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Battery Energy Storage System Optimization for Grid-Connected Wind-PV Hybrid System

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Abstract

This research work comprises feasibility study to incorporate battery energy storage technologies with hybrid PV-Wind-Diesel connected power system to effectively dispatch the generated power by incorporating peak shaving and valley filling. Then the calculated size of batteries are further optimized using Genetic Algorithm in MATLAB software platform to effectively minimize the cost of investment and losses incurred by the system. 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 five different types of battery systems, from conventional Lead-acid battery, Lithium-ion (Li-ion) and Nickel Cadmium (Ni-Cd) batteries to upcoming flow batteries (Vanadium Redox Flow) and Sodium Sulphur (Na-S) battery, considering Nepalese power market scenario taking hourly load profile of a rural test feeder and historical meteorological data. Various economic parameters are explored to effectively quantify the benefits gained from the integration of battery energy storage systems. Findings indicate that the integration of storage systems reduces the Loss of Power Supply Probability (LPSP) from 41.87% to 2.51%, resulting in reliable power delivery and optimum utilization of the renewable energy sources connected in the microgrid. Furthermore, conducting case studies with various generation mix of solar PV and wind turbine for different sizing of the battery storage shows that the most economical choice of battery size lies between 275 kWh and 550 kWh for a total installed capacity of 275 kW.

Keywords

Battery Energy Storage, Distributed Generation, Hybrid Renewable Energy System (HRES), MATLAB, Nepal, techno-economic analysis

1. Introduction

Distributed Generation (DG) refers to any electric power production technology that is integrated within distribution systems, close to the point of use. The Institute of Electrical and Electronics Engineers (IEEE) defines DG as “the generation of electricity by facilities that are sufficiently smaller than central generating plants so as to allow interconnection at nearly any point in a power system” [1]. Distributed generators are connected to the medium or low voltage grid. They are not centrally planned and they are typically ranging from less than a kW to tens of MW. The technologies for Distributed Generators are based on reciprocating engines, photovoltaics, fuel cells, combustion gas turbines, micro turbines and wind turbines. It is an emerging concept in the electricity sector, which represents good alternatives for electricity supply instead of the traditional centralized power generation concept, often providing lower-cost electricity and higher power reliability and security with fewer environmental consequences than traditional power generators. Energy storage systems can be employed in conjunction with the DG resources to effectively utilize the available renewable resources, which are intermittent in nature, thereby increasing the power delivered to the load. The general benefits of the application of energy storage systems in power grid are: supply for peak demands; efficient supply for demands that change quickly and that are constrained by generation and transmission systems; support for grid ancillary services, such as, frequency regulation and power quality improvement with efficient and reliable operation; integration of distributed and intermittent renewable energy resources into the electricity supply systems [2].

2. Methodology and Mathematical Modelling

An attempt has been made to model Photovoltaic Solar and Wind Power as Distributed Generation power sources interconnected to the grid. The rating of wind turbine is 200 kW which has an asynchronous machine operating at 690 V [3], whereas, the solar panel is modelled to be 75 kW and is connected through a rectifier to deliver AC power. It is assumed that the proposed wind-PV system acts as a power injection system to the power grid and lacks the features to exert any kind of power quality control on the power generated. 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 input data is in the form of solar irradiation, temperature, wind velocity and load demand at each instant or hour. Also, the cost of supply, back-up energy, investment of the energy storage system and inverter are to be considered.

2.1 WIND POWER MODELING

The power generated in a wind turbine has been evaluated using equations 1 and 2 [4]. 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:

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

$$P_w(v) = \begin{cases} 0 & \text{if} \quad v \le v_{ci} \text{ or } v \ge V_{co} \\ P_r\left(\frac{v^3 - v_{ci}^3}{v_r^3 - v_{ci}^3}\right) & \text{if} \quad v_{ci} \le v \le v_r \\ P_{rated} & \text{if} \quad v_r \le v \le v_{co} \end{cases} \tag{2}$$

2.2 PV System Modelling

A silicon PV module power output depends on many variables including the type of material, temperature, and solar radiance incident on the surface of the module. Temperature and irradiance data are taken for each time period and its corresponding power output is calculated in proportion to the rated power output of the PV module. Its output power can be expressed as in [5].

$$P_{pv} = Y_{pv} f_{pv} \frac{G_c}{G_{STC}} \left[1 + \alpha\left(T_c - T_{STC}\right)\right] \tag{3}$$

Figure 1: Mean daily global solar radiation in kWh/m^2/day from 2008 to 2012 for Pokhara [6]

The figure 1 shows a typical variation of Global Solar Radiation (GSR) in kWh/m^2/day from the years 2008 to 2012 as measured at Pokhara, Nepal. The minimum monthly mean daily solar radiation was recorded as 3.222 kWh/m^2/day in the month of December whereas the maximum monthly mean daily global solar radiation was recorded as 5.95 kWh/m^2/day in May.

2.3 Battery System Modelling

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.

1. When the charge state of batteries is below SOC_{max} and $P_{dem} < P_{gen}$, the excess of energy [(P_{gen} - P_{dem})ΔT] is stored in batteries, during the corresponding period ΔT.
2. When it is above SOC_{min} and $P_{dem} > P_{gen}$, energy previously stored is used to support lack of energy, $[(P_{dem} - P_{gen}).\Delta T]$ is discharged from batteries.
3. When the state of charge is equal to SOC_{max} and $P_{dem} < P_{genn}$, the excess energy [(P_{gen} - P_{dem}).ΔT] is lost, during the corresponding period ΔT.
4. When the state of charge is less than or equal to SOC_{min} and $P_{dem} > P_{gen}$, an unmet load occurs. In this case, P_{dem} must be equal to P_{gen} by load shedding.

Table 1: Battery Energy Storage System Ratings (per module)

S.N	Type	Rating	Voltage (V)	Life(in years)	Charging $\eta(\%)$	Discharging $\eta(\%)$	DOD (%)	Cost (in USD)
1	Lead-Acid	225 Ah	6	6	95	80	70	160/ module (118.52/kWh)
2	Li-ion	200 Ah	12	10	99	95	80	2000/ module (833.33/kWh)
3	Ni-Cd	100 Ah	12	15	87	80	100	700/ module (583.33/kWh)
4	Na-S	50 kW	48	15	99	88	100	400/kWh
5	VRB	50 kW	48	18	98	85	75	600/kWh

The characteristics of these batteries are tabulated in table 1, and these data are utilized in our calculations. These characteristics are obtained from their corresponding data sheets [7–10].

2.4 Power Dispatch Curve

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. Thus, the power output from the hybrid system will be averaged for 30 min. Let P_{gen} be the total power generated by the hybrid system given as below. We have:

$$P_{gen}(t) = P_w(t) \times \eta_{wt} + P_{pv}(t) \times \eta_{pv} \tag{4}$$

The power dispatch curve is obtained by following the power generated at each instant $P_{gen}(t)$ and the power demand at each instant $P_{dem}(t)$ per day. At times of off-peak demand, some of the energy generated is stored in batteries and the rest is delivered to the load. And during peak load, this stored energy is dispatched. Figure 2 shows the dispatch curve with power generation from DG sources but without battery energy storage, along with the peak load at each half-hour interval.

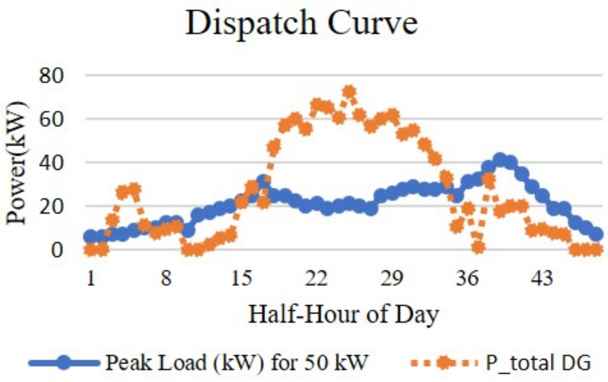

Figure 2: Dispatch curve for 24 hours with Power Generation from DG sources only, along with the peak load at each half-hour

2.5 Optimal Sizing of Energy Storage

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.
Consider:

$$\begin{aligned} P_{diff}(t) &= P_{gen}(t) - P_{dem}(t) \\ E_{batt}(kWh) &= max\left\{\Sigma_{i=1}^{N} P_{diff} \times \Delta t\right\} \end{aligned} \tag{5}$$

A simple model of battery is implemented to evaluate the nominal size of the battery system Ebattery(kWh) [11]. The model needs to take into account the depth of discharge (DoDautonomy (D), 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 28 ^0C is found to be 0.964. The aging characteristics of the battery are considered by assuming an aging factor of 15%. A common correction factor is evaluated in equation (5) and included in equation (6) for battery sizing as follows:
Correction factor for effect of temperature and aging:

$$\begin{aligned} &= (0.964 \times 1.15) \\ &= 1.108 \\ &\approx 110\% \end{aligned} \tag{6}$$

Required Battery capacity in kWh:

$$E_{batt(max)}(kWh) = \frac{110 E_{batt}(kWh/day) \times D}{\eta_{batt} \times DoD\%} \tag{7}$$

Required Battery capacity in Ah:

$$E_{cap}(Ah) = \frac{E_{batt(max)}(kWh) \times 1000}{V} \tag{8}$$

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.

2.6 Problem Formulation

The objective function given below represents annualized capital cost of the proposed BESS, where the term battery cost includes energy storage element costs and the cost of inverter. Losses cost is the economic value of the energy lost inferred due to load spilling and load shedding:
Minimize:
Annualized Cost = Battery Cost + Losses
where,

Battery Cost

$$\begin{aligned} &= (E_{bess} \times \chi_1 \times CRF_1 + E_{inv} \times \chi_2 \times CRF_2) \times (1+\gamma) \\ &= \frac{r(1+r)^n}{(1+r)^n - 1} \\ &= \frac{int - inf}{1 + inf} \end{aligned} \tag{9}$$

Here, the objective function is to minimize investment costs and losses and is formulated as summation of the two terms. First is battery cost, which is a function of battery size E_{bess} in kWh along with the inverter size E_{inv} in kW, and is the optimization variable in the equation. Second term “Losses” include losses incurred due to power spilling and load shedding caused by inadequate storage. As the losses have an inversely proportionate relationship with the battery size (a larger battery ensures greater reliability and lesser losses and vice versa), they are included in the cost minimization function.

3. Result and Discussion

The calculations are done based on the specifications of the wind turbine. The results are obtained based on the recorded solar and wind data obtained from Lumle station of Western Nepal [6]. Solar irradiation, temperature and wind velocity data are taken for a typical 24 hours for each minute interval.The demand curve of Palpa bazaar feeder, Palpa DCS is taken for consideration, where required power is seen to be delivered only when generation is more than or equal to the demand. 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.

3.1 Before Battery Placement

After running the simulation in MATLAB platform, it is seen that the wind-PV system generated 746.23 kWh of energy in the 24-hour simulation period; of this 380 kWh (51%) was from the solar photovoltaic. Albeit, the power generated from wind turbine account for 366 kWh (49 %), most of it was intermittent in nature and does not help to fulfill the sustained demand. 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. These losses add up to a sum of Rs 2,728,088 annually, if supplied by diesel generator at a high cost, with a LPSP ratio of 41.87%, delivering only 108,205 kWh of electricity per year against a total demand of 186,150.

3.2 After Battery Placement

Battery energy storage has been utilized to meet all the deficit in power delivery, which is calculated to be 213.55 kWh for one day (77,945 kWh per year) when the surplus power is 449.78 kWh per day (164,170 kWh per year). 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.

3.3 Optimizing the Battery Size

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 system (in kW). For lead acid batteries, the solution is met on 73_{rd} generation with minimum calculated operating cost of the system (Rs 1,573,100) at 281.71 kWh of battery size and 41.88 KW of inverter size. The loss comprises of annuitized investment cost of battery and the losses incurred by shedding of the demand and spilling of generated power. The power deficit has been assumed to be supplied by the diesel generator at the rate of PRD=Rs 35/kWh, while the power spill is assumed to be lost at the rate of PR_{dq}= Rs 7.3/kWh.

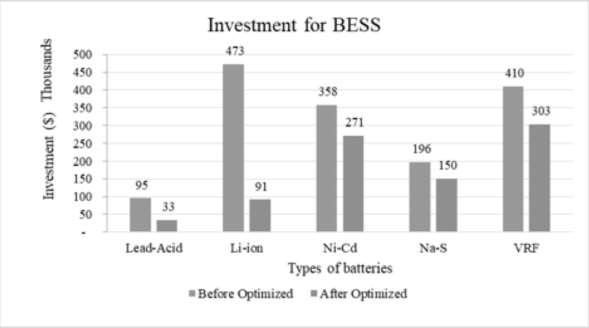

Figure 3: Investment for BESS (in USD) before and after optimized for five different types of batteries

The figure 3 shows the change in Investment for various types of BESS before and after optimization process considering all five battery types incorporated in a single chart for comparison.

The economic parameters are calculated and then tabulated below for both cases of battery system, i.e. before and after optimization. Investment costs are calculated in rupees with exchange rate of Rs 110/USD. As the delivered power is the same for all battery cases, the benefits earned remain equal. Only the investment cost change according to each battery type. The economic matrices calculated for the five different battery types are tabulated in table 2 and 3, where the table 2 shows the matrices when battery size is determined by equations (6) and (7), to fulfill all the power deficit in the system, whereas table 3 shows the similar calculations performed after the battery sizes are optimized using genetic algorithm.

4. Conclusion

As the share of renewables are increasing in the modern generation mix, not only their benefits but also their constraints are being fully explored. One of the major back-drop of these renewable generations are their intermittency.

This study outlines an optimized sizing methodology for different types of battery energy storage technologies, considering peak shaving and valley filling features in the power dispatch to minimize the revenue loss and maximize the benefits gained.

Genetic Algorithm optimization criteria is used to effectively minimize the cost of the battery system using MATLAB software. It is then validated in a PV-Wind grid-connected microgrid system to eliminate power curtailment losses and utilize the potential of the power evacuation, taking hourly load profile of a rural test feeder and historical meteorological data of Nepalese scenario.

The methodology is tested on five different types of battery systems, from conventional Lead-acid battery, Lithium-ion (Li-ion) and Nickel Cadmium (Ni-Cd) batteries to upcoming flow batteries (Vanadium Redox Flow) and Sodium Sulphur (Na-S) battery. Various economic parameters are then explored to effectively quantify the benefits gained from the integration of battery energy storage systems. Economic, reliability and environmental parameters are evaluated to analyze the feasibility of the storage systems. The following conclusions could be drawn from the study:

1. Although the batteries require high initial investments, the study proved that the benefits gained over time and increased reliability will more than justify them. Profits gained by cutting down on spilling and shedding losses, were used as payback for recovering the investments. In the process, reducing the LPSP from 41.87% to 2.63% hence, improving the reliability of the system.

2. Among the various alternatives, lead-acid battery is found to have the least investment costs ($ 33,388) and shortest payback periods (1.33 years). Lithium-ion technology, which is considered the most promising alternative, proved to be less beneficial due to higher initial costs but with better BCR (1.99). However, sodium sulphur battery outperformed the lead-acid battery in SOC characteristic with highest NPV (Rs 21,411,950) and satisfactory BCR (1.67), thereby providing a better solution with reduced maintenance problems and longer life.

3. From the case studies performed with seven different generation mix of solar PV and Wind

Table 2: Economic Analysis before Optimization

Type	Energy Delivered in kWh	Revenue Earned (Rs.)	SPBP	DPBP	NPV	LPSP	BCR
Lead-Acid	182160	2,003,760	4.60	6.45	1,641,695	0%	0.95
Li-ion	182160	2,003,760	15.25	N/A	(29,896,127)	0%	0.41
Ni-Cd	182160	2,003,760	12.01	N/A	(7,316,153)	0%	0.65
Na-S	182160	2,003,760	7.44	13.81	10,488,665	0%	1.04
VRF	182160	2,003,760	13.48	N/A	(8,238,736)	0%	0.63

Table 3: Economic Analysis after Optimization

Type	Energy Delivered in kWh	Revenue Earned (Rs.)	SPBP	DPBP	NPV	LPSP	BCR
Lead-Acid	181,250	1,993,750	1.33	1.48	14,390,879	2.51%	3.28
Li-ion	181,250	1,993,750	3.11	3.89	17,484,979	21.20%	1.99
Ni-Cd	181,250	1,993,750	8.08	16.25	7,993,702	2.46%	0.96
Na-S	181,250	1,993,750	4.64	6.54	21,411,950	2.50%	1.67
VRF	181,250	1,993,750	9.06	21.08	8,986,492	2.37%	0.94

Turbine, from 0% to 100%, for various battery sizes it is observed that the scenario with 100% wind turbine and 0% solar PV is seen to have the least annual operating cost, proving to be the most beneficial. In addition, the battery size between 275 kWh and 550 kWh is seen to be the most optimum for the total installed capacity of 275 kW.

5. APPENDIX

The notation used throughout this paper is reproduced below for quick reference.

Abbreviations

BESS	Battery Energy Storage System
CRF	Capital Recovery Factor
MATLAB	MATrix LABoratory
PV	Photo Voltaic
LPSP	Loss of Power Supply Probability
LV	Low Voltage

Parameters

P_w	power generated by wind turbine, in kW
ρ	air density and is taken as 1.225 kg/m^3
A	rotor swept area of wind turbine
P_pv	output power from the PV module in kW
Y_p	rated power output of the PV module, 75 kW

Parameters (continued)

G_c	global horizontal irradiance incident on the cell in W/m^2
GSTC	global horizontal irradiance at standard test condition which is taken to be 1000 W/m^2
α	Temperature coefficient, taken as 0.4%
f_{pv}	Derating factor, considered as 97%
T_c	temperature of solar cell
T_STC	temperature at standard test condition which is taken as 25^0C
E_{bess}	Battery Capacity in kWh
E_{inv}	Inverter Capacity in kW
χ_1	Cost of Battery system (Rs/kWh)
χ_2	Cost of Inverter (Rs/kW)
γ	Fraction of Operation and Maintenance cost to Fixed Cost
r	Discounted rate of interest
int	interest rate
inf	inflation rate
η	lifetime of battery
P_{gen}	total power generated by the renewable DG sources at any instant t
ηwt	efficiency of the wind energy conversion system = 95%
ηpv	efficiency of the photovoltaic energy conversion system = 97%

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