Adaptive and Reliable Control Algorithm for Hybrid System Architecture

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Abstract

A stand-alone system is defined as an autonomous system that supplies electricity without being connected to the electric grid. Hybrid systems combined renewable energy source, that are never depleted (such solar (photovoltaic (PV)), wind, hydroelectric, etc.) , With other sources of energy, like Diesel. If these hybrid systems are optimally designed, they can be more cost effective and reliable than single systems. However, the design of hybrid systems is complex because of the uncertain renewable energy supplies, load demands and the non-linear characteristics of some components, so the design problem cannot be solved easily by classical optimisation methods. The use of heuristic techniques, such as the genetic algorithms, can give better results than classical methods. This paper presents to a hybrid system control algorithm and also dispatches strategy design in which wind is the primary energy resource with photovoltaic cells. The dimension of the design (max. load) is 2000 kW and the sources is implemented as flow 1500 kw from wind, 500 kw from solar and diesel 2000 kw. The main task of the preposed algorithm is to take full advantage of the wind energy and solar energy when it is available and to minimize diesel fuel consumption.

Keywords: *wind turbine, economic control algorithm, dispatch strategy, hybrid system, renewable energy sources, photovoltaic cells (PV), genetic algorithms.*

1. Introduction

The economic dispatch is a significant function in the modern energy system [1]. It consists in programming correctly the electric production in order to reduce the operational cost ([2], [3]). The economic dispatch problem can be formulated as a multi objective optimization problem ([4],[5],[6],[7],[8]). It includes in hybrid systems to distribute the renewable productions between the Diesel power stations by the most economic way, to reduce the emissions of the polluting gases and to maintain the stability of the network after penetration of renewable energy. This production poses many technical problems for their integration in the electric system. The number of decision variables of the problem is related to all the nodes of the network (diesel power, wind power and solar power). The control system is subject to the specific constraints of a particular application. Hybrid energy systems are recognised as a viable alternative to reticulated grid supply or conventional, fuel-based, remote area power supplies [10]. The design and operation control [9] is not a linear problem due to non-linear component characteristics with a large number of variables [11]. The optimal design of problems like this cannot be achieved easily using classical optimisation methods. This paper presents a method of optimisation economic dispatch for Wind-PV-Diesel systems using a Genetic Algorithm (GA). The proposed Architecture for hybrid system is shown in Figure 1. There are some programs that simulate hybrid systems, as HYBRID2 [12], and TRNSYS [19]. HYBRID2 simulates hybrid systems with very high precision calculations, but it does not optimise the system. TRNSYS was initially developed to simulate thermal systems but it has incorporated PV systems to simulate hybrid systems such as those proposed here, however it cannot optimise them. The NREL developed the program HOMER [19], which optimizes hybrid systems. This program uses the kinetic battery model [13]. The user must enter the parameters for the optimisation by choosing the different combinations for PV array power, the battery power and the inverter power. HOMER does not give the number of panels and their type as a solution, only a PV array power, from ones chosen by the user. The user must select the type of battery, and no optimization between different types of battery is made. Barley [14] has set a guideline about main dispatch strategies. Ohsawa [15] applied an artificial neural network to the operation control of PV-Diesel systems. Ashari [9] proposed the optimisation of the dispatch strategy, based on Barley [14], by means of the Diesel generator stopping and starting set points. Kaiser [11] and El-Hefnawi [17] presented a method to design PV-Diesel systems. The optimization procedure starts by the definition of the model of the Diesel generator, and then optimizing the PV and battery

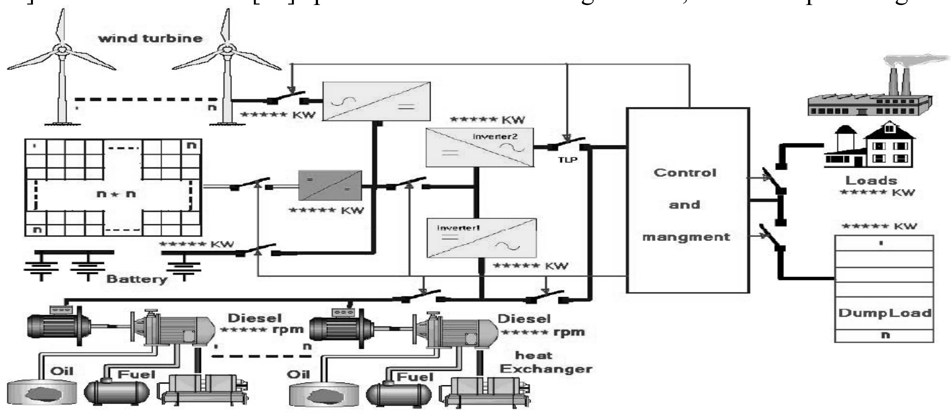

Fig. 1 Actual components of the proposed hybrid system

sizes, determining the minimum number of storage days and the minimum PV array area. The algorithm program described in this article, based on medium-penetration concept, improve hybrid wind - PV - diesel system using genetic algorithms.

2. Background

2.1 Renewable Penetration

When incorporating renewable-based technologies into remote stand-alone systems, the amount of energy that will be obtained from the renewable sources must be determined in order to properly size the added components. And because this will dictate which components will be used. Steve Drouilhet [18] developed the following classification and definitions of system penetration that characterize the levels of system complexity. A few criteria must be evaluated to determine the optimal hybrid configuration to size the wind turbine for this application. The percentage of renewable energy or renewable penetration can be classified in the following ways as per Drouihet [18]:

Instantaneous Penetration = (Wind Power Output (kW) / Primary Electrical Load) (kW) *(1)*

Average Penetration = (Wind Power Energy Output (kWh) / Primary Electrical Load) (kWh) *(2)*

Instantaneous penetration is the ratio of how much power is being produced by the renewable resources at any specific instant and falls in the realm of the engineer. The average penetration is in the domain of the economist and includes a time domain thus it measured over days, months, or even years. A three level classification hybrid system based on system penetration that separates systems along power and system control needs.

2.2 Renewable energy sources models

To achieve an optimum reliability versus cost ratio in a hybrid system designs the share percentage of renewable energy sources in terms of system capacity is 70%-85% of load. In practice the share of renewable sources in a system would mostly be around 40%-60% [11].

2.2.1 Available Wind Power (Pw)

The power of an air mass that flows at speed v, through a rotor disk of area A computed as in Eq. (3) ([20], [21]). Eq. (3) gives power in the wind, the actual power that can extract from the wind is significantly less than this figure suggests.

$$p_w = 0.5\rho A d V^3 \qquad (3)$$

The theoretical optimum for utilizing the power in the wind by reducing its velocity was first discovered by Betz, in 1926. According to Betz, the theoretical maximum power, P_{Betz}, which can be extracted from the wind, is as shown Eq. (4).

$$P_{Betz} = 0.5\rho A d V^3 C_{pBetz} \qquad (4)$$

Where: ρ = air density (kg/m3); v = wind speed (m/s); The power in the wind is proportional to the air density ρ, the intercepting area A, and the cubic of velocity v. Cp is coefficient of performance and has a value of 0.59. Thus, even if power extraction without any losses were possible, only 59% of the wind power could be utilized by a wind turbine.

2.2.2 Solar energy

Solar energy is energy produced by the solar radiation, directly or in a diffuse way through the atmosphere. Because of various processes, it can be transformed into another form of useful energy for the human activity, in particular in electricity or heat ([20],[21]). The maximum power provided by a solar panel is given by Eq. (5).

$$P_s = P_1.E_C[1+P_2(T_j - T_{jref})] \qquad (5)$$

Where Ec is solar radiation, T_{jref} is the reference temperature of the panels of 25°C, T_j is the cells junction temperature (°C), P1 represent the characteristic dispersion of the panels and the value for one panel is included enters 0.095 to 0.105 and the parameter P2= -0.47%/C° ; is the drift in panels temperature. The addition of one parameter , P3 to the characteristic as shown in Eq. (6), gives more satisfactory results:

$$P_s = P_1.E_C[1+P_2(T_j - T_{jref})].(P_3+E_C) \qquad (6)$$

This simplified model makes it possible to determine the maximum power provided by a group of panels for solar radiation and panel temperature given, with only three constant parameters P1, P2 and P3 and simple equation to apply. A thermal solar power station consists of a production of solar system of heat which feeds from the turbines in a thermal cycle of electricity production [30].

2.2.3 Diesel generator sizing and operation

The diesel should be sized to be able to meet full load. The renewable energy sources could then cover maintenance intervals or fuel shortage intervals. For systems around 250kW or larger, it might make sense to operate multiple diesels of different sizes. The resolution takes account of the fuel costs and reducing of the emissions of the polluting gases. The aim of real power economic dispatch (ED) is to make the generator's fuel consumption or the operating cost of the whole system minimal by determining the power output of each generating unit under the constraint condition of the system load demands [22]. The fundamental of the economic dispatch problem is the set of input - output characteristic of a power generating unit. The output of the generating unit will be designed by P_G, the megawatt net power output of the unit. In addition to the fuel consumption cost, the operating cost of a unit includes labour cost, maintenance cost, and fuel transportation cost. It is difficult to express these costs directly as a function of the output of the unit, so these costs are included as a fixed portion of the operating cost. The Characteristic of the generating unit is nonlinear. It is a convex curve, which is shown in Figure (2). It can be observed from the input - output characteristic of the generating unit that the power output is limited by the minimal and maximal capacity of the generating unit Eq. (7), that is, the maximal power output of the generating unit is determined by the design capacity or rate capacity of turbine or generator. Generally, the input - output characteristic of the generating unit is a quadratic function, as shown in Eq. (8).

$$PG\ min \leq PG \leq PG\ max \qquad (7)$$

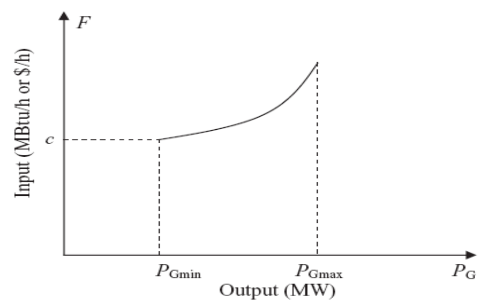

Fig.2 Input - output characteristic of the generating unit

$$F = a\,P^2_G + b\,P_G + c \qquad (8)$$

Where a, b, and c are the coefficients of the input - output characteristic. The constant c is equivalent to the fuel consumption of the generating unit operation without power output, which is shown in above Figure (4).

3. Economics of Hybrid Systems Definition and Constraints

The use of hybrid off-grid electricity depends on the comparative costs, affordability, quality of service, and accessibility of other energy options which are locally available. This paper will concentrate on hybrid system design in terms of minimizing life cycle costs and also optimising the dispatch strategy while meeting a given demand reliably. Life cycle costs (LCC) are the sum of the equipment costs; the initial costs incurred at the beginning of a hybrid system electrification project; and discounted operation costs ;include running costs, maintenance and replacement costs; arising during the project until the end of the project horizon, which is usually set between 20 and 30 years. As shown in Figure (3). In The optimization problem the aim is to determine the new generation plants in terms of when to be available, what type and capacity

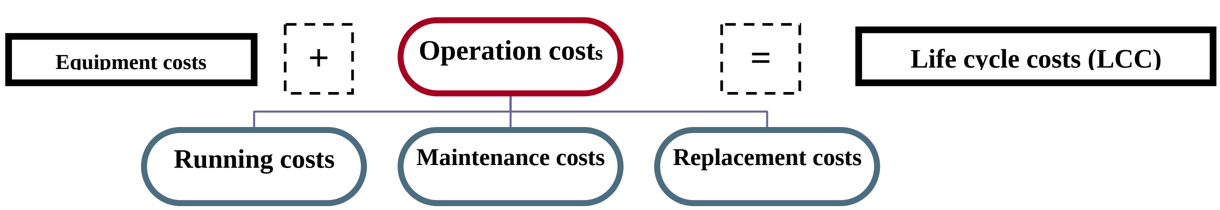

Fig.3 Life cycle costs

they should be and where to allocate so that an objective function is optimized and various constraints are met. It may be of static type in which the solution is found only for a specified stage (typically, year) or a dynamic type, in which, the solution is found for several stages in a specified period. The objective function or Life cycle costs (LCC) according to figure (3) consists of two term described in Eq.(9)

$$\text{Objective function} = \text{Capital costs} + \text{Operation costs} \quad (9)$$

The first term is, mainly due to Investment costs (C_{inv}), Salvation value of investment costs (C_{salv}) and Fuel inventory costs (C_{finv}) While the second term consists, mainly, of Fuel costs (C_{fuel}), Non-fuel operation and maintenance costs ($C_{O\&M}$) and Cost of energy not served (C_{ENS}). The objective function terms and the constraints are described in the following subsections.

3.1 Objective Functions

Total cost, C_{total}, to be minimized may be described in Eq.(10)

$$C_{total} = C_{inv} + C_{fuel} + C_{O\&M} + C_{ENS} \quad (10)$$

Where: C_{inv} The investment cost, C_{fuel} the fuel cost, $C_{O\&M}$ The operation and maintenance cost, C_{ENS} The cost of energy not served and the details are as follows.

3.2 The Investment Cost

X_{it} represents the number of unit type i required in year t, C_{inv} is given by Eq.(11)

$$C_{inv} = \sum_{i=1}^{T} \sum_{i=1}^{NG} \text{Cost\_Inv}_{it} \, PG_i X_{it} \quad (11)$$

Where: Cost_Inv_{it} (The cost in \$/MW for unit type i in year t), PG_i(The capacity of unit i (MW)), T (The study period (in years)), NG(The number of units types)

3.3 The Fuel Cost

The fuel cost of each unit is a function of its energy output, normally in a nonlinear form. However, for simplicity, here we assume a linear function given by Eq.(12). Where

$$C_{fuel} = \sum_{i=1}^{T} \sum_{i=1}^{NG} \text{Cost\_Fuel}_{it} \text{Energy}_{it} X_{it} + \text{Cost\_Fuel}_{et} \quad (12)$$

Cost_Fuel_{it} The cost of fuel in \$/MWh for unit type i in year t), Energy_{it}(Energy output for unit type i in year t), Cost_Fuel_{et} (The fuel cost of existing units in year t)

3.4 The Operation and Maintenance Cost

Similar to C_{inv}, the operation and maintenance cost is given as a linear function of PG_i given by Eq.(13)

$$C_{O\&M} = \sum_{i=1}^{T} \sum_{i=1}^{NG} \text{Cost\_O\&M}_{it} PG_i X_{it} \quad (13)$$

Where: $\text{Cost\_O\&M}_{it}$(The operation and maintenance cost (in \$/MW) for unit type i in year t)

3.5 The Cost of Energy not served

A generation unit may be tripped out in a rate given by its Forced Outage Rate (FOR). The so called Energy Not Served (ENS) cannot be made zero, but should be minimized as a cost term. It is given by Eq.(14)

$$C_{ENS} = \sum_{i=1}^{T} \text{Cost\_ENS}_t \text{ENS}_t \quad (14)$$

Where: Cost_ENS_t(The cost of the energy not served in year t (\$/MWh)), ENS_t(The energy not served in year t (MWh)). Some constraints have to be observed during the optimization process such generation capacity which should be sufficient in meeting the load, Fuel Constraint and Fuel Pollution Constraint. Besides the objective function, some constraints should also be met. A simple constraint is the one which describes the available generating capacity to be greater than the load.

3.6 Fuel Constraint and Pollution cost function

The fuel cost function $C(P_G)$ in \$/h is represented by a quadratic function Eq. (15) ([26],[25]). The coefficients a_i,

$$C(P_G) = \sum_{i=1}^{NG} a_i P_{G_i}^2 + b_i P_{G_i} + c_i \quad (15)$$

b_i and c_i are appropriate to every production unit, P_{Gi} is the real power output of i-th generator and NG is the number of thermal generators. The atmospheric emission can be represented by a function that links emissions with the power generated by every unit. The emission of SO_2 depends on fuel consumption and has the same form as the fuel cost [27]. The emission function in ton/h which represents SO_2 and NO_x emission is a function of generator output and is expressed as follow in Eq.(16) [29].

$$E(P_G) = \sum_{i=1}^{NG} \alpha_i + \gamma_i P_{G_i}^2 + \beta_i P_{G_i} + \xi_i \exp\left(\lambda_i P_{G_i}\right) \quad (16)$$

Where α_i, β_i and γ_i are the coefficients of emission function corresponding to the i^{th} generator. These three parameters are determined by adjustment techniques of curves based on reel tests [28].

3.7 Problem constraints

The Production capacity constraints the generated real power of each generator at the bus i is restricted by lower limit max P_{Gi} and upper limit min P_{Gi} Eq. (17).

$$P_{Gi\,\min} \le P_{Gi} \le P_{Gi\,\max} \rightarrow i = 1,\ldots, N_G \quad (17)$$

The Power balance constraint the total power generation and the wind power must cover the total demand ' P' D and the power loss p in transmission lines Eq. (18).

$$P_D' + P - \sum_{i=1}^{NG} P_{Gi} = 0 \qquad (18)$$

The Active power loss constraint the transmission and transport lines are positives Eq. (19). Renewable power

$$p > 0 \qquad (19)$$

constraint the renewable power used for dispatch should not exceed the 10 % of total power Demand Eq. (20),

$$0.10 \leq P_S + P_W \leq 0.85 P_D \qquad (20)$$

thus, the problem to be solved is formulated as follow
Minimize of C (P_G), E (P_G)

4. The Proposed Strategy and Control Algorithm

This paper mainly deals with hybrid system design and operation control problem which is non-linear due to non-linear component characteristics and the complexity of the hybrid system component interaction. The proposed system configuration is composed from six 250 kW wind turbine , PV arrays resulting in a total rated power of 200 kWp, and diesel generators sets arranged as follow six 250 kVA, four 100 kVA and ten 20 kVA acting as a backup system. When the PV and wind resources are not sufficient to supply the load demand (2000 kw) with its minimum operational level the diesel generators will recompense this demand. Based on the costs of components, fuel, labour, transport and

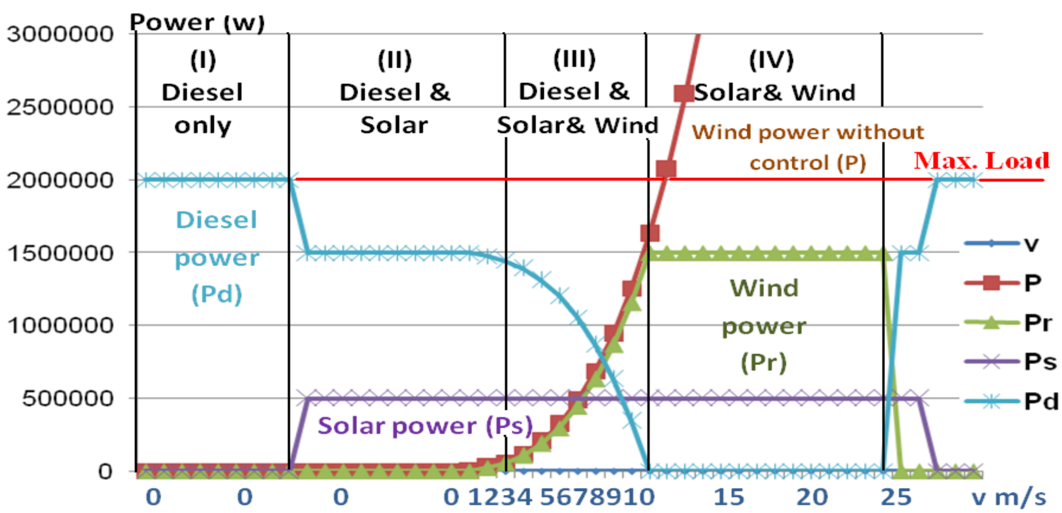

Fig.4. Hybrid system operation strategy

maintenance, the most cost-effective dimensions of all components and their operation strategy is evaluated as a target for the design algorithm. Operating the components effectively influences operation costs and, therefore, overall life cycle costs. The necessary optimization of the operation strategy in a hybrid system will focus on efficiency of diesel and prolonging component lifetimes. The proposed strategy for hybrid system operation is depicted as shown in Figure (4). It divided into four regions where region (I) represent the diesel unite operation only, region (II) represent the diesel and solar operation, region (III) represent the diesel, solar and wind turbine operation, finally region (IV) represent the operation of solar and wind turbine operation. Region (III) represents the management of demand and adjustment the renewable energy sources to maximizing the power and region (IV) represents the power regulation. The maximization of load factors is very important and has a significant influence on life cycle costs and sizing. The Control Algorithm Architecture, shown in Figure (5), for proposed hybrid system is developed according to the operation strategy conditions described in Figure (4). The renewable generators will reduce fuel consumption and engine generator maintenance. This is the task of the design optimization to recommend a least-cost and reliable design suitable for a given application with the aim to improve the system performance and lower costs. To develop the optimization problem of hybrid system design the electricity demand profile for a selected location with estimated weather conditions, costs for components, labour, transport and maintenance should be formulated. The demand is fixed to be 2 Mw in every design process and stage. Renewable energy resources, depend on the data of the climate such as the wind speed for wind energy, solar radiation and the temperature for solar energy, are calculated. So diesel power also calculated for each month of the year for each hour of the day as shown in Table 1.

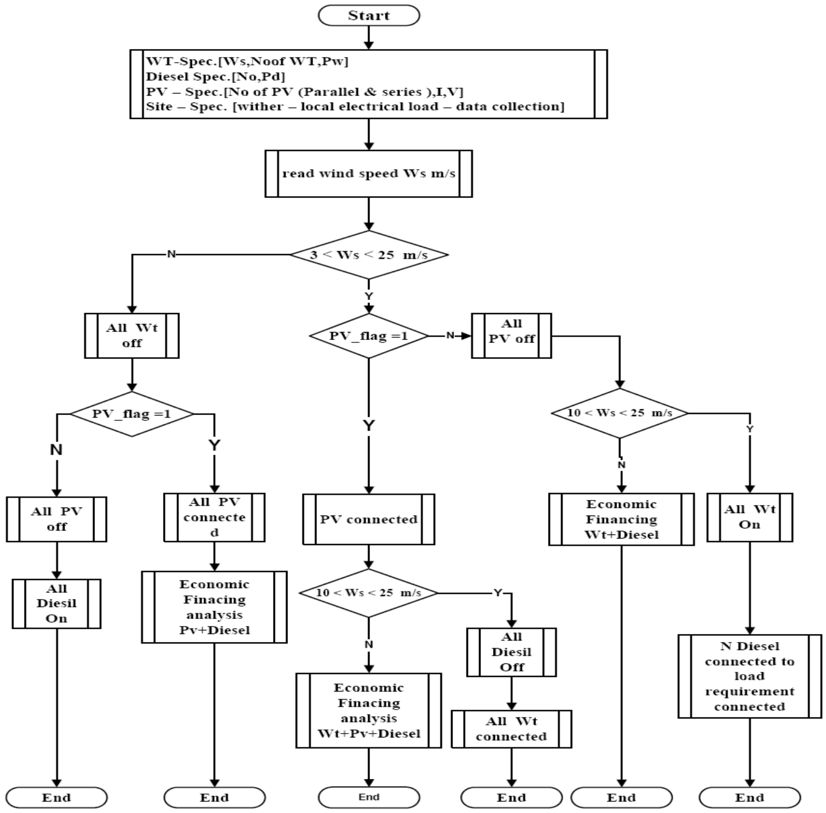

Fig.5. Control Algorithm Architecture for Hybrid System

Table 1: Average Diesel Power for each month of the year; calculated for each hour of the day

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0	1760000	1625000	1400000	1205000	950000	875000	935000	905000	845000	1115000	1535000	1700000
1	1790000	1655000	1460000	1265000	1010000	890000	965000	965000	905000	1205000	1595000	1715000
2	1790000	1685000	1520000	1310000	1055000	950000	1040000	1040000	950000	1250000	1580000	1715000
3	1790000	1700000	1535000	1385000	1100000	1040000	1115000	1100000	1010000	1310000	1595000	1715000
4	1790000	1715000	1595000	1460000	1115000	1055000	1160000	1115000	1100000	1355000	1595000	1700000
5	1790000	1700000	1595000	1505000	1160000	1115000	1220000	1205000	1145000	1385000	1625000	1700000
6	1290000	1230000	1125000	1020000	690000	570000	720000	690000	660000	915000	1125000	1215000
7	1275000	1215000	1170000	960000	615000	465000	615000	600000	600000	885000	1110000	1230000
8	1245000	1170000	1110000	885000	510000	390000	555000	495000	465000	750000	1020000	1230000
9	1200000	1065000	975000	855000	540000	390000	540000	450000	405000	660000	945000	1155000
10	1110000	1020000	915000	810000	540000	405000	600000	465000	405000	615000	900000	1110000
11	1065000	975000	855000	810000	510000	435000	615000	510000	405000	615000	855000	1035000
12	1020000	945000	840000	810000	495000	405000	600000	540000	405000	645000	840000	1005000
13	975000	900000	840000	795000	495000	405000	615000	510000	390000	645000	855000	945000
14	1005000	885000	840000	750000	495000	375000	645000	540000	390000	660000	885000	960000
15	1020000	900000	885000	810000	510000	375000	645000	540000	435000	705000	945000	975000
16	1080000	1005000	945000	885000	555000	405000	660000	570000	495000	795000	1020000	1065000
17	1170000	1095000	1020000	915000	540000	450000	690000	615000	555000	915000	1110000	1185000
18	1260000	1155000	1080000	975000	510000	465000	705000	660000	570000	885000	1125000	1200000
19	1730000	1655000	1535000	1415000	935000	890000	1145000	1055000	950000	1205000	1580000	1685000
20	1715000	1580000	1415000	1310000	785000	785000	905000	830000	815000	1055000	1505000	1655000
21	1700000	1565000	1355000	1160000	725000	725000	800000	755000	755000	1040000	1505000	1655000
22	1730000	1520000	1340000	1145000	785000	725000	800000	755000	755000	1055000	1475000	1655000
23	1745000	1565000	1355000	1160000	845000	800000	845000	815000	785000	1115000	1535000	1685000
PdC (Kw)=	34045	31525	28705	25600	17470	15385	19135	17725	16195	22780	29860	32890

Pdc (Power of Diesel Consumed) Kw = Load demand Kw – (wind power + solar power) Kw

5. The Proposed Economic Genetic Algorithms

Genetic algorithms (GA) are used in this paper to solve the economic dispatch problem and to optimize the developed hybrid system design model through minimizing its life cycle costs while still meeting required system performance. The developed Genetic algorithms Architecture for proposed economic dispatch is shown in Figure (6). GA provides a solution to a problem by working with a population of individuals each representing a possible solution. Each possible solution is termed a "chromosome." New points of the search space are generated through GA operations, known as reproduction, crossover, and mutation. These operations consistently produce fitter offspring through successive generations, which rapidly lead the search toward global optima.

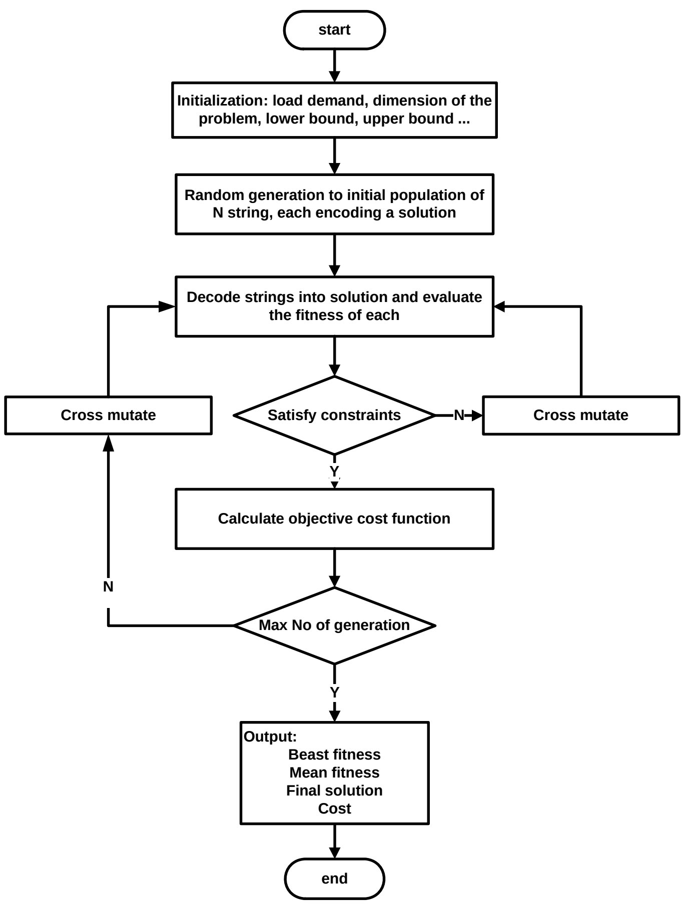

Fig.6. Genetic algorithms for economic dispatch

The economic dispatch (ED) problem can be stated as below in Eq. (21) and Eq. (22). The outputs of the (N – 1)

$$\min \quad F = \sum_{i=1}^{N} Fi\,(P_{Gi}) \qquad (21)$$

$$\sum_{i=1}^{N} P_{Gi} = P_D \qquad (22)$$

free generators can be chosen arbitrarily within limits while the output of the reference generator is constrained by the power balance. It is assumed that the N th generator is the reference generator. These (N − 1) strings are concatenated to form a consolidated solution bit string of 8 * (N − 1) bits called the genotype. A population of m genotypes must be initially generated at random. Each genotype is decoded to a power output vector. The output of the reference unit is described in Eq. (23). Adding penalty factors h1, h2 to the violation of power output of

$$P_{GN} = P_D - \sum_{i=1}^{N} P_{Gi} \qquad (23)$$

the slack bus unit; we can combine the above equations in Eq. (24).

$$F_a = \sum_{i=1}^{N} Fi(P_{Gi}) + h_1(P_{GN} - P_{GN\max})^2 + h_2(P_{GN\min} - P_{GN})^2 \qquad (24)$$

Where $P_{GN\ min}$, $P_{GN\ max}$ are the lower and upper limits of the power output of the Slack bus unit, respectively. The value of the penalty factors should be large so that there is no violation for unit output at the final solution. The
GA fitness function is defined as the inverse of (F_a) Eq. (24) as in (25).

$$F_{fitness} = \frac{1}{F_A} \qquad (25)$$

The unit step size can be computed by Eq. (26). Where n is the length of the substring in binary codes corresponding to a unit.

$$S_i = \frac{P_{Gi\max} - P_{Gi\min}}{2^n - 1} \qquad (26)$$

6. Results

The optimization using genetic algorithms has the following parameters Total load = 350000, Dimension of problem or No. of diesels (6*250kw,4*100kw,5*20kw) = 15 units, Max No of iterations = 1000, 25 .
Population size = 100 and give the following results

6.1 Final solution

D1 = 24.99154, D2= 24.98670, D3 = 24.98876, D4 = 24.08463, D5 = 24.98483, D6 = 24.99022, D7 = 24.28500, D8 = 23.08660, D9 = 24.05695, D10 = 33.54844, D11= 19.99843, D12 = 19.99944, D13 = 19.99942,
D14 = 19.99955, D15 = 19.99949e+004] kw.
Associated cost: = 7.267849e+007

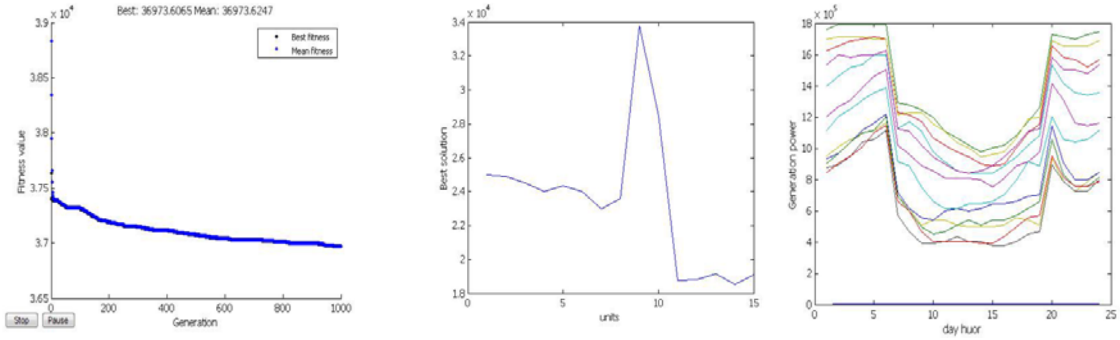

Fig.6. Control Algorithm results from lift to right. (a) Best fitness, (b) best solution, (c) generation power

Decreasing Max No of iterations from 1000 to 20 make the algorithm more faster than previous and give the following results with Total load = 450000 and Max No of iterations = 20

6.2 Final solution is
[D1 = 34.74849, D2= 34.74840, D3 = 34.88047, D4 = 27.4924, D5 = 33.84436, D6 = 34.75015, D7 = 34.77807, D8 = 34.70787, D9 = 34.74953, D10 = 46.69673, D11= 19.74678, D12 = 19.74588, D13 = 19.68406, D14 = 19.70812, D15 = 19.72366] kw

Associated cost: = 1.267935e+008

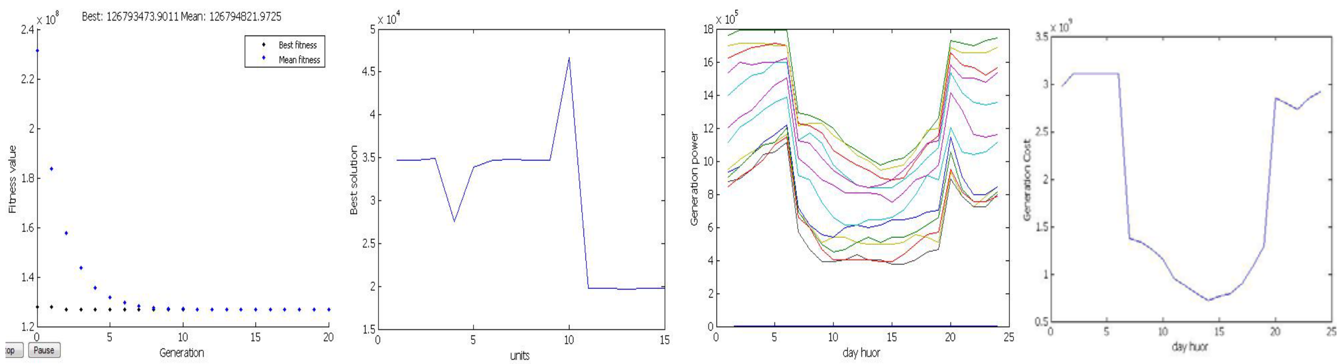

Fig.7. results from lift to right. (a) Best fitness, (b) best solution, (c) generation power,(d) generation cost for one day

6.3 Finally the Associated cost for monthly average hours diesel power generation: cost =1.0e+009 *
Columns 1 through 6
2.7357 2.7961 2.7961 2.7961 2.7357 2.7357
Columns 7 through 12
1.1876 1.2237 1.2237 1.0506 0.9557 0.8192
Columns 13 through 18
0.7690 0.6724 0.6959 0.7199 0.8722 1.1176
Columns 19 through 24
1.1522 2.6761 2.5591 2.5591 2.5591 2.6761

7. Conclusion

The algorithm described in this paper, based on medium-penetration concept, improve hybrid (wind - PV - diesel) system using genetic algorithms. The program calculates the optimum configuration of the system according to the weather data as well as the period of operation of solar cells, either morning or evening. Hybrid system is a combination of diesel power available continuously and are available locally, and pollution-free wind power, solar energy which is one of the advantages of this system. Where the annual diesel fuel consumption reduced and the pollution minimized at the same time. The control algorithm takes full advantage of the wind energy and solar energy when it is available and minimizes diesel fuel consumption. A hybrid energy (wind-PV-Diesel) system has greater reliability for electricity production than a PV-only system or wind only (Diesel engine production is independent of atmospheric conditions). This provides greater flexibility, higher efficiency and lower costs for the same energy quantity produced. Also, PV-Diesel systems, compared with Diesel-only systems, provide a reduction of the operation costs and air pollutants emitted to the atmosphere.

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