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Optimum Design of Small Autonomous System with Unconventional Energy Sources.

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OPTIMUM DESIGN OF SMALL AUTONOMOUS SYSTEM WITH UNCONVENTIONAL ENERGY SOURCES

التصميم الامثل لمنظومة قوى مستقلة صغيرة مرتبطة بمصادر طاقة غير تقليدية

BY

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الخلاصة – يقدم هذا البحث طريقة مقترحة لحساب التصميم الامثل لانظمة القوى الكهربية المكونة من : مولدات الديزل وتربينات الرياح ومصفوفات الخلايا الكهروضوئية وبطاريات التخزين . وتستخدم هذه الطريقة أيضا فى حساب الجدوى الاقتصادية الناتجة عن مشاركة مصفوفات الخلايا الكهروضوئية وتربينات الرياح وبطاريات التخزين لمولدات الديزل المستخدمة فى تغذية أحمال المناطق البعيدة . والطريقة المقدمة تحدد : حجم ونوع مولدات الديزل – عدد ونوع تربينات الرياح – حجم مصفوفة الخلايا الكهروضوئية – سعة البطاريات المستخدمة فى معالجة الزيادة والنقص فى الطاقة الكهربية المولدة . وتعتمد هذه القيم أساسا على : الاحمال المطلوب تغذيتها وخصائص الموقع التى تتمثل عادة فى شدة الاشعاع الشمسى الساقط وفى سرعات الرياح المؤثرة على الموقع . وتقوم هذه الطريقة بحساب القيم التالية :

١ – مجموعات الديزل المشاركة فى تغذية الحمل على أساس تحقيق أقل سعر تكلفة للوقود المستغل فى توليد الطاقة الكهربية المطلوبة .
٢ – نوع وحجم تربينات الرياح المشاركة فى تغذية الحمل والتى تولد أكبر طاقة متاحة لكل وحدة مساحة من المساحة المكنوسة بريش التربينة .
٣ – حجم مصفوفة الخلايا الكهروضوئية اللازمة والناتجة عن تحرج نقطة التشغيل العظمى .
٤ – سعة بطاريات التخزين الأولية اللازمة .

وفى حساب الجدوى الاقتصادية الناتجة عن مشاركة تربينات الرياح والخلايا الكهروضوئية وبطاريات التخزين لمولدات الديزل فقد تم مقارنة سعر تكلفة الكيلووات . ساعة الناتج بسعره عند استخدام مولدات الديزل فقط .
وفى نهاية البحث قد تم عرض مثال عددى يوضح كيفية تطبيق الطريقة المقترحة والنتائج المستنبطة والتوصيات الهامة المستنتجة .

ABSTRACT

This paper pre:ents a suggested methed in computing the optimum design of a combined power system. This system contains: diesel generators, wind turbine generators, solar cells arrays, and storage batteries. This method is also used in determining the economic benefits obtained on interconnecting the wind turbine generators,solar cells arrays and storage batteries with the diesel generators used in feeding loads of remote sites. The proposed method determines: sizes and types of the diesel generators-numbers and types of wind turbine generators-solar cells arrays sizes and battery storage capacity used in compensating the surplus or the deficit occured in the generated energy. These parameters are essentially dependent upon the required load and the characteristics of the site at which the system is installed. These characteristics are represented by the solar radiation data and the wind speed profile. A numerical application is presented in the end of this paper revealing the validity of the proposed method and the developed results are discussed.

INTRODUCTION

In recent years escalation in the cost of energy derived from fossil and nuclear fuels has caused an increased interest in the development and utilization of alternative sources, like the wind and solar energy. New technologies for electrical power generation from energy sources, like the sun and wind, have been developed and considerable research is being done to improve them. These new technologies in their performance and operating characteristics.

In places where small autonomous system have been built, the use of unconventional energy sources such as wind and solar energy, when the weather condition permit it, gives considerable advantages in meeting efficiently the energy demand. The production cost of the oil-fired units is very high, thus the unconventional energy systems is favoured. A large unconventional penetration into a diesel power system faces technical and economical problems.

This paper adreases the problem of the economic design of the suggested system. The system consists of diesel generators, wind turbine generators, photovoltaic panels and a storage battery. A forecast of the hourly power demand, average wind velocity and average insolation is given. The design of each resource is computed.

Previous contributions in this area include the definition of the structure of a power management scheme for an autonomous system and the formulation and solution of the problem of the optimum operation of the autonomous system.

A method for the optimal scheduling of both generation and storage in an autonomous system was presented. It is based on the decomposition of the optimal resource scheduling problem in an optimal unit commitment and an optimal energy storage subproblem. Both subproblems were solved using dynamic programming [1].

In this paper a method for the optimal design of a small autonomous system with unconventional energy sources is presented. It is based on the forecast hourly power demand, average wind velocity and average insolation.

The power that the diesel plant must supply at a certain time equals the load demand minus the available generation of the unconventional sources and the battery discharge. A linear diesel unit cost function is used. For reason of simplicity of analysis only the WIGS will be considered identical. Each of them supplies the mean power of the wind park power. The photovoltaic panels are connected through a DC/DC converter to the battery bus bar. There is a maximum power tracking control of the converter so that maximum power can be drawn from the panels. The solar plant is connected to the load through DC/AC inverter and a step-up transformer. The storage battery can be charged either by the solar plant or by the WIGS. The battery storage efficiency is taken into account only during battery charging. The depth of discharge of the battery is also considered. There are many different types of storage batteries commercially available. Selection of a battery type for a particular solar electrical generator involves many considerations. The solar plant and the battery are connected to a load through a common DC/AC inverter and a step-up transformer. The inverter controls the flow of power between the solar plant-battery combination and the load. The direction of the power flow can be either from solar plant-battery combination to the load or opposite. The power output from the unconventional resources is fully utilized primarily in feeding the load demand.

A large dynamic programming is used for optimizing the design of the energy resources.

2. SYSTEM DESCRIPTION

A typical generation system of a small autonomous with unconventional energy resources is shown in Figure 1. The basic components of the system are: the diesel plant and the unconventional sources (the wind park and the solar plant). A battery is also available for energy storage. A brief description of the basic parts of the system follows:

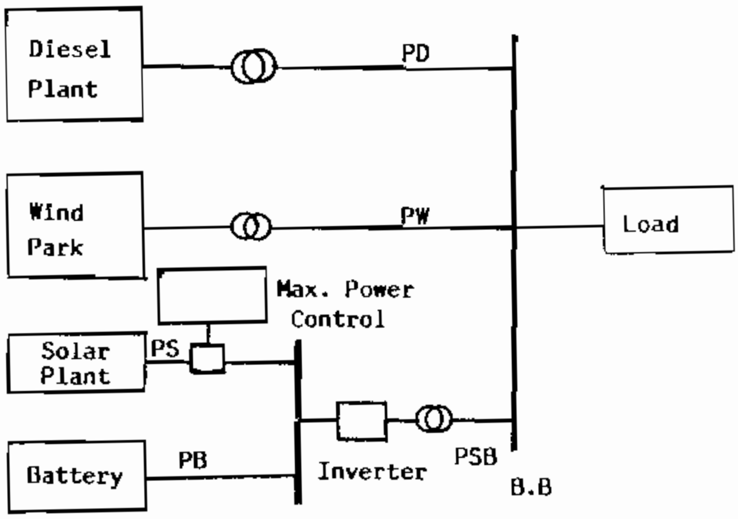


Fig.1. Small autonomous power system with unconventional energy sources.

2.1. The Diesel Plant

The cost of the diesel unit consists of the fixed cost of the unit and the production cost. The production cost of the diesel unit is shown in Figure 2. A linear diesel unit cost function is used:

$$PC = \begin{cases} NLC + IC \cdot PD & (PD)_{min.} \leq PD \leq (PD)_{max.} \\ 0 & \end{cases} \quad \ldots (1)$$

Where, PC is the production cost, NLC is the unit no load cost, IC is the incremental cost and PD is the total diesel plant output.

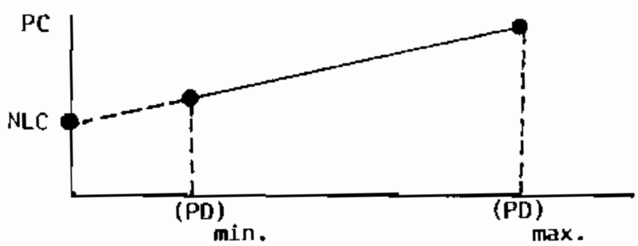


Fig.2. Production cost vs. power output curve

The diesel units can follow the load demand variations by means of their speed/power control mechanism. The power that the diesel plant must supply at a certain time equals the load demand minus the available generation of the unconventional sources and the battery discharge. The diesel plant controls the voltage level and the frequency of the system. Also, if a diesel unit operates at a small fraction of its nominal power output, its efficiency is considerably reduced. For these reasons, the diesel plant output must never undershoot a certain value $(PD)_{min}$.

2.2. The Wind Park

The wind park consists of a number of wind turbine generators (WTGs). For reason of simplicity of analysis only the WTGs will be considered identical. Each of them supplies a power which is the mean power of the wind park power. The type of the wind turbine generator used can be determined from the hourly wind velocity as follows:

From the weather service data used in determination of the proper wind turbine generator, the following table can be executed [3]:

Table 1. Percent of time wind is in a given wind speed range.

wind speed range → month ↓	$v_1 - v_2$	$v_2 - v_3$	$v_3 - v_4$	--------	$v_{n-1} - v_n$
1	t_{11}	t_{12}	t_{13}	--------	t_{1n}
2	t_{21}	t_{22}	t_{23}	--------	t_{2n}
3	t_{31}	t_{32}	t_{33}	--------	t_{3n}
⋮					
12	$t_{12\ 1}$	$t_{12\ 2}$	$t_{12\ 3}$	--------	$t_{12\ n}$

For month 1 the pairs of values (V_{mean}, t) would be:

$$\left(\frac{v_1+v_2}{2}, \frac{t_{11}}{100}\right), \left(\frac{v_2+v_3}{2}, \frac{t_{11}+t_{12}}{100}\right), \left(\frac{v_3+v_4}{2}, \frac{t_{11}+t_{12}+t_{13}}{100}\right),$$

$$, \left(\frac{v_4+v_5}{2}, \frac{t_{11}+t_{12}+t_{13}+t_{14}}{100}\right), \ldots\ldots\ldots\ldots, \text{and}\left(\frac{v_{n-1}+v_n}{2}, \frac{t_{11}+t_{12}+t_{13}+\ldots+t_{1n}}{100}\right).$$

For n pairs of (v_{mean}, t),

$$a = \frac{\sum v_{mean} \cdot t - \frac{\sum v_{mean} \sum t}{n}}{\sum v_{mean}^2 - \frac{(\sum v_{mean})^2}{n}} \qquad \ldots (2)$$

$$b = \frac{1}{n} \sum v_{mean} - \frac{a}{n} \sum v_{mean} \qquad \ldots (3)$$

where all summation from 1 to n.
The scale and shape parameters of the site c and k are:

$$k = a \qquad \ldots (4)$$

$$c = \exp.\ (-b/k) \qquad \ldots (5)$$

The values of c and k are computed for the twelve months and then averaged to compute the average values of c and k.
We can select V_R (or V_R/C)to maximize wind energy factor, which then allow the wind system to produce the most possible energy per unit area of the rotor. The rotor and the tower represent at least 60 % of the total system cost, so maximum energy per unit area will closely correspond to minimum cost per k Wh.

Plots of wind energy factor, WF versus V_R/C for various values of k and $v_C = 0.5\ v_R$ are given in Figore 3. This makes the design problem significantly easir [2].

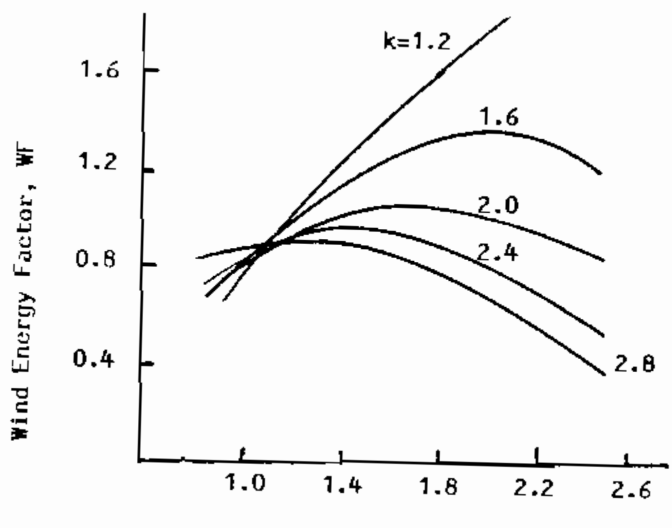
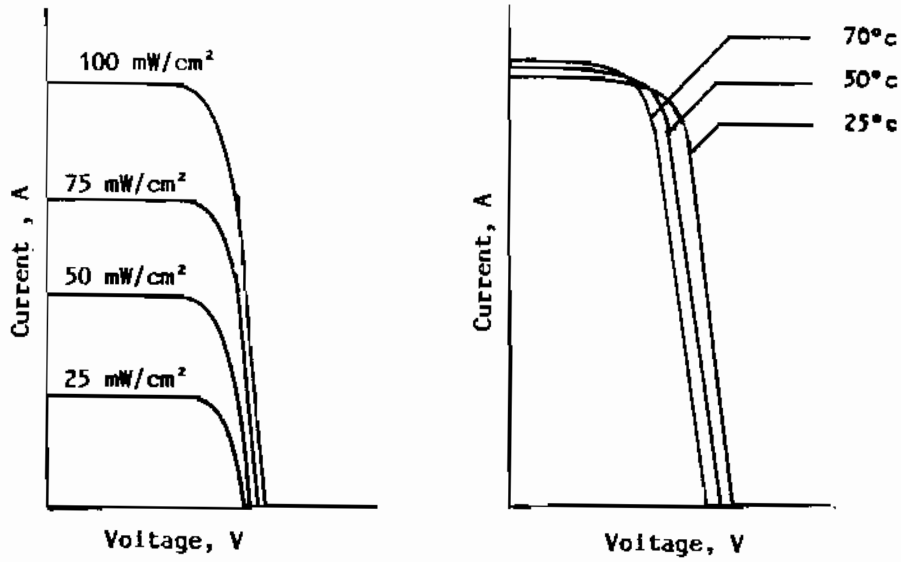


Fig. 3. Wind energy factor for a cut-in speed of 0.5 the rated speed

For certain values of c and **k**, the normalized wind speed, V_R/C that achieves the maximum wind energy factor, WF can be determined from Figure 3. Therefore, the cut-in, rated, and cut -out wind speeds those allow the wind system to produce the most possible energy per unit area of the rotor are determined (notice that, cut-out wind speed = 2 x rated wind speed).

2.3. The Solar Plant

The solar plant consists of a number of photovoltaic panels. In general the panel output is a function of the solar radiation and the panel temperature as shown in Figure 4.



a. performance at various light intensities (constant temperature).

b. performance at various temperature (constant solar radiation intensity).

Fig. 4. Voltage - current curves for a panel.

So the ambient temberature and wind velocity influence the solar plant power output. Measurements have shown that the available photovoltaic plant output for a given photovoltaic installation is with good approximation in linear proportion to the global insolation [1]:

$$PS = CS \cdot SRI \qquad \ldots (6)$$

Where PS is the solar plant output (w), CS is a proportionality factor, and SRI is the solar radiation intensity (mW/cm^2).

The photovoltaic panels are connected through a DC/DC converter to the battery bus bar. There is a maximum power tracking control of the converter so that maximum power can be drawn from the panels. The solar plant is connected to the load through a DC/AC inverter and a step-up transformer.

2.4. The Storage Battery

The storage battery is connected to the solar plant through a Dc/Dc converter and to the load through the solar plant DC/AC inverter and transformer. The storage battery can be charged either by the solar plant or by the WTGs. The battery efficiency is (η_a) and it is taken into account during battery charging only. The depth of discharge of the battery is also considered There are many different types of storage batteries commercially available. Selection of a battery type for a particular solar electric generator involves many considerations. Included among these are [5]:

1. Voltage requirement.
2. Current requirement.
3. Operating schedule.
4. Ampere-hour capacity.
5. Operating temperature range.
6. Size and weight.
7. Required life.
8. Cost.

Several different types of sealed lead acid batteries have become available in recent years. These are usually more expensive than the vented battery but the saving in maintenance can often justify the additional cost. Sealed automobile batteries carrying a five-year maintenance-free warrant are readily available. These batteries are well suited for use in many solar electric generators.

2.5. The Solar Plant-Battery-Inverter Combination

The solar plant and the battery are connected to the load through a common DC/AC inverter and a step-up transformer as shown above. The inverter controls the flow of power between the solar plant-battery combination and the load. The direction of the power flow can be either from solar plant-battery combination to the load or opposite. The inverter efficiency is a function of the power delivered by the inverter as shown in Figure 5.

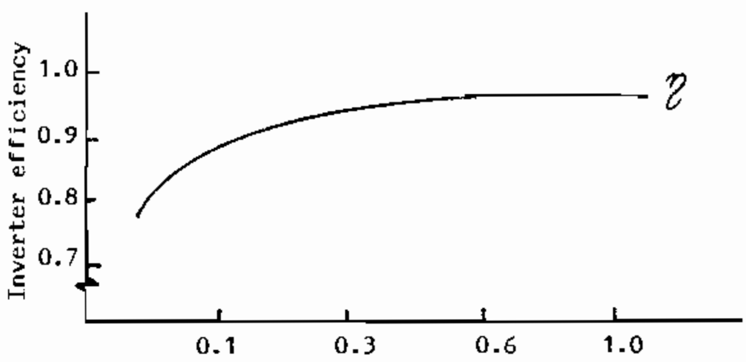


Fig.5. Inverter efficiency as a function of the inverter output

3. PROBLEM DEFINITION

Given the short term forecast of:

a. The load demand (hourly),
b. The average wind veloeity (hourly), and
c. The average global insolation (hourly). determine:

(a) The diesel generators units required,

(b) The type and number of the necessitated WIGs,
(c) The solar plant size, and
(d) The storage battery capacity.

So as to minimize the prlce of the Kilowatthour (KWh). The hourly output power of the solar plant and wind park are forecasted from the hourly average wind velocity and lnsolation levels.

4. SOLUTION STATEMENTS OF THE PROBLEM

1. Representation of the operatlon characteristics of the avallable deisel generators as dlscussed in seetion 2.1.

2. Execution of the proper type of WTG that allows to produce the maximum possible power from the wlnd. Thls due to the average wind velocity of the sIte as demonstrated in section 2.2. The proper WTG ls taken as size unit of the wlnd park.

3. Consldcration of a certain size of solar cells as a slze unlt of the solar plant.

4. Computatlon of the hourly output power from:

   a. The solar plant size unit

$$P_s = (KW_p) \text{ of the solar plant size unit} \times \frac{SRI}{100} \qquad \ldots (7)$$

   b. The WTG:

$$P_w = \begin{cases} 0 & V \leq V_c \\ 0.647\, \eta_o A\, V^3 & V_c \leq V \leq V_R \\ P_{eR} & V_R \geq V \leq V_F \end{cases} \qquad \ldots (8)$$

Where η_o ls the overall efflclency of the WTG , A is the swept area of the turbine rotor, V ls the wind velocity, and P_{eR} is the rated electrical power of the wlnd turbine generator. The hourly output power is developed from the hourly average wlnd veloclty, and global insolatlon.

5. For a certain number of WTGs and a specific size of solar plant, the following table can be derived:

Table 2: Hourly average power output from the wind park and the solar plant

day hours	1	2	3 -------24
power output from the wlnd park	pw1	pw2	pw3 ------ pw24
power output from the solar plant	ps1	ps2	ps3 ------ ps24

6. The power output from the unconventional resources, wind park and solar plant, is fully utilized primarily in feeding the load demand. If the total power output from the wind park and the solar plant is greater than the power required for the load, the surplus in power is storred in the storage battery. While, if the global power is less than the required one, the deficit in power is supplied from the diesel generators. The diesel generators are chosen on the base of achieving the minimum production cost. If the deficit in power is less than the minimum power output can be derived from the smallest diesel generator available, in this case the deficit in power can be supplied from the storage battery. Therefore, the needed diesel generators output, P_D can be deduced from the following:

$$PD = PL - (\eta_c \times \eta_i \times PS + PW + PB) \qquad \ldots (9)$$

Where PL is the load demand, η_c and η_i are the converter and inverterefficienc. and P_B is the battery output. The battery output power can be derived as follows:

$$P_B = \begin{cases} (\eta_c \eta_i P_s + P_w) - P_L & \text{at } (\eta_c \eta_i P_s + P_w) - P_L > 0 \\ (\eta_c \eta_i P_s + P_D) - PL & \text{at } (\eta_c \eta_i P_s + P_w) - P_L < 0 \\ 0 & \text{at } (\eta_c \eta_i P_s + P_w) - P_L = 0 \end{cases} \qquad \ldots (10)$$

8. For each specific size of solar plant and wind park the optimum aggregation of diesel generators, that achieves the minimum production cost through out the day hours, and the required battery storage capacity are determined.

9. The cost of the autonomous system (diesel generators) and the unconventional sources (solar plant and wind park) are computed as follows:

A. <u>The cost of solar plant</u> [2]:

a. The cost of the photovoltaic array:
(Photovoltaic array rating in KW_p/degradation factor) •

Cost per KW_p . ... (11)

b. The cost of the storge battery:
(capacity of the battery in KAh /depth of discharge) •

Cost per KAh ... (12)

C. The cost of the power conditioner:

Rating of power conditioner in KWxcost per KW ... (13)

d. Indirect Costs:

These include the cost of:
1. Engineering
2. Installation
3. Management.

These costs are taken as %age ratios of the total cost of the photovoltaic array, storage battery and power conditioner.

e. The Maintenance and operation cost:
is the costs sum of array and battery x annual

recurring costs (% age of first costs) . . . (14)

f. The battery replacement cost [2]:

battery cost x 0.695 x 0.9 . . . (15)

B. Wind Park Cost:

a. The combined cost of rotor, tower, and land is assumed to be C_1 per square meter of rotor swept area.

b. The cost of the electrical generator, circuit breakers and interconnection is assumed to be C_2 per KW rating of the turbine generator.

Therefore, the total cost of the wind park of n WTGs is:

Total cost of wind park = n (C_1xRotor swept Area+C_2xGenerator Rating) . . . (16)

(The WTGs are considered indentical for simplicity of the analysis only.)

C. The cost of the diesel generators:

Total diesel generator cost=First cost + operation and maintenance cost+ Fuel production cost . . . . (17)

First cost of the diesel generator is essentially dependent upon its rating. The fuel production cost is discussed in section 2.1.

10- Determination of the KWh price for different:

Solar plant sizes, no. of WTGs and diesel aggregations.

11- The solar plant size, number of WTGs, aggregation of diesel generators and storage battery those minimze the KWh price determine the optimum design of the autonomous system and the unconventional sources interconnected with it.

5. NUMERICAL APPLICATION

Use the proposed method in the previous section for determining the optimum design of the:

1. solar plant,
2. wind park, and
3. diesel generator aggregation.

utilized in powering load installed in a certain site. The hourly load demand, average wind velocity, and average insolation intensity of the site are presented in Table 3.

Table 3: The hourly load demand, average wind velocity, and average insolation intensity of the site

daytime (hrs)	average wind velocity (m / s)	average insolation (m W/cm²)	load demand (KW)
1	10.17	0.0	99.00
2	10.68	0.0	42.00
3	11.16	0.0	42.00
4	11.65	0.0	42.00
5	11.88	0.0	54.00
6	11.27	0.0	54.00
7	11.90	5.02	825.60
8	12.37	13.00	120.00
9	13.67	24.13	427.20
10	14.68	32.62	1017.13
11	14.84	42.13	801.12
12	14.34	49.33	720.00
13	13.90	50.60	730.80
14	13.73	44.34	618.00
15	13.29	43.91	624.00
16	12.65	35.05	648.00
17	12.07	21.58	882.900
18	11.22	10.68	1218.00
19	10.76	4.45	672.00
20	10.61	1.97	990.00
21	10.71	0.20	1179.00
22	11.00	0.00	1308.00
23	10.31	0.00	51.00
24	9.84	0.00	99.00

The characteristics of the available diesel generator are described in Table 4

Table 4: The characteristics of the available diesel generators

No.	$(PD)_{min.}$ (KW)	$(PD)_{max.}$ (KW)	NLC ($/hr)	IC ($/kWh)	First cost ($/KW)
1	50	530	3.57	0.0615	500
2	50	530	3.57	0.0615	500
3	30	200	3.57	0.0661	550
4	30	100	1.07	0.0657	600
5	30	100	1.07	0.0657	600

From the average wind velecity of the site, the proper WTC can be selected. Its properties are [4]:

V_c = 4 m/s , V_R = 12 m/s , V_F = 25 m/s,

D = 13.2 m , and P_{eR} = 30 KW .

where, D is the blade rotor diameter, in metre. The solar plant used consists of ten panels, the size of each is 30 KW_p. The hourly average output power from the chosen wind turbine generator and the 30 KW_p panel are tabulated in Table 5.

Table 5: The average output power from the chosen wind turbine generator (P_w), and the 30 KW_p panel (P_s).

Time (hrs)	P_w (KW)	P_s (KW)
1	17.45	0.00
2	19.13	0.00
3	21.98	0.00
4	24.83	0.00
5	26.45	0.00
6	26.25	0.00
7	27.00	1.50
8	27.00	3.76
9	27.00	7.24
10	27.00	12.64
12	27.00	14.80
13	27.00	15.18
14	27.00	13.30
15	27.00	13.17
16	27.00	10.51
17	27.00	6.47
18	23.55	3.20
19	19.56	1.33
20	18.75	0.59
21	19.23	0.06
22	20.88	0.00
23	17.51	0.00
24	14.97	0.00

From the previous table, the daily energy generated out from the chosen wind turbine generator and the 30 KW_p panel are 540.525 and 113.5597 KWh, respectively. Note that, the daily energy required for the load is 13264.746 KWh.

Figs 6.a, 6.b, and 6.c illustrate the KWh price resulted from using different combinations of wind parks, solar plants, and diesel generators aggregations in powering the pre-described load. These Figs are deduced at different prices of W_p which is taken as 5, 2, and 0.5 dollars. In these curves the vertical straight solid line labelled by D is considered a guideline showing the change in the KWh price due to introducing the solar plants and wind parks into the diesel generators aggregations. This line intersects the vertical axis at the price of KWh on otillzlng the diesel generators only in powering the load. The dashed curves show the price of the KWh on using different number of ehosen WTGs but the size of the solar plant is maintained constant at the solar plant varies from 0 to 300 KWp (10 panels) while the number of WTGs changlng from 0 to 10 WTGs. In Figs 6.a and 6.b the price of the KWh increases with increasing the number of WTGs and solar plant size. In these curves the price of the W_p, the most effective factor,

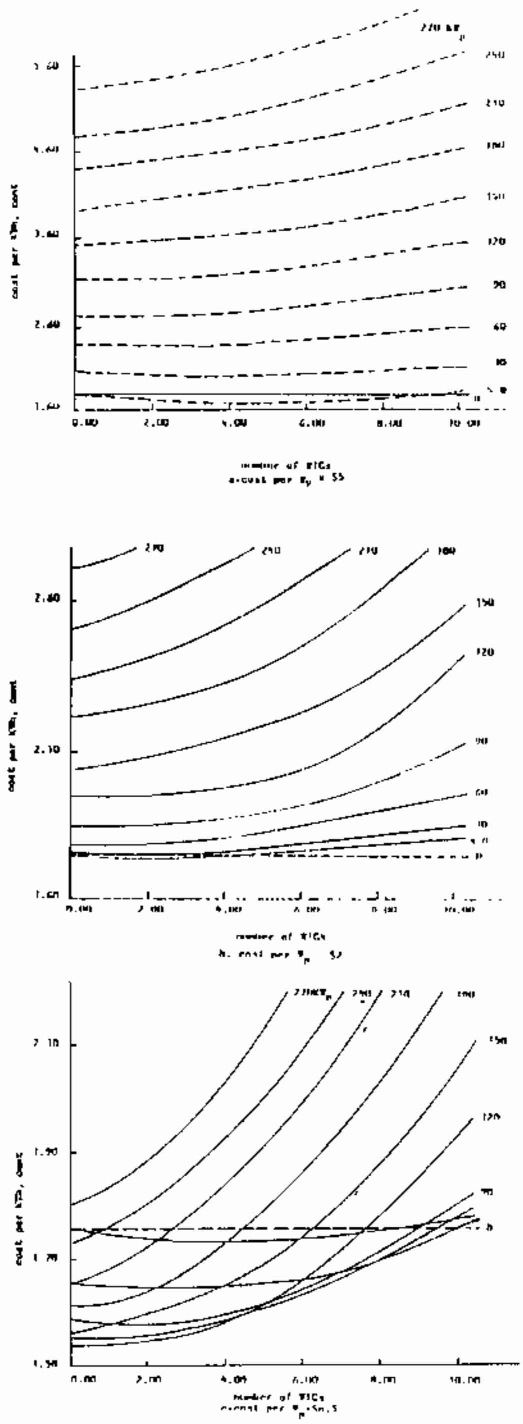


Fig.6. cost per KWh for different designs

do not allow to the prlce of the KWh to be lowered under the prlce of the KWh on uslng the diesel generators only. Fig.6.c demonstrats the resulted reductlon in the price of the KWh due to different sizes of wind parks and solar plant. In thls Figure the priee of the W_p which is taken 0.5 dollars permits to the KWh price to be lowered under the guideline.

Therefore, the benefits obtained on introducing the wind parks and the solar plants into the diesel generators for feeding loads are essentially dependent upon several factors. These factors are:

1. load demand,
2. site characteristics, and
3. system's elements costs.

6. CONCLUSIONS

A method for optimal design of an autonomous system (diesel generators) interconnected with solar plants and wind parks has been presented. The proposed method can be used ln optimisation of the design of an autonomous system with both conventional and unconventional energy sources. It ean also be used in plannlng the optimal generation scheduling of an autonomous system. The optimum design is essentlally dependent upon the load demand, average wind velocity, average insolation intensity, and system's elements costs. Based on this analysis the optimum configuration can be selected.

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