Electrical Power and Energy Systems 43 (2012) 1354–1362

Contents lists available at SciVerse ScienceDirect

Electrical Power and Energy Systems

journal homepage: www.elsevier.com/locate/ijepes

Comprehensive modeling of flexible transmission services in stochastic joint energy and spinning reserve market

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ARTICLE INFO

Article history:
Received 24 October 2011
Received in revised form 23 April 2012
Accepted 13 June 2012

Keywords:
Dispatchable transmission services
Flowgate bidding
Stochastic joint energy and reserve market

ABSTRACT

To attract more investments for developing smart transmission networks and increasing their flexibility and efficiency, recently policies have been suggested which provide finical incentives in transmission network investment. One of these policies is price biding for incremental transmission capacity and transmission elements in power markets. According to Federal Electricity Regulatory Committee, flowgate bidding is defined as allowing a line's flow to exceed its rated capacity for a short period of time for a set penalty, i.e., price. This paper concentrates on the development of a comprehensive model for flowgate bidding and Dispatchable Transmission Services (DTSs) in stochastic joint energy and reserve market. In this paper a stochastic joint energy and reserve market with DTS are proposed to minimize the cost of supplying load and reliability expenses.

The effectiveness of the proposed model in an electricity market is demonstrated by the use of two stage stochastic mix-integer non-linear programming (TSSMINLP). DTS and flowgate biddings are used during contingencies and steady state to determine optimal required energy and reserve values. As the scale of problem is large, the benders decomposition algorithm is used to solve the stochastic joint energy and reserve market problem. To investigate the efficiency of the proposed strategy, IEEE 6 and 24 bus case tests are studied. According to the obtained results, this strategy decreases energy and reserve marginal prices, as well as reliability cost. Furthermore, the suggested plan is an incentive to the owners of transmission companies.

1. Introduction

1.1. Background and literature review

In the last decade, transmission network has been a passive player in electricity markets. Recently policies have been suggested to make transmission owners more active market participants.

To attract more investments for developing smart transmission networks and increasing their flexibility and efficiency, recently policies have been suggested which provide finical incentives in transmission network investment. These policies included transmission switching, price biding for incremental transmission capacity and dispatchable transmission services in power markets.

Transmission network services can provide flexible control actions for contingency management. An example in smart networks is switching the transmission lines for congestion management.

Federal Energy Regulatory Commission orders 890 calls for better economic operations of the transmission grid. One part of the smart grid concept aims at making better use of the current infrastructure as well as additions to the grid that enable more sophisticated use of the network [1–3,9–16]. This study focuses on an idea that improves the use of the current infrastructure with employing DTS and flowgate bidding.

Transmission networks for bulk power flow have been modeled as static systems, except during times of forced outages or maintenance [1–3,9–16]. This traditional view does not describe them as assets that operators have the ability to control. However in smart networks, switching transmission lines is a common practice with a mature technology; circuit breakers can open and close transmission lines.

Transmission switching may change the status of the power systems and whereupon affect the power flow in lines and voltage profiles of power systems. This idea was first proposed in [1]. There are a few instances of practical applications of transmission switching in [2].

Transmission switching can provide flexible control actions which result into technical benefits like Congestion management, optimal generation dispatch, loss reduction, security enhancement [1–8].

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http://dx.doi.org/10.1016/j.ijepes.2012.06.067

Nomenclature

i	index of generating units
s	index of segments of piecewise linear cost function of generating units
k	index of lines representing the added flowgate capacity
m	index of mth step of added flowgate capacity of the line k
j	index of lines with phase-shifting transformers and FACTS devices
p	index of pth segment of phase-shifting transformer and FACTS devices transmission capacity
t	index of time horizon
b	index of bus
c	index of contingency
l	index of total transmission lines
NG	number of generating units
Nk	number of lines representing the added flowgate capacity
Nm	number of steps of added flowgate capacity of the line k
NJ	number of lines with phase-shifting transformers and FACTS devices
Np	number of segments of phase-shifting transformer and FACTS devices transmission capacity
NT	number of scheduling hours
NS	number of segments of piecewise linear cost function of generating unit
Nb	number of total buses
NGb	number of generating units connected to bus b
Lb	number of lines connected to bus b
NC	number of contingency
Nl	number of total transmission lines
$\rho^s(i,t)$	offered energy cost segment s of unit i in time t
$P^s(i,t)$	power generation of unit i in segment s at time t
$SUC(i)$	start up cost unit i
$SUC(i,t)$	start up cost unit i in time t
$SDC(i)$	shutdown cost unit i
$SDC(i,t)$	shutdown cost unit i in time t
$P^{s,\max}(i)$	upper limit of real generation of unit i in segment s
$P(i,t)$	real power generation of unit i at time t
$P^{\min}(i)$	minimum production of unit i
$\mu(i,t)$	commitment state of unit i at time t
$P^{\max}(i)$	maximum production of unit i
T_i^{on}	minimum up time of unit i
T_i^{off}	minimum down time of unit i
$X_{i,t}^{on}$	on time of unit at time t
$X_{i,t}^{off}$	off time of unit at time t
$UR(i)$	ramp up rate limit of unit i
$DR(i)$	ramp down rate limit of unit i
$PD(b,t)$	load demand of bus b at time t
$x_{FACTSDevice}^{p}(j,t)$	situation of the pth segment of phase-shifting transformer and FACTS device transmission capacity in line j at time t
$P_{FACTSDevice}^{AddCap,p}(j,t)$	the capacity of pth segment of phase-shifting transformer and FACTS device transmission capacity in line j at time t
$PL(j,t)$	transmission flow in lines with phase-shifting transformers and FACTS devices
$ACC(j,t)$	reservation cost for changing power shift at time t in phase-shifting transformers and FACTS devices in line j
ACC	Reservation cost for changing power shift in phase-shifting transformers and FACTS devices
$P_{FB-Reservation}^{m,max}(k,t)$	maximum reservation capacity of the mth segment of capacity of the kth line
$\rho_{FB-Reservation}^{m}(k,t)$	offered reservation cost for capacity of the mth segment of capacity the kth line
$\rho_{FB-Usage}^{m}(k,t)$	offered usage cost for capacity of the mth segment of capacity of the kth line
$P(k)$	percent of the steady-state operating level of transmission element k
$State^m(k,t)$	statement of the reservation capacity of the mth segment of capacity the kth transmission line element exceeds its steady state operating level
$P_{FB-Usage}^{m}(k,t)$	useable capacity of the mth segment of capacity of the kth line
$P_{FB-Usage}(k,t)$	useable capacity of the kth line
$VOLL(b,t)$	value of lost load in bus b at time t
$PL(k,t)$	transmission flow in of the kth line
$\pi(i,t)$	marginal change in violations with increase in unit generation at time t
$\delta(m,t)$	phase angle of bus m at time t
$\mu^c(i,t)$	the contingency state of unit i at time t in contingency c
$\delta_n^c(l,t)$	phase angle of bus m at time t in contingency c
x_l	reactance of line l

The concept of optimal transmission dispatch in a market context was introduced by O'Neill [9]. From an economic point of view, transmission switching can provide great benefits when compared to other control methods such as generation unit rescheduling or load shedding for contingency management. Furthermore, it can be also employed as a fast control approach under emergency states. Ref. [10] formulates the problem of finding an optimal generation dispatch and transmission topology to meet a specific inflexible load as a mixed integer program.

Ref. [11] examines sensitivity of the formulation stated in [10] and some of its economic impacts. Ref. [12] investigates how transmission switching can increase economic efficiency while maintaining an $N-1$ secure network. A co-optimization formulation of the generation unit commitment and transmission switching problem while ensuring $N-1$ reliability has been presented in [13].

The optimal transmission switching for alleviating overloads based on SCUC, while taking into account prevailing generating unit and transmission network constraints, is considered in [14].

Another idea that improves the use of the current infrastructure in transmission networks and more efficiency is flowgate bidding. Flowgate bidding is defined as allowing a transmission line's flow to exceed its steady-state rated capacity for a set price [9–16].

Flowgate bidding or added flowgate capacity permits increasing power system transfer under normal operating conditions to a maximal but safe load level by allowing the maximal loading of system elements in post-contingency state without compromising the system reliability [9–16].

One possible benefit of flowgate bidding is that there can be situations in which a line temporarily operates beyond its steady-state capacity instead of starting up a peak generating unit [9–16].

DTSand flowgate biddings can provide economic benefits compared to other control methods such as generation unit rescheduling or load shedding for contingency management.

The authors of [9] examined the dynamic operation and compensation of transmission lines on a small example network without any mathematical modeling.

In [15], authors have proposed a way in which transmission assets should be changed and have presented two concepts for the smart grid: just-in-time transmission and flowgate bidding. They also have presented a simple model for flowgate bidding in DCOPF.

In [16] a novel approach for using the adaptive transmission rates of electrical facilities was proposed to increase the utilization of existing transmission without deterioration of system reliability.

Although Ref. [9] to discuss about transmission services in the electricity markets, but do not presented mathematical modeling of transmission services in power markets.

1.2. Contribution

Although transmission switching has been studied in many papers, modeling of DTS and flowgate bidding has not been specifically carried out. In this paper, a comprehensive modeling of DTS and flowgate bidding with cost's function in a well-known engineering test case is proposed to gain a better understanding of its potential impact in IEEE standard systems. So considering a stochastic joint energy and reserve market with DTS, the cost of supplying the load and reliability expenses are minimized. Then benders decomposition algorithm is used to solve the stochastic joint energy and reserve market problem.

The studied dispatchable transmission services include phase-shifting transformers and FACTS devices with adjustment-change sets and flowgate bidding representing the added flowgate capacity.

1.3. Organization

The remainder of this paper is organized as follows. Section 2 represents problem formulation. Section 3 gives solution methodology used in this paper. Section 4 provides some results for case study, and the corresponding discussions. Finally, Section 5 lists some relevant conclusions drawn in this paper.

2. Problem formulation

In power systems, it is very important to maintain a certain amount of reserve capacity to avoid power shortage due to generators and lines transmission random outages, load fluctuations, etc.

System operators procure spinning reserve using control methods such as generation unit rescheduling or load shedding for contingency management [16–22].

The objective of stochastic joint energy and reserve market with considering DTS is to determine a day-ahead unit commitment and DTS for minimizing the system operating cost while satisfying the prevailing constraints.

Refs. [20–31] show examples of applications of SMIP in different engineering sciences and in power systems for unit commitment considering uncertainties. In this paper, the complete model of SMINLP, based on [20–29], is extended.

In the objective function, ISO minimizes the summation of the energy and reserve procurement costs, over the scheduling horizon with considering DTS as formulated below:

$$
\begin{aligned}
&\mathit{Total\ Cost} = \mathit{Min}\left(\begin{array}{c}\text{Energ}\,y\text{ and Reserve P}\mathit{roduction\ Costs}\text{ During the Steady State} + \text{Total Expected}\\ \text{Cost Associated with the Deployment of Resourses in the}\\ \text{Post-Contingency States for System Security}\end{array}\right) = \\
&\mathit{Min}\sum_{t=1}^{NT}\left\{\begin{array}{l}
\left\{\begin{array}{l}
\sum_{i=1}^{NG}\left(\begin{array}{l}\left\{\sum_{i=1}^{NG}(F_{ci}(P(i,t))\times\mu(i,t)+SUC(i,t))\right\}+\\ \rho_{SP}^{Up}(i,t)SR^{Up}(i,t)+\rho_{SP}^{Dn}(i,t)SR^{Dn}(i,t)\end{array}\right)+\\
\sum_{j=1}^{NJ}\left\{\begin{array}{l}\left\{\sum_{p=1}^{Np}\left\{\begin{array}{l}\rho_{FACTS\ Device}^{Add\ Cap,p}(j,t)\times\\ \left(P_{FACTS\ Device}^{AddCap,p}(j,t)\times x_{FACTS\ Device}^{p}(j,t)\right)\end{array}\right\}\right\}+\\ ACC(j,t)\end{array}\right\}+\\
\sum_{k=1}^{Nk}\left\{\sum_{m=1}^{Nm}\begin{array}{l}P_{FB-Reservatione}^{m}(k,t)\times\rho_{FB\text{-}Reservation}^{m}(k,t)\times\\ State^{m}(k,t)\end{array}\right\}
\end{array}\right\}+\\
\sum_{c=1}^{NC}\Pr(c,t)\times\left\{\begin{array}{l}
\left\{\sum_{b=1}^{Nb}VOLL(b,t)LC^{c}(b,t)\right\}+\\
\left\{\sum_{k=1}^{Nk}\left\{\sum_{m=1}^{Nm}P_{FB\text{-}Usage}^{m}(k,t)\times\rho_{FB-Usage}^{m}(k,t)\right\}\right\}+\\
\sum_{i=1}^{NG}(\Delta P^{Up,c}(i,t)+\Delta P^{Dn,c}(i,t))\times\rho^{RealTime\mathrm{Price}}
\end{array}\right\}
\end{array}\right\}
\end{aligned}
\tag{1}
$$

The total cost is given in (1), in which the first, second terms in the right hand side of equation refer to energy and reserve production costs during the steady state. In the mentioned terms, first one represents energy production cost function, generating units' startup cost and capacity cost of the spinning reserve provided by generating units. Second one is the cost of DTS including cost for scheduling additional capability through operation of phase-shifting transformers and FACTS devices and adjustment-change costs for them. Third term denotes the cost of scheduling reservation of *m*th step of added flowgate capacity in line *k*.

Fourth term denotes total expected cost associated with the deployment of recourses in the contingency states for security, including the cost of load curtailment and scheduling cost of useable *m*th step of added flowgate capacity in line *k* to manage the contingencies occurred.

2.1. Sets of variables in energy and reserve production costs object function during the steady state

Sets of variables in (1) for system energy requirement and DTS are below.

Real power generation constraints:

$$F_{ci}(P_{it}) = a + bP(i,t) + cP^2(i,t) \tag{2}$$

$$
\begin{aligned}
&P^{\min}(i)\times\mu(i,t)+SR^{Dn}(i,t)\leqslant P(i,t)\leqslant P^{\max}(i)\times\mu(i,t)-SR^{Up}(i,t)\\
&i=1,2,\ldots NG\quad t=1,\ldots NT
\end{aligned}
\tag{3}
$$

Generating units shutdown cost constraints

$$SUC(i,t)\geqslant(\mu(i,t)-\mu(i,t-1))\times SUC(i)\quad i=1,2,\ldots NG\quad t=1,\ldots NT \tag{4}$$

Ramping up/down limits:

$$
\begin{aligned}
&P(i,t)-P(i,t-1)\leqslant[1-\mu(i,t)(1-\mu(i,t-1))]\times RRU(i)\\
&\quad i=1,\ldots,NG\\
&+\mu(i,t)\times(1-\mu(i,t-1))\times P^{\min}(i)\\
&P(i,t-1)-P(i,t)\leqslant[1-\mu(i,t-1)(1-\mu(i,t))]\times RRD(i)\\
&\quad i=1,\ldots,NG\\
&+\mu(i,t-1)\times(1-\mu(i,t))\times P^{\min}(i)
\end{aligned}
\tag{5}
$$

Minimum up/down time limits:

$$
\begin{aligned}
&\left[X_{i(t-1)}^{on}-T_{i}^{on}\right]\times[\mu(i,t-1)-\mu(i,t)]\geqslant 0\\
&\quad i=1,\ldots,NG\ t=1,\ldots,NT\\
&\left[X_{i(t-1)}^{off}-T_{i}^{off}\right]\times[\mu(i,t)-\mu(i,t-1)]\geqslant 0
\end{aligned}
\tag{6}
$$

Up- and down-spinning reserve limits

$$0\leqslant SR^{Up}(i,t)\leqslant RRU(i)\times 10\,\text{min}\quad i=1,2,\ldots NG\ t=1,\ldots NT \tag{7}$$

$$0\leqslant SR^{Dn}(i,t)\leqslant RRD(i)\times 10\,\text{min}\quad i=1,2,\ldots NG\ t=1,\ldots NT \tag{8}$$

$$
\begin{aligned}
&P^{\min}(i)\times\mu(i,t)+SR^{Dn}(i,t)\leqslant P(i,t)\leqslant P^{\max}(i)\times\mu(i,t)-SR^{Up}(i,t)\\
&i=1,2,\ldots NG\ t=1,\ldots NT
\end{aligned}
\tag{9}
$$

Power balance in each bus:

$$\sum_{i=1}^{NGb}P(i,t)-PL(b,t)-\sum_{l=1}^{Lb}PL(l,t)=0b=1,2,\ldots,Nb \tag{10}$$

Transmission flow limits in lines without DTS:

$$
\begin{aligned}
&-PL^{\max}(l,t)\leqslant PL(l,t)\leqslant PL^{\max}(l,t)l=1,2,\ldots,Nl\neq NJ\\
&t=1,\ldots NT
\end{aligned}
\tag{11}
$$

Following are the states, settings and transmission flow limits in lines with phase-shifting transformers and FACTS devices:

$$x^{p}_{FACTSDevice}(j,t) \in \{0,1\} \tag{12}$$

$$\sum_{p=1}^{Np} x^{p}_{FACTSDevice}(j,t) \leqslant 1 \tag{13}$$

$$P^{AddCap,p}_{FACTSDevice}(j,t) = x^{p}_{FACTSDevice}(j,t) \times P^{AddCap,p}_{FACTSDevice}(j,t) \tag{14}$$

Transmission flow limits in lines with FACTS devices:

$$\begin{cases} PL(j,t) \leqslant PL^{\max}(j,t) + P^{AddCap,p}_{FACTSDevice}(j,t) \\ PL(j,t) \geqslant PL^{\min}(j,t) - P^{AddCap,p}_{FACTSDevice}(j,t) \end{cases} \quad j = 1,2,\ldots,NJ \; t = 1,\ldots NT \tag{15}$$

Adjustment change cost for DTS:

$$ACC(j,t) \geqslant ACC \times \left|\left(\left(x^{p}_{FACTSDevice}(j,t) + x^{p}_{FACTSDevice}(j,t-1)\right)\right)\right|$$
$$p = 1,\ldots,Np \; ACC(j,t) \geqslant 0 \tag{16}$$

DC power flow in each line:

$$\left(\frac{\delta_n(l,t) - \delta_m(l,t)}{x_l}\right) = PL(l,t) \quad l = 1,2,\ldots,NJ,\ldots,Nk,\ldots,Nl$$
$$t = 1,\ldots,NT \tag{17}$$

Phase angle limit:

$$\delta_n^{\min}(l,t) \leqslant \delta_n(l,t) \leqslant \delta_n^{\max}(l,t) \quad l = 1,2,\ldots,NJ,\ldots,Nk,\ldots,Nl \tag{18}$$

Constraints for lines with added flowgate capacity:

$$P^{m,\max}_{FB\text{-}Reservation}(k,t) \leqslant P(k) \times PL^{\max}(k,t) \tag{19}$$

$$0 \leqslant P^{m}_{FB\text{-}Reservation}(k,t) \leqslant P^{m,\max}_{FB\text{-}Reservation}(k,t) \tag{20}$$

$$State^{m}(k,t) \in \{0,1\} \tag{21}$$

2.2. Sets of variables in total expected cost associated with the deployment of recourses in the contingency states for security

Sets of variables in (1) related to contingencies are below.

DC load flow in each bus for each contingency:

$$\sum_{i=1}^{NGb} \xi^{c}(i,t) \times P(i,t) + \sum_{i=1}^{NGb} \Delta P^{Up}(i,t) - \sum_{i=1}^{NGb} \Delta P^{Dn}(i,t) + LC^{c}(b,t)$$
$$- PL(b,t) - \sum_{l=1}^{Lb} \mu^{c}(l,t) \times PL(l,t) = 0$$
$$b = 1,2,\ldots,Nb \; c = 1,2,\ldots,NC \tag{22}$$

Deployed spinning reserve limit:

$$0 \leqslant \Delta P^{Up}(i,t) \leqslant \xi^{c}(i,t) \times SR^{Up}(i,t) \tag{23}$$

$$0 \leqslant \Delta P^{Dn}(i,t) \leqslant \xi^{c}(i,t) \times SR^{Dn}(i,t) \tag{24}$$

Load curtailment limit:

$$0 \leqslant LC^{c}(b,t) \leqslant PL(b,t) \tag{25}$$

Constraints for lines with added flowgate capacity during contingencies:

$$State^{m}_{Usage}(k,t) \in \{0,1\} \tag{26}$$

$$0 \leqslant P^{m}_{FB-Usage}(k,t) \leqslant State^{m}(k,t) \times P^{m}_{FB-Reservation}(k,t) \tag{27}$$

$$P_{FB-Usage}(k,t) = \sum_{m=1}^{Nm} P^{m}_{FB-Usage}(k,t) \tag{28}$$

$$\begin{cases} PL(k,t) \leqslant PL^{\max}(k,t) + P_{FB-Usage}(k,t) \\ PL(k,t) \geqslant PL^{\min}(k,t) - P_{FB-Usage}(k,t) \end{cases} \quad k = 1,2,\ldots,Nk \; t = 1,\ldots NT \tag{29}$$

DC power flow in each line during contingencies:

$$\mu^{c}(l,t) \times \left(\frac{\delta_n(l,t) - \delta_m(l,t)}{x_l}\right) = PL(l,t)$$
$$l = 1,2,\ldots,NJ,\ldots,Nk,\ldots,Nl$$
$$t = 1,\ldots NT \tag{30}$$

Phase angle limit during contingencies:

$$\delta_n^{\min}(l,t) \leqslant \delta_n(l,t) \leqslant \delta_n^{\max}(l,t) \quad l = 1,2,\ldots,NJ,\ldots,Nk,\ldots,Nl \tag{31}$$

A two-state model of generating units, transmission lines and independent behavior of components has been used. Considering an N-bus power system with B independent components consisting of generation units and transmission lines with failure rate λ_i, for contingency state c with exactly F failed components, the probability of each contingency state c in time t can be written as follows:

$$\Pr(c,t) = \prod_{i \in NGc} ORR(i,t) \times \prod_{l \in NLc} ORR(l,t) \tag{32}$$

$$ORR(i,t) \approx \lambda_i \times T \tag{33}$$

3. Solution methodology

This section describes the solution methodology based on Benders decomposition method [13,20,24,30–39]. Because the scale of problem is large, benders decomposition algorithm is used to solve the SMINLP problem. At first, the relationship between Benders decomposition and stochastic programming problem is explained.

In the following the mathematical formulation of the master problem and subproblems resulting from the application of Benders decomposition to (1)–(33) are presented.

The two-stage stochastic programming model addresses the following structure:

$$Min\ Z = C.X + \sum_{c=1}^{NC} P(c).D^{c}.Y^{c} \tag{a}$$

S.t. :

$$A \cdot X \geqslant B \tag{b}$$

$$E \cdot X + F \cdot Y \geqslant H \tag{c}$$

Problems (a–c) can be represented as a two-stage decision problem:

In first stage, considering only constraint (b), a feasible x^* is obtained from the master problem in iteration ν:

$$Min\ Z_{LB} = C.X + \sum_{c=1}^{NC} P(c).\alpha(c) \tag{d}$$

S.t. :

$$A.X \geqslant B \tag{e}$$

$$\alpha(c) \geqslant \alpha_c(X^*)^{\nu-1} + \lambda^{\nu-1} \cdot (X^* - X) \tag{f}$$

where $\alpha_c(X)$ is an approximation of the second-stage problem optimal value as a function of the first-stage decision variable x. Z_{LB} is a lower bound of the whole problem and will be updated iteratively by the second stage problem.

In second stage for each $c \in NC$ the subproblem is solved with considering constraint (c) and the given x^* from the first-stage problem.

$$\alpha_c(X)^{\nu} = Min\ D^{c}.Y^{c} \tag{g}$$

S.t. :

$$F \cdot Y \geqslant H - E \cdot X^{\nu *} \tag{h}$$

The optimal solution x^* from the first-stage and the optimal solution Y^{c*} from the second stage are obtained. If the upper bound $Z_{UB} = C \cdot X^{\nu *} + \sum_{c=1}^{NC} P(c) \cdot D^{c} \cdot Y^{c\nu *}$ is equal to the lower bound from the first-stage problem, then the (x^*, Y^{c*}) is the optimal solution for the complete problem. In other words, the problem is optimal only when its subproblems are also optimal. Otherwise, the optimality cut (6) is added to the master problem:

$$\alpha(c) \geqslant \alpha_c(X^*)^v + \lambda^v \cdot (X^* - X) \tag{i}$$

where λ is the Lagrangian multiplier vector of inequality constraints (32). Then $v = v + 1$ is set and the process is continued from first stage. In iteration v master problem is:

$$Min\, Z_{LB} = (\text{Energy and Reserve } Production Costs \text{ During the Steady State})$$

$$+\sum_{c=1}^{NC} P(c).\alpha(c) =$$

$$Min \sum_{t=1}^{NT} \left\{ \begin{array}{l} \left\{ \begin{array}{l} \sum_{i=1}^{NG} \left(\begin{array}{l} \left\{ \sum_{i=1}^{NG} (F_{ci}(P(i,t)) \times \mu(i,t)(+SUC(i,t)) \right\} + \\ \rho_{SP}^{Up}(i,t) SR^{Up}(i,t) + \rho_{SP}^{Dn}(i,t) SR^{Dn}(i,t) \end{array} \right) + \\ \sum_{j=1}^{NJ} \left\{ \begin{array}{l} \left\{ \sum_{p=1}^{Np} \left\{ \begin{array}{l} \rho^{AddCap,p}_{FACTSDevice}(j,t) \times \\ \left(P^{AddCap,p}_{FACTSDevice}(j,t) \times x^{p}_{FACTSDevice}(j,t) \right) \end{array} \right\} \right\} + \\ ACC(j,t) \end{array} \right\} + \\ \sum_{k=1}^{Nk} \left\{ \sum_{m=1}^{Nm} \begin{array}{l} P^{m}_{FB-Reservatione}(k,t) \times \rho^{m}_{FB-Reservation}(k,t) \times \\ State^{m}(k,t) \end{array} \right\} \end{array} \right\} + \\ \sum_{c=1}^{NC} P(c).\alpha(c) \end{array} \right\} \tag{34}$$

Sets of variables in (34) for system energy requirement and DTS are Eqs. (2)–(21) and cut (35):

$$\begin{aligned} \alpha(c) \geqslant{} & \alpha_c(X^*)^{v-1} + \sum_{i=1}^{NG} \pi(i,t) \times (P(i,t) \times \mu(i,t) - P(\hat{i},t) \times \mu(\hat{i},t)) \\ & + \sum_{i=1}^{NG} \sigma(i,t) \times (SR^{Up}(i,t) \times \mu(i,t) - SR^{\widehat{Up}}(i,t) \times \mu(\hat{i},t)) \\ & + \sum_{i=1}^{NG} \omega(i,t) \times (SR^{Dn}(i,t) \times \mu(i,t) - SR^{\widehat{Dn}}(i,t) \times \mu(\hat{i},t)) \\ & + \sum_{j=1}^{NJ} \psi(j,t) \times \left(x^{p}_{FACTSDevice}(j,t) - \widehat{x^{p}_{FACTSDevice}(j,t)} \right) \\ & + \sum_{j=1}^{NJ} \eta(j,t) \times \left(P^{AddCap,p}_{FACTSDevice}(j,t) - \widehat{P^{AddCap,p}_{FACTSDevice}(j,t)} \right) \\ & + \sum_{k=1}^{Nk} q(k,t) \times \left(P^{m}_{FB\text{-}Reservatione}(k,t) - \widehat{P^{m}_{FB\text{-}Reservatione}(k,t)} \right) \\ & + \sum_{k=1}^{Nk} s(k,t) \times (State^{m}(k,t) - State^{\hat{m}}(k,t)) \end{aligned}$$

which X is:

$$X = \left\{ \begin{array}{l} \mathrm{P(i,t)} \times \mu(\mathrm{i,t}), \mathrm{SR^{Up}(i,t)}, \mathrm{SR^{Dn}(i,t)}, P^{AddCap,p}_{FACTSDevice}(j,t), \\ x^{p}_{FACTSDevice}(j,t), P^{m}_{FB\text{-}Reservatione}(k,t), State^{m}_{Reservatione}(k,t), \end{array} \right\} \tag{36}$$

X^* is a value from master problem in iteration $v - 1$. $\alpha_c\,(X^*)^{v-1}$ is a subproblem function in iteration $v - 1$.

Then with considering values from master problem, for each $c \in NC$ solve the subproblem:

Superscript $\wedge$ is an index for given variables from master problem in iteration v.

$$\left\{ \begin{array}{ll} P(i,t) = P(\hat{i},t) \times \mu(\hat{i},t) \leftrightarrow \pi(i,t) & i = 1,\ldots,NG \\ SR^{Up}(i,t) = SR^{\widehat{Up}}(i,t) \times \mu(\hat{i},t) \leftrightarrow \sigma(i,t) & i = 1,\ldots,NG \\ SR^{Dn}(i,t) = SR^{\widehat{Dn}}(i,t) \times \mu(\hat{i},t) \leftrightarrow \omega(i,t) & i = 1,\ldots,NG \\ x^{p}_{FACTSDevice}(j,t) = \widehat{x^{p}_{FACTSDevice}(j,t)} \leftrightarrow \psi(b,t) & j = 1,\ldots,NJ \\ P^{AddCap,p}_{FACTSDevice}(j,t) = \widehat{P^{AddCap,p}_{FACTSDevice}(j,t)} \leftrightarrow \eta(j,t) & j = 1,\ldots,NJ \\ P^{m}_{FB\text{-}Reservatione}(k,t) = \widehat{P^{m}_{FB\text{-}Reservatione}(k,t)} \leftrightarrow q(k,t) & k = 1,\ldots,Nk \\ State^{m}(k,t) = \widehat{State^{m}(k,t)} \leftrightarrow s(k,t) & k = 1,\ldots,Nk \end{array} \right. \tag{37}$$

Considering Eq. (37), For each $c \in NC$ the following subproblem is solved:

$$Min\alpha_c(X)^v = \left\{ \begin{array}{l} \text{Total Expected Cost Associated with the Deployment of} \\ \text{Resourses in the Post} - \text{Contingency States for Security} \end{array} \right\} =$$

$$\sum_{t=1}^{NT} \left\{ \left\{ \begin{array}{l} \left\{ \sum_{b=1}^{Nb} VOLL(b,t) LC^{c}(n,t) \right\} + \\ \left\{ \sum_{k=1}^{Nk} \left\{ \sum_{m=1}^{Nm} P^{m}_{FB-Usage}(k,t) \times \rho^{m}_{FB-Usage}(k,t) \right\} \right\} + \\ \sum_{i=1}^{NG} (\Delta P^{Up,c}(i,t) + \Delta P^{Dn,c}(i,t)) \times \rho^{RealTimePrice} \end{array} \right\} \right\} \quad c = 1,\ldots,NC \tag{38}$$

Sets of variables in (38), considering contingencies, are Eqs. (22)–(33).

After solving the subproblem, the optimal solution Y^{c*} from the second stage are obtained. Y^{c*} is:

$$Y^{c*} = \left\{ LC^{c}(n,t), P^{m}_{FB-Usage}(k,t), \Delta P^{Up,c}(i,t), \Delta P^{Dn,c}(i,t) \right\} \tag{39}$$

The optimal solution X^* from the Eq. (34) and the optimal solution Y^{c*} from the Eq. (38) are obtained.

Again, if the upper bound $Z_{UB} = C.X^{v*} + \sum_{c=1}^{NC} P(c) \cdot D^{c} \cdot Y^{cv*}$ is equal to the lower bound from the Eq. (34), then the (x^*, Y^{c*}) are the optimal solutions for the complete problem. In other words, the problem is optimal only when its subproblems are also optimal. Otherwise, $v = v + 1$ and the optimality cut (40) is added to the master problem:

$$\begin{aligned} \alpha(c) \geqslant{} & \alpha_c(X^*)^{v} + \sum_{i=1}^{NG} \pi(i,t) \times (P(i,t) \times \mu(i,t) - P(\hat{i},t) \times \mu(\hat{i},t)) \\ & + \sum_{i=1}^{NG} \sigma(i,t) \times (SR^{Up}(i,t) \times \mu(i,t) - SR^{\widehat{Up}}(i,t) \times \mu(\hat{i},t)) \\ & + \sum_{i=1}^{NG} \omega(i,t) \times (SR^{Dn}(i,t) \times \mu(i,t) - SR^{\widehat{Dn}}(i,t) \times \mu(\hat{i},t)) \\ & + \sum_{j=1}^{NJ} \psi(j,t) \times \left(x^{p}_{FACTSDevice}(j,t) - \widehat{x^{p}_{FACTSDevice}(j,t)} \right) \\ & + \sum_{j=1}^{NJ} \eta(j,t) \times \left(P^{AddCap,p}_{FACTSDevice}(j,t) - \widehat{P^{AddCap,p}_{FACTSDevice}(j,t)} \right) \\ & + \sum_{k=1}^{Nk} q(k,t) \times \left(P^{m}_{FB\text{-}Reservatione}(k,t) - \widehat{P^{m}_{FB\text{-}Reservatione}(k,t)} \right) \\ & + \sum_{k=1}^{Nk} s(k,t) \times (State^{m}(k,t) - State^{hatm}(k,t)) \end{aligned} \tag{40}$$

Fig. 1 describes the procedure for stochastic joint energy and reserve market with DTS.

4. Numerical study

In order to show the effect of flowgate bidding and DTS on Cost Reduction in Co-optimization energy and reserve market, a case

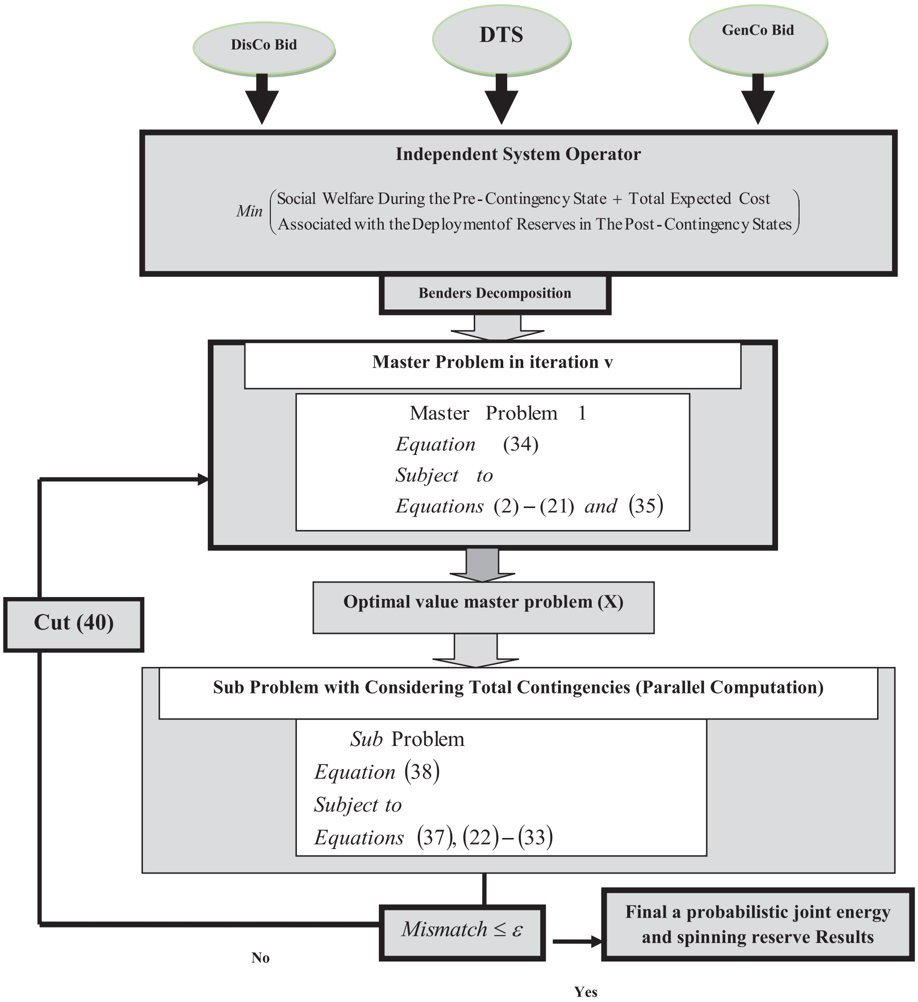

Fig. 1. The procedure for stochastic joint energy and reserve market with DTS.

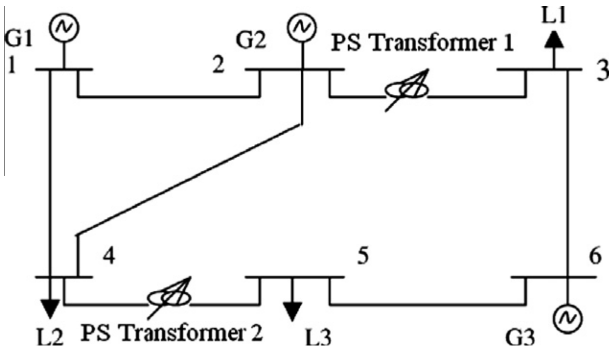

Fig. 2. 6-Bus test system.

Table 2
Mean time to failure (h) for components.

Components	G1	G2	G3	L1	L2	L3	L4	L5	L6	L7
MTTF (h)	650	450	560	400	350	360	300	400	450	420

Table 3
Hourly load demand.

Hour	Pd (MW)	Hour	Pd (MW)
1	175.19	13	242.18
2	165.15	14	243.6
3	158.67	15	248.86
4	154.73	16	255.79
5	155.06	17	256
6	160.48	18	246.74
7	173.39	19	245.97
8	177.6	20	237.35
9	186.81	21	237.31
10	206.96	22	232.67
11	228.61	23	195.93
12	236.1	24	195.6

Table 1
Generator data.

Gen no.	Bus with gen	A ($)	B ($/MW)	STC ($)	SDC ($)	P^{min} (MW)	P^{max} (MW)	R (MW/min)	MUT (h)	MDT
1	1	200	20	50	10	100	200	2.5	4	4
2	2	150	23	40	20	10	100	2.0	3	2
3	6	50	30	0	0	10	100	2.0	1	1

Table 4
Line data.

Line no.	From	To	X (pu)	Flow limit (MW)
1	1	2	0.170	130
2	2	3	0.037	100
3	1	4	0.258	100
4	2	4	0.197	100
5	4	5	0.037	50
6	5	6	0.140	100
7	3	6	0.018	100

Table 5
Offer prices for quantity the transmission element exceed its steady state operating level in contingencies.

Block flowgate bidding based on percentage of steady state rating	5%	10%	15%
Offer price for each block	10 ($/MW h)	20 ($/MW h)	40 ($/MW h)

Table 6
Offer price for FACTS device.

Offered shifts of flow by the phase-shifting transformers	5 MW	10 MW	15 MW
Offer price for shifts of flow	5 ($/MW h)	10 ($/MW h)	15 ($/MW h)

study based on the 6-bus system is presented in this section. The six bus system, shown in Fig. 2, has three units, seven transmission lines and two phase-shifting transformers. The phase-shifting transformers are considered as FACTS device which are dispatchable service and can offer price for shifts of flow by the phase-shifting mechanism.

Data and information for the 6-bus system are derived from [25,26]. The system load for a 24-h scheduling period and Line data are extracted from [25].

The spinning reserve market lead time is assumed to be 10 min. It is assumed that generating units offer cost of up- and down-spinning reserves at the rates of 100% and 40% of their highest incremental cost of producing energy, respectively. The cost curves of generating units given as a quadratic function in [25]. Generator data, Mean time to failure (h), Hourly load demand and Line data are presented in Tables 1–4.

The remaining load in each bus is set as the maximum involuntary load curtailment in that bus at a cost of 7000 $/MWh. The offer prices for added flowgate capacity during contingencies has been presented in Table 5 and offer prices for FACTS devices which are dispatchable services is based on Table 6. Adjustment change cost for Facts devices is 10$.

The following cases are considered:

Case 1: Base case co-optimization of energy and reserve without considering flowgate bidding and DTS
Case 2: Base case co-optimization of energy and reserve without considering flowgate bidding and DTS with benders decomposition
Case 3: case co-optimization of energy and reserve with considering flowgate bidding and DTS.
Case 4: Base case co-optimization of energy and reserve with considering flowgate bidding and DTS with benders decomposition

Table 7 presents the optimal results associated with Case 1, in which unit G1 is committed at all hours, while the expensive unit G2 is committed only at peak hours 8–10, 13–19 and is loaded at its minimum capacity.

Based on the last row of Table 7, it is more economic to curtail loads instead of scheduling reserve in those scenarios with low likelihood of occurrences.

Table 8 presents the number of variables, run time, number of constraints and number of iterations associated with cases 1 and 2.

In this case, it can be seen that the computational time was decreased almost 65% comparing to case 1.

In this section, we examine the effect of DTS in stochastic of energy and reserve market. Table 6 presents the optimal results associated with Case 3.

Table 7
Units schedule of 6-bus system in case 1.

Time	G G1(MW)			G2(MW)			G3(MW)			LC cost $
	$P(i,t)$	$SR^{Up}(i,t)$	$SR^{Dn}(i,t)$	$P(i,t)$	$SR^{Up}(i,t)$	$SR^{Dn}(i,t)$	$P(i,t)$	$SR^{Up}(i,t)$	$SR^{Dn}(i,t)$	
1	155	0	55	0	0	0	20.19	0	0	4402.292
2	155	0	55	0	0	0	10.15	0	0	4392.61
3	158.67	0	55	0	0	0	0	0	0	4651.893
4	154.73	0	54.73	0	0	0	0	0	0	4365.096
5	155.06	0	55	0	0	0	0	0	0	4389.117
6	160.48	0	55	0	0	0	0	0	0	4783.645
7	155	0	55	0	0	0	18.39	0	0	4398.992
8	155	10	55	10	0	0	12.6	0	0	4645.318
9	155	17.086	55	17.086	0	0	14.724	0	0	4824.687
10	155	29.176	55	29.176	0	0	22.784	0	0	5158.519
11	155	44.3296	55	0	0	0	73.61	0	0	4979.709
12	155	45	55	0	0	0	81.1	0	0	5060.668
13	155	45	55	44.32966	0	0	42.85034	0	0	5639.538
14	155	45	55	46.43316	0	0	42.16684	0	0	5757.8
15	155	45	55	54.22497	0	0	39.63503	0	0	6146.608
16	155	45	55	50.79	0	0	50	0	0	6032.904
17	155	45	55	51	0	0	50	0	0	6045.814
18	155	10	55	51.08454	0	0	40.65546	0	0	6015.618
19	155	17.086	55	49.94392	0	0	41.02608	0	0	5968.041
20	155	0	55	0	0	0	82.35	0	0	5074.179
21	155	0	55	0	0	0	82.31	0	0	5073.747
22	155	0	55	0	0	0	77.67	0	0	5023.593
23	155	0	55	0	0	0	40.93	0	0	4626.471
24	155	0	55	0	0	0	40.6	0	0	4622.904

G time	G1(MW)			G2(MW)			G3(MW)			LC $	DTS $
	$P(i,t)$	$SR^{Up}(i,t)$	$SR^{Dn}(i,t)$	$P(i,t)$	$SR^{Up}(i,t)$	$SR^{Dn}(i,t)$	$P(i,t)$	$SR^{Up}(i,t)$	$SR^{Dn}(i,t)$		
1	155	0	0	0	0	0	20.19	0	0	3462.897	225
2	165.15	0	0	0	0	0	0	0	0	4326.292	225
3	158.67	0	0	0	0	0	0	0	0	3908.9	225
4	154.73	0	0	0	0	0	0	0	0	3672.976	225
5	155.06	0	0	0	0	0	0	0	0	3692.736	225
6	160.48	0	0	0	0	0	0	0	0	4017.282	225
7	155	0	0	18.39	0	0	0	0	0	4116.672	225
8	155	0	0	11.41	0	0	11.19	0	0	3366.541	225
9	155	0	0	16.936	0	0	14.874	0	0	3471.152	225
10	155	0	0	29.026	0	0	22.934	0	0	3719.134	225
11	155	0	0	42.016	0	0	31.594	0	0	4040.889	225
12	155	0	0	46.51	0	0	34.59	0	0	4194.068	225
13	155	0	0	44.32966	0	0	42.85034	0	0	4274.151	225
14	155	0	0	46.43316	0	0	42.16684	0	0	4340.799	225
15	155	0	0	54.166	0	0	39.694	0	0	4538.629	225
16	155	0	0	50.79	0	0	50	0	0	4675.958	225
17	155	0	0	51	0	0	50	0	0	4684.948	225
18	155	0	0	51.08454	0	0	40.65546	0	0	4484.593	225
19	155	0	0	49.94392	0	0	41.02608	0	0	4465.004	225
20	155	0	0	0	0	0	82.35	0	0	4632.29	225
21	155	0	0	0	0	0	82.31	0	0	4631.537	225
22	155	0	0	0	0	0	77.67	0	0	4544.181	225
23	155	0	0	0	0	0	40.93	0	0	3852.995	225
24	155	0	0	0	0	0	40.6	0	0	3846.788	225

It can be seen that the total system cost in Case 3 is reduced when DTS is utilized. The DTS application will result in a similar schedule, but expensive units are not committed in the some scheduling horizon or expensive units generation are reduced. the expected load curtailment costs is reduced in comparing to case 1, because of using FACTS device in steady state and Flowgate biding in contingencies.

Table 9 presents the number of variables, run time, number of constraints and number of iterations associated with cases 3 and 4.

It can be seen that the computational time in case 4 was decreased almost 65% comparing to case 3. This reduction shows efficiency of used algorithm for solving problem. Fig. 3 shows how implementing DTS helps reduce expected load curtailment cost.

To show the efficiency of the proposed strategy in reduction of operation and reliability cost, a case study based on the IEEE-RTS 24-bus system is examined in the following.

The IEEE-RTS includes 24 nodes (buses), 38 branches (transmission lines and transformers) and 32 generating units ranging from 12 MW to 400 MW. The total installed generating capacity and the system peak load is 3405 MW and 2850 MW, respectively. This case was solved using Matlab and GAMS softwares [39].

Table 8
Optimization characteristics in cases 1 and 2.

	Case 1	Case 2
Number of variables	1522	2002
Run time (s)	126	44
Number of constraints	4078	4558
Number of iterations	1	4

Table 9
Optimization characteristics in cases 3 and 4.

	Case 3	Case 4
Number of variables	10,162	10,642
Run time (s)	198.2	68
Number of constraints	8756	9236
Number of iterations	1	8

The proposed model was solved using CPLEX solver in GAMS on PC computer (2.2 GHz) processor and 2 GB of RAM.

IEEE 24-bus Reliability Test System (IEEE RTS) has three phase shifting transformers. In order to show the impact of the flowgate bidding and DTS, the capacity of all branches is decreased by 30%. The phase-shifting transformers installed in lines 11–9, 11–10, and 11–13 are considered as FACTS devices which are dispatchable services and can offer price for shifts of flow by the phase-shifting mechanism. The offer prices for added flowgate capacity during contingencies have been shown in Table 5 and offer price for FACTS device which are dispatchable service is based on Table 6.

In this case, the flowgate bidding and DTS in stochastic joint energy and reserve market with incorporating DC flow constraints are applied. The total operating cost without DTS is 598752 $. Flowgate bidding and DTS solution results are displayed in Table 10.

In Table 10, the operating cost in raw 2 is smaller than that of raw 1, resulting into a cost saving of 4.8%, as expected LMPs are reduced at system buses, too.

Fig. 4 depicts the LMP at bus 1 for the two cases over the 24-h horizon. compared to the case without flowgate bidding and DTS, it can be seen from the figure that LMPs are reduced when flowgate bidding and DTS in peak hours are considered.

In peak hours 11–15 which load is in high level, the phase-shifting transformer in line 11–9, 11–10 and 11–13 are switched on.

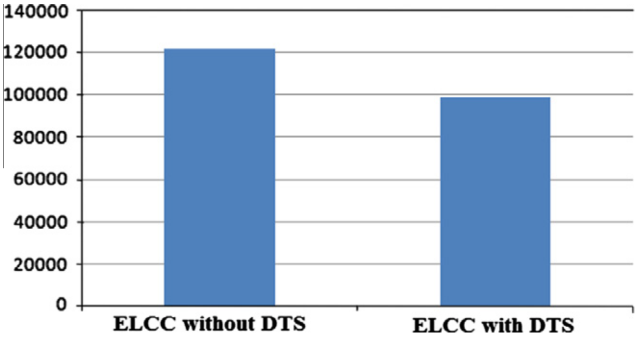

Fig. 3. Effect of DTS in ELCC.

Table 10
Flowgate bidding and DTS solution results.

Total operating cost without DTS	578852 $
Total operating cost with DTS	551067 $
DTS cost	5325 $
Total cost saving	27,785 $

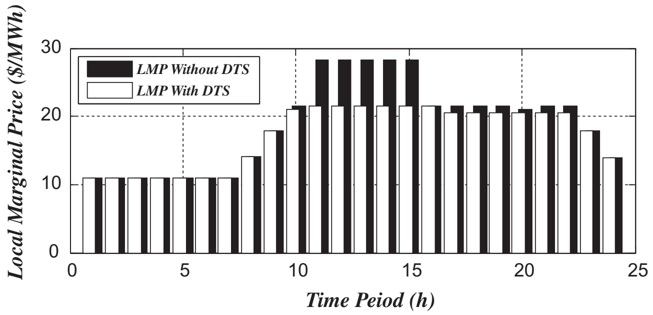

Fig. 4. Effect of flowgate bidding and DTS in LMP at bus 1.

5. Conclusions

This paper presented a comprehensive model of dispatchable transmission services and flowgate bidding in a well-known engineering test case to gain a better understanding of its potential impact in large systems. The flowgate bidding and DTS in stochastic joint energy and reserve market introduced here, can provide a market with greater efficiency and competition. Flowgate bidding and DTS in stochastic joint energy and reserve market do not exist today; however, these results are informative to show that this is a topic worthy of further research based on the possible savings. In this paper it was showed that DTS and flowgate bidding could be parts of the smart grid concept and they can be used to make better use of the current infrastructure as well as additions to the grid that enable more active use of the network. Flowgate bidding and DTS add flexibility to the optimization problem and may allow for better and more economical generation dispatch solutions. Applying Flowgate bidding and DTS solution on 6 and 24 bus test cases resulted into the reduction of operation cost and LMP in buses. It is concluded that the overall cost of the network, including the additional flowgate bidding and DTS costs, would be lower and thereby creating net savings.

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