Application of Benders decomposition in stochastic scheduling of thermal units with coordination of wind farm and energy storage system considering security constraint

MOHSEN VATANPOUR[1] **AND AHMAD SADEGHI YAZDANKHAH**[2]

[1] *PHD Candidate, Electrical Engineering Dept., Sahand University of Technology, Tabriz, Iran.*
[2] *Associate Professor, Renewable Energy Research Center, Sahand University of Technology, Tabriz, Iran.*
[*] *Corresponding author:sadeghi@sut.ac.ir , Phone: +984133459321*

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Green electrical power resources, especially wind farms have ascending growth in power generation technologies. Although growing trend of wind farm penetration is beneficial from environmental view of point, wind speed uncertain nature and fluctuations threaten system reliability and security. Energy storage systems are good choices as backup for such systems with high volatility. The main concern of this paper is about solving stochastic security constraint unit commitment (SCUC) problem in presence of wind farms and storage systems and modelling of storage systems in Benders decomposition method. To achieve a robust solution, the SCUC problem is solved by a scenario based method in which benders cuts are generated to remove congestion from electrical power lines and check feasibility and optimality of the solution in all scenarios. To generate Benders cuts, security, feasibility and optimality sub-problems have been formulated and solved in an iterative structure. Wind power scenarios are generated by Monte Carlo sampling method and followed by a scenario reduction technique to reduce computation burden. Investigating the simulation results on a six-bus standard test system demonstrates economic advantages of the proposed method while power system technical and security constraints are satisfied.

keywords: *Security constrained unit commitment (SCUC), day-ahead stochastic programming, energy storage system, Benders decomposition, wind energy.*

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1. INTRODUCTION

Environmental concerns and fossil fuel resources limitations, have persuade countries to design promotional policies to utilize renewable energy resources and accelerate investments in its infrastructures. Subsequently it would lead to further participation of the renewable energy resources in producing electrical energy [1]. Wind energy is one of the fast growing renewable energy sources (RES) [2]. The main problem of large incorporation of integrated wind farms is their highly erratic nature [3, 4]. Wind power production may often tolerate by 20% of installed power of wind farm capacity [5].In systems with high incorporation of wind energy (approximately more than 20% of total power generation), volatilities face system operators with the challenge of determining accurate wind power generation [6]]. If wind power forecast does not materialize in real time, power balance problems may confront to the power system. Penalty factors method has been proposed in [7] to diminish forecast errors risk. Here the shortage power due to overestimation, should be purchased from the other alternate resources or load shedding should be executed. On the other hand the excess power at underestimation circumstance should be paid by the system operator (SO). Many scholars have applied demand response (DR) methodology using authority of control of loads to balance total generation and demand in real time [8–10]. Price sensitivity in DR-based load forecasts in power systems with considerable wind penetration, would deteriorate forecasting accuracy. In such power systems alternate back up generations should be planned [5]. Dynamic ramping is the potential capability of the power system which can be activated by applying stochastic programming. In stochastic programming the reserved capacity of thermal units which are capable for adjusting their generation over the required response time are programmed as backups and their ramp constraints are considered in scenarios [11]. In state-of-the-art energy management strategies of RESs, energy storage systems (ESS) are used and recommended as beneficial technologies [1, 12, 13]. ESSs in cooperation with wind farm would enhance both of system reliability and utilization from available wind in real time [14, 15]. Accordingly ESS act as supplementary source for wind farm by absorbing excess power and suppressing shortage power, in underestimation and overestimation conditions respectively. A comprehensive investigation about coordination of various technologies of ESSs with wind farms has been studied in [16]. In [17–20] the coordination of ESSs with wind farms to decrease wind curtailments has been discussed. Unit commitment is a complicated mixed integer programming optimization problem subjected to the units and system operational constraints [21, 22]. From technical view of point, power network security is the most important aspect of the power system operation in a market driven planning, also as reported in [23], neglecting security considerations in scheduling process, can lead to bulk wind curtailments. In order to find a feasible and financially viable schedule, security constraint unit commitment is essential [24]. The main challenge of SCUC problem is modelling security constraint. However this constraint is violated rarely for special lines, it should be remained relaxed in all time periods throughout the network. To apply security constraint into the UC problem, three different frameworks have been used in the literature; direct, indirect and decomposition based methods. In a direct method, security constraint along with other constraints are formulated in a unified frame. The main drawback of this method is that it adds constraints to the bulk of problem and consequently may hamper convergence [25]. Indirect methods split the SCUC problem into two separate stages. In the first stage, network security constraints are omitted from the optimization problem and the feasible solution will be achieved in the second stage, by optimal power flow or security constrained economic dispatch. As an advantage of indirect methods, computational burden will be decreased significantly and their convergence time will be reduced subsequently. However this procedure does not provide a mechanism within the first stage to optimize the generation distribution throughout a transmission network. So applying indirect methods may cause to start from an inferior point to find final feasible solution. As the third strategy, in [26] Benders decomposition method has been applied to the SCUC problem. It introduces a recursive procedure which decouples SCUC into a master problem and a security subproblem. Using Benders decomposition to control power flow of the deviated lines, constraints of master problem would be adjusted according to the results of security subproblem. In [27] Benders decomposition method considers the lines power flow and bus voltages for a system with thermal units only. A stochastic SCUC in the presence of wind farm has been proposed in [5]. Here due to consider stochastic nature of wind energy, feasibility and optimality cuts are added into the master problem formulation. In reference [24], ac security constraints in hydrothermal scheduling problem have been considered using Benders decomposition. A hybrid bacterial foraging algorithm has been implemented to solve non convex SCUC problem. Reference [8] proposes, demand response control to alleviate the effect of forecast errors and consequently wind curtailments in a wind integrated power system. SCUC problem is solved in the presence of RESs and EES by an indirect method. In first stage of the proposed method unit commitment problem has been solved by Genetic algorithm and the feasible solution is evaluated by a probabilistic optimal power flow in the second stage. In this paper, stochastic security constrained unit commitment is modeled as a mixed integer linear programming (MILP) optimization problem and solved for a system with thermal units in cooperation with wind units and ESS. By applying Benders decomposition ESS is modeled using the proposed stochastic scenario based method by reformulating Benders optimality and feasibility cuts. The proposed method is applied on a modified six bus test system and its results compared with cases in which storage flexibility features are not considered in optimality and feasibility cuts. Subsequent sections are organized as follow. Section 2 presents a scenario based model to solve the stochastic SCUC problem. Modelling and formulation of the energy storage system in Benders optimality and feasibility cuts is applied in section 3. In section 4 the simulation results of applying the proposed model on the test system are investigated, and the conclusion is extracted in section 5.

2. PROBLEM STATEMENT

SCUC problem modeling in a scenario based stochastic method is described in this section. To generate wind speed scenarios, Monte Carlo (MC) simulation method has been implemented in which wind speed follows a predicted Weibull probability distribution function with a diurnal wind pattern. The diurnal pattern of wind implies wind speed intermittency in a region during 24 hours, which has been modeled by a sinusoidal term. More detail about this modelling is given in [28]. Because of high dependency of the execution time in scenario based methods to the number of scenarios, a scenario reduction has been done. The main objective of the scenario reduction methods is to eliminate scenarios with low probability and merge similar scenarios, so that the preserved scenarios would be the most probable scenarios [29–31]. In this work SCENRED tool of GAMS optimization software has been used for scenario reduction in which the fast backward/forward method has been selected because of its accuracy and computational advantages [32]. In the rest of the paper wherever scenario word is used, it implies reduced scenarios concept. As depicted in 1, Available wind power of each scenario procures by a typical curve which relates wind farm power to the wind speed.

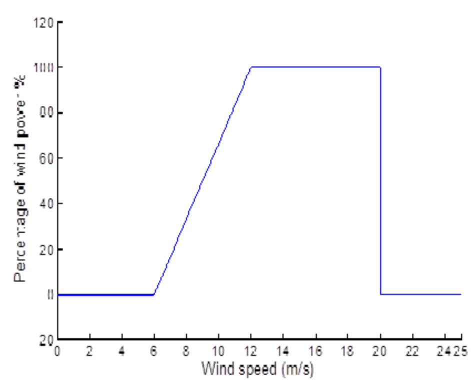

Fig. 1. Wind to power conversion curve for a wind farm [28].

A. Objective function

SCUC problem in the market driven power system is executed by independent system operator (ISO) [33]. The main objective is to minimize total operation cost of the system as given in Eq. (1).

$$\min \left\{ TC = \overbrace{\left[\sum_{j=1}^{NG} \sum_{K=1}^{NH} FC_j(p_{j,k}) + SU_{j,k} \right]}^{\text{Main solution cost}} + \overbrace{\left[\sum_{k=1}^{NH} \sum_{jsn=1}^{NS} \rho_{sn} \psi_{sn}^{k} \right]}^{\text{Transition Cost to Scenarios}} \right\} \quad (1)$$

$$FC_j(P_{j,k}) = \alpha_j + \beta_j P_{j,k} + \gamma_j P_{j,k}^2 \quad (2)$$

Objective function consists of two terms .The first term in equation Eq. (1) models the generation cost of the thermal units in the main scenario over the time horizon in which each unit power generation cost has been calculated by a piecewise linearized approximation of quadratic function shown in Eq. (2). Also, at the time of change in the status of each unit, its startup cost will be added to the objective function as a constant charge. The second term of equation Eq. (1), demonstrates the cost of transition from main scenario into the probable reduced scenarios weighted by the probability factor of each scenario. Generation planning of the thermal units based on main scenario would be affected by the occurrence of other probable scenarios. This transition leads to a new generation allocation cost, which is called "transition cost" in this paper. It should be noted that determining the transition cost of each scenario requires another optimization problem to be solved under the condition that on-off status of the thermal units remain unchanged.

B. Constraints

Optimization problem is subjected to two categories of constraints; units constraints and system constraints. Constraints of thermal generation units are formulated in equations Eq. (3)-Eq. (8). Equation Eq. (3) models power generation limits of each thermal unit. The range of possible changes in power generation at two consecutive periods of time, is restricted by ramping up and down rates as expressed in Eq. (4). In equation Eq. (5) minimum up and down time constraints for each unit are modeled, which enforce each unit remain in the same on/off status for a certain time. Wind turbines generation limits is modeled in equations Eq. (7). As shown in the first tree equations of Eq. (8), the rates of loading and depletion power of ESS are related to the storage capacity and stored energy in its reservoir. Maximum and minimum charge/discharge power rates, and ramp up/down rates for ESSs are formulated consequently. Efficiency of the ESS system is one of the characteristics of the storage system and relates to the employed technology. In this study a typical constant value (0.9) is assumed to model storage efficiency $\eta_{st,k}$ [14].

$$\begin{cases} P_{j,k} \le P_j^{max} I_{j,k} \\ -P_{j,k} \le -P_j^{min} I_{j,k} \end{cases} \quad (3)$$

$$\begin{cases} P_{j,k+1} \le P_{j,k}^{t} + Rup_j I_{j,k} \\ -P_{j,k+1} \le -P_{j,k}^{t} + Rdn_j I_{j,k} \end{cases} \quad (4)$$

$$\begin{cases} X_{j,k}^{on} = (X_{j,k}^{on} + 1) I_{j,k-1} \\ (X_{j,k-1}^{on} - MU_j + 1)(I_{j,k-1} - I_{j,k}) \ge 0 \end{cases} \quad (5)$$

$$\begin{cases} X_{j,k}^{off} = (X_{j,k}^{off} + 1)(1 - I_{j,k-1}) \\ (X_{j,k-1}^{on} - MD_j + 1)(I_{j,k-1} - I_{j,k}) \ge 0 \end{cases} \quad (6)$$

$$PW_{jw,k} \le PW_{jw,k}^{f} \quad (7)$$

$$\begin{aligned} Psd_{st,k} &\le Es_{st,k} \quad \eta_{st}^{dis} \\ Psc_{st,k}\eta_{st,k}^{dis} &\le (Es_{st,k} - Es_{st,k}^{max}) \\ Es_{st,k} &= \sum_{t=1}^{k-1} (Psc_{st,t} \quad \eta_{st}^{chrg} - Psd_{st,t}/\eta_{st}^{dis}) \\ Psc_{st,k} &\le Ps_{chrg}^{max}(1 - Is_{st,k}) \\ -Psc_{st,k} &\le -Ps_{chrg}^{min}(1 - Is_{st,k}) \\ Psd_{st,k} &\le Ps_{dis}^{max} s_{st,k} \\ -Psd_{st,k} &\le -Ps_{dis}^{min} s_{st,k} \\ Psc_{st,k} &\le Psc_{st,k-1} + Rup_{st}^{chrg}(1 - Is_{st,k}) \\ -Psc_{st,k} &\le -Psc_{st,k-1} + Rdn_{st}^{chrg}(1 - Is_{st,k}) \\ Psd_{st,k} &\le Psd_{st,k-1} + Rup_{dis}^{st} s_{st,k} \\ -Psd_{st,k} &\le -Psd_{st,k-1} + Rdn_{dis}^{st} s_{st,k} \end{aligned} \quad (8)$$

System constraints including power flow limits and system power balance has been stated in Eq. (9) and Eq. (10). Eq. (9) determines balance between generations and consumptions. Network security constraint for the main scenario would be relaxed while equation Eq. (10) does not pervert.

$$\sum_{j} P_{j,k} + \sum_{st} Ps_{dis}^{st,k} - \sum_{st} Ps_{chrg}^{st,k} + \sum_{w} Pw_{jw,k} = PD_k \quad (9)$$

$$-PL_l^{max} \le \sum_{b=1}^{Nb} SF_{l,b}(KP_{b,j}P_{j,k} - KD_{b,k}PD_{b,k} - KST_{b,st}Psc_{st,k} + KST_{b,st}Psd_{st,k}) \quad (10)$$

$$PL_l^{max} \ge \sum_{b=1}^{Nb} SF_{l,b}(KP_{b,j}P_{j,k} - KD_{b,k}PD_{b,k} - KST_{b,st}Psc_{st,k} + KST_{b,st}Psd_{st,k})$$

In each scenario transition, system security and balance constraints and dispatch restrictions of the units including maximum and minimum power generations, and ramp rates should be satisfied. Also all constraints of ESSs should be considered for scenarios as presented in Eq. (11).

$$\sum_{j} P_{j,k}^{sn} + \sum_{st} Ps_{dis}^{sn,st,k} - \sum_{st} Ps_{chrg}^{sn,st,k} + \sum_{w} Pw_{jw,k}^{sn} = PD_k \quad \textbf{(11)}$$

$$-PL_l^{max} \leq \sum_{b=1}^{Nb} SF_{l,b}(KP_{b,j}P_{j,k}^{sn} - KD_{b,k}PD_{b,k} - KST_{b,st}Psc_{st,k}^{sn} + KST_{b,st}Psd_{st,k}^{sn})$$

$$PL_l^{max} \geq \sum_{b=1}^{Nb} SF_{l,b}(KP_{b,j}P_{j,k} - KD_{b,k}PD_{b,k} - KST_{b,st}Psc_{st,k} + KST_{b,st}Psd_{st,k})$$

$$\begin{cases} P_{j,k}^{sn} \leq \hat{P}_{j,k}^{t} + Rup_j I_{j,k} \\ -P_{j,k}^{sn} \leq -\hat{P}_{j,k} + Rdn_j I_{j,k} \end{cases}$$

$$\begin{cases} P_{j,k}^{sn} \leq P_j^{max} I_{j,k} \\ -P_{j,k}^{sn} \leq -P_j^{min} I_{j,k} \end{cases}$$

$$Psd_{st,k}^{sn} \leq Es_{st,k} \quad \eta_{st}^{dis}$$

$$Psc_{st,k}^{sn}\eta_{st}^{dis} \leq (Es_{st,k} - Es_{st,k}^{max})$$

$$Es_{st,t}^{sn} = \sum_{t=1}^{k-1}(Psc_{st,t}^{sn} \quad \eta_{st}^{chrg} - Psd_{st,t}^{sn}/\eta_{st}^{dis})$$

$$Psc_{st,k}^{sn} \leq Ps_{chrg}^{max}(1 - \hat{I}s_{st,k})$$

$$-Psc_{st,k}^{sn} \leq -Ps_{chrg}^{min}(1 - \hat{I}s_{st,k})$$

$$Psd_{st,k}^{sn} \leq Ps_{dis}^{max}\hat{I}s_{st,k}$$

$$-Psd_{st,k}^{sn} \leq -Ps_{dis}^{min}\hat{I}s_{st,k}$$

$$Psc_{st,k}^{sn} \leq \hat{P}sc_{st,k-1} + Rup_{st}^{chrg}(1 - \hat{I}s_{st,k})$$

$$-Psc_{st,k}^{sn} \leq -\hat{P}sc_{st,k-1} + Rdn_{st}^{chrg}(1 - \hat{I}s_{st,k})$$

$$Psd_{st,k}^{sn} \leq \hat{P}sd_{st,k-1} + Rup_{dis}^{st}\hat{I}s_{st,k}$$

$$-Psd_{st,k}^{sn} \leq -\hat{P}sd_{st,k-1} + Rdn_{dis}^{st}\hat{I}s_{st,k}$$

3. BENDERS DECOMPOSITION AND ITS APPLICATION

In [34] J.F. Benders introduces a technique to solve combinatorial optimization problems. This method has been frequently used to solve power system optimization problems [5,24,33,35]. By Benders decomposition method, original optimization problem is decoupled into a master problem and some subproblems in which the complicating constraints are splitted from master problem. An iterative procedure as illustrated in Figure 2 adjoins the master problem to subproblems. Knowing that, the splitted constraints would not be taken into account in the first step to find the initial solution. In the next step feasibility subproblems would be executed to check feasibility of the splitted constraints. Any deviation in this stage, generates a feasibility cut as a constraint which would be added into the master problem formulation. Lower bound (LB) solution is obtained by solving renewed master problem as depicted in the flowchart. On the other hand if the LB solution is feasible, then optimality subproblem is solved and consequently optimality cut is added to the objective function of the master problem. Upper bound (UB) solution would be achieved by solving master problem adopted by optimality cuts. This procedure would be iterated until the difference between upper bound and lower bound is less than a predetermined small value.

A. Master problem

Master problem is formulated by equationsEq. (1)-Eq. (9) and the constraints which would be added by Benders cuts as depicted

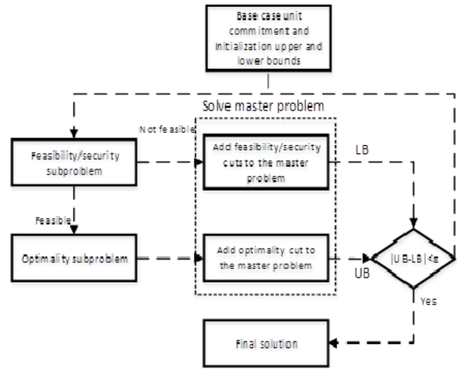

Fig. 2. Flowchart of the Benders decomposition

in Figure 2. In the following of this section Benders subproblems and their related cuts are described.

B. Security subproblem

By the security constraint, flowed power through the network lines should be limited according to the capacity of each line in all of the time periods. Considering this constraint, will enlarge the unit commitment problem dimension and would make it difficult for any solver to solve such a bulk problem without falling in local minima. Whereas the overflow problem often occurs in some particular lines in some period of times (mostly peak load time), a procedure that considers only overloaded lines, could be helpful in overcoming the security constrained problem with better performance. Benders decomposition is a beneficial method to solve such an optimization problem with sparsely activated constraints. More details about this method is available in [33]. The security subproblem formulated as Eq. (12) yields the surplus power of overloaded lines and the dual parameters for violated constraints. The values assigned with uch as, $\hat{P}_{j,k}$, $\hat{P}sc_{st,k}$ and $\hat{P}sd_{st,k}$ are founded after solving the main problem. In this paper shift factors ($KP_{b,j}$, $KD_{b,k}$ and$KST_{b,st}$) have been used to calculate line power flows according to the procedure explained in [36]. If any violation is occurred, Benders feasibility cut formulated in Eq. (13) will be added to the master problem as new constraint.

$$min\{sv_{l,k}\} \quad \textbf{(12)}$$

$$-sv_{l,k} \leq PL_l^{max} - \sum_{b}^{Nb} SF_{l,b}(KP_{b,j}\hat{P}_{j,k} - KD_{b,k}PD_{b,k} - KST_{b,st}\hat{P}sc_{st,k} + KST_{b,st}\hat{P}sd_{st,k}) \quad \lambda 1_{l,k}$$

$$-sv_{l,k} \leq PL_l^{max} + \sum_{b}^{Nb} SF_{l,b}(KP_{b,j}\hat{P}_{j,k} - KD_{b,k}PD_{b,k} - KST_{b,st}\hat{P}sc_{st,k} + KST_{b,st}\hat{P}sd_{st,k}) \quad \lambda 2_{l,k}$$

$$sv_{l,k} \geq 0$$

$$s\hat{v}_{l,k} + (\hat{\lambda}2_{l,k} - \hat{\lambda}1_{l,k})\sum_{b}^{Nb} SF_{l,b}[(KP_{b,j}(P_{j,k} - \hat{P}_{j,k}) - KST_{b,st}(Psc_{st,k} - \hat{P}sc_{st,k}) + KST_{b,st}(Psd_{st,k} - \hat{P}sd_{st,k})] \leq 0 \quad \textbf{(13)}$$

C. Scenarios feasibility subproblem

In the scenario based method, the solution found from the master problem should be able to adjust with new conditions occurs in each scenario. This problem is checked by solving feasibility subproblem as expressed in Eq. (14)-Eq. (17). Generally, in feasibility subproblem three types of constraints are exist. Equation Eq. (15) guarantees the security of the power lines in all scenarios. In Eq. (16), dispatch constraints related to the generation power of units in all scenarios are checked. Finally constraints of energy storage systems in all of scenarios has been considered in Eq. (17). Any positive value of the objective function ($S_{sn,k}$) of this subproblem, implies that the main solution could not be responsible for new conditions in scenario sn and time period$k$. To overcome this incompatibility, in the next iteration a feasibility cut as formulated in Eq. (18) should be added to the master problem for any positive value of $\hat{S}_{sn,k}$.

$$minimize\left\{S_{sn,k}=\sum_{l=1}^{NL}S0_{sn,l,k}+S1_{sn,k}+S2_{sn,k}\right\} \quad (14)$$
$$S0_{sn,l,k}+S1_{sn,k}+S2_{sn,k}\geq 0$$

$$Network\ \ Constraints\left\{ \right. \quad (15)$$
$$S0_{sn,l,k}\leq PL_l^{max}-\sum_{b}^{Nb}$$
$$SF_{l,b}(KP_{b,j}P_{j,sn,k}-KD_{b,k}PD_{b,k}-KST_{b,st}Psc_{st,sn,k}+KST_{b,st}Psd_{st,sn,k})$$
$$S0_{sn,l,k}\leq PL_l^{max}+\sum_{b}^{Nb}$$
$$\left. SF_{l,b}(KP_{b,j}P_{j,sn,k}-KD_{b,k}PD_{b,k}-KST_{b,st}Psc_{st,sn,k}+KST_{b,st}Psd_{st,sn,k})\right\}$$

$$generation\ \ unit\ \ constraints\left\{ \right. \quad (16)$$
$$PD_k=\sum_{j}P_{j,sn,k}^{sn}+\sum_{st}Ps_{dis}^{sn,st,k}-\sum_{st}Ps_{chrg}^{sn,st,k}+\sum_{w}Pw_{w,sn,k}+S1_{sn,l,k}-S2_{sn,l,k}$$
$$P_{j,sn,k}\leq P_j^{max}\hat{I}_{j,k}\quad \mu 1_{sn,j,k}$$
$$-P_{j,sn,k}\leq -P_j^{min}\hat{I}_{j,k}\quad \mu 2_{sn,j,k}$$
$$P_{j,sn,k}\leq \hat{P}_{j,k}+Rup_j\hat{I}_{j,k}\quad \lambda 1_{sn,j,k}$$
$$-P_{j,sn,k}\leq -_{j,k}+Rdn_j\hat{I}_{j,k}\quad \lambda 1_{sn,j,k}$$
$$\left. Pw_{jw,sn,k}\leq Pw_{jw,sn,k}^{f}\right\}$$

$$Storages\ \ constraints\left\{ Es_{st,sn,k}=\sum_{t=1}^{k-1}(Ps_{chrg}^{sn,st,k}\ \ \eta_{sn,st,k}^{chrg}-Ps_{dis}^{sn,st,t}/\eta_{sn,kst}^{dis}) \right. \quad (17)$$
$$Es_{sn,st,k}\leq Es_{st}^{max}$$
$$Psd_{sn,st,k}\leq Es_{sn,st,k}\quad \eta_{sn,kst}^{dis}$$
$$Psc_{sn,st,k}\leq Ps_{chrg}^{max}(1-\hat{I}s_{st,k})\qquad \mu c_{1,st}^{k}$$
$$-Psc_{sn,st,k}\leq Ps_{dis}^{min}(1-\hat{I}s_{st,k}))\qquad \mu c_{2,st}^{k}$$
$$Psd_{sn,st,k}\leq Ps_{dis}^{max}\hat{I}s_{st,k})\qquad \mu d_{1,st}^{k}$$
$$-Psd^{sn,st,k}\leq -Psc_{dis}^{min}\hat{I}s_{st,k}\qquad \mu d_{2,st}^{k}$$
$$Psc_{sn,st,k}\leq \hat{P}sc_{st,k}+Rup_{st}^{chrg}(1-\hat{I}s_{st,k}))\qquad \lambda c_{1,st}^{k}$$
$$-Psc_{st,k}\leq -\hat{P}sc_{st,k}+Rdn_{dis}^{chrg}(1-\hat{I}s_{st,k})\qquad \lambda c_{2,st}^{k}$$
$$Psd_{sn,st,k}\leq \hat{P}sd_{st,k}+Rup_{dis}^{st}\hat{I}s_{st,k}\qquad \lambda d_{1,st}^{k}$$
$$\left. -Psd_{sn,st,k}\leq -\hat{P}sd_{st,k}+Rdn_{dis}^{st}\hat{I}s_{st,k}\qquad \lambda d_{2,st}^{k}\right\}$$

$$\sum_{j}^{N_G}[(\lambda 1_{sn,j,k}-\lambda 2_{sn,j,k})(P_{j,k}-\hat{P}_{j,k}) \quad (18)$$
$$+(\lambda 1_{sn,j,k}Rup_j+(\lambda 1_{sn,j,k}Rdn_j+\mu 1_{sn,j,k}P_j^{max}-\mu 2_{sn,j,k}P_j^{min})(I_{j,k}-\hat{I}_{j,k})]$$
$$+\sum_{st}^{N_{st}}[\mu c_{2,st}^{k}Ps_{chrg}^{min}-\mu c_{1,st}^{k}Ps_{chrg}^{max}+\mu d_{1,st}^{k}Ps_{dis}^{max}-\mu d_{2,st}^{k}Ps_{dis}^{min}$$
$$-\lambda c_{1,st}^{k}Rup_{st}^{chrg}-\lambda c_{2,st}^{k}Rdn_{st}^{chrg}+\lambda d_{1,st}^{k}Rup_{dis}^{st}$$
$$+\lambda d_{2,st}^{k}Rdn_{dis}^{st})(Is_{st,k}-\hat{I}s_{st,k})$$
$$+(\lambda c_{1,st}^{k}-\lambda c_{2,st}^{k})(Psc_{st,k}-\hat{P}sc_{st,k})$$
$$+(\lambda d_{1,st}^{k}-\lambda d_{2,st}^{k})(Psd_{st,k}-\hat{P}sd_{st,k})]+\hat{S}_{sn,k}\leq 0$$

D. Optimality subproblem

To assign the optimum value for the transition cost in the Eq. (1) from the main scenario into the other scenarios ψ_{sn} , the security constraint optimization problem should be solved for each scenario by solving Eq. (19). Accordingly if the objective function $WO_{sn,k}$ is greater than the scenario transition cost ψ_{sn}^{k} , optimality cut will be added to the master problem as a constraint shown in Eq. (20).

$$min\{WO_{sn,k} = \sum_{j=1}^{NG} \sum_{g}^{Nseg} FC_j(P_{j,sn,k})\} \quad \textbf{(19)}$$

$$0 \leq PL_l^{max} - \sum_{b}^{Nb} SF_{l,b}(Kp_{b,j}P_{j,sn,k} - KD_{b,k}PD_{b,k} - KST_{b,st}Psc_{st,sn,k} + KST_{b,st}Psd_{\cdot}$$

$$0 \leq PL_l^{max} + \sum_{b}^{Nb} SF_{l,b}(Kp_{b,j}P_{j,sn,k} - KD_{b,k}PD_{b,k} - KST_{b,st}Psc_{st,sn,k} + KST_{b,st}Psd_{\cdot}$$

$$\sum_j P_{j,sn,k} + \sum_{st} Ps_{dis}^{sn,st,k} - \sum_{st} Ps_{chrg}^{sn,st,k} + \sum_{w} Pw_{w,sn,k} = PD_{sn,k}$$

$$P_{j,sn,k} \leq \hat{P}_j^{max}\hat{I}_{j,k} \qquad \mu 1_{sn,j,k}$$

$$-P_{j,sn,k} \leq -\hat{P}_j^{min}\hat{I}_{j,k} \qquad \mu 2_{sn,j,k}$$

$$P_{j,sn,k} \leq \hat{P}_{j,k} + Rup_j\hat{I}_{j,k} \qquad \lambda 1_{sn,j,k}$$

$$-P_{j,sn,k} \leq -\hat{P}_{j,k} + Rdn_j\hat{I}_{j,k} \qquad \lambda 2_{sn,j,k}$$

$$Pw_{jw,k}^{sn} \leq Pw_{jw,k}^{f}$$

$$Ps_{dis}^{sn,st,k} \leq Es_{sn,st,k}\eta_{sn,st,k}^{dis}$$

$$Es_{sn,st,k} = \sum_{t=1}^{k-1}(Ps_{shrg}^{sn,st,t}\eta_{chrg}^{sn,st,t} - Ps_{dis}^{sn,st,t}/\eta_{dis}^{sn,st,t})$$

$$Es_{sn,st,k} \leq Es_{st}^{max}$$

$$Psc_{sn,st,k} \leq Ps_{chrg,st}^{max}(1 - \hat{I}s_{st,k}) \qquad \mu c_{1,st}^{k}$$

$$-Psc_{sn,st,k} \leq -Ps_{chrg,st}^{min}(1 - \hat{I}s_{st,k}) \qquad \mu c_{2,st}^{k}$$

$$Psd_{sn,st,k} \leq Ps_{dis,st}^{max}.\hat{I}s_{st,k} \qquad \mu d_{1,st}^{k}$$

$$-Psd^{sn,st,k} \leq -Ps_{dis,st}^{min}.\hat{I}s_{st,k} \qquad \mu d_{2,st}^{k}$$

$$Psc_{sn,st,k} \leq \hat{P}sc_{st,k} + Rup_{st}^{chrg}.(1 - \hat{I}s_{st,k}) \qquad \lambda c_{1,st}^{k}$$

$$-Psc_{sn,st,k} \leq -\hat{P}sc_{st,k} + Rdn_{st}^{chrg}.(1 - \hat{I}s_{st,k}) \qquad \lambda c_{2,st}^{k}$$

$$Psd_{sn,st,k} \leq \hat{P}sd_{st,k} + Rup_{dis}^{st}.\hat{I}s_{st,k} \qquad \lambda d_{1,st}^{k}$$

$$-Psd_{sn,st,k} \leq -\hat{P}sd_{st,k} + Rdn_{dis}^{st}.\hat{I}s_{st,k} \qquad \lambda d_{2,st}^{k}$$

$$\psi_{jsn} \geq WO_{sn,k} + \{\sum_{j}^{N_G}[(\lambda 1_{sn,j,k} - \lambda 2sn,k,j)(P_{j,k} - \hat{P}_{j,k}) \quad \textbf{(20)}$$
$$+ (\lambda 1_{sn,j,k}Rup_j + \lambda 2sn,k,jRdn_j + \mu 1_{sn,j,k}P_j^{max} - \mu 2_{sn,j,k}P_j^{min})(I_{jk} - \hat{I}_{jk})]$$
$$+ \sum_{st}^{N_{st}}[(\mu c_{2,st}^{k}Ps_{chrg}^{min} - \mu c_{1,st}^{k}Ps_{chrg}^{max} + \mu d_{1,st}^{k}Ps_{dis}^{max} - \mu d_{2,st}^{k}Ps_{dis}^{min}$$
$$- \lambda c_{1,st}^{k}Rup_{st}^{chrg} - \lambda c_{2,st}^{k}Rdn_{st}^{chrg} + \lambda d_{1,st}^{k}Rup_{dis}^{st} + \lambda d_{2,st}^{k}Rdn_{dis}^{st})[Is_{st,k} - \hat{I}s_{st,k}]$$
$$+ (\lambda c_{1,st}^{k} - \lambda c_{2,st}^{k})(Psc_{st,k} - \hat{P}sc_{st,k}) + (\lambda d_{1,st}^{k} - \lambda d_{2,st}^{k})(Psd_{st,k} - \hat{P}sd_{st,k}))]$$

4. SIMULATION RESULTS

To simulation the presented modelling, modified six bus IEEE test system has been considered. In which three conventional units and one wind farm units and one storage unit are committing for supplying loads. Network of the system has been represented in Figure 3.

Technical data of three conventional generation units and the wind farm has been presented in Table 1. Also an energy storage system is connected to bus 4. Table 2 represents network line data.

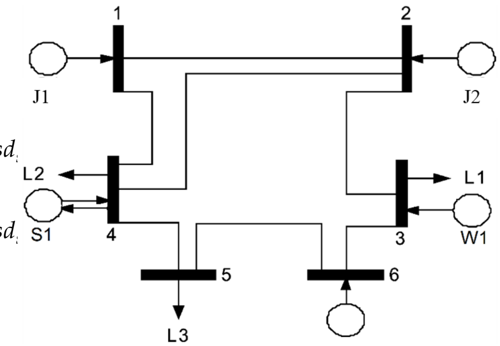

Fig. 3. IEEE modified 6 bus test system

Table 1. Generators Data

dim1	Bus Num	α	β	γ	Start up Cost	Min up time	Min down timen	Fuel price	Pmax	Pmin	Ramp up	Ramp down
J1	1	176.9	13.5	0.0005	100	4	4	1.247	220	100	85	85
J2	2	129.9	32.6	0.001	200	1	1	1.246	100	10	50	50
J3	6	137.4	17.6	0.005	0	1	1	1.246	20	10	20	20
wind	3					1	1		75	0	75	75
ESS1	4					1	1		40	0	20	20

Weibull distribution function has been selected to generate wind speed data in which scale factor is 11.28 and shape factor is 2.3. Also a sinusoidal daily pattern has been considered which its magnitude is equal to 10% of mean speed and its peak is occurred at 17. In Figure 4, one hundred primary scenarios generated by Monte Carlo simulation method are depicted. After executing scenario reduction by SCENRED toolbox of GAMS optimization software, four scenarios are remained which they are converted to wind power scenarios by a typical approximate wind farm conversion function given in [28] as shown in Figure 1. Four reduced wind speed scenarios and their converted power are shown in Figure 5 and Figure 5 respectively. In following of this section, three different cases have been executed to show the effect of modelling storage system in security, feasibility and optimality cuts. In case I storage unit is not considered in any cut and it is considered only in the master problem. In case II storage system is considered in security and feasibility cuts. In case III the storage is modeled in all of

Table 2. Line data

Line Num	From Bus	To Bus	r(ω)	x(ω)	B(mho)	Max Power(MW)
11	1	2	0.0005	0.17	0.02	200
12	2	3	0	0.037	0.02	100
13	1	4	0.003	0.258	0.03	100
14	2	4	0.007	0.197	0.03	100
15	4	5	0	0.037	0.03	100
16	5	6	0.002	0.014	0.07	100
17	3	6	0.0005	0.018	0.01	100

Benders cuts and finally their results are compared.

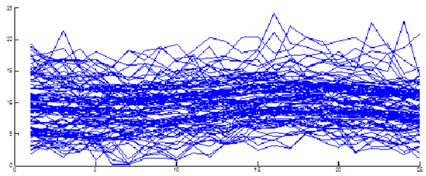

Fig. 4. Initial wind speed scenarios generated by Monte Carlo

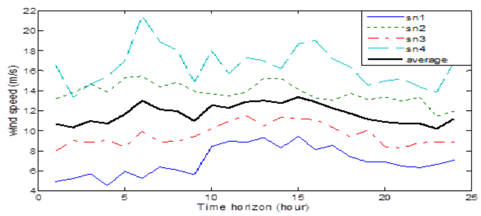

Fig. 5. Wind speed reduced scenarios and the average speed

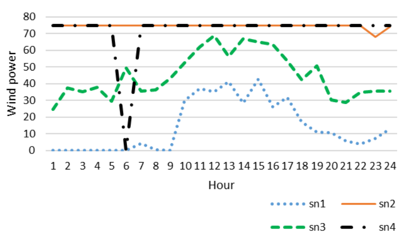

Fig. 6. Wind power for reduced scenarios Data

.1. Case I: Results without modelling storage as a variable

In this case ESS is modeled in the main scenario and it is not considered in the Benders cuts as a variable. So feasibility and security cuts do not apply any limit on ESS performance through the cuts applying to the main problem. By executing this case for the load profile given in Figure 7, the algorithm is not converged. In scenario 1, line 3 which connects buses 1 and 4 is overloaded in peak-load hours 14 – 16, 18, 20 and 22. After executing feasibility cuts, the power flows will be below the line capacities as depicted in Figure 8 in all scenarios in which main solution cost is increased from $ 62859.898 into $ 64185.63. Also sum of probability weighted transition cost into other probable scenarios is $ 21191.87.

.2. Case II: Results considering ESS in feasibility and security cuts and not in optimality cut

In this case EES is modeled as a variable in the security and feasibility subproblems by equations Eq. (12) and Eq. (14),Eq. (17) respectively. If there is a violation in any of the subperoblems, related Benders cuts would be generated according to the equations presented by Eq. (13) and Eq. (18) and would be added to the master problem, as new constraints in each iteration. By executing the algorithm for this case a feasible solution has been

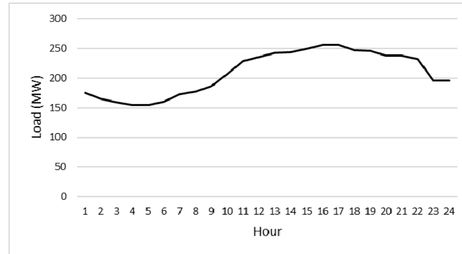

Fig. 7. Day ahead Hourly load data

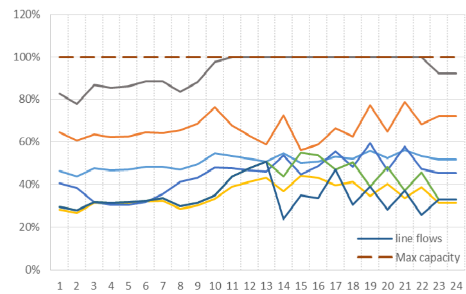

Fig. 8. Power flows through the lines in scenario 1.

selected as optimum in which the value of objective function is obtained $ 77264.84. The cost of generation for the main scenario is $ 66597.08. Sum of probability weighted costs of transition from main scenario into the other probable scenarios is $ 10667.75. The units status (unit commitment results) and their generation details are given in Table 3. In Table 3 the negative signed values for ESS means power consumption (storing mode) and positive values imply power generation (spending mode). In this case storage is able to adjust according to the wind farm situation to compensate its volatility in scenarios and also it is obvious from the storage capacity illustrated in Figure 9 that the ESS charging occurs in off peak hours and spends its stored power in peak load hours of the main scenario.

Table 3. Power dispatch of generation units and energy storage system in case II

Time	1	2	3	4	4	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
g1	117	111	100	100	100	100	100	103.2	125	132	143.6	151.1	157.2	158.6	163.8	163.8	163.7	163.7	163.7	163.7	163.7	163.7	143.6	131.1
g2														10	10	10	10	10						
g3											10	10	10						10	10	10	10		
wind	58.17	54.13	61.88	58.99	70.43	75	75	74.35	61.83	75	75	75	75	75	75	75	75	71.45	64.24	61.16	58.95	58.75	52.33	64.51
EES	0	0	-3.21	-4.26	-15.4	-14.5	-1.61	0	0	0	0	0	0	0.81	7.011	7.306	1.603	8.071	2.532	4.696	0.266	0	0	
LOAD	175.2	165.2	158.7	154.7	155.1	160.5	173.4	177.6	186.8	207	228.6	236.1	242.2	243.6	248.9	255.8	256	246.7	246	237.4	237.3	232.7	195.9	195.6

.3. Case III: Simulation results considering storage in both feasibility and optimality cuts

In this case, the effect of considering ESS model in Benders optimality subproblem and cuts will be investigated in accordance with equations Eq. (19) and Eq. (20), respectively. The unit commitment results of generation and storage units and their power generation dispatch are shown in Table 4. Table 5 represents a brief comparison between the results of the three cases. For case III, the optimal value of objective function is achieved $ 76573.79 which causes to save $ 691.05 rather than the solution of Case II. It verifies the effectiveness of modelling ESS in finding the optimum solution. A comparison between generation costs of three cases has been shown in Figure10. It is concluded that the

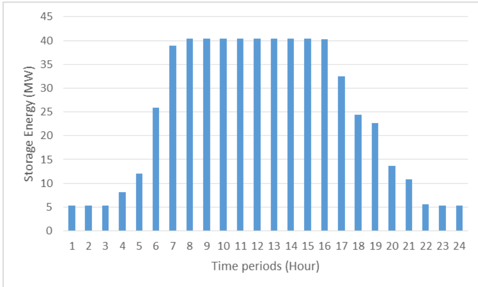

Fig. 9. Hourly variations of energy stored in storage unit

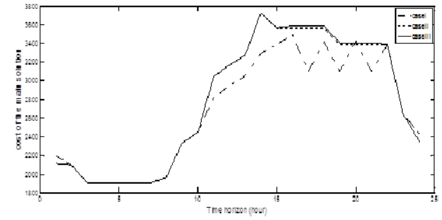

Fig. 10. The comparison of hourly generation cost of the cases

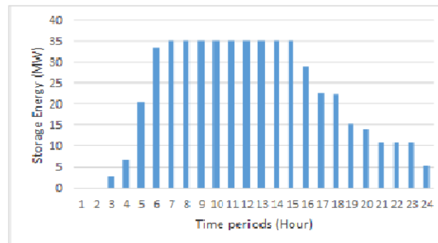

Fig. 11. Hourly status of energy storage capacity for case III

cost of main solutions in cases III and II are higher than that of case I, however the overall cost is decreased based on the reduction of transition cost in cases II and III. Also the hourly status of the energy storage capacity is depicted in Figure 11. In which it is demonstrated in off-peak hours (3 to 8) energy storage capacity has been fully charged and in peak load hours it has begun to deplete. Also it is obvious that energy storage capacity has been kept full in peak load periods which will cause to reduce transition costs of scenarios. It should be noted that, unit J3 is a more economic unit than unit J2 so it is committed in time periods 11 - 13 and 19 - 22. At the time periods 14-18 for security considerations and eliminating congestion from the line between buses 1 and 4, unit J2 has been committed.

Table 4. Power dispatch of generation units and energy storage system case III

Time	1	2	3	4	4	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
g1	112.2	111	100	100	100	100	100	103.2	125	132	143.6	151.1	157.2	158.6	163.9	165.2	165.2	165.2	165.2	165.2	165.2	163.9	143.6	126.3
g2														10	10	10	10	10						
g3											10	10	10						10	10	10	10		
wind	58.2	54.1	61.9 59	70.4	75	75	74.3	61.8	75	75	75	75	75	75	75	75	71.5	64.2	61.1	58.9	58.7	52.3	64.51	
EES	4.78	0	-3.21	-4.26	-15.4	-14.5	-1.61	0	0	0	0	0	0	0	0	5.56	5.76	0.05	6.50	0.99	3.13	0	0	4.781
LOAD	175.2	165.1	158.7	154.7	155.1	160.5	173.4	177.6	186.8	207	228.6	236.1	242.2	243.6	248.9	255.8	256	246.7	246	237.4	237.3	232.7	195.9	195.6

Table 5. Comparison of costs in three cases

****	Total cost	Transition cosy to scenarios	Cost of main solution	Run time(sec)
case1	85377.5	21191.87	64185.63	25
case2	77264.84	10667.75	66597.08	55
case3	76573.79	9976.25	66597.54	65

5. CONCLUSIONS

Integrating wind power technologies, faces power system managers with considerable uncertainties because of stochastic nature of wind speed. In this paper a cooperation of energy storage system besides of conventional thermal units and wind farm has been investigated in a stochastic scenario-based framework. Moreover to have a practical solution, power delivery security constraints has been considered in the model. For this purpose, to decrease computational burden, Benders decomposition technique has been implemented in which energy storage system has been modeled in feasibility and optimality cuts as a variable. Executing proposed model on three different cases concludes that modelling of energy storage system in probable scenarios as an alternative energy resource, would significantly enhance both feasibility and optimality features of cooperation. Proposed method would have economical and technical benefits for systems in which renewable energy resources have significant penetration and power security is the challenge of the system.

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