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Optimal Design of Battery Bank for Standalone PV/Wind Hybrid System

Santosh Adhikari [a], Tek Nath Tiwari [b]

[a] *Department of Electrical Engineering, Western Region Campus, IOE, TU, Nepal*
[b] *Provincial office ,Nepal Electricity Authority,Pokhara*
Corresponding Email: [a] sadhikari7793@gmail.com [b] tntiwari@gmail.com

Abstract

In this paper optimal sizing of Battery bank for grid connected hybrid PV/wind system is developed.This paper proposes an optimal design for hybrid grid-connected Photovoltaic wind(PV/wind)Battery Energy Storage Systems (BESS). A smart grid consisting of PV generation units, wind turbine, stationary Energy Storage Systems (ESS), and domestic loads develops a multi objective optimization algorithm. The optimal solution for the optimization of the PV-battery system sizing with regard to economic viability and the stability of operation is found while using the Genetic Algorithm (GA) in matlab. The reliability of the MG system is modeled based on the loss of power supply probability (LPSP). For optimization, Genetic Algorithm (GA) is used to minimize the total cost of the system over a 20-year period, while satisfying some reliability and operation constraints. The optimization criteria is validated in a PV-Wind-Diesel connected microgrid system to eliminate power curtailment losses and utilize the potential of the power evacuation. The methodology is tested on two different types of battery systems, from conventional Lead-acid battery and Lithium-ion (Li-ion) batteries considering Nepalese power market scenario taking hourly load profile of a annapurna housing and historical meteorological data. Various economic parameters are explored to effectively quantify the benefits gained from the integration of battery energy storage systems.Although the batteries require high initial investments, the study proves that the benefits gained over time and increased reliability will be more. Profits gained by cutting down on spilling and shedding losses, are used as payback for recovering the investment

Keywords

Battery Energy Storage System, Capital Recovery Factor, Distributed Generator, Depth of Discharge, State of Charge, Payback Period, Genetic Algorithm, Loss of power supply probability, Voltage Drop

1. Introduction

The rapid depletion of fossil-fuel resources on a worldwide basis has necessitated an urgent search for alternative energy sources. Of the many alternatives, photovoltaic and wind energy have been considered as promising toward meeting the continually increasing demand for energy. The wind and photovoltaic sources of energy are inexhaustible, the conversion processes are pollution-free, and their availability is free. For remote systems such as radio telecommunications, satellite earth stations, or at sites that are far away from a conventional power system, the hybrid systems have been considered as attractive and preferred alternative sources. Based on the fact that solar power is clean, environment friendly, photovoltaic (PV) system has become a sustainable option for isolated electrical power generation for locations receiving abundant sunshine, played an important role worldwide [1]. The rapid growth in PV capacity in electricity distribution networks has an increasingly significant impact on the operation of the grid, and challenges traditional business models of electricity generators, retailers and network operators. The high penetration of grid-connected PVs may reverse power flow in the network and introduce new technical challenges to the system, such as voltage raise and imbalance [2]. One of the solutions to solve these problems is to use battery in addition to PV in each residential house to realize time-shifting demand.

2. METHODOLOGY

An attempt has been made to model Photovoltaic Solar and Wind Power as Distributed Generation power sources interconnected to the grid. Then a formulation of the desired optimization problem with constraints for various energy storage systems has been developed. The proposed battery storage explores a number of various energy storage devices integrated to the Wind-PV hybrid renewable energy system. The optimization problem considered various operational constraints of the battery systems, such as power delivered by battery in an instant, State of Charge (SOC) of battery limitations, energy discharge limitations, etc. The solution of this problem would be to optimized maximum energy delivered of the selected storage systems with minimum annuitized cost. The sizing methodology is then validated with a 275 kW grid-connected Wind-PV hybrid renewable system and tested with two different types of batteries, and comparisons are made based on techno economic metrics. The grid is considered as a LV distribution system and simulation/modeling works has been carried out in MATLAB software and all evaluations are done based on the Nepalese power market scenario to attain peak shaving and power delivery improvement. The choice of the optimum number of PV modules and batteries was based on the minimum cost of the system [3].

2.1 Wind Turbine Modeling

The power generated in a wind turbine is evaluated using (1) . The turbine starts generating power at wind speeds greater than cut-in speed $V_{ci}(\lambda,\beta)$ is the power coefficient of the wind turbine which is a function of pitch angle β and tip-speed ratio λ. we have

$$P_w = \frac{1}{2}\rho A C_p(\lambda,\beta)V^3 \tag{1}$$

$$P_w(v) = \{0 if V \leq V_{ci} or V \geq V_{co}\} \tag{2}$$

$$P_w(V) = P_r\{\frac{V^3 - V_{ci}^3}{V_r^3 - V_{ci}^3} if V_{ci} \leq V \leq V_r\} \tag{3}$$

$$P_w(v) = P_{rated} if V_r \leq V \leq V_r \tag{4}$$

2.2 PV system modeling

A silicon PV module output depends on many variables including the type of material, temperature, and solar radiance incident on the surface of the module. Its output can be expressed as:

$$P_{PV} = Y_{PV} f_{PV}\left[\frac{G}{G_s tc}\right][1 + \alpha(T_c - T_{stc})]$$

where,G_{STC} and T_{STC} are taken to be $1000 w/m^2$ and 25degree c, respectively. Temperature coefficient(α) and Derating factor (f_{pv}) are considered as 0.4% and 97%, respectively.

2.3 Battery system modeling

An intelligent battery charging/discharging management system must be established to control the power flow in or out from the battery while trying to meet the load demand [4]. -when the charge state of battery is below SOC_{max} and P_{dem} is less than P_{gen},the excess of energy $[(p_{gen} - P_{dem})\Delta T]$ is stored in batteries,during the corresponding period ΔT.

-When it is above SOC_{min} and $P_{dem}$is greater than P_{gen}, energy previously stored is used to support lack of energy,$[(P_{dem} - P_{gen})\Delta T]$ %is discharged from batteries.

-When the state of charge is equal to SOC_{max} and $P_{dem}$is less than P_{gen}, the excess energy $[(P_{gen} - P_{dem}]\Delta T$ is lost, during the corresponding period ΔT.

-When the state of charge is less than or equal to SOC_{min} and $P_{dem}$is greater than P_{gen}, an unmet load occurs. In this case, P_{dem} must be equal to P_{gen} by load shedding.

The State-of-Charge (SOC) is the percentage of the maximum possible charge that is present inside a rechargeable battery. SOC is normally used when discussing the current state of a battery in use.The battery is charged when demand is excess than generation and SOC is below the maximum level(i.e 100%) and discharged when demand is excess than generation and SOC is above the minimum level(i.e above 0%). The characteristics of batteries are shown in table 1 and these characteristics value are used as reference data for our calculation.

2.4 Problem Formulation

The system is modeled using the following objective function:

Table 1: Characteristics of lead Acid and Li-ion battery

S.N	Type	Rating	Voltage	Life (years)	charging eff(%)	Discharging eff(%)	DOD	Cost in (USD)
1	lead -acid	225 Ah	6	6	95	80	70	160/module
2	Li-ion	200 Ah	12	10	99	95	80	2000/module

2.5 Objective Function

The objective of this optimization problem is to minimize the capital and operating costs of the hybrid MG over a total life period , while satisfying some reliability, operational and stability constraints [1]. This optimization problem is expressed as below:

$$min f(N_{PV}, N_{WT}, ESS) = C_{PV} * N_{PV} + C_{WT} * N_{WT} + C_{ESS} * E$$

$$C_{PV} = (C^{PV}_{Cap} + 20 * C^{PV}_{Cap}) * P_{PV}$$

$$C_{WT} = (C^{WT}_{cap} + 20 * C^{WT}_{cap}) * P_{WT}$$

$$C_{ESS} = C^{ESS}_{cap} + Y_{ESS} * C^{ESS}_{cap} + (20 - Y_{ESS} - 1) * C^{ESS}_{cap}$$

where N_{PV} is the number of PV panels; N_{WT} is the number of wind turbines; E_{ESS} is the storage capacity of the ESS in (Wh); C_{PV} and C_{WT} are the total costs in ($) of a PV and a WT, respectively.C_{ESS} is the per unit cost of the ESS in $(\$/kwh)$ of the $ESS.C^{PV}_{cap}$,C^{WT}_{cap} and C^{ESS}_{cap} are the capital cost of the PV,WT in $(\$/W)$ and ESS in $(\$/Wh)$ respectively.Y_{ESS} is the expected number of ESS replacement over the 20 years.The capital cost of each component includes the purchase and installation cost of that component. The operation cost of each component includes the maintenance and operation cost of that component.

Constraints:
The following are constraints should be satisfied:
Reliability: LPSP $\leq LPSP_{set}$
ESS stored energy and power limits:$ESS_{min} \leq E(t) \leq E_{ESSmax}$
$E_{ESSmax} = (1 - DOD) * E_{ESSmax}$ in addition to the stored energy constraints,the charge and discharge powers of the ESS must be kept within a certain limit at any point of time.
Power balance:$P_{PV}(t) + P_{WT}(t) + P_{ESS}(t) = P_{load}(t)$

2.6 Load Curve

Renewable power systems cannot be considered as a dispatchable generation due to their intermittent nature. On the contrary, load dispatch centers demand a 15 minute time block at the least for scheduling and dispatch of power to the grid. However, energy storages can be employed in making this intermittent power dispatchable .In this study, power dispatch is scheduled for every 30 minutes (computation for two time blocks) and any mismatch of generated power in this time interval is to be nullified by the battery storage.

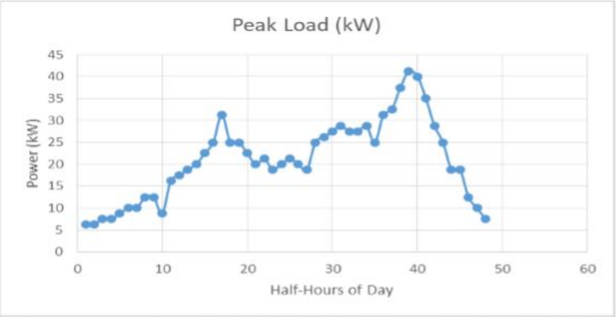

Figure 1: load profile for annapurna housing pokhara

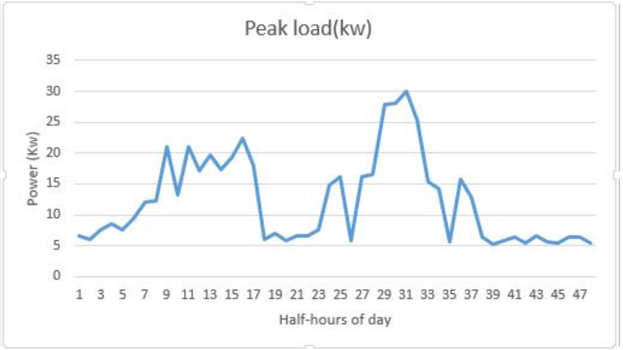

Figure 2: load profile for Pokhara homes pokhara

2.7 Annual solar radiation

the average annual solar radiation data around pokhara airport for twelve month was taken in our calculation.

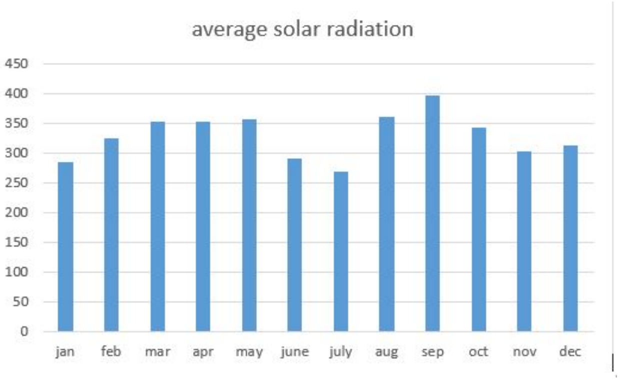

Figure 3: solar radiation data for pokhara airport

2.8 Optimal sizing of energy storage

This study compares two types of batteries which include the conventional (lead acid), Lithium-ion Rechargeable lead-acid batteries have been in the market for more than a decade now. Low self-discharge, easy availability, and low cost make them highly suitable for renewable integration applications.Let E_{batt} be the average energy requirement for the battery per day in kWh. It is evaluated from the maximum power surplus/deficit $(P_{diff}(t))$ calculated as below where $P_{dem}(t)$ is the power that is to be dispatched over a time period Δ t. Let N depict the number of days in the simulation period.
$P_{diff}(t) = P_{gen}(t) - P_{dem}(t)$
$E_batt(kWh) = max\{\Sigma P_{diff} * \Delta t\}$ A simple model of battery is implemented to evaluate the nominal size of the battery system Ebattery(kWh).The model needs to take into account the depth of discharge (DOD)and battery aging. The operating temperatures and aging also affect the operation of the BESS. Hence, the temperature correction factor for an average operating temperature of 25 degree centigrade is found to be 0.965. A common correction factor is evaluated in equation (5) and included in equation (6) for battery sizing as follows:
$correctionfactorforeffectoftemperatureandaging = (0.965 * 1.15)$
$= 1.108$
$= 110\%$

Required battery capacity in kWh:

$$E_{battmax}(kWh) = \frac{110E_{batt}(kwh/day) * D}{\eta_batt * DOD}$$

Required Battery capacity in Ah:

$$E_{cap}(Ah) = \frac{E_{batt}(max)(kWh) * 1000}{V}$$

where,E_{cap} is the required capacity of battery in Ampere hours (Ah). The ratio of E_{cap} to the Ah rating of the individual battery module/cell yields the number of batteries to be connected in parallel (N_p). Battery size obtained is minimized further by implementing an optimization algorithm by considering E_{cap} as a maximum boundary limit for the population selection.

3. RESULT AND DISCUSSION

The calculations are done based on the specifications of the wind turbine [5]. The results are obtained based on the recorded solar radiation and wind data obtained from metrological department kathmandu Babarmahal.Solar radiation,temperature and wind velocity data are taken for a typical 24 hours for each minute interval.The PV output and wind turbine output are calculated using these data and battery placement is designed according to the energy excess and deficit amount.The load data is taken from two load station Pokhara homes and annapurna housing,pokhara. The power from solar PV is generated only at day-time while wind power is generated mostly at morning and evening, although the peak demand occurs mainly at morning and night time creating a great mismatch in power delivery. This mismatch in power is either spilled or shed according to generation demand unbalance. The solar PV seem to generate power effectively from 8 am in the morning to 6 pm in the evening, with a peak power output of 104.10 kW at 12:21 pm when the global horizontal solar irradiance is $1456W/m^2$ for just a minute, while 80% (298.24 kWh) of solar power is generated between 10:00 am to 16:00 pm. Similarly, wind turbine generates a peak power of 153.13 kW at 15:58 pm when the wind velocity is 10.71 m/s, which is the closest reading to the rated wind velocity of 11.5 m/s for our selected wind turbine. Most of the times the wind turbine generates very small quantity of power due to lack of significant wind flow, and substantial quantity of power generation occurs only sporadically.

3.1 Power loss in IEEE 33 Bus system

Figure 4 shows the graph of active power loss in ieee 33 bus system where type 1 DG is of active source type and Type 2 DG is of Reactive source type.On comparing these two sources it was seen that active source DG minimizing the power loss more in comparision to reactive source DG.

3.2 Before Battery Placement

The graph of the power generated from wind-PV system without BESS shows that the delivered power is unable to meet the scheduled dispatch curve. Revenue losses occurring in the system include losses due to load spilling, and load shedding.Before battery placement graph shows that at day time excess of

Table 2: sizing of batteries for supplying the demand with DG resourse before optimization

S.N	Type	Rating in Ah/module	Capacity in Ah	No.of modules	investment in USD	Investment in rupees
1	Lead-Acid	225	49487.94	440	70,383	7,953,279
2	Li-ion	200	34991.4	175	349,915	38,490,619

Table 3: sizing of batteries for supplying the demand with DG resourse after optimization

S.N	Type	Rating in Ah/module	Capacity in Ah	No of modules	Investment in USD	Investment in rupees
1	Lead-Acid	225	21418.33	190	30,642	3,462,546
2	Li-ion	200	18945.67	95	189,457	21,408,641

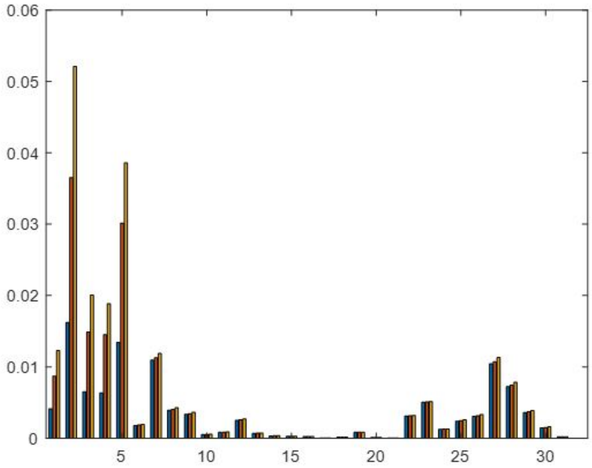

Figure 4: Active power loss with type 1 and type 2 DG placement in ieee test system

energy is loss where as during peak time load need to be shed due to low generation and large demand.These losses add up to a sum of Rs 2,518,066 annually, if supplied by diesel generator at a high cost, with a LPSP ratio of 40.08%, delivering only 98,205 kWh of electricity per year against a total demand of 166,350 kwh.

3.3 After battery placement

Battery energy storage has been utilized to meet all the deficit in power delivery, which is calculated to be 68,145 kwh annually (186.7 kWh/day). The simulation has been run to determine the power surplus or deficit in each minute for a total of 9000 minutes (6.25 days) so that the battery charging/ discharging cycle is considered for more than a single day.

3.4 Optimizing of battery

After optimization of the battery size, using genetic algorithm in MATLAB software, the results are obtained as shown on following figures. The process of GA optimization is run on MATLAB platform, with a population size of 200, and two optimization variables namely size of battery (in kWh) and size of inverter (in KW).During optimization process number of population is considered as 200.The battery and inverter size before optimization is found as 347 kWh and 179 kw respectively where as,after optimization the size of battery and inverter is found as 232 kWh and 59 kw respectively.which save Rs 1,219,900 annually through battery sizing optimization only.The economic parameter are calculated and listed in table below.Table 2 shows the size of battery by using the formula in equation(1)and (2) where as table 3 shows the optimized size of battery by using GA optimizing tools in Matlab software.

Table 2 shows the sizing of battery before optimization where as Table 3 shows the sizing of battery after optimization.from table it was seen that in both type of batteries(i.e lead Acid and Li-ion) battery capacity in Ah and number of module is decreased after optimization and save annual amount.

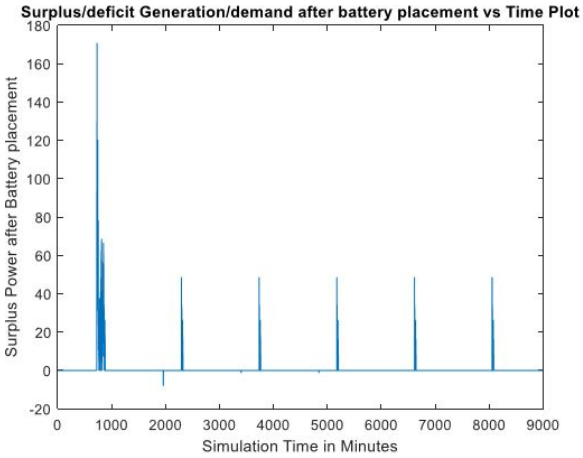

Figure 5: surplus and deficit of energy after battery placement

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