Proposed a Fast Solution for Transmission switching in joint energy and reserve markets

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Abstract

There is a great resolution calling for smart grids in recent years. Introduction of new technologies, that make the network flexible and controllable, is a main part of smart grid concept and a key factor to its success. Transmission network as a part of system network has drawn less attention. Transmission switching as a transmission service can release us from load shedding and remove the constraints' violations.

In addition to removing the congestion and decreasing the system cost, transmission switching may damage generating units due to transient states in instance of reconfiguration. Therefore, in optimal transmission switching, the system security, practical limitations and possible damages should be considered.

Considering dynamic constraints in proposed model avoid the occurrence of transient instability when opening the line in transmission switching action.

To investigate the efficiency of the proposed strategy IEEE 57 bus test system is studied.

Key Words: smart grids, transmission switching, security, day-ahead market

NOMENCLATURE

i: Index of generating units.

l: Index of total transmission lines.

j: Index of switchable transmission lines.

b: Index of bus.

NG: Number of generating units.

NGb: Number of generating units connected to bus b.

Lb: Number of lines connected to bus b.

NT: Number of scheduling hours.

NJ: Number of switchable transmission lines.

NS: Number of segments of piecewise linear cost function of generating unit.

NC: Number of contingency.

Nb: Number of total buses.

Nl: Number of total transmission lines.

$\rho^s(i,t)$: Offered energy cost segment s of unit i at time t.

$P^s(i,t)$: Power generation of unit i in segment s at time t.

$SUC(i)$: startup cost unit i.

$SUC(i,t)$: startup cost unit i in time t.

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.

$\rho^{Up}{}_{SP}(i,t)$: Offered Up reserve cost of unit i at time t.

$SR^{Up}(i,t)$: Offered Up reserve capacity of unit i at time t.

$\rho^{Dn}{}_{SP}(i,t)$: Offered Down reserve cost of unit i at time t.

$SR^{Dn}(i,t)$: Offered Down reserve capacity of unit i at time t.

$\Delta P^c(i,t)$: ΔP Megawatt of unit i at time t for management contingency c.

$VOLL(b,t)$: Value of loss load in bus b at time t.

$LC^c(b,t)$: Load curtailment in bus b at time t in contingency c.

$\mu(i,t)$: Commitment state of unit i at time t.

$P(i,t)$: Real power generation of unit i at time t.

$P^{\min}(i,t)$: Lower limit of real generation of unit i.

$P^{\max}(i,t)$: Upper limit of real generation of unit i.

$PD(b,t)$: Load demand of bus b at time t.

$RRU(i)$: Ramp rate up unit i (MW/min).

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$RRD(i)$: Ramp rate down unit i (MW/min).

$\xi^c(i,t)$: Binary parameter that is 0 when the unit iis in the contingency c, 1 otherwise.

$\mu^c(l,t)$: Binary parameter that is 0 when the transmission lins in the contingency c, 1 otherwise.

$PL^c(l,t)$: Power flow of line l 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.

$z(l,t)$: Binary variable for income of line l at time t, if line l incomes 1 otherwise 0.

M : Big positive value.

1. Introduction

Transmission switching studies were of the interest to the researches from Eighties. In primary studies, the main focus was decreasing the load shedding. Next, the efficiency of optimal transmission switching to solve other operation issues such as voltage drop, network loss and system security was analyzed. After restructuring in power systems and introduction of smart grid concept, transmission switching problem was redefined in the new environment [1-7].

Switching was used in [8-9] for congestion removal. A method based on DC Optimal Power Flow (OPF) was used in these references. In [10-11] the N-1 security criteria have been added to the model presented in [8-9].

In [12-14], heuristic methods were used to restrict the search space and therefore, to reduce the execution time. In these papers the lines with highest impact on congested lines were categorized based on a sensitivity analysis. In most of studies on transmission switching only the DC network constraints have been considered and the AC constraints voltage security constraints and reactive load flow have been neglected. Since the switching may cause violation in voltage constraints as well as other AC constraints, the methods presented based on DC load flow are less efficient [15].

On the other hand the AC constraints cause nonlinearity in the problem. Therefore, with these constraints the switching problem is a Mixed Integer Non-linear Programming (MINLP) problem. These problems take so long to be solved and it is possible that no solution is found. The global optimality is also not guaranteed. Problem decomposition has been proposed to solve the issue.

Reference [15] found the switching scheme and generation schedule using a DC OPF at the first step. The results then were tested using an AC power flow and in the case of constraint violation, the switching scheme was ban and a new switching scheme was found. As the result of separation of DC and AC sub-problems this method also fails to guarantee the global optimum solution.

In [15-17] Benders decomposition was used. In the main problem, the generation schedule and switching scheme was found based on DC OPF. In sub-problems, AC constraints were checked and in the case of violation the violated constraints were linked to the main problem. These newly introduced constraints change the results of main problem to remove the constraint violations in sub-problem.

Security constraints were included in [17] through N-1 criteria. The security checking sub-problem was not linked to the main problem. This restricts the chance of global optimum solution. The method presented to find the order of switching has also some problems that cause the solution to deviate from the optimum solution in some cases.

Based on the results of researches that some of them have been reported in this section, transmission switching can be useful for operation cost reduction. However, this switching may cause the system instability in some instances. This increase the network security cost. This paper analyses and models the transmission switching with dynamic constraints in a probabilistic co-optimization model for energy and spinning reserve scheduling. Using this model the safe operation considering the dynamic switching constraints has been guaranteed.

Moreover considering dynamic constraints, to reduce the computation time, the network reduction technique is used. Using the network reduction technique, available transmission lines in network is divided to the two sections: switchable and The remainder of this paper is organized as follows. Section 2 represents transmission switching cost modeling, Section 3 represents problem formulation, section 4 presented proposed algorithm for problem solving and section 5 provides some results for case study, and the corresponding discussions. Finally, Section 6 lists some relevant conclusions drawn in this paper.

2- Problem Formulation

In this paper, the optimal TS for procurement optimum spinning reserve is considered in energy and reserve market using Stochastic mixed integer nonlinear programming (SMINLP) that would take into account prevailing generating unit and transmission network constraints.

In the objective function, ISO minimizes the summation of the energy and spinning reserve procurement costs, over the scheduling horizon with considering optimal transmission switching and NJ transmission line with statues transformative in constraints stochastic mixed integer programming.

The cost of switching, including the cost of opening and closing operations and the cost related to the depreciation of the switch insulators, is modeled based on the reinvestment costs for installing the new switches. In a short period, the cost of switching is considered to be proportional to the number of switching operations.

In [18-30] different MINLP problem were solved in different engineering branches including the Unit Commitment (UC) problem. In this section a probabilistic MINLP model is proposed for co-optimization of day-ahead energy and reserve markets. Switching capability is just considered for some network lines. The objective function of (1) is considered to minimize the energy, spinning reserve and switching costs in a 24 hour time period. This statement is mathematically presented as follows:

nonswitchable lines.

$$Min\ \ Total\ \ Cost =$$

$$\sum_{t=1}^{NT}\left\{\begin{array}{l}\sum_{i=1}^{NG}\left(\begin{array}{l}\left\{\begin{array}{l}F_{ci}\left(PG(i,t)\right)+\\ \rho^{Up}{}_{SP}(i,t)SR^{Up}(i,t)+\\ \rho^{Dn}{}_{SP}(i,t)SR^{Dn}(i,t)\end{array}\right\}\times\mu(i,t)+\\ SUC(i,t)\end{array}\right)+\\ \sum_{c=1}^{NC}\Pr(c,t)\times\left\{\begin{array}{l}\left\{\sum_{b=1}^{Nb}VOLL(b,t)LC^{c}(n,t)\right\}+\\ \sum_{i=1}^{NG}\left(\Delta P^{Up,c}(i,t)+\Delta P^{Dn,c}(i,t)\right)\times\\ \rho^{\mathrm{Real}TimePrice}\end{array}\right\}\end{array}\right\} \tag{1}$$

In (1), units' production costs, startup costs and reserve capacity costs are shown in the first term. The second term includes load shedding costs and the cost associate with reserve applications (change in production schedule). Switching cost is shown in third term.

The network and units' constraints should be considered for both pre and post contingency states. The constraints can be divided into two groups, post-contingency and pre-contingency constraints. A complete list of constraints is found in [26-30].

In order to model the dynamic constraints, synchronous machine classical model has been used. In this model the transient stability equations are as follows, considering a constant field voltage.

$$\begin{array}{l}\dot{\gamma}(i)=\Omega_b\times\left(w(i)-1\right)\\ \dot{w}(i)=\dfrac{1}{M(i)}\times\left(P_G(i)-P_e(i)\right)\end{array} \tag{2}$$

In (2), $P_G(i)$ is the input mechanical power of unit, which is considered to be constant. Ω_b is the rate of frequency and $w(i)$ and $\gamma(i)$ are the rotor speed in per unit and rotor angle of unit *i* respectively. The unit inertia constant is *M*(*i*). the electrical power output of the unit can be written as equation (3).

$$Pe(i,t)=E(i)\sum_{j}E(j)\begin{bmatrix}B_{ij}(t)\times\\ \sin\left(\gamma\ (i,t)-\gamma(j,t)\right)+G_{ij}(t)\times\\ \cos\left(\gamma(i,t)-\gamma(j,t)\right)\end{bmatrix} \tag{3}$$

In (8), *E*(*i*) is the electrical motive force of stator field. $B_{ij}(t)$ and $G_{ij}(t)$ are the element of row *i* and column *j* of reduced susceptance and reduced conductance matrices respectively.

$$\gamma^{n+1}(i,t)=\gamma^{n}(i,t)+\frac{\Delta t}{2}\times\left(w^{n+1}(i,t)+w^{n}(i,t)-2\right)$$

$$w^{n+1}(i,t)=w^{n}(i,t)+\frac{\Delta t}{2M(i,t)}\times\begin{pmatrix}PG(i,t)-\\ Pe^{n}(i,t)+\\ PG(i,t)-\\ Pe^{n+1}(i,t)\end{pmatrix} \quad (4)$$

$$n=1,\ldots,Nend \qquad i=1,\ldots,NG$$

$$Pe^{n}(i,t)=E(i)\times \sum_{j}E(j)\begin{bmatrix}B^{n}_{ij}(t)\times\sin\left(\gamma^{n}(i,t)-\gamma^{n}(j,t)\right)+\\ G^{n}_{ij}(t)\times\cos\left(\gamma^{n}(i,t)-\gamma^{n}(j,t)\right)\end{bmatrix} \quad (5)$$

The rotor angle and speed can be found through dividing the time span of transient state into *Nend*steps using (4). In these equations Δt is the length of time steps and *Nend* is the number of time steps indexed by *n*. Considering the switchable lines Bn(t) and Gn(t) can be defined using (6).

$$Y_{bus}=G_{bus}+jB_{bus}=\begin{bmatrix}y_{11} & y_{12}\times Z^{n}(l,t) & \ldots & y_{1n}\\ y_{12}\times Z^{n}(l,t) & \vdots & \vdots & \vdots\\ \vdots & \vdots & \vdots & \vdots\\ y_{n1} & \cdots & \cdots & y_{nn}\end{bmatrix}$$
$$Z^{1}(l,t)=Z(l,t-1)$$
$$Z^{n}(l,t)=Z^{n+1}(l,t)=Z(l,t) \qquad n=2,\ldots,Nend-1$$
$$G_{loadi}=P_{loadi}/V_i^2,\ B_{loadi}=Q_{loadi}/V_i^2 \quad i=1,\ldots,Nb \quad (6)$$

Finally the safe switching constraint is given in (7) for unit *i*.

$$\gamma^{n}(i,t)-\frac{\sum_{k=1}^{NG}H_k\gamma^{n}(k,t)}{\sum_{k=1}^{NG}H_k}\le\gamma^{critical}(i,t) \quad (7)$$

The formulation presented in [26-30] and (1) to (7) models the probabilistic joint energy and reserve problem considering the transmission switching.

Problem is solved with Benders decomposition method. This section describes the solution methodology based on Benders decomposition. Because of problem is large scale, in this paper was used the benders decomposition algorithm for solving the stochastic mixed-integer linear programming problem. The relationship between Benders decomposition and stochastic linear programming problem is explained in section.

We present the mathematical formulation of the master problem and the subproblem resulting from the application of Benders decomposition to problem (1).

Here, the master problem is formulated as an optimization problem which minimizes the objective function (1) while satisfying constraints for the secure operation of power system in steady states.

Here, the sub-problem 1 is network security check in contingencies with considering sub-problem 2 that is cost of expected involuntary load curtailment in contingency c while sub-problems satisfying constraints for prevent the power system in coming to the emergency state.

Sub-problem 1 as formulated in following which is a MIP problem would check the transmission constraints. The objective is:

$$\hat{V}_t=Min\sum_{b=1}^{Nb}BPM_1(b,t)+BPM_2(b,t) \quad (8)$$

The bus power mismatch in bus b is presented by (8), where SLbt,1 and SLbt,2 are surplus and deficit variables.

$$\begin{cases}P(i,t)=\hat{P}(i,t)\times\hat{\mu}(i,t) & \leftrightarrow\ \pi(i,t) \quad i=1,\ldots,NG\\ SR^{Up}(i,t)=\hat{SR}^{Up}(i,t)\times\hat{\mu}(i,t) & \leftrightarrow\ \sigma(i,t) \quad i=1,\ldots,NG\\ SR^{Dn}(i,t)=\hat{SR}^{Dn}(i,t)\times\hat{\mu}(i,t) & \leftrightarrow\ \omega(i,t) \quad i=1,\ldots,NG\\ LC^{c}(b,t)=\hat{LC}^{c}(b,t)\times\hat{I}^{c}(b,t) & \leftrightarrow\ \psi(b,t) \quad b=1,\ldots,Nb\\ x_{in}(l,t)=\hat{x}_{in}(l,t) & \leftrightarrow\ \eta(l,t) \quad l=1,\ldots,NJ\end{cases} \quad (9)$$

Where $\hat{P}(i,t)$, $\hat{\mu}(i,t)$, $\hat{SR}^{Up}(i,t)$, $\hat{SR}^{Dn}(i,t)$ and $\hat{x}_{in}(l,t)$ are fixed values calculated by the master problem and $\hat{LC}^{c}(b,t)$ is fixed value calculated by the sub problem 2.

$$\sum_{i=1}^{NGn} P(i,t)\xi^c(i,t) + \sum_{i=1}^{NGb} \Delta P^{Up}(i,t) - \sum_{i=1}^{NGb} \Delta P^{Dn}(i,t) - PD(b,t) + LC^c(b,t) - \sum_{l\in Lb} \begin{matrix} PL^c(l,t) + \\ BPM_1(b,t) - BPM_2(b,t) \end{matrix} = 0 \quad (10)$$

$$b = 1,2,...Nb \quad c = 1,...NC$$

Power flow of switchable lines in each contingency with considering switchable transmission lines:

$$\begin{cases} \left(\dfrac{\delta_n^c(l,t) - \delta_m^c(l,t)}{x_l}\right) - PL^c(l,t) + x_{out}^c(l,t) \times \\ M + \mu^c(l,t) \times M + x_{in}^c(l,t) \times \varepsilon \ge 0 \\ \left(\dfrac{\delta_m^c(l,t) - \delta_n^c(l,t)}{x_l}\right) - PL^c(l,t) - x_{out}^c(l,t) \times \\ M - \mu^c(l,t) \times M - x_{in}^c(l,t) \times \varepsilon \le 0 \\ x_{out}^c(l,t) + x_{in}^c(l,t) = 1 \end{cases} \quad (11)$$

$$l = 1,2,..\text{و}NJ,...,Nll \quad c = 1,...NC \quad t = 1,...NT$$

Transmission line flow limits in each contingency:

$$-PL^{\max}(l,t) \le PL^c(l,t) \le PL^{\max}(l,t) \quad (12)$$
$$l = 1,2,..\text{و}NJ,...,Nll \qquad t = 1,...NT$$

Sub-problem 2 as formulated below:

$$Min \ \ TotalCost^{With\ Contigency}_{NJ} = \sum_{t=1}^{NT}\left\{\sum_{c=1}^{NC}\begin{matrix} \Pr(c,t) \times \\ \left\{\sum_{b=1}^{Nb} VOLL(b,t) \times LC^c(b,t) \times I^c(b,t)\right\}\end{matrix}\right\} \quad (13)$$

Constraints:

Load curtailment for network in each contingency:

$$\sum_{b=1}^{Nb} LC^c(b,t) = W \times \begin{Bmatrix} \sum_{i=1}^{NG} P(i,t)\left(1-\xi^c(i,t)\right) + \\ \sum_{i=1}^{NG} SR^{Up}(i,t)\left(1-\xi^c(i,t)\right) - \\ \sum_{i=1}^{NG} SR^{Up}(i,t)\left(\xi^c(i,t)\right) \end{Bmatrix} \quad (14)$$

$$t = 1,2,...NT \quad c = 1,...NC$$

$$\frac{\begin{Bmatrix} \sum_{i=1}^{NG} P(i,t)\left(1-\xi^c(i,t)\right) + \sum_{i=1}^{NG} SR^{Up}(i,t)\left(1-\xi^c(i,t)\right) - \\ \sum_{i=1}^{NG} SR^{Up}(i,t)\left(\xi^c(i,t)\right) \end{Bmatrix}}{\sum_{i=1}^{NG} P^{\max}(i,t)} \le W \le 1 + \frac{\begin{Bmatrix} \sum_{i=1}^{NG} P(i,t)\left(1-\xi^c(i,t)\right) + \sum_{i=1}^{NG} SR^{Up}(i,t)\left(1-\xi^c(i,t)\right) - \\ \sum_{i=1}^{NG} SR^{Up}(i,t)\left(\xi^c(i,t)\right) \end{Bmatrix}}{\sum_{i=1}^{NG} P^{\max}(i,t)} \quad (15)$$

Load curtailment limit:

$$0 \le LC^c(b,t) \le PD(b,t) \times I^c(b,t) \quad (16)$$

Cut 1 as followed:

$$\hat{V}_t + \sum_{i=1}^{NG} \pi(i,t) \times \left(P(i,t) \times \mu(i,t) - \hat{P}(i,t) \times \hat{\mu}(i,t) \right) + \sum_{i=1}^{NG} \sigma(i,t) \times \left(SR^{Up}(i,t) \times \mu(i,t) - \hat{SR}^{Up}(i,t) \times \hat{\mu}(i,t) \right) + \sum_{i=1}^{NG} \omega(i,t) \times \left(SR^{Up}(i,t) \times \mu(i,t) - \hat{SR}^{Up}(i,t) \times \hat{\mu}(i,t) \right) + \sum_{l=1}^{NJ} \eta(l,t) \times \left(x_{in}(l,t) - \hat{x}_{in}(l,t) \right) \le 0$$

Cut 2 as followed:

$$\hat{V}_t + \sum_{b=1}^{Nb} \psi(b,t) \times \begin{pmatrix} LC^c(b,t) \times I^c(b,t) - \\ \hat{LC}^c(b,t) \times \hat{I}^c(b,t) \end{pmatrix} \le 0$$

3- Numerical Results

IEEE 57 bus system is selected to analyze the results of considering the transmission switching in a probabilistic joint energy and reserve problem. This system contains 80 lines and 7 generation units. The total load is 1250.8 MW. The single phase diagram is given in fig. 1.

To analyze the effect of switching operations the following case studies will be analyzed:

a) Joint energy and reserve clearing without switching.
b) Joint energy and reserve clearing with switching neglecting the transient stability constraints.

Tables 1 and 2 show the UC status in joint energy and reserve clearing without switching operation. Energy and reserve costs are 319156 \$ 59840 \$ respectively for this case. The probabilistic security cost (cost of applied reserve) is 62544 \$ in this case. The average marginal prices are given in fig 2 for different hours.

Table 1- UC status in energy market

Bus Generator	Hours (1-24)																						
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
3	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
6	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0
8	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	0	0
9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	0	0
12	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Table 2- UC status in spinning reserve market

Bus Generator	Hours (1-24)																						
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
2	1	1	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
3	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
6	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0
8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	0	0	0
9	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	0	0
12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	0	0	0	0

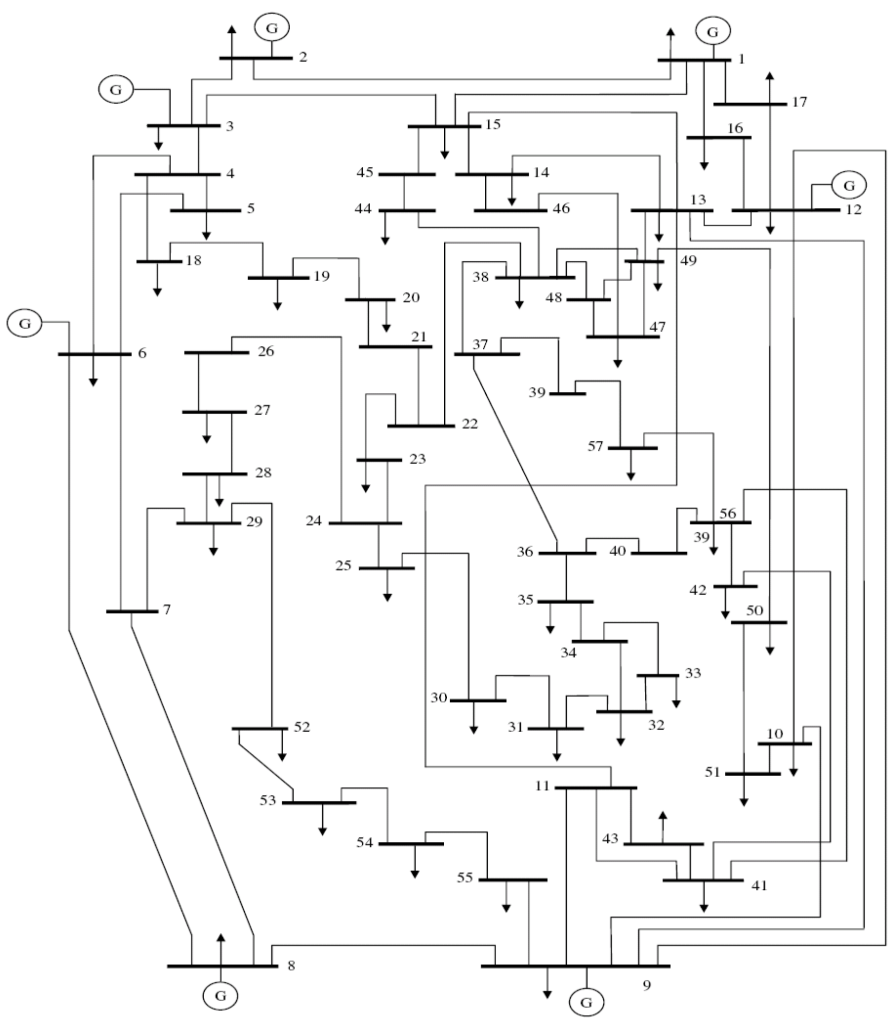

Fig 1- Single phase diagram of 57-bus system

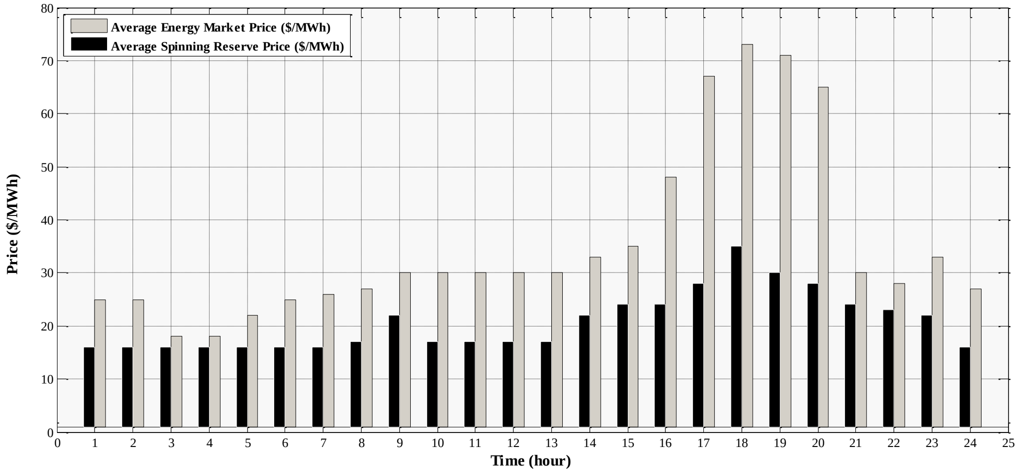

Fig. 2- Average marginal price in energy and reserve markets

3-1- Joint energy and reserve clearing with switching operations neglecting the transient stability constraints

The dynamic constraints are neglected in this case. The UC status is given in Tables 3 and 4 for energy and reserve markets respectively. Comparing to the previous study, the status of some units has not been changed. However, production of the expensive units has been decreased. The switching order is given in Table 5. Table 6 compares the costs of case (a) to those associated with this case. As can be seen the energy, reserve and security cost are reduced by 8%, 7% and 4% of the values reported in case (a). For switching operations the switching status of hour 0 is considered to be same as the base case.

Table 3- UC status in energy market, case (b)

Bus Generator	Hours (1-24)																							
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	0
3	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
6	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0
8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	0	0
9	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	1	1	1	1	1	1	0	0
12	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0

Table 4- UC status in spinning reserve market, case (b)

Bus Generator	Hours (1-24)																							
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	0
3	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	0	0
8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	0	0	0
9	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0
12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	0	0	0	0

Table 5- Switching status, case (b)

switchable Lines	Hours (1-24)																						
1-15	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	0	0
7-29	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	0	0
8-9	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	1	1
22-38	1	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	0	0	0	0	0	1	1	1
48-49	0	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	1	1	1	1	0	0	1	1
48-44	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1
13-15	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	0	0
3-4	1	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	1	1
12-16	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0
1-2	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0

Table 6- Operation costs, case (b)

costs	Before switching action	After switching action without stability limitation
Energy market cost	319156$	293623$
Spinning reserve market cost	59840$	55651$
Security network cost	62544$	60042$

3-2- Joint energy and reserve clearing with switching considering the transient stability constraints

Tables 7 and 8 show the UC status of in energy and spinning reserve markets with stability constraints. Considering these constraints, the UC status has been changed. In fact the system costs are higher with stability constraints included. These costs are still lower than the base case without switching operations. Table 9 shows the system energy, reserve and security costs. As can be seen these costs decrease by the values of 6.5%, 5.5% and 3% comparing to the case without switching operations. Table 10 shows the switching status for this case study. As can be seen due to stability constraints opening or closing operations of some switches have performed in different hours comparing to Table 5.

Table 7- UC status in energy market, case (c)

Bus Generator	Hours (1-24)																						
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	0
3	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
6	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0
8	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	0	0
9	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	0
12	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0

Table 8- UC status in spinning reserve market, case (c)

Bus Generator	Hours (1-24)																						
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
2	0	0	0	0	0	0	0	1	1	0	0	0	0	0	1	1	1	1	1	1	1	1	1	0
3	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0
6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	0
8	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	0	0	0
9	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	0
12	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0

Table 9- Operation costs, case (b)

costs	Before switching action	After switching action without stability limitation	After switching action with stability limitation
Energy market cost	319156$	293623$	298410$
Spinning reserve market cost	59840$	55651$	56548$
Security network cost	62544$	60042$	60667$

Table 10- Switching status, case (c)

switchable Lines	Hours (1-24)																						
1-15	1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	0
7-29	1	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0
8-9	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	1
22-38	1	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	0	0	0	0	0	1	1	1
48-49	0	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	1	1	1	1	0	0	1	1
48-44	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1
13-15	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	0	0
3-4	1	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	1
12-16	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	1
1-2	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0

The results show that though the transmission switching is useful for system cost reduction, it may cause transient instability in some instances. Therefore, considering the stability constraints in switching is inevitable. With the stability constraints considered in optimization, the performance of the cost reduction is lower. As can be seen the energy cost reduction considering and neglecting the stability constraints are 6.5 and 8 percent. However, these constraints reduce the risk of instability and reduce the instability costs.

For switching of the line 16-12, in case (b) the status of this line is changed from close in hour 16 to open in hour 17. The simulation of this switching in PSAT shows that this switching causes system instability. However, with stability constraints considered (case (c)) this switching takes place from hour 18 to hour 19. The simulations show that the system is stable in this case.

Fig. 3 shows the average marginal price in energy and reserve markets for cases (a), (b) and (c) in 24 hour. As can be seen, these prices are higher for the case including the stability constraints. This increase in the prices with respect to the prices in case study (b) shows that though considering the switching operations in the joint energy and reserve market neglecting the stability constraints leads to the lower prices, this causes the instability in some system units and imposes the high instability cost to the system.

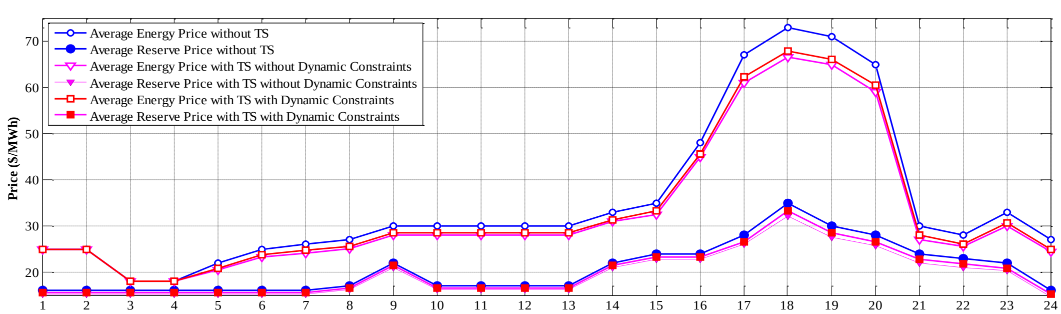

Fig.3- Average marginal price in energy and reserve markets for cases (a), (b) and (c)

In addition to reduction of the energy and spinning reserve, transmission switching can improve the voltage at different system buses. Fig 4 shows the Switching effects on voltage at bus 18. The switching has improved the voltage at bus 18 in most of hours. Without switching this voltage is out of allowable range in some instances.

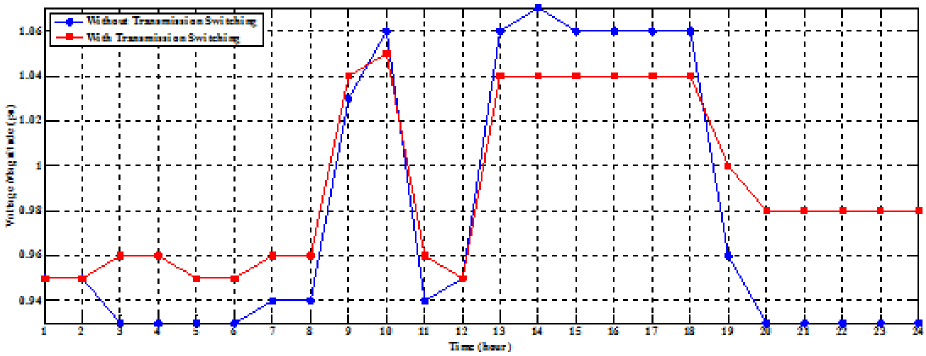

Fig. 4- Switching effects on voltage at bus 18

Therefore it can be concluded that the proposed methods for decreasing the execution time do not render sub-optimal solutions; the accuracy of the results is the same while the execution time has significantly decreased.

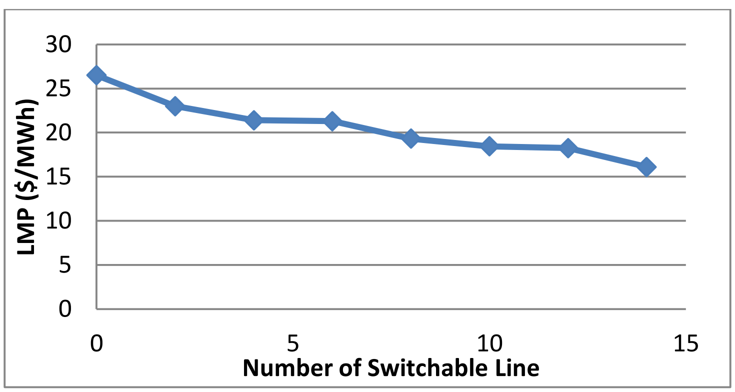

Fig5. LMP change with considering number of switchable transmission line

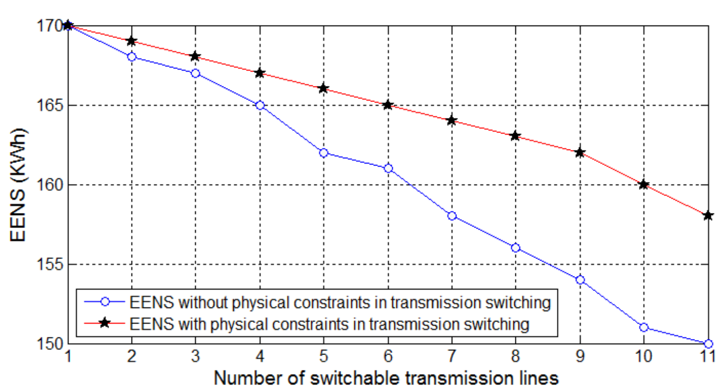

Fig6. EENS change with considering number of switchable transmission line

The above results demonstrate that due to transmission switching operation and consideration of the stability constraints regarding this operation, the problem execution time has increased. Therefore, in order to decrease the execution time, Benders decomposition and branch based network reduction approaches are employed, so the switching operation can be done for large-scale power systems. LMP in peak hours for bus num 1 is almost 26.5 ($/MWh) for base case. Fig 5 show change LMP with considering switchable transmission lines. As well as Fig 6 show change EENS in bus 1 with considering switchable transmission lines.

4- Conclusion

In this paper the transmission switching has been modeled in joint energy and reserve market clearing. It was observed that through the proper switching operations not only the energy cost but also the spinning reserve and security costs have been reduced. In addition it was shown in case studies that though the switching operation can reduce the operation cost, it may cause dynamic instability and therefore, can impose the additional costs to the system. Therefore, it is necessary to develop appropriate switching strategy to reduce the chance of instability and damage to the units. This paper proposed a methodology to develop such strategies in a day-ahead market. As the results show that the reduction in system cost is lower when the dynamic stability constraints are considered in the mode, but the system stability is preserved under this setup. Considering the large number of continuous and binary variables and also increase in the number of lines with switching ability, the problem execution time increases significantly. In order to overcome this burden, Benders decomposition and branch based network reduction methods were proposed. Employing these methods the problem execution time decreased significantly.

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