Optimal Combination and Sizing of a New and Renewable Hybrid Generation System

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Abstract

Since solar, wind and tidal energies mainly depend upon statistical parameters with respect to changing climate and environment, focus on hybrid generation system design increases the availability of the power generation system. The hybrid system also reduces the dependence on one environment parameter thus providing the consumer with reliable and cheap electricity. Therefore optimal combination and sizing design of hybrid generation system considering the battery has a very important role in the use of renewable energy effectively and economically. Several approaches were developed to achieve the optimal configurations of the hybrid systems such as the least square method, the trade-off method and the probabilistic approach method. This study presents a method to design the optimal combination and unit sizing for new and renewable hybrid systems. The method is to find the optimal configuration and sizing among sets of system components, that meets the desired system requirements, with the lowest value of the energy cost. The availability of the methodology is demonstrated with the field data acquired from sets of experiments.

Keywords: *Hybrid generation system, optimal combination and sizing, lowest value of the energy cost*

1. Introduction

Recently the increased interest in the problem of global warming due to the use of fossil fuels has led to a growing concern in new and renewable energy resources. One of its main hazards of fossil fuels is the destruction of the Eco-system. One way to solve this problem is the use of natural renewable energy resources instead of hydrocarbon fuels. The new and renewable energy sources are non-polluting, continuous, and free in their availability. Therefore the new and renewable energy sources have been attractive for many applications as alternative resources.

Among many new and renewable energy sources, the wind generator system is free from the environmental concerns. It is also competitive in cost compared to that of the conventional power from the grid. The photovoltaic system, which is one of the major renewable energy and environmentally safe, is still expensive. The operation and maintenance required for the wind and photovoltaic generation systems is very little when compared with the other generation systems such as diesel generation system.

Since the new and renewable energy resources such as solar, wind and tidal energies mainly depend upon weather and climatic changes, they are very unpredictable. Therefore they have the important drawback associated with their inability to guarantee reliable and uninterrupted supply of energy at a cost that can compete with the conventional power from the grid. Combining two or more renewable energy systems can solve the problem. For example, the two random sources such as the wind and solar energy which are individually less reliable could have a higher reliability when used together. Castle [1] documented the hybrid generation system that uses wind and photovoltaic energy together is better than an individual wind or photovoltaic power system. These facts make many researchers develop the hybrid generation system as an alternative energy system.

Hybrid generation system basically consists of merging system of two or more different types of generation systems. In recent years, the hybrid generation system has become significant because of the complementary characteristics among the new and renewable energy resources. It reduces the dependence on one environment parameter thus providing the consumer with reliable and cheap electricity, and is more effective than utilization of single renewable energy source.

To use the energy resources of a hybrid system more efficiently, the combination and sizing of different types of generation systems that constitute the hybrid systems are very important because the energy cost depends on the unit sizing of each generation system and types of new and renewable energy resources. However, the combination and sizing of the hybrid system is performed on the basis of experience and intuition, which is not attained by optimum efficiency.

Several approaches were developed to achieve the optimal configurations of the hybrid systems. Bucciarelli [2] modified the method for the design of photovoltaic-only system to include the additional energy from the wind turbine. He developed a new technique that can provide more accurate results by the comparison of the original method. Salameh and Safari[3] discussed the method for determining the optimal number of photovoltaic arrays and the number of batteries to meet a given reliability. Bagul [4] modified the two event approximation method, and has increased the accuracy of the system by using the three event approximation without any significant increase in the effort and time consumed computation.

Borowy and Salameh [5] demonstrated a methodology for calculation of the size of the photovoltaic array for wind and photovoltaic hybrid system for a given load. The method is based on the use of long term data for both wind speed and irradiance. It calculates the average power outputs of both the wind and photovoltaic module and matches to a given load using a least square method.

Ramakumar [6] developed a linear programming (LP) model for the design of integrated renewable energy system. Swift [7], Kellogg [8] and Chedid [9] also reported the methods based on linear programming. Musgrove [10] reported a computer model RAPSODY that facilitates the design, sizing and operation of a remote area power supply. This model can simulate the operation of systems that use various combinations of renewable energy source, the capital cost, and the operating and maintenance costs of system components.

Gavanidou [11] proposed a trade-off approach that can design a standalone power system under uncertain conditions. Ramakumar [12] used a database and a search algorithm to find the combination of photovoltaic and wind energy conversion system ratings and the size of energy storage that minimizes the capital cost while maintaining the required loss of power supply probability. Kabouris [13] took into account the stochastic nature of meteorological conditions and load to determine the optimal expansion plan of an autonomous generation system.

On the other hand, many researchers have developed probabilistic approaches to assess their performance as standalone or grid connected system. Giosetti [14] suggested a general procedure to combine a wind power output probability curve with wind farm availability data to obtain a wind farm reliability model. Wang [15] developed a method of probabilistic wind generator model, which is used to determine the annual energy output of the wind farm connected to a grid. Singh [16] have used a chronological simulation method for the reliability evaluation of electric power system with wind and solar energy sources. Bakirtzis [17] used a convolution method by assuming statistical independence of customer load and wind speed in other to modify the load duration curve using a wind array generation curve of a set of identical wind turbines.

Abouzahr [18] studied the performance of an autonomous wind energy conversion system composed of a wind turbine feeding load via battery storage. Since the method is very simple they could develop a closed form analytical solution allowing the calculation of the loss of power supply probability and storage. They applied the same technique to an autonomous PV system [19]. Bakirtzis [20] proposed a probabilistic approach for the calculation of energy of a standalone system consisting of a wind generator and batteries supplying a consumer load. Gavanidous [21] also presented a probabilistic method that can evaluate the reliability of an autonomous system consisting of a wind park and a diesel generating system.

Karaki et al.[22] have developed a general numerical probabilistic model, which is adapted to determine a solar park model and wind farm model considering the capacity levels due to hardware failure of the solar modules and wind turbines, the combinations of the two models to obtain a hybrid HSWPS is carried using convolution. Conti et al. [23] have developed a probabilistic model and have calculated the long term system performance in terms of the monthly average fraction of the load met by generation systems.

Yokoyama et al. [24] developed multi-objective method, and Yang [25] and Beyer [26] have obtained the set of different configurations which meet the load using the autonomy level of the system. Protogeropoulos [27] presented general methodology by considering design factor such as autonomy for sizing and optimization. Recently, Diaf at al.[28] suggest very accurate mathematical approach for characterizing PV module, wind generator and battery.

This paper suggests a method for designing the optimal combination and sizing of the hybrid generation system with storage batteries. The method uses a LPSP concept which was developed by Diaf [28]. By modifying the LPSP, we present a method to perform the optimal combination and sizing of a new and renewable hybrid generation system. The method is to find the combination and sizing, among sets of generation systems, that meets the desired system requirements, with the lowest value of energy cost. The availability of the methodology is demonstrated with the field data acquired from sets of experiments.

2 Mathematical Modeling of Hybrid System Components

There are many kinds of new and renewable energy resources. In this paper, we consider the most common new and renewable energy resources such as wind, PV, tidal energy resources. Any other new and renewable energy resources can also be considered to be the component that constitutes the hybrid system as far as it can be modeled mathematically.

2.1 Modeling of Wind Generator System

There are many types of wind generators that have different power output performance curves, so that the model used to describe the performance of wind generators is expected to be different. Shedid [29] and Eftichios [30] assumed that the power curve of a wind generator has a linear, quadratic or cubic form. Bueno [31] approximated the power curve with a piecewise linear function that consists of a few nodes. On the other hand, Bogdan [32] and Borowy [33] applied a similar model that takes into account the Weibull parameters.

In this study, we use the original mathematical model of output power for wind generation system. This may be somewhat different from the actual power curves. The model, however, can be applied any types of wind generation system. The mathematical model of wind turbine output can be defined as:

$$P_w = \frac{1}{2} C_p \cdot (\rho A v) \cdot v^2 = \frac{1}{2} C_p \rho A v^3 \quad (1)$$

Where C_p is the power coefficient, ρ is air density, A is the cross sectional area of the rotor, and v is wind speed.

If the power output curve of the wind generator is given by the manufacturer, a model can be developed according to the given power curve. In this case the wind generator power output is estimated through the interpolation of the values of the data provided by the manufacturer. Akai [34] approximated the power curves using a cubic or linear spline interpolation by assuming they are quite smooth. The approximated equation of the power output curve for a linear interpolation can be expressed as:

$$P_w(v) = \begin{cases} 0 & v \le v_i \text{ or } v \ge v_o \\ a_1 v + b_1 & v_i < v \le v_1 \\ a_2 v + b_2 & v_1 < v \le v_2 \\ \quad \dots\dots\dots\dots\dots\dots. & \\ a_n v + b_n & v_{n-1} < v \le v_r \\ P_r & v_r < v < v_o \end{cases} \quad (2)$$

Where $P_w(v)$ is the output power of the wind generator at wind speed v, P_r is the rated power, and v_i, v_r and v_o are the cut-in, rated and cut-out wind speed, respectively. n is the number of interpolation functions, a and b are the polynomial coefficients of the interpolation functions that depend on the type of the wind turbine generator.

If the height of the wind turbine is different from that of the wind speed measurement, the adjustment of the wind profile for height can be taken into account by using a height adjustment equation. The following power law is applied for the adjustment of the wind profile [35].

$$v = v_0 \left(\frac{H}{H_0}\right)^{\alpha} \quad (3)$$

Where v is the wind speed at hub height, v_0 is the wind speed measured at the height H_0 , and α is the power law exponent which varies with the climate and environmental conditions. The typical value of 1/7 corresponding to low roughness surfaces and well exposed sites is used in this study [36].

2.2 Modeling of PV System

The amount of solar radiation that reaches the PV module depends on the latitude and altitude and on the climatic condition such as cloud cover besides on the daily and yearly apparent motion of the sun. It has proved that cloudiness is the main factor affecting the difference between the values of solar radiation measured outside the atmosphere and on earthly surface by many studies.

As the operation and the performance of PV generator is interested to its maximum power, the models that describe the maximum power output behavior of PV modules are more practical for PV system assessment. A mathematical model for estimating the power output of PV modules is used in this paper.

If the solar radiation on the tilted surface, the ambient temperature and the manufacturers data for the PV modules are available, the power output of the PV generator, P_{PV}, can be calculated according to the following equations.

$$P_{PV} = \eta_g N A_m G_t \tag{4}$$

Where η_g is the instantaneous PV generator efficiency, N is number of modules, A_m is the area of a single module used in a system, and G_t is the global irradiance incident on the titled plane.

We assumed that all the losses in a PV generator including wiring losses, connection losses and other losses is zero. The instantaneous PV generator efficiency, η_g, is represented by the following equation.

$$\eta_g = \eta_r \eta_{pt}\left[1 - \beta_t(T_c - T_r)\right] \tag{5}$$

Where, η_r is the PV generator reference efficiency, η_{pt} is the efficiency of power tracking equipment which is equal to 1 if a perfect maximum power point tracker is used, T_c is the temperature of PV cell (℃), T_r is the PV cell reference temperature and β_t is the temperature coefficient of efficiency, ranging from 0.004 to 0.006 per ℃ for silicon cells. However, to simplify the model, we use the general PV generator efficiency that is used many practical approach.

Based on the energy balance, Duffie [37] suggested that the PV cell temperature can be expressed as follows:

$$T_c = T_a + G_t\left(\frac{\tau\alpha}{U_L}\right) \tag{6}$$

Where T_a is the ambient temperature τ and α represent, respectively, the transmittance and absorptance coefficients of PV cells, and U_L is the overall heat loss coefficient.

The overall heat loss coefficient, $\tau\alpha/U_L$, can be expressed as the normal operating cell temperature (NOCT) as follows [37]:

$$\left(\frac{\tau\alpha}{U_L}\right) = \frac{NOTC-20}{800} \tag{7}$$

2.3 Modeling of Tide Generator System

There are many types of tidal generation system. Among them the most popular one is a horizontal axis blade type of tidal generation system which is basically no different from the horizontal axis wind turbine system. In this study, the horizontal axis blade type of tidal generation system is assumed. It, therefore, has the same mathematical model as that of wind generation system stated in Eq.(1). That is,

$$P_t(v_{cur}) = \frac{1}{2} C_p \rho_{sea} A {v^3}_{cur} \tag{8}$$

Where ρ_{sea} is sea water density, A is diameter of rotor, ν_{cur} is the speed of current. Since ρ_{sea} is about $1052.2 kg/m^3$ the tidal energy is much greater than wind energy when the current speed is equal to wind speed. If the power output curves are given by the manufacturer, the curve can be also approximated as the cubic or linear interpolation using Eq. (3)

2.4 Modeling of Battery System

Since the state of battery is related to the previous state of charge and to the energy production and consumption situation of the system during the time from $t-1$ to t, it should be modeled differently according to the generation and load conditions. When the total power from the hybrid generation system is greater than the load required, the battery is in charging state and modeled as follows [38]:

$$C(t) = C(t-1)(1-\sigma) + \left(E_G(t) - \frac{E_L}{\eta_{inv}}\right)\eta_{bat} \tag{9}$$

Where, $C(t)$ is battery bank capacity, $E_G(t)$ is total power of the hybrid system, $E_G(t)$ is the power needed by the load at time t, σ is self discharge rate of the battery, η_{bat} is the battery efficiency, and η_{inv} is the inverter efficiency. During discharging process, the battery discharging efficiency was set equal to 1, and during charging, the efficiency is 0.65 to 0.85 depending on the charging current.

On the other hand, when total power is less than the load demand, the battery is in discharging state and modeled as follow:

$$C(t) = C(t-1)(1-\sigma) - \left(\frac{E_L(t)}{\eta_{inv}} - E_G(t)\right) \tag{10}$$

At any time, the storage capacity of the battery should follow the condition:

$$C_{min} \leq C(t) \leq C_{max} \tag{11}$$

Where C_{min} and C_{max} are, respectively, the minimum and maximum allowable storage capacity.

3 Optimal Design Model

3.1 The R_{LP} Model

To determine the optimal combination of the new and renewable energy sources and to achieve the optimal configurations of the hybrid system in term of technical analysis, the R_{LP} model is developed, which is modified from the method of LPSP, and can be summarized in the following steps.

The total power, P_{tot}, generated by the wind turbine, PV generator and tide generator at time t is calculated as follow:

$$P_{tot} = \sum_{i=1}^{n} P_i(t) \tag{12}$$

Where P_i is the output power of the i-th individual generation system that constitutes the hybrid system.

The inverter input power, $P_{inv}(t)$, is, then, calculated using the corresponding load power requirements.

$$P_{inv}(t) = \frac{P_{load}(t)}{\eta_{inv}} \tag{13}$$

Where $P_{load}(t)$ is the power required by the load at time t, and η_{inv} is the inverter efficiency.

The different two situations may appear during the operation of the hybrid generating system. First, the total power generated by the hybrid generators is greater than the power needed by the load P_{inv} . In this case, the energy surplus is stored in the batteries and the new battery capacity is calculated using Eq.(9) until the full capacity is obtained. The remainder of the available power is not used.

Second, the total power generated by the hybrid generators is less than the power needed by the load, P_{inv}, the batteries supply the energy deficit, and a new battery capacity is calculated using Eq.(10). In case when the total power generated by the hybrid generators is equal to the power needed by the load P_{inv}, the batteries remains unchanged.

The battery storage control system stops the charging process if the battery capacity reaches a maximum value. On the other hand, if the battery capacity reaches the minimum level, then the battery storage control system disconnect the load.

If the power generated by the hybrid system is less than the load demand, the batteries should supply the energy deficit. However, if the battery capacity reaches to the minimum capacity stat, C_{min}, in which the batteries cannot discharge anymore, the hybrid system can no more supply energy deficit. In this case the power deficit must be supplied from the external energy system. The power deficit in this case is called as ' Lack of power', P_{LP}, and can be defined as:

$$P_{LP}(t) = P_{load}(t)\Delta t - (P_G(t)\Delta t + C(t-1) - C_{min})\eta_{inv} \tag{14}$$

Where, $P_G(t)$and$P_{load}(t)$ are total power and load power requirement. $P_{load}(t)\Delta t$ represents total load demand power, and the last term represents the power consumed by the load. In Eq. (14), it is assumed that power generated by the hybrid system during Δt is unchanged. The amount of power discharged until the battery capacity reaches C_{min}, C_{out} is written as:

$$C_{out} = P_{load}(t)\Delta t - P_G(t)\Delta t\eta_{inv} \tag{15}$$

The ratio of lack of power, R_{LP}, for a period T, can be defined as the ratio of total lack of power over the total load required during that period.

$$R_{LP} = \frac{\sum_{t=1}^{T} P_{LP}(t)}{\sum_{t=1}^{T} P_{load}(t)} \tag{16}$$

Using Eq. (16), the optimal sizing of the hybrid system components is performed.

3.2 Economical Model

For hybrid generation systems the most important concern is to achieve the lowest energy cost, and the economical approach can be the best benchmark of cost analysis. Several methods are used to get different options for energy system; the levelised cost of energy is often the preferred indicator [39]. However, the method is not easy to apply in a practical application because it is very complicated.

In this study, a simple economical model is developed. Let M_i be the output power of i-th individual generation system that constitutes the hybrid system per *Wh*, and n be the total number of the generation systems in the hybrid system. Also let E_i be the generation capacity of i-th individual generation system. The total cost per *Wh*, M_{tot}, can be expressed as follows.

$$M_{tot} = \sum_{i=1}^{n} M_i E_i + M_{bat} C \tag{17}$$

Where, M_{bat} is the cost of battery per *Wh*, and C is battery capacity.

4. Experimental Verifications

4.1 Design of Optimal Combinations

Figure 1 shows the algorithm of the design of optimal combination and sizing of the hybrid system. It assumes a combination of the size of each component of the hybrid system. Using the given data, it calculates the total power generated by the hybrid system. The power is then compared with the power required by the load. During the process P_{LP} is calculated and summed for the total period T. Finally, R_{LP} is calculated. If the resulting R_{LP} satisfies the required R_{LP}, the assumed combination of the size is a candidate for an optimal combination. Among the many candidates, it finds optimal combination of sizes by applying the economical model.

The major new and renewable energy sources, such as wind, PV and tide energy, are selected for the simulation. Figure 2 through Figure 4 shows wind data, solar irradiance data, and tidal current data respectively. The data were acquired for 3 days at Jeju island. The design condition is shown in table 1. The load is assumed as 20W and operates for 24 hours a day. The size of wind turbine is set to 3W because it is the smallest one among the commercialized wind system. Table 2 shows the parameters necessary for the optimal design.

The required R_{LP} is set to 0, which meet the stand-alone system that need no external supply of energy. For the given design conditions the algorithm finds optimal combinations and sizes of the hybrid system that meet the lowest cost for the generation of the power required by the load. Table 3 shows the results of total generation costs for various combinations of the hybrid system. The cost of the wind-PV combination is higher than those of the other combinations. On the other hand, the optimal combination that satisfies the lowest cost is the wind-PV-tide hybrid system.

Figure 5 and Figure 6 show the design results of tide generation system and battery sizes when the wind and PV generation systems are fixed. In the figures, all the dots represent the combinations of sizes that satisfy the required R_{LP}. Among the combinations the optimal one that can satisfy the economical model is shown in Table 4. This result is valid only for the energy resources shown in Figures 2 through 4. Different combinations may be optimal for different new and renewable energy resources.

The algorithm yields only one combination for the optimum solution; where the cost of *Wh* energy is a minimum. This result can be different when the cost of *Wh* for each component is changed. However, the algorithm can still find the optimal solution with consistency.

```
Input wind speed, solar radiation, current data
For j=1 to N          ▶ N is the assumed number of sets for valid combinations.
    Assume combination (E_W, E_PV, E_t)
    v_n ← 0           ▶ v_n : the total number of valid combinations.
    For i=1 to total period (total number of data set)
        P_tot ← Eq.(12)
        if  P_tot == P_load  then
            P_LP ← 0
        end
        if  P_tot > P_load  then
            C(t) ← Eq. (9)
            P_LP ← 0
        end
        if  P_tot < P_load  then
            C(t) ← Eq. (10)
            P_LP  ← Eq. (14)
        end
    end
    R_LP ← Eq. (16)
    if  R_LP =< required R_LP
        store the combination
        v_n ← v_n+1
    end
end
```

Figure 1. Optimal Design Algorithm

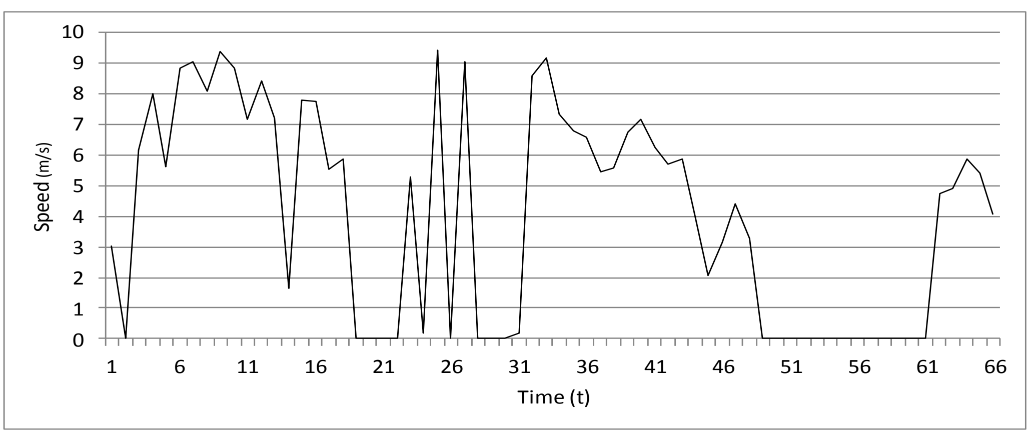

Figure 2. Wind Speed

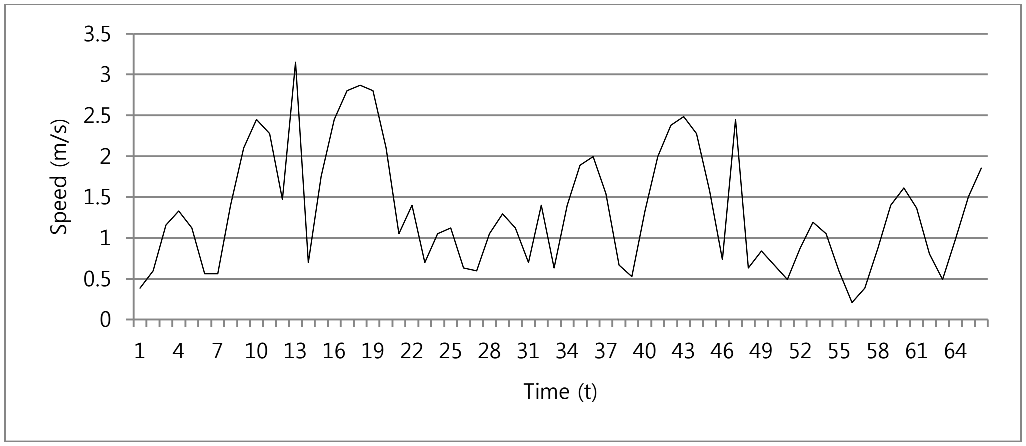

Figure 3. Current Speed

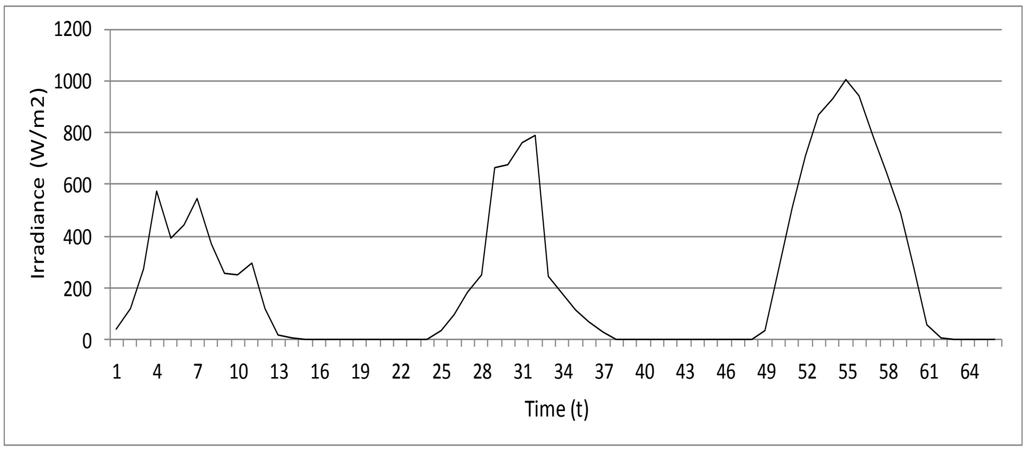

Figure 4. Irradiance Data

Table 1. Design Conditions

Type	Unit Size	Total Size	Cost (Won/kWh)
wind	3W	3W	110
PV	30W	to be designed	680
tide	5W	//	450
battery	5Wh	//	400
load	-	20Wh	-

Table 2. Design Parameters

Parameters	Values
Inverter Efficiency, η_{inv}	1
PV Generator Efficient, η_g	0.8
Battery self discharge rate, σ	0.00058 %/h
Minimum Allowable Storage Capacity, C_{min}	0.2
Cut in wind speed	1.5 m/s
Cut in current speed	0.5 m/s
Wind Power Coefficient, C_p	0.2
Tidal Power Coefficient, C_{p_cur}	0.1
R_{LP}	0

Table 3. Results of Optimal Combinations

Hybrid Type	Cost (Won/kWh)	Remark
Wind-PV	127.72	-
Wind-Tide	111.77	-
PV-Tide	118.83	-
Wind-PV-Tide	106.73	Optimum

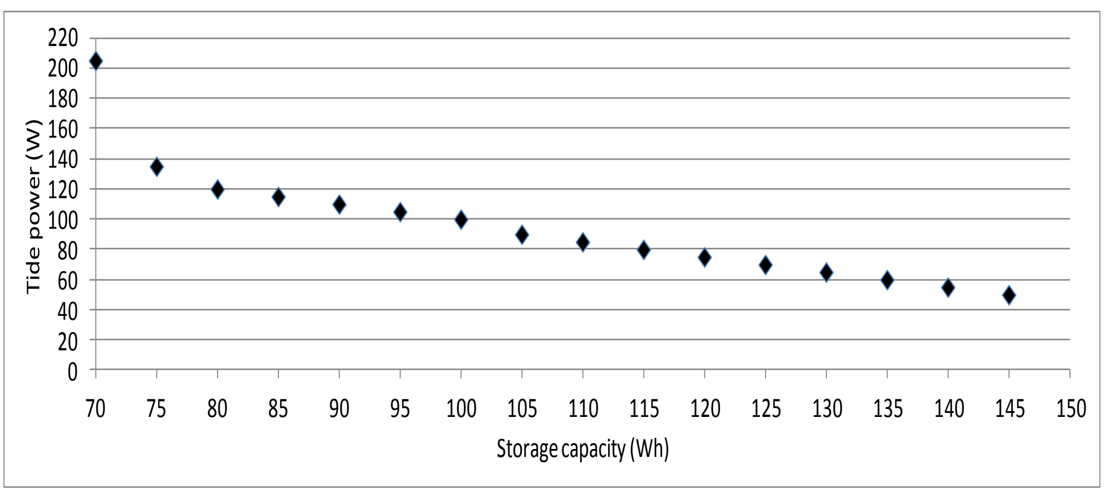

Figure 5. Design Results (PV power is 30W)

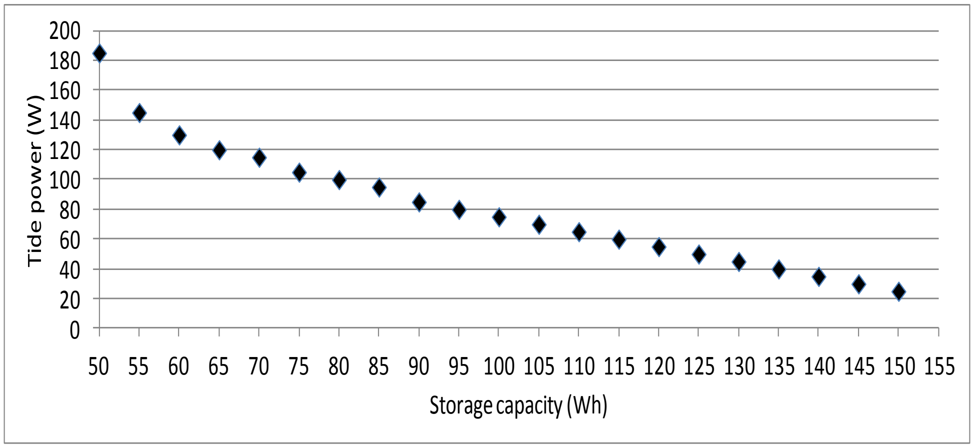

Figure 6. Design Results (PV 60W)

Table 3. Results of Optimal Sizing

Type	Size	remark
Wind Generator	3W	1 set
PV Generator	30W	1 panel
Tide Generator	120W	blade radius : 0.107m
battery	80Wh	12V-6.7Ah

4.2 Experimental Results

The results of optimal combination and sizing are applied to actual hybrid generation system. Figure 7 shows the wind-PV-tidal hybrid generation system. The experiments were carried out for 66 hours on the sea near the Jeju island.

Figure 8, Figure 9 and Figure 10 represent the power generated by the wind turbine, the PV system and tidal system respectively. The total measured power of the hybrid generation system is shown in Figure 11. One can realize that the shape of the graph of Figure 11 is much similar to that of Figure 10. This is because the output power from the tidal system is much greater than those from the other systems.

Figure 12 shows the difference between the total generating power of the hybrid system and the load demanded. In the figure, the sections below the 0W represent the total power of the hybrid system is less than the power needed by the load, so that the energy deficit was covered by the storage. On the other hand, the sections above the 0W represent the total power of the hybrid system is greater than the power needed by the load, so that the energy surplus is stored in the batteries. No 'lack of power' was observed during the experiment.

Figure 13 shows the battery charging state. The total power of the hybrid system for 66 hours was about 4,331 Wh, and the total load requirements for the same duration was about 1,320 Wh. Therefore the availability of the generating power is 30.5%. In other words, 69.5% of the generating power was not used for driving the load. If we let R_{LP} as another design variable for the optimal combination and sizing algorithm the availability of the generating power can be increased. However the results cannot be applied to a stand-alone hybrid generation system where R_{LP} must be zero.

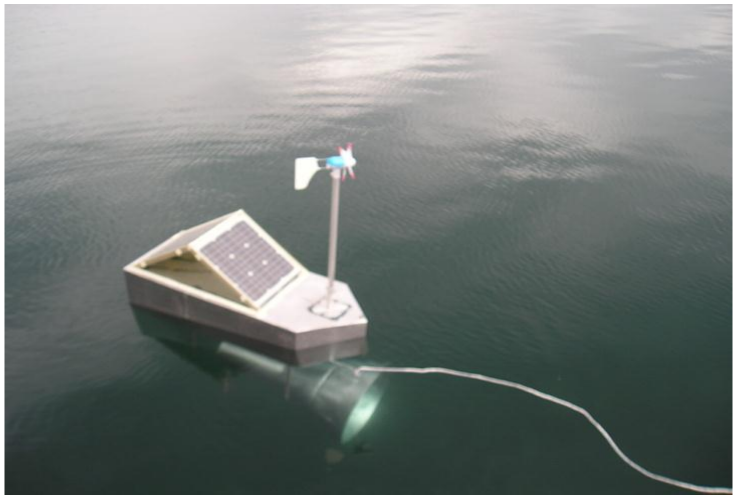

Figure 7. View of the wind-PV-tide Hybrid Generation System

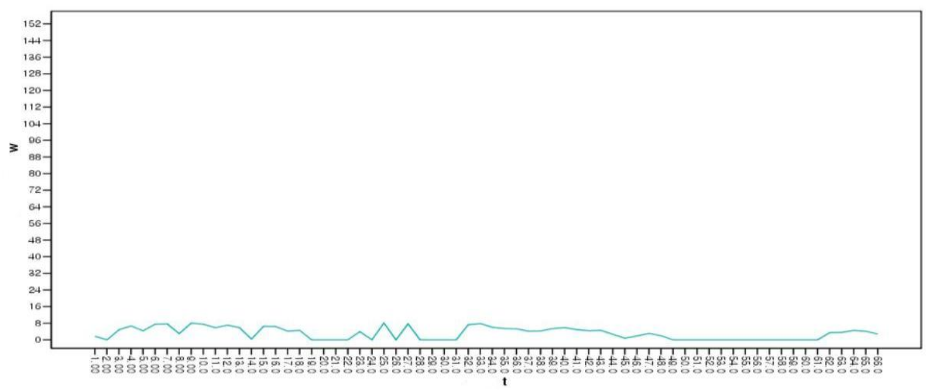

Figure 8. Hourly Measured Output Power of Wind Generator

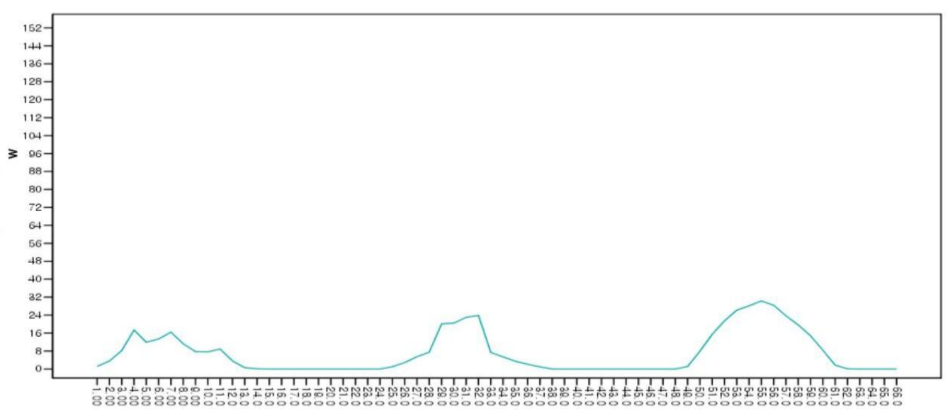

Figure 9. Hourly Measured Output Power of PV Generator

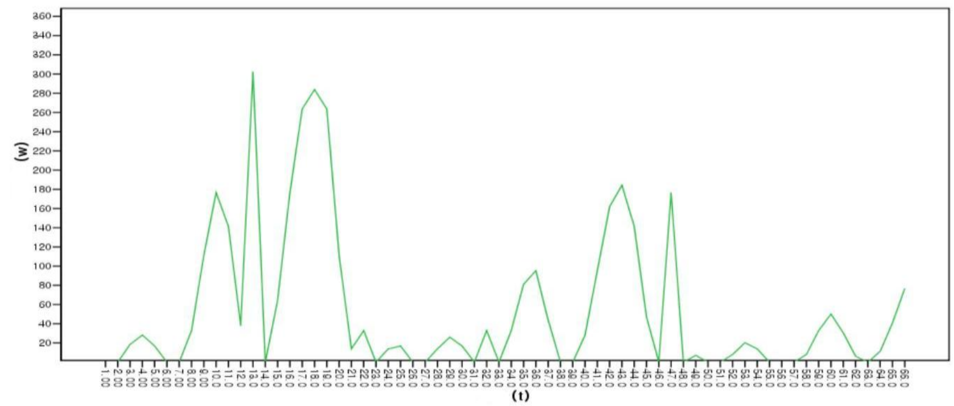

Figure 10. Hourly Measured Output Power of Tidal Generator

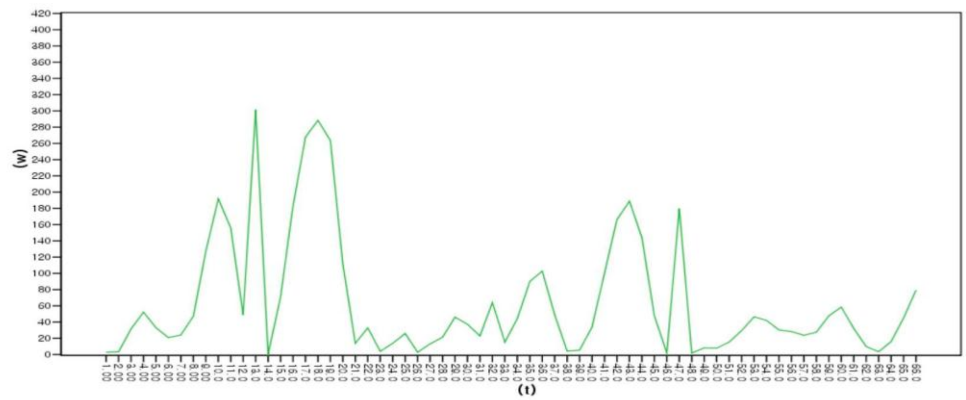

Figure 11. Hourly Total Measured Output Power

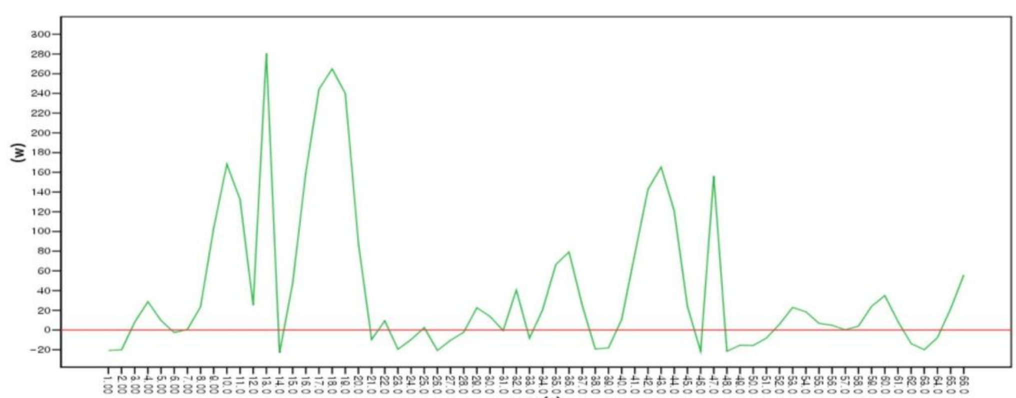

Figure 12. Hourly Difference between the Total Generating Power and the Load Demanded

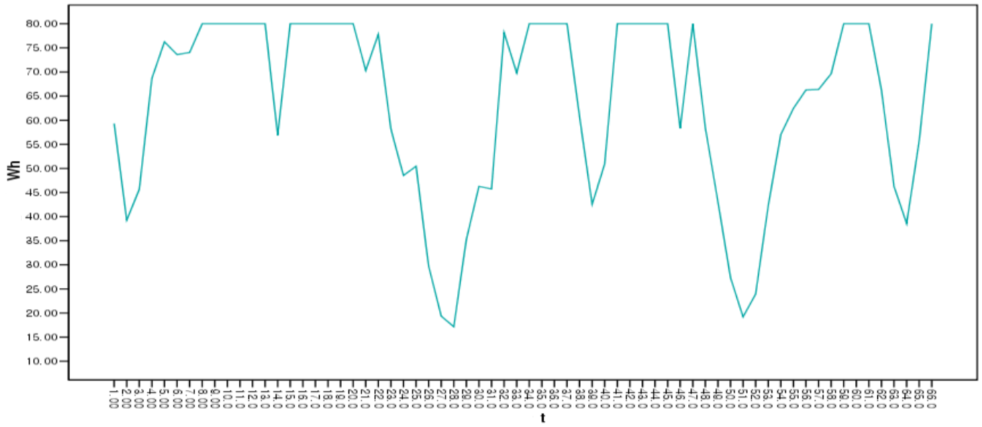

Figure 13. Hourly Battery Charging State

5 Conclusions

The major aspects in the design of a hybrid new and renewable generation system are the reliable power supply of the consumer under varying atmospheric conditions and the corresponding total system cost. In this paper, methodology for optimal combination and sizing of hybrid, stand alone renewable generation system has been studied. Using practical simple models for typical new and renewable energy systems, the method of designing the optimal combination of the hybrid system was developed. The system configurations can be obtained in terms of a system power supply reliability requirement by using R_{LP} (Ratio of Lack of Power) concept.

A simple mathematical modeling for each component of hybrid wind-PV-tide generation system was developed. Using the models, the method of optimal combination and sizing of the hybrid system components was developed. Also, a very simple model was considered as the economical configurations. The method aims at finding the configuration, among a set of system components, which meets the desired system requirements, with the lowest value of the energy cost. The method was applied to hybrid wind-PV-tide generation system. The availability of the methodology was successfully demonstrated with the field data acquired from sets of experiments. The experimental results showed that the proposed method can find the optimal combinations and sizes with consistency.

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