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A Robust Integrated Approach for Optimal Management of Power Networks Encompassing Wind Power Plants

Aliasghar Baziar, Mohammad Reza Akbarizadeh, Amin Hajizadeh, Mousa Marzband, Rui Bo

***Abstract*-- This paper basically concentrates on providing some significant steps for congestion management of the power systems based on an interval-based robust chance constrained transmission switching (IBRCC-TS) approach for decreasing the congestion of the system while increasing the robustness of the system against uncertainties of the wind turbines. However, the utilization of TS approach in the power system is a severe challenge, since there is no limitation over the switching rate during a certain timespan in the network as well as the power switches' failure uncertainty. Besides, the frequent switching by the TS method decreases the switch maintenance and puts the network reliability at risk. To overcome this problem, the reliability of the circuit breakers (CBs) is considered in the studied model aiming to determine the optimal number of the switching of the CBs. In addition, due to the nonlinear relation of CBs' reliability, a linearization technique is performed to linearize the CBs' reliability relation. Another step which is pursued in this paper is the utilization of energy storage system (ESS) to increase the reliability and decrease the congestion of the system. The effectiveness of the algorithm is compared with some of the well-known meta-heuristic algorithms and the proposed model is implemented on the IEEE 6-bus and 24-bus test systems. The obtained results proved the authenticity and validity of the work.**

***Index Terms*-- Wind Power, Interval based Robust Chance Constraint (IBRCC), energy storage system, allocation algorithm, Reliability.**

I. NOMENCLATURE

Sets/Indices

$\mho^b / b$	Indice and buses
Ω^g / g	Indices of generators
$\mho^k / k$	Indices of lines.
Ω^s / s	Indices of scenario.
$\mho^n / n$	Indices and set of control variable for the optimization allocation algorithm.
$\mho^m / m$	Indices and set of matrix W variables.
$\mho^j / j$	Indices and set of the number of iterations.
$\mho^M / M$	Indices and set of matrix K'', $\mho^M = \{1,..,n\}$.
$\mho^i / i$	Indices and set of $H_{w_i}, \mho^i = \{1,..,m\}$.

Constants

$C\ , C1$	Price of generation for generators.
P_g^{max}, P_g^{min}	Generation max/min of generators.
P^{max}, p^{min}	Max/min of exchange power of battery.
P	Matrix of subway's stations candidates.
$PD_{b,t}^s$	Amount of demand in each bus.
E^{max}, E^{min}	Max/min of energy of battery.
A_1	number of switching which is occurred before t
zc_k^s, uc_g^s	Contingency state of (line k)/(unit g).
$R_{\ g}^{s+}, SR_g^+$	ramp up/ramp down rate.
$SU_{g,t}, SD_{g,t}$	Start-up and shut-down cost for generators.
N	Candidate points
n	chosen point of N .
Y	Parameter of linearizing model.
SWT	Wind speed.
ρ, A	Wind density, Area of rotor blades.
γ, κ	Coefficients related to failure probability of CB
B_{bm}	Susceptance of lines.
Θ_{DU}	Number of DU.
$\bar{\delta} / \underline{\delta}$	Max/min radius of continues uncertainty.
α	Risk tolerance level

Variables

$Cost_l, Cost_e$	EENS cost and ,maintenance cost.
C_s	Binary variable that indicates constraint related to scenario s if it is imposed or not.
$E_{b,t}^{Bat}$	Energy of battery.
K	Matrix of control variables.
KT	Matrix of replaced elements in the optimization algorithm.
k', k''	Auxiliary variables of the optimization algorithm.
$P^0_{\ g,t}, Q^0_{g,t}$	Generator active/reactive power.
$Pw^{s\pm}_{\ s,t}$	Uncertain wind power generation.

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P^{S}_{kt}	Active power flows of line.
$PL_{k,t}, QL_{k,t}$	Active/reactive power losses of line.
$P^{Bat}_{b,t}, P^{ch}_{b,t}, P^{dis}_{b,t}$	Exchange power, charge power and discharge power of battery.
$Pr_{s,t}$	Generation power of wind turbine.
$U(N)$	The failure measure.
N_{k}	Number of switching in line k
R_{k}	Reliability of CB
ES	Expected Energy Not Supplied
$j_{k,j}$	Binary variables for linearizing
$v^{s}_{g,t}, w^{s}_{g,t}$	Start-up/shutdown binary variable for Generators
F	Objective function
F^{best_sort}	Sorted matrix of the best values of the objective function.
$F1_{r}$	Objective function of the elements of matrix ψ_r
$F1^{Best}$	Best solution of the matrix Fl_r
H_{w_i}	Matrix of k'_n
w'_j	Sorted format of matrix W based on best values of the objective function.
ψ_r	Auxiliary matrix in optimization algorithm.
ψ^{Best}	Best member of matrix ψ_r based on best values of the objective function.

I. INTRODUCTION

Recently, a significant growing trend in wind turbine systems (WTSs) installation with various capacities and applications can be observed across the world. Apart from the uncertainty associated with the output power of the wind turbines, WTSs are suitable choices to generate electricity. Employing the Transmission Switching (TS) in the Security-Constrained Unit Commitment (SCUC) increases the security of the power network, voltage inconstancy and leads to contingency improvements [1-4]. Hence, the TS approach has been vastly investigated by researchers to handle contingencies in power system. In [2-3], the TS is utilized to implement the security benchmark of treat *N-1*, and also to deal with the overvoltage and power flow improvement which is also pursued in [4]. Authors in [5-7] investigated one of the challenges in TS studies based on selecting switchable lines because of the TS implementation on reliability test system (RTS). According to the historical data of swedish transmission network, a complete reliability model is suggested for special type of CB [8]. The CB reliability significance and its major role in the power network is pointed out in [7]. A reliability model for CB is required which defines the reliability and number of switching of the CBs.

In addition to the mentioned references, the TS has been employed in several studies with various aims. For instance, the TS is used in reference [9] to reduce EENS. reference [10] proposed an algorithm in which the switchable lines are optimally selected disregarding the number of switching of the lines. To extend an advanced uncertainty management method, different types of uncertainties are categorized into Continues Uncertainties (CUs) and Discrete Uncertainties (DUs). The first type of uncertainty belongs to the typically known continuous intervals and happens in high frequency for a short period. Power system operation based on the CUs with known upper and lower bounds of the uncertainty scope, has been investigated by means of several methods such as standard robust optimization approach (SROA) [11], and Interval-Based Robust Approach (IBRA) which focuses on the boundary of uncertainty instead of probability density function (PDF). The decision making procedure in the IBRA is a type of conservative strategy based on the worst cases in the uncertainty resources realization. The two-stage SROA has been employed for the day-ahead power system operation in reference [11]. The SROA is also developed in reference [12] to solve the security-constraint unit commitment (SCUC) problem with short-lived uncertainty due to wind power generation. In contrary to the SROA used in [11] and [12] which needs to determine the uncertainty range, the IBRA in this paper makes an effort to find out the highest feasible unknown variation range of the CUs that the system can tolerate with an acceptable operating cost. Implementing the suggested IBRA for each optimization model is simple while it does not make the problem complex. The presented IBRA is appropriate for unstructured CUs whereas it requires less information on the uncertainty set. Without a doubt, the IBRA can be more suitable for structured CUs as well. The major disadvantage of IBRA is that it cannot characterize the DUs in power system problems while it is DUs are not types of interval based structure. The other techniques for investigating the DUs effects on the power system operation are probabilistic methods, e.g., stochastic programming and chance-constrained Programming (CCP) [13], [14]. Indeed, the stochastic programing is highly dependent upon the number of generated scenarios to specify the DUs probable realizations [13]. Unlike the stochastic programming, the constraints are satisfied based on the predefined probability levels using the CCP. Utilizing this approach, the constraints are defined as deterministic constraints with respect to the scenario-dependent constraints in the stochastic programming [14]. In this study, to handle the mentioned shortcomings of the IBRA and CCP, an effective Interval Based robust chance constraint (IBRCC) method is proposed based on the integrated optimization framework of IBRA and CCP models, which gathers the advantages of the both techniques. As a robust method, the IBRA is implemented to maximize the variation range of wind uncertainty toleration for the system, whereas the CCP is employed to manage the DUs (random outages of generating units and transmission lines) under the CUs' conditions. Robust Chance Constraint (DRCC) optimization is another technique to cope with the uncertainty presented in the previous research works [15], [16], [17] and [18].

Frankly speaking, apart from the uncertainty of renewable energy sources and different ways to deal with, the applicability of sustainable energy resources considering their predominant advantages has generated much disputes over the usage of such clean sources of energy in the power systems. Although the energy storage system and wind power plants are accounted as inseparable parts of the power grid which enhance the system performance [19], the applicability of such system heavily linked to their optimal locations in the power system, which has been vastly investigated by many literatures with different point of views [20] and is one concern of this paper. In [21], in addition to the system cost, benefit of the system and ESS's possessor in ESS allocation problem is represented by a high wind penetration in the distribution. In [22] the optimal allocation of the ESS is pursued with the goal of minimizing the investment and operation costs of the power network. In this regard, diverse meta-heuristic algorithms including genetic algorithm (GA), PSO and bat algorithm have been expressed for the allocation of ESS [23]. Since the allocation of ESS is a discrete problem, it is much more preferred to use mathematical based methods to the meta-heuristic algorithms for allocation of ESS. Therefore, representing a new mathematical based algorithm-in order to reduce the total cost of the system-is another concern of this paper. Considering the above explanations, this paper mainly seeks to provide effective steps for properly managing the congestion issue in the power system by means of IBRCC-TS approach and optimal allocation of ESSs in the system. The IBRCC-TS approach effectively reduces the congestion of system while increases the robustness of the system against uncertainties of WTs and guarantees the maximum contribution of WTs in the operation problem. These approaches inevitably come up with some challenges, which need to be wisely dealt with. For instance, frequent switching within a specific time is a critical problem in the TS method. Needless to say, any variations in the reliability of an equipment strongly affects the overall power system's reliability.

The choice of battery storage in the grid is to help damping the power oscillations of the renewable energy sources. For instance, having wind turbine in the grid would create power based on the wind speed patterns. It is quite possible that the power of the wind unit may change at some hours due to the unpredictable nature of the wind speed. In this case, having some amount of power stored in the battery would help to support the grid as a spinning reserve power. The very fast and reliable nature of this injected power would help to improve the power quality and reliability in the system.

A worthwhile step can be considering the maintenance cost of the CBs in the cost function of the problem. To this end, an effective model of reliability of the CBs according to the number of switchings is adopted in this paper to overcome the proposed problem. Allocation of the ESS as another contribution of this work, has its own challenges since it is carried out by meta-heuristic algorithms, some of which are time consuming and less accurate. Hence, the accuracy and solution time are two main concerns of this paper in the allocation problem. In this regard, this paper also deploys the bat algorithm (BA) for finding the optimal locations of the ESSs in a fast and less time consuming manner [20].

2.1 Assumptions

For the sake of more clarification, the main assumptions made in the modelling are summarized as below:

- The continuous uncertainty merely relates to the wind power generation and the discrete uncertainty relates to the unit and line failures. However, the developed model has the capability of considering the load demand uncertainty as well. The discrete uncertainty of assets failure is determined by a feasible scenario set in accordance with the known Forced Outage Rates (FORs).
- Linear cost function of generating units is used.
- The power factor of all wind farms is assigned to the problem as 1.

2.2 SCUC Model Formulization

$$\min F=\sum_{t}\sum_{g}\left[C\left({P^{S}}_{g,t}\right)+SU_{g,t}({v^{s}}_{g,t})+SD_{g,t}({w^{s}}_{g,t})+C\Delta r^{s}_{g,t}\right] \tag{1}$$

$$P_{g}^{min}{u^{s}}_{g,t}uc_{g}^{s}\leq {P^{s}}_{g,t}+\Delta r^{s}_{g,t}\leq P_{g}^{max}{u^{s}}_{g,t}uc_{g}^{s} \tag{2}$$

$${v^{s}}_{g,t}-{w^{s}}_{g,t}={u^{s}}_{g,t}-{u^{s}}_{g,t-1} \tag{3}$$

$$\sum_{t'=t-UT_{g}+1}^{t}{v^{s}}_{g,t'}\leq {u^{s}}_{g,t},\qquad \forall g,t\in\left\{UT_{g},\ldots,T\right\} \tag{4}$$

$${P^{s}}_{g,t}-{P^{s}}_{g,t-1}\leq R^{s+}_{g}{u^{s}}_{g,t-1}+R_{g}^{SUs}{v^{s}}_{g,t} \tag{5}$$

$$\sum_{t'=t-DT_{g}+1}^{t}{w^{s}}_{g,t'}\leq 1-{u^{s}}_{g,t},\qquad \forall g,t\in\left\{DT_{g},\ldots,T\right\} \tag{6}$$

$${P^{s}}_{g,t-1}-{P^{s}}_{g,t}\leq R^{s+}_{g}{u^{s}}_{g,t}+R_{g}^{SUs}{w^{s}}_{g,t} \tag{7}$$

$$-SR_{g}^{+}\leq \Delta r^{s}_{g,t}\leq SR_{g}^{+} \tag{8}$$

$$\sum_{g}{P^{S}}_{g,t}+Pr_{s,t}-\sum_{k(b,m)}{P^{S}}_{kt}+\sum_{k(m,b)}{P^{S}}_{kt}=PD_{b,t}^{s}-{L^{s}}_{sh_{b,t}} \tag{9}$$

$$-\overline{P}_{k}.{T^{s}}_{k,t}.zc_{k}^{s}\leq P_{k,t}^{s}\leq \overline{P}_{k}.{T^{s}}_{k,t}.zc_{k}^{s} \tag{10}$$

$$P_{b,m,k,t}^{s}-M\left(1-{T^{s}}_{k,t}zc_{k}^{s}\right)\leq P_{k,t}^{s}\leq P_{b,m,k,t}^{s}+M\left(1-{T^{s}}_{k,t}zc_{k}^{s}\right) \tag{11}$$

$$P_{b,m,k,t}^{s}=B_{bm}\cdot\left(\theta_{bt}^{s}-\theta_{bt}^{s}\right) \tag{12}$$

$$-\overline{\theta}_{b}\leq {\theta^{s}}_{bt}\leq\overline{\theta}_{b} \tag{13}$$

$$P^{Bat}_{b,t} = P^{ch}_{b,t} - P^{dis}_{b,t} \qquad \forall t \in \Omega^{T}, \forall b \in \Omega^{b} \qquad (14)$$

$$E^{Bat}_{b,t} = E^{Bat}_{b,t-1} + P^{Bat}_{b,t}\eta^{Bat} \qquad \forall t \in \Omega^{T}, \forall b \in \Omega^{b} \qquad (15)$$

$$P^{min} \le P^{Bat}_{b,t} \le P^{max} \qquad \forall t \in \Omega^{T}, \forall b \in \Omega^{b} \qquad (16)$$

$$E^{min} \le E^{Bat}_{b,t} \le E^{max} \qquad \forall t \in \Omega^{T}, \forall b \in \Omega^{b} \qquad (17)$$

$$Pr_{f,t} = \frac{1}{2}\rho A(SWT_{t})^{3} \qquad \forall t \in \Omega^{T} \qquad (18)$$

In this paper, a SCUC model based on TS and DC power flow is presented. The objective function of the problem is defined in (1). The objective function of the problem focuses on minimizing the total operating cost of the system. Furthermore, the generation cost and the reserve costs are considered in the modelling. Constraint (2) indicates the limitation over the generated power of the units. The constraints related to the start-up and shut-down of the power units are provided in (3)-(7). The constraint on the generating units' reserve is stated in (8). The studied model of wind turbine has been considered regardless of any costs. On the other hand, the power capacity is used in the power constraints. The most important constraint in the power system is the power balance shown in (9). The network security constraints through the constraints of the transmission lines as represented in (10)-(13) considering the TS. $z^{s}{}_{k,t}$ is a binary variable ,which determines whether a power line is connected or not in the operation problem since the TS method basically switches the power lines. Hence, the value of 1- $z^{s}{}_{k,t}$ would be zero if $z^{s}{}_{k,t} = 1$ and it shows that the TS has connected the power line. Some explanations are necessary here. As previously mentioned, the TS technique determines whether a transmission line is considered in the modelling or not. Such definition is instilled in the problem by binary variable $z^{s}{}_{k,t}$. If this variable gets 0 value, it indicates the power line is ignored in the operation problem and if gets 1, it points out the opposite definition. Same goes for binary variable zc^{s}_{k}, while it imposes the contingency definition of the power lines into the SCUS problem. Focusing on constraints (10)-(12), these constraints are valid and considered in the operation problem if and only if both of the variables $z^{s}{}_{k,t}$ and zc^{s}_{k} are 1, which indicates that the power line is not disconnected by the TS method nor by the contingency event. Hence, the power flow equations are valid in this particular occasion. Assuming $z^{s}{}_{k,t}$,$zc^{s}_{k} = 1$, constraint (11) will be turned into $P^{s}_{k,t} = P^{s}_{b,m,k,t}$. Variable $P^{s}_{b,m,k,t}$ indicates the injected power through the lines and is obtained using equation (12). This value need to be limited due to the technical limitation of power lines, which is done by using constraint (10). Furthermore, (13) represents the constraint of the bus angles.

Constraints (14)-(17) are related to the ESSs. Constraint (14) shows the injection/consumption power of the ESSs. In this case, if the batteries draw power from the grid, $P^{Bat}_{b,t}$ will take a positive value [19]. Constraint (15) indicates the hourly energy level of the ESSs with respect to the previous hour power injection/consumption. The charging and discharging power of the batteries are restricted to their maximum and minimum values by imposing constraint (16) to the model. Also, the energy level of the battery is not allowed to exceed its minimum and maximum values which is modelled by (17). Finally, the equation (18) models the power output of the wind generations units [19].

II. CIRCUIT BREAKER RELIABILITY MODELING

The CBs are used in the transmission systems to connect/disconnect transmission lines to/from the system. Longevity restriction of the CBs is affiliated to the number of switching on the transmission lines. Jeopardy value is the failure possibility of a working component at lifetime *t*. In addition, the mentioned capability can be employed to specify the CB reliability. Two important sections for reliability of CBs are open and closed function locks. Accordingly, the impacts rate of other section, taking account into its repair and maintenance on the CB reliability is in low level [8]. The CB failure as a function of the number of switching number is stated in (19).

$$U(N) = \frac{\kappa}{\gamma}\left(\frac{N}{\gamma}\right)^{\kappa-1} e^{-\left(\frac{N}{\gamma}\right)^{\kappa}} \qquad (19)$$

Where *U (N)* is a measure to characterize the CB failure without any dimension. The number of switching at time *t* is *N* considering the number of switching occurred before time *t*. The constants κ and γ are related to the failure. Any changes in number of switching during time period *t* will cause the *U (N)* to be changed. As an example, to calculate *U (N)* over a 24-hour period, the number of switching which will occur in that period must be considered.

$$\chi_{K}(N_{K}) = \frac{1}{U}\frac{\kappa}{\gamma}\left(\frac{N_{K}}{\gamma}\right)^{\kappa-1} e^{-\left(\frac{N_{K}}{\gamma}\right)^{\kappa}} \qquad (20)$$

Equation (15) shows the failure possibility operation of the CB according to the number of switching. Each CB failure possibility is characterized by $\mathcal{X}_{k}(N_{k})$ and U is the switch failure in the worst situation (i.e. Maximum number of switching in period *t*). N_{k} is the number of CB switchings in line *k*, assuming that only one CB is employed for each line. The relation of CB reliability relating to the failure possibility is expressed in (21).

$$R_{k} = 1 - \chi_{k} \qquad (21)$$

$R_k$indicates the CB reliability. This paper aims to enhance the CB reliability through diminishing the number of switchings. This goal will be met when $\mathcal{X}_k$tends to zero. In the SCUC problem along with TS, there is a CB considered on each line, thus the CB failure causes the transmission line outage. Accordingly, it is concluded that a high eventuality of CB failure results in transmission line outage. More switchings in CBs enhances the failure possibility and transmission line outage probability. The line outage has a considerable impact on the power balance equation and load shedding. The contribution of the EENS caused by the CB failure can be characterized considering the CB reliability.

$$ES = \sum_{k} \sum_{b} \sum_{t} \chi_k \, L_{sh\,b,t} \tag{22}$$

In (5), $L_{sh_{b,t}}$ is the load shedding variable with respect to the CB failure and EENS denotes the Expected Energy Not Supplied due to the CB failure. Constraints (2) and (4) are non-linear functions and they must be linearized. A linear approximation is provided for the ES according to the probability of scenario [9]. As a binary variable function, Eq. (20) must be rewritten as follows:

$$N_k = \sum_{y} \left| T_{k,t} - T_{k,t-1} \right| + A_1 \qquad \forall_k \tag{23}$$

$$N_k = \sum_{y} j_{k,y} y + A_1 \qquad \forall_k \tag{24}$$

$$\chi_K\left(N_K\right) = \frac{1}{U}\frac{\kappa}{\gamma}\left(\frac{\sum_{y} j_{k,y} Y + A_1}{\gamma}\right)^{\kappa-1} e^{-\left(\frac{\sum_{y} j_{k,y} Y + A_1}{\gamma}\right)^{\kappa}} \tag{25}$$

$$ES = \frac{1}{U}\sum_{t}\sum_{b}\sum_{k}\sum_{y}\frac{\kappa}{\gamma}\left(\frac{j_{k,y} Y + A_1}{\gamma}\right)^{\kappa-1} e^{-\left(\frac{j_{k,y} Y + A_1}{\gamma}\right)^{\kappa}} L_{sh_{b,t}} \tag{26}$$

The number of switchings is determined by Eq. (23) where T_k is a binary variable indicating the outage of line *k*. Line *k* will be out of service if T_k is equal to 0; otherwise line *k* is in-service. Since j_y is a binary variable and *Y* is a constant parameter, Eq. (24) can be used to calculate the number of switchings. In this regard, the total number of switchings would vary between 0 to 23 for a 24-hour period. Thus, *Y* can be determined as a parameter within 0 to 23 range. The binary variable will be changed, hence, *Y* parameters of each line would be equal to the switching number of that line, when (23) and (24) are equalized. The EENS and eventuality of the failure are provided in (25) and (26), where the number of switchings is replaced by (24).

$$L_{b_{b,k,y,t}} = \frac{\kappa}{\gamma}\left(\frac{j_{k,y} Y + A_1}{\gamma}\right)^{\kappa-1} e^{-\left(\frac{j_{k,y} Y + A_1}{\gamma}\right)^{\kappa}} L_{sh_{b,t}} \tag{27}$$

$$\frac{\kappa}{\gamma}\left(\frac{A_1}{\gamma}\right)^{\kappa-1} e^{-\left(\frac{j_{k,y} Y + A_1}{\gamma}\right)^{\kappa}} L_{sh_{b,t}} - j_{k,y} M \le L_{b_{b,k,y,t}} \quad \forall_k, \forall_y, \forall_t \tag{28}$$

$$L_{b_{b,k,j,t}} \le \frac{\kappa}{\gamma}\left(\frac{A_1}{\gamma}\right)^{\kappa-1} e^{-\left(\frac{j_{k,y} Y + A_1}{\gamma}\right)^{\kappa}} L_{sh_{b,t}} + j_{k,y} M \tag{29}$$

$$\frac{\kappa}{\gamma}\left(\frac{Y + A_1}{\gamma}\right)^{\kappa-1} e^{-\left(\frac{j_{k,y} Y + A_1}{\gamma}\right)^{\kappa}} L_{sh_{b,t}} - \left(1 - j_{k,y}\right) M \le L_{b_{b,k,j,t}} \tag{30}$$

$$L_{b_{b,k,j,t}} \le \frac{\kappa}{\gamma}\left(\frac{Y + A_1}{\gamma}\right)^{\kappa-1} e^{-\left(\frac{j_{k,y} Y + A_1}{\gamma}\right)^{\kappa}} L_{sh_{b,t}} + \left(1 - j_{k,y}\right) M \tag{31}$$

$$ES = \frac{1}{U}\sum_{t}\sum_{b}\sum_{k}\sum_{y}\left(L_{b_{b,k,j,t}}\right) \tag{32}$$

It is noteworthy that Eq. (27) must be linearized where the non-linear terms due to the multiplication of binary, continuous and exponential variables. Equations (28)-(31) are used to linearize these nonlinearities. The multiplications of the failure probability and the load shedding value, is replaced by $L_{b,k,t,j}$ as shown in (27). According to (27), if binary variable $j_{k,y}$ is equals 1, $L_{b,k,t,y}$ is determined based on (28)-(29). Otherwise, $l_{b,k,t,y}$ is computed according to (30)-(31). To activate this, constraints (28)-(32) are used. Also EENS cost are evaluated using Eq. (33).

$$Cost_r = VOLL \times ES \tag{33}$$

$Cost_r$ is the EENS cost and VOLL is a large positive value. Since each CB has its maintenance cost, this cost must be added to the operating costs of the system.

$$Cost_l = U\left(N_K\right) \times Cost_e \tag{34}$$

$$Cost_l = \frac{1}{U}\frac{\kappa}{\gamma}\left(\frac{N_K}{\gamma}\right)^{\kappa-1} e^{-\left(\frac{N_K}{\gamma}\right)^{\kappa}} \times Cost_e \tag{35}$$

Repair and maintenance cost ($Cost_l$) of the switch is proposed in (34). In (38), U_k is replaced taking into account Eq. (20). It is clear that the nonlinearity of the equation is due to the exponential term. To linearize equation (35), a piecewise linearization procedure is employed in equations (36)-(40). The equation (35) behaves nonliner. This function is divided into linear parts. The equation of linear parts is provided in (36) where W_b and b_b are the line equation parameters, S_b is the number of switchings in each part, and R_b is a binary variable showing the outage of each part. Constraint (37) shows the restrictions of the parts and constraint (38) indicates the limitations of the binary variable R_b . The summation of S_b for all parts should be equal to the total number of switchings (39), so that the summation of failure probabilities of the parts would be equal to the total failure probability of the switch.

$$\chi_K(N_K)=\frac{1}{U}\sum_{l}\left(W_{b_{k,l,t}}S_{b_{k,l}}+R_{b_{k,l}}b_{b_{k,l,t}}\right) \tag{36}$$

$$R_{b_{k,l}}S^{\min}{}_{b_{k,l}}\leq S_{b_{k,l}}\leq R_{b_{k,l}}S^{\max}{}_{b_{k,l}} \tag{37}$$

$$\sum_{l}R_{b_{k,l}}=1 \tag{38}$$

$$\sum_{l}S_{b_{k,l}}=N_k \tag{39}$$

$$Cost_l=\frac{1}{U}\sum_{k}\sum_{l}\left(W_{b_{k,l,t}}S_{b_{k,l}}+R_{b_{k,l}}b_{b_{k,l,t}}\right)\times Cost_e \tag{40}$$

In this regard, the switch reliability model and updated maintenance cost (40) will be added to the SCUC problem.

III. CASE STUDIES AND DISCUSSION

In this study, the suggested model is tested on the IEEE 6-bus and single-area IEEE Reliability Test systems (RTS) [25]. Table I and II show the technical specifications of the lines and generators of the 6-bus test system, respectively. The mentioned RTS system includes 24 buses, 32 generating units, 3 wind farms and 38 transmission lines [25]. The studied wind farms are geographically dispersed and located at buses 7, 11, and 24. The proposed wind farms have similar patterns for the anticipated wind power generation depicted in Fig. 1 scaled with the factors of 2.5 and 1, respectively. Moreover, the daily load prediction is illustrated in Fig. 2. For the sake of better representing the results, several characteristics of the RTS system are modified similar to the represented in [26]. Modifying the test system is a common action which is also pursued in previous research studies [1] and [27]. In order to evaluate different aspects of the work, 3 different cases are considered as follows:

Case I: analysis of the BA algorithm

Case II: Impact of uncertainty on the allocation problem

Case III: SCUC Implementation using TS, Considering the IBRCC and Reliability of the Switches

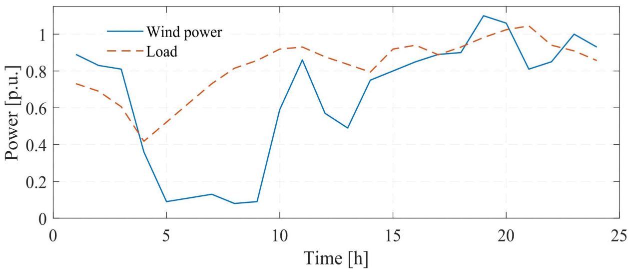


Fig. 1. Daily system's wind power and load curve

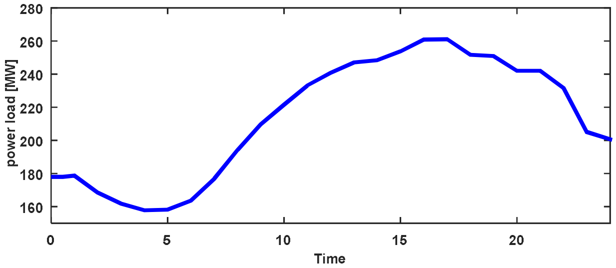


Fig. 2. Load curve of 6-bus system

TABLE I
TRANSMISSION LINES DATA FOR 6-BUS SYSTEM

Line number	From bus	To bus	X_l (pu)	R_l (pu)	Flow limit (MW)
L1	**1**	**2**	0.17	0.005	150
L2	**1**	**4**	0.258	0.003	150
L3	**2**	**3**	0.037	0.022	150
L4	**2**	**4**	0.197	0.007	150
L5	**3**	**5**	0.018	0.005	150
L6	**4**	**5**	0.037	0.002	37
L7	**5**	**6**	0.14	0.002	150

TABLE II
GENERATORS DATA FOR 6-BUS SYSTEM

	G1	G2	G3
Energy bid price ($/MWh)	20	23	35
Ramp up/down rate (MW/h)	55	50	20
Start-up cost ($)	100	100	100
P_{max} (MW)	220	200	50
P_{min} (MW)	100	10	10
Q_{max} (MW)	200	70	50
Q_{min} (MW)	-80	-40	-40
Minimum up time (h)	4	3	1
Minimum down time (h)	4	2	1

A. *Case I: analysis of the BA algorithm*

In order to find the optimal location of ESSs, the BA algorithm as a novel method is used which is validated in this section. Fig. 3 shows the convergence diagram of the BA. It reveals that the proposed optimization method has accurately found the buses 2, 8 and 17 as the optimal locations for the ESSs after 10 iterations (see Fig. 4). Fig. 6, illustrates the charging and discharging power of the energy storage units. As it is evident, the energy storages (1) and (3) are more tended to be discharged during peak hours aiming to support the grid to serve its demand loads, while energy storage (2) is more tended to be charged during non-peak hours. The performance of the proposed method is also compared with different common optimization methods including improved fast evolutionary programming (IFEP), evolutionary based particle swarm optimization (ESO), particle swarm optimization-local random search (PSO-LRS), improved genetic algorithm (GA), hybrid particle swarm optimization with wavelet mutation (HPSOWM), improved genetic algorithm with multiplier updating method (IGAMU), hybrid differential evolution (HDE) algorithm and new PSO-LRS (NPSO-LRS) algorithm [33]. In Table III different factors are evaluated in terms of the best, average, worst solutions and CPU process time. As can be seen, with the BA method, the iterative process time to find the solution is much more lower compared to the other optimization methods. As an example, the running CPU time for finding the solution has been reduced 66.77%, 54.15% and 50.12% compared to the IGAMU, HDE and NPSO-LRS. In addition, the answer deviation in the BA algorithm is approximately zero.

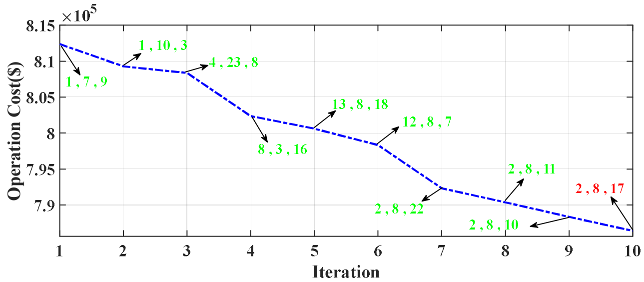


Fig. 3. Convergence diagram of the BA algorithm

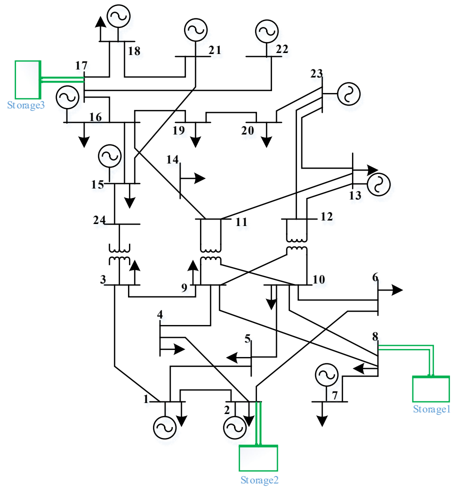
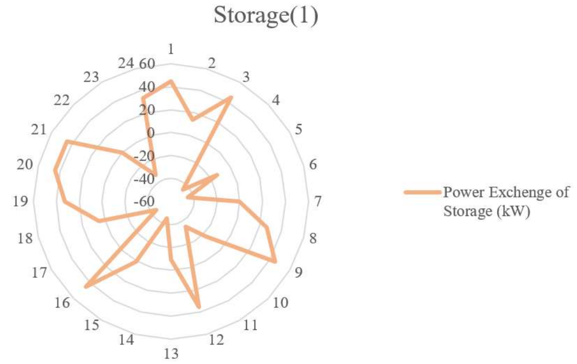
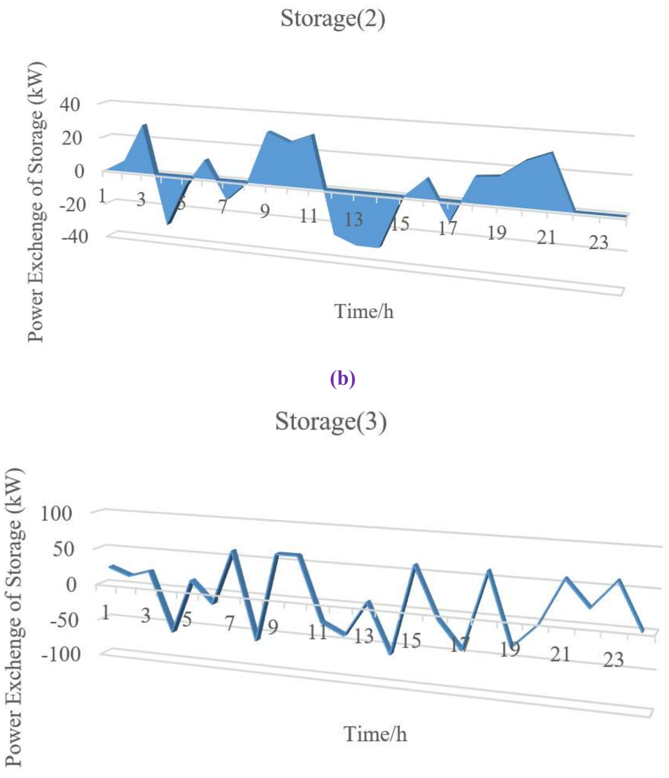


Fig. 4. Illustrates the placement of ESSs within IEEE Reliability Test systems



(a)



(b)

(c)

Fig. 5. Charging/discharging power of the energy storage systems

TABLE III
Performance evaluation of the BA algorithm

Method	Best	Average	Worst	CPU (min)
IFEP	8.0396×10^5	8.138654×10^5	8.139125×10^5	35.43
ESO	8.0214×10^5	8.134894×10^5	8.139125×10^5	23.87
PSO-LRS	8.0214×10^5	8.137654×10^5	8.138256×10^5	25.15
Improved GA	8.0093×10^5	8.137654×10^5	8.138256×10^5	NA
HPSOWM	7.9896×10^5	8.1312547×10^5	8.133985125×10^5	30.54
IGAMU	7.9134×10^5	8.1312547×10^5	8.133985125×10^5	30.85
HDE	7.9134×10^5	8.13012514×10^5	8.1312547×10^5	22.356
NPSO-LRS	7.9134×10^5	8.13012514×10^5	8.1312547×10^5	20.548
BA	**7.8640×10^5**	**7.8640×105**	**7.8640×105**	**10.25**

Case III: Impact of uncertainty in allocation problem

In this section, impact of the uncertainty on the performance of the allocation problem is represented. Table IV summarizes the results of different study cases investigated in this paper. Optimal places of the ESSs in each case and total cost are represented as well. As previously mentioned, the uncertainties associated within the power network are basically of two types: 1) continuous uncertainties 2) discrete uncertainties. The continuous uncertainness are the type that need to be continuously modelled such as sun light, wind speed, etc. Discrete uncertainties are the type which fairly occurs in the system almost due to any unpredictable internal or external event such as generator(s) or line(s) outage(s). Table IV shows a comparison between different analyses of the work. In this regard, optimal locations of the ESSs are provided considering two different study cases including 1) normal condition 2) uncertain condition. As can be seen, the locations of the ESSs are changed from buses 2, 8 and 17 in the normal model to buses 4, 8 and 21 due to the uncertainty factors. Also, the cost values are varied and enhanced by almost 3.4 %. All these explanations show the inevitable impact of the uncertainty factors on optimal solutions of the problem.

TABLE IV
COMPARISON OF DIFFERENT STUDY CASES

	Energy Storage (1)	**Energy Storage (2)**	**Energy Storage (3)**	**Total cost ($)**
	Bus of System			
Normal Conditioner	Bus(2)	Bus(8)	Bus(17)	7.8640×105
Uncertainty Conditioner	Bus(4)	Bus(8)	Bus(21)	8.1369×105

C. analyst system Considering the IBRCC and Reliability of the Switch

As it was mentioned in the IBRCC problem, the rate of δ indicates the robustness of the system against the uncertainties. Furthermore, increasing δ leads to the system robustness enhancement against wind power uncertainty. In this problem, higher WPPs capacity utilization, will lead to the robustness index δ increament. The lines' congestion will be reduced by employing the TS approach in the SCUC problem. On the other hand, the utilizing of wind generation and low-cost generating units will be improved through mitigating the transmission lines congestion. Under such conditions, the power system faces several variations such as operation cost reduction as well as δ rate and system robustness enhancement.

Table V represents the generated power for the three case studies presented in this paper as follows: (I): Implementation of the model regardless of the IBRCC and TS. (II): Implementing the SCUC problem using the IBRCC model. (III): Implementing the studied model using the IBRCC-TS considering the switch reliability. As it is shown in the results, low-cost generating units such as units 15-22 are more employed in the third case. In this model, the lines' congestion is reduced through the switching of the lines. Similarly, the total use of WPPs' capacity in the power system is increased compared to the other studied cases. Hence, the proposed model has significant impact on the operation cost reduction and δ rate enhancement in the IBRCC problem. In addition, it leads to increasing the system robustness. To show the TS on the IBRCC model, the δ rate is considered through three models with different number of scenarios in the Table VI. With respect to (47) related to the IBRCC model, α indicates the risk tolerance rate, which in this problem, $\alpha = 0.05$ is assigned to the model. The considered scenarios in this problem are provided as follows:

1- Line7 outage
2- Generator 10 outage
3- Generator 11 outage

Regarding the previous discussions, it is clear that along with scenario's numbers increment, the δ rate will be decreased. As can be seen, δ value for cases IBRA, IBRCC and IBRCC-Ts for scenario 1 is 0.651, 0.758 and 0.805 (see Table VI), respectively. Also, δ index for scenario 2 is 0.562 ,0.625 and 0.701 for the proposed three cases. In addition, the δ rate for scenario 3 is obtained as 0.443, 0.502 and 0.597, respectively. In this problem, WPPs are located on the buses 7, 11, and 24. It is tried to take into account the TS in the proposed model with the aim of maximizing δ robustness index and minimizing the operation cost. To do so, the lines switching should be carried out in order to maximize the contribution level of the WPPs. Under such situation, the WPPs will be more operated. On one hand, the δ rate will be increased to satisfy both above mentioned aims. By δ value enhancement, the WPPs generated power range will be increased in different scenarios. It is noteworthy to mention that by utilizing the TS approach in the third model, the operation cost is decreased since the wind power plant is a zero-operation cost power producer that caused the congestion of the lines to be plummeted. In addition, the δ robustness index in the third model, which is performed based on the IBRCC-TS, has a higher value compared to the other studied models. Hence, the network in the third model will be more robust against the contingencies.

Table V: Optimal power schedule of generating units in different models (in p.u).

Unit	**Base case**	**IBRCC**	**IBRCC-TS**
1	0	0	0
2	0	0	0
3	0.76	0.76	0.76
4	0.76	0.76	0.76
5	0	0	0
6	0	0	0
7	0.76	0.76	0.76
8	0.76	0.76	0.76
9	0	0	0
10	1	1	1
11	1	0.343363	0.301727
12	1.97	1.97	0
13	1.656104	0	0

14	0.69	1.498541	0
15	0	0	0.024386
16	0	0	0.12
17	0	0	0.12
18	0	0	0.12
19	0	0	0.12
20	0	0	1.55
21	0	0	0
22	0	0	0
23	3.661396	3.154434	4
24	0.5	0.5	0.5
25	0.5	0.5	0.5
26	0.5	0.5	0.5
27	0.5	0.5	0.5
28	0.5	0.5	0.5
29	0.5	0.5	0.5
30	1.55	1.55	1.55
31	1.55	1.55	1.55
32	3.5	3.5	3.5
Total Wind power	2.665	4.76	5.31

Equipment failure such as the power switches failure is one of the uncertainty presence factors in the power system. In TS-based optimal power flow problem, the connection of the lines are performed by the CBs. To improve the TS performance, the switching number must be restricted in a certain period of time. Limited number of switches causes the reliability increment as well as the operation cost reduction. In order to derive the validity of the proposed model, the proposed method is implemented on different case studies.

Table VI: Results of δ

	δ		
Θ_{DU}	**IBRA**	**IBRCC**	**IBRCC-TS**
1	0.651	0.758	**0.805**
2	0.562	0.625	**0.701**
3	0.443	0.502	**0.597**

IV. CONCLUSION

This paper is intended to give an effective approach for congestion management of the power system. The approach is basically twofold: 1) utilization of an improved IBRCC using TS method and 2) allocation of ESSs in the power network. According to results, by using the IBRCC-TS model, the output power of WPPs is enhanced while at the same time, reduces transmission lines' congestion. Utilizing the IBRCC-TS model considering the switch reliability caused the contribution level of the WPPs and the robustness index of the network to be effectively increased. Also, by considering the accurate model of the CB's reliability through a proper linearization achievement, the number of switching is reduced and accordingly the reliability of the network switches is improved. The main paper limitations are the dynamic modeling the battery in the system. Moreover, the uncertainties of the problem can be modeled using different methods and based on different probability density functions.

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