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Designing of Photovoltaic/Fuel Cell/Wind Hybrid System Considering Failure

and Repair Rate

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ABSTRACT

In this paper a stand-alone Photovoltaic/Fuel Cell/Wind Hybrid System (PFWS) considering failure and repair rate of components is optimized with aim of optimal sizing based on a modified particle swarm optimization (MPSO) algorithm. The optimal sizing problem has not been addressed sufficiently yet considering failure and repair rate and expected generation energy of hybrid system. The optimal sizing is implemented based on reliability of load supply with a minimum cost of energy (CE). The PFWS costs involve investments, operation and maintenance as well as loss of load costs. In this paper the impact of failure and repair rate of PFWS components is investigated on optimal sizing. The results showed that considering failure and repair rate causes more reliability level of load supply, so to achieve the actual behavior of PFWS, the failure and repair rate of components must be considered in suitable insight to designer for supply the load and not considering the rates causes better reliability indices but this is misleading to design the PFWS, technically and economically.

Keywords: optimal sizing, reliability indices, failure and repair rate, modifiedPSO algorithm.

1. INTRODUCTION

The industrialization and growing population during the past years caused the increase of electricity demand. Limitation of space and the slow improvement of the networks also caused some areas with high load density which could result in declining of power quality and voltage collapse. At the same time, non-urban areas are witnessing poor performance of the networks like high voltage drops and high losses along the distribution lines [1]. In contrast, despite limitations in networks and available financial resources, utilities are also hardly trying to expand and boost networks. In this way, distribution generation could be one of the suitable options. One of the solutions for increasing economic efficiency in renewable power plant is using different hybrid systems. The sun and wind are two main sources in renewable energies which seem to devote a large portion of generating energy in future.

The supplied energy from these resources is predictable and as a result the power of these power plants and their storage systems will be considered much more than the amount of load power demand, to increase load reliability and availability. In hybrid systems, the generation predictability with combining the several resources is increased and in fact these resources cover each others' deficits. From this perspective wind and the sun have presented suitable overlap for each other, so the power of units and also necessary storages in combining wind-sun units compared to only wind unites or sun units have been significantly reduced. Various definitions are presented for reliability, but the definition that is widely accepted is as follows; Reliability is the probability of a system or a component correct operation under exploitation condition in specified time [2].

Reliability calculations are major issues which should be considered along with economic and environmental evaluations resulting from using energy renewable sources. Accurate evaluation of economic profit used from these units needs investigation of rate of systems` reliability. Obviously, available energy limitation in renewable energy sources and also its discontinuous behavior reduces level of system reliability [3-5].

Various methods are presented for minimization of hybrid power plant costs. Wide range of optimization methods, from classical combination like linear, non-linear analytical and numerical programming mainly based on partial derivatives calculation to applying modern intelligent algorithms like Genetic algorithm and particle swarm optimization (PSO) are used in different researches.

In [6] a hybrid system consists of wind turbine and fuel cell is studied for improving profitability of wind power. In another study, wind farm equipped with Superconductor Magnetic Energy Storage (SMES) is studied [7]. SMES is suitable for improving power quality. In [8] hybrid system consists of solar array, fuel cell and SMES is investigated. Unit sizing determination and PV/Wind/FC hybrid system costs analysis is analyzed in [9]. In another study, performance and sizing of PV/Wind/FC hybrid system is considered [10]. In study [11], the method of determining optimal sizing of PV/Wind hybrid system is depicted independent from



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stand-alone clearly. In a similar study, capacity of diesel generator with wind turbine is optimized [12].

In this paper the impact of considering reliability indices is investigated along with economic factors for design an optimal combination for PFWS with minimum cost and maximum of responding to load power demand. To obtain an optimal design using an intelligent algorithm seems more effective according to extent of variables and magnitude of objective function. In this paper a modified PSO algorithm is used for optimization. The optimal sizing problem has not been addressed sufficiently yet considering failure and repair rate, so the impact of failure and repair rate of PFWS is evaluated on optimal sizing problem.

In section 2, the mathematical modeling of PFWS components is presented. The optimal sizing problem based on reliability and system cost using objective function optimization is described in section 3. In section 4, the results of optimization problem and impact of

considering failure and repair rate are presented and in final section, the results are concluded.

2. PFWS MODELING

A schematic diagram of PV/FC/Wind hybrid system (PFWS) consists of PV array, wind turbine (WT), electrolyzer (EL), hydrogen storage tank (HST), fuel cell (FC) and inverter is shown in Figure.1.The PV array and wind turbine work together to satisfy the load demand. When the total generated energy of the PFWS is greater than the load power demand, the extra energy will be supplied to feed the EL for hydrogen production. Also when the total generated energy of the PFWS is lower than the load demand, the deficit energy is compensated by FC until the hydrogen of HST is depleted.



Figure.1.The schematic diagram of PV/FC/Wind hybrid system

I. PV Modeling

Photovoltaic (PV) [13] converts solar radiation energy to electrical energy. PV temperature and solar radiation changes bring about changes in PV voltage level and output power as follow

$$P_{PV} = 0.001G \times P_{PV,rated} \times \eta_{PV,conv} (1)$$

$$G(t,\theta_{PV}) = G_V(t)\cos(\theta_{PV}) + G_H(t)\sin(\theta_{PV})$$
(2)

Where, G is perpendicular radiation at array's surface (W/m2), $P_{PVrated}$ is rated power of each PV array at G= 1000W/m², and $\eta_{PV,conv}$ is the efficiency of PV's DC/DC converter and Maximum Power Point Tracking System (MPPT). Θ_{PV} is the PV panel tilt angle, $G_H(t)$ and $G_v(t)$ are the horizontal and vertical components of solar irradiation.

It should be noted that, temperature effects are neglected here.

II. Wind Modeling

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The simplified model to simulate the power output of a wind turbine [14] can be defined by

$$P_{W}(v) = \begin{cases} P_{R} \cdot \frac{v - v_{C}}{v_{R} - v_{C}} & \left(v_{C} \leq v \leq v_{R}\right) & (2) \\ P_{R} & \left(v_{R} \leq v \leq v_{F}\right) & (3) \\ 0 & \left(v \leq v_{C} \text{ and } v \geq v_{F}\right) \end{cases}$$

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$$v_W^h = v_W^{ref} \times \left(\frac{h}{h_{ref}}\right)^{\alpha}$$
(4)

Where, P_R refers to the rated power, v_C is the cut-in wind speed, v_R is the rated wind speed and v_F is the cut-off wind speed. v_W^h is wind speed at a specific height, v_W^{ref} wind speed at the reference height (h_{ref})

III. EL Modeling

Water by EL can be decomposed into its elementary components. This process is done by passing electrical current between two electrodes that are separated by an aqueous electrolyte [15].

The energy delivered to HST from EL can be calculated as follows:

$$P_{EL-HST} = P_{\text{Re}n-EL} \times \eta_{EL}(5)$$

Where $P_{\text{Ren-EL}}$ is delivered power to EL and η_{EL} is efficiency of EL.

IV. HST Modeling

Physical HS is one of the storage techniques that use HST to store compressed hydrogen. After compressing under high pressure, the hydrogen which is required by PEMFC is sent from the HST [16].

The stored energy in HST for each step-time can be calculated by

$$E_{HST}(t) = E_{HST}(t-1) + P_{EL-HST}(t)\Delta t - P_{HST-FC}(t)\Delta t\eta_{HST}$$
(6)

Where P_{HST-FC} is delivered power to FC from HST and η_{HST} is HST efficiency.

The stored energy in HST can't exceed the following constraints as follows:

$$E_{HST,Min} \le E_{HST}(t) \le E_{HST,Max}$$
(7)
$$E_{HST}(t=0) \le E_{HST}(8760)$$
(8)

V. FC Modeling

FC converts oxygen and hydrogen chemical energy to electrical energy during which some heat and water is generated as well [17]. FC output power can be defined by

$$P_{FC-Inv} = P_{HST-FC} \cdot \eta_{FC} \qquad (9)$$

Where η_{FC} refers to efficiency of FC.

VI. Inverter Modeling

The inverter is electrical device to convert electrical power from DC into AC form at the desired frequency of the load. The power delivered to load from inverter is calculated by

$$P_{Inv-Load} = (P_{FC-Inv} + P_{Ren-Inv})\eta_{Inv}(10)$$

Where $P_{\text{Ren-Inv}}$ is delivered power to inverter and η_{Inv} is efficiency of inverter.

3. OPTIMAL SIZING PROBLEM

To find and optimal sizing of a PWHS to satisfy the load demand, the calculations may be carried on the reliability concept and concept of economy of power supply. In this paper the proposed methodology for PWHS calculation is based on two concepts as follow:

- Technical concept (Reliability indices like: LOLE, LOLD and LPSP)
- Economical concept (PFWS cost as CE)

The optimal configuration with the minimum CE is selected from the set of configurations which satisfy the reliability of power supply.

I. Reliability Calculation of PFWS

In this paper the applied reliability indices, can be expressed by the following equations [18,19]:

Loss of load expectation can be defined by

$$LOLE = \sum_{t=1}^{N} E\left[LOL(t)\right] \quad (11)$$

Where E [LOL] refer to expectation of loss of load which is defined by

$$E\left[LOL\right] = \sum_{s \in S} T_s \times P_s \qquad (12)$$

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Where T_s and P_s refer to duration and probability of load

loss respectively.

Loss of Energy Expectation (LOLE) can be

expressed by

$$LOEE = EENS = \sum_{t=1}^{N} E \left[LOE(t) \right]$$
 (13)

Where E [LOE] is expectation of loss of energy which can

be calculated as follows:

$$E\left[LOE\right] = \sum_{s \in S} Q_s \times P_s$$
(14)

Where Q_s is amount of load loss.

The reliability of PFWS is expressed in terms of loss of power supply probability (LPSP). The LPSP can be expressed as:

$$LPSP = \frac{LOEE}{\sum_{t=1}^{N} D(t)}$$
(15)Where $D(t)$ is load demand (kWh)

in time step t.

So the reliability of PFWS can be defined by

Reliability=
$$1-LPSP_{(16)}$$

The Equivalent Loss Factor is calculated by

 $ELF = \frac{1}{N} \sum_{t=1}^{N} \frac{Q(t)}{D(t)} (17)$

Where Q(t) is total load loss at step-time t.

II. Expected Generation Energy Calculation of PFWS

In this section the expected generation energy (EGE) of PWHS is calculated in terms of the outage probability and availability rate of per PWHS components. The expected generation energy of PWHS is defined by

$$EGE_{PFWHS} = \sum_{\substack{n_{COM}^{fail} = 0}}^{N_{COM}} \left(P_{PFWHS} \left(n_{COM}^{fail} \right) \times f_{PFWHS} \left(n_{COM}^{fail} \right) \right)$$
(19)

(18)

Where n_{COM}^{fail} is the number of components being forced outage of the grid.

Where the failure probability of PWHS in terms of failure and repair rate of components can be expressed by

$$f_{PFWHS}(n_{COM}^{fail}) = \sum {\binom{N_{COM}}{n_{COM}^{fail}}} (\frac{\mu_{COM}}{\lambda_{COM} + \mu_{COM}})^{N_{COM} - n_{COM}^{fail}} \times (1 - \frac{\mu_{COM}}{\lambda_{COM} + \mu_{COM}})^{n_{COM}^{fail}}$$
(19)

Where, λ_{COM} and μ_{COM} refer to failure and repair rate of per PFWS components and $P_{PFWHS}(n_{COM}^{fail})$ is power generated by PFWS considering failure of components.

III. Economical Calculation based on CE

In this section the cost of energy (CE) of PWHS takes into account the initial capital cost (CC), maintenance and repair cost (MRC), replacement cost (RC) of components as well as the associated cost to load curtailment during 20 years. The main constraint of problem is the maximum permissible level of the Equivalent Loss Factor (ELF) index.

The net preset-value cost (NPC) for a specific component can be calculated as follow [20,21]:

$$NPC_{i} = (N_{i} \times CC_{i} + N_{i} \times K_{i} \times RC_{i} + N_{i} \times MRC_{i} \times PWA(ir, R))^{(20)}$$

Where K_i and PWA(ir,R) are factors that convert replacement costs and operational costs into the net present cost, respectively. The definition of these factors is well presented in [20,21].

The net-present-value cost (NPC) of load loss can be obtained by

$$NPC_{loss} = LOEE \times C_{loss} \times PWA(ir, R)_{(21)}$$

So the CE can be defined as follows:

$$CE = \left(\sum_{i} NPC_{i} + NPC_{loss}\right)$$

$$IV. \qquad Objective Function$$
(22)

The objective function of optimization problem is defined by

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 $OF = \left\{ Minimize \ CE \right\}$ (23)

The objective function should be optimized considering follow constraints:

$$E\left[ELF\right] \le ELF_{\max} \tag{24}$$

Min $(N_{PV}, N_{HST}, N_{WT}) \ge 0$ (25)

$$0 \le \theta_{PV} \le 90 \tag{26}$$

4. MODIFIED PSO ALGORITHM

The optimization problem is defined as follows:

Min
$$OF(x)$$
 s.t. $x_i \in X_i$, $i = 1, 2, 3, ..., N$

(27)

The OF(x) is the objective function and the x is the collection of each of the decision variables x_i . The X_i is the collection of possible range of each variable and the *N* is the number of variables. The PSO optimization algorithm [22-24] is one of the latest and strongest Heuristics methods and has been used in solution of several complex problems up to now. The PSO algorithm has some disadvantages that the most important of them are [25-27]:

* Perch in the local optimal locations.

* Ability of weak local search.

In this paper, the modified PSO algorithm has been used to solve these disadvantages and to improve the PSO algorithm performance. The modified PSO algorithm starts to work with a group of the random replies (i.e. particles) and then searches the optimal reply in the problem with updating the generations. Each particle is defined by the S_i and V_i which show the spatial position and the velocity stage of the ith particle. At each stage of the population movement, each particle is updated by the two values of best. The first value is the best reply in terms of the competency, which is obtained separately for each particle up to now. This value is Pbest. The other best value that is obtained by the algorithm is the best value that is obtained by the all of the particles among the population, up to now. This value is G_{best}. After finding the values of the P_{best} and G_{best}, each particle updates its new velocity and position based on the following equations:

$$V_i^{k+1} = W * V_i^k + C_1 * rand_1 * (P_{best_i} - S_i^k) + C_2 * rand_2 * (G_{best_i} - S_i^k)$$

$$S_i^{k+1} = S_i^k + V_i^{k+1}$$
(28)
(29)

The problem convergence is dependent on the PSO algorithm parameters such as W, C_1 , C_2 . W is the updating factor of the particles velocity. C_1 and C_2 are the acceleration factors, which are the same and are in the range of [0, 2]. The *rand*₁ and *rand*₂ are two random number in the range of [0,1]. The W that is the inertia weight is the constant in the PSO algorithm. In modified PSO to strengthen the PSO algorithm performance and to solve its disadvantages with updating the W for obtaining the best reply in terms of the convergence velocity and accuracy in the optimization problem, the following equation is used:

$$W = W_{\text{max}} + \left(\left(W_{\text{min}} - W_{\text{max}} \right) / iter Max \right)^* iter$$
(30)

Which W_{\min} and W_{\max} are the minimum and maximum values of the inertia weight, the *iterMax* is the maximum number of the algorithm iterations, and the *iter* is the current iteration of the algorithm. The inertia weight is varied by the equation (30) and causes the convergence, which is defined as a variable in the range of [0.2-0.9]. The modified PSO algorithm, because of updating the inertia weight with updating the particles velocity, has a better performance in comparison to the PSO algorithm. In the optimization problem solving process, the number of algorithm iterations has been reduced and the convergence power has been increased under the conditions of the increased community members. Finally the optimization algorithm is finished by the particles convergence to a certain extent.

5. OPTIMIZATION RESULTS

Using modified PSO algorithm, case study PFWS is optimized. Specifications of PFWS components which their model is provided are depicted in TABLEI and the failure and repair rate data of PFWS components are presented in TABLEII. The assumptions of case study PFWS is presented in TABLEIII. The applied wind and radiation datasets belong to northwest region (Jolfa, latitude: 38_56, longitude: 45_37, altitude: 710, m) of Iran are shown in Figure.2.andFigures.3., respectively. Figure.4. illustrates the IEEE RTS load pattern with 50 kW annual peak load. Load curtailment cost also is considered in case study with 5.6 US\$/kWh.



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TABLEI
SPECIFICATION OF CASE STUDY PFWS COMPONENTS [12]

Device	Investment Cost (US\$/unit)	Replacement Cost (US\$/unit)	Maintenance and Repair Cost (US\$/unit-yr)	Efficiency (%)	Lifetime (Year)
Wind Turbine	19400	15000	75	-	20
PV Array	7000	6000	20	-	20
Electrolyzer	2000	1500	25	75	20
Hydrogen Tank	1300	1200	15	95	20
Fuel Cell	3000	2500	175	50	5
ConverterDC/AC	800	750	8	90	15

TABLEII

THE FAILURE AND REPAIR RATE DATA OF PFWS COMPONENTS

Component	PV	WT	EL	HS	FC	Inv
Failure Rate (λ)	0.005	0.005	0.005	0.005	0.01	0.002
Repair Rate (μ)	200	250	150	100	300	100



Figure.2. Annual wind speed in 15 m heigh



Figure.3. Annual horizontal/vertical radiation



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Figure.4. Curve of annual load IEEE with peak 50 Kw

At first the optimal sizing problem is optimized without considering failure and repair rate of components in complete availability of PFWS. Then the optimization is implemented considering failure and repair rate of components according to TABLEII. The optimization results including the costs and reliability indices are presented in TABLEIV. According to TABLEIV, PFWScosts and reliability indices rate considering the failure and repair rateare more than not considering the rates. The PFWS optimal sizing results are presented in TABLEV. It is clear that the storage system due to complete availability of component in not considering the rates, especially PV and Wind, less energy is generated in not considering the rates compared to considering components rates and uncertainty in wind speed and solar irradiance.

The Reliability indices are illustrated in Figure.5.andFigure.6. As it is clear that in Figure.5. and Figure.6., better reliability indices are resulted not considering the rates compared to considering the rates because of complete availability of PFWS components. Also the expectation of stored energy in HST is illustrated Figure.8.andFigure.9. shown in As as in Figure.7.andFigure.8. the stored energy rate considering the rates is more than not considering the rates and causes more CE. According to obtained results, neglecting the failure and repair rate in hybrid power generation systems has unsuitable results on reliability of load supply, so the failure and repair rate of PFWS components causes actual insight to designer for reliable and economic designing the hybrid power generation systems.

TABLEIII THE CASE STUDY PFWSASSUMPTIONS

PFWS Lifetime	Real Interest Rate	$ELF_{\rm max}$	Load Pattern	Peak Load	Load Curtailment Cost
20 Years	6%	0.01	IEEE RTS	kW50	5.6 US\$/kWh

TABLEIV THE PFWSRELIABILITY/COST EVALUATION

Param. State	CE (MUS\$)	ELF	LOEE (MWh/yr)	LOLE (hr/yr)	Reliability
Not Considering The rates	2.43	0.0022	2.16	316.5	0.995
Considering The rates	2.62	0.003	2.216	331	0.983

TABLEV THE RESULTS OF OPTIMAL SIZING IN PFWS

Param. State	$N_{\scriptscriptstyle WG}$	N _{PV}	$P_{_{el}}$	M _{tank}	P_{FC}	P _{inv}	$ heta_{\scriptscriptstyle PV}$
Not Considering The rates	7	247	103.2	128.4	39.63	47.21	36.92
Considering The rates	8	226	119.8	143.83	43.65	45.92	34.56

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Figure.5. Reliability indices not considering the rates



Figure.6.Reliability indices considering the rates



Figure.7.The expectation of stored energy in HST not considering the rates





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Figure.8. The expectation of stored energy considering the rates

6. CONCLUSION

In this paper is presented optimal sizing of a standalone PV/FC/Wind Hybrid System (PFWS). A modified PSO algorithm is applied to gain optimal solution. The optimization problem is developed to determine the optimal sizing of PFWS that can achieve the load required power supply probability (Reliability) with a minimum cost of energy (CE).

Also to investigation the impact of availability of PFWS components on optimal sizing considering technical and economical indices, two states are considered. As it is clear thatnot considering failure and repair rate of components causes better reliability indices compared to considering the rates but this is misleading to design the PFWS, technically and economically. According to obtained results, neglecting the failure and repair rate of components in hybrid power generation systems has unsuitable results on reliability of load supply, so to achieve the actual behavior of PFWS, the rate of components availability or probability of components operation must be considered in suitable insight to designer for reliable and economic designing.

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