS. With region A being the exporting region, the inter-region flow represented by an export E_a is allocated 21% of the MLS in regional A (15% of Total MLS) based on its demand ratio in region A. The 15% of total MLS is then transferred into region B that has only incurred 30% of total MLS. After this adjustment, the final results are region A having 55% and region B getting 45%.

Table 4.2. MLS Allocation - Conforming Regional Method

Region	Resource	Schedule	Price	Regional MLS	Regional MLS allocation	Final MLS allocation
A	G1	-7063	40	32285 (69%)	N/A	25566 (55%)
	D1	5000	51.65		25566	
	E_a	1314	43.04		6719	
B	I_b	-1314	43.04	14185 (31%)	N/A	20904 (45%)
	G2	-4000	41.49		N/A	
	D2	5000	47.34		14185	

In the non-conforming method (Table 4.3), the same amount of MLS incurred in region A and region B as in the conforming method. The difference is only in the MLS allocation to the inter-region flow. In the non-conforming method, it assume that G1 serves D1&loss and E_a proportionally, so G1 serves 5749MW to D1&loss and 1314MW to E_a。 The MLS from G1 serving E_a is 3995 which is a much less value than that in the conforming regional method which is 6719. The MLS incurred from 1314MW from G1 serving E_a is transferred into region B, so the final results are region A getting 61% and region B getting 39% of total MLS.

Table 4.3. MLS Allocation - Non-Conforming Regional Method

Region	Resource	Schedule	Price	Regional MLS	Regional MLS allocation	Final MLS allocation
A	G1->D1	-5749	40	32285 (69%)	N/A	28290 (61%)
	D1	5000	51.65		28290	
	G1->E_a	-1314	40		N/A	
	E_a	1314	43.04		3995	
B	I_b	-1314	43.04	14185 (31%)	N/A	18180 (39%)
	G2	-4000	41.49		N/A	
	D2	5000	47.34		14185	

Table 4.1, Table 4.2, and Table 4.3 list the final MLS in each region by using the system-wide method, the conforming regional method and the non-conforming regional method respectively. The loss factor in region A is higher than that in region B, both the conforming regional method and the non-conforming regional method separate two regions first and then calculate each region as a self balance system. By doing this, the different loss factors are considered separately in each region, region A gets 69% and region B gets 31% of total MLS in both regional methods. The value of MLS be allocated to E_a and eventually transferred to region B need to be calculated before get final MLS in

each region. After adjusting, eventually region A gets 55%, region B gets 45% of total MLS in the conforming regional method, region A gets 61%, region B gets 39% of total MLS in the non-conforming regional method. Hence, the region A can get the most MLS by using the non-conforming method, less MLS by using the conforming regional method and least MLS by using the system-wide method. The reason why the non-conforming regional method gets most MLS in region A is caused by the non-conforming nature of the new principle (P3: The inter-region export will be allocated MLS per the cost to serve it) to the system-wide principle, which adopt cost causation basis rather than demand ratio basis.

4.2. LARGE SCALE EXAMPLE

Three MLS allocation methods were tested in the California ISO market using actual day-ahead market data. A total of 96-hours continuous observations were selected first in the June of 2012 to analyze and compare the different MLS allocations. The results are shown in Figure 4.2. Then, different MLS allocation based on a total of 190-hours radium were analyzed observations in 2012. The result is shown in Figure 4.3.

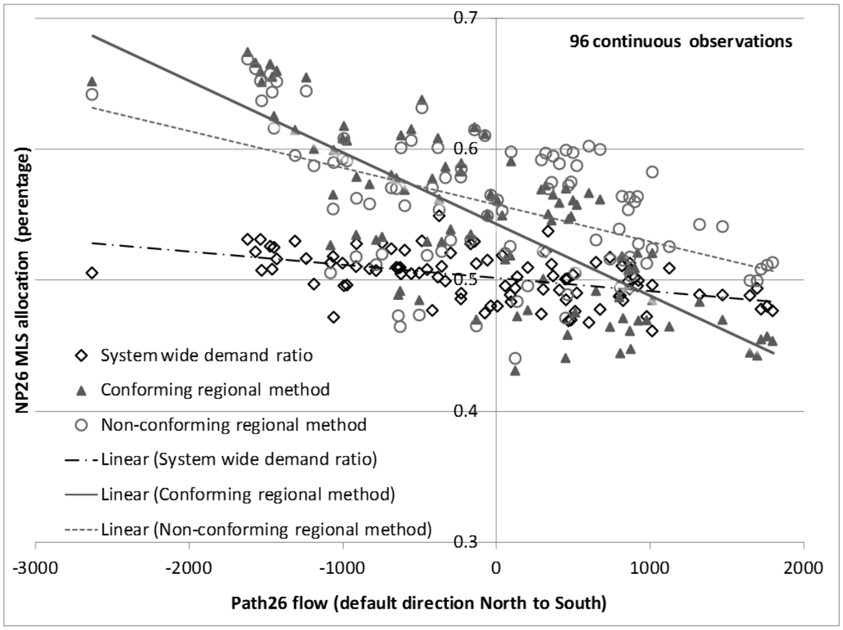


Figure 4.2. Continuous Observations of NP26 MLS Allocation in CAISO Market [30]

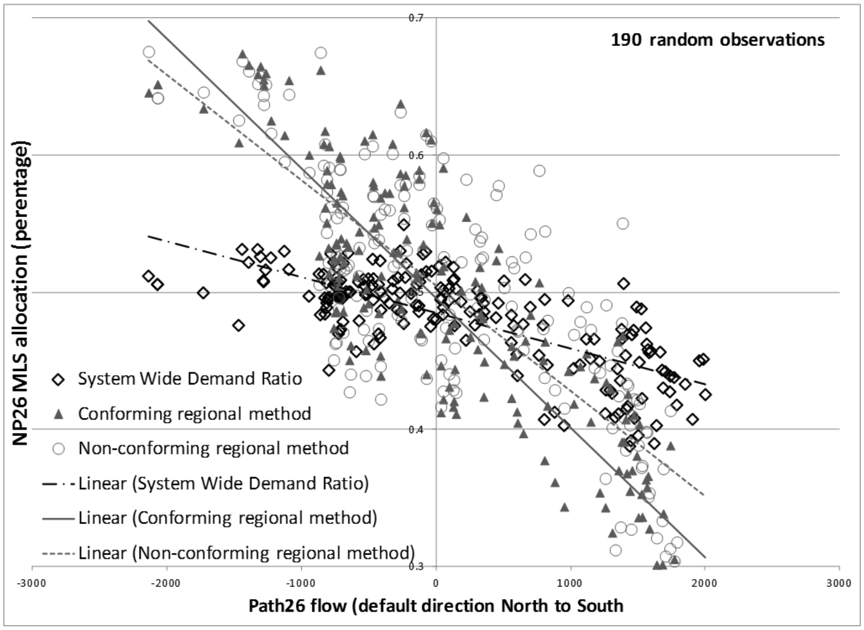


Figure 4.3. Random Observations of NP26 MLS Allocation in CAISO Market [30]

Figure 4.2 and Figure 4.3 have three series of points. These points represent the system-wide demand ratio method, the conforming regional method, and the non-conforming regional method. The x-axis is the path 26 flow, and the y-axis is the percentage of MLS allocated to northern of Path 26 (NP26). Each series consists of data points, that correspond to the hour observations, and has a trend line added.

Theoretically, if the inter-region flow is zero, both the conforming regional method and the non-conforming regional method should produce the same results. This can be verified in Figure 4.2 and 4.3. From the points, those correspond to both methods close to the vertical line of path 26 flows equal to zero. The two trend lines intersect at a point with path 26 flow approximately equal to –500 MW in Figure 4.2 and around –300 MW in Figure 4.3. If the sample observation distribution had sufficient density around path 26 flow equal to zero, the two trend lines of the conforming method and the non-conforming method would intersect at a point with path 26 flow equal to zero.

The system-wide method has a relatively steady slope trend line. The conforming method and the non-conforming method have a more rapid changing slope of trend line, which can be illustrated both in Figure 4.2 and Figure 4.3. The difference between the conforming regional method and the non-conforming regional method manifests itself primarily in the slope difference between the trend lines. When path 26 flow is positive (from North to South), northern Path 26 (NP26) is considered as the exporting region. The conforming method trend line is below the non-conforming method trend line for NP26 MLS. When path 26 flow is negative (from South to North), southern Path 26 (SP26) is the exporting region. The conforming method trend line is above the non-conforming method trend line for NP26.

Based on the 96 continuous observations over the four days in Figure 4.2, the share of MLS for NP26 and SP26 in different methods can be summarized as Table 4.4.

Table 4.4. A Continuous-Observations Example

Methods	Share of MLS in NP26	Share of MLS in SP26
System-wide method	50%	50%
Conforming regional method	54%	46%
Non-conforming regional method	56%	44%

Based on the 190 radium observations over 2012 in Figure 4.3, the share of MLS for NP26 and SP26 in different methods can be summarized as Table 4.5.

Table 4.5. A Random-Observations Example

Methods	Share of MLS in NP26	Share of MLS in SP26
System-wide method	48%	52%
Conforming regional method	48%	52%
Non-conforming regional method	49%	51%

The non-conforming regional method allocates most MLS to NP26 in both cases. Compared with the system-wide method, the conforming regional method allocates more MLS to NP26 in 96 continuous observations and same MLS to NP26 in 190 random observations.

The trend line of the conforming regional method (see Figure 20) intersects the trend line of the system-wide method at a point with path 26 flow approximately equal to 1000 MW. Thus based on the 4 days of continuous observations, if the path 26 flow is lower than 1000 MW in the north to south direction, the conforming regional method will allocate more MLS to the NP26 region than the system-wide method allocates. However if the path 26 flow is higher than 1000 MW in the north to south direction, the conforming regional method will allocate less MLS to the NP26 than the system-wide method allocates. In contrast, the non-conforming regional method always allocates more MLS to NP26 than the system demand ratio method regardless of path 26 flow.

Radium observations offer a similar conclusion (see Figure 4.3). The trend line of the conforming regional method intersects the trend line of the system-wide method at a point with path 26 flow approximately equal to 200 MW, while the trend line of the non-conforming method intersects at a point with path 26 flow approximately equal to 500 MW. Thus, based on the 190 radium observations, when the path 26 flow is lower than 200 MW in the north to south direction, the conforming regional method will allocate more MLS to the NP26 region than does the system-wide method. However, when the path 26 flow is higher than 200 MW in the north to south direction, the conforming regional method will allocate less MLS to the NP26 than does the system-wide method.

In contrast with the conforming regional method, when the path 26 flow is lower than 500 MW in the north to south direction, the non-conforming regional method will allocate more MLS to the NP26 region than the system-wide method. However, when the path 26 flow is higher than 500 MW in the north to south direction though, the non-conforming regional method will allocate less MLS to the NP26 than the system-wide method allocates.

The flow of path 26 has a range between -3000 MW and 3000 MW. The intersecting point with the system-wide method in the non-conforming method is larger than the conforming regional method. Thus, the MLS generally is allocated more to NP26 by using the non-conforming regional method than using the conforming regional method (see Table 4.4 and 4.5). In this instance, the non-conforming regional method always allocates most MLS to NP26. Compared with the system-wide method, the conforming regional method allocates more MLS to NP26 (see Table 4.4). It allocates the same MLS to each region as the system-wide method (see Table 4.5)

4.3. TWELVE-CASE EXAMPLE

MLS allocation on different regions may vary with many factors, including the inter-region flow's direction, magnitude, time of year and so forth. A 12 cases table under California ISO's real market is selected to better analyze these factors (See Table 4.6).

Table 4.6. 12-Cases Example

Path 26 Flow			Trade Time		Final Share of MLS Allocation					
Dir.	Size	Mag. MW	Date	HOUR	Sys. wide method		Con.reg. method		Non.reg. Method	
					NP26	SP26	N26	SP26	NP26	SP26
N->S	< 2,500	1,800	23/05/12	12	46%	54%	46%	54%	50%	50%
		800	15/06/12	14	49%	51%	49%	51%	54%	46%
		1,200	07/09/12	21	44%	56%	44%	56%	50%	50%
		2,200	28/01/12	19	47%	53%	47%	53%	55%	45%
	> 2,500	2,700	17/05/12	16	44%	56%	41%	59%	38%	62%
		3,200	20/07/12	16	43%	57%	32%	68%	34%	66%
		3,300	02/09/12	14	43%	57%	29%	71%	29%	71%
		2,700	17/02/12	18	47%	53%	32%	68%	38%	62%
S->N	< 2,500	500	30/03/12	10	49%	51%	51%	49%	50%	50%
		380	15/06/12	5	50%	50%	61%	39%	60%	40%
		836	31/01/12	4	48%	52%	66%	34%	67%	33%
	> 2,500	2600	2/06/12	10	51%	49%	65%	35%	68%	32%

12 different trade times were selected in Table 4.6. In 8 cases, the direction of path 26 is from NP26 to SP26. In 4 cases, it is from SP26 to NP26. The magnitude of path 26 flow was separated into two parts in each direction: anything over 2,500MW was considered as a big flow, anything under 2,500 MW was treated as a normal flow. The trade dates are randomly selected (for example: March-May, June-August, September-November, December-January). Trade hours were also randomly selected. The final share of MLS in NP26 and SP26 were obtained with the system-wide method, the conforming regional method, and the non-conforming regional method.

When the direction is from northern California to southern California, both the conforming regional method and the non-conforming method could realize separating the different losses in northern California and south California. The MLS for path 26 part is adjusted to SP26 eventually.

When the flow is smaller than 2,500 MW, the conforming region method could allocate the same MLS to each region as does the system-wide method. All four cases, NP26 got most MLS by using the non-conforming regional method than the system-wide method and the conforming regional method.

When the path 26 flow is over 2,500 MW, the MLS for path 26 will be larger. Both the conforming regional method and the non-conforming region tend to transfer more MLS from NP26 to SP26. Therefore, the final MLS in NP26 by using both the conforming regional method and the non-conforming regional method is much lower than using the system-wide method.

According 96 continuous observations (see Figure 4.2), the path 26 flows' direction and magnitude can be extracted (see Figure 4.4). Nearly 90% path 26 flows were between -1500 MW and 1500 MW.

The non-conforming regional method usually allocate more MLS to NP26 region than the conforming method when the path 26 flow was from northern California to south California,. It is also proved by Figure 4.2 and Figure 4.3 where the overall trend line in the non-conforming regional method is higher than the conforming regional method.

The MLS for path 26 flow in SP26 were allocated to NP26 when the direction of Path 26 was from southern California to northern California. Under both the conforming regional method and the non-conforming regional method, the NP26 will not only keep its own MLS but also be transferred the MLS of path 26 from SP26. Therefore, NP26 will typically gain more MLS by through both the conforming regional method and the non-conforming regional method than it will through the system-wide method.

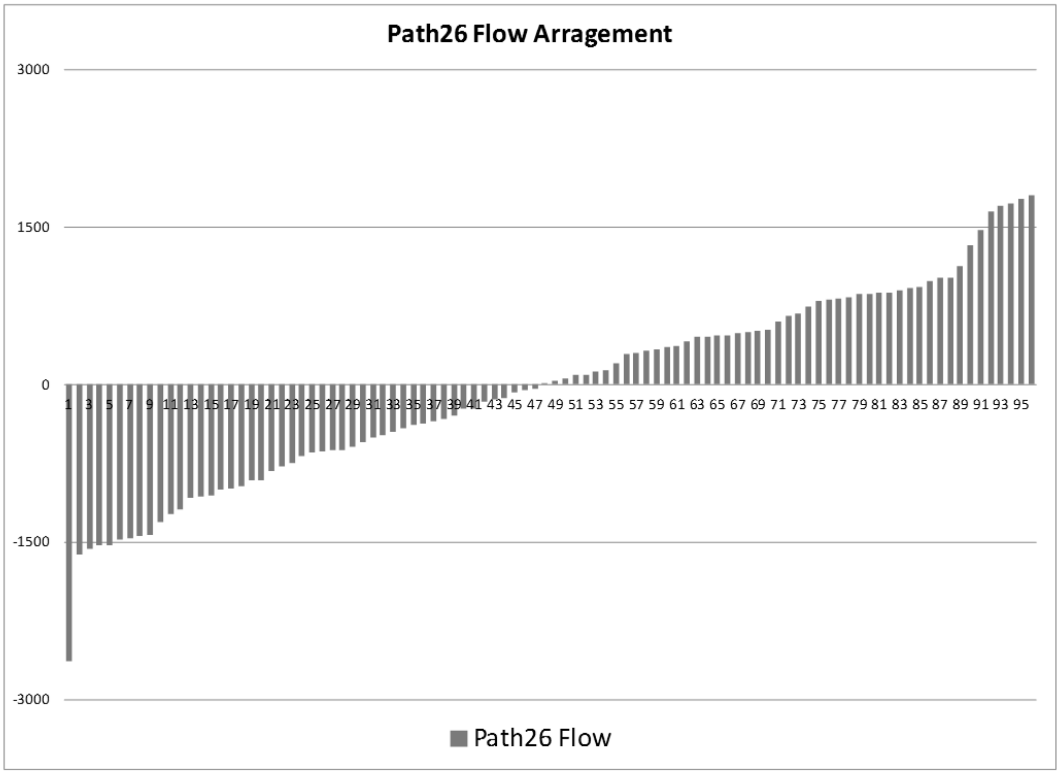


Figure 4.4. Path 26 Flow Distribution

The difference between the three methods can clearly be seen in these 12 cases. Both the direction and magnitude of Path 26 were different on time. When the flow direction occurred from northern California to southern California, the system-wide method allocated equal or more MLS than did the conforming regional method, and allocated more MLS than did the non-conforming method only when the flow was large enough. When the flow direction occurred from southern California to northern California, the system-wide method allocated less MLS than did the conforming regional method and the non-conforming regional method.

The non-conforming method allocated more MLS to NP26 than did the conforming method in 8 cases. The non-conforming method allocated less MLS to NP26 than did the conforming method in 3 cases. The MLS to NP26 was the same in both the conforming method and the non-conforming method in 1 case.

4.4. CONCLUSION

The study confirms that the conforming regional method does not always allocate more MLS to the exporting region compared with the system-wide method. The non-conforming regional method, however, always allocates more MLS to the exporting region than the conforming regional method. It also always allocates more MLS than the system-wide method except when the inter-region flow is very high. The non-conforming regional method introduces a new principle. The principle is inconsistent with the system-wide demand ratio principle. In the non-conforming method the inter-region flow is treated differently from other loads, it is a cost causation basis. In California ISO, FERC has approved demand ratio principle rather than cost causation principle. Even though, FERC approves cost causation principle, only the inter-region flow is treated different is not tenable in the non-conforming regional method, because other loads and exports in the exporting region also exhibit different loss factors. To maintain consistently in non-conforming regional method, each load and export should be treated the same way as what we do on the inter-region flow.

The conforming method is consistent with the system-wide method. it can solve the MLS allocation issue when the system has heterogeneous loss in different regions.

5. CONFORMING REGIONAL METHOD MARKET ANALYSIS

The conforming regional method is an extension of the system-wide method. This method could allocate MLS regionally and be precise consistent to the system-wide method principle. Both the direction and magnitude of the inter-region flow act as significant factors influencing the final MLS allocation (see Figure 4.2 and 4.3). Mathematical models were used to analyze the relationships among the inter-region flow, loss, and final MLS in different regions.

A method is proposed to simulate inter-region flows when they are unsaved in historical database. The estimated inter-regions flow was used in a 12-month California ISO market example to further analyze the difference between the system-wide method and the conforming regional method in MLS allocation.

5.1. THE INTER-REGION FLOW AND LOSS EFFECT

5.1.1. Inter-region Flow Function. The conforming regional method can be illustrated by Figure 5.1. The whole system is divided into region A and region B.

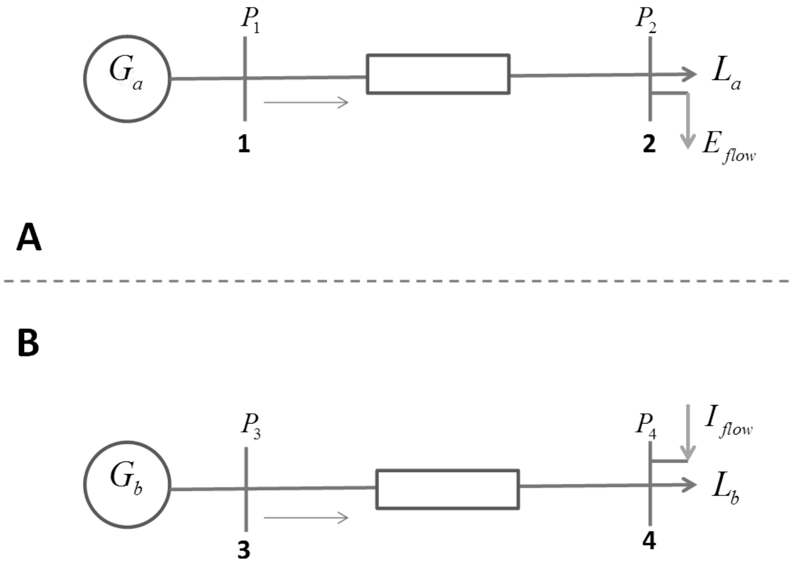


Figure 5.1. Conforming Regional Method Model

where

G_a is the total generator of region A;

L_a is the total load of region A;

E_a is the exporting flow form region A to region B;

G_b is the total generator of region B;

L_b is the total load of region B;

I_b is the importing flow from region A to region B, $E_a = I_a$;

P_1, P_2, P_3, P_4 is the average LMP value for Bus 1, Bus 2, Bus 3, Bus 4 respectively;

The inter-region line's voltage is usually very high, the loss on the line is very small (loss factor is small), hence the $LMP_2 \approx LMP_4 (P_2 \approx P_4)$

According to above data, the MLS results for the conforming regional method can summarized in Table 5.1.

Table 5.1. Conforming Method Results in Simple Example

Reg.	Resource Schedule	Price	Regional MLS	Regional MLS allocation	Final MLS allocation
A	$-G_a$	P_1	$MLS_A = 0.5E_a(P_2 + P_4)$ $-G_aP_1 + L_aP_2$	N/A	$\frac{MLS_A \cdot L_a}{L_a + E_a}$
	L_a	P_2		$\frac{MLS_A \cdot L_a}{L_a + E_a}$	
	E_a	$0.5(P_2 + P_4)$		$\frac{MLS_A \cdot E_a}{L_a + E_a}$	
B	$-I_b$	$0.5(P_2 + P_4)$	$MLS_B = 0.5I_b(P_2 + P_4)$ $-G_bP_3 + L_bP_4$	N/A	$MLS_B + \frac{MLS_A \cdot E_a}{L_a + E_a}$
	$-G_b$	P_3		N/A	
	L_b	P_4		MLS_B	

The total MLS in the system is $MLS = MLS_A + MLS_B$, in order to make the discussion simper, only the MLS in region A will be considered, region B's MLS will be gotten by using equation $MLS_B = MLS - MLS_A$.

According to Table 5.1, $MLS_{A,final}$ can be written as

$$MLS_{A,final} = \frac{(0.5E_a(P_2 + P_4) - G_a P_1 + L_a P_2) \cdot L_a}{L_a + E_a} \tag{47}$$

The derivation value of $MLS_{A,final}$ is shown in (48) to discuss the relationship between E_a and $MLS_{A,final}$.

$$MLS'_{A,final} = \frac{(0.5L_a P_4 - 0.5L_a P_2 + G_a P_1) \cdot L_a}{(L_a + E_a)^2} \tag{48}$$

Because

$$L_a > 0, (L_a + E_a)^2 > 0$$

$$P_2 \approx P_4 \Rightarrow 0.5L_a P_4 - 0.5L_a P_2 + G_a P_1 > 0$$

Thus

$$MLS'_{A,final} > 0 \tag{49}$$

$MLS'_{A,final}$ is an increasing function to E_a, which means with the inter-region flow E_a increasing, the final MLS in region A $MLS'_{A,final}$ will increase, with the inter-region flow E_a decreasing, the final MLS in region A $MLS'_{A,final}$ will decrease.

$MLS''_{A,final}$ will be discussed in (50) to determine whether $MLS_{A,final}$ and E_a is a convex function or a concave function.

$$MLS''_{A,final} = \frac{-(L_a P_4 - L_a P_2 + 2G_a P_1) \cdot L_a}{(L_a + E_a)^3} \tag{50}$$

Because

$$(L_a P_4 - L_a P_2 + 2G_a P_1) > 0, L_a > 0, (L_a + E_a) > 0$$

Thus

$$MLS''_{A,final} < 0 \tag{51}$$

Therefore, $MLS_{A,final}$ is an increasing and convex function to E_a .

5.1.2. Loss Function. The total loss in a region is not usually given. It can be calculated, however, with an energy balance function (42). For example, the loss in the exporting region can be calculated as (52), based on Table 5.1 and energy balance system function (42).

$$Loss^{ex} = G_a - L_a - E_a \tag{52}$$

The loss in the exporting region ($Loss^{ex}$) has an inverse function relationship with the inter-region flow E_a (52). $MLS_{A,final}$ is a decreasing and convex function to E_a (known from 5.1.1). Therefore, $MLS_{A,final}$ is an increasing and concave function to $(Loss^{ex})$. This relationship is verified by the examples in 5.2.

5.2. ESTIMATE AN INTER-REGION FLOW

The 12-cases example (see Table 15) is based on a limited data from California ISO's market. The inter-region flow must be known in both the conforming regional method and the non-conforming regional method. Inter-region flows are recorded in the ISO's market database. ISOs did not, however, save its historical inter-region flow data. For example, in California ISO the path 26 flow is only recorded when it is above 85% of the flow limit. As previously discussed, inter regional flow is crucial to the conforming regional method. In order to have a better view of how the conforming regional method works on a long period of historical time, a method to estimate inter-region flows is needed.

The ratio of one region's loss over the total loss is usually around a constant in a power balance system. For example, in California ISO's market, the NP26 region's loss is averages 60% of the total loss within California ISO's market. It can be proved by the 4 continuous days (96 hours) example from Figure 4.2. In the example, the path 26 flow's information is available. According to (52), the loss in NP26 and loss in SP26 could be calculated. The ratio of loss in NP26 over the total loss is shown in Figure 5.2.

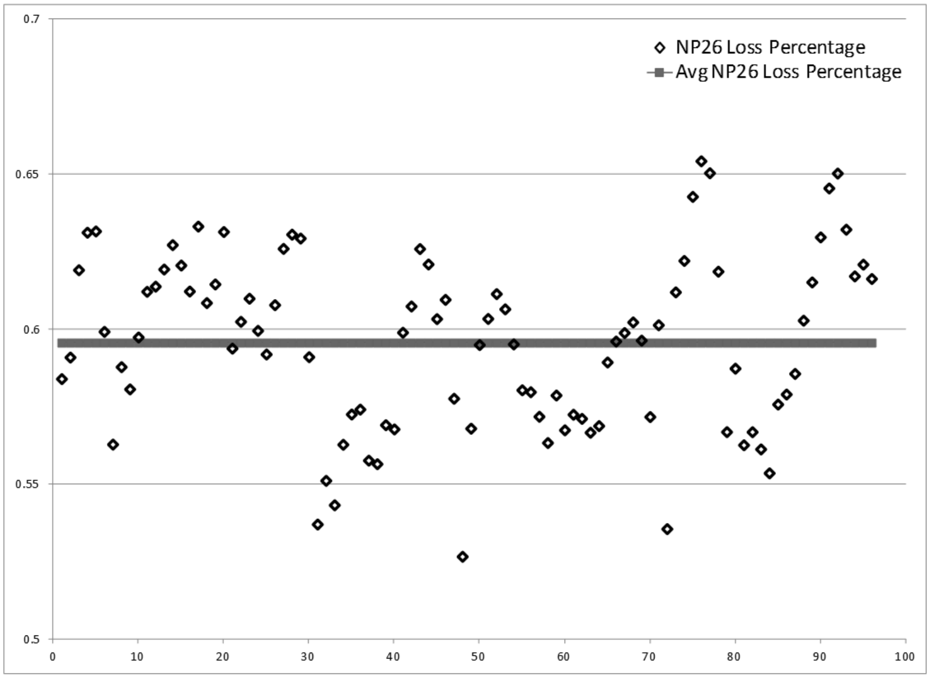


Figure 5.2. NP26 Loss Ratio Distribution

The average loss percentage in NP26 was 59.5% (see Figure 5.2,). 95% of NP26 loss ratio locates in between 55% and 65%. This finding verifies that the loss ratio in one region over the total is around a constant. The loss in each region can be calculated from the loss ratio. The inter-region flow can be obtained by applying energy balance equation.

For example, Table 5.1, if E_a is unknown, the total loss in the system is

$$Loss = G_a + G_b - L_a - L_b \tag{53}$$

If we assume the ratio of loss in exporting region is α of total loss, the loss in exporting region will be

$$\begin{aligned} Loss^{ex} &= Loss \cdot \alpha \\ &= (G_a + G_b - L_a - L_b) \cdot \alpha \end{aligned} \tag{54}$$

Exporting region is a self balance system, the inter-region flow E_a will be

$$\begin{aligned} E_a &= G_a - L_a - Loss^{ex} \\ &= (1-a)(G_a - L_a) - \alpha(G_b - L_b) \end{aligned} \tag{55}$$

Apply (55) to Table 5.1, the final MLS in region A and region B can be calculated based on α .

5.3. ACCURACY OF USING ESTIMATED INTER-REGION FLOWS

The 4 continuous day example was used to verify the accuracy of estimated the inter-region flow method. Because α is close to 60% in this case, a series of α will be selected to estimate path 26 flow and calculate final MLS in NP26, the results will be compared with results by using real path 26 flow in Table 5.2.

Table 5.2. Estimated Inter-region Flows Accuracy Check

Estimate Path 26 flow NP26's loss is α of Total loss	
α	Final MLS in NP26($)
50%	1,033,460
53%	986,423
55%	955,032
57%	923,613
59%	892,177
60%	876,454
62%	844,995
65%	797,779
Real Path 26 flow	**882,325**

The total MLS of NP26 in four continuous days by using real path 26 flow in the conforming regional method is $882325. When α is 59%, the final MLS in NP26 is $892177, the difference between it and real path 26 flow case is 1.11%. When α is 60%, final MLS in NP26 is $876454, the difference between it and real path 26 flow case is only -0.67%. Therefore, using estimated path 26 flows is a good alternative method to complete the conforming regional method when path 26 flows' information is unavailable.

With increasing value of α, the final MLS in NP26 is decreasing, which verifies the conclusion of 5.1.2 that the loss in exporting region and the inter-region flow is a decreasing function. The decreasing concave function between loss in NP26 and final MLS in NP26 when path 26 flow goes from NP26 to SP26 is verified in Table 5.3. The average value of 55% loss in NP26 and 65% loss in NP26 is less than the value of 60%. The difference between them is very small, thus, we can assume it as linear function.

Table 5.3. Concave Function Check

Hour	55% Loss in NP26	65% Loss in NP26	Avg. 55% &65%	60% Loss in NP26
9	7891.58	6492.026	7191.803	7193.236
10	10433.38	8797.474	9615.426	9617.073
11	12264.3	10457.36	11360.83	11362.66

5.4. MONTHLY EXAMPLE

If the loss information is known, the inter-region flow can be calculated. When regional loss ratio over the total is known, the path 26's flow's information can be estimated. The system-wide total loss can be calculated, and the north region loss is typically between 50% and 60% of the system total loss. North region loss can be set 50%, 55%, and 60% of the total system total loss. After this, Path 26's information can be calculated.

One year of data (December 2011 to November 2012) in California ISO market will be used to compare the system-wide method and the conforming regional method. The loss ratio in NP26's effect on final MLS is discussed.

Table 5.4 is the one year's final MLS results in NP26 and SP26 by using the system-wide method, the results' data is rounded, path 26 flows' information is not needed here.

Table 5.4. One Year MLS-System-wide Method

System-wide Demand Ratio MLS Allocation Method			
Month	**NP26's MLS($)**	**SP26's MLS($)**	**Total MLS($)**
Dec-11	5,152,000	5,331,000	10,482,899
Jan-12	4,226,000	4,697,000	8,922,739
Feb-12	4,169,000	4,611,000	8,780,307
Mar-12	3,884, 000	4,244,000	8,128,043
Apr-12	4,067, 000	4,242,000	8,308,623
May-12	5,053,000	5,463,000	10,515,198
Jun-12	5,578,000	5,932,000	11,509,576
Jul-12	7,116,000	8,025,000	15,141,105
Aug-12	8,934,000	11,581,000	20,514,980
Sep-12	7,924,000	9,924,000	17,847,554
Oct-12	7,942,000	9,099,000	17,041,603
Nov-12	6,848,000	6,734,000	13,582,599
Total	**70,893,000**	**79,882,000**	**150,775,226**
Ratio	47%	53%	100%

The total MLS equal to the sum of NP26's MLS and SP26's MLS. The MLS in NP26 was usually less SP26, this means the loads in southern California were heavier than northern California in 2012. Within California ISO control area, the total MLS in 12 months is shown as Figure 5.3.

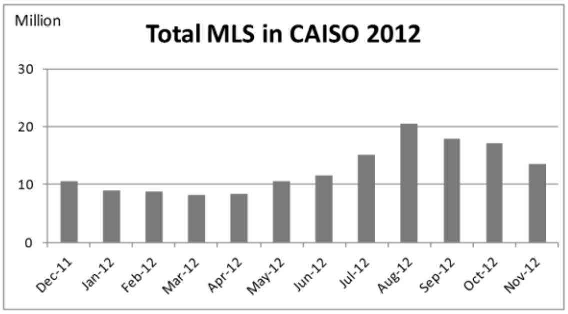


Figure 5.3. California ISO's Total MLS in Different Months

The total MLS is determined by total loss, the total loss depends on the total demand, therefore, from Figure 5.3, we can see in August the MLS reaches the peak, which matches the peak load time through one year in California. In contrast, in March and April, load is the lowest through the whole year.

As discussed above, in California ISO the loss ratio in NP26 is nearly 60% of the total, when NP26's loss ratio was assumed 60% of total, the conforming regional method generated result in Table 5.5.

Table 5.5. 60% Loss in North-Conforming Regional Method

Conforming Regional MLS Allocation Method		
	NP26 Loss is 60% of Total	
Month	**NP26's MLS($)**	**SP26's MLS($)**
Dec-11	5,890,000	4,593,000
Jan-12	4,241,000	4,682,000
Feb-12	2,954,000	5,827,000
Mar-12	3,093,000	5,035,000
Apr-12	4,176,000	4,133,000
May-12	5,296,000	5,219,000
Jun-12	5,769,000	5,741,000
Jul-12	6,478,000	8,663,000
Aug-12	6,763,000	13,752,000
Sep-12	3,707,000	14,141,000
Oct-12	5,505,000	11,537,000
Nov-12	5,779,000	7,803,000
Total	**59,650,000**	**91,125,000**
Ratio	40%	60%

The NP26 got 40% of total MLS. This is less than 47% by using the system-wide method. In contrast, SP26 region got 60% total MLS, which was more than 53% in the system-wide method. The loss percentage in NP26 was nearly 60% of the total. Within a range, continued decreasing the NP26's loss ratio to 55% and 50% of the total loss, the conforming regional method generated result in Table 5.6.

Table 5.6. 50% &55% Loss in North-Conforming Regional Method

Conforming Regional MLS Allocation Method				
	NP26 Loss is 50% of Total		**NP26 Loss is 55% of Total**	
Month	**NP26's MLS($)**	**SP26's MLS($)**	**NP26's MLS($)**	**SP26's MLS($)**
Dec-11	6,801,000	3,682,000	6,346,000	4,137,000
Jan-12	5,033,000	3,889,000	4,638,000	4,285,000
Feb-12	3,720,000	5,061,000	3,337,000	5,443,000
Mar-12	3,813,000	4,315,000	3,453,000	4,675,000
Apr-12	4,982,000	3,327,000	4,579,000	3,729,000
May-12	6,328,000	4,187,000	5,813,000	4,702,00
Jun-12	6,870,000	4,639,000	6,320,000	5,190,000
Jul-12	7,882,000	7,259,000	7,181,000	7,960,000
Aug-12	8,519,000	11,996,000	7,643,000	12,872,000
Sep-12	5,195,000	12,652,000	4,452,000	13,395,000
Oct-12	7,018,000	10,024,000	6,262,000	10,779,000
Nov-12	7,016,000	6,567,000	6,398,000	7,184,000
Total	**73,177,000**	**77,598,000**	**66,423,000**	**84,353,000**
Ratio	49%	51%	44%	56%

When the NP26 loss ratio was 55% of the total loss, the final MLS in NP26 was 44%. It was less than 47% by using the system-wide method. When the NP26 loss ratio was 50% of the total loss, the final MLS in NP26 is 49% which was more than 47% by using the system-wide method. It verifies the decreasing function between exporting region's final MLS and exporting region's loss.

Because NP26’s ratio of loss is close to 60% and within a range of 55%-60%, the final MLS in NP26 should be around 40% and maximum 44% of total MLS, whereas, SP26 can get around 60% and minimum 56% of total MLS.

5.5. CONCLUSION

Both the direction and magnitude of the inter-region flow are determinable factors affecting final MLS allocation. The inter-region flow can be calculated by exporting the region’s loss. The final MLS in exporting region has a decreasing concave function with exporting region’s loss. The ratio of loss in one region over the total is usually around a constant. A method for estimating the inter-region flows is proposed to complete the conforming regional method by assuming one region’s loss ratio when the inter-region flows are unavailable. The MLS allocation in different regions can be very accurate by using estimated the inter-region flows. This value can also be locked in two constants. The results are important reference for different methods comparison during stakeholders’ process.

6. SUMMARY AND CONCLUSION

LMP methodology is used to both manage grid congestion and calculate electricity prices for United States wholesale power markets. Adoption of LMPs will result in a surplus of revenue associated with marginal losses. To maintain marginal price signals which reflect locational price differences in marginal loss costs, the ISO used the system-wide method to allocate MLS pro-rata to all Measured Demand. This method, however, fails to recognize the regional differences in actual loss costs.

This thesis proposes a new method for allocating MLS on a regional basis. This method is an extension of the system-wide method. In each region, the new method precisely conforms to the system-wide MLS allocation method. A non-conforming method is also proposed to allocate MLS to regions. Compared with the non-conforming method, the conforming method produces coherently consistent results without introducing inconsistencies between the system-wide MLS allocation principle and the inter-region flow MLS allocation principle. An approach that could generate estimated inter-region flows are also proposed when the inter-region flows are not saved in ISO’s database. Different MLS allocation methods are tested under California ISO’s 2012 data. The results showed that the conforming regional method did generate different results from the system-wide method. It is fairer to allocate MLS to each region by using the conforming regional method.

6.1. FUTURE WORK

The conforming regional MLS allocation method acts as an optional method to allocate MLS to regions. The conforming regional MLS allocation method is independent of the system-wide MLS allocation method, and can be widely applicable. This method should be tested for an acceptable period of time with real inter-region flows information. The estimated the inter-region flow method discussed in this thesis can be used to run the historical data, before starting save the inter-region flows information into ISO’s market database. ISO should start a stakeholder process to discuss the principles and results of the conforming regional method. Eventually, the conforming method must be accepted by FERC to replace the system-wide method for marginal loss surplus allocation.

In contrast with the system-wide method’s principle, the arguments on cost causation principle related with the non-conforming regional method may be continuing. New methodologies need to be developed if FERC agrees to adopt this new principle on marginal loss surplus allocation.

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VITA

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