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OPTIMAL SIZING OF A STAND ALONE HYBRID SYSTEM FOR ARDABIL AREA OF IRAN

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Abstract- In this study an optimized wind/PV hybrid system with battery and diesel back up is designed. The optimization is subject to the hybrid system cost minimization during its 20-year life time to be allotted for covering a fixed load profile. Total cost embraced investment, operating, fuel cost and maintenance. Here the optimization was done by Particle Swarm Optimization algorithm. Load profile, wind speed and solar radiation data are available for Ardabil province in North West of Iran.

Keywords: PSO, Hybrid System, Optimization, Wind, PV, Diesel, Battery.

I. INTRODUCTION

As recently the energy demand is growing increasingly, fossil fuel supplies are decreasing rapidly. Thus, water and wind have emerged as alternative sources of renewable energy supplies. However, the uncertainty and unpredictability are the two most considerable disadvantageous features of such renewable resources. Therefore, these features turn the production and detailed power programming rather impossible [1-6]. According to renewable energies' dependability on environmental conditions, some back up sources should be counted beside them regarding to load covering in all time. This will modify reliability of power production effectively. Based on previous studying, a precise designed back up capacity is essential regarding of power changes management. This system can be assumed as a micro grid [2, 4 and 5].

Bagul et al. (1996) were the first who considered the Load Power System Probability (LSPS) to conduct the optimal sizing of standalone hybrid system. To this end, they plotted the PV array against battery size to obtain the desired LSPS and defined the optimal solution, which reduced the total system cost, as a point on the sizing curve [6]. A methodology for optimal sizing of hybrid PV/WG/Battery system is presented by E. Koutroulis et al. The total annual cost for each configuration is calculated by the hourly average data of wind speed; solar radiation and load power profile, many types of commercial devices such as PV's, WG's and Batteries are considered. In other words, optimization has been carried out by genetic algorithm; and the purpose of optimization is cost minimization of the system for one year through covering the fixed load profile [7].

Choosing an optimized system is so complicated, so using of intelligent algorithm due to optimizing is common. PSO algorithm among all methods makes more sense according to its merits [8]. It is based on particle swarm optimization and it is newer than others. It was initially expressed in 1995 [9]. PSO results faster than other algorithm and the possibility of error due to local extermums are quite low.

A short preview of studying was done along this are as follows. A wind/DG system was modeled in micro point of view. So power electronics was the subject of matter in this paper [10]. Another studying analyzed reliability in a wind/DG system and modeled wind turbine error. This paper didn't consider maintenance cost in optimization [11]. Moreover, Particle Swarm Optimization (PSO) algorithm has been employed to minimize the total cost of hybrid system in its life time (20 year). The total project cost entailed investments, fuel, operation and maintenance. Load profile, wind speed and solar radiation data are available for Ardabil province in North West of Iran (latitude: 38°17', longitude: 48°15', altitude: 1345m). Figure 1 depicts the general schematic of proposed hybrid system.

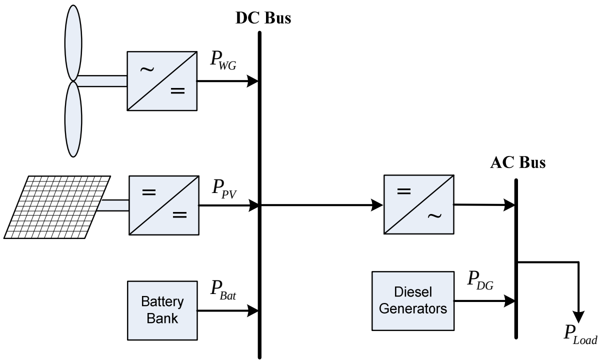

Figure 1. Block diagram of a hybrid wind/PV/Diesel generation with battery back up

II. SYSTEM STRUCTURE

In this study, the proposed system was simulated for 1 year with 1 hour step time. The PV and wind turbine generation considered constant in each step time (1 hour). This system made of wind turbine, PV, battery and DG (diesel generator) in which expressed as follow:

A. Wind Generator

The output power from wind turbine versus wind speed usually given by manufacturer in hour *t* of day *i*, is calculated from Equation (1) [11, 13]:

$$P_{WG}(t,i)=\begin{cases}0 & v(t,i)<V_{Cut\,in},v(t,i)>V_{Cut\,out}\\ P_{WG,\max}\times\left(\dfrac{v(t,i)-V_{Cut\,in}}{V_{rated}-V_{Cut\,in}}\right)^m & V_{Cut\,in}<v(t,i)<V_{rated}\\ P_{WG,\max}+\dfrac{P_{furl}-P_{WG,\max}}{V_{Cut\,out}-V_{rated}}(v(t,i)-V_{rated}) & V_{rated}<v(t,i)<V_{Cut\,out}\end{cases} \tag{1}$$

Figure 2 depicts the hourly wind speed data along a year for the area of Ardabil in North West of Iran. The characteristic of the WG is tabulated in Table 1.

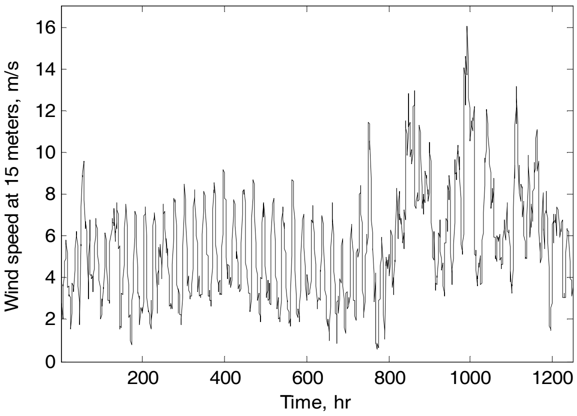

Figure 2. Hourly wind speed during a year at a height of 15 meter

B. PV

The maximum output power of PV, $P_M^i(t)$, in day *i* ($1\le i\le 365$) and hour *t* ($1\le t\le 24$), using of PV module properties in STC (Standard Test Constant, T_{cell}=25°C and G_a=1Kw/m^2) will be calculated. If ambient temperature and irradiation were available, module behavior described as equations (2-5) [7]:

$$P_M^i(t)=N_S N_P V_{OC}^i(t) I_{SC}^i(t) FF^i(t) \tag{2}$$

$$I_{SC}^i(t)=\left\{I_{SC,STC}+K_I\left[T_C^i(t)-25°C\right]\right\}\frac{G^i(t)}{1000} \tag{3}$$

$$V_{OC}^i(t)=V_{OC,STC}-K_V T_C^i(t) \tag{4}$$

$$T_C^i(t)=T_A^i(t)+\frac{NCOT-20°\mathrm{C}}{800}G^i(t) \tag{5}$$

The real transferring power from PV to battery bank, $P_{PV}^i(t)$ and maximum output power of PV arrays $P_M^i(t)$ using of transferring factor of battery charger n_s derived from Equation (6):

$$n_s\equiv\frac{P_{PV}^i(t)}{P_M^i(t)}=n_1 n_2 \tag{6}$$

where, n_1 is power electronics coefficient and n_2 is transferring factor. Also n_2 is related to charge algorithm. If battery chargers work based on MPPT, n_2 will be 1. During bulk-charging PV arrays connect to battery bank directly. In this paper it considered that battery chargers work based on MPPT. Number of PV battery chargers, which equals to PV blocks (each block, one battery charger), related to PV modules, (N_{PV}).

$$N_{ch}^{PV}=\frac{N_{PV}P_{PV}^m}{P_{ch}^m} \tag{7}$$

Figure 3 shows the solar radiation data along a year. Also the data measured in average of 7 data. Each week averaged in 1 day. The characteristic of the PV module is tabulated in Table 1.

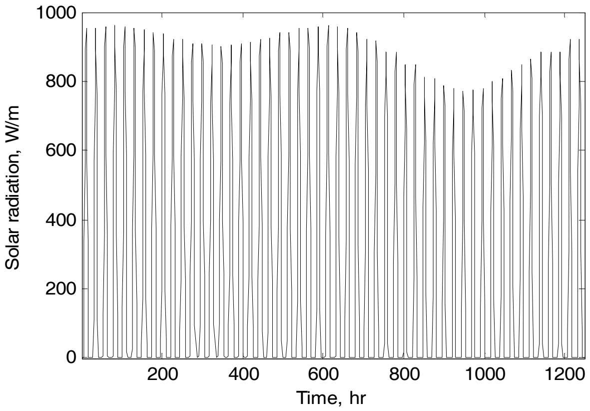

Figure 3. Hourly solar radiation during a year

Table 1. Characteristics of the components

Components	Capital cost (Euro/unit)	Replacement cost (Euro/unit)	Maintenance (Euro/year-unit)	Life time (yr)	Efficiency	Rated Power (kW)
Wind Generator	12298	10032	130	20	-	50
PV array	7000	6000	20	20	-	1
Diesel Generator	15180	14000	160	15	-	60
Battery	264	200	3	3	-	2.76 kWh
Inverter	598	500	5	15	90	6
Battery Charger	518	490	6	15	85	5

C. Battery

Battery bank with nominal voltage as equal to C_n (Ah) is allowed to be discharge to a limited amount and this will be determined by designer at the beginning of optimization process [12].

$$C_{\min}=(1-DOD).C_n \tag{8}$$

Regarding to PV and WG power and demanded load, the battery SOC along simulation time will be derived as follows:

$$C^i(t)=C^i(t-1)+n_B\frac{P_B^i(t)}{V_{BUS}}\Delta t \quad (9)$$

$$C^i(24)=C^i(0) \quad (10)$$

where, n_B=80% is charge round-trip efficiency and n_B=100% is discharge round-trip efficiency.

$$n_B^S=\frac{V_{BUS}}{V_B} \quad (11)$$

The previous equations were applied in a simulation process to check if it can cover the load along a year or not. The algorithm inputs are solar irradiation, wind speed, hourly ambient temperature and demanded load along a year.

D. Diesel Generator

Diesel generator as backup system beside battery bank is considered. The fuel-power trend of diesel generator is not a fixed function, so it changes by different function according to load power. In study according to the following trend the optimization was done. Figure 4 depicts the fuel consumption of diesel generator by its function in load percent as below.

Equation (12) depicts each diesel generator consumption by its parameter as below [14, 15]:

$$Fuel_i=a_i+b_iPLR_i+c_iPLR_i^2 \quad (12)$$

Where, PLR is the load percentage of each diesel generator related to its nominal load. Also *a*, *b* and *c* are the coefficients of optimal trend and fuel is the fuel rate cost by each diesel generator. These coefficients depicted in Table 2.

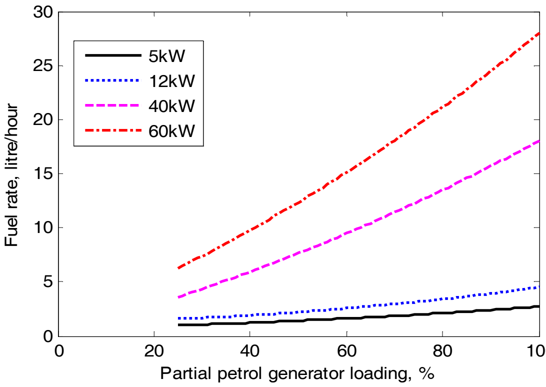

Figure 4. Fuel consumption ratio versus partial generated power

Table 2. Characteristics of the diesel generators

Type	Power Rating (kVA)	Fuel Consumption equation
1	5	$y = 1.16x^2 + 0.834x + 0.712$
2	12	$y = 2.76x^2 + 0.442x + 1.302$
3	40	$y = 6.1x^2+11.58x+0.3375$
4	60	$y = 9.07x^2 + 50.56x + 8.316$

E. Load Demand

The load profile is based on a bus feeder for Ardabil area in North West of Iran. Figure 5 shows the load profile for one year. Regarding simplification it is assume that the load demand for 20 year of the simulation is repeated yearly based on Figure 5.

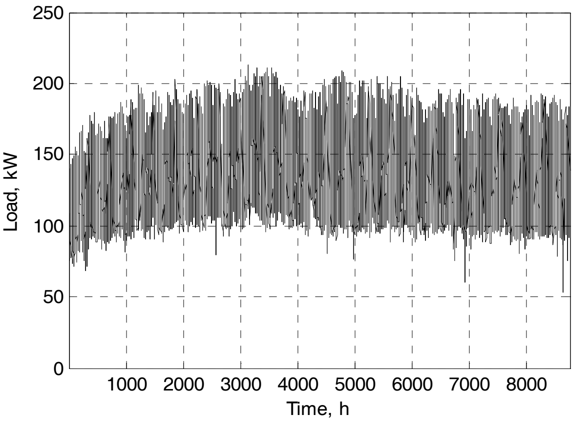

Figure 5. Hourly load profile for one year

III. OPTIMAL SIZING

In the following section, the findings of the optimum combination of WG’s, diesels, PV’s and batteries for covering the typical load demand over 20 years are presented. It should be pointed out that the total system cost entails the capital, replacement, operation, maintenance and fuel costs.

In order to simplify, the following assumptions have been taken into account:

- The solar radiation is repeated annually as it is depicted in Figure 3.
- The wind speed is repeated annually as it is depicted in Figure 2.

Systems are simulated in 20 year long time with an hour time step for several types of components whose devices are commercially available and their parameters are illustrated Table 1. Since the load profile is fixed, the component design should result in the total cost reduction in a year.

A. Optimization Method

In this method, the numbers of the whole equipment remain constant during the power station life span. The objective is determining the optimum number of them in a way that the total cost and the consumed fuel of diesels are minimized and on the other hand the load is supplied.

Total power of *WG* and PV that transferred to battery banks, $P_{re}^i(t)$ in day i ($1\le i\le 365$) and hour t ($1\le t\le 24$), is as follows:

$$P_{re}^i(t)=N_{PV}.P_{PV}^i(t)+N_{WG}.P_{WG}^i(t) \quad (13)$$

Then, input power of DC/AC inverter, $P_L^i(t)$ is calculated by (14) using demanded load power.

$$P_L^i(t)=\frac{P_{Load}^i(t)}{n_i} \quad (14)$$

The remain capacity of battery will determined as follows:

- If $P_{re}^i(t)=P_L^i(t)$ then battery capacity is remain without change.

- If then the excess power, $P_B^i(t)=P_{re}^i(t)-P_L^i(t)$, will charge the battery and the battery new capacity derived from (11). But if SOC reached to 100% then the excess power won't save.

- If $P_{re}^{i}\left(t\right)<P_{L}^{i}\left(t\right)$, then the remained demanded power , $P_{B}^{i}\left(t\right)=P_{re}^{i}\left(t\right)-P_{L}^{i}\left(t\right)$ will produce by battery bank and Diesel Generator, so the battery new capacity derived by (11).

This cycle repeats till simulation time along 365 day by 24 hours finished or battery SOC goes under the allowable amount in (8). The first state means system operates successfully but the second one state shows the system function is unacceptable.

In this proposed method, the optimization outputs using PSO are the number of WG, PV modules, diesel generator and batteries. These variables should be determined in which total cost of the system be minimized. Fitness function is the sum of capital cost, $C_c(x)$ (€), plus maintenance ($C_m(x)$ (€)) and fuel consumption ($C_F(x)$ (€)).

$$Fitness=C_C(x)+C_m(x)+C_F(x) \tag{15}$$

where x is the number of the component vector which describe as below:

$$x=\left[N_{PV},N_{WG},N_{BAT,}N_{DG}\right] \tag{16}$$

For computation the fitness function the capital cost, maintenance and fuel cost can calculate as follow:

$$\begin{aligned}C_C\left(x\right)&=N_{PV}.C_{PV}+N_{WG}.C_{WG}+N_{DG}.C_{DG}+\\&+N_{BAT}.C_{BAT}.\left(y_{BAT}+1\right)+N_{ch}^{PV}.C_{ch}^{PV}.\left(y_{ch}^{PV}+1\right)+\\&+N_{INV}.C_{INV}.\left(y_{INV}+1\right)\end{aligned} \tag{17}$$

$$\begin{aligned}C_m(x)&=N_{PV}\sum_{j=1}^{20}M_{PV}\frac{1}{CRF(ir,j)}+\\&+N_{WG}\sum_{j=1}^{20}M_{WG}\frac{1}{CRF(ir,j)}+N_{DG}\sum_{j=1}^{20}M_{WG}\frac{1}{CRF(ir,j)}+\\&+N_{BAT}\sum_{j=1}^{20}M_{BAT}\left(20-y_{BAT}-1\right)\frac{1}{CRF(ir,j)}+\\&+N_{ch}^{PV}\sum_{j=1}^{20}M_{ch}^{PV}\left(20-y_{ch}^{PV}-1\right)\frac{1}{CRF(ir,j)}+\\&+N_{INV}\sum_{j=1}^{20}M_{INV}\left(20-y_{INV}-1\right)\frac{1}{CRF(ir,j)}\end{aligned} \tag{18}$$

$$C_F(x)=N_{DG}\sum_{j=1}^{20}F_{DG}\times FuelCost\times\frac{1}{CRF(ir,j)} \tag{19}$$

where F_{DG} is total fuel consumption per diesel which can be calculated through the Equation (20):

$$F_{DG}=\sum_{i=1}^{365}\sum_{t=1}^{24}Fuel(t,i) \tag{20}$$

The ir is the interest rate (here 12% based on Iran Central Bank [16]), CRF is capital recovery factor for single payment present worth [13] which can be defined as follows:

$$CRF(ir,j)=\frac{ir\times(1+ir)^{j}}{(1+ir)^{j}-1} \tag{21}$$

According to constants the constraints can be written as Equations (22) and (23).

$$\begin{cases}0\le N_{PV}\\0\le N_{WG}\\0\le N_{DG}\\0\le N_{BAT}\end{cases} \tag{22}$$

$$P_{Supply}\left(i,t,X\right)\ge P_{Demand}\left(i,t\right)\ ,1\le i\le 365\ ,\ 1\le t\le 24 \tag{23}$$

Point: the first installation is included in number of replacement.

The last constants of optimization is regarding of load covering. The constant in each step of simulation will be tested and if it didn't meet the favorite results, that system combination will remove from the other state sets. Table 1 expresses the properties of each component which is used in the optimization program.

IV. SIMULATION RESULTS

Regarding simplification, in the following simulation it is assumed that the SOC of batteries (if batteries exist in hybrid system) is 100% at the start of the simulation. In the combined systems with diesel generators the air pollutant effect has been ignored according to the hypotheses. Figure 6 depicts the convergence of PSO algorithm in proposed system optimization. Table 3 shows yearly total cost, maintenance, wind turbine nominal power, PV nominal power and diesel generator power. In this PSO process the number of iteration is 150 and the population considered 50.

Figure 7 depicts SOC (State of Charge) among 24 hours of 52 weeks in each year (7 days of a week averaged to be 1 day so each hour of 52 weeks 24 hour is the average of 7 numbers). Figure 8 shows each diesel power as it can be seen when battery SOC reached to the minimum value, the rest of demanded power will produced by diesel. Also Figure 9 depicts the amount of fuel used by each diesel generator. Figures 10 and 11 show the total power of PV arrays and total power of wind turbines.

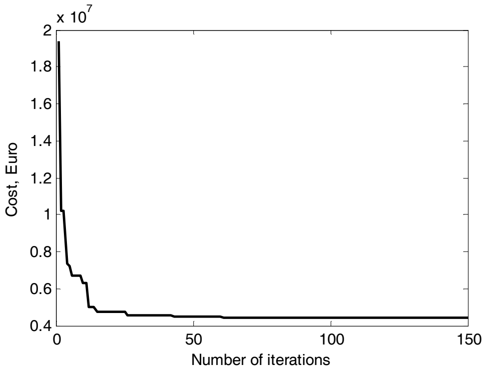

Figure 6. PSO convergence

Table 3. The optimization results

	PSO Result
Number of wind generator	38
Number of PV	320
Number of Battery bank	197
Number of Diesel generator	6
Cost (Million Euro)	4.4446

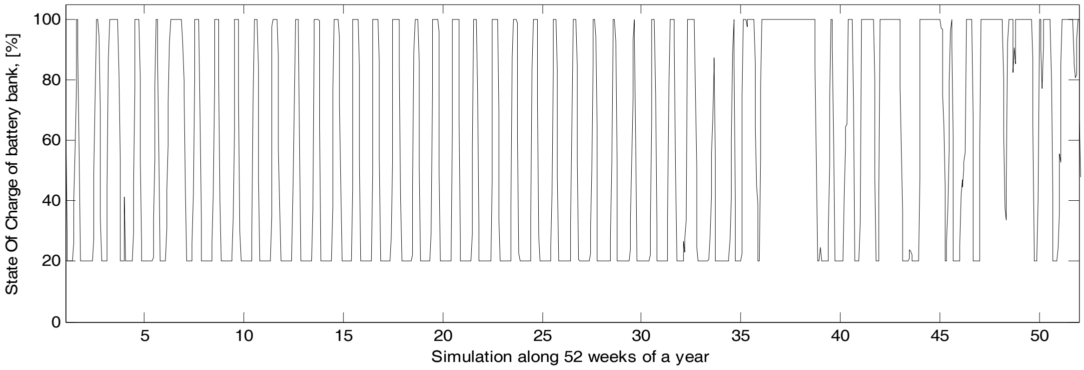

Figure 7. State of charge of battery bank along 52 weeks of a year

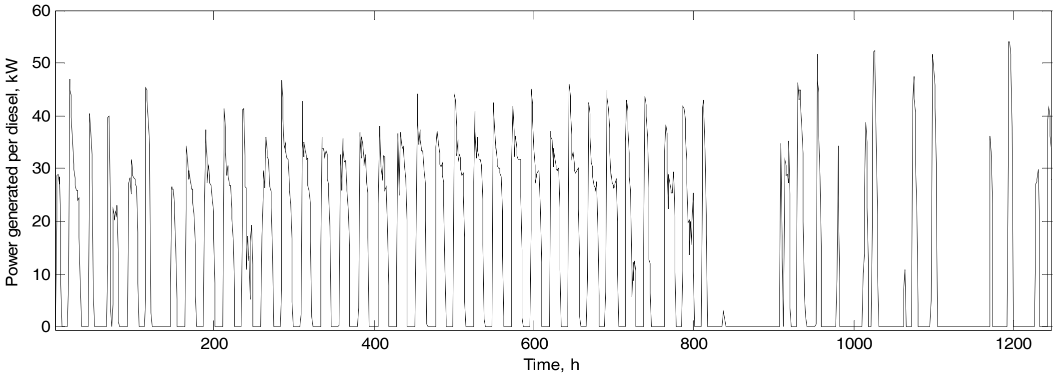

Figure 8. Power generated per diesel

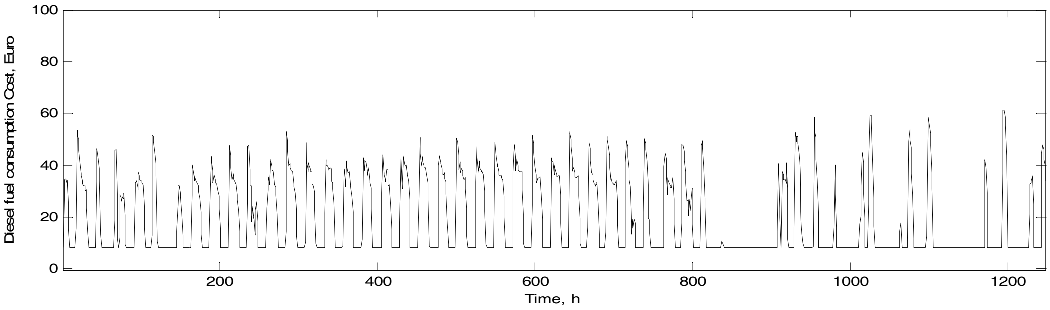

Figure 9. Fuel consumption per diesel

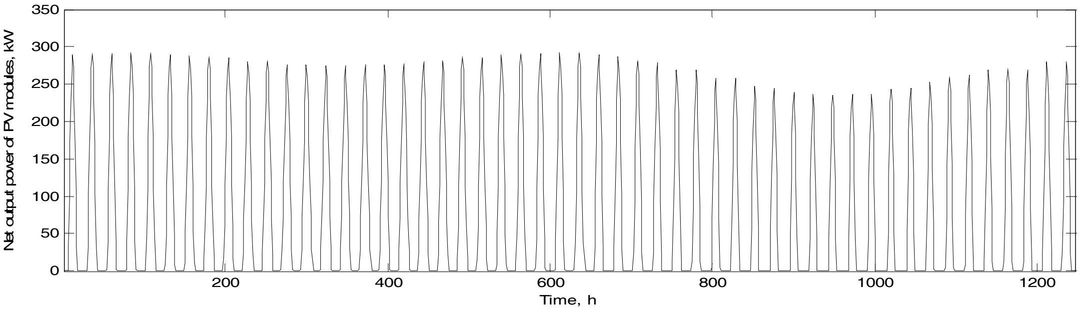

Figure 10. Total power generated by PV modules

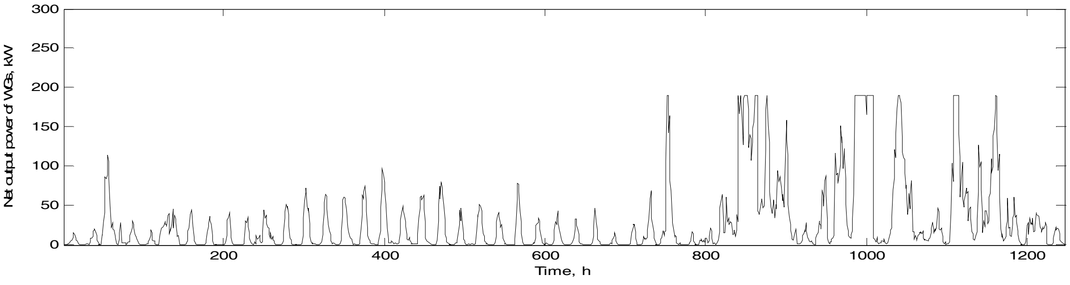

Figure 11. Total power generated by wind generators

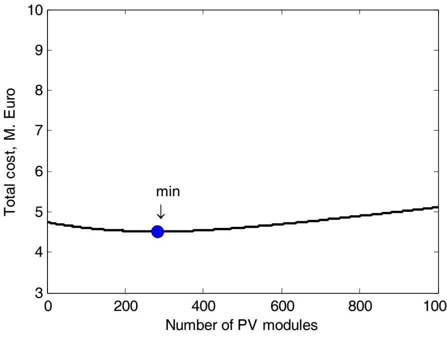

Figure 12. Total cost variation versus the number of PV modules

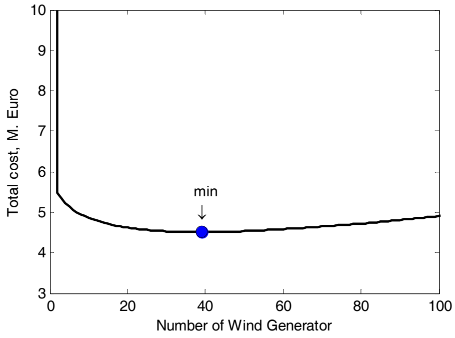

Figure 13. Total cost variation versus the number of wind generator

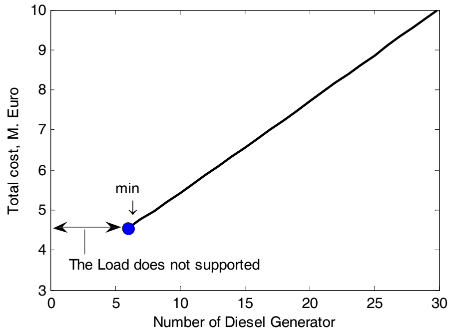

Figure 14. Total cost variation versus the number of diesel generator

For better analysis and validating the simulation result a sensitivity analysis has been carried out for a number of solar cells from 0 to 1000 (312% it's optimum value). According to the sensitivity analysis illustrated in Figure 12, it can be concluded that increase the number of PV's will increase (maximize) the cost of the hybrid power system. In addition, the reduction of the solar cells will increase the cost of the power system, as well. This is particularly due to the reduction of the solar cells which results in the increase of the produced power in every diesel which will consequently lead to the increase of fuel consumption of the diesels. However, since the load covering isn't carried out, the number of diesels and wind turbines cannot reduce from its optimum points which is shown in Figures 13 and 14.

V. CONCLUSIONS

As it was discussed, the present was an attempt to benchmark a wind/PV system with diesel generator and battery back up in accordance with available industrial models. This standalone system was optimized by real data of wind speed, PV arrays and load profile of defined area. In this system, where battery and diesel generator were used as backup system, optimization was employed due to total cost of the components, their replacements, and maintenance and fuel consumption reduction of diesel generator. In this process, the optimization was carried out through intelligent algorithm (i.e. PSO) and application of diesel generator fuel power.

According to adequacy of this algorithm and certainty of this hybrid system, application of this optimized system in specified area is extremely cost effective. in addition, this result can be generalized and developed to other areas with real data. Finally, accessibility and diversity of diesel generators turns them into favorable systems. Thus, in this study through optimization of hybrid power system the demand for application of diesel generators beside renewable energies was carried out efficiently and economically.

NOMENCLATURES

y_{BAT}: Number of replacement of battery in 20 years

F_{DG}: Yearly fuel consumption of each diesel

F_C: Fuel price in a year

$v(t,i)$: Wind speed of the installation place at the hour t of day i

$P_{WG,\max}$: Output power of WG at the rated speed

P_{furl}: Output power of WG at cut out speed

V_{Rated}: Nominal wind turbine speed

m: Exponent constant for curve fitting

$P_{WG}^{i}(t)$: The input power of battery bank from turbine in hour t of day i

$v^{i}(t)$: Wind speed installation place

$P_{M}^{i}(t)$: The maximum output power of PV, in day i ($1 \le i \le 365$) and hour t ($1 \le t \le 24$)

STC: Standard Test Constant

$I_{SC}^{i}(t)$: Module short circuit current

$I_{SC.STC}$: STC module short circuit current

$G^{i}(t)$: Irradiation reached to PV surface

K_I: Temperature coefficient of short circuit current

$V_{OC}^{i}(t)$: Open circuit voltage

$V_{OS,STC}$: STC open circuit voltage

K_V: Temperature coefficient of open circuit voltage

$T_{A}^{i}(t)$: Ambient temperature

$NCOT$: Nominal Cell Operating Temperature

$P_{PV}^{i}(t)$: The real transferring power from PV to battery bank

$P_{M}^{i}(t)$: Maximum output power of PV arrays

n_1: Power electronics coefficient

n_2: Transferring factor

P_{ch}^{m}: Nominal battery chargers power

P_{PV}^{m}: Maximum PV module output power in STC

SOC: State of Charge

$C_{\min}$: Minimum allowable battery capacity (Ah) during discharge

$C^i(t)$: Accessible battery capacity (Ah) at hour t and day i
V_{Bus}: DC bus voltage
$P_B^i(t)$: Battery discharge input/output power
n_B^S : Number of battery which is serried to DC bus
V_B: Nominal voltage of battery
N_{PV}: Total number of PV modules
N_{WG}: Number of wind generation
$P_{Load}^i(t)$: Load power at hour t in day i
n_i: DC/AC inverter efficiency
y_{inv}: Number of replacement of inverter in 20 years
y_{ch}^{PV} : Number of replacement of PV battery charger in 20 years

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BIOGRAPHIES

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