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Optimal sizing design and energy management of stand-alone photovoltaic/wind generator systems

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Abstract

Presently, the photovoltaic (PV) and the wind energies are the most important energetic alternative resources. So far, a lot of researches are developed and conducted concerning the cost-optimally design and energy management for the stand-alone hybrid PV-wind generator (WG) systems. In this study, a methodology for optimal sizing design and strategy control based on differential flatness approach is applied to the hybrid stand-alone PV-WG systems. The purpose is to find the optimal number of units ensuring that the 20 years round total system cost is minimized subject to the constraint that the load energy requirements are completely covered. The optimization methodology, using the genetic algorithm and the formulation of the problem are detailed. Finally, an optimal configuration is obtained with a lifetime of 20 years; also the results of the control algorithm based on the flatness properties obtained under Matlab/Simulink are given.

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Keywords: Design; Genetic algorithm; Hybrid source; Optimization; Photovoltaic; Stand-alone; total system cost; wind energy;flatness control.

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1. Introduction

The managing between generation periods of renewable resources and consumption periods is very convoluted issue in stand-alone photovoltaic (PV) and Wind Generator (WG) hybrid power systems .They can generate electricity in order to serve a local energy demand, and it generally operates in areas that are far from the national

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grid. The optimal sizing design method is an important objective in the autonomous hybrid power systems. However, design of small-scale stand-alone power sources for use in remote or off-grid locations is yet to reach a commercially feasible stage [1].

A several researches have been performed for the optimal design of hybrid PV and wind power generating systems [2–3]. These resources are clean, free and renewable. But the high capital cost made its progression a slow one. In recent years, thanks to the advance materials and technologies, improved manufacturing developments have decreased their capital costs making them more attractive. Another way to try to decrease the cost of these systems is by using the hybrid designs that use both wind and photovoltaic energies.

Actually, various researches have been performed about optimization of the hybrid renewable energy systems [4–5, 6]; also a lot of techniques have been employed to reach the optimization objective [7-8, 9]. So, the problem is on defining which structure will be the most cost effective while supplying demand. This paper presents an optimization procedure capable to design hybrid PV-wind energies for the stand-alone systems using genetic algorithm (GA) approach in order to find the most effective way to use wind and solar energy at the lowest possible cost, so the objective of this paper is to provide a methodology for the sizing of the stand-alone hybrid PV-wind energies system using genetic algorithm, also intends to provide a better optimization formulation problem.

2. Optimization problem formulation

In this study, the objective function of the PV-wind system design is the total design cost C_T which involves the total capital cost C_{Cpt} and the total maintenance cost C_{Mtn}.

The model of the hybrid PV–wind power generation system involves PV arrays, wind turbines, batteries bank, inverters, MPPT controllers, also other devices and cables.

To minimize the total design cost C_T using the GA, the general form of the objective function should be expressed as follows:

Minimize: $f(x)$ (1)

Subject to: $g(x) = 0$ (2)

$H(x) \leq 0$ (3)

Where, $f(x)$ is the objective function; $g(x)$ is the equality constraints and $H(x)$ is the inequality constraints.

According to the equations (1), (2) and (3), the optimization problem can be expressed as follows:

$$\text{Minimize} \quad C_T = C_{cpt} + C_{Mtn} \tag{4}$$

$$\text{Subject to:} \quad \Sigma_1^{24}(P_{pv}^t \times \Delta t) + \Sigma_1^{24}(P_{wind}^t \times \Delta t) \geq \Sigma_1^{24}(P_{dmd}^t \times \Delta t) \tag{5}$$

$$\text{total wattage installed} \leq \sum_d P_{inv} \times N_{inv} \tag{6}$$

$$\text{photovoltaic maximum power STC} \leq \sum_e P_{contr} N_{contr} \tag{7}$$

$$\text{Where,} \quad P_{pv}^t = N_{pv} \times P_s^t \tag{8}$$

$$\text{And} \quad P_{wind}^t = N_{wind} \times P_w^t \tag{9}$$

N_{pv} is a decision variable which is the number of the solar panels and P_s^t is the power generated by each solar panel at time t; P_s^t can be obtained using insolation data and insolation-power characteristic curve [10]. The P_{wind}^t which is the power generated by wind turbine, N_{wind} is a decision variable which is the number of wind turbines and P_w^t is the power generated by each wind turbine and can be obtained using wind speed data, turbine hub height correction function, and wind speed-power characteristic curve [8].

To calculate the total wattage installed, one should sum all the power of all the loads.

$$\text{total wattage installed} = \sum P_{loads} \tag{10}$$

P_{inv} is the maximum power that can be supplied by the inverter and N_{inv} is a decision variable which represents the number of the inverters required.

The number of the batteries can be determined by the following function [8]:

$$N_{batt} = \text{Roundup}\left[\frac{S_{req}}{\gamma \times S_{batt}}\right] \tag{11}$$

Where, S_{batt} is the rated capacity of each battery and γ is usage % of rated capacity which guarantees battery's life span. And the roundups function to find the nearest positive integer of the formula.

S_{req} is the required storage capacity, which can be calculated by the following equation [8]:

$$S_{req} = \sum_{t=1}^{\max t}\left(P_{pv}^{t}+P_{wind}^{t}-P_{dmd}^{t}\right)\times \Delta t - \sum_{t=1}^{\min t}\left(P_{pv}^{t}+P_{wind}^{t}-P_{dmd}^{t}\right)\times \Delta t \tag{12}$$

Where $\max t$ is the time when the energy generated is at the maximum; $\min t$ is the time when the generated energy is lowest; and Δt is the unit of time (considered 1 hour). P_{dmd}^{t} is the power demanded (kW) at time t.

The initial capital cost I is converted into annual capital cost A using the following capital-recovery factor [10, 11]:

$$C_{conv} = \frac{i(1+r)^{L}}{(1+r)^{L}-1} \tag{13}$$

Where the index (L) is the life span of the system and (r) is the annual interest rate.

The total capital cost in eq. (4) can be expressed by the following function:

$$C_{cpt} = C_{conv} \times \sum_{a} C_{pv} \times N_{pv} + \sum_{b} C_{w} \times N_{w} + \sum_{c} C_{batt} \times N_{batt} + \sum_{d} C_{inv} \times N_{inv} + \sum_{e}\left(C_{contr} \times N_{contrv}\right) + C_{BG} \tag{14}$$

Where, C_{pv}, C_{w}, C_{batt}, C_{inv}, C_{contr}, C_{BG} are the costs of solar panel, wind turbine, battery, inverter, MPPT controller and the buck up generator respectively.

Also, the maintenance cost in the eq. (1) can be:

$$C_{Mtn} = \left(C_{mtn}^{pv} \times \sum_{t}^{24}(P_{pv}^{t} \times \Delta t)\right) \times 365 + \left(C_{mtn}^{wind} \times \sum_{t}^{24}(P_{wind}^{t} \times \Delta t)\right) \times 365 \tag{15}$$

Where, C_{mtn}^{pv} is the maintenance cost per kWh for PV array; and C_{mtn}^{wind} is the maintenance cost per kWh for wind turbine.

3. Results and discussion

The proposed method is applied to the design of a stand-alone hybrid PV-WG system in order to power a supply load. Using the following numerical example:

In the PV system the model of KYOCERA KD215-LPU for a cost of 322 $/panel have been chosen, where the PV maximum power is 215W under the Standard Test Conditions (STC), and operational and maintenance (O&M) cost for PV array is considered 0.5 cent/kWh and its lifetime is of 20 years. Wind turbine cost is taken to be 17.681$/kW, the model of API-10KW with blades diam 3-7.0m and height 16m has been used. O&M costs for the wind turbine are considered to be equal to 2 cents/kWh and its lifetime is of 20 years.

The Surrette 12CS11Ps (12 V, 375 Ah) storage batteries are utilized in this system. Cost of one battery is 1300 $ with a replacement cost of 900 $.The usage % of the battery rated capacity is of 80% and the battery's rated capacity is 4.28kW/h. The life time of the Surrette 12CS11Ps is 10 years.

The converter cost may vary from 200 $/kW to 6500 $/kW. Cost used in the current work is of 3597 $/kW, the model of SET48/220-10kW has been chosen.

The distribution of the consumer power requirements during a day is shown in Fig. 3, (b).

The average hourly power generated by a solar panel in a day and the average hourly power generated by the WG, are plotted in Fig 2, 3.

3.1. The GA's sizing optimization methodology

A general block diagram representing the cost optimization methodology with (GA) is shown in Fig. 1. Wherever, the optimization algorithm have a database containing the technical and economical (prices) characteristics of the commercially devices used in the system with their associated per unit maintenance costs. The type of PV module and WG, battery with nominal capacity, inverter type etc., are stored in the input database. The next step of the optimal sizing procedure consists of a method employing GAs, which dynamically searches for the system configuration.

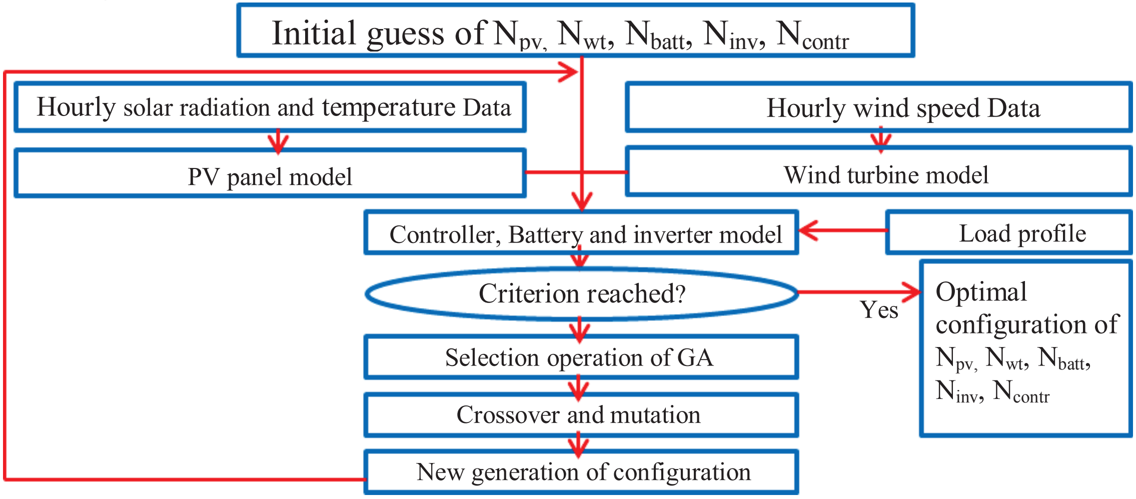

Fig. 1. Flowchart of the optimal sizing design PV-wind using GA.

Hybrid solar–wind systems usually meet well load demands because of the good complementary effect of the solar radiation and wind speed. In the first case, when the example was solved with wind generator resources limitation constraints, the optimal solution for the cost of the system was US\$14,022.99, with $N_{wind} = 0$. Therefore, in the second case; in order to use some wind turbines, the following constraints can be added to the formulation:

$$N_{wind} = 1 \tag{16}$$

With Eq. (21), also, in order to make a more realistic optimization for the given problem, the output wind power was reduced into 75% of its original power as follows:

$$P_w^t = 0.75 \times P_w^t \tag{17}$$

The optimal solution vector was as follows:

Table 1. The optimal sizing results –PV-Wind system

Variable type	Value (1st case)	Value(2nd case)
Photovoltaic panel	158	12
Wind generator	0	3
MPPT controller	47	4
Battery	40	37
Inverter	1	1
Total cost US\$	14,022.99	12,220.15

It is obvious that in the first case, the optimal configuration results in a higher annualized cost of system compared to the hybrid solar–wind system given in the second case.

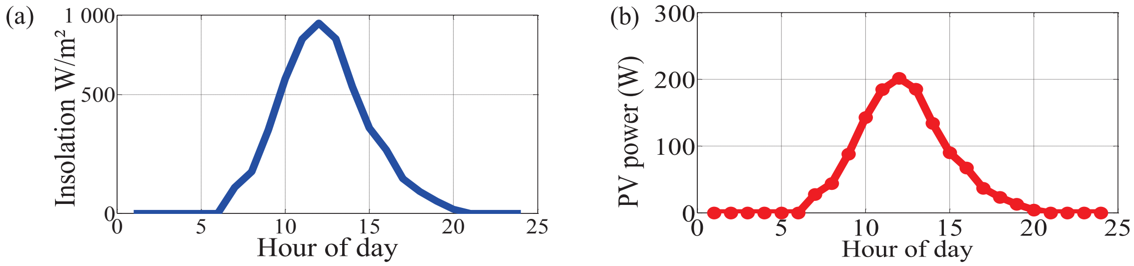

Fig. 2. (a) Solar radiation in 24 hours; (b) Average hourly power generated by a solar panel in a day.

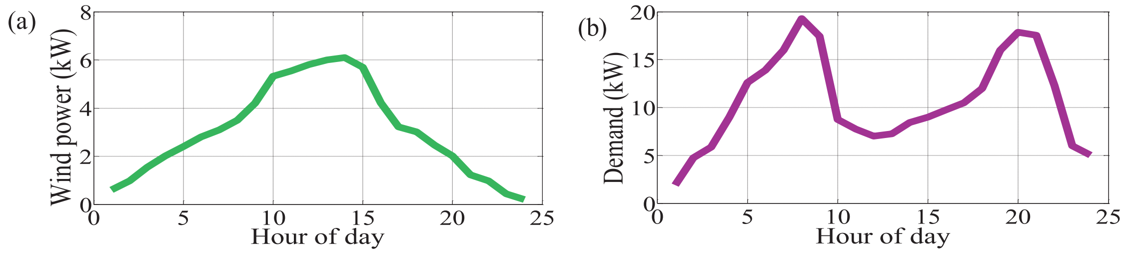

Fig. 3. (a) Average hourly power generated by a wind turbine in a day; (b) Average hourly electrical demand in a day.

4. Energy management and the control law of the hybrid power sources

The energy management of the hybrid sources has been studied via a control based on differential flatness approach using the results of the sizing design (Table 1, 2nd case).The advantage of this control algorithm is that the state variable and control system are downright estimated by the trajectories of the flat output derived from these outputs without the need to integrate any differential equation. The flatness property of a system is a relatively new concept in automatic control. It was proposed and developed by M. fliess and al. [12]. A system of ordinary differential equations is said to be differentially flat if there are variables such as:

$$\dot{x} = f(x, u) \tag{18}$$

$$u = [u_1, u_2, \ldots, u_m]^T \qquad u \in R^m \tag{19}$$

$$x = [x_1, x_2, \ldots, x_n]^T \qquad x \in R^n \tag{20}$$

$$y = [y_1, y_2, \ldots, y_m]^T \qquad y \in R^m \tag{21}$$

x is the vector of random variables, u is the control vector, y is the vector of flat outputs, and (n, m) ϵ N².

The power converter structure of the system is shown in Fig. 3. PV and WG power- systems may deliver direct or alternative current (DC or AC) to satisfy the power needs. The current, voltage and power quality are controlled by electronic power-conditioning systems. Usually, voltage regulators and DC–DC converters are used to control and to regulate the PV and wing turbine output voltages to useful values [13, 14].

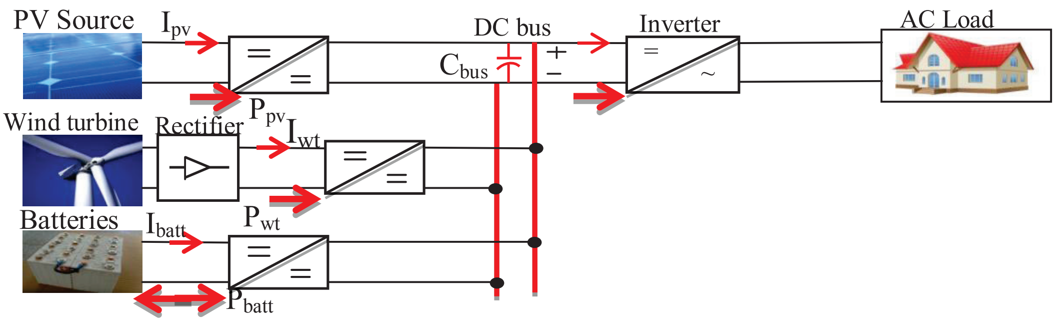

Fig. 4. Structure of the multi-sources system.

The DC-DC converters have been considered ideal without losses. The principal equations for the operation of the system can be written as follows:

$$P_s = P_{pv} = V_{pv} \times I_{pv} \tag{22}$$

$$P_w = P_{wt} = V_{wt} \times I_{wt} \tag{23}$$

$P_{battref} = P_b = P_{batt} = V_{batt} \times I_{batt}$, where P_{batt} is the power generated from the batteries bank. (24)

$V_{pv}, V_{wt}, I_{pv}, I_{wt}$ are the voltage and the current of the photovoltaic and wind turbine sources respectively.

The energy y_{bus} stored in the DC link is: $y_{bus} = \frac{1}{2} C_{bus} v_{bus}{}^2$ (25)

The Energy y_{bus} according to P_{pv}, P_{wt}, P_{batt} and P_{dmd}:

$$\dot{y}_{bus} = P_{pv} + P_{wt} + P_{batt} - P_{dmd} \tag{26}$$

Where:

$$P_{batt} = v_{batt}.i_{batt} = \sqrt{\frac{2y_{batt}}{C_{batt}}}.i_{batt} \tag{27}$$

$$P_{dmd} = v_{bus}.i_{dmd} = \sqrt{\frac{2y_{bus}}{C_{bus}}}.i_{dmd} \tag{28}$$

The battery energy y_{batt} is given by: $y_{batt} = \frac{1}{2} C_{batt} v_{batt}{}^2$ (29)

From equations (26) and (20), the control variable P_{batt} can be written as follows:

$$P_{batt} = \sqrt{\frac{2y_{bus}}{C_{bus}}}.i_{dmd} + \dot{y}_{bus} - P_{pv} - P_{wt} = h_{P_{batt}}(y_{bus}, \dot{y}_{bus}) \tag{30}$$

4.1. Energy Regulation of the DC link

To control the energy of the DC link using the flatness law a desired reference trajectory for the DC link energy is defined. Therefore, considering y_{busref} as the reference trajectory for the desired flat output variable y_{bus} (stored energy in the DC bus). y_{busref} is given as follows:

$$y_{busref}(t) = \frac{1}{2} C_{bus} v_{busref}(t)^2 \tag{31}$$

A linearizing feedback control law that performs exponential asymptotic tracking of the trajectory is given by the following expression [15], [16]:

$$(\dot{y}_{bus} - \dot{y}_{busref}) + k_{11}(y_{bus} - y_{busref}) + k_{12}\int_0^t (y_{bus} - y_{busref})dt = 0 \tag{32}$$

Where k_{11} and k_{12} are the controller parameters chosen by imposing the roots of the characteristic equation as follows:

$$s^2 + k_{11}s + k_{12} = 0 \tag{33}$$

Those are written:

$$\begin{cases} k_{11} = 2\xi w_n \ [\mathrm{rad.s^{-1}}] \\ k_{12} = {w_n}^2 \ \ [\mathrm{rad.s^{-2}}] \end{cases} \tag{34}$$

Where ξ and w_n are the desired dominant damping ratio and the natural pulse, respectively.

4.2. *Energy management*

The available power for charging batteries can be given as follows:

$$P_r = P_L - P_g \tag{35}$$

And: $P_g = P_{pv} + P_{wt}$ (36)

Where P_g represent the power supplied by the generation PV-Wind system.

In order to manage energy during power flow between the PV –Wind-batteries sources and the load: three modes are considered:

- Charge mode : $\begin{cases} \text{if } P_r > 0 \\ P_{batt} = P_g - P_l \end{cases}$ (37)
- Discharge mode: In this mode, the load power exceeds the maximum power that can provide the main sources. $\begin{cases} \text{if } P_r < 0 \\ P_{batt} = P_l - P_g \end{cases}$ (38)
- Normal mode : $\begin{cases} \text{if } P_r = 0 \\ \text{disconnection·of the·batteries sources} \end{cases}$ (39)

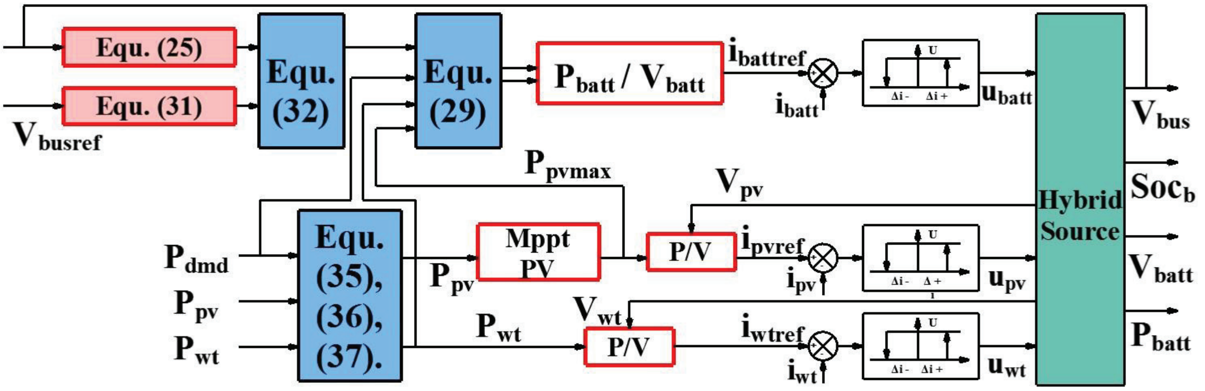

Fig. 5. Control scheme for the proposed hybrid PV-Wind-Batteries system.

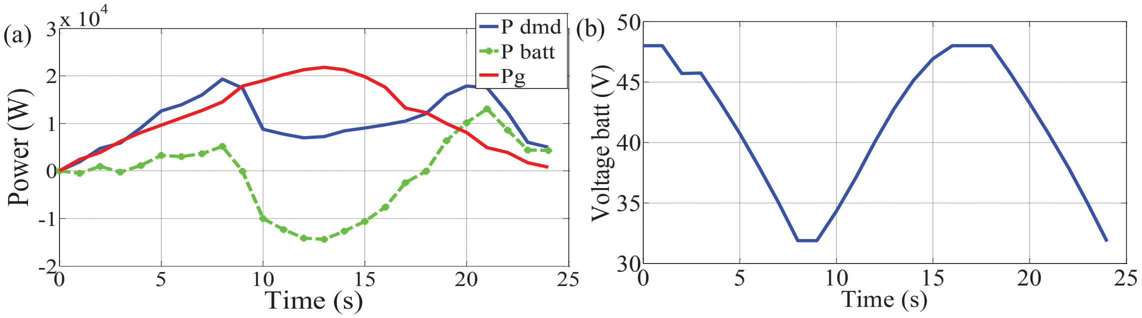

Fig. 6. (a) Power curves of the hybrid system; (b) Batteries voltage.

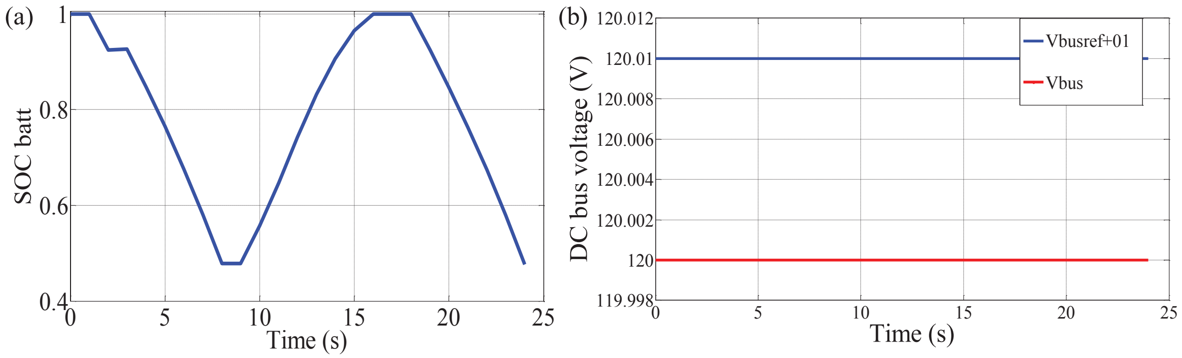

Fig. 7. (a) Batteries state of charge; (b) DC link voltage and its reference.

5. Conclusions

In this paper, a methodology for the optimal sizing of hybrid, stand-alone PV-WG systems with genetic algorithm, and strategy control based on differential flatness approach has been presented. The purpose of the proposed methodology is the selection of the optimal number of PV modules, WGs and batteries, the PV modules MPPT controllers and the inverters, also the energy management via a control based on differential flatness approach of the hybrid system using the results of the sizing design.

However, the optimal number of each system component is calculated such that the 20-years round total system cost is minimized subject to the constraint that the load power requirements are completely covered, thus resulting. The 20-years round total system cost is equal to the sum of the respective components capital and maintenance costs. The cost function minimization is implemented using genetic algorithms, when compared to conventional optimization methods, such as dynamic programming and gradient techniques, have the aptitude to attain the global optimum with relative computational simplicity. An energy management strategy is presented to control and manage the energy between the PV-Wind, load and batteries as hybrid power sources to supply a residential household.

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