International Journal of Industrial Electronics, Control and Optimization © 2021 IECO
Vol. 4, No. 1, pp. 127-139, Jan (2021)

Coordinated Operation of Wind Farms, Cascaded Hydro, Photo-voltaic, and Pump-storage Considering WT-ANN-ICA Hybrid Prediction Method

Ehsan Jafari †

1, † Department of Electrical Engineering, Lenjan Branch, Islamic Azad University, Isfahan, Iran

ABSTRACT

In this paper, a new algorithm is presented to reduce the uncertainty effects of wind farms power generation (WFPG) and photo-voltaic generation (PVG) in both day-ahead energy and ancillary services markets. Firstly, this research tries to predict the uncertainty of short-term WFPG with acceptable accuracy. Indeed, it uses the hybrid method of wavelet transform (WT) in order to reduce the fluctuations in the input historical data along with the improved artificial neural network (ANN) based on the nonlinear structure for better training and learning. Furthermore, the imperialist competitive algorithm (ICA) is adopted to find the best weights and biases for minimizing the mean square error of predictions.

In addition, regarding the high-level penetration of wind farms (WFs) on the power system, cascaded hydro units (CHUs) and pump-storage units (PSUs) are taken for the first time as supplementary units. Therefore, they are coordinated with WFs and photo-voltaic (PV) operations. Considering uncertainties of energy price, spinning and non-spinning reserves in the electricity market, WFPG, PVG and the availability of WFs, PV, CHUs and PSUs along with their effects on energy supply reliability lead to a scenario-based stochastic optimization problem. The aim of this problem is to increase the profit and decrease the financial risk (FR) of all of the units. The proposed method is implemented on WFs, PV, CHUs and PSUs of IEEE 118-bus standard system. Studying the results of profit and FR in the coordinated operation (CO) and the independent operation (IO) confirms that the profit is increased and the FR is reduced in the CO. Hence, the ability and merit of hybrid method of WT-ANN-ICA is verified.

Article Info

Keywords:
Availability, Cascaded hydro units, Photo-voltaic, Pump-storage units, and Wind farms.

Article History:
Received 2019-07-30
Accepted 2020-04-26

NOMENCLATURE

i	Index of each energy resources,	T / t	Total number / index of time intervals
$M(i,t)$	Commitment state of i-th generation unit	α / β	Surplus/Deficit charge
$N(i,t)$/ $N'(i,t)$	Status/Shutdown operation state	η	Coefficient of imbalance cost

†**Corresponding Author**: jafari@iauln.ac.ir Tel: +98-3152437001
Fax: +98-3152432211, Faculty of Department of Electrical Engineering, Lenjan Branch, Islamic Azad University, Isfahan, Iran.

$Z_{CH}(pv,t)/Z_{DCH}(pv,t)$	Charge/discharge state of energy saving battery	W_N, PV_N, PS_N, H_N	Number of units
$U_{COST}(i,t)/D_{COST}(i,t)$	Startup/shutdown cost of $i-th$ generation unit	$P_{WN}(W)$	Rated power of W-th wind farm
$\rho(s_w,s_P,s_{pv},s_{ps},s_h)$	Probability of each scenarios	δ	Efficiency factor
$S_{NP}, S_{NW}, S_{Npv}, S_{Nps}, S_{Nh}$	Total number of scenarios	$P_{BATT}^{DCH}(K,t)$ $P_{BATT}^{maxDCH}(K)$	Power delivered
$s_p, s_w, s_{pv}, s_h, s_{ps}$	Index of scenarios	$R_T(i,t), R_S(i,t), C_T(i,t)$, $C_{imb}(i,t)$	Values of total profit, revenue from selling, total generation cost and imbalanced revenue/cost
$E_P(s_p,t)$ $E_{SR}(s_p,t)$, $E_{NSR}(s_p,t)$	Price of the market for energy, spinning and non-spinning reserve for s_p-th scenario of price($/MW)	$v(ps,end)/v(ps,ini), v(ps,t)$:	Terminal/Initial reservoir water volume, reservoir water volume of $ps-th$ pump-storage unit
$pr_{\max}(ps)/pr_{\min}(ps)$	Max/Min of water charge rate in $ps-th$ pump-storage unit	$v_{\min}(ps)/v_{\max}(ps)$	Min/Max reservoir water volume limit
$gr_{\max}(ps), gr_{\min}(ps)$	Max/Min of water discharge rate	$I^p(ps,t)/I^g(ps,t)$	Commitment condition of generating/pumping
$gr_{(s_w,s_p,s_{pv},s_{ps},s_h,ps,t)}$ / $pr_{(s_w,s_p,s_{pv},s_{ps},s_h,ps,t)}$	Generation-discharge/pumping-charge water	$p_{\min}^{g}(ps)$ / $p_{\max}^{g}(ps)$	Min / Max power generation
$p_{\max}^{p}(ps)$	Maximum purchased power of pumping operation	$N.SR.on_{(s_w,s_p,s_{pv},s_{ps},s_h,ps,t)}$ $N.SR.down_{(s_w,s_p,s_{pv},s_{ps},s_h,ps,t)}$	non spinning reserve of up/down condition
A_w, A_{ps}, A_h, B_h	Cost coefficients	$\hat{y}_{in}$ / y_{in}	Predicted/ Real value for in-th input
$SR^g_{(s_w,s_p,s_{pv},s_{ps},s_h,ps,t)}$ / $SR^p_{(s_w,s_p,s_{pv},s_{ps},s_h,ps,t)}$	spinning reserve of generation / pumping operation	$QSC(ps)$	Generation capacity in the rapid startup
$SR(ps,t)$, $R_{C,PS}(ps,t)$ / $N_{C,PS}(ps,t)$	Total spinning reserve, spinning/non spinning reserve bids	$P_{BATT}^{CH}(k,t)$, $P_{BATT}^{maxCH}(k)$	Charging power of $k-th$ battery at hour t and its maximum limit
$BATT_{COST}$	The cost of buying energy for battery charging	$ENR(k,t)$	The amount of saved energy in $k-th$ battery
$P_{BATT}^{DCH}(k,t)$, $P_{BATT}^{maxDCH}(k)$	Power delivered while discharging $k-th$ battery and its maximum limit	$QT_h(\hat{h},t-\tau_{h,\hat{h}})$:	Discharge to $\hat{h}-th$ unit from turbine path of upstream $h-th$ unit
$R_{\hat{h},h}$	The vector of reservoir connection, if $h-th$ hydro unit is directly upstream of the $\hat{h}-th$	$q(s_w,s_p,s_{pv},s_{ps},s_h,h,t)$ / $S(s_w,s_p,s_{pv},s_{ps},s_h,h,t)$	discharge/spillage water volume from $h-th$ hydro unit
$u(h,t)$	Natural inflow of $h-th$ hydro unit in Hm^3/h	k_{1h}, k_{2h}, k_{3h}	Water to power conversion coefficients

I. INTRODUCTION

One of the main goals in countries with restructured electricity market where governmental support and subsidies are omitted is to establish a complete competition in the market. Additionally, lack of financial support from renewable resources like wind and photo-voltaic resources in one hand, and compulsory expansion of them due to environmental reasons in the other hand along with the uprising cost of fossil fuels could make this market unlikely prolific for the investors and producers. Therefore, optimal planning is of particular importance [1-3]. In [1], A chance-constrained model is developed to handle optimal operation and emergency conditions of Microgrid including renewable resources outage and unwanted islanding. An optimization method to optimize the parameters of the Microgrid controller in islanding mode. The controller optimal parameters have been obtained by using the particle swarm optimization (PSO) [2]. In [3], a method has been proposed that can be used to determine the location, power, and capacity of the energy storage systems with consideration of the technical and economic aspects, simultaneously.

Owners of renewable resources need to predict the uncertainties for optimal planning such as WF power generation/wind speed [2-9], market price, and load forecasting. In [4] Autoregressive Moving Average (ARMA) was used to predict WFPG. In addition, [5] used adaptive neuro-fuzzy inference system (ANFIS) and [6] hired ANFIS and PSO together for prediction of WFPG. In [7], firstly, historical data of WF is decomposed using WT; then, WFPG is predicted by ANN. This method is tested in two regions of china. Afterwards, comparing WT-ANN, ANN, and ARMA methods reveal that WT-ANN can significantly reduce the error in spite of ANN and ARMA methods. In [8], the optimal weights and biases of ANN are determined by genetic algorithm (GA), ICA, and ICA-GA methods; then tested on six specified data-bases. In the end, the obtained results confirmed that ICA has higher capabilities. Similarly, ANN is employed to predict WFPG and ICA, GA and PSO are chosen to determine the optimal weights and biases [9]. The prediction results were more satisfactory when ICA algorithm was utilized.

The second solution for uncertainty reduction in renewable units including WF is to coordinate other energy resources which are quite expensive, but available and more reliable, such as PSU, CHU, gas turbines, combine cycle power plants and energy storage batteries. However, the share of these energy sources should diminish for many reasons [10]. In [11] the coordinated planning of WF, PSU, and thermal units is presented by the multi-stage stochastic planning and solved by scenario decreasing algorithm of PSO. In [12], the required reserve level is estimated in presence of high-level WF penetration. In [13], the optimal strategy of WF is determined in the real-time market. The wind speed and market price are predicted by ARMA. Also the expected profit is limited by FR and the required reserve is determined because of error prediction in WFPG. In [14], the coordinated planning problem of WF and thermal power plants is solved by artificial immune optimization method. This optimization method is implemented on a system including ten thermal power plants and two WFs. A mixed integer programing algorithm is adopted for period planning of operation status/shutdown and generating/pumping mode of PSU to maximize the profit in CO of WF and PSU [15]. A scenario-based and chance constrained optimization method is hired to consider the WFPG prediction error. The optimal coordinated strategy in stochastic planning for WF and CHUs is discussed in [16]. This stochastic planning is based on PBUC, and includes the imbalance cost in WF. A chance-based method is chosen to solve the optimization problem, and the results were compared with Monte Carlo method. Studying the risk and the limitation of FR in GENCOs is discussed in [17]. A rolling optimization method for WF coordination with the energy-storage systems in the day-ahead market is presented to increase the profit of these power plants. The CO and IO of a system including a WF, PSUs, and photovoltaic resources are compared in [18]. Predicting WFPG is carried out through ARMA method. The results show growth in profit and decline in FR of CO. The optimal cascaded hydro unit scheduling and biding strategies considering price uncertainty and risk management is analyzed in [19]. The optimal scenario-based operation management of Micro-Grid including WF, Photovoltaic, Micro-Turbine/Fuel Cell, and Energy Storage devices were studied in [20]. In this paper, the considered uncertainties are load, WFPG, Photovoltaic power generation, and market price. Optimal biding strategy model in an electricity distributed company in order to make maximum profit in a day-ahead market is considered in [21]. In [22], the reliability of WF in coordination with PSU in power system is estimated. This research uses a Monte Carlo simulation method to establish coordination between WF and PSU with an objective function to compute the adequacy indexes for one-year period.

The presented issue, in this paper, can be shortly explained as follows:

1-Prediction of WFPG via hybrid method (HM) of WT-ANN-ICA. According to the studies in [7-9], prediction of WFPG using the proposed method can lessen errors of prediction in comparison to ARMA, ANN, WT-ANN, WT-ANN-PSO, and WT-ANN-GA methods. Therefore, this approach may generate scenarios closer to reality and lead to the optimal programming.

2-Generating the scenarios of WFPG, PVG, market price (energy, spinning reserve and non-spinning reserve) and decreasing the scenarios with the Scenario-reduction backward method, availability of WFs, PV, CHUs and PSUs, and modeling them by scenario tree method.

3-The coordination programming of WFs, PV, CHUs and PSUs, by considering constraints of these units and the uncertainties of WFPG, PVG, market price and availability of WFs, PV, CHUs and PSUs.

4-Studying the expected profit and FR in the CO and IO of all four unit types with and without considering the availability.

II. The Proposed Method

The proposed algorithm for programming of generation and unit commitment of WFs, PV, CHUs and PSUs including two WFs, one PV, three CHUs and three PSUs in both CO and IO states in both day-ahead energy and ancillary services markets is shown in Fig. (1).

A.Publication Prediction and scenario generation

a) WFPG prediction using HM of WT-ANN-ICA: The proposed method for prediction of WFPG is depicted in Fig. (1). First, it is assumed that the prediction for d-th day can be done and historical data is available for every hour of 24 hours since 100 days ago.

Stage 1: data homogenization: the historical data is recalled and normalized to improve data homogenization through MinMax normalization method.

Stage 2: Data Processing Using Wavelet Theory: the components and features of data can be extracted via mathematical equations. More specifically, the components and features of time and frequency domain of data signal can be extracted using wavelet technique. The basic equations of WT are as Eq. (1), (2).

$$WT(a,b)=\frac{1}{\sqrt{a}}\int_{-\infty}^{+\infty} f(t)\psi(\frac{t-b}{a})dt \quad (1)$$

$$a=2^{-j}, b=k2^{-j}\in R, a\neq 0$$
$$f(t)=\frac{1}{C_{\Psi}^{2}}\iint_{a,b}\Psi_{\psi}\frac{1}{a^{2}}\psi(\frac{t-b}{a})dadb \quad (2)$$

Where, ψ (a,b) is wavelet function and f(t) is input signal on which wavelet function is done until resulting the WT (a,b) signal. Also a and b are the parameters related to the WT which depend on the kind of wavelet function. The approximated values are again decomposed after some iterations; therefore, the signal is decomposed into smaller parts [7, 23]. In Fig. (2, a) the output power of wind farm 1(WF1) is shown along with its WT signal for every hour of the past year. WT is useful here to suppress the disturbances in historical data and to alleviate the fluctuation of input data. A fast technique to execute WT has been used, which contains two stages: decomposition and reconstruction. At first, the original wind data series is decomposed into one approximation series and some detail series. Next, detail and approximation series are assembled back into the original series. More mathematical details of the technique can be found in [20]. Fig. (3) depicts the corresponding wavelet decomposition. The input data is decomposed into three approximated components (Dh1, Dh2, Dh3) with lower accuracy along with a more precise component (Ah) which plays the most important role in the prediction process.

Stage 3: Artificial Neural Network (ANN): McCulloch and Pitts tried to simulate the ANN by a logical model for the first time but today it is widely used in many fields. The chosen ANN here in this paper comprises three perception layers (multi-level perceptron method); the output layer with one neuron, the input layer with five neurons, and the hidden layer with three neurons. This ANN can predict the information of hours d(t+1,……t+24) for the output signals of WT as the initial data.

Stage 4: Imperialist Competitive Algorithm (ICA): ICA is a new optimization strategy based on political and social evolution of human. More precisely, this algorithm is the mathematical model of social-political process of imperialists. Basically, GA and PSO are inspired of biological evolutions, chromosomes and particles, to determine the best solution. However, the source of inspiration in ICA is the social-political evolution, and it uses colonies (countries) as the variable for finding the optimal solution [8, 9]. The steps of ICA can be summarized as follow:

- Creating the initial colonies: according to the neural network input signals (Ah,Dh1,Dh2,Dh3), and the five neurons in the input layer (IL), three neurons in hidden layer (HL), and one neuron in output layer(OL), the matrixes of weights (W) and biases (B) are respectively.
- Hence, each colony constitutes 47 variables. Initial colonies are selected randomly through specific range based on initial training of ANN. Then, regarding the cost function based on decreasing the prediction error, the optimization of weights and biases are performed within the neural network for better training. A multi-layer feed forward neural network is considered to predict the wind power. Since the input data and target data of the system are normalized between -1 and 1, Tan-Sigmoid transfer function is used in the neurons of hidden layers. The linear transfer function is also used in the neurons of output layer. The proposed neural network is feed forward with one hidden layers trained by ICA. Table 1 represents Layer's transfer functions of neural network layers and number of layer's neurons. Table 2 represents the characteristic of neural network. The cost function here is mean square error (MSE) which is implied as Eq. (3).

$$\min\ FunctionCost \qquad MSE=\frac{1}{IN}\sum_{in=1}^{IN}\left|\hat{y}_{in}-y_{in}\right|^{2} \quad (3)$$

TABLE I

Number of Layer's Neurons and Layer's Transfer Function of Neural Network

Number of Layers	Number of Neurons	Transfer Function
1	5	Tan-Sigmoid
2	3	Tan-Sigmoid
3	1	Liner

TABLE II

Characteristic of Neural Network.

Network Type	Feed Forward
Training Function	Gradient Descent Momentum and an Adaptive Learning Rate
Adaption Learning Function	Gradient Descent Weight and Bias
Performance Function	Mean of Squared Errors

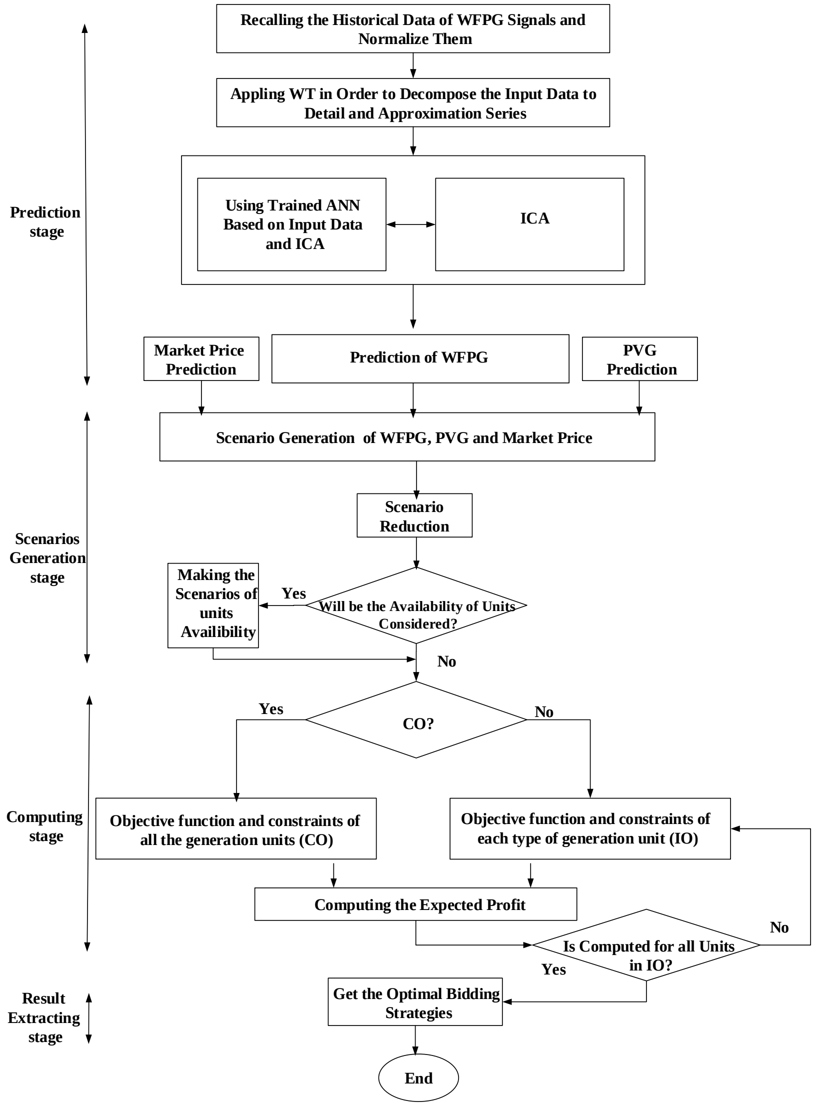


Fig. 1: The flowchart of the proposed method

- Selecting the imperialist: in this stage the colonies which have minimum cost are selected as the imperialists.
- Allocating the other countries as the colony to the imperialists: in this step, some colonies are allocated to each of imperialists and empires. This allocation is done according to imperialists fitness (fewer cost) by stochastic universal sampling method. The stages of 1-3 are the initialization stages of ICA.
- Performing the act of assimilation or absorption policy: in this stage, each of the colonies is moved towards the imperialist in each empire. This stage proceeds to improve the exploitation of algorithm.
- Performing the act of revolution: In this stage, the random changes are applied on each of the colonies. This action can improve the exploration of algorithm, and prevent from involving the optimization in the local optimal points.
- Computing the cost of colonies and imperialists
- Comparing the cost of colonies with imperialist in each empire: if a colony has a lower cost than the imperialist, it will take its place.
- Evaluating the empires: the cost for each empire is computed according to Eq. (4).

$$Cost_{empire} = Cost_{imperialist} + \frac{0.1}{N_{COL}} \sum_{n=1}^{N_{COL}} (Cost_n) \tag{4}$$

where: N_{CLO} is the number of colonies.

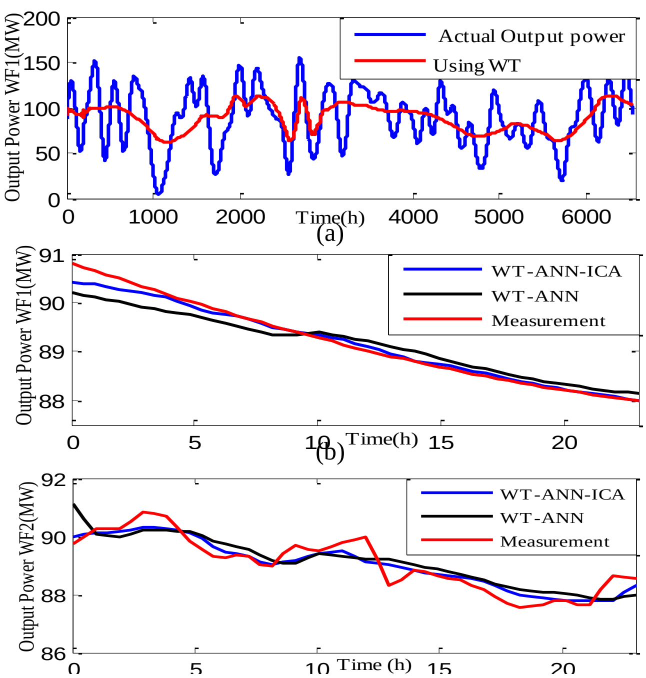
- Decreasing the colonies: in this stage, a colony is omitted from the weakest empire and transmitted to another empire by roulette wheel method. According this method, the empire with the lower cost has more chance to seize the colony.

-Omitting the empire: if the weakest empire has no colony, the related imperialist will be transmitted to another empire as a colony.

Stage 5: Studying the termination condition: the stop condition is set based on the number of iterations obtained by trial and error method. If the stop condition of program is satisfied, the results move to the scenario generation stage; otherwise, the algorithm returns to (4) to generate new colonies. ICA flowchart is illustrated in Fig. (4). WFPG prediction curves are shown in Fig. (2, b-c).

b) Generating scenarios for WFPG, PVG and market price: After predicting the uncertainty variables, the predicted error of each one is considered with a known probability distribution function. This distribution function is discretized to N parts with the mean of zero from the center with the width of α. It is allocated to the occurrence probability and specific error percentage for each level as shown in Fig. (5). The probability of each occurrence is normalized so that their accumulated distribution function is equal to 1. Then a number is randomly selected for each uncertainty variable and each time interval by roulette wheel method; hence, an intended scenario is generated.

The rate of each scenario is obtained by the sum of the error and the predicted amount of variable [20]. Eq. (5) shows the amount of scenario for the WFPG. Consequently, 500 scenarios are generated for each WFPG, PVG, and market price.



(c)

Fig. 2: (a): The real output power after noise removal by WT in a period of one year of WF1. The output power measured and predicted by methods of WT-ANN and WT-ANN-ICA related to (b):WF1 (c):WF2 in d=101.

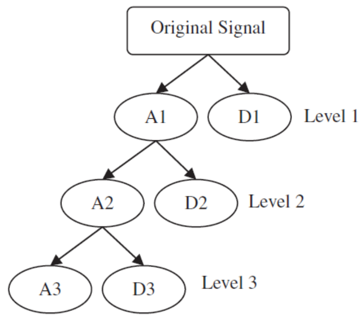


Fig. 3: Wavelet decomposition

$$P_G^W(w,s,t) = P_{Gforcasted}^W + \Delta P_G^W(w,s,t) \quad (5)$$

$$t = 1,....,24, \qquad s = 1,......, s_w, \qquad w = 1,......, W_N$$

c) Backward method scenarios reduction: For modelling all three uncertainty parameters including WFPG, PVG and market price many scenarios are generated. However, the huge number of scenarios makes it burdensome to solve the stochastic problem. In order to solve this problem, the number of scenarios should decline by the backward method. The basis of this method is to merge the scenarios with close probability into one. This process could continue until reaching the favorable numbers [18, 20]. In this research, the number of scenarios abates down to 10 for each state. WFPG scenarios are shown in Fig. (6).

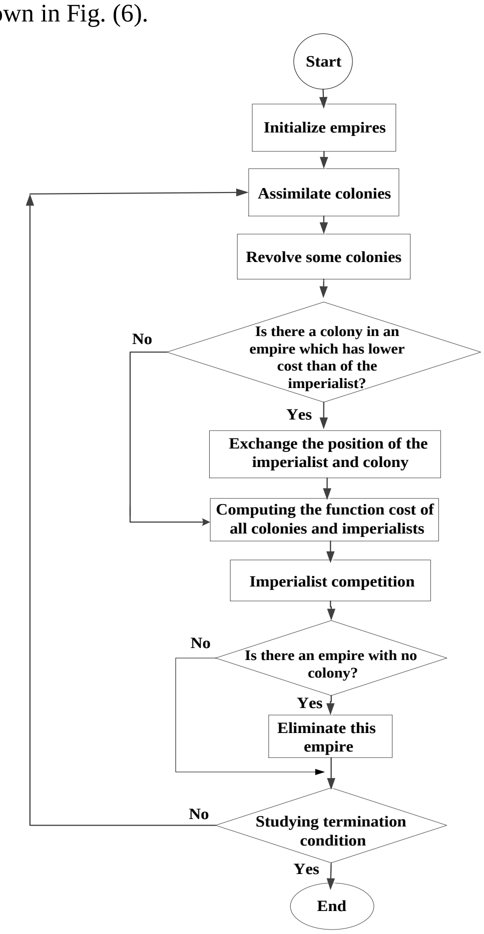


Fig. 4: Flowchart of ICA

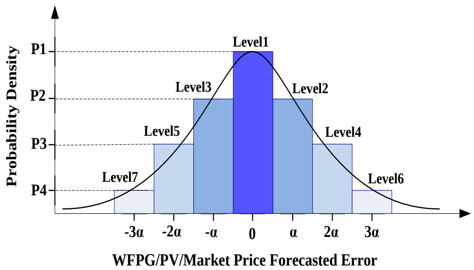
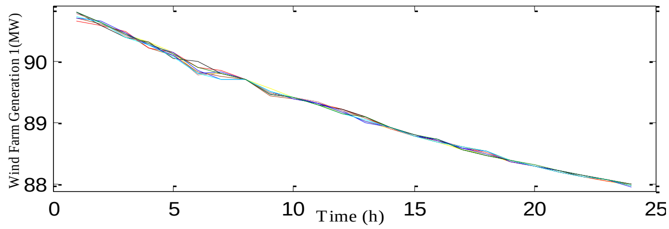
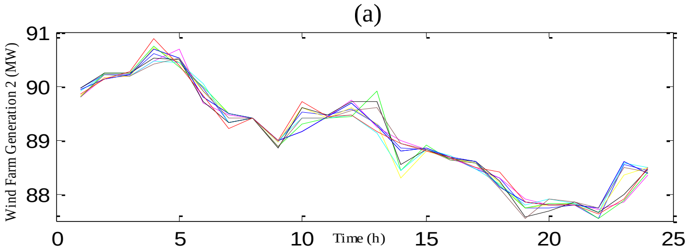


Fig. 5: The probability density of function of the WFPG, PVG and market price.



(a)



(b)

Fig. 6: WFPG scenarios (a):WF1 (b):WF2.

d) Modelling of the units availability uncertainty: An important issue in a restructured market is the reliability and availability effects on the behavior of generation unit owners. In fact, the reliability of the overall system may not be of concern; however, the main objective of these owners is to maximize their own profit. Hence, the owners need to pay extra attention to availability and reliability of their proposed generation values. A scenario-based method is proposed to generate the units' availability scenarios. In this paper, the two-stage Markov model is selected. Since the operation of each WFs, PV, CHUs and PSUs in each hour is dependent to the system operation at the previous hour, Monte-Carlo simulation method is employed for generating the availability scenarios of WFs, PV, CHUs and PSUs. Therefore, availability scenarios of each unit in each hour (5 scenarios for each unit) are achieved based on random numbers between 0 and 1 with normal distribution.

Then, each of these random numbers is compared with the force outage rate (FOR) of the intended unit. If the intended random number is greater than FOR, the unit is available in that scenario and hour. Otherwise, the unit is not available by the number of hours of mean time to repair (MTTR) in that scenario. Practically, if a unit is switched off because of the failure, it will not be available until the complete repair [22].

After determining the availability/unavailability of each unit in each scenario and hour, the capacity of generation units is achieved from aggregating of available capacity in each unit.

B. Coordinated operation (CO) of WFs, PV, CHUs and PSUs

In the day-ahead market, GENCOs and consumers submit their bids to ISO according to the predicted market price and demand. In this condition, the profit of generation units is determined with regard to the market clearing price, operation cost, imbalance revenue/cost, proposed energy, and delivered energy as Eq. (6). These parameters are computed in Eq. (7)-Eq. (9) [13, 15]. Where Eq. (7), shows the revenue earned from the sold energy equal to $P_S(i,t)$ with price $E_P(t)$. Eq. (8) also shows the operation cost as a function of unit generation power $P_G(i,t)$. Eq. (9) shows the imbalance revenue/cost of unit as a function of difference between proposed and generation (delivered) energy $(P_S(i,t)-P_G(i,t))$. Eq. (10) indicates imbalance revenue/cost function. Where $\alpha(t)$ and $\beta(t)$ are variously defined in different markets. In this paper, the relation between imbalance penalty factor and generation power is illustrated as Eq. (11). In Eq. (11) η is a number between zero and one, also three variables $P_G(t)$، $\tilde{C}_{imb}(t)$, and $E_P(t)$ are unknown before the energy delivery time. These three variables cause uncertainties and risks in programming.

$$R_T(i,t)=R_S(i,t)-C_T(i,t)-C_{imb}(i,t) \tag{6}$$

$$R_S(i,t)=P_S(i,t).E_P(t)+P_{SR}(i,t).E_{SR}(t)+P_{NSR}(i,t).E_{NSR}(t) \tag{7}$$

$$C_T(i,t)=(a_i+b_i.P_G(i,t)+c_i.P_G^2(i,t)).M(i,t).AV(s,i,t) + (U_{COST}(i,t)+D_{COST}(i,t)).AV(s,i,t) \tag{8}$$

$$C_{imb}(i,t)=\tilde{C}_{imb}(i,t).f(P_S(i,t)-P_G(i,t)) \tag{9}$$

$$C_{imb}(i,t)=\left(\alpha(t)+\beta(t).(\frac{P_S(t)}{P_G(t)})^2\right).(P_S(t)-P_G(t)) \tag{10}$$

$$\begin{cases}\beta(t)=(1+\eta).E_P(t),\alpha(t)=0 & P_S\rangle P_G\\ \alpha(t)=(1-\eta)E_P(t),\beta(t)=0 & P_S\langle P_G\end{cases} \tag{11}$$

a) Problem modeling of unit coordination programming:

In this section, an optimal bidding strategy is modeled and analyzed. The objective function of this optimization problem utilized for the first time is as Eq. (12). The aim is to maximize the expected profit (difference between incomes and costs (Eq. (13)) of units considering constraints related to unit usages. The revenues are earned from selling energy and reserve delivered to the market. In fact, the revenue from generation is more than the proposed amounts to the market (positive imbalance revenue) by all of the units (Eq. (14). Also the costs include the expenditure of operation, startup and shutdown, purchased power of PSUs in the state of pumping operation, the cost of battery of PV resources and also imbalance cost as

Eq. (15), Eq. (16).

$$\max \quad ER_T = \sum_{t=1}^{T} \sum_{s_p=1}^{S_{NP}} \sum_{s_w=1}^{S_{NW}} \sum_{s_h=1}^{S_{NH}} \sum_{s_{ps}=1}^{S_{NPS}} \sum_{s_{pv}=1}^{S_{NPV}} \rho(s_w, s_p, s_{pv}, s_{ps}, s_h).\left(\sum_{w=1}^{W_N} \sum_{ps=1}^{PS_N} \sum_{h=1}^{H_N} \sum_{pv=1}^{PV_N} R_T(s_w, s_p, s_{pv}, s_{ps}, s_h, w, pv, ps, h, t) \right) \tag{12}$$

$$R_T(s_w, s_p, s_{pv}, s_{ps}, s_h, w, pv, ps, h, t) = \begin{pmatrix} R_S(s_p, t) - C_T(s_w, s_p, s_{pv}, s_{ps}, s_h, w, pv, ps, h, t) - \\ C_{imb}(s_w, s_p, s_{pv}, s_{ps}, s_h, w, pv, ps, h, t) \end{pmatrix} \tag{13}$$

$$R_S(s_p, t) = \left(E_P(s_p, t).P_S(t) + E_{SR}(s_p, t).P_{SR}(t) + E_{NSR}(s_p, t).P_{NSR}(t) \right) \tag{14}$$

$$C_{imb}(s_w, s_p, s_{pv}, s_{ps}, s_h, w, pv, ps, h, t) = \widetilde{C}_{imb}(s, t).\, f\left(P_S(t) - P_G(s_w, s_p, s_{pv}, s_{ps}, s_h, w, pv, ps, h, t) \right) \tag{15}$$

$$C_T(s_w, s_p, s_{pv}, s_{ps}, s_h, w, pv, ps, h, t) = \tag{16}$$

$$\begin{pmatrix} \left(\sum_{w=1}^{W_N} A_w.AV(s_w, w, t) \right) + \left(\sum_{ps=1}^{PS_N} (A_{ps} + U_{COST}(ps, t)).AV(s_{ps}, ps, t) \right) \\ + \left(\sum_{h=1}^{H_N} (A_h + B_h.P_G^H(s_w, s_p, s_{pv}, s_{ps}, s_h, w, pv, ps, h, t) + U_{COST}(h, t).N(h, t) + D_{COST}(h, t).N'(h, t)).AV(s_h, h, t) \right) \\ + \left(\sum_{pv=1}^{PV_N} (BATT_{COST}(k = pv, t)).AV(s_{pv}, pv, t) \right) \end{pmatrix}$$

Where: $BATT_{COST}(k,t) = [a^{CH}(k) Z_{BATT}^{CH}(k,t) + b^{CH}(k) P_{BATT}^{CH}(k,t)] + [a^{DCH}(k) Z_{BATT}^{DCH} + b^{DCH} P_{BATT}^{DCH}(k,t)] + CC(k)$

a) Constraints of the proposed optimization problem:

1. General constraints:

- Maximum energy propose limit (Eq. (A.1)).
- Available output generation power of the CO (Eq. (A.2)).

2. Constraints of PSUs:

-Produced/consumed power of PSU in Generation/pumping operation: (Eq. (A.3).

- Balance of water constraints: (Eq. (A.4), Eq. (A.5)).
- Upper/lower water reservoir volume limits: (Eq. (A.6), Eq. (A.7)).

-Initial /terminal water reservoir volume: (Eq. (A.8)-Eq. (A.9)).

- Charge/discharge of water limits: (Eq. (A.10), Eq. (A.11)).
- Proposed power to the energy and ancillary services markets limits: (Eq. (A.12), Eq. (A.13)).

Non-spinning reserve limit in down state: (Eq. (A.14)).

Operation in pumping /generating mode: (Eq. (A.15)).

-Reserve power supply generated in pumping mode: (Eq. (A.16)).

- Proposed spinning/non-spinning reserve limits: (Eq. (A.17), Eq. (A.18)).

3. WFs constraint:

- Wind power generation limit: (Eq. (A.19)).

4. CHUs Constraints: In this section, the programming constraints used in this paper are presented. These constraints consist of both electrical and hydro operation parts. Because of the complicated nature of stream on a reservoir, a matrix model is assumed [26]. In this matrix model indicates each variable of charge and discharge water from the dam, turbine, and units. Subsequently, two main variables in the matrix modeling constraints of hydro system are taken as Eq. (A.20).

It should be mentioned that unit is directly upstream of unit (Eq. (A.21)).

- The balance constraint of water for CHUs: According to this constraint, the volume of water stored in hydro unit at hour is obtained based on the reservoir water volume at hour, the reservoir natural inflow at hour, the reservoir discharge, and the reservoir spillage at hour (t-1), as Eq. (A.22):
- Water discharge rate limit: (Eq. (A.23)).
- Reservoir water volume limit: (Eq. (A.24)).
- Initial /terminal reservoir water volume: (Eq. (A.25)).
- The generation power of CHU: (Eq. (A.26)).
- Ramping up/down limits: (Eq. (A.27), Eq. (A.28)).
- Water spillage limit: (Eq. (A.29)).
- Operation status/shutdown state: (Eq. (A.30), Eq. (A.31)).

5. PV Constraints:

- Limits on the battery of the photo-voltaic unit while getting charged and discharged: (Eq. (A.32), Eq. (A.33)).
- Charge/discharge switching constraint: (Eq. (A.34)).
- Initial / terminal energy of the PV: (Eq. (A.35)).
- Amount of saved energy in the battery: (Eq. (A.36)).
- The power generation of the photo-voltaic unit and battery: (Eq. (A.37)).

C. Coordinated operation (CO) and independent operation (IO) without considering availability

In order to consider an independent or coordinated planning of units without reliability, uncertainty parameters are WFPG, PVG and market price (s_w, s_p, s_{pv}) and the availability of the units are taken constantly equal to 1 ($AV(s,i,t) = 1$). First, the objective function of each type of unit and related constraints are optimized separately. Then, the generation bids and in turn the expected profit and FR are calculated.

This process is repeated for CO, so that the objective function of WFs, PV, CHUs and PSUs units (Eq. (12)) is optimized considering constraints of all four unit types in parallel with other constraints forced by CO. Afterwards, a generation bid is offered to ISO, and WFs, CHUs and PSUs will participate in a day-ahead energy and ancillary services markets considering maximum generation power of each unit. In this case, the expected profit and FR are calculated and compared. This optimization problem is solved using GAMS / CPLEX software.

D. Coordinated operation (CO) and independent operation (IO) considering availability

Due to the increasing number of units and generation volume, reliability and availability of each unit may have a great effect on determine the biding strategy of WFs, CHUs and PSUs in CO and IO.

In this case, uncertainty parameters are WFPG, PVG, market price and availability of WFs, PV, CHUs and PSUs ($s_w, s_p, s_{pv}, s_{ps}, s_h$).

III. Numerical Example

The improved IEEE 118-bus standard system contains two WFs, one PV, three CHUs and three PSUs. The WFs nominal power rates are $P_{\max}^{MW} = 300$ and $P_{\min}^{MW} = 10$. IEEE standard values are assumed for the historical data of WFPG. The PV nominal generation power is $P_{\max}^{MW} = 4.68, P_{\min}^{MW} = 0$ and $\delta = 0.75$. The CHUs nominal power limits are $H_1 : P_{\max}^{MW} = 70, P_{\min}^{MW} = 9$, $H_2 : P_{\max}^{MW} = 70, P_{\min}^{MW} = 4$ and $H_3 : P_{\max}^{MW} = 115, P_{\min}^{MW} = 17$, where, H_1 and H_2 are upstream units of H_3 as shown in Fig. (7). Besides, their additional information is listed in [16]. The information related to PSUs is presented in [25]. In this paper, η is equal to 0.9. Finally, the market price data are available in Fig. (8).

a. Without considering availability: The generation bids of CO and IO of units and the expected profit of CO and IO of units are shown in table (3) and table (4) respectively. Without considering reliability through WT-ANN-ICA method, the expected profit in CO (WFs, PV, CHUs and PSUs coordinated) is $198318.3, which is increased by $15764.84 in comparison with sum of expected profit in IO. Using WT-ANN-ICA method is more accurate comparing with WT-ANN method in which the mathematical expected profit is respectively increased to 7034.47 and $4292.8 for IO and CO.

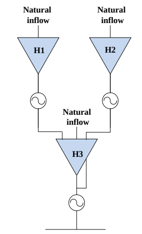


Fig. 7: Hydro system configuration used in this study

b. With considering availability: The energy generation bids, when availability is taken into account in some hours, are less than its amounts without considering availability as listed in table (3); indeed, they may downsize the expected profit. These are the same expected results because if availability is considered the less number of units are available in some hours. Since FOR of WFs are quite low, in most hours, WFs bids are the same in two states.

Considering reliability and using WT-ANN-ICA method, the expected profit can increase to the rate of $13474.32 in CO (WFs, PV, CHUs and PSUs coordinated) than IO as displayed in table (4). It is observed that the expected profit when availability is ignored is more than the state where availability is taken into account.

The sum of expected profits gained by CO of three types of generation units and the other type of unit, are also given in table (2). The obtained results confirm the growth of profit in CO of four unit types.

c. Financial risk (FR)

Because risk assessment is one of the important quantities in environments involving uncertainties [26], In order to study the imbalance revenue/cost, which is one of the main factors of FR in the proposed model, imbalance revenue is provided in a table (5). Vividly, its value is elevated in CO comparing with IO. Using WT-ANN-ICA method, imbalance revenue decreases in both CO and IO. Obviously, when the generation units fail in delivering scheduled power, they will get penalties; on the other hand, if they generate more than enough, they will get paid in lower prices.

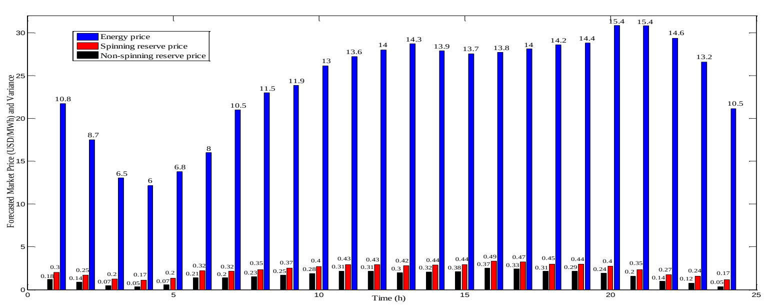


Fig. 8: The forecasted market price (energy price, spinning reserve and non-spinning reserve) and their variance.

TABLE III

Power generation bids (MW) of WFs, PV, CHUs and PSUs in CO and IO with and without availability using WT-ANN-ICA method

Reliability		Without Availability					With availability				
State operation		IO				CO	IO				CO
Load	Time	WFs	PV	CHUs	PSUs		WFs	PV	CHUs	PSUs	
250	t1	171	0	93	-36	240.5	171	0	93	-26	248
180	t2	171.5	0	57.6	-98	129.1	۸۴	0	57.6	-98	46.5
185	t3	171	0	26	-98	85	۸۴	0	26	-98	22
190	t4	170	0	27.3	-98	110.7	83.5	0	27.3	-98	24.5
195	t5	168.5	0	30.3	-98	115.6	168.5	0	30.3	-68	125.5
200	t6	168.5	1.008	40	-98	125	168.5	1.008	40	-98	125
260	t7	167.3	1.548	57.7	12	259.5	167.3	1.548	57.7	2	239.7
250	t8	168	1.95	80.1	-89	178	168	1.95	80.1	-89	178
310.5	t9	166.5	2.002	101.5	44	310.5	166.5	0	101.5	-16	256.1
355	t10	165.5	2.56	111.2	58	349	165.5	0	111.2	68	355
355.5	t11	165	3.2	118.9	58	355.5	165	3.2	118.9	58	355.5
361	t12	165	4.12	121.5	58	361	165	4.12	121.5	58	361
350	t13	164.5	4.68	124	58	349.5	164.5	4.68	63.5	58	295
365	t14	165.7	4.61	126.2	58	365	165.7	4.61	65.7	58	300.5
375.5	t15	163	4.2	130.7	58	371.4	163	4.2	130.7	62	375.2
381	t16	163.6	3.31	145.87	58	380.6	163.6	3.31	109.4	58	329
378	t17	164	3	147.3	58	378	164	3	110.5	58	341
394	t18	163	2.145	148.9	58	382.3	163	2.145	148.9	68	393.1
390	t19	159.5	1.45	152.6	-36	281	159.5	1.45	152.6	-16	298
395	t20	161.5	0	162.5	98	431.5	161.5	0	162.5	98	431.5
390	t21	161	0	162.8	58	386.8	161	0	162.8	58	386.8
395	t22	159	0	162.8	68	395	159	0	162.8	68	395
380	t23	158.6	0	140.1	-4	308.8	158.6	0	140.1	-4	308.8
360	t24	158.5	0	120.5	58	349	158.5	0	120.5	68	358

TABLE IV

Expected profit in CO and IO with and without availability using WT-ANN-ICA and WT-ANN methods

		Expected Profit (USD)			
		Without Reliability		With Reliability	
		WT+ANN	WT+ANN+ICA	WT+ANN	WT+ANN+ICA
IO	WFs	89915.82	94208.77	86175.65	90389.54
	PV	1068.28	1068.28	955.7	955.7
	CHUs	74525.01	74525.01	62671.24	62671.24
	PSUs	12751.42	12751.4	12307.9	12307.9
	Total	178260.57	182553.46	162110.49	166324.38
CO	(WFs+PV+CHUs)&PSUs	182378.65	188355.37	166523.1	171265.45
	(WFs + PSUs+PV)&CHUs	186856.3	192123.42	170272.6	175434.6
	WFs+PV+CHUs+PSUs	191283.83	198318.3	174183	179798.7

TABLE V

Imbalance revenue ($) in CO (WFs+PV+CHUs+PSUs) and IO using WT-ANN-ICA and WT-ANN methods

	Without Reliability				With Reliability			
	WT-ANN		WT-ANN-ICA		WT-ANN		WT-ANN-ICA	
State Operation	IO	CO	IO	CO	IO	CO	IO	CO
Imbalance revenue	24946.63	28904.77	21162.3	25863.65	22008.45	25018.52	28721.33	22417.84
[16]	24396.54	28585.21	20771	24639.9	Not studied			
[18]	24435.76	25311.74	21082	25761.2				

IV. CONCLUSIONS

In this paper, two methods were proposed for decreasing WFPG and PVG uncertainty as a main factor of decreasing profit and increasing FR.

The first method, HM of WT-ANN-ICA, tries to predict more accurately and improve short-term errors of WFPG. Proposed method results in less error prediction than previous studies. Therefore, more real scenarios might be generated with a greater probability and WFs optimal programming is done more accurately. As a result, the expected profit may enhance.

In the second method, for the first time, establishing a unit commitment policy among WFs, PV, CHUs and PSUs, the uncertainty and FR of WFs can diminish using two pumping and generating PSUs and CHUs. Indeed, CHUs utilization occurs when PSUs generation mode does not have enough capacity while WFPG and PVG drops severely. In addition, considering shift capabilities of WFPG and PVG based on PSUs and CHUs capabilities during peak time, the profit of these units might accrue in comparison with IO.

In the end, probabilistic programming model of WFs, PV, CHUs and PSUs with consideration of reliability is presented. Since the generation bids are based on this model, it is possible to achieve them in real time generation with acceptable reliability.

APPENDIX

$$P_S(t) \le \begin{pmatrix} \sum_{w=1}^{W_N} P_{G\max}^{W}(w).AV(s_w,w,t) + \sum_{ps=1}^{PS_N} P_{G\max}^{PS}(ps).AV(s_{ps},ps,t) + \sum_{h=1}^{H_N} P_{G\max}^{H}(h).AV(s_h,h,t) \\ + \sum_{pv=1}^{PV_N} (P_{G\max}^{PV}(pv) + \delta P_{BATT}^{\max DCH}(k=pv)).AV(s_{pv},pv,t) \end{pmatrix} \tag{A.1}$$

$$P_G(s_w,s_p,s_{pv},s_{ps},s_h,t) = \begin{pmatrix} \sum_{ps=1}^{PS_N} P_G^{PS}(s_w,s_p,s_{pv},s_{ps},s_h,ps,t) + \sum_{w=1}^{W_N} P_G^{W}(s_w,w,t) + \\ \sum_{h=1}^{H_N} P_G^{H}(s_w,s_p,s_{pv},s_{ps},s_h,h,t) + \sum_{pv=1}^{PV_N} P_G^{PV}(s_{pv},pv,t) \end{pmatrix} \tag{A.2}$$

$$P_G^{PS} = \begin{cases} P_g^{PS}(s_w,s_p,s_{pv},s_{ps},s_h,ps,t) = (a_{ps}(qr(s_w,s_p,s_{pv},s_{ps},s_h,ps,t))^2 + b_{ps}qr(s_w,s_p,s_{pv},s_{ps},s_h,ps,t) + c_{ps})\, generation MOD \\ -P_P^{PS}(s_w,s_p,s_{pv},s_{ps},s_h,ps,t) = -(a_{ps}(pr(s_w,s_p,s_{pv},s_{ps},s_h,ps,t))^2 + b_{ps}pr(s_w,s_p,s_{pv},s_{ps},s_h,ps,t) + c_{ps})\, pumping MOD \end{cases} \tag{A.3}$$

$$v^u(ps,t) = v^u(ps,t-1) - gr(s_w,s_p,s_{pv},s_{ps},s_h,ps,t-1) + pr(s_w,s_p,s_{pv},s_{ps},s_h,ps,t-1) \tag{A.4}$$

$$v^L(ps,t) = v^L(ps,t-1) + gr(s_w,s_p,s_{pv},s_{ps},s_h,ps,t-1) - pr(s_w,s_p,s_{pv},s_{ps},s_h,ps,t-1) \tag{A.5}$$

$$v_{\min}^u(ps) \le v(s_w,s_p,s_{pv},s_{ps},s_h,ps,t) \le v_{\max}^u(ps) \tag{A.6}$$

$$v_{\min}^L(ps) \le v(s_w,s_p,s_{pv},s_{ps},s_h,ps,t) \le v_{\max}^L(ps) \tag{A.7}$$

$$v^u(ps,t=T) > v^u(ps,end)\ \ v^u(ps,t=1) = v^u(ps,ini), \tag{A.8}$$

$$v^l(ps,t=T) = v^l(ps,end)\ \ v^l(ps,t=1) = v^l(ps,ini), \tag{A.9}$$

$$gr_{\min}(ps).I^g(ps,t).AV(s_{ps},ps,t) \le gr(s_w,s_p,s_{pv},s_{ps},s_h,ps,t) \le gr_{\max}(ps).I^g(ps,t).AV(s_{ps},ps,t) \tag{A.10}$$

$$pr_{\min}(ps).I^p(ps,t).AV(s_{ps},ps,t) \le pr(s_w,s_p,s_{pv},s_{ps},s_h,ps,t) \le pr_{\max}(ps).I^p(ps,t).AV(s_{ps},ps,t) \tag{A.11}$$

$$\begin{pmatrix} P_G^{PS}(s_w,s_p,s_{pv},s_{ps},s_h,ps,t).I^g(ps,t) \\ + SR^g(s_w,s_p,s_{pv},s_{ps},s_h,ps,t) + N.SR.on(s_w,s_p,s_{pv},s_{ps},s_h,ps,t) \end{pmatrix} \le p_{G\max}^{PS}(ps).I^g(ps,t).AV(s_{ps},ps,t) \tag{A.12}$$

$$\begin{pmatrix} P_P^{PS}(s_w,s_p,s_{pv},s_{ps},s_h,ps,t).I^p(ps,t) \\ + SR^p(s_w,s_p,s_{pv},s_{ps},s_h,ps,t) + \mathrm{N.SR.down}(s_w,s_p,s_{pv},s_{ps},s_h,ps,t) \end{pmatrix} \ge -\mathrm{p}_{\max}^{\mathrm{p}}(ps).I^p(ps,t).AV(s_{ps},ps,t) \tag{A.13}$$

$$\mathrm{N.SR.down}(s_w,s_p,s_{pv},s_{ps},s_h,ps,t) \le \left(QSC(ps).(1 - I^g(ps,t) - I^p(ps,t))\right).AV(s_{ps},ps,t) \tag{A.14}$$

$$I^g(ps,t) + I^p(ps,t) \le 1 \tag{A.15}$$

$$\begin{pmatrix} SR^p(s_w,s_p,s_{pv},ps,t).I^p(ps,t) \\ + \mathrm{N.SR.down}(ps,t).I^p(s_w,s_p,s_{pv},ps,t) \end{pmatrix} \le P_p^{PS}(s_w,s_p,s_{pv},ps,t).I^p(ps,t) \tag{A.16}$$

$$R_{C,PS}(ps,t) \le (SR^p(s_w,s_p,s_{pv},s_{ps},s_h,ps,t) + SR^g(s_w,s_p,s_{pv},s_{ps},s_h,ps,t)) \tag{A.17}$$

$$N_{C,PS}(ps,t) \le (N.SR.on(s_w,s_p,s_{pv},s_{ps},s_h,ps,t) + N.SR.down(s_w,s_p,s_{pv},s_{ps},s_h,ps,t)) \tag{A.18}$$

$$P_G^W(w,t) \le P_{G\max}^W(w).AV(s_w,w,t) \tag{A.19}$$

$$Q_h(\hat{h},t) = QS_h(\hat{h},t-\tau_{h,\hat{h}}) + QT_h(\hat{h},t-\tau_{h,\hat{h}}) \tag{A.20}$$

$$Q_h(\hat{h},t+\tau_{h,\hat{h}}) = q(h,t) + S(h,t) = QS_h(\hat{h},t) + QT_h(\hat{h},t) \tag{A.21}$$

$$v(h,t) = v(h,t-1) + \left(\sum_{\hat{h}=1}^{H_N} (R_{\hat{h},h}.Q_{\hat{h}}(s_w,s_p,s_{pv},s_{ps},s_h,h,t-1)) - q(s_w,s_p,s_{ps},s_{pv},s_{ps},s_h,h,t-1) + u(h,t-1) - S(s_w,s_p,s_{pv},s_{ps},s_h,h,t-1) \right) \tag{A.22}$$

$$q_{\min}(h).M(h,t).AV(s_h h,t) \le q(s_w,s_p,s_{pv},s_{ps},s_h,h,t) \le q_{\max}(h).M(h,t).AV(s_h,h,t) \qquad t \in \{1,....T\} \tag{A.23}$$

$$v_{\min}(h) \le v(h,t) \le v_{\max}(h) \qquad t \in \{1,....T\} \tag{A.24}$$

$$v(h,0) = v(h,ini), v(h,T) = v(h,end), \qquad t \in \{1,.....T\} \tag{A.25}$$

$$P_G^H(s_w, s_p, s_{pv}, s_{ps}, s_h, w, ps, h, t) = \tag{A.26}$$

$$(k_{1h} \times q^2(s_w, s_p, s_{pv}, s_{ps}, s_h, w, ps, h, t) + k_{2h} \times q(s_w, s_p, s_{pv}, s_{ps}, s_h, w, ps, h, t) + k_{3h}) \qquad t \in \{1,....T\}$$

$$P_G^H(s_w, s_p, s_{pv}, s_{ps}, s_h, w, ps, h, t+1) - P_G^H(s_w, s_p, s_{pv}, s_{ps}, s_h, w, ps, h, t) \le 60.RU_h.AV(s_h, h, t) \tag{A.27}$$

$$P_G^H(s_w, s_p, s_{pv}, s_{ps}, s_h, w, ps, h, t) - P_G^H(s_w, s_p, s_{pv}, s_{ps}, s_h, w, ps, h, t+1) \le 60.RD_h.AV(s_h, h, t) \tag{A.28}$$

$$S_h^{\min}.AV(s_h, h, t) \le S_h(s_w, s_p, s_{pv}, s_{ps}, s_h, w, ps, h, t) \le S_h^{\max}.AV(s_h, h, t) \tag{A.29}$$

$$M(h,t) - M(h,t-1) = N'(h,t) - N(h,t) \tag{A.30}$$

$$N'(h,t) - N(h,t) \le 1 \tag{A.31}$$

$$0 \le P_{BATT}^{CH}(pv, s_{pv}, t) \le P_{BATT}^{\max CH}(pv) Z_{CH}(pv, s_{pv}, t) \tag{A.32}$$

$$0 \le P_{BATT}^{DCH}(pv, s_{pv}, t) \le P_{BATT}^{\max DCH}(pv) Z_{DCH}(pv, s_{pv}, t) \tag{A.33}$$

$$Z_{CH}(pv, t) + Z_{DCH}(pv, t) \le 1 \tag{A.34}$$

$$ENR(k, t=1) = ENR_{ini}(k), ENR(k, s_{pv}, t=24) \ge ENR_{end} \tag{A.35}$$

$$ENR(k, s_{pv}, t) = ENR(k, s_{pv}, t-1) + P_{BATT}^{CH}(k, s_{pv}, t-1) - P_{BATT}^{DCH}(k, s_{pv}, t-1) \tag{A.36}$$

$$P_S^{pv}(pv, s_{pv}, t) = P_G^{pv}(pv, s_{pv}, t) - P_{BATT}^{CH}(pv, s_{pv}, t) + \delta P_{BATT}^{DCH}(pv, s_{pv}, t) \tag{A.37}$$

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Ehsan Jafari was born in Shahrekord, Iran, in 1986. He received Ph.D. degree in Department of Electrical Engineering, Science and Research Branch, Islamic Azad University, Tehran, Iran in 2017. He is now a Assistant Professor in Department of Electrical Engineering, Lenjan Branch, Islamic Azad University, Isfahan, Iran. His research interests are operation and planning of deregulated power system, load and energy management, renewable energy and smart grids.

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