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Assessment of Market Flows for Interregional Congestion Management in Electricity Markets

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***Abstract*—This paper gives the background and role of the market flow in the interregional congestion management process for market-based operating entity and describes the market flow methodology. It proposes that the market flow method calculates the same impact result on a flowgate as the unit dispatch system (UDS) flow does and proves it mathematically. The equivalence of market flow and UDS flow shows that the UDS flow change on a constraint due to the UDS binding will have the same effect on the change in the market flow under the electricity market operations. In addition, it proves that, in an interconnected system, the sum of the market flows of all of the market entities, the generation-to-load impacts of nonmarket entities, and the total tagged transaction impact among the entities is equal to the dc flow for any constraint. The assessment of market flow methodology demonstrates the effectiveness of using the market flow in the congestion management process and coordinated management of transmission constraints. The proposed methodology can help identify the cause of loop flow problem in power systems. The numerical results on a 23-bus test system and a 7917-bus system are also illustrated.**

***Index Terms*—Congestion management, flowgate, generation shift factor, independent system operator (ISO), load shift factor, market flow, regional transmission organization (RTO), security-constrained economic dispatch.**

I. Introduction

MARKET flow is widely used by ISOs/RTOs in the congestion management process. Market flow means the amount of energy flows (or parallel flows) on a specified flowgate or facility as a result of dispatch of generating resources serving market load within a market-based operating entity's market (excluding tagged transactions) [1], [2]. A flowgate is a proxy for transmission limitation and transmission service usage on the interconnected electric power network to maintain stability, keep voltages within appropriate limits, or keep loading within appropriate rating for both normal and contingency conditions. Flowgates are facilities or group of facilities that may act as significant constraint points on the system [1]. A transaction means the transporting of scheduled power from a seller to a buyer along a prescribed contract path. Since all of the bilateral transactions between different balancing authorities (BAs) are tagged in the North American Electric Reliability Corporation (NERC) congestion management process, they are called tagged transactions, and their parallel flow impacts on constraint are defined as tag impacts. In the RTO real-time market operations, the UDS dispatches generation resources and manages constraints or flowgates to meet load economically and reliably. The UDS calculates the UDS flow on a flowgate in a different manner than the market flow calculation. The identification of the relationship between the market flow and the UDS flow is critical to ensure the most cost-effective congestion management for market-operating entities. This paper will attempt to address the connection between them.

Market flows play a major role in the transmission congestion management process for the market entities, e.g., Midcontinent Independent System Operator, Inc. (MISO), PJM Interconnection, L.L.C. (PJM), and Southwest Power Pool, Inc. (SPP). They are widely used by RTOs for the real-time management of transmission constraints through the NERC transmission loading relief (TLR) process and the market-to-market (M2M) coordination. To assure reliability of the bulk electric system, NERC standard IRO-006-5 implements TLR procedures to prevent and mitigate potential or actual system operating limit and interconnection reliability operating limit exceedances [3]. For the coordination between market and nonmarket entities, the interregional congestion management is mainly performed by the NERC TLR procedure. In the TLR process, NERC will use the RTO reported market flows to calculate the relief obligation and target market flow for RTO under TLR event. Each RTO needs to bind the market flow in its UDS and provides the required market flow obligation in order to meet the NERC TLR requirements. The accuracy of market flow is important to ensure power system reliability as well as equitable share of congestion cost among all entities of the interconnected system.

MISO and PJM established an M2M coordination to manage congestion under the joint operating agreement (JOA) since April 1, 2005 [1]. The MISO–PJM JOA provides a process to facilitate power system operations between RTOs and to allow coordinated management of transmission constraints (M2M flowgates) that are significantly impacted by generation dispatch in both markets. The M2M process is essential to ensure efficient dispatch of generation to manage congestion, promote price convergence between the seams of the two markets, and facilitate pricing and congestion management in both areas

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[1], [4]. In the real-time market, the least cost management of transmission congestion can be achieved through joint and iterative security-constrained economic dispatch (SCED). Market flow provides a measure in the parallel flow management on the M2M flowgates through coordinated market under JOA. The MISO-PJM M2M coordination has become an industry template for ISOs/RTOs in the interregional congestion management coordination. Recently, New York Independent System Operator, Inc. (NYISO) and PJM have started the M2M coordination under their JOA since January 15, 2013 [5], [6]. In addition, MISO and SPP are in the discussion of the M2M process in the near future under the guidance of Federal Energy Regulatory Commission (FERC) [7]. The M2M coordination allows multiple market entities to manage the real-time transmission constraints simultaneously in a coordinated manner. It not only improves power system reliability by utilizing the generation resources from both RTOs to jointly control constraints, but also results in reduced production cost and achieves a more efficient redispatch solution for coordinated constraints across multiple systems. In the M2M process, the market flows quantify the impact of an RTO's market operations on the transmission constraints. The accuracy of market flow calculation is crucial for the efficient congestion management through M2M as well as for the after-the-fact M2M settlement. In this paper, a systematic assessment of market flow calculation and its role in the interregional congestion management is presented.

Various methods have been proposed to calculate the impact of generator serving load on the transmission system [8]–[20]. References [9] and [10] proposed a topological trace algorithm to estimate the contribution of generator and load to flows. References [11] and [12] proposed the upstream- and downstream-looking algorithms to trace the flow of electricity. All of these algorithms are built based on the proportional sharing principle [13], [14] by which the market flow calculation is adopted. It should be mentioned that there are also other proposed methods to trace power flow, such as the circuit-based method [13], [15], graph theory [16], evolutionary computation algorithm [8], and min-max fairness [18].

This paper is organized as follows. In Section II, the market flow calculation background and procedure are described. Section III describes and proves the relationship between the market flow and the UDS flow. Section IV demonstrates the impact of multiple RTOs market operations on the parallel flow. Section V illustrates and compares the results using a PSS/E test case and an Eastern Interconnection system case. Section VI gives the conclusion.

II. Market Flow Methodology

The market flow calculation is based on the linear distribution factors using generation shift factors (GSFs) of the RTO's generators and the load shift factors (LSFs) of its loads [1], [2], [21]. The GSF describes a generator's impact on a flowgate. It represents the change in flow on a flowgate due to an incremental injection at the generator bus and a corresponding withdrawal at the swing bus. The LSF describes how changes in system load affect a flowgate. It represents the impact on a flowgate due to a decremental change of load and the same amount of change at the swing bus. The generation-to-load distribution factor (GLDF) describes a generator's impact on a flowgate while serving load. It is determined through superposition by subtracting the LSF from the GSF. The determination of the market flow contribution of a unit to a specific flowgate is the product of the generator's GLDF multiplied by the real-time output of generator calculated by the state estimator (SE) in energy management system (EMS). The market flow contributions can be divided into native impact and transfer impact by separating the generator output into native portion and transfer portion, separately. In the market flow calculation, the generation output, market load, and shift factor values are all obtained based on the SE solution. All of the input information is updated every five minutes, and the real-time market flow calculation also runs every five minutes. In addition, the market flow calculation uses all flows, in both directions, down to a 5% threshold for NERC to assign TLR curtailments and down to a 0% threshold for congestion management such as the M2M coordination.

Suppose an RTO has n number of control areas (CAs) under its control within the BA footprint, namely, $\mathrm{CA}_1, \mathrm{CA}_2, \ldots, \mathrm{CA}_n$. For each CA, the total generation output is $P_1, P_2, \ldots, P_n$, and the total load amount is $L_1, L_2, \ldots, L_n$, respectively. For a given flowgate, the CA weighted GSFs are $\mathrm{GSF}_1, \mathrm{GSF}_2, \ldots, \mathrm{GSF}_n$, and the CA weighted LSFs are $\mathrm{LSF}_1, \mathrm{LSF}_2, \ldots, \mathrm{LSF}_n$, respectively [21]. Assuming that the RTO is power balanced as a whole, if the transmission loss is included in the load, there is $\sum_{i=1}^{n} P_i = \sum_{i=1}^{n} L_i$.

Note that, under real-time operations, there are import and export physical schedules between RTO and external BAs. The RTO as a BA will dispatch the generation resources to maintain load-interchange-generation balance and utilize automatic generation control to control the net actual interchange to match the net scheduled interchange calculated based on scheduled import and export transactions. Assuming that the total RTO export and import are EXP and IMP, respectively, and there is no inadvertent interchange, we have

$$\sum_{i=1}^{n} P_i - EXP = \sum_{i=1}^{n} L_i - IMP. \tag{1}$$

For CA_i, suppose it has g_i number of generators with the output of $p_i^1, p_i^2, \ldots, p_i^{g_i}$ and GSFs of $\mathrm{gsf}_i^1, \mathrm{gsf}_i^2, \ldots, \mathrm{gsf}_i^{g_i}$, respectively. It also contains h_i number of loads with the amount of $l_i^1, l_i^2, \ldots, l_i^{h_i}$ and LSFs of $lsf_i^1, lsf_i^2, \ldots, lsf_i^{h_i}$, respectively. We have

$$\sum_{j=1}^{g_i} p_i^j = P_i, \ \sum_{j=1}^{h_i} l_i^j = L_i \tag{2}$$

$$\sum_{j=1}^{g_i} \mathrm{gsf}_i^j p_i^j = \mathrm{GSF}_i P_i, \ \sum_{j=1}^{h_i} lsf_i^j l_i^j = LSF_i L_i. \tag{3}$$

The procedure of the market flow calculation is described as follows.

1) Scale down the generation and load across the RTO footprint on a pro-rata basis to account for RTO export and import, respectively. The proportional adjustment is also called "slice of system" methodology which adopts the

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proportional sharing method. For p_i^j and l_i^j in CA_i, assume that the generation and load after adjustments are $\hat{p}_i^j$ and $\hat{l}_i^j$, then

$$\hat{p}_i^j = p_i^j \left(1 - \frac{EXP}{\sum_{i=1}^{n} P_i}\right), \quad \hat{l}_i^j = l_i^j \left(1 - \frac{IMP}{\sum_{i=1}^{n} L_i}\right). \tag{4}$$

For CA_i, the total generation and load after adjustments are

$$\hat{P}_i = \sum_{j=1}^{g_i} \hat{p}_i^j, \quad \hat{L}_i = \sum_{j=1}^{h_i} \hat{l}_i^j. \tag{5}$$

From (1), (2), (4), and (5), it can be obtained that

$$\sum_{i=1}^{n} \hat{P}_i = \sum_{i=1}^{n} \hat{L}_i \tag{6}$$

which means that the power balance can still be maintained after the adjustments.

2) Determine the native and transfer portions for each RTO CA's generation and distribute them among the generators. The native portion N_i is the CA's generation serving the CA's native load and the transfer portion (or generation surplus) T_i corresponds to the CA's generation serving other CAs' load within the market area. The CA's generation shortage S_i must be served by generation in other CAs within the RTO that have excess generation in order to maintain the power balance after the adjustments. They are defined as

$$N_i = \min(\hat{P}_i, \hat{L}_i) \tag{7}$$

$$T_i = \begin{cases} \hat{P}_i - \hat{L}_i, & \text{if } \hat{P}_i > \hat{L}_i \\ 0, & \text{if } \hat{P}_i \le \hat{L}_i. \end{cases} \tag{8}$$

$$S_i = \begin{cases} \hat{L}_i - \hat{P}_i, & \text{if } \hat{L}_i > \hat{P}_i \\ 0, & \text{if } \hat{L}_i \le \hat{P}_i. \end{cases} \tag{9}$$

For unit j in CA_i, its native and transfer portions are $\hat{p}_i^j N_i/\hat{P}_i$ and $\hat{p}_i^j T_i/\hat{P}_i$. Their parallel flow impacts on flowgate while serving load are called native impact and transfer impact, respectively.

3) Calculate the RTO LSF $\mathrm{LSF}'_{\mathrm{RTO}}$ which is the weighted load shift factor of all CAs with generation shortage and GLDF of each RTO unit and defined as follows:

$$\mathrm{LSF}'_{\mathrm{RTO}} = \frac{\sum_{i=1}^{n} S_i LSF_i}{\sum_{i=1}^{n} S_i}. \tag{10}$$

For each unit, the native GLDF is calculated by subtracting LSF_i from gsf_i^j and is used in the native impact calculation. The transfer GLDF is the difference between gsf_i^j and $\mathrm{LSF}'_{\mathrm{RTO}}$ and is used in the transfer impact calculation. The purpose of $\mathrm{LSF}'_{\mathrm{RTO}}$ is to eliminate the impact of importing CAs' load on the constraint by shifting LSF to the load center of all the importing CAs in the transfer impact calculation. As a result, we only need to use the transfer GLDF to calculate the transfer impact of the exporting CAs with respect to $\mathrm{LSF}'_{\mathrm{RTO}}$.

4) Calculate the native and transfer impacts of each RTO generator as follows:

$$\text{Native Impact} = \frac{(\mathrm{gsf}_i^j - \mathrm{LSF}_i)\hat{p}_i^j N_i}{\hat{P}_i} \tag{11}$$

$$\text{Transfer Impact} = \frac{(\mathrm{gsf}_i^j - \mathrm{LSF}'_{\mathrm{RTO}})\hat{p}_i^j T_i}{\hat{P}_i}. \tag{12}$$

The native impact is the parallel flow of a generator on a flowgate while serving its internal CA's load where the generator resides in. The transfer impact relates to the parallel flow of the generator on the flowgate while serving other CAs' load of RTO with the generation shortage.

5) Aggregate all of the generator native and transfer impacts together to determine the directional market flows and net market flow. The total market flow on a specific flowgate is calculated in both forward and reverse directions. The forward market flow is the sum of the positive market flow contributions of each generator within the market area, while the reverse market flow is the sum of the negative market flow contributions of each generator within the market footprint.

It should be pointed out that, although the market flow is calculated based on dc-type models using linear shift factors, the accuracy of dc model-based market flow calculation is acceptable in most cases. Reference [22] revisited the dc power flow and pointed out it is reasonably accurate for the heavily loaded lines that constrain system operation. In the realistic operations, the dc-type models are widely used in the electric power industry, especially for market operations of RTOs such as SCED.

III. Market Flow and UDS Flow

In the real-time energy market operations, RTO utilizes SCED (or UDS) to economically serve load and manage congestion. The SCED is a 5-min look-ahead dispatch and calculates the set point for each unit within the market footprint in the next 5 min. The transmission congestion in SCED is managed through the unit redispatch based on the generator offer price taking into account its sensitivity (or GLDF) on the constraint. The UDS flow quantifies the impact of unit redispatch on a flowgate. In UDS, the weighted LSF of RTO $\mathrm{LSF}_{\mathrm{RTO}}$ is calculated first, and each unit's GSF gsf_i is then shifted by $\mathrm{LSF}_{\mathrm{RTO}}$ as the adjusted GSF gsf'_i, shown as follows:

$$\mathrm{LSF}_{\mathrm{RTO}} = \frac{\sum_{i=1}^{n} \sum_{j=1}^{h_i} lsf_i^j l_i^j}{\sum_{i=1}^{n} \sum_{j=1}^{h_i} l_i^j} = \frac{\sum_{i=1}^{n} LSF_i L_i}{\sum_{i=1}^{n} L_i}. \tag{13}$$

It can be seen that $\mathrm{LSF}_{\mathrm{RTO}}$ is a constant number at each UDS dispatch interval and is the same for all the RTO units when the flowgate is specified. For any unit, the impact of the unit redispatch on a flowgate is gsf'_i multiplied by the unit scheduled set point calculated by UDS. When all of the RTO units follow the dispatch signal, each unit actual output $\hat{p}_i^j$ equals to the unit set point in UDS. The UDS flow is the aggregated impact of all of the units in the market footprint. Therefore, the UDS flow on the flowgate due to the UDS redispatch considering adjustments is given as

$$\mathrm{UDSF} = \sum_{i=1}^{n}\sum_{j=1}^{g_i}(\mathrm{gsf}_i^j - \mathrm{LSF}_{\mathrm{RTO}})\hat{p}_i^j. \quad (14)$$

Proposition 1: Assuming that all of the units of RTO follow the dispatch signal, the calculated market flow is the same as the UDS flow on any flowgate.

Proof: We consider the following two scenarios.

Scenario I: If all of the n CAs are power balanced, i.e., for any $i \in [1, n]$, $\hat{P}_i = \hat{L}_i$. Since no CA has generation shortage, $N_i = P_i$, and $T_i = 0$. From (11) and (13) it can be seen that there is no transfer impact and all the impacts are native. Thus

$$\begin{aligned}\mathrm{MF} - \mathrm{UDSF} &= \sum_{i=1}^{n}\sum_{j=1}^{g_i}(\mathrm{gsf}_i^j - \mathrm{LSF}_i)\hat{p}_i^j \\ &\quad - \sum_{i=1}^{n}\sum_{j=1}^{g_i}(\mathrm{gsf}_i^j - \mathrm{LSF}_{\mathrm{RTO}})\hat{p}_i^j \\ &= -\sum_{i=1}^{n}\sum_{j=1}^{g_i}\mathrm{LSF}_i\hat{p}_i^j + \mathrm{LSF}_{\mathrm{RTO}}\sum_{i=1}^{n}\sum_{j=1}^{g_i}\hat{p}_i^j \\ &= -\sum_{i=1}^{n}\mathrm{LSF}_i\hat{P}_i + \frac{\sum_{i=1}^{n}\mathrm{LSF}_i\hat{L}_i}{\sum_{i=1}^{n}\hat{L}_i}\sum_{i=1}^{n}\hat{P}_i \\ &= -\sum_{i=1}^{n}\mathrm{LSF}_i\hat{P}_i + \sum_{i=1}^{n}\mathrm{LSF}_i\hat{L}_i = 0. \end{aligned} \quad (15)$$

Scenario II: If power balance is not maintained in all of the CAs, without loss of generality, there is

$$\begin{cases} \hat{P}_i > \hat{L}_i, & \text{if } i \in [1, m] \\ \hat{P}_i = \hat{L}_i, & \text{if } i \in (m, r) \\ \hat{P}_i < \hat{L}_i, & \text{if } i \in [r, n]. \end{cases} \quad (16)$$

Since the whole RTO is power balanced after export and import adjustments, from (6) and (16), we have

$$\sum_{i=1}^{m}(\hat{P}_i - \hat{L}_i) = \sum_{i=r}^{n}(\hat{L}_i - \hat{P}_i). \quad (17)$$

For any unit j in CA_i, $j \in [1, g_i]$.

1) When $i \in [1, m]$, using (7), (8),and (11)–(13), its native and transfer impacts are as follows:

$$\text{Native Impact} = (\mathrm{gsf}_i^j - \mathrm{LSF}_i)\left(\hat{p}_i^j - \frac{\hat{P}_i - \hat{L}_i}{\hat{P}_i}\hat{p}_i^j\right) \quad (18)$$

$$\text{Transfer Impact} = (\mathrm{gsf}_i^j - \mathrm{LSF}'_{\mathrm{RTO}})\frac{\hat{P}_i - \hat{L}_i}{\hat{P}_i}\hat{p}_i^j \quad (19)$$

where

$$\mathrm{LSF}'_{\mathrm{RTO}} = \frac{\sum_{i=r}^{n}(\hat{L}_i - \hat{P}_i)\mathrm{LSF}_i}{\sum_{i=r}^{n}(\hat{L}_i - \hat{P}_i)} = \frac{\sum_{i=r}^{n}(\hat{L}_i - \hat{P}_i)\mathrm{LSF}_i}{\sum_{i=1}^{m}(\hat{P}_i - \hat{L}_i)}. \quad (20)$$

Similar to $\mathrm{LSF}_{\mathrm{RTO}}$ in (13), $\mathrm{LSF}'_{\mathrm{RTO}}$ is the same for all of the generators on any specific flowgate. Note normally $\mathrm{LSF}'_{\mathrm{RTO}} \neq \mathrm{LSF}_{\mathrm{RTO}}$.

The total impact of the unit is

$$\begin{aligned}&\text{Unit Impact} \\ &\quad = \text{Native Impact} + \text{Transfer Impact} \\ &\quad = \mathrm{gsf}_i^j\hat{p}_i^j - \mathrm{gsf}_i^j\frac{\hat{P}_i - \hat{L}_i}{\hat{P}_i}\hat{p}_i^j - \mathrm{LSF}_i\hat{p}_i^j + \mathrm{LSF}_i\frac{\hat{P}_i - \hat{L}_i}{\hat{P}_i}\hat{p}_i^j \\ &\qquad + \mathrm{gsf}_i^j\frac{\hat{P}_i - \hat{L}_i}{\hat{P}_i}\hat{p}_i^j - \mathrm{LSF}'_{\mathrm{RTO}}\frac{\hat{P}_i - \hat{L}_i}{\hat{P}_i}\hat{p}_i^j \\ &\quad = (\mathrm{gsf}_i^j - \mathrm{LSF}_i)\hat{p}_i^j + (\mathrm{LSF}_i - \mathrm{LSF}'_{\mathrm{RTO}})\frac{\hat{P}_i - \hat{L}_i}{\hat{P}_i}\hat{p}_i^j. \end{aligned} \quad (21)$$

2) When $i \in (m, n]$, its native and transfer impacts and the total unit impact are as follows.

$$\text{Native Impact} = (\mathrm{gsf}_i^j - \mathrm{LSF}_i)\hat{p}_i^j \quad (22)$$

$$\text{Transfer Impact} = 0 \quad (23)$$

$$\text{Unit Impact} = (\mathrm{gsf}_i^j - \mathrm{LSF}_i)\hat{p}_i^j. \quad (24)$$

Therefore, from 1) and 2), the total market flow is

$$\begin{aligned}\mathrm{MF} &= \sum_{i=m+1}^{n}\sum_{j=1}^{g_i}(\mathrm{gsf}_i^j - \mathrm{LSF}_i)\hat{p}_i^j + \sum_{i=1}^{m}\sum_{j=1}^{g_i}\Big[(\mathrm{gsf}_i^j \\ &\quad - \mathrm{LSF}_i)\hat{p}_i^j + (\mathrm{LSF}_i - \mathrm{LSF}'_{\mathrm{RTO}})\frac{\hat{P}_i - \hat{L}_i}{\hat{P}_i}\hat{p}_i^j\Big] \\ &= \sum_{i=1}^{m}\sum_{j=1}^{g_i}(\mathrm{LSF}_i - \mathrm{LSF}'_{\mathrm{RTO}})\frac{\hat{P}_i - \hat{L}_i}{\hat{P}_i}\hat{p}_i^j \\ &\quad + \sum_{i=1}^{n}\sum_{j=1}^{g_i}(\mathrm{gsf}_i^j - \mathrm{LSF}_i)\hat{p}_i^j. \end{aligned} \quad (25)$$

The UDS flow is

$$\mathrm{UDSF} = \sum_{i=1}^{n}\sum_{j=1}^{g_i}(\mathrm{gsf}_i^j - \mathrm{LSF}_{\mathrm{RTO}})\hat{p}_i^j. \quad (26)$$

Notice that

$$\begin{aligned}&\sum_{i=1}^{m}\sum_{j=1}^{g_i}(\mathrm{LSF}_i - \mathrm{LSF}'_{\mathrm{RTO}})\frac{\hat{P}_i - \hat{L}_i}{\hat{P}_i}\hat{p}_i^j \\ &\quad = \sum_{i=1}^{m}[\mathrm{LSF}_i(\hat{P}_i - \hat{L}_i) - \mathrm{LSF}'_{\mathrm{RTO}}(\hat{P}_i - \hat{L}_i)] \\ &\quad = \sum_{i=1}^{m}(\hat{P}_i - \hat{L}_i)\mathrm{LSF}_i - \sum_{i=1}^{m}(\hat{P}_i - \hat{L}_i)\frac{\sum_{i=r}^{n}(\hat{L}_i - \hat{P}_i)\mathrm{LSF}_i}{\sum_{i=1}^{m}(\hat{P}_i - \hat{L}_i)} \\ &\quad = \sum_{i=1}^{m}(\hat{P}_i - \hat{L}_i)\mathrm{LSF}_i - \sum_{i=r}^{n}(\hat{L}_i - \hat{P}_i)\mathrm{LSF}_i \\ &\quad = \sum_{i=1}^{n}(\hat{P}_i - \hat{L}_i)\mathrm{LSF}_i \end{aligned} \quad (27)$$

$$\sum_{i=1}^{n}\sum_{j=1}^{g_i}\mathrm{LSF}_{\mathrm{RTO}}\hat{p}_i^j = \frac{\sum_{i=1}^{n}\mathrm{LSF}_i\hat{L}_i}{\sum_{i=1}^{n}\hat{L}_i}\sum_{i=1}^{n}\sum_{j=1}^{g_i}\hat{p}_i^j = \frac{\sum_{i=1}^{n}\mathrm{LSF}_i\hat{L}_i}{\sum_{i=1}^{n}\hat{L}_i}\sum_{i=1}^{n}\hat{P}_i = \sum_{i=1}^{n}\mathrm{LSF}_i\hat{L}_i. \quad (28)$$

Therefore,

$$\mathrm{MF}-\mathrm{UDSF} = \sum_{i=1}^{n}(\hat{P}_i-\hat{L}_i)\mathrm{LSF}_i + \sum_{i=1}^{n}\sum_{j=1}^{g_i}(\mathrm{gsf}_i^j - \mathrm{LSF}_i)\hat{p}_i^j - \sum_{i=1}^{n}\sum_{j=1}^{g_i}\mathrm{gsf}_i^j\hat{p}_i^j + \sum_{i=1}^{n}\mathrm{LSF}_i\hat{L}_i = 0. \quad (29)$$

■

The equivalence of the market flow and the UDS flow shows that the UDS flow change on a constraint due to the look-ahead UDS binding will have the same effect on the change in the real-time market flow and furthermore, the same change in the actual physical flow of the constraint. As a result, the SCED can redispatch the generation resources in the most economical manner to serve the forecasted demand and at the same time, manage the congestion in the system with the least cost using the market flow.

IV. Market Flows of Multiple RTOs

In an interconnected system, such as the Eastern Interconnection, there are multiple RTOs and nonmarket entities with tagged interchange transactions among them. Each RTO's market operation has an impact on any constraint in the system quantified by its market flow. Here, the market flows of multiple RTOs are investigated to demonstrate that their impacts on any flowgate can be treated in the same manner without causing loop flow issue.

Let us first examine the impact of proportional adjustment on the distribution factors. For CA_i, we assume that the CA export and import are EXP_i and IMP_i, respectively. After the generation adjustment for export and load adjustment for import, the aggregated CA GSF and LSF become

$$\mathrm{GSF}_i' = \frac{\sum_{j=1}^{g_i}\mathrm{gsf}_i^j\hat{p}_i^j}{\sum_{j=1}^{g_i}\hat{p}_i^j} \qquad \mathrm{LSF}_i' = \frac{\sum_{j=1}^{h_i}lsf_i^j\hat{l}_i^j}{\sum_{j=1}^{h_i}\hat{l}_i^j} \quad (30)$$

where $\hat{p}_i^j = p_i^j(1 - EXP_i/\sum_{k=1}^{g_i}p_i^k)$, and $\hat{l}_i^j = l_i^j(1 - IMP_i/\sum_{k=1}^{h_i}l_i^k)$.

Proposition 2: For any CA, the CA GSF and LSF remain the same after the proportional scaling down the CA generation for export and CA load for import, i.e., for any $i \in [1,n]$, $\mathrm{GSF}_i' = \mathrm{GSF}_i$ and $\mathrm{LSF}_i' = \mathrm{LSF}_i$.

Proof:

$$\begin{aligned}
\mathrm{GSF}_i - \mathrm{GSF}_i' &= \frac{\sum_{j=1}^{g_i}\mathrm{gsf}_i^j p_i^j}{\sum_{j=1}^{g_i}p_i^j} - \frac{\sum_{j=1}^{g_i}\mathrm{gsf}_i^j\hat{p}_i^j}{\sum_{j=1}^{g_i}\hat{p}_i^j} \\
&= \frac{\sum_{j=1}^{g_i}\mathrm{gsf}_i^j p_i^j\sum_{j=1}^{g_i}\hat{p}_i^j - \sum_{j=1}^{g_i}\mathrm{gsf}_i^j\hat{p}_i^j\sum_{j=1}^{g_i}p_i^j}{\sum_{j=1}^{g_i}p_i^j\sum_{j=1}^{g_i}\hat{p}_i^j} \\
&= \frac{\sum_{j=1}^{g_i}\mathrm{gsf}_i^j p_i^j\sum_{j=1}^{g_i}\left[p_i^j\left(1-\frac{EXP_i}{\sum_{k=1}^{g_i}p_i^k}\right)\right]}{\sum_{j=1}^{g_i}p_i^j\sum_{j=1}^{g_i}\hat{p}_i^j} - \frac{\sum_{j=1}^{g_i}\mathrm{gsf}_i^j\left[p_i^j\left(1-\frac{EXP_i}{\sum_{k=1}^{g_i}p_i^k}\right)\right]\sum_{j=1}^{g_i}p_i^j}{\sum_{j=1}^{g_i}p_i^j\sum_{j=1}^{g_i}\hat{p}_i^j} \\
&= \frac{\sum_{j=1}^{g_i}\mathrm{gsf}_i^j p_i^j\left(\sum_{j=1}^{g_i}p_i^j - EXP_i\right)}{\sum_{j=1}^{g_i}p_i^j\sum_{j=1}^{g_i}\hat{p}_i^j} - \frac{\sum_{j=1}^{g_i}\mathrm{gsf}_i^j p_i^j\left(\sum_{j=1}^{g_i}p_i^j - EXP_i\right)}{\sum_{j=1}^{g_i}p_i^j\sum_{j=1}^{g_i}\hat{p}_i^j} = 0. \quad (31)
\end{aligned}$$

Similarly, we can also obtain $\mathrm{LSF}_i = \mathrm{LSF}_i'$. ■

Proposition 3: For any RTO consisting of multiple CAs, the RTO GSF and LSF are unchanged after the proportional scaling down the RTO generation for export and the RTO load for import.

Proof: Proof is similar to the proof process of Proposition 2 and is omitted. ■

Proposition 4: For any CA or RTO, there is $\sum \mathrm{GSF}(p_i^j - \hat{p}_i^j) = \sum \mathrm{gsf}_i^j(p_i^j - \hat{p}_i^j)$ after the proportional scaling down the CA or RTO generation for export.

Proof: Proof is similar to the proof process of Proposition 2 and is omitted. ■

Proposition 5: For a system with two RTOs, namely RTO_1 and RTO_2, without loss of generality, RTO_1 is exporting power of P_{12} to RTO_2, as shown in Fig. 1. For any flowgate, the sum of the market flows of RTO_1 and RTO_2 plus the tag impact of interchange transaction P_{12} is equal to the actual physical flow (dc flow) of the flowgate. In other words,

$$\text{Tag Impact} + MF_{\mathrm{RTO}_1} + MF_{\mathrm{RTO}_2} = \sum_{\mathrm{RTO}_1\cup\mathrm{RTO}_2} p_i^j(\mathrm{gsf}_i^j - \mathrm{LSF}_{sys}) \quad (32)$$

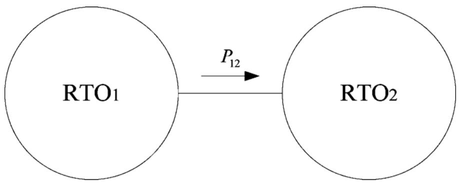

Fig. 1. Two RTOs with one-way interchange transactions.

where

$$MF_{\mathrm{RTO}_1} = \sum_{\mathrm{RTO}_1} \hat{p}_i^j(\mathrm{gsf}_i^j - \mathrm{LSF}_{\mathrm{RTO}_1}) \quad (33)$$

$$MF_{\mathrm{RTO}_2} = \sum_{\mathrm{RTO}_2} p_i^j(\mathrm{gsf}_i^j - \mathrm{LSF}_{\mathrm{RTO}_2}) \quad (34)$$

$$\text{Tag Impact} = (\mathrm{GSF}_{\mathrm{RTO}_1} - \mathrm{LSF}_{\mathrm{RTO}_2})P_{12}. \quad (35)$$

$$\mathrm{LSF}_{sys} = \frac{\sum_{\mathrm{RTO}_1 \cup \mathrm{RTO}_2} l_i^j lsf_i^j}{\sum_{\mathrm{RTO}_1 \cup \mathrm{RTO}_2} l_i^j}. \quad (36)$$

Proof: Using Propositions 2–4, we have

$$\begin{aligned} P_{12} &= \sum_{\mathrm{RTO}_1} (p_i^j - \hat{p}_i^j) = \sum_{\mathrm{RTO}_1} p_i^j - \sum_{\mathrm{RTO}_1} l_i^j \\ &= \sum_{\mathrm{RTO}_2} l_i^j - \sum_{\mathrm{RTO}_2} p_i^j \end{aligned} \quad (37)$$

$$\begin{aligned} \mathrm{GSF}_{\mathrm{RTO}_1} P_{12} &= \sum_{\mathrm{RTO}_1} \mathrm{GSF}_{\mathrm{RTO}_1}(p_i^j - \hat{p}_i^j) \\ &= \sum_{\mathrm{RTO}_1} \mathrm{gsf}_i^j p_i^j - \sum_{\mathrm{RTO}_1} \mathrm{gsf}_i^j \hat{p}_i^j \end{aligned} \quad (38)$$

$$\begin{aligned} \sum_{\mathrm{RTO}_1 \cup \mathrm{RTO}_2} p_i^j \mathrm{LSF}_{sys} &= \mathrm{LSF}_{sys} \sum_{\mathrm{RTO}_1 \cup \mathrm{RTO}_2} l_i^j \\ &= \mathrm{LSF}_{\mathrm{RTO}_1} \sum_{\mathrm{RTO}_1} l_i^j + \mathrm{LSF}_{\mathrm{RTO}_2} \sum_{\mathrm{RTO}_2} l_i^j \\ &= \mathrm{LSF}_{\mathrm{RTO}_1} \sum_{\mathrm{RTO}_1} p_i^j - \mathrm{LSF}_{\mathrm{RTO}_1} P_{12} \\ &\quad + \mathrm{LSF}_{\mathrm{RTO}_2} \sum_{\mathrm{RTO}_2} p_i^j + \mathrm{LSF}_{\mathrm{RTO}_2} P_{12} \end{aligned} \quad (39)$$

$$\begin{aligned} \sum_{\mathrm{RTO}_1 \cup \mathrm{RTO}_2} p_i^j(\mathrm{gsf}_i^j - \mathrm{LSF}_{sys}) &= \sum_{\mathrm{RTO}_1} p_i^j \mathrm{gsf}_i^j + \sum_{\mathrm{RTO}_2} p_i^j \mathrm{gsf}_i^j \\ &\quad - \mathrm{LSF}_{\mathrm{RTO}_1} \sum_{\mathrm{RTO}_1} p_i^j + \mathrm{LSF}_{\mathrm{RTO}_1} P_{12} \\ &\quad - \mathrm{LSF}_{\mathrm{RTO}_2} \sum_{\mathrm{RTO}_2} p_i^j - \mathrm{LSF}_{\mathrm{RTO}_2} P_{12}. \end{aligned} \quad (40)$$

Considering (37)–(40), there is

$$\begin{aligned} &\text{Tag Impact} + MF_{\mathrm{RTO}_1} + MF_{\mathrm{RTO}_2} \\ &\quad - \sum_{\mathrm{RTO}_1 \cup \mathrm{RTO}_2} p_i^j(\mathrm{gsf}_i^j - \mathrm{LSF}_{sys}) \\ &= (\mathrm{GSF}_{\mathrm{RTO}_1} - \mathrm{LSF}_{\mathrm{RTO}_2})P_{12} \\ &\quad + \sum_{\mathrm{RTO}_1} \hat{p}_i^j(\mathrm{gsf}_i^j - \mathrm{LSF}_{\mathrm{RTO}_1}) \\ &\quad + \sum_{\mathrm{RTO}_2} p_i^j(\mathrm{gsf}_i^j - \mathrm{LSF}_{\mathrm{RTO}_2}) \\ &\quad - \sum_{\mathrm{RTO}_1 \cup \mathrm{RTO}_2} p_i^j(\mathrm{gsf}_i^j - \mathrm{LSF}_{\mathrm{sys}}) \\ &= \sum_{\mathrm{RTO}_1} \mathrm{gsf}_i^j p_i^j - \sum_{\mathrm{RTO}_1} \mathrm{gsf}_i^j \hat{p}_i^j - \mathrm{LSF}_{\mathrm{RTO}_2} P_{12} \\ &\quad + \sum_{\mathrm{RTO}_1} \hat{p}_i^j \mathrm{gsf}_i^j \\ &\quad - \mathrm{LSF}_{\mathrm{RTO}_1} \sum_{\mathrm{RTO}_1} \hat{p}_i^j + \sum_{\mathrm{RTO}_2} p_i^j \mathrm{gsf}_i^j \\ &\quad - \mathrm{LSF}_{\mathrm{RTO}_2} \sum_{\mathrm{RTO}_2} p_i^j \\ &\quad - \sum_{\mathrm{RTO}_1} p_i^j \mathrm{gsf}_i^j - \sum_{\mathrm{RTO}_2} p_i^j \mathrm{gsf}_i^j + \mathrm{LSF}_{\mathrm{RTO}_1} \sum_{\mathrm{RTO}_1} p_i^j \\ &\quad - \mathrm{LSF}_{\mathrm{RTO}_1} P_{12} + \mathrm{LSF}_{\mathrm{RTO}_2} \sum_{\mathrm{RTO}_2} p_i^j \\ &\quad + \mathrm{LSF}_{\mathrm{RTO}_2} P_{12} \\ &= -\mathrm{LSF}_{\mathrm{RTO}_1} \sum_{\mathrm{RTO}_1} \hat{p}_i^j + \mathrm{LSF}_{\mathrm{RTO}_1} \sum_{\mathrm{RTO}_1} p_i^j \\ &\quad - \mathrm{LSF}_{\mathrm{RTO}_1} P_{12} \\ &= \mathrm{LSF}_{\mathrm{RTO}_1} \sum_{\mathrm{RTO}_1} (p_i^j - \hat{p}_i^j) - \mathrm{LSF}_{\mathrm{RTO}_1} P_{12} = 0. \end{aligned} \quad (41)$$

■

Proposition 6: For a system with two RTOs, namely RTO_1 and RTO_2, the total directional interchange transaction from RTO_1 to RTO_2 and from RTO_2 to RTO_1 are P_{12} and P_{21}, respectively, as shown in Fig. 2. For any flowgate, the sum of the market flows in RTO_1 and RTO_2 plus the total tag impact of all interchange transactions is equal to the actual physical flow (dc flow) of the flowgate. In other words,

$$\begin{aligned} &\text{Tag Impact} + MF_{\mathrm{RTO}_1} + MF_{\mathrm{RTO}_2} \\ &\qquad = \sum_{\mathrm{RTO}_1 \cup \mathrm{RTO}_2} p_i^j(\mathrm{gsf}_i^j - \mathrm{LSF}_{sys}) \end{aligned} \quad (42)$$

where

$$MF_{\mathrm{RTO}_1} = \sum_{\mathrm{RTO}_1} \hat{p}_i^j(\mathrm{gsf}_i^j - \mathrm{LSF}_{\mathrm{RTO}_1}) \quad (43)$$

$$MF_{\mathrm{RTO}_2} = \sum_{\mathrm{RTO}_2} \hat{p}_i^j(\mathrm{gsf}_i^j - \mathrm{LSF}_{\mathrm{RTO}_2}) \quad (44)$$

$$\begin{aligned} \text{Tag Impact} &= (\mathrm{GSF}_{\mathrm{RTO}_1} - \mathrm{LSF}_{\mathrm{RTO}_2})P_{12} \\ &\quad + (\mathrm{GSF}_{\mathrm{RTO}_2} - \mathrm{LSF}_{\mathrm{RTO}_1})P_{21}. \end{aligned} \quad (45)$$

Proof: Proof is similar to the proof process of Proposition 5 and is omitted. ■

Section III shows that, in a single-RTO system containing only market impact, the market flow of RTO equals to the actual flow on any flowgate. In this section, we have also proved that in a system with multiple RTOs, the sum of market flows and

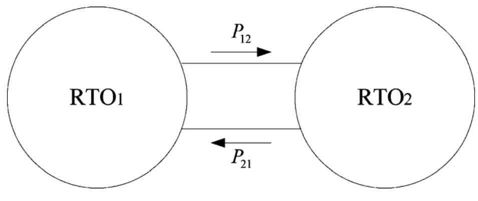

Fig. 2. Two RTOs with two-way interchange transactions.

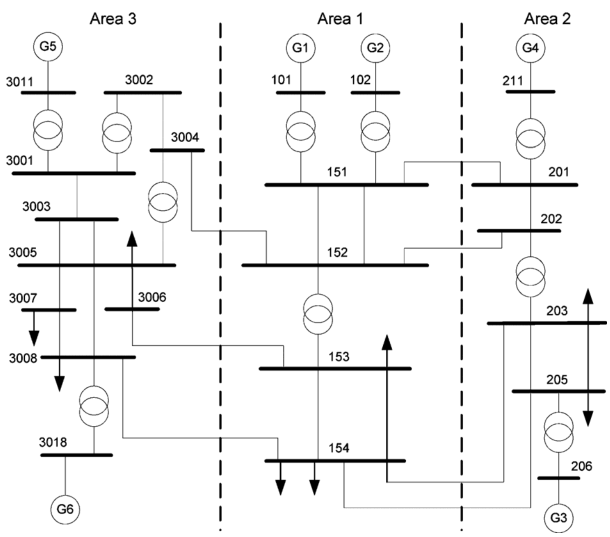

Fig. 3. Schematic diagram of the 23-bus test system.

tag impacts is also equal to the actual flow on the flowgate. It demonstrates the accuracy of market flow calculation methodology to quantify the market impact. As a result, it can be concluded that the single-RTO and multiple-RTO approaches yield the same solution. It should be mentioned that the same conclusion can also be derived for a system with both RTOs and non-RTOs.

V. Numerical Results

The market flow methodology is tested on a 23-bus system and a simplified Eastern Interconnection 7917-bus system with one and multiple RTOs, respectively. The detailed numerical results are described as follows.

A. Six-Generator 23-Bus System

A 23-bus system is used to demonstrate the results. The system is a test case in PSS/E as shown in Fig. 3 [23]. The system is divided into three CAs. It contains six units and eight loads. The total system generation is 3258.6 MW. A 500-kV tie line connecting bus 151 in CA_1 and bus 201 in CA_2 is chosen in the market flow analysis. It should be pointed out that the same methodology can also be applied to any constraints with contingency.

Two scenarios are considered in the analysis which involves either one RTO or multiple RTOs in the system.

1) Single RTO: Assuming that the whole system is a single RTO, Table I shows the system information and the CA LSFs. The transmission losses are included in the CA loads and the power balance is maintained in the system. Notice that CA_2 and

TABLE I
System Control Area Information

CA No.	L_i (MW)	P_i (MW)	LSF_i	Native (MW)	Transfer (MW)
1	1222.4	1500	−0.058968	1222.4	277.6
2	1530	1400	−0.088685	1400	0
3	506.2	358.6	−0.026782	358.6	0

TABLE II
Generator Impact Information

Unit No.	CA No.	gsf_i^j	p_i^j (MW)	Native Impact (MW)	Transfer Impact (MW)	UDS Impact (MW)
G1	1	0.413391	750	288.7058	65.1197	360.984
G2	1	0.413391	750	288.7058	65.1197	360.984
G3	2	−0.090999	800	−1.8512	0	−18.4623
G4	2	−0.341829	600	−151.886	0	−164.345
G5	3	0	258.6	6.9258	0	17.5644
G6	3	−0.041585	100	−1.4803	0	2.6336

CA_3 have the generation shortage, it can be calculated from (10) and (13) that

$$\mathrm{LSF}_{\mathrm{RTO}} = \frac{\sum_{i=1}^{3} \mathrm{LSF}_i L_i}{\sum_{i=1}^{3} L_i} = -0.067921 \tag{46}$$

$$\mathrm{LSF}'_{\mathrm{RTO}} = \frac{\sum_{i=2}^{3} \mathrm{LSF}_i (L_i - P_i)}{\sum_{i=2}^{3} (L_i - P_i)} = -0.055771. \tag{47}$$

Based on the CA generation and load information, the native and transfer portions of each CA can also be obtained and are shown in Table I. The native and transfer MWs of each generator in the system can be determined on a proportional basis from the CA native and transfer MWs information. Therefore, the corresponding native and transfer impacts of each generator on the line 151–201 can then be calculated. The native impact is calculated by the native MWs multiplied by the GLDFs with respect to the CA LSF. The transfer impact is calculated by the transfer MWs multiplied by the GLDFs with respect to $\mathrm{LSF}'_{\mathrm{RTO}}$. Table II shows the detailed generator impacts on the market flow separated by the native and transfer impacts. The market flow of RTO on the constraint is the sum of all the native and transfer impacts, which equals 559.36 MW.

For each unit, its UDS impact is calculated as the generator output multiplied by its GLDF with respect to $\mathrm{LSF}_{\mathrm{RTO}}$. Table II also gives the UDS impact by each unit. The UDS flow is the sum of the UDS impacts of all the units and is equal to 559.36 MW. It is exactly the same as the market flow, as well as the dc flow on the constraint. The analysis on other constraints under different generation and load patterns also yields the identical value between the market flow and the UDS flow.

2) Multiple RTOs: Assuming that the system contains two RTOs, where CA_1 forms RTO_1 and RTO_2 consists of CA_2 and CA_3, the generation and load information is the same as in the previous scenario for comparison purpose. There is energy interchange between the two RTOs for economic operation. The

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TABLE III
CA GENERATION AND LOAD AFTER ADJUSTMENTS

CA No.	RTO No.	L_i (MW)	P_i (MW)	LSF_i	Native (MW)	Transfer (MW)
1	1	1222.4	1222.4	−0.058968	1222.4	0
2	2	1321.4	1400	−0.088685	1321.4	78.6
3	2	437.2	358.6	−0.026782	358.6	0

TABLE IV
GENERATOR IMPACT INFORMATION

Unit No.	gsf_i^j	Native Portion (MW)	Transfer Portion (MW)	Native Impact (MW)	Transfer Impact (MW)
G1	0.413391	611.2	0	288.7058	0
G2	0.413391	611.2	0	288.7058	0
G3	−0.090999	755.1	44.9	−1.7473	−2.8838
G4	−0.341829	566.3	33.7	−143.3603	−10.6110
G5	0	258.6	0	6.9258	0
G6	−0.041585	100	0	−1.4803	0

total tagged transaction is 277.6 MW sourcing from RTO_1 and sinking into RTO_2 and its impact on the line 151–201 is treated as tag impact.

The adjusted CA generation and load are shown in Table III after the import and export adjustments due to the tagged transactions. It can be seen that only CA_3 in RTO_2 has generation shortage. Thus, for RTO_2 there is $\mathrm{LSF}'_{\mathrm{RTO}_2} = \mathrm{LSF}_3 = -0.026782$.

Table IV gives the detailed impact information for each generation. For example, for unit G3 in CA_2 of RTO_2, the unit's native impact is $755.1 * (-0.090999 + 0.088685) = -1.7473$ and the transfer impact is $44.9 * (-0.090999 + 0.026782) = -2.8838$. By summing up the native and transfer impacts, it can be calculated that RTO_1 and RTO_2 have the market flows of 577.412 and -153.157 MW, respectively.

For the tag impacts, we can calculate that $\mathrm{GSF}_{\mathrm{RTO}_1} = 0.4134$ and $\mathrm{LSF}_{\mathrm{RTO}_2} = -0.0733$. Therefore, the impact of 277.6 MW transactions from RTO_1 to RTO_2 on the line is $277.6 * (0.4134 + 0.0733) = 135.104$ MW. Finally, the total market flow plus the tag impact is $577.412 - 153.157 + 135.104 = 559.36$ MW which remains unchanged and is still equal to the actual line flow.

B. 1325-Generator 7917-Bus System

The market flow methodology is also tested on a 7917-bus system representing the simplified Eastern Interconnection. It is divided into 64 CAs (CA_1-CA_{64}). The system contains 10796 transmission lines and 2219 transformers. It has 1325 generators with the total generation output of 367.2 GW, where 27 generators have negative output totally of -3402.5 MW and are treated as loads in the market flow calculation. It also has 5590 loads with the total load amount of 360.7 GW, where 50 loads are negative totally of -2857.8 MW and are considered as generators in the calculation. The total transmission loss is 6533.9 MW and treated as load on a CA basis. A 345-kV tie line between bus 1715 in CA_{17} and bus 4458 in CA_{47} is chosen in the market flow analysis.

Similarly, two scenarios are considered in the analysis which contains either one RTO or multiple RTOs in the system.

TABLE V
RTO A'S MARKET FLOW BY CAS

CA No.	L_i (MW)	P_i (MW)	Native Portion (MW)	Transfer Portion (MW)	Native Impact (MW)	Transfer Impact (MW)
5	16316	16504.6	14632.9	0	−36.840	0
9	2319.4	2470.6	2109.9	80.5	−2.029	0.410
20	90.6	8110.6	82.4	7108.4	0	30.504
21	2060.2	3268.6	1874.2	1023.8	−0.051	5.770
22	1666.7	1550.6	1374.7	0	0.077	0
23	3082	2053.4	1820.5	0	−0.002	0
24	4423.2	3647.8	3234.1	0	0.068	0
25	6203	4617.1	4093.4	0	−0.202	0
26	8842.2	6693.6	5934.5	0	−0.638	0
27	4387	2468.4	2188.4	0	0.022	0
28	4257.4	4157.5	3686	0	−0.116	0
47	16236.7	16299	14450.6	0	67.724	0
50	15076.6	15332	13593.2	0	−2.879	0

1) Single RTO: Assume the system has a single RTO A which consists of 13 CAs (5, 9, 20–28, 47, and 50). Table V shows the RTO's CA information. The CA loads include the transmission losses within the CA. The RTO A's total generation and load are 87173.7 and 84961 MW, respectively. By summing up the export and import of the 13 CAs, we assume that the RTO's export and import are 9886 and 7673.3 MW, respectively. After the generation adjustment for export and load adjustment for import, the CA native and transfer portions can be calculated by comparing the adjusted generation with the adjusted load, as shown in Table V. The native and transfer impacts for each RTO unit can then be calculated and are summarized by CA. The RTO A's market flow on the constraint is 61.817 MW after summing up all of the native and transfer impacts.

For the nonmarket operating entities of the remaining 51 CAs, they are operating as individual BAs. There are tagged interchange transactions among these CAs, where the total export and import transactions are 15087.5 and 17300.2 MW, respectively. For any non-RTO, the parallel flow on a flowgate caused by nonmarket entity's generation serving the respective load is called the GTL impact. It can be calculated similar to the market flow methodology, except that each entity only contains one CA instead of multiple CAs like RTO. Therefore, there is only native impact (or GTL impact for non-market entity) and no transfer impact. It can be calculated that the GTL impacts of the 51 CAs are 216.307 MW. The tag impacts of the tags within the 51 CAs and between them and the RTO A are 13.782 and -4.993 MW, respectively. Therefore, the sum of the market flow of RTO A, the GTL impacts of nonmarket BAs and the tag impacts is $61.817 + 216.307 + 13.782 - 4.993 = 286.913$ MW, which is exactly the same as the total unit impact (or UDS flow) assuming the whole system is operating as a single BA. The line flows of dc and ac power flow solutions are 286.8 and 284.8 MW (measured at the sending end). It can be seen that the calculated unit impact result is very close to the dc flow solution. The minor difference is caused by the transmission losses which are not considered in the dc flow calculation.

It should be mentioned that, when more CAs join RTO and energy market expands, the previously tagged transactions among the RTO's CAs will disappear and become part of RTO's market flow. This will affect the export and import amount of

TABLE VI
RTO B's Market Flow by CAs

CA No.	L_i (MW)	P_i (MW)	Native Portion (MW)	Transfer Portion (MW)	Native Impact (MW)	Transfer Impact (MW)
10	1599.9	1590.4	1577.1	4	−0.047	−0.133
16	2105.2	2103	2075.2	15.5	−6.418	−0.392
17	2662.7	2259.4	2246.2	0	196.587	0
18	5356.7	5359.4	5280.5	47.7	1.092	−0.338
19	7590.4	7904.9	7482.4	376.4	−3.251	−4.608
48	6443.6	6444.7	6351.9	55.2	−2.887	−7.329
64	29248	28880.2	28711.6	0	14.668	0

RTO and therefore, the RTO's market flow and tag impacts on any constraint. However, since the whole interconnected system is balanced, the equivalence between the actual line flow and the sum of the market flows of all RTOs, the GTL impacts of all non-RTOs, and the total tag impact among them still exists. Based on this information, we will be able to identify the loop flow and its causes on any transmission constraint.

2) Multiple RTOs: Assuming that the system contains two RTOs, RTO A remains the same and RTO B consists of seven CAs (10, 16–19, 48, and 64). RTO B's generation and load information is shown in Table VI. RTO B's total generation and load are 54542 and 55006.6 MW, and its export and import are 318.3 and 782.9 MW, respectively.

For RTO B, the CA native and transfer portions together with the impacts are given in Table VI. RTO B's market flow on the constraint is 186.947 MW. It is calculated that the total GTL impact of the remaining 44 CAs is 31.614 MW and the impact of the tagged transactions is 6.535 MW. As a result, the sum of market flows of RTO A and B, the GTL impact of non-RTOs, and the tag impacts is $61.817 + 186.947 + 31.614 + 6.535 = 286.913$ MW. This is the same as the actual line flow. It can be seen that, regardless of the number of RTOs, the market operations will not cause unidentified loop flow issue as long as the market flow and tag impact are calculated in a proper manner.

VI. Conclusion

Market flow plays a major role in the interregional congestion management process for the market-based operating entities. In this paper, the assessment of market flow methodology together with its impact on the electricity market operations is described. The paper proposes that the market flow method produces the same result as the UDS flow due to the generation redispatch. The mathematical proof is given to show the equivalence of the market flow and the UDS flow. As a result, the 5-min look-ahead UDS flow change on a constraint due to the UDS binding will have the same effect on the change in the real-time market flow. This relationship is important so that RTO can control the UDS flow to effectively manage congestion by binding the constraint in UDS and at the same time, use market flow to accurately measure the impact of energy market operation on the constraint in the coordinated interregional congestion management process.

In addition, in an interconnected system consisting of multiple RTOs, the market flow of each RTO can be calculated independently in the same manner without causing any unaccounted flow problem. It proves that the sum of market flows and the total impact of all export and import schedules is equal to the actual physical flow on the flowgate, regardless of the number of RTOs. It demonstrates the accuracy of market flow calculation methodology, which is important to ensure power system reliability as well as equitable share of congestion cost among all entities in the interconnected system. The numerical results are described to verify.

Acknowledgment

The views expressed in this paper are solely those of the authors and do not necessarily represent those of MISO.

References

[1] *Joint Operating Agreement between the Midwest Independent Transmission System Operator, Inc. and PJM Interconnection, L.L.C.*, [Online]. Available: http://www.pjm.com/markets-and-operations/energy/~/media/documents/agreements/joa-complete.ashx

[2] *Joint Operating Agreement between the Midwest Independent Transmission System Operator, Inc. and Southwest Power Pool, Inc.*, [Online]. Available: http://www.spp.org/publications/2011-03-25_Midwest%20ISO_SPP%20JOA%20and%20CMP.pdf

[3] *North American Electric Reliability Corporation (NERC) Reliability Standards for the Bulk Electric Systems of North America*, [Online]. Available: http://www.nerc.com/docs/standards/rs/Reliability_Standards_Complete_Set.pdf

[4] T. T. Bowe, T. Mallinger, A. J. Rodriquez, and D. Zwergel, "PJM-MISO congestion management process," in *Proc. IEEE PES Power Syst. Conf. Expo.*, New York, NY, USA, Oct. 10–13, 2004, pp. 1582–1587.

[5] *Joint Operating Agreement Among and Between New York Independent System Operator Inc. (NYISO) and PJM Interconnection, L.L.C. (PJM)*, [Online]. Available: http://www.pjm.com/documents/agreements/~/media/documents/agreements/nyiso-pjm.ashx

[6] *New York Independent System Operator, Inc. and PJM Interconnection, L.L.C., Docket No. ER12-718-002; Third Jointly Submitted Market-to-Market Coordination Compliance Filing*, [Online]. Available: https://www.pjm.com/~/media/documents/ferc/2012-filings/20121022-er12-718-002_m2mcompliance.ashx

[7] *Sourhwest Power Pool, Inc. Docket No. ER12-1179-002, Federal Energy Regulatory Commission*, [Online]. Available: http://www.ferc.gov/whats-new/comm-meet/2013/032113/E-4.pdf

[8] J. G. Vlachogiannis and K. Y. Lee, "Determining generator contributions to transmission system using parallel vector evaluated particle swarm optimization," *IEEE Trans. Power Syst.*, vol. 20, no. 4, pp. 1765–1774, Nov. 2005.

[9] D. Kirschen, R. Allan, and G. Strbac, "Contributions of individual generators to loads and flows," *IEEE Trans. Power Syst.*, vol. 12, no. 1, pp. 52–60, Feb. 1997.

[10] G. Strbac, D. Kirschen, and S. Ahmed, "Allocating transmission system usage on the basis of traceable contributions of generators and loads to flows," *IEEE Trans. Power Syst.*, vol. 13, no. 2, pp. 527–534, May 1998.

[11] J. Bialek, "Tracing the flow of electricity," *Proc. Inst. Elect. Eng.—Gener. Transm. Distrib.*, vol. 143, no. 4, pp. 313–320, Jul. 1996.

[12] J. Bialek, "Topological generation and load distribution factors for supplement charge allocation in transmission open access," *IEEE Trans. Power Syst.*, vol. 12, no. 3, pp. 1185–1193, Aug. 1997.

[13] W.-C. Chu, B.-K. Chen, and C.-H. Liao, "Allocating the costs of reactive power purchased in an ancillary service market by modified Y-bus matrix method," *IEEE Trans. Power Syst.*, vol. 19, no. 1, pp. 174–179, Feb. 2004.

[14] M. Pantoš, G. Verbič, and F. Gubina, "Modified topological generation and load distribution factors," *IEEE Trans. Power Syst.*, vol. 20, no. 4, pp. 1998–2005, Nov. 2005.

[15] R. Shoults and L. D. Swift, "A comparison between circuits based methods for determining the contribution of each generator to load and line flows," in *Proc. Available Transfer Capability Conf.*, Jun. 1997, pp. 167–182.

[16] F. F. Wu, Y. Ni, and P. Wei, "Power transfer allocation for open access using graph theory—Fundamentals and applications in systems without loop flow," *IEEE Trans. Power Syst.*, vol. 15, no. 3, pp. 923–929, Aug. 2000.

[17] J. W. Bialek, S. Ziemianek, and R. Wallace, "A methodology for allocating transmission losses due to cross-border trades," *IEEE Trans. Power Syst.*, vol. 19, no. 3, pp. 1255–1262, Aug. 2004.

[18] M. S. S. Rao, S. A. Soman, P. Chitkara, R. K. Gajbhiye, N. Hemachandra, and B. L. Menezes, “Min-max fair power flow tracing for transmission system usage cost allocation: A large system perspective,” *IEEE Trans. Power Syst.*, vol. 25, no. 3, pp. 1457–1468, Aug. 2010.

[19] A. R. Abhyankar, S. A. Soman, and S. A. Khaparde, “Optimization approach to real power tracing: An application to transmission fixed cost allocation,” *IEEE Trans. Power Syst.*, vol. 21, no. 3, pp. 1350–1361, Aug. 2006.

[20] A. J. Conejo, F. D. Galiana, and I. Kockar, “Z-bus loss allocation,” *IEEE Trans. Power Syst.*, vol. 16, no. 1, pp. 105–110, Feb. 2001.

[21] A. J. Wood and B. F. Wollenberg, *Power Generation, Operation and Control*, 2nd ed. New York, NY, USA: Wiley, 1996.

[22] B. Stott, J. Jardim, and O. Alsaç, “DC power flow revisited,” *IEEE Trans. Power Syst.*, vol. 24, no. 3, pp. 1290–1300, Aug. 2009.

[23] “PSS/E Online Documentation,” Power Technologies Inc., Schenectady, NY, USA, 2010.

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