On the Use of Pumped Storage for Wind Energy Maximization in Transmission-Constrained Power Systems

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***Abstract*—Owing to wind power inherent characteristics and technical constraints of power systems operation, a considerable amount of wind energy cannot be delivered to load centers and gets curtailed. Transmission congestion together with temporal mismatch between load and available wind power can be accounted as the main reasons for this unpleasant event. This paper aims to concentrate on the wind energy curtailment for which it provides a combinatorial planning model to maximize wind power utilization. Jointly operating the wind power generation system with pumped hydro energy storage (PHES), the planning procedure tries to reach schemes with the minimum level of wind energy curtailment as well as low imposed cost of transmission network reinforcement. In this regard, a well-organized posterior multi-objective (MO) optimization framework is proposed aimed to properly deal with wind energy curtailment cost, total social cost, and also storage units' revenue as some unavoidable factors in planning studies of power systems. The presented method is conducted on the modified IEEE Reliability Test System (IEEE-RTS) and the obtained results introduce its applicability and efficiency in planning procedure of the renewable-based power systems.**

***Index Terms*—Multi-objective (MO) optimization, non-dominated sorting genetic algorithm II (NSGA II), pumped hydro energy storage (PHES), transmission reinforcement, wind energy curtailment, wind farms.**

NOMENCLATURE

Variables

C_{cong}	Total congestion cost (\$).
$C^{\text{op}}_{\text{ESS}_{i,t}}$	Operation cost of the ith PHES unit at hour t (\$).
C_{foss}	Fossil fuel generators cost (\$).
C_{LC}	Total load curtailment cost (\$).
$D_{L_{i,t}}$	Load curtailment at bus i at hour t (MW).
$P_{D_{i,t}}$	Load at bus i at hour t (MW).
$P_{G_{i,t}}$	Output of the ith generator at hour t (MW).
$P_{S_{i,t}}$	Power of the ith PHES unit at hour t (MW).
$P^{\max}_{S_i}$	Power rating of the ith PHES unit (MW).
$P_{W_{i,t}}$	Output of the ith wind farm at hour t (MW).
$P^{\max}_{W_{i,t}}$	Maximum available power of the ith wind farm at hour t (MW).
P^t_{WL}	Total curtailed wind power at hour t (MW).
$S_{i,t}$	Stored energy in the ith PHES unit at hour t (MWh).
$S^{\max}_i$	Maximum energy capacity of the ith PHES unit (MWh).
x_i	Binary decision variable of the ith PHES unit.
x_l	Binary decision variable for adding new line in the lth corridor.
μ_{fi}	Membership function value for the ith objective function.
π_t	Lagrange multiplier of equality constraint.
$\tau_{i,t}$	Lagrange multiplier associated with inequality constraint of the ith generator.

Parameters

a_i, b_i, c_i	Cost function coefficients for the ith generator.
$C^{\text{inv}}_{\text{ESS}_i}$	Annualized investment cost of the ith PHES unit (\$).
$f^{\max}_l$	Maximum capacity of line l (MW).
$\text{GSF}_{l,i}$	Generation shift factor of line l to generator i.
m	Number of objective functions.
n^0_l	Initial number of lines in corridor l.
$P^{\min}_{G_i}, P^{\max}_{G_i}$	Minimum and maximum power of the ith generator (MW).
s_l	Sensitivity of wind energy curtailment subject to transmission congestion of line l.
T	Simulation time horizon (h).
α_l	Annualized investment cost of the lth corridor (\$).
λ_D	Load curtailment penalty cost (\$/MWh).
λ_W	Wind curtailment penalty cost (\$/MWh).
μ_i	Desired level of the ith objective function for the membership function.
η_i	Round-trip efficiency for the ith PHES unit.

Sets

Ω_D	Set of load buses.
Ω_G	Set of conventional generators.
Ω_L	Set of transmission lines.

Manuscript received February 27, 2014; revised July 10, 2014 and September 06, 2014; accepted October 17, 2014. Paper no. TPWRS-00281-2014.

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Digital Object Identifier 10.1109/TPWRS.2014.2364313

Ω_S Set of PHES units.

Ω_W Set of wind farms.

I. Introduction

WIND power is widely recognized as a promising alternative electric power generation source at the time of uncertain fossil fuel costs and concerns over the harmful effects of climate change. Wind energy has experienced a fast growth over last decades. The global installed wind power capacity of 282.5 GW by the end of 2012 represents a growth of more than 19% compared to the corresponding amount in 2011 [1]. Various incentive programs and binding regulations such as renewable portfolio standards (RPS) are designed to increase the wind power quota in generation portfolios of power systems. South Australia has set a goal for having 33% of electricity generated by renewable resources in 2020 [2]. According to Energy Roadmap 2050 [3], the European Commission is moving toward a low-carbon economy and has committed to reduce greenhouse gas emissions by 80%–95% by 2050. This de-carbonization target will be possible with a 97% of renewable sources share in power systems of European countries [4].

Being non-dispatchable and also uncertain in output generation of wind farms as a result of the wind speed inherent volatility, growing share of wind power has raised many challenging questions in power system operation and planning issues. Wind as an intermittent energy resource cannot provide “firm” power, as conventional units do. Sometimes, due to the power system security constraints and operating limits, all of the available wind farms power cannot be transmitted, which means that a part of wind power has to be curtailed [5]–[7]. Congestion in transmission network is a main reason of wind energy curtailment issues. Temporal mismatch between load and available wind power is the other reason of this unpleasant event. Taking into account the system dynamic stability limits, a minimum number of thermal generators should always be kept online [8]. Furthermore, thermal generators cannot operate at very low output levels because of minimum generation constraints. As a result, the operator cannot handle the entire large amount of available wind energy when the demand level is low.

Wind power curtailment is a growing concern in highly wind penetrated power systems. Consequently, offering some remedial actions in order to accommodate more renewable energies in the future is inevitable. Aimed to alleviate the wind energy curtailment issues, two main solutions can be proposed. Transmission lines expansion plans are usually presented as a direct and effective approach to incorporate more wind energy in power systems. Decreasing the amount of congestion in transmission lines, network reinforcement can help wind energy to more efficiently be integrated into the system. However, transmission reinforcement projects are usually expensive and take a lot of time to be completed. Furthermore, it may be sometimes economically inefficient to invest on a network reinforcement plan for the sake of wind energy curtailment reduction [9].

Employing energy storage system (ESS) is the other promising solution to relieve wind power curtailment. ESSs can be used to time-shift wind farms energy output and therefore decrease the amount of curtailed wind energy. Times that either wind farms output generation cannot be delivered to the load centers or it is more than the demand, it can be stored to be used in upcoming generation shortage events. Pumped hydro energy storage (PHES) system is the most mature storage technology available and the first economic option for storing electrical energy in large scales [10].

In the literature, some studies have already addressed the results of transmission expansion planning (TEP) studies for highly wind penetrated power systems [11]–[15]. The authors in [11] and [12] propose a probabilistic TEP strategy in which the random nature of wind power is properly modeled. The effects of obtained plans on amount of curtailed wind energy, however, have not been considered. Interconnection capacity expansion studies with the main target of wind power integration in the Iberian Peninsula is investigated in [14]. Reference [15] also introduces a transmission planning model considering a 20% wind energy penetration goal.

Optimal placement, sizing and operation of energy storage units for integrating more renewable energy in the system has been another attractive ongoing area of research which has eventuated in some tremendous number of papers revealed [16]–[21]. Reaching some results being pleasant in the viewpoint of investors, [19] proposes an operation strategy with the main goal of maximizing storage owners’ revenue. Different system costs including the costs of wind energy curtailment and storage units are considered as the objective of planning studies proposed in [20]. Optimal placement and sizing of storage in a highly wind penetrated system is addressed in [21].

While there have been many individual works in the literature investigating the effects of either TEP or energy storage studies on the optimal integration of wind energy in power systems, the need for a comprehensive research considering both of these two factors on wind energy maximization is still felt. In response, this paper tries to investigate the effects of PHES usage along with the local network reinforcement as a long-term solution to wind energy curtailment in power systems. In this regard, through a multi-objective (MO) optimization algorithm, a novel planning method is proposed. To the best of the authors’ knowledge, it is for the first time that such an integrated planning strategy is proposed aimed to maximize the wind power capacity credit. The presented expansion approach takes into account the wind energy curtailment cost, total social cost and energy storage units revenue as its objective functions. Using this new framework, the attained plans can more efficiently handle the inherent characteristics of wind farms. The performance of the presented method is evaluated on the IEEE 24-bus reliability test system (IEEE-RTS) and the results are presented and analyzed.

II. Problem Description

The ability in managing energy imbalances over time makes the PHES plants as an unavoidable complement to wind farms.

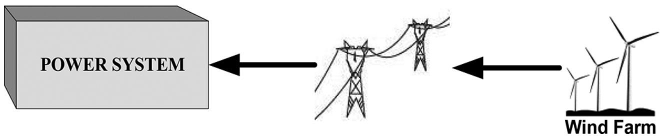

Fig. 1. Power system before installing PHES and transmission reinforcement.

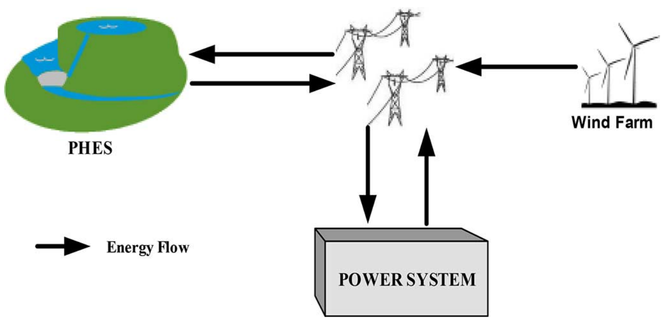

Fig. 2. Power system after installing PHES and transmission reinforcement.

The PHES plants are composed of two reservoirs placed at different heights and a number of turbine/pump units. Being dependent on the existence of two reservoirs in different elevations, the presence of the PHES plant in power systems are usually determined by some geological factors. Remote locations like mountains are suitable options for placing PHES, where transmission networks are usually not strong enough to transmit the electricity power. On the other hand, wind farms are also located at far distant sites.

Fig. 1 shows a power system in presence of wind farms before PHES usage and new lines installation. In this case, the only way to transmit the produced power of wind farms to load centers is through the transmission network. As a result, any congestion in transmission lines can curtail this green power and consequently lessen the wind farms capacity factor. In contrast, as depicted in Fig. 2, along with installation of the PHES plans in a power system, the produced output power of wind farms which had to be curtailed in the system shown in Fig. 1 can now effectively be transmitted to PHES via the local transmission network and will be used when the need arises. Hence, a comprehensive cost/benefit analysis of PHES plans is required to determine the abilities of this storage technology in attaining higher share of wind energy in supplying the electrical loads. Also, this study can lend the power system decision makers a hand in more optimistically looking forward to higher penetration of wind energy.

Based on this discussion, a comprehensive study needs to be run with the goal of minimizing wind energy curtailment cost aimed to find the optimal locations, nominal power and energy capacity of PHES units along with the optimal transmission reinforcement plans. Anyhow, implementing the results of this study calls for some new investments in power systems. Generally, increasing the number and the size of ESS units, more produced power of wind farms can be used and as a consequence the wind energy curtailment cost would be reduced. It also will lead to transmission congestion relief during on-peak times and can decrease the congestion cost. On the other hand, increase of stored wind energy will lower need of the conventional thermal generators and as a result it can reduce fossil fuels costs in the system. However, irregular increase of ESSs is not economically worthwhile and may impose a huge cost on system, much more than the revenue out of the wind power more efficient use.

To reach some optimal reinforcement plans in viewpoint of power system decision makers, both imposed costs and benefits of ESS need to be properly modeled in planning studies. It should be noted that even though the cost of wind energy curtailment may be much lower than the other imposed costs like the additional operation cost of system, this cost can be aggravated in highly wind penetrated scenarios. In addition, different types of supportive policies for renewable energy production usually applied around the world forces the system operators to more cautiously face with the curtailment issues of wind energy. So, factors such as curtailment cost, thermal generation units cost and ESSs cost cannot be considered in a same way. In this regard, a posterior optimization approach is presented in this paper to determine the optimal combination of storage and transmission reinforcement plan with the main goal of wind power curtailment minimization. A main feature of this optimization approach is that it separately considers different types of costs rather than considering them as a whole. It is used to find some optimal plans with different levels of priority and importance in viewpoint of different market participants, power system planners and operators. The objective functions of this optimization problem are considered as follows:

- **Wind Energy Curtailment Cost**
  A penalty cost for wind energy curtailment is applied to minimize the curtailed wind energy. It should be notified that defining the curtailment cost as a function of the amount of curtailed power, one can conclude that minimizing the curtailment cost of the system can result in the minimum amount of curtailed wind energy.
- **Total Social Cost**
  It consists of the ESSs and new transmission lines investment costs, congestion cost, conventional generators operating cost and load curtailment cost.
- **Energy Storage Units Revenue**
  An ESS can make profit by price arbitrage. Storing energy during low-price periods and selling during high-price periods is an income for storage units. The difference between the income and the operation cost is considered as the ESS net revenue in this paper. This revenue is considered to present the interests and benefits of the ESS units owners.

III. Modeling Structure and Methodology

A. *Wind Farms Output Modeling Procedure*

The wind speed owns a random nature and changes rapidly in short period of time. As a result, the output generation of a wind farm becomes a stochastic variable. In order to properly model the stochastic behavior of wind farms production in planning studies of power system, an efficient probabilistic model needs to be used. Up to now, different wind speed modeling approaches have been proposed [22]–[24]. Among these approaches, the Weibull distribution has been introduced an effective way to model the wind speed variations in power system studies [25], [26].

In this paper, variations in wind speed are modeled based on the Weibull distribution fitted by hourly wind speed historical data. The Monte Carlo simulation (MCS) is then used to model the wind speed variations applying the Weibull distribution function for each hour [11]. Finally, the wind turbine power output is resulted using the nonlinear relationship of wind power output and wind velocity [22].

B. Storage Systems

PHES can provide several facilitations for power systems with high wind penetration. Wind farms energy time-shifting, reducing wind power forecasting errors, relieving transmission bottlenecks and frequency control issues are some of these facilitations which can result in more efficient integration plans of wind energy. In this paper, the PHES units store surplus wind energy when either demand is low or the wind power cannot be transmitted due to the transmission congestion problems. The stored energy would be, then, released during high-price hours at the time of peak demand. The storage units' power and energy constraints can be modeled as follows:

$$|P_{S_{i,t}}| \leq P_{S_i}^{\max} \quad \forall t \in T \tag{1}$$

$$0 \leq S_{i,t} \leq S_i^{\max} \quad \forall t \in T. \tag{2}$$

At each time, the amount of stored energy in PHES units can be calculated as

$$S_{i,t} = \begin{cases} S_{i,t-1} - \eta_i P_{S_{i,t}} & \forall t \in T, \text{ if } P_{S_{i,t}} < 0 \\ S_{i,t-1} - P_{S_{i,t}} & \forall t \in T, \text{ if } P_{S_{i,t}} \geq 0. \end{cases} \tag{3}$$

Negative and positive values of $P_{S_{i,t}}$ represent the charging and discharging power levels of the PHES systems, respectively. The investment cost of PHES technology is relatively high. It ranges from \$600/kW to upwards of \$2000/kW, depending on a number of factors such as size, location, and connection to the power grid. In contrast, the annual operation cost of PHES systems is low, about 1–2% of their investment costs. The operation cost of a PHES can be divided as fixed and variable terms which are respectively considered \$3.8/kW-year and \$0.34/kWh according to [27].

C. Problem Formulation

Here, mathematical formulation of the proposed MO planning strategy is presented. An important factor which needs to be modeled as the first objective function of this study is the total wind energy curtailment cost. This factor is formulated as follows:

$$\min(f_1) = \sum_{t=1}^{T} \lambda_W P_{WL}^t \tag{4}$$

$$P_{\mathrm{WL}}^t = \sum_{i \in \Omega_W} \left(P_{W_{i,t}}^{\max} - P_{W_{i,t}}\right) \quad \forall t \in T. \tag{5}$$

In these relations, the maximum available power of the ith wind farm is equal to the sum of all turbines power levels. The wind energy curtailment penalty cost represented by λ_W, is set to be \$50/MWh [15].

The second objective function of the proposed method is the total social cost (TSC) which consists of the equivalent annual costs of new storage units and new lines, total congestion cost, load curtailment cost and fossil fuel generators cost. This objective function which should be minimized is formulated as follows:

$$\min(f_2) = \mathrm{TSC} = \sum_{l \in \Omega_l} \alpha_l x_l + \sum_{i \in \Omega_S} x_i C_{\mathrm{ESS}_i}^{\mathrm{inv}} + C_{\mathrm{cong}} + C_{\mathrm{LC}} + C_{\mathrm{foss}} \tag{6}$$

$$C_{\mathrm{cong}} = \sum_{t=1}^{T} \sum_{(i,j) \in \Omega_L} f_{ij,t}(\mathrm{LMP}_{j,t} - \mathrm{LMP}_{i,t}) \tag{7}$$

$$C_{\mathrm{LC}} = \sum_{t=1}^{T} \sum_{i \in \Omega_D} \lambda_D D_{L_{i,t}} \tag{8}$$

$$C_{\mathrm{foss}} = \sum_{t=1}^{T} \sum_{i \in \Omega_G} [a_i P_{G_{i,t}}^2 + b_i P_{G_{i,t}} + c_i]. \tag{9}$$

*LMP*s are the Lagrange multipliers or shadow prices of the optimal power flow (OPF) problem addressed in (10). The load curtailment cost is calculated considering single-contingency (N-1) criterion [28].

At each time, the following OPF problem needs to be solved in order to obtain the output level of each generation unit, state of charge (SOC) of PHES units and also LMPs of the network buses:

$$\mathrm{Min} \left(\sum_{i \in \Omega_G} \left(a_i P_{G_{i,t}}^2 + b_i P_{G_{i,t}} + c_i \right) \right) \quad \forall t \in T$$

$$\text{s.t.} \tag{10}$$

$$\sum_{i \in \Omega_G} P_{G_{i,t}} + \sum_{i \in \Omega_W} P_{W_{i,t}} + \sum_{i \in \Omega_S} x_i P_{S_{i,t}} = \sum_{i \in \Omega_D} P_{D_{i,t}} \quad \forall t \in T \tag{11}$$

$$P_{G_i}^{\min} \leq P_{G_{i,t}} \leq P_{G_i}^{\max} \quad \forall t \in T \tag{12}$$

$$0 \leq P_{W_{i,t}} \leq P_{W_i}^{\max} \quad \forall t \in T \tag{13}$$

$$\sum_{i=1}^{n} \mathrm{GSF}_{l,i} \times (P_{G_{i,t}} - P_{D_{i,t}}) \leq f_l^{\max} \times (n_l^0 + x_l) \quad l \in \Omega_L, \quad \forall t \in T. \tag{14}$$

In this OPF problem, Load generation balance constraint is presented in (11). Equations (12) and (13) are the conventional and wind generators power limits. Equation (14) presents the power flow constraint for the transmission lines.

Using the Lagrange multipliers of the assumed DCOPF model, the LMP at each bus is obtained as follows:

$$\mathrm{LMP}_{i,t} = \mathrm{LMP}_{i,t}^{\mathrm{energy}} + \mathrm{LMP}_{i,t}^{\mathrm{congestion}} = \pi_{i,t} + \sum_{l \in \Omega_L} \mathrm{GSF}_{l,i} \times \tau_{i,t}. \tag{15}$$

The third objective function is to maximize the PHES units' revenue. Usually, Electrical energy is stored by ESS units during off-peak periods, when the electricity price is low. In such periods, there is almost no transmission congestion in the network. The stored energy in these storage units would be then discharged during peak demand periods; when the electricity price is higher. So, the ESSs can earn profit from the difference in price as a side effect of energy storage and congestion relieving actions. The PHES units' revenue is considered as the difference between price arbitrage revenue and the storage units operation cost. In this regard, the third objective function is defined as follows:

$$\min\,(f_3)=\sum_{t=1}^{T}\sum_{i\in\Omega_S} x_i\left(C^{\mathrm{op}}_{\mathrm{ESS}_{i,t}}-(P_{S_{i,t}}\times \mathrm{LMP}_{i,t})\right).\quad(16)$$

D. Multi-Objective Optimization Method

As discussed in the previous part, in the proposed planning strategy, three different criteria needs to be modeled in the optimization procedure. To properly involve the effects of these criteria in the attained optimization framework, a well-organized optimization tool should be applied. The MO optimization methods are appropriate tools for handling the problems with more than one objective. Each objective can be a minimization or a maximization of an essential criterion. The objectives may have supporting, conflicting or mathematically unrelated relations with each other. Generally, an optimal solution at which all objectives are optimized is unachievable. As a result, the MO optimization strategies try to find a set of non-dominated optimal solutions, namely, the Pareto optimal solutions [29]. A solution candidate for an MO optimization problem is called non-dominated only if none of the objective functions are improved qualitatively unless some of the other objective values are degraded.

Up to now, several methods have been proposed to solve an MO optimization problem and find the non-dominated solutions [29]. Genetic algorithm in general and the genetic-based NSGA II in particular are applicable and appropriate tools to handle non-convex and mixed-integer problems [30]. The NSGA II sorts a population of solutions into a number of non-dominated fronts. The non-dominated fronts are ranked according to their non-dominancy level.

E. Final Decision-Making Method

As mentioned before, a multi-objective problem has not a unique solution. A decision-making method is needed, then, to select the final solution among the optimal non-dominated solutions. Fuzzy decision-making approach is an efficient tool which can model the decision maker's preferences into mathematical equations [31]. In this method, a membership function which is a monotonically decreasing set is assigned to each objective. It shows the degree at which a solution meets the decision maker's criteria about that objective. Membership function value ranges from zero to one, with zero denoting incompatibility and one indicating full compatibility with the decision maker's preferences. If objective function of the optimization problem should be minimized, the membership function is equal to zero and one at the maximum and minimum points of the objective function. The linear membership function used in this paper is as follows:

$$\mu_{f_i}(X)=\begin{cases}0 & f_i(X)>f_i^{\max}\\ \dfrac{f_i^{\max}-f_i(X)}{f_i^{\max}-f_i^{\min}} & f_i^{\min}\le f_i(X)\le f_i^{\max}\\ 1 & f_i(X)<f_i^{\min}.\end{cases}\quad(17)$$

After defining the membership functions, the decision maker assigns his desirable level (also called reference value) for each objective function (μ_i). The final solution is then acquired by solving the optimization problem (18):

$$\min_{X\in \mathrm{Solutionset}}\sum_{i=1}^{m}|\mu_i-\mu_{f_i}(X)|^n\quad n\in[1,\infty)\quad(18)$$

where $1\le n\le\infty$. Equation (18) tries to minimize the total deviations from the desired levels with respect to membership function of all solutions. The sensitivity of final solution to the values of desired levels is less for larger values of n.

F. Algorithm of the Proposed Method

Flowchart of the proposed algorithm is shown in Fig. 3. As can be seen in this Figure, the first population is produced taking into account the boundaries of decision variables. It consists of binary variables for new line candidates, binary variables for adding PHES units and the PHES plants capacity variables. After the new transmission lines and the PHES plants locations and capacities have been set in the first population, the studies are repeated for three typical days of three different seasons (summer, winter and spring/autumn) in order to represent the wind turbines power fluctuations and storage plants utilization taking into account various operating conditions. Then, based on the relations presented in (4)–(16), the annual values of three objective functions are calculated for this population.

Sorting the first population into Pareto fronts through examining the non-dominancy concept, the next generation is produced using the conventional operators of genetic algorithm, i.e., mutation and cross over. The same steps are also performed for the next generations. The termination criterion which is the number of iterations is regularly checked. If it is not satisfied, the next generation will be formed by the NSGA II operators. Else, the fuzzy decision-making method would be applied to select the final optimal solution.

IV. Numerical Results

A. Test System

The proposed algorithm is implemented in MATLAB environment using MATPOWER functions. The modified IEEE-RTS has been considered as the test system under study. Data associated with this test system can be found in [32]. The proposed planning method targets the future requirements of power system and assumes network expansion for the next ten years. Hence, the load demand and generation are increased by 2 times their original values, i.e., the load and generation levels of 5700 MW and 6810 MW, respectively. The original test system is modified by adding 30% penetration of wind energy. In this regard, three wind farms with an individual installed

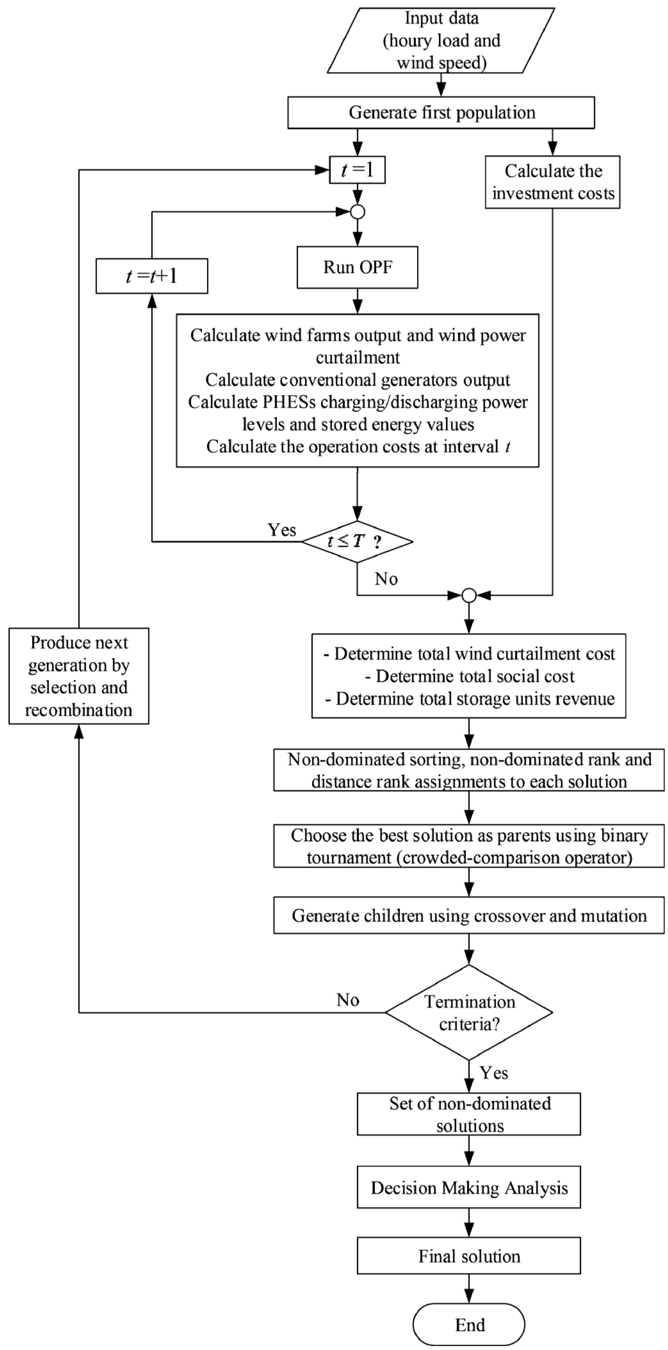

Fig. 3. Flowchart of the proposed algorithm.

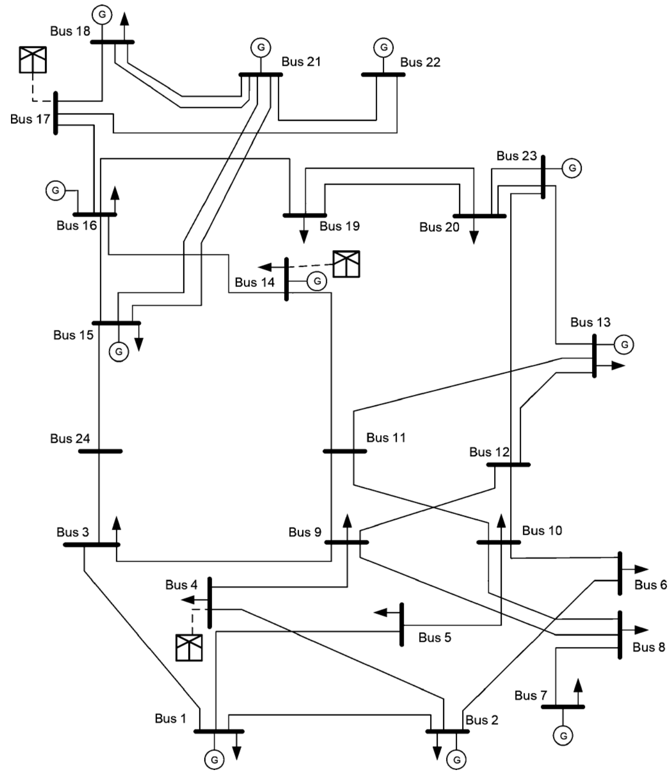

Fig. 4. Modified IEEE-RTS.

capacity of 1000 MW (totally 3000 MW) are added to buses 4, 14, and 17. Fig. 4 shows the single line diagram of the modified IEEE-RTS. The penalty cost associated with load shedding is considered to be 2000$/MWh [15]. In order to obtain the optimal locations, power ratings and energy capacities of PHES units, regarding the siting and geographical limitations, buses 3, 7, 13, and 22 are considered as candidates for PHES installation. The PHES systems round-trip efficiency and investment cost are considered to be 0.85 and 1300 $/kW, respectively. Maximum PHES capacities are assumed to be 2000 MW.

Since the local transmission reinforcement is considered in the proposed plan, 10 corridors are selected as candidates for adding new lines. The sensitivity of wind energy curtailment subject to transmission congestion of line l is defined as the marginal decrease in total curtailed wind power due to increase of the corresponding congested line capacity [33]:

$$s_l = \frac{\partial P_{\mathrm{WL}}}{\partial f_l^{\max}}. \tag{19}$$

To evaluate s_l for line l, the line capacity is increased by 1 MW while the other system parameters are unchanged. The new amount of total wind power curtailment is then calculated. s_l will be the difference between the new and old values of total wind power curtailment. As a result, 10 lines with highest values of s_l calculated by (19) are selected as the transmission reinforcement candidates. These lines are between buses 1–5, 2–4, 4–9, 6–10, 7–8, 8–9, 11–14, 14–16, 16–17, and 17–22. The investment cost of installing a transmission line is assumed to be 350 $/MW-Mile.

B. Load and Wind Speed Data

The system is studied in three different periods of time which represent summer, winter and spring/autumn conditions of load profile and wind speed variations. Therefore, the three typical days of July 30, 2008 in summer, January 20, 2009 in winter, and April 20, 2009 in spring are arbitrarily selected and the IEEE-RTS hourly peak load data of these dates are applied in the study. Three different wind farms of the test system are assumed to be located in three parts of Iran, i.e., Manjil, Chabahar, and Loutak. Their historical wind speed data are available in [34]. The wind speed data are applied to the Vestas V90 3-MW wind turbines to model the wind farms output generation [35].

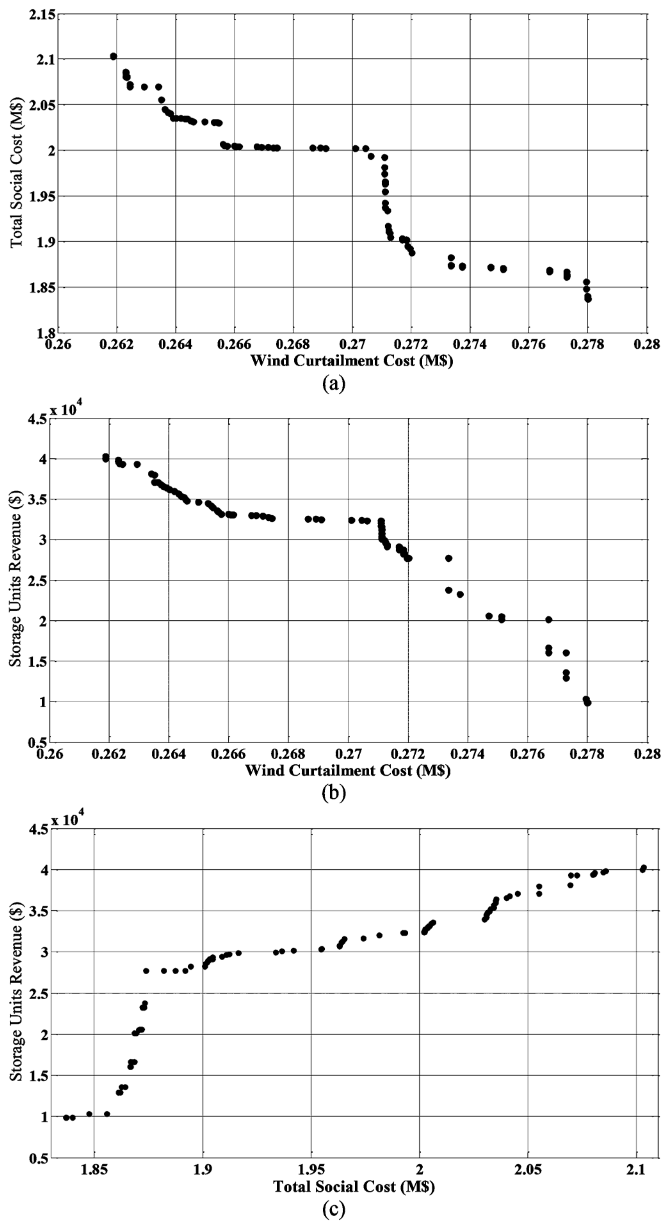

Fig. 5. Non-dominated solutions. (a) Trade-off between wind curtailment cost and total social cost. (b) Trade-off between wind curtailment cost and storage units revenue. (c) Trade-off between total social cost and storage units revenue.

C. *Results and Discussions*

Considering the introduced three objective functions, the proposed algorithm is applied with a population size of 200. One hundred non-dominated solutions are obtained after 100 iterations performed by the NSGA II algorithm. Fig. 5 shows the non-dominated solutions in which the equivalent daily values of objective functions have been presented. The optimal solutions represent a range of wind energy curtailment cost between \$0.2617M and \$0.2781M while the total social cost is between \$1.837M and \$2.103M. The PHES units' revenue varies between \$9847 and \$40 267 in optimal solutions.

Considering the Pareto fronts, the decrease in wind curtailment cost is less than the total social cost enhancement. However, the curtailment cost value is dependent on the power system policies and regulations along with the assumed curtailment penalty cost. The less wind energy curtailment cost, more wind energy is used in the system. As can be traced in Fig. 5(a), once the total social cost of optimal solutions increases, the curtailment cost follows a decreasing trend. More wind energy utilization in system leads to less conventional thermal generation and less fossil fuels cost. However, the TSC would be increased due to the investment costs of the PHES units and new transmission lines.

In Fig. 5(a), in some ranges of the TSC, variation in the amount of wind curtailment cost is very fast and for the other ranges, it varies slowly. The fast changes represent solutions having a new PHES unit which imposes a relatively high investment cost. In contrast, slow increments in the TSC are the reflection of adding new transmission lines or increasing the PHES power ratings. As the wind energy curtailment decreases by storing the excess wind energy, revenue of storage units increases because of the energy arbitrage as depicted in Fig. 5(b). This event can also be deduced in Fig. 5(c) from another point of view. As the TSC goes up by adding new storage units, the revenue of PHES systems increases via storing energy during off-peak hours and releasing the stored energy during peak hours.

To choose a final solution among the optimal non-dominated solutions, fuzzy decision-making method is applied. The desirable levels of μ_i $(i = 1, 2, 3)$ depend on the planners' preferences and the renewable energy policies of power systems. One of the multi-objective optimization features is that the decision maker can analyze different costs trends in order to choose appropriate value of the desired levels for the considered objective function (μ_i). It will lead to an optimal solution representing the actual importance and value of the objective function. The number and ratings of ESSs increase in final solution with the higher values of μ_1 and μ_3. Table I shows the optimal final solutions based on different desirable levels of μ_i. The wind utilization, addressed in this table, is ratio of the utilized wind energy in the system to the available wind energy. As can be traced in the table, an increase in the value of μ_1 from 0.8 to 1, while μ_2 and μ_3 are fixed, will result in a decrease in wind curtailment cost. Although the increase in total social cost is much higher than the curtailment cost decrement, it leads to a high wind utilization level.

It should be notified that the wind energy utilization without expansion plans is 43.15%. Fig. 6 represents the amount of wind energy curtailed during a summer day for three different conditions, i.e., without any expansion plan, with adding some new lines, and applying the final optimal solution of proposed method. As can be seen in this figure, the transmission reinforcement helps integrating wind power more efficiently especially during peak hours. PHES systems, however, show their remarkable performance in alleviating wind energy curtailment at off-peak hours when the available wind power exceeds load demand.

D. *Sensitivity Analysis*

The optimal locations and capacities of PHES plants and also optimal transmission lines depend on a number of assumptions

TABLE I
FINAL OPTIMAL PLAN CONSIDERING DIFFERENT MEMBERSHIP FUNCTIONS DESIRED LEVELS

		$\mu_1=0.8,\ \mu_2=0.6,\ \mu_3=0.6$		$\mu_1=1,\ \mu_2=0.6,\ \mu_3=0.6$		$\mu_1=1,\ \mu_2=0.6,\ \mu_3=0.8$	
PHES Units	Optimal Place (bus number)	3	7	3	13	3	13
	Power Rating (MW)	1025.926	1199.404	1222.455	1057.784	1470.724	1290.407
	Energy Rating (GWh)	7.19	8.54	8.81	7.24	11.46	8.19
	Added Transmission Lines	4-9, 11-14, 16-17		2-4, 4-9, 11-14, 16-17		2-4, 4-9, 11-14	
	Wind Utilization (%)	87.92		88.83		89.78	
	Wind Curtailment Cost ($)	267453.3		264980.2		264013.1	
	Total Social Cost (M$)	2.003		2.031		2.035	
	Storage Units Revenue ($)	32595		34591		36189	

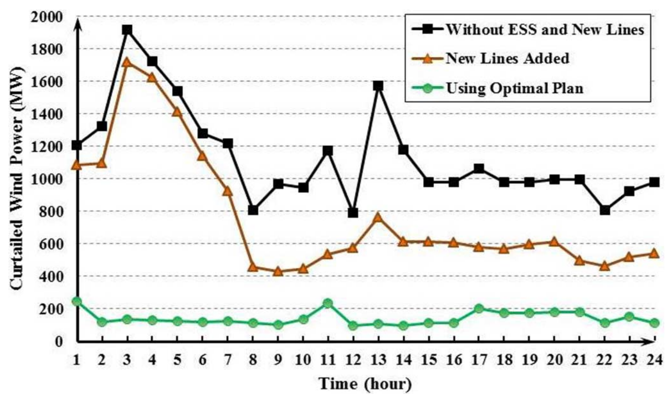

Fig. 6. Wind power curtailment during a 24-h period.

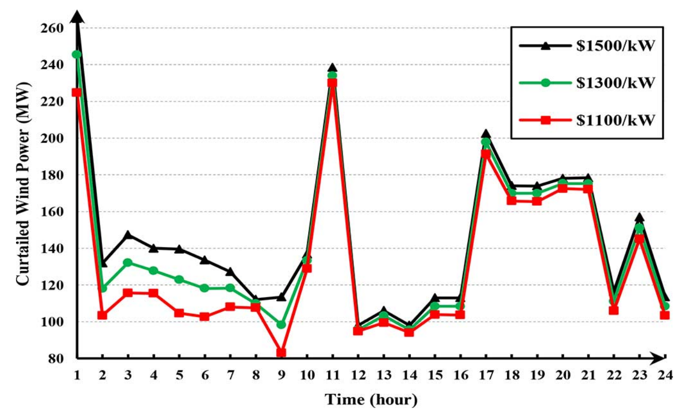

Fig. 7. Wind power curtailment during a 24-h period using optimal plan with different PHES investment costs.

such as investment costs and penalty costs. To evaluate the impacts of these parameters on the obtained optimal plans, a sensitivity analysis is carried out. Fig. 7 depicts how the wind curtailment varies in a summer day in the final optimal solution with different investment costs of PHES systems. As can be traced in this figure, once the investment cost of PHES plants increases, the system adopts more curtailment in wind energy. This increase in the curtailment of the wind energy is more observable at first hours of the day at which the demand is low and the need for ESS is more sensible to store the produced power of wind turbines. To measure the new transmission lines investment cost influence on the final solution, wind power curtailment during the same 24-h time is studied with different transmission lines investment cost. Fig. 8 shows that for higher investment costs of transmission lines, the wind energy curtailment will be higher during peak periods. It is mostly due to the transmission congestion at on-peak hours.

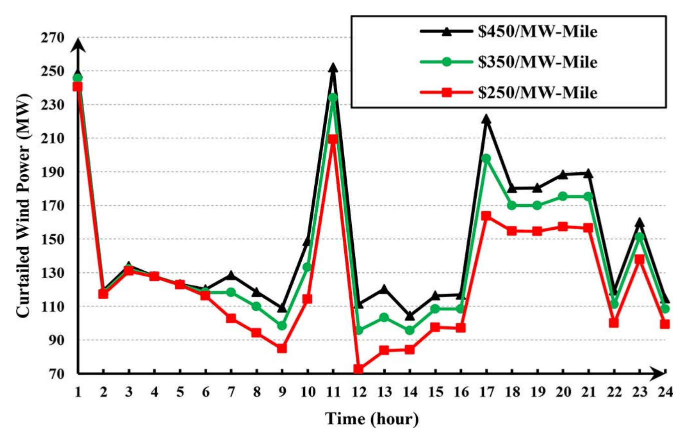

Fig. 8. Wind power curtailment during a 24-h period using optimal plan with different transmission lines investment costs.

V. CONCLUSION

This paper proposes a combinatorial planning procedure for highly wind penetrated power system with main goal of maximizing the wind energy usage. The proposed method finds optimal placement and sizing of PHES units as well as efficient transmission reinforcement schemes so as to integrate more wind power into the system. Economics of the PHES systems are assessed by an arbitrage model. Three different criteria, i.e., the wind energy curtailment cost, total social cost and energy storage units revenue, are introduced as objective functions of the proposed planning procedure and their necessities were well proven in this paper. The attained optimization problem is modeled as an MO posterior framework and the genetic-based NSGA II is employed to find the Pareto optimal solution set. Finally, the fuzzy decision-making method is used to find the final optimal plan based on the planners' preferences.

Implementing the proposed method on the 24-bus IEEE-RTS, the obtained optimal plans confirm the robustness of proposed method. Also, employing combinatorial expansion plans can lend the system operator a hand in more efficiently utilize the available produced power of wind farms with lower imposed costs.

In this regard, excess wind energy can be stored during the first hours of day and would be used as need arises. In addition, the new added lines help PHES plants to relieve transmission congestion and reduce wind energy curtailment during peak hours.

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