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Designing option FTRs for the lossy FTR system

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Abstract: The objective of this study is to upgrade the lossy financial transmission right (FTR) mechanism through the introduction of lossy option FTRs. The lossy FTR mechanism retains the potential to deliver superior risk hedging performance compared with the traditionally deployed lossless FTR mechanism since the locational marginal price decomposition is unnecessary for the settlement of lossy FTRs. The existing lossy FTR theory is, however, based on only obligation FTRs. Although obligation FTRs are the primary risk hedging instruments under any FTR mechanism, option FTRs can improve market competition by allowing flexible hedge positions. Therefore, an investigation is carried out to explore a lossy version of option FTRs. The configuration template and the settlement rule for lossy option FTRs are established. A suitable auction model is prepared for the issuance of lossy option FTRs. The lossy FTR auction formulation is carried out based on a novel representation of power flow equations. Detailed case studies are presented to show the practical utility of the proposed lossy FTR instrument.

Nomenclature

Indices

c	network contingency index
fr	index indicating the 'From' end bus of a line
i, j, n	bus indices
k	FTR index
l	line index
r	auction round index
s	line flow segment index
to	index indicating the 'To' end bus of a line
w	index representing a particular active–inactive combination of lossy option FTRs (0 for all active FTRs)

Numbers

η_{ftr}	total number of lossy FTRs present at a time
L	total number of transmission lines
N	number of network buses
R	number of rounds in an FTR auction
S	number of segments in each half of the piecewise linear loss curve

Variables

$\boldsymbol{\delta}$	$(N \times 1)$ bus voltage angle vector
χ	change in line loss to change in line flow ratio
$\boldsymbol{P}_{\text{fl}}$	$(L \times 1)$ vector representing terminal-averaged power flows over transmission lines
$\boldsymbol{\Delta P}_{\text{fl}}$	$(L \times 1)$ vector representing incremental changes of line flows from a base case
$\boldsymbol{P}_{\text{rsg},\,s}$	$(L \times 1)$ vector representing absolute values of line flow components corresponding to the sth segment on the right half of the piecewise linear loss curve
$\boldsymbol{P}_{\text{lsg},\,s}$	$(L \times 1)$ vector representing absolute values of line flow components corresponding to the sth segment on the left half of the piecewise linear loss curve
$\boldsymbol{P}_{\text{inj}}$	$(N \times 1)$ vector representing actual nodal active power injections
$\tilde{\boldsymbol{P}}_{\text{inj}}$	$(N \times 1)$ vector representing lossless nodal power injections
$\boldsymbol{\Delta}\tilde{\boldsymbol{P}}_{\text{inj}}$	$(N \times 1)$ vector representing incremental changes in lossless nodal power injections from a base case
$P_{\text{fir}}^{\text{fo}}$	variable indicating the involuntary loss component assigned to a lossy FTR in the day-ahead market
$\boldsymbol{P}_{\text{loss}}$	$(L \times 1)$ vector representing the line losses
$\boldsymbol{\Delta P}_{\text{loss}}$	$(L \times 1)$ vector representing incremental changes of line losses from a base case
$\boldsymbol{P}_{\text{slack}}$	$(N \times 1)$ slack power injection vector
$\boldsymbol{p}_{\text{fo}}$	$(N \times 1)$ vector representing the involuntary point of loss contribution of a lossy FTR
$\boldsymbol{X}_{\text{fir}}^{\text{vo}}$	$(\eta_{\text{ftr}} \times 1)$ vector representing the cleared amounts toward voluntary loss components of lossy FTR bids
$\boldsymbol{X}_{\text{ftr}}$	$(\eta_{\text{ftr}} \times 1)$ vector representing the cleared amounts toward transportation components of lossy FTR bids
$\boldsymbol{z}_{\sigma}$	$(\eta_{\text{ftr}} \times 1)$ vector representing the cleared LCFs toward lossy FTR bids against voluntary loss contribution specifications
u	variable indicating the status of a lossy FTR (1 for active and 0 for inactive)

Fixed parameters/constants

$\boldsymbol{\Psi}$	$(L \times N)$ line flow sensitivity matrix corresponding to the lossless DCPF approximation
β_{fir}	price quoted for the voluntary loss component in a lossy FTR bid
β_{ftr}	price quoted for the transportation component in a lossy FTR bid
ξ	reactance-to-impedance ratio of a transmission line
$\boldsymbol{A}_{\text{fir}}$	$(N \times \eta_{\text{ftr}})$ incidence matrix between the network buses and voluntary loss components of lossy FTRs
$\boldsymbol{A}_{\text{ftr}}$	$(N \times \eta_{\text{ftr}})$ incidence matrix between the network buses and transportation components of lossy FTRs
$\boldsymbol{A}_{\text{tl}}$	$(N \times L)$ element-node incidence matrix
b	series susceptance (capacitive) of a transmission line (in pu)
$\boldsymbol{I}_x$	$(x \times x)$ identity matrix
m_s	absolute slope of the sth segment on any half of the piecewise linear loss curve
P_{B}	base MVA

$P_{\text{fir}}^{\text{vo}}$ MW amount of the voluntary loss component of a lossy FTR

P_{ftr} MW amount of the transportation component of a lossy FTR

$\boldsymbol{p}_{\text{vo}}$ $(N \times 1)$ vector representing the voluntarily specified point of loss contribution of a lossy FTR

$\mathbf{0}_x$ $(x \times 1)$ vector of all zeros

$(\,.\,)_{\max}$ specified maximum limit of the variable (.)

$(\,.\,)_{\min}$ specified minimum limit of the variable (.)

Market results

λ_n day-ahead LMP at node n

$\Delta\lambda_{j,\,i}$ day-ahead LMP difference between node j and node i

$\boldsymbol{\rho}_{\text{ftr}}$ $(\eta_{\text{bid}} \times 1)$ vector representing auction clearing prices for the transportation components of lossy FTR bids

$\boldsymbol{\rho}_{\text{fir}}$ $(\eta_{\text{bid}} \times 1)$ vector representing auction clearing prices for the loss components of lossy FTR bids

$(\,.\,)^*$ optimal solution of a variable

1 Introduction

Efficient utilisation of the network capacity is of prime concern in any electricity market. One important consideration to be made while releasing the network capacity in the market is to maximise the chance of forward contracts. There should be more encouragement for longer-term power contracts, which are necessary to maintain the proper competitive environment in the electricity market [1]. Having separate marketplaces for clearing power contracts of different terms often require discounting the network capacity improvement performed by counterflows [2]. This is because of the uncertainty involved in the actual execution of a forward contract. In addition, since it is unreasonable to prepare a financially binding schedule in the long term, the network capacity can be blocked by spurious forward contracts so as to raise the market power in the spot market by turning down genuine forward contracts [3]. Therefore, modern electricity markets operate a single marketplace on daily basis to clear all the power contracts simultaneously in the form of financially binding schedules based on the principle of locational marginal pricing [4–7]. The long-term and medium-term forward contracts are assisted with financial transmission rights (FTRs) to overcome the spot price risk that arises in the form of network access charges levied on bilateral transactions in the day-ahead market (DAM). The FTR is basically a financial instrument that generates a stream of revenue for its owner based on the DAM price outcome. By holding an FTR of appropriate configuration, a market player receives a source to fund its network access payment in the DAM. Effectively, FTRs enable forward contracts to pay network access charges in advance without endowing those authorities to block the network capacity. Apart from risk hedging, FTRs can also be issued to speculators as market derivatives to invest in [8, 9]. Such a provision, in effect, helps in keeping the FTR market more active.

In principle, FTRs should be settled directly according to locational marginal prices (LMPs) [3, 10–14]. At the same time, FTRs are preferred to be point-to-point (PtP) balanced [10, 11]. It is possible to satisfy both the requirements by evaluating LMPs without considering network losses. However, in most of the advanced electricity markets, network losses are duly addressed in the LMP calculation itself [4–7]. Under such a situation, the FTR system cannot be implemented with only PtP balanced FTRs if the direct LMP-based settlement is intended. This is because the PtP balanced FTRs can never ensure simultaneous feasibility over a lossy network model. The simultaneous feasibility test (SFT) is a necessary mechanism for the revenue adequate issuance of FTRs. To resolve the conflict between the requirements of PtP balanced configuration and direct LMP-based settlement, the principle of LMP decomposition is followed in present power markets [15]. The LMP decomposition is basically an attempt to separate out the effects of congestion and loss on LMPs. The FTR owners are paid only according to the congestion components of LMPs [16–19]. The particular settlement rule enables the utilisation of a lossless network model for conducting the SFT of FTRs. By performing the LMP decomposition, FTRs can still be issued only in the PtP balanced configuration; however, the recovery of the DAM network access charge is to be compromised with. Unfortunately, the loss component of an LMP difference is not always negligible [20]. Even in the Pennsylvania, New Jersey, Maryland market, the loss collection is comparable with the congestion collection [21]. Moreover, the ratio of congestion and loss prices within an LMP difference is variable. Therefore, though preserving the PtP balanced configuration makes the utilisation and issuance of FTRs easier, there remains a gap in hedging the spot price risk for forward contracts. In [22], a loss hedging FTR concept was proposed to provide separate price guards against the loss components of LMP differences. However, issuance of loss hedging FTRs requires the information of linearised loss parameters from the DAM. This, in turn, makes the implementation of loss hedging FTRs difficult since the linearised loss parameters are not stable quantities.

Instead of modifying the price reference for the FTR settlement, an alternative approach can be to compromise with the FTR configuration. In the particular line, a concept of lossy FTRs was proposed in [23, 24]. Only the obligation version of the lossy FTR is presented in the literature. The lossy obligation FTR is, basically, a point-to-point unbalanced FTR, which is equivalent to the portfolio of a PtP balanced FTR and a financial injection right (FIR) at the source bus. The FIR is basically an unbalanced FTR of the injection type [24]. Thus, the lossy obligation FTR can be decomposed into a transportation component (indicated by a PtP balanced FTR) and a loss component (indicated by an FIR). The transportation component can perfectly hedge the price risk for a bilateral power transaction. The price risk generated by the loss component can be circumvented by self-scheduling power generation of the equal amount at the source bus while recovering the cost of the particular power generation from the FTR auction. In [22], the concept of a dummy bilateral transaction based on a floating contract has been suggested to help manage the matching active power generation for the FIR concerned. It is also verified in [24] that there exists sufficient scope for issuing lossy FTRs in practice. Thus, the lossy FTRs retain the potential to generate a better risk-free environment for forward contracts.

This paper contributes toward developing the theory of lossy option FTRs. As mentioned previously, the lossy FTR theory that is available in the literature is made by considering only the obligation form. There can, however, be market players who have the genuine requirement of option FTRs. By keeping the particular fact in view, the lossy FTR mechanism is upgraded with the introduction of lossy option FTRs. In specific, the following issues are addressed:

i. Designing the template of lossy option FTRs.
ii. Modelling the network capacity for carrying out the SFT.
iii. Developing the auction model for the issuance of lossy option FTRs.

Unlike lossy obligation FTRs, it may not be possible to design lossy option FTRs as foolproof price guards for forward contracts. Therefore, the lossy option FTR is not presented as a better alternative to the conventional PtP balanced option FTR. However, since obligation FTRs are much more dominant in the market compared with option FTRs [25], the lossy FTR mechanism with the only obligation FTRs may be able to generate a more favourable market environment for forward contracts. The lossy option FTR concept is introduced to further improve the scenario.

The rest of this paper is organised as follows. The format and the settlement rule of the lossy option FTR tool proposed are explained in Section 2. The power flow modelling for the revenue adequate issuance of lossy option FTRs is discussed in Section 3. The formulation of the lossy FTR auction problem with both obligation and option requests is presented in Section 4. Section 5 presents a case study on the risk hedging performance of the proposed lossy option FTRs. Finally, this paper is concluded in Section 6.

2 Principle of lossy option FTRs

The generalised lossy FTR template that can be thought of should include a transportation component, a voluntary loss component and an involuntary loss component. A lossy FTR is qualified as active or inactive depending on the active–inactive status of its transportation component. The loss components of a lossy FTR always remain active. Therefore, the target payment toward a lossy FTR at a particular hour is given by the following equation:

$$\mathrm{TP} = \left\{ u\Delta\lambda_{j,\,i} - \sum_{n=1}^{N} (\sigma_{\mathrm{vo}} p_{\mathrm{vo},\,n}\lambda_n + \sigma_{\mathrm{fo}} p_{\mathrm{fo},\,n}\lambda_n) \right\} P_{\mathrm{ftr}} \tag{1}$$

where

$$\sigma_{\mathrm{vo}} = \frac{P_{\mathrm{fir}}^{\mathrm{vo}}}{P_{\mathrm{ftr}}} \tag{2}$$

$$\sigma_{\mathrm{fo}} = \frac{P_{\mathrm{fir}}^{\mathrm{fo}}}{P_{\mathrm{ftr}}}. \tag{3}$$

Here, buses i and j are considered to be the source and sink buses, respectively, of the transportation component. Symbols σ_{vo} and σ_{fo} represent the voluntary and involuntary loss contribution factors (LCFs), respectively, of the particular lossy FTR. The FIR that indicates the voluntary or involuntary loss contribution of the given lossy FTR may be concentrated at a particular bus or can be distributed over several buses in a certain proportion. Therefore, the point of loss contribution (PLC) is, in general, shown by a distribution vector $\boldsymbol{p}$. In the case of the concentrated loss contribution, there should be only one non-zero entry (that is 1) in $\boldsymbol{p}$ corresponding to the specific bus at which the entire loss contribution is made.

Similarly to conventional option FTRs, a lossy option FTR becomes active or inactive depending on the direction of congestion over its transportation path. The positive LMP difference makes the FTR active. On the other hand, the FTR goes into the inactive state on the occurrence of the negative LMP difference. As usual, a lossy obligation FTR always remains active. The involuntary loss components are enforced by the independent system operator (ISO) depending on the set of inactive lossy FTRs in the DAM. The loss component that is involuntarily assigned to a lossy FTR may vary from one hour to another hour. Only inactive lossy FTRs have the liability to hold additional loss components as per the hourly condition of the day-ahead energy market. Thus, the involuntary loss component assigned to a lossy obligation FTR is always zero. The voluntary loss component is assigned according to the willingness of the FTR owner to contribute toward the network loss in the SFT. The particular loss component remains fixed over the entire validity period of the respective lossy FTR. A lossy FTR is auctioned or traded only according to its transportation and voluntary loss components. The loss component that is voluntarily accepted by an FTR owner is payable in the auction. The PLC of the voluntary loss component can be chosen to be the same as the source bus of the corresponding transportation component. Thus, the liability of the voluntary loss component can be counterbalanced through an excess generation contract at the source bus of the actual power transaction to be made [24]. In its active state, the transportation component of a lossy option FTR completely recovers the network access charge of a power transaction of the same or less MW amount on the same path. When the FTR becomes inactive, it is assigned an extra loss component. As a result, some downside risk [14] still exists with the lossy option FTR. However, it is expected that the downside risk associated with a lossy option FTR would be much lower than that for a lossy obligation FTR since the value of an LCF should be very low.

The SFT of lossy FTRs involves explicit verifications of two sets of network constraints such as:

i. nodal power balance constraints and
ii. line flow limit constraints.

In the case of the traditional FTR system, the explicit treatment of the nodal power balance constraints is not necessary since those are automatically satisfied because of issuing only balanced FTRs based on a lossless SFT. For lossy FTRs, the loss components should be assigned in a way so that the line losses, as per the loss model considered in DAM, can be compensated. In the presence of lossy option FTRs, the nodal injection profile corresponding to the physical equivalents of transportation components that are accountable in DAM becomes variable. It is usually difficult to use a fixed set of loss components for compensating line losses caused by different active groups of transportation components. As a result, some variable loss components are to be involuntarily assigned. The variable loss components can be visualised as the slack power injections in the power flow analysis underlying the SFT. The respective slack power injections should be necessary only when some of the lossy option FTRs are inactive. An appropriate slack power injection model is required for conveniently expressing line flows as the functions of nodal injections caused by the physical equivalents of fixed (i.e. voluntary) loss components and active transportation components of existing FTRs. To determine the fractions of aforementioned nodal slack power injections to be assigned toward the variable loss component of an inactive lossy FTR, the following numbers are to be evaluated:

i. The fraction of a line loss variation that is compensated via the slack power injection at a particular bus.
ii. The fraction of a line flow variation that is caused by a particular inactive lossy FTR.

All the flow and loss variations are to be assessed with respect to the base case indicated by the active status of all the lossy FTRs. It may further be assumed that inactive lossy option FTRs contribute to the line loss variation in the same proportion as they contribute to the line flow variation. The share of the variable loss component of an inactive lossy option FTR in the slack power injection at a node is obtained by combining above two fractions for each line followed by the addition of related loss quantities over all the transmission lines.

3 Power flow modelling in SFT

The power flow formulation employed to conduct the SFT is based on the concept of lossless active power injections. To define lossless active power injections, the nodal power balance equations should, first, be written down in the following form [24]:

$$\boldsymbol{P}_{\mathrm{inj}} = \boldsymbol{A}_{\mathrm{tl}}\boldsymbol{P}_{\mathrm{fl}} + 0.5|\boldsymbol{A}_{\mathrm{tl}}|\boldsymbol{P}_{\mathrm{loss}}. \tag{4}$$

The lossless active power injection vector is given by the following equation:

$$\tilde{\boldsymbol{P}}_{\mathrm{inj}} = \boldsymbol{P}_{\mathrm{inj}} - 0.5|\boldsymbol{A}_{\mathrm{tl}}|\boldsymbol{P}_{\mathrm{loss}}. \tag{5}$$

From (4) and (5)

$$\tilde{\boldsymbol{P}}_{\mathrm{inj}} = \boldsymbol{A}_{\mathrm{tl}}\boldsymbol{P}_{\mathrm{fl}}. \tag{6}$$

The elements of vector $\tilde{\boldsymbol{P}}_{\mathrm{inj}}$ maintain zero sum. This can be easily proven based on the fact that the summation of the rows of the matrix $\boldsymbol{A}_{\mathrm{tl}}$ leads to a zero vector. Hence, elements of $\tilde{\boldsymbol{P}}_{\mathrm{inj}}$ are referred to as lossless power injections. By assuming fixed one per unit voltage at each bus along with DC power flow (DCPF) approximation of trigonometric quantities, the terminal-averaged power flow over a transmission line can be expressed as follows [24]:

$$P_{\mathrm{fl},\,l} = P_{\mathrm{B}} b_l \sin(\delta_{\mathrm{to}(l)} - \delta_{\mathrm{fr}(l)}) \simeq P_{\mathrm{B}} b_l (\delta_{\mathrm{to}(l)} - \delta_{\mathrm{fr}(l)}). \tag{7}$$

Here, all the power quantities are expressed in the actual unit. Similarly to the relationship between line flows and actual nodal power injections for a lossless system [26], the following relation can be easily found between terminal-averaged line flows and lossless nodal power injections for a lossy system:

$$\boldsymbol{P}_{\text{fl}} = \underbrace{\hat{\boldsymbol{\xi}}^{2}\boldsymbol{\Psi}}_{\tilde{\boldsymbol{\Psi}}}\tilde{\boldsymbol{P}}_{\text{inj}} \tag{8}$$

where $\hat{\boldsymbol{\xi}}$ is an $(L \times L)$ diagonal matrix with $\hat{\xi}_{l,\,l} = \xi_l$. The matrix $\tilde{\boldsymbol{\Psi}}$ can be referred as the DCPF-based line flow sensitivity matrix for a lossy network. The active power loss in a line can be directly expressed as a function of the respective line flow. That is

$$P_{\text{loss},\,l} = f^{\text{lf}}_{\text{loss},\,l}(P_{\text{fl},\,l})\,. \tag{9}$$

The derivation of the function $f^{\text{lf}}_{\text{loss},\,l}(.)$ and its approximation are discussed in [24].

To perform the SFT of a given set of FTRs, a power flow analysis needs to be carried out with the equivalent active power injection profile corresponding to each possible FTR combination (in terms of active and inactive statuses). The combination in which all the FTRs remain active is recognised as the base combination. The power flow quantities corresponding to the wth FTR combination are represented by '(w)' in superscripts.

The net nodal injection vector corresponding to a particular status combination of lossy FTRs can be derived as follows:

$$\boldsymbol{P}^{(w)}_{\text{inj}} = \boldsymbol{A}_{\text{ftr}}\hat{\boldsymbol{u}}^{(w)}\boldsymbol{P}_{\text{ftr}} + \boldsymbol{A}_{\text{fir}}\boldsymbol{P}^{\text{vo}}_{\text{fir}} + \boldsymbol{P}^{(w)}_{\text{slack}} \tag{10}$$

where

$$\boldsymbol{P}_{\text{ftr}} = \begin{bmatrix} P_{\text{ftr},\,1} & P_{\text{ftr},\,2} & \cdots & P_{\text{ftr},\,\eta_{\text{ftr}}} \end{bmatrix}^{\text{T}} \tag{11}$$

$$\boldsymbol{P}^{\text{vo}}_{\text{fir}} = \begin{bmatrix} P^{\text{vo}}_{\text{fir},\,1} & P^{\text{vo}}_{\text{fir},\,2} & \cdots & P^{\text{vo}}_{\text{fir},\,\eta_{\text{ftr}}} \end{bmatrix}^{\text{T}}. \tag{12}$$

Here, the $(\eta_{\text{ftr}} \times \eta_{\text{ftr}})$ diagonal matrix $\hat{\boldsymbol{u}}$ is obtained by placing u_k at the kth diagonal position. Matrix $\boldsymbol{A}_{\text{ftr}}$ is constructed in the same way as $\boldsymbol{A}_{\text{tl}}$ is constructed (i.e. '$+1$' for the source and '-1' for the sink). The other matrix $\boldsymbol{A}_{\text{fir}}$ is obtained just by juxtaposing the PLC vectors of the respective fixed loss components. As mentioned previously, the variable loss components assigned to lossy FTRs are regarded as slack power injections to the network. The following slack power injection model is chosen:

$$\begin{aligned} \boldsymbol{P}^{(w)}_{\text{slack}} &= \boldsymbol{0}_N \text{ if } w = 0 \\ &= 0.5|\boldsymbol{A}_{\text{tl}}|\boldsymbol{\Delta P}^{(w)}_{\text{loss}} \text{ otherwise} \end{aligned} \tag{13}$$

where

$$\boldsymbol{\Delta P}^{(w)}_{\text{loss}} = \boldsymbol{P}^{(w)}_{\text{loss}} - \boldsymbol{P}^{(0)}_{\text{loss}}\,. \tag{14}$$

For the base FTR combination, no slack power injection is intended since there should not be any variable loss component assignment to an active lossy FTR. The slack power injection patterns for other FTR combinations are chosen in a way so that the verification of line flow limits as well as the calculation of variable loss components can be simplified.

The lossless active power injection vector corresponding to the base FTR combination is given by the following equation:

$$\tilde{\boldsymbol{P}}^{(0)}_{\text{inj}} = \boldsymbol{A}_{\text{ftr}}\boldsymbol{P}_{\text{ftr}} + \boldsymbol{A}_{\text{fir}}\boldsymbol{P}^{\text{vo}}_{\text{fir}} - 0.5|\boldsymbol{A}_{\text{tl}}|\boldsymbol{P}^{(0)}_{\text{loss}} \tag{15}$$

For the given lossy FTRs to be simultaneously feasible in the base combination, there must exist a solution for $\tilde{\boldsymbol{P}}^{(0)}_{\text{inj}}$ as per the above expression while satisfying (8) and (9). That is, there must exist a system state for which $\tilde{\boldsymbol{P}}^{(0)}_{\text{inj}}$, as per (15), would balance line flows at each node. In the case of other FTR combinations, the nodal power balance is always maintained by means of slack power injections.

To verify line flow limits, the line flow vector is also to be decomposed as follows:

$$\boldsymbol{P}^{(w)}_{\text{fl}} = \boldsymbol{P}^{(0)}_{\text{fl}} + \Delta\boldsymbol{P}^{(w)}_{\text{fl}} \tag{16}$$

where

$$\boldsymbol{\Delta P}^{(w)}_{\text{fl}} = \tilde{\boldsymbol{\Psi}}\boldsymbol{\Delta}\tilde{\boldsymbol{P}}^{(w)}_{\text{inj}} \tag{17}$$

$$\boldsymbol{\Delta}\tilde{\boldsymbol{P}}^{(w)}_{\text{inj}} = \boldsymbol{A}_{\text{ftr}}\big(\hat{\boldsymbol{u}}^{(w)} - \boldsymbol{I}_{\eta_{\text{ftr}}}\big)\boldsymbol{P}_{\text{ftr}}\,. \tag{18}$$

After replacing (17) and (18) into (16), the following expression is obtained:

$$\boldsymbol{P}^{(w)}_{\text{fl}} = \boldsymbol{P}^{(0)}_{\text{fl}} + \underbrace{\tilde{\boldsymbol{\Psi}}\boldsymbol{A}_{\text{ftr}}}_{\boldsymbol{\Upsilon}_{\text{ftr}}}\big(\hat{\boldsymbol{u}}^{(w)} - \boldsymbol{I}_{\eta_{\text{ftr}}}\big)\boldsymbol{P}_{\text{ftr}}\,. \tag{19}$$

Therefore, revenue adequate lossy FTRs should satisfy the following conditions:

$$\boldsymbol{P}^{(0)}_{\text{fl}} + \boldsymbol{\Upsilon}_{\text{ftr}}\big(\hat{\boldsymbol{u}}^{(w)} - \boldsymbol{I}_{\eta_{\text{ftr}}}\big)\boldsymbol{P}_{\text{ftr}} \le \boldsymbol{P}_{\text{fl, max}}\ \forall w \tag{20}$$

$$\boldsymbol{P}^{(0)}_{\text{fl}} + \boldsymbol{\Upsilon}_{\text{ftr}}\big(\hat{\boldsymbol{u}}^{(w)} - \boldsymbol{I}_{\eta_{\text{ftr}}}\big)\boldsymbol{P}_{\text{ftr}} \ge -\boldsymbol{P}_{\text{fl, max}}\ \forall w\,. \tag{21}$$

On the basis of the same constraint reduction technique as was shown in [27], conditions (20) and (21) can be simplified in the form of only $2L$ equations as are shown below:

$$\boldsymbol{P}^{(0)}_{\text{fl}} + \acute{\boldsymbol{\Upsilon}}_{\text{ftr}}\boldsymbol{P}_{\text{ftr}} \le \boldsymbol{P}_{\text{fl, max}} \tag{22}$$

$$\boldsymbol{P}^{(0)}_{\text{fl}} + \grave{\boldsymbol{\Upsilon}}_{\text{ftr}}\boldsymbol{P}_{\text{ftr}} \ge -\boldsymbol{P}_{\text{fl, max}} \tag{23}$$

where elements of the matrices $\acute{\boldsymbol{\Upsilon}}_{\text{ftr}}$ and $\grave{\boldsymbol{\Upsilon}}_{\text{ftr}}$ are given by $\acute{\Upsilon}_{\text{ftr},\,l,\,k} = \max(0, \Upsilon_{\text{ftr},\,l,\,k})$ and $\grave{\Upsilon}_{\text{ftr},\,l,\,k} = \min(0, \Upsilon_{\text{ftr},\,l,\,k})$ for a lossy option FTR. For an obligation FTR, $\acute{\Upsilon}_{\text{ftr},\,l,\,k} = \grave{\Upsilon}_{\text{ftr},\,l,\,k} = 0$. It is to be noted that the particular simplification of line flow limit verification could be possible only because of the chosen slack power injection model.

The final task is to decompose the slack power injection vector into FIRs to be assigned to different lossy FTRs as involuntary loss components. The incremental line losses caused by the inactiveness of certain lossy FTRs can be expressed as follows:

$$\Delta\boldsymbol{P}^{(w)}_{\text{loss}} = \hat{\boldsymbol{\chi}}^{(w)}\boldsymbol{\Upsilon}_{\text{ftr}}\big(\hat{\boldsymbol{u}}^{(w)} - \boldsymbol{I}_{\eta_{\text{ftr}}}\big)\boldsymbol{P}_{\text{ftr}}\,. \tag{24}$$

The matrix $\hat{\boldsymbol{\chi}}$ contains χ_l variables in the diagonal. For a given FTR combination, elements of $\hat{\boldsymbol{\chi}}$ can be directly determined based on (9), (14), (17) and (18). After replacing (24) into (13), the following relationship is obtained:

$$\boldsymbol{P}^{(w)}_{\text{slack}} = \boldsymbol{\Gamma}^{(w)}\boldsymbol{P}_{\text{ftr}} \tag{25}$$

where

$$\boldsymbol{\Gamma}^{(w)} = 0.5|\boldsymbol{A}_{\text{tl}}|\hat{\boldsymbol{\chi}}^{(w)}\boldsymbol{\Upsilon}_{\text{ftr}}\big(\hat{\boldsymbol{u}}^{(w)} - \boldsymbol{I}_{\eta_{\text{ftr}}}\big)\,. \tag{26}$$

The matrix $\boldsymbol{\Gamma}^{(w)}$ can be partitioned as follows:

$$\boldsymbol{\Gamma}^{(w)} = \begin{bmatrix} \boldsymbol{\Gamma}^{(w)}_1 & \boldsymbol{\Gamma}^{(w)}_2 & \cdots & \boldsymbol{\Gamma}^{(w)}_{\eta_{\text{ftr}}} \end{bmatrix}. \tag{27}$$

The kth column of matrix $\boldsymbol{\Gamma}^{(w)}$ defines the share of the kth lossy FTR into the slack power injection vector. Therefore, the LCF and PLC of the involuntary component to be assigned to the kth lossy FTR can be derived from the following equations:

$$\sigma^{(w)}_{\text{fo},\,k} = \boldsymbol{1}^{\text{T}}_N\boldsymbol{\Gamma}^{(w)}_k \tag{28}$$

$$\boldsymbol{p}_{\mathrm{fo},\,k}^{(w)} = \frac{\boldsymbol{\Gamma}_k^{(w)}}{\sigma_{\mathrm{fo},\,k}^{(w)}}. \tag{29}$$

The variability in the involuntary loss component parameters takes place because of the variabilities in $\widehat{\boldsymbol{u}}$ and $\widehat{\boldsymbol{\chi}}$. In the case of an active FTR, the LCF for the involuntary loss component automatically takes zero value; therefore, no further calculation of PLC is necessary.

4 Lossy FTR auction model for the issuance of option FTRs

The basic SFT framework for the lossy FTR mechanism with option FTRs is established in the previous section. The issuance of lossy FTRs in an auction should ensure the SFT compliance of FTRs available after the auction. The lossy FTR auction model with only obligation FTRs is presented in [24]. The network (i.e. simultaneous feasibility) constraints of the particular auction model need to be updated because of the incorporation of lossy option FTRs. For the sake of completeness, the other elements of the lossy FTR auction model are also briefly reviewed. Similarly to [24], the lossy FTR auction model is prepared by using the DC optimal power flow formulation with the piecewise linear loss approximation. Without losing generality, the lossy FTR auction formulation is presented by considering only purchase bids and with no existing FTR. Sale offers or retainment of already issued FTRs can be easily accommodated within this formulation through some equivalent representations. For the sake of simplicity, only uncontrolled AC lines are considered in the network.

4.1 Objective function

In a lossy FTR auction, each participant needs to provide separate price quotes for the transportation and voluntary loss components in its lossy FTR request portfolio. The prices quoted indicate the maximum and minimum prices that the concerned market player is willing to pay and receive for the transportation component and the loss component, respectively. The auction is cleared by minimising the social cost function according to the lossy FTR bids. Mathematically, the problem objective can be formulated as

$$\text{minimise}\underbrace{\left\{\sum_{k=1}^{\eta_{\mathrm{ftr}}}\left(\beta_{\mathrm{fir},\,k}X_{\mathrm{fir},\,k}^{\mathrm{vo}} - \beta_{\mathrm{ftr},\,k}X_{\mathrm{ftr},\,k}\right)\right\}}_{f(\boldsymbol{X}_{\mathrm{ftr}},\,\boldsymbol{X}_{\mathrm{fir}})}. \tag{30}$$

A sale offer can equivalently be represented as surrendering the original FTR along with submitting a bid for the fresh purchase of an FTR with the same configuration [14]. Retainment of an already issued FTR can be visualised as a sale offer with a very high price. An FTR can be partially offered for sale by splitting it into two FTRs.

4.2 Bidders' constraints

The bidder of a lossy FTR needs to specify the required transportation quantity as well as the voluntary loss contribution that it can make. The request for the transportation quantity should be made with a specific MW number. With regard to the loss component, the market player may specify an LCF range that is acceptable to it. This is in accord with the Design A-1 of [23]. Thus, the lossy FTR issuance is subjected to the following bid limit constraints:

$$\boldsymbol{q}_1 : \boldsymbol{X}_{\mathrm{fir}} - \hat{\boldsymbol{z}}_{\sigma,\,\max}\boldsymbol{X}_{\mathrm{ftr}} \le \boldsymbol{0}_{\eta_{\mathrm{ftr}}} \tag{31}$$

$$\boldsymbol{q}_2 : -\boldsymbol{X}_{\mathrm{fir}} + \hat{\boldsymbol{z}}_{\sigma,\,\min}\boldsymbol{X}_{\mathrm{ftr}} \le \boldsymbol{0}_{\eta_{\mathrm{ftr}}} \tag{32}$$

$$\boldsymbol{q}_3 : \boldsymbol{X}_{\mathrm{ftr}} - \boldsymbol{X}_{\mathrm{ftr},\,\max} \le \boldsymbol{0}_{\eta_{\mathrm{ftr}}} \tag{33}$$

$$\boldsymbol{q}_4 : -\boldsymbol{X}_{\mathrm{ftr}} \le \boldsymbol{0}_{\eta_{\mathrm{ftr}}}. \tag{34}$$

Matrix $\hat{\boldsymbol{z}}_{\sigma,\,\max}$ and matrix $\hat{\boldsymbol{z}}_{\sigma,\,\min}$ are $(\eta_{\mathrm{ftr}} \times \eta_{\mathrm{ftr}})$ diagonal matrices with $\hat{z}_{\sigma,\,(.),\,k,\,k} = z_{\sigma,\,(.),\,k}$. Typically, in a regular purchase bid, the minimum LCF limit specified is expected to be zero. In the case of the equivalent purchase bid for a sale offer, the LCF must be set to a fixed value (which is equal to the LCF of the original lossy FTR). This is, in effect, equivalent to setting the maximum and minimum LCF limits equal.

4.3 Power balance constraints

As mentioned previously, the nodal power balance constraints should be enforced only for the base FTR combination. In addition, the nodal power balance condition is, typically, not very strictly considered to represent security constraints (i.e. constraints pertaining to network contingencies) in the dispatch scheduling. Therefore, nodal power balance constraints corresponding to a post-contingency network topology are not required. The complete set of power balance constraints to be considered is presented below. Notations for power flow quantities should be interpreted in the same way as those are stated in Section 3

$$\boldsymbol{h}_1 : \tilde{\boldsymbol{P}}_{\mathrm{inj}}^{(0)} - \boldsymbol{A}_{\mathrm{ftr}}\boldsymbol{X}_{\mathrm{ftr}} - \boldsymbol{A}_{\mathrm{fir}}\boldsymbol{X}_{\mathrm{fir}}^{\mathrm{vo}} + 0.5|\boldsymbol{A}_{\mathrm{tl}}|\boldsymbol{P}_{\mathrm{loss}}^{(0)} = \boldsymbol{0}_N \tag{35}$$

$$\boldsymbol{h}_2 : \boldsymbol{P}_{\mathrm{fl}}^{(0)} - \tilde{\boldsymbol{\Psi}}\tilde{\boldsymbol{P}}_{\mathrm{inj}}^{(0)} = \boldsymbol{0}_L \tag{36}$$

$$\boldsymbol{h}_3 : \boldsymbol{P}_{\mathrm{loss}}^{(0)} - \sum_{s=1}^{S}\widehat{\boldsymbol{m}}_s\left\{\boldsymbol{P}_{\mathrm{rsg},\,s}^{(0)} + \boldsymbol{P}_{\mathrm{lsg},\,s}^{(0)}\right\} = \boldsymbol{0}_L \tag{37}$$

$$\boldsymbol{h}_4 : \boldsymbol{P}_{\mathrm{fl}}^{(0)} - \sum_{s=1}^{S}\left\{\boldsymbol{P}_{\mathrm{rsg},\,s}^{(0)} - \boldsymbol{P}_{\mathrm{lsg},\,s}^{(0)}\right\} = \boldsymbol{0}_L \tag{38}$$

$$\boldsymbol{q}_{5,\,s} : \boldsymbol{P}_{\mathrm{rsg},\,s}^{(0)} - \boldsymbol{P}_{\mathrm{rsg},\,\max} \le \boldsymbol{0}_L \text{ for } s = 1 \text{ to } (S-1) \tag{39}$$

$$\boldsymbol{q}_{6,\,s} : \boldsymbol{P}_{\mathrm{lsg},\,s}^{(0)} - \boldsymbol{P}_{\mathrm{lsg},\,\max} \le \boldsymbol{0}_L \text{ for } s = 1 \text{ to } (S-1) \tag{40}$$

$$\boldsymbol{q}_{7,\,s} : -\boldsymbol{P}_{\mathrm{rsg},\,s}^{(0)} \le \boldsymbol{0}_L \text{ for } s = 1 \text{ to } S \tag{41}$$

$$\boldsymbol{q}_{8,\,s} : -\boldsymbol{P}_{\mathrm{lsg},\,s}^{(0)} \le \boldsymbol{0}_L \text{ for } s = 1 \text{ to } S \tag{42}$$

where $\widehat{\boldsymbol{m}}_s$ is an $(L \times L)$ diagonal matrix with $\widehat{m}_{s,\,l,\,l} = m_{s,\,l}$. Constraints (35) and (36) are already defined. Constraints (37)–(42) determine line losses for given line flows based on the piecewise linear loss approximation. There is no need to separately impose an upper limit on the *S*th segment in (39) or (40). The same is automatically taken care of via the network capacity constraints.

4.4 Network capacity constraints

The network capacity constraints are to be enforced by considering both the normal network topology as well as line outages. In addition, an FTR auction may consist of multiple rounds [16]. Therefore, the network capacity is to be evenly released over different rounds. The network capacity constraints corresponding to the normal network topology should then be formulated as follows:

$$\boldsymbol{q}_9 : \tilde{\boldsymbol{\Psi}}\tilde{\boldsymbol{P}}_{\mathrm{inj}}^{(0)} + \acute{\boldsymbol{\Upsilon}}_{\mathrm{ftr}}\boldsymbol{X}_{\mathrm{ftr}} - \left(\frac{r}{R}\right)\boldsymbol{P}_{\mathrm{fl},\,\max} \le \boldsymbol{0}_L \tag{43}$$

$$\boldsymbol{q}_{10} : -\tilde{\boldsymbol{\Psi}}\tilde{\boldsymbol{P}}_{\mathrm{inj}}^{(0)} - \grave{\boldsymbol{\Upsilon}}_{\mathrm{ftr}}\boldsymbol{X}_{\mathrm{ftr}} - \left(\frac{r}{R}\right)\boldsymbol{P}_{\mathrm{fl},\,\max} \le \boldsymbol{0}_L \tag{44}$$

The post-contingency network capacity constraints are formulated based on the assumption that the loss offset in the lossless nodal injection profile remains unaltered following a contingency [28]. The power flow model parameters corresponding to a post-contingency network topology are represented by † in superscripts. Equations (45) and (46) show the formulation of post-contingency network capacity constraints in the lossy FTR auction

$$q_{11,c}: \tilde{\Psi}_c^{\dagger}\tilde{P}_{\text{inj}}^{(0)} + \acute{\Upsilon}_{\text{ftr},c}^{\dagger}X_{\text{ftr}} - \left(\frac{r}{R}\right)P_{\text{fl, max}} \le \mathbf{0}_L \quad \forall c. \tag{45}$$

$$q_{12,c}: -\tilde{\Psi}_c^{\dagger}\tilde{P}_{\text{inj}}^{(0)} - \grave{\Upsilon}_{\text{ftr},c}^{\dagger}X_{\text{ftr}} - \left(\frac{r}{R}\right)P_{\text{fl, max}} \le \mathbf{0}_L \quad \forall c. \tag{46}$$

For the sake of simplicity in representation, the power flow equations of a tripped line are also included in the formulation. The outage status of the respective line is reflected through the element-node incidence matrix for the corresponding network topology.

4.5 Auction pricing

The Lagrangian function of the optimisation problem (30)–(46) can be written down as follows:

$$\begin{aligned}\Lambda = f + \sum_{t=1}^{4}\kappa_t^{\mathrm{T}}h_t + \sum_{t=1}^{4}\mu_t^{\mathrm{T}}q_t + \sum_{t=5}^{6}\sum_{s=1}^{S-1}\mu_{t,s}^{\mathrm{T}}q_{t,s} \\ + \sum_{t=7}^{8}\sum_{s=1}^{S}\mu_{t,s}^{\mathrm{T}}q_{t,s} + \sum_{t=9}^{10}\mu_t^{\mathrm{T}}q_t + \sum_{t=11}^{12}\sum_{c=1}^{C}\mu_{t,c}^{\mathrm{T}}q_{t,c}.\end{aligned} \tag{47}$$

Here, all the κ and μ terms are Lagrangian multipliers. The prices at which the transportation and voluntary loss components of lossy FTR requests are cleared are given by the following equations:

$$\begin{aligned}\rho_{\text{ftr}} = \acute{\Upsilon}_{\text{ftr}}^{\mathrm{T}}\mu_9^* - \grave{\Upsilon}_{\text{ftr}}^{\mathrm{T}}\mu_{10}^* + \sum_{c=1}^{C}\acute{\Upsilon}_{\text{ftr},c}^{\dagger\mathrm{T}}\mu_{11,c}^* \\ - \sum_{c=1}^{C}\grave{\Upsilon}_{\text{ftr},c}^{\dagger\mathrm{T}}\mu_{12,c}^* - A_{\text{ftr}}^{\mathrm{T}}\kappa_1^*\end{aligned} \tag{48}$$

$$\rho_{\text{fir}} = A_{\text{fir}}^{\mathrm{T}}\kappa_1^*. \tag{49}$$

Both the above equations are obtained from the principle of marginal pricing. The transportation components are charged and the loss components are paid according to ρ_{ftr} and ρ_{fir}, respectively. Vector κ_1^* essentially indicates the LMPs in the FTR auction [24]. Thus, the price of the loss component or the price of the transportation component of a lossy obligation FTR can simply be related to the auction LMPs. Similarly to PtP balanced option FTRs, the detailed shadow price information of network capacity constraints is required to determine the price for the transportation components of lossy option FTRs.

5 Case study

Case studies are performed on a 2383-bus system. The original data of the 2383-bus system is available in [29]. Certain modifications are made to the particular system so as to make the case studies practically more relevant:

i. The line R/X ratios are wrapped within a moderate range. In one case, the range of line R/X ratios are taken to be 0.1–0.2. Thus, the R/X ratio of a transmission line is reset to 0.1 or 0.2 if the same has a value lower than 0.1 or higher than 0.2, respectively, in the original data. Similarly, in the other case, the line R/X ratios are restricted within the range of 0.2–0.4. The first case reflects the normal scenario of the practical transmission systems. The second case is additionally studied to verify the robustness of the proposed lossy option FTR by taking line R/X ratios on a little bit higher side.
ii. The line loadability is determined by considering both the stability limit and the thermal limit [30]. The stability limit of the line flow is obtained by setting an upper limit on the voltage angle separation across each transmission line. The maximum permissible voltage angle separation across a transmission line is taken to be $\pi/4$. The line flow limits specified in [29] are taken as thermal limits.
iii. To create diversity among generator cost curves, those are redefined. The generator cost curves of the present system are derived from the generator cost curves of the IEEE 118-bus [29] system. Generators of the 2383-bus system are divided into seven groups according to their actual numbering order. Each of the first six groups contains 54 generators and the remaining 3 generators belong to the last group. The cost curve of a particular generator in the 118-bus system is borrowed to the 2383-bus system for generators with the same ordinal number in different groups.

In addition to the above modifications, the shunt susceptances of all the transmission lines are ignored. The line reactances are, however, maintained at the original values. In a dispatch scheduling, loads are assumed to be purely inelastic and generators are assumed to offer their full capacities at prices equal to the respective full load average production costs [26]. For the sake of simplicity, the minimum generation limit of each generator is set to zero and the contingency constraints are ignored. The base MVA is taken as 100.

To conduct the FTR auction, a reference set of lossy FTR bids is initially prepared by considering every possible path that originates from a generator bus and terminates at a load bus. All those paths are arranged in descending order according to the magnitudes of LMP differences from a sample LMP calculation. The sample LMP profile is obtained by carrying out dispatch scheduling with the base system load of 14761.49 MW. The nodal load distribution ratio remains the same as that in [29]. The MW amounts of the reference lossy FTR bids are also determined with reference to the generator and load data considered in the sample LMP calculation. It is enforced that the physical equivalents of the transportation components of reference lossy FTR bids would, simultaneously, neither use more than 80% of generation capacity nor serve more than 80% of the load at a bus. Subsequently, the MW requests for the transportation components are obtained by sequentially maximising the power transactions over different paths. In the case of the lower R/X ratio, the upper and lower limits on the LCF offers (for voluntary loss components) are set to 0.015 and 0, respectively. The above limits are taken to be 0.025 and 0, respectively, when the line R/X ratios are adjusted within the range 0.2–0.4. The bid price of a transportation component is set equal to the magnitude of the sample LMP difference over the respective path. For a loss component, the offer price is given by the sample LMP at the respective node.

Out of all the above reference bids, the top 400 of highest MW requests are actually considered in the auction. The first 350 bids are taken as obligation requests and the remaining 50 bids are taken as option requests. The auction is assumed to be consisting of only one round. The auction clearing results for the transportation components are shown in Fig. 1. Lossy option FTR requests could be sufficiently awarded, which, in turn, shows no significant technical burden in the practical issuance of lossy option FTRs.

As mentioned previously, lossy option FTRs are not completely free of the downside risk. It is, therefore, of interest to compare the downside risk associated with a lossy option FTR with that associated with its obligation counterpart. A suitable metric to perform this comparison can be the relative downside risk index (RDRI). The RDRI is defined as the ratio between the positive reverse (i.e. from owner to ISO) payments that may arise because of the involuntary loss component of a lossy option FTR and the transportation component of the corresponding obligation FTR. The RDRI values for inactive lossy option FTRs (cleared in the above auction) are evaluated for the LMP outcomes at the different load levels. The total system load is varied from 50% (i.e. 7380.74 MW) to 150% (i.e. 22142.23 MW) with a step size of 10% while maintaining the original nodal load distribution. The maximum and minimum RDRI values (among inactive lossy option FTRs) at different load levels are plotted in Fig. 2. It can be seen that the lossy option FTR can reduce the downside risk even up to the 100% (i.e. RDRI is 0%). This is the case when the FTR owner receives a positive payment (because of negative LCF or some negative elements in the PLC vector) from the ISO for the involuntary loss component of its lossy option FTR. For most of the cases, lossy option FTRs are found to reduce the downside risk by more than 80% (i.e. RDRIs are below 20%). It is to be noted

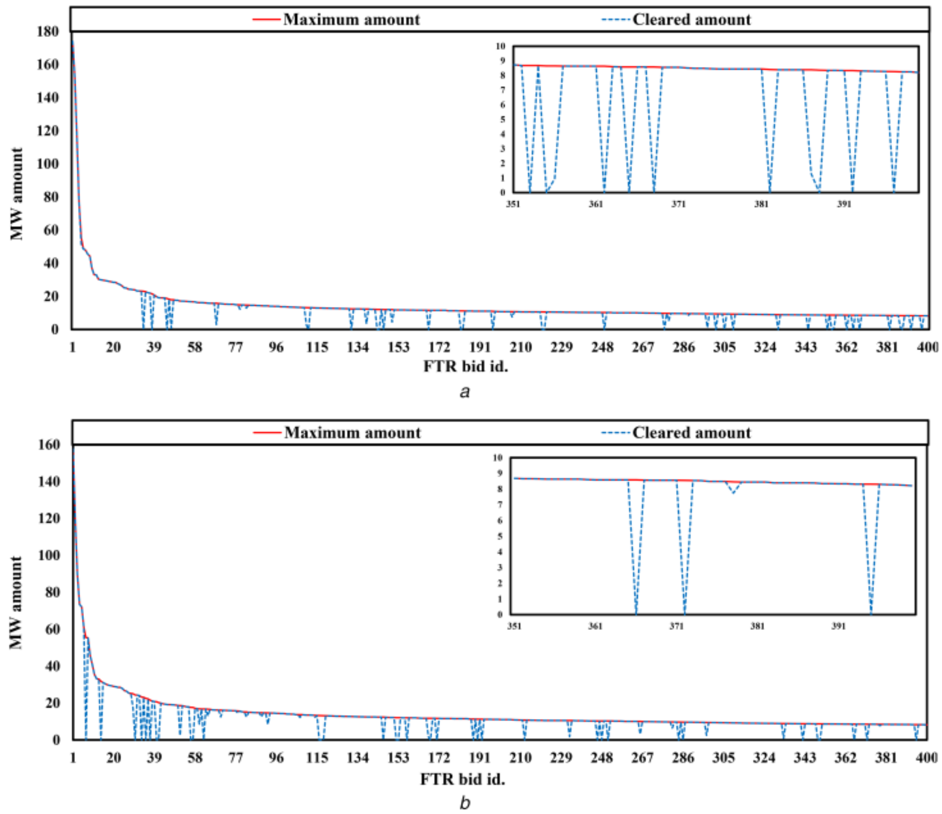

Fig. 1 *Auction clearing results for transportation components*
(a) Low R/X ratio, ***(b)*** Higher R/X ratio

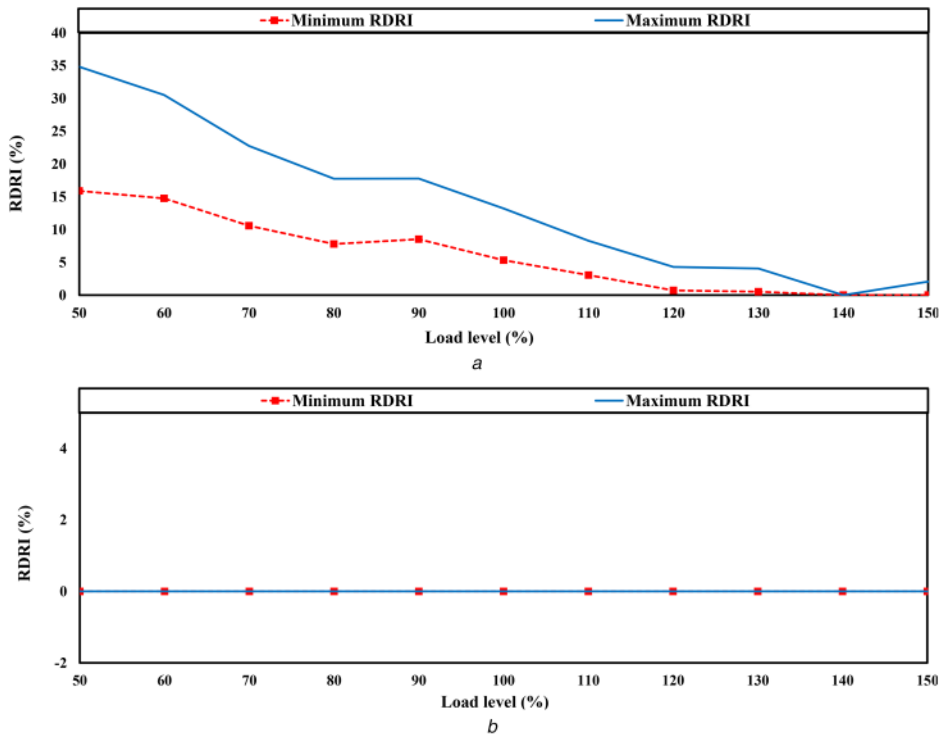

Fig. 2 *Relative downside risks of lossy option FTRs evaluated at LMP scenarios corresponding to different load levels*
(a) Low R/X ratio, ***(b)*** Higher R/X ratio

that in the case of the higher R/X ratio, RDRI is zero for all the inactive option FTRs. In the other words, the lossy option FTRs do not cause any downside risk for the present system in the case of higher R/X ratio.

6 Conclusion

In this paper, the template of the lossy option FTR is prepared as well as a market is designed for the issuance of lossy option FTRs. Similarly to a lossy obligation FTR, a lossy option FTR is also defined with transportation and loss components. There is, however, a structural difference between the lossy obligation FTR and the lossy option FTR. The loss component of a lossy obligation FTR is always voluntarily chosen by the user, which eventually remains fixed over the validity period of the FTR. A variable loss component is additionally required for the settlement of a lossy option FTR. The upside price risk (i.e. when congestion occurs in the forward direction) can be completely hedged by a lossy option FTR. The capability to hedge the downside risk may be undermined by the assignment of an involuntary loss component. It is, however, verified through the case study that the lossy option FTRs still retain the capability to hedge the downside risk to a great extent and in a similar manner as the option FTRs in the traditional FTR system can do.

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