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# AN ASSESSMENT ON THE STATE OF LEAD ACID AND ZINC BROMIDE BATTERY IN PV-WIND HYBRID SYSTEM

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**ABSTRACT**

Hybrid renewable energy systems are more reliable and economical compared to the stand-alone system which is powered by only one source. An off-grid PV-wind hybrid system is considered in this work, where the reactive power requirement of the wind-driven induction generator (IG) is met only by the battery banks when there is insufficient solar output from the PV Panels. In this work for such a design, to provide effective storage capacity, Zinc bromide battery and their parameters are scrutinized and compared with the conventional lead-acid battery.Based on the analysis and comparison the most appropriate battery type is chosen. The Storage efficiency of the batteries has been computed under two situations. In the first case the battery banks supplies both active and reactive power when there is inadequateness in solar and wind power. In the next case, battery banks supplies only reactive power for the induction generator during the unavailability of solar output from PV modules. Storage equipment analysis for different conditions, aids in selecting the most optimal battery type for the hybrid unit.

**Keywords:** induction generator, state of charge, hybrid systems, DC-DC boost converter.

## 1. INTRODUCTION

In hybrid system the ratings of the wind and solar units can be chosen flexibly by the engineers depending upon the source availability and load demand in the working site. In addition to that Hybrid systems are considered to be more cost effective than the standalone system due to its less storage requirement relatively [1, 2].Nevertheless, battery bank performs a crucial function in hybrid system by meeting out the load demand when there is lack of power generation from the sources and also stores the surplus energy from the fluctuating sources. At present, lead-acid batteries are commonly used in hybrid system because of its cheapness, good efficiency and maintenance free nature. Charging and discharging rate of the batteries highly influences the functioning and life of the batteries [3, 4]. While deciding the ratings of the storage equipment, predictions are made on depth and rate of discharge of the battery. Generally SOC is considered between 50% and 80%, which is an appropriate operating range to ensure longer battery life [3].

In this work, comparative analysis is done on conventional lead acid and zinc bromide battery parameters using their respective Simulink models at different environmental conditions, especially when the storage bank is subjected to provide the reactive power demand to the wind- driven Induction generator (IG) while getting charged simultaneously.

## 2. SCHEME DESCRIPTION

The schematic representation of the suggested design is presented in Figure-1, which consists of a photovoltaic module with number of solar cells arranged in parallel and series to obtain the desired output voltage .Perturb and observe, Maximum Power Point Tracking algorithm((P&O) is implemented to obtain the maximum output from the photovoltaic source [6]. The DC output from the solar unit is boosted using a Boost converter (DC-DC) which is then followed by a battery bank (1-lead acid battery, 2-zinc bromide battery).

An IGBT based inverter (180 conduction mode) is used for conversion of DC to AC where battery banks act as DC link. A three phase load and a wind-driven induction generator are coupled to the output of the inverter such that it is synchronised with the inverter frequency and voltage. The load demand is met out by the solar and wind source depending on the illumination and wind velocity respectively. Batteries get charged when the power generation from both the source are surplus. In case of non-availability of any one source, the other source and the battery feeds the load. When both the sources become incapable of sufficient power generation due to low wind speed and irradiation level, then the battery bank only will feed the demand of the load. The unpredictable changes in irradiance and wind speed will affect the functioning point of the PV array and shaft torque of induction generator, which leads to change in the operating conditions of the battery charging current or discharging current.

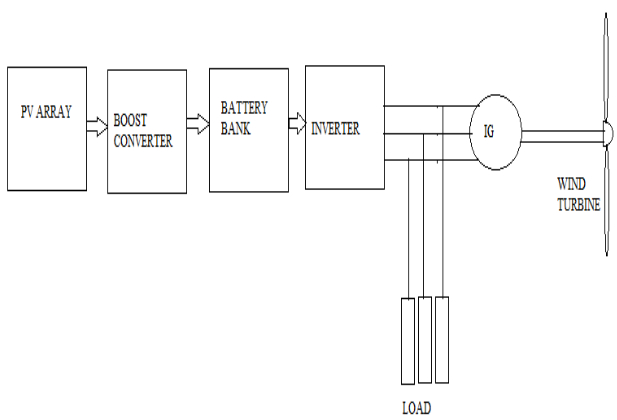


**Figure-1.** Hybrid PV and wind-driven induction generator with battery bank.

## 3. MODELING OF SYSTEM COMPONENTS

### 3.1 Modeling of Photovoltaic Cells (PV)

The PV module consists of number of solar cells arranged in parallel and series to obtain the required output voltage and current respectively. The conversion of solar energy into electrical energy is due to an effect called photovoltaic effect. Using the given equations PV array is modelled in MATLAB to obtain I-V (current-voltage) characteristics from which maximum power point is determined [8].

The modelling of PV cell is accomplished using the equivalent circuit in Figure-2.In which the light flux, the losses are modelled by a current source and two resistances namely shunt and series respectively. This model includes five unknown parameters Iph,Rs, Rsh,Is,and N.[10]

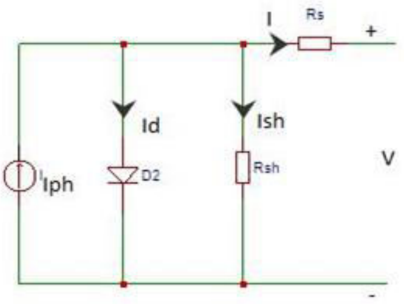


**Figure-2.** Equivalent circuit of PV cell

**Open circuit voltage**

The voltage measured across the PV cell,during which no load is connected across its terminals. Voc corresponds to the amount of forward bias of a P-N junction due to photoCurrent. The upper limit for the open circuit voltage is set by the band gap of the material that is larger the band gap higher is the Voc.

$V_{oc}$=KTqln(Isc$I_0$+1) (1)

Where, $V_{oc}$- open circuit voltage
Current equations of the solar cell are as follows:

The output current Ip is obtained by applying Kirchhoff's current law (KCL),

$I_P=I_{ph}-I_d-I_{sh}$ (2)

Where Iph is the PV output current, Id is the diode current and Ish is the current through the shunt path.

$I_d = I_s$ (exp( q.(V+$IR_s$)/Nkt)-1) (3)

Where boltzman constant k =1.38*10^-23.
The current through the shunt resistance ($R_{sh}$) is given by,
$I_{sh}$=(V+$IR_s$)/$R_{sh}$ (4)

Substituting eq(3) and eq(4) in eq(2), we get the equation which relates PVcell output current and the terminal voltage according to the above single-diode model is,

$I_p= I_{ph}-I_s$ *(exp (q.(V+$IR_s$)/Nkt)-1)-(V+$IR_s$)$R_{sh}$ (5)

### 3.2 Maximum power point technique

All Solar cells possess an I-V curve which depends on temperature and irradiation level. Higher the illumination level and lower the temperature better is the curve characteristics. At a particular operating point in the curve (I-V), called as knee point the power delivered by the solar cell or array is maximum. Generally, Temperature and Irradiance keeps on changing thereby knee point of the I-V curve keeps varying, so to track this maximum point continuously an algorithm is used which is called as Maximum Power Point tracking algorithm (MPPT). The perturb and observe algorithm (P&O) is one of the MPPT technique to locate the knee point of the solar cell [8].

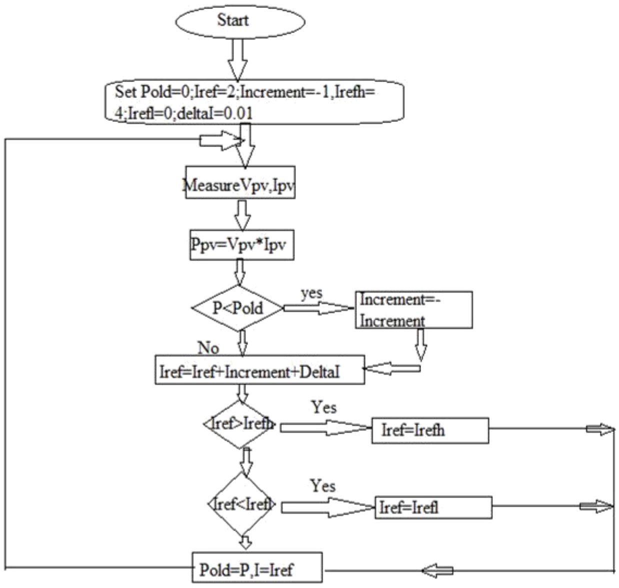


**Figure-3.** Flow chart of MPPT technique.

### 3.3 Modeling of batteries

Energy storage device have a vital role in Solar-wind hybrid system that is battery bank determines the operating voltage of PV module and act as the source during the absence of solar and wind output.

Modeling of Lead acid and zinc bromide battery system is done to examine their performance at various working conditions [11].

The general equivalent circuit of a battery is given in Figure-4.

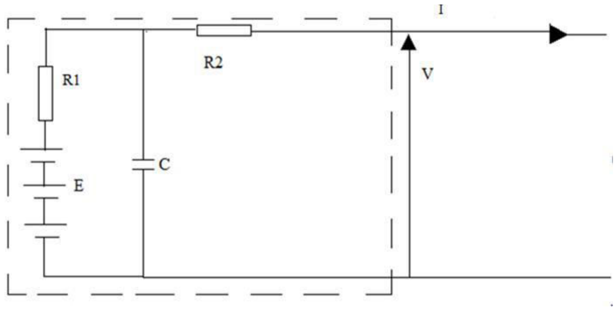


**Figure-4.** Equivalent circuit of battery.

### 3.3.1 Modeling of lead acid battery

The dynamics and battery behaviour of lead acid batteries at the end of charging cycle is modelled by two branches namely main branch and parasitic branch respectively [11].

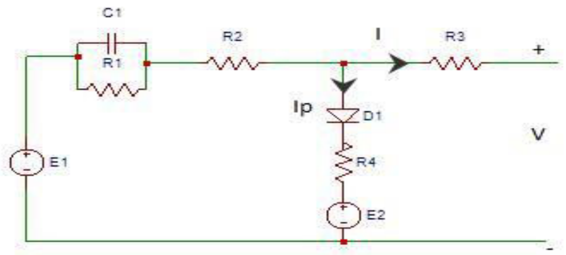


**Figure-5.** Equivalent circuit of Lead acid battery

Lead-acid battery is mathematically modelled using the following non-linear equations. The non-linear equations involves states and parameters, where the parameters depends on empirically determined constants, and state included circuit voltages, currents, electrolyte temperature and stored charge.

Main branch voltage

The open circuit voltage or electromotive force (EMF) is approximated using eq (6),

In this modeling, EMF value of the battery is assumed to be constant at fully charged condition, but the electromotive force varies with respect to state of charge (SOC) and temperature of the battery at other instants.

$$E = E_{m'} - K_E (273 + \Theta)(1 - SOC) \quad (6)$$

Where, $K_E$- Constant (volts/$^0$c), E- Open circuit voltage in volts, $E_{m'}$-Open circuit voltage at fully charged condition.

Terminal Resistance ($R_3$)

The terminal resistance of the battery is assumed to be independent of temperature, but varies with the (SOC) of the battery.

$$R_3 = R_{30}\,[1 + A_0(1 - SOC)] \quad (7)$$

Where, $R_3$-Resistance (ohms), $R_{30}$-Resistance at SOC=1 (ohms)

Terminal resistance ($R_1$)

$$R_1 = -\ln(DOC) \quad (8)$$

Where, DOC- depth of charge

Capacitance(C)

The capacitance of the main branch is approximated using the equation (9), the time constant of the battery depicts a voltage delay proportional to the change in battery current

$$C = T/R_1 \quad (9)$$

Where, T-Time constant in secs

Resistance ($R_2$)

The main branch resistance depends on SOC and branch currents. The resistance affects initially the charging currents of battery, but it becomes relatively inconsequential during discharging.

$$R_2 = [R_{20}\exp(A_2(1-SOC))]/[1+\exp(A_3.Im.I^*)] \quad (10)$$

Where, I*-Nominal battery current, Im-Main branch current.

State of charge (SOC)

(SOC) of the battery calculated the amount of available charge left in the battery, and the depth of charge (DOC) calculated the amount of coulombs still present in it.DOC (depth of charge) was always lesser than or equal to SOC.

$$SOC = 1 - Q_e/\{C(0,\Theta)\} \quad (11)$$

Where, $Q_e$- Extracted charge (Amp-seconds)

Depth of charge (DOC)

$$DOC = 1 - Q_e/\{C(Iavg, \Theta)\} \quad (12)$$

Where -Electrolyte temperature ($^0$c), $C_0$- No-load capacity at $0^0$c, I-discharge current (amps).

Total capacity(C)

The capacity of the battery is approximated using the equation (13), which depends on parameters like temperature of the electrolyte and discharging currents, but the capacity depends on current only for the discharge.

$$C(I,\Theta) = K_c C_0 K_t/\{(1+(K_c-1)(I/I^*)^{\delta}\} \quad (13)$$

Where, I*-Nominal battery current (amps)

Extracted charge (Q)

The charge taken out from the battery is obtained by integrating the main branch current during charging and discharging cycles.

$$Q(t) = Q_{initt} + \int_0^t -Im(\tau)\,d\tau \quad (14)$$

Average Current

The average current equation of the battery is given by

$I_{avg}=I_m/(\tau s+1)$ (15)

### 3.3.2 Zinc bromide battery model

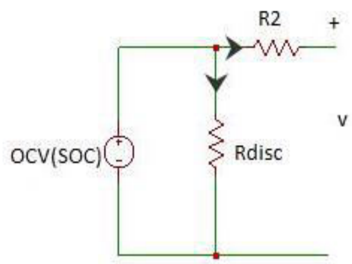


**Figure-6.** Discharging model of zinc bromide battery.

The discharging model of the zinc bromide battery is shown in Figure-6; with two resistances which are terminal resistance (R2) and Rdisc resistance approximated the self-discharging characteristics of zinc bromide battery [4]. Similarly Zinc-bromide battery model is accomplished using the following equations give below:

Open circuit voltage

The polynomial function of degree four relating SOC (state of charge) and OCV (open circuit voltage) is obtained by plotting various SOC VS OCV graphs by conducting different tests in MATLAB Simulink.

$OCV=-1.9*e-6(S)^4+5.3e-4*(S)^3-0.054*(S)^2+2.4*(S)+63$ (16)

Where, S - State of charge, OCV- open circuit voltage

Terminal resistance

Battery resistance varies with cells ambient temperature and SOC, but in this case, the temperature is assumed to be constant during the test.

$R_2 = (OCV-V_{batt})/I_{dis}$ (17)

$R_2 = 5.94*exp(-0.135*S)+0.063*exp(-5.77e-3*S)$ (18)

Where, $I_{dis}$- discharging current, OCV-Open circuit voltage.

Self-discharge resistance ($R_{disc}$)

Self-discharging characteristics of a battery modelled by placing a parallel resistance in the equivalent circuit.

$R_{disc} = (OCV-V_{batt})/(\Delta q/\Delta t)$ (19)

Where, Δt-Time during which discharge take place

Peukert's coefficient (P)

Peukerts coefficient is calculated using the below equation (19), by obtaining discharge curves of the battery at different discharge currents.

$P=[\log Y_2-\log Y_1]/[\log X_1-\log X_2]$ (20)

Where, $Y_1$,$Y_2$ - full discharge time at current $X_1$,$X_2$ respectively.

Discharge time (t)

Discharging time of the zinc bromide battery is function of peukerts coefficient as shown in equation (20).

$T_k=T_n.\ (I_n/I_k \wedge p)$ (21)

Where, P-peukerts coefficient, $T_k$-discharge time, $T_n$-Nominal discharge time

Capacity(C)

Capacity of the battery is approximated using the following equation below, where it depends on nominal discharge current and peukert's coefficient.

$C=C_n(I_n/I_k)\wedge(p-1)$ (22)

Where, $C_n$- Nominal capacity of battery,In-nominal discharge current

State of charge (SOC)

SOC is calculated using coulomb counting technique, given by the equation (23),

$SOC = SOC(0)+\{\{0.085*100/3600\}*\int_0^t \frac{i}{Cn}\,.dt\}$ (23)

Where, $C_n$ - nominal capacity (Ah)

## 4. STORAGE REQUIREMENTOF HYBRID PV-WIND SYSTEM

In hybrid PV-wind system, generally the battery banks are used to store surplus energy from the sources and supply it to the load during lack of power generation by the sources and in some cases battery bank are also being used to minimize frequency deviation. But in this proposed scheme, Battery banks become highly mandatory due to the wind - driven IG (Induction generator). Normally IG are excited by the capacitor banks or from the utility networks, whereas in this scheme excitation from the grid is impossible as it is an off grid plant and Capacitor excited induction generator leads to complicated control and poor voltage regulation. The IG act as an active power generator and also as a reactive power consumer. When there is lack of output from solar modules ,battery banks feed the reactive power requirement of IG ,while IG itself act as an active power source .Here, the charging and discharging of the batteries depends upon the wind –speed. When the wind turbine produces real power which is higher than the required load demand, then this surplus active power is used for charging the battery banks. Conversely, the discharge of the battery bank happens when the real power generation of Induction Generator is lesser than the active power requirement of the load.

## 5. SIMULATION RESULTS OF LEAD ACID AND ZINC BROMIDE BATTERY

A four pole,Y-connected and 1500 rpm squirrel cage IG (induction generator) is chosen. The parameters of

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the IG (induction generator),(stator resistance $R_s$=0.01965 ohm, Stator inductance $L_s$= 0.0397H),(Rotor resistance $R_{s'}$=0.01909 ohm, Rotor inductance $L_{s'}$ = 0.0397H, Lm = 1.354 H). A three phase resistive load was connected inverter terminals. DC-DC boost converter (L = 100 mH and C2 = 1000 F) with perturb and observe maximum power point algorithm was used in this work. A case study is taken to analyse the parameters like SOC(State of Charge),voltage and current of the Lead acid and Zinc bromide batteries to determine the more efficient and optimal battery for the hybrid system. Lead acid and zinc bromide battery of same capacity (675Ah) and initially with SOC of 100% are chosen.

Two cases are taken to analyse the battery parameters are as follows:

a)when there is insufficient generation from wind units, Consider if the real power produced by the wind driven induction generator is zero; therefore the load demand is met only by the solar units and battery bank. Here depending upon the illumination and temperature of solar irradiation the battery banks undergoes both charging and discharging cycles. So in this case batteries are forced to provide both active and reactive power.

b) When there is sufficient generation from wind units, in this case there is sufficient amount of real power generation from the wind units to feed the load demand. So battery banks are only used to provide the reactive power demand of the wind-driven Induction generator (IG).

Comparisons are drawn between the lead acid and zinc bromide battery at two different conditions .one is battery bank providing both active and reactive power and the other one is providing only the reactive power during the deficiency of solar power. SOC (state of charge), current and voltage response of both the batteries are obtained by implementing the MATLAB model of the hybrid scheme in Simulink [3,10].MATLAB model of Zinc bromide battery is given in Figure-7 and Figure-8.

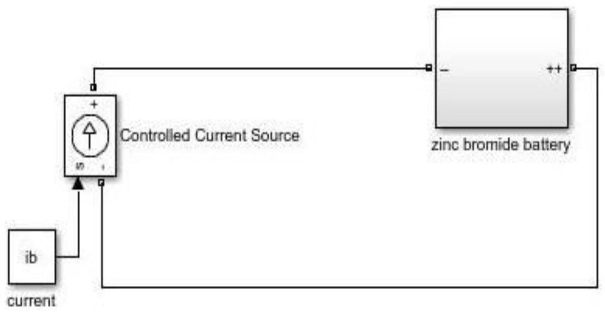


**Figure-7.** Zinc bromide battery model in Simulink.

Different test was conducted to obtain different OCV VS SOC curves, and then using curve fitting toolbox in MATLAB gives a proper relationship between OCV and SOC as shown by equation (16).The internal resistance of the zinc bromide battery is defined by the equation (17), which depends on three factors which are cell temperature, SOC and ambient temperature. [4]

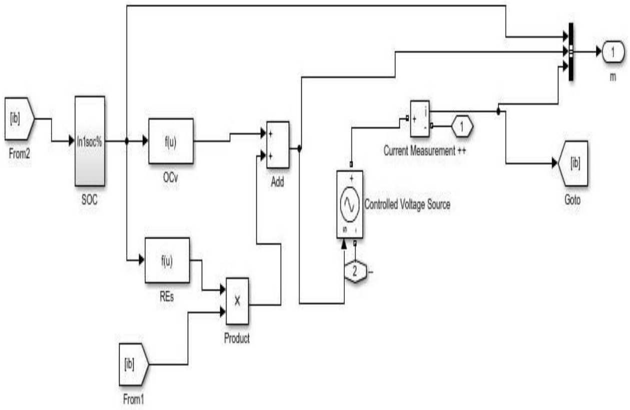


**Figure-8.** Zinc bromide model in Simulink.

The first case in which there is no real power generation from wind units).Here the battery bank is subjected to feed real power to the load and reactive power to the Induction generator in the absence of solar power. The response of lead acid and zinc bromide battery is given in Figure-9 and Figure-10, respectively.

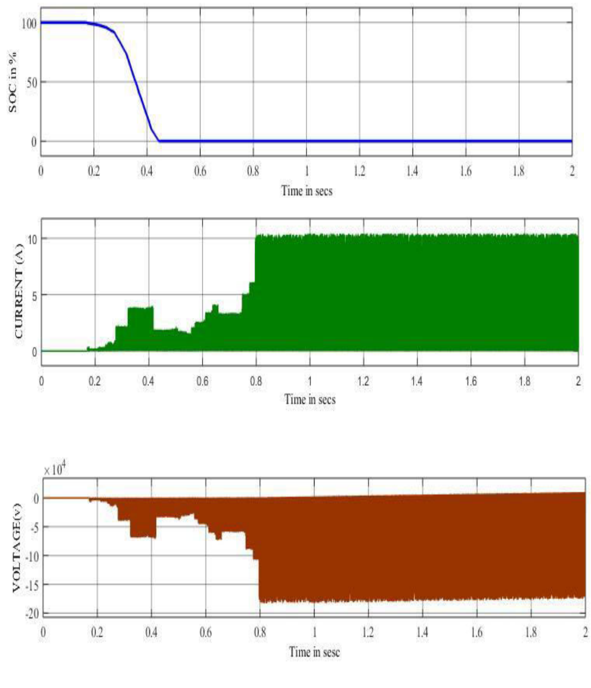


**Figure-9.** Output response of Lead acid battery feeding both active and reactive power.

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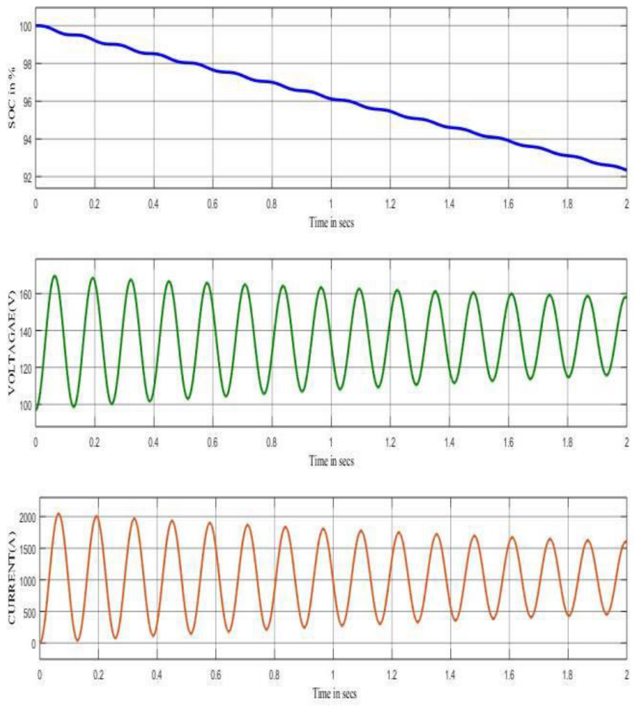


**Figure-10.** Output response of Zinc bromide battery feeding both active and reactive power.

Inference obtained from the above figures is that in Case (1), SOC of the zinc-bromide battery retained to 94% little close to the initial SOC of 100% in the simulation time, the positive value of battery current reflects the battery is getting discharged in the given simulation period and it varies between (0 to 2000A )and voltage between(100v to 165v) ,whereas the SOC of lead-acid battery shows a steady decline from its initial state of charge(100%) and finally reaching SOC of 0% with the highly oscillating discharging current varying between (0A to 10A ) and voltage ranges to negative values which is not the case in zinc bromide batteries ,which proves the inefficiency of lead acid battery in hybrid systems during the battery is made to provide both active and reactive power.

In second case, when there is sufficient power generation from wind units. In this condition battery bank feeds only reactive power to the Induction generator, because there is sufficient generation of real power from wind units to supply the load even in the absence of Photovoltaic source. The response for this condition is represented in Figure-11 and Figure-12.

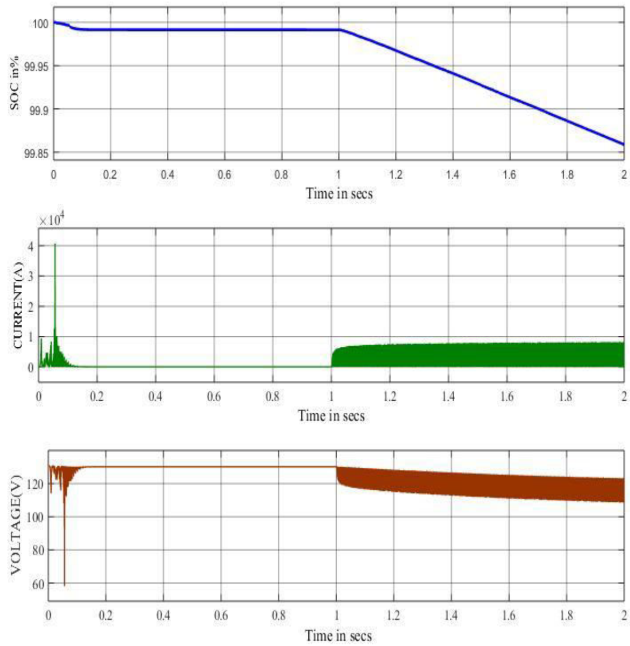


**Figure-11.** Output response of Lead acid battery feeding only reactive power.

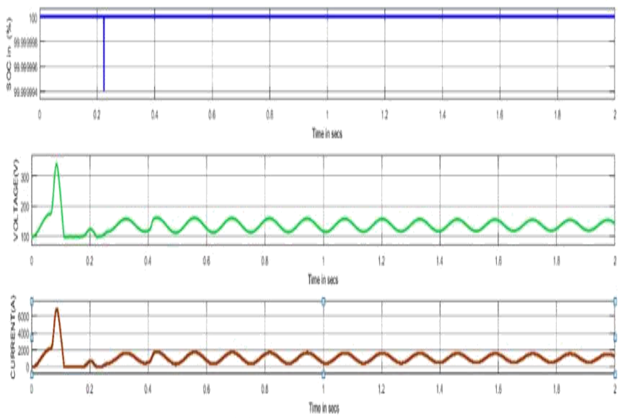

**Figure-12.** Output response of Zinc bromide battery feeding only reactive power.

While considering the case (2) when the battery is made to supply only reactive power the SOC of the zinc bromide battery remains almost close to initial soc of 100%, with a sharp dip in SOC at 0.25 secs. Initially the voltage and current rises to 300v and 6000A respectively and then voltage oscillates between (100V to 200V), and the current varies between (0 to2000A). But in the case of lead acid battery similar to case(1) there is gradual decline from initial SOC(100%)The current waveform of lead acid battery reaches to zero value during the simulation test period which again throw light on the ineffectiveness of the lead acid battery.

However, if the same range of irradiation persists for more than two days then the SOC of the batteries will decline, below 50% for lead acid battery and below 60% for Zinc bromide batteries which will eventually it affects the life of the batteries.

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## 6. COMPARISON OF LEAD ACID AND ZINC BROMIDE BATTERY

### 6.1 Based on technical parameters

#### 6.1.1 Lead acid battery

A discharge characteristic of lead acid battery is shown in Figure-13. Discharge curves at various discharging currents are taken by simulating the model in MATLAB and used to calculate Peukerts coefficients, efficiency, discharging rate, SOC, discharging time of the battery.

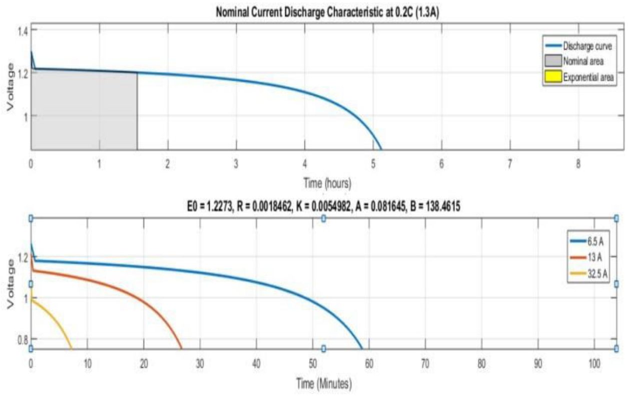


**Figure-13.** Discharging characteristics of Lead acid battery.

Using this discharging characteristics the peukert's coefficient of the lead acid battery is calculated using the equation (19), which gives the value of P =1.1 for lead acid battery. Variation of Open circuit voltage with state of charge of lead acid battery is simulated in MATLAB Simulink and the result is shown in Figure-14.As it is seen from the graph that open circuit voltage (60V) increases to 65V when the state of charge increases, that is as the battery is getting charged.

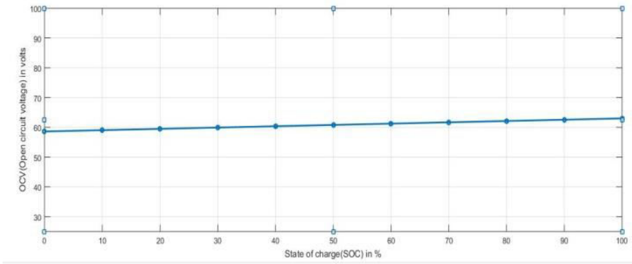


**Figure-14.** OCV VS SOC of lead acid battery during charging.

#### 6.1.2 Zinc bromide battery

Using the above proposed mathematical model of zinc bromide battery, the SOC, voltage and current waveforms of the battery during discharging period is shown in Figure-15.

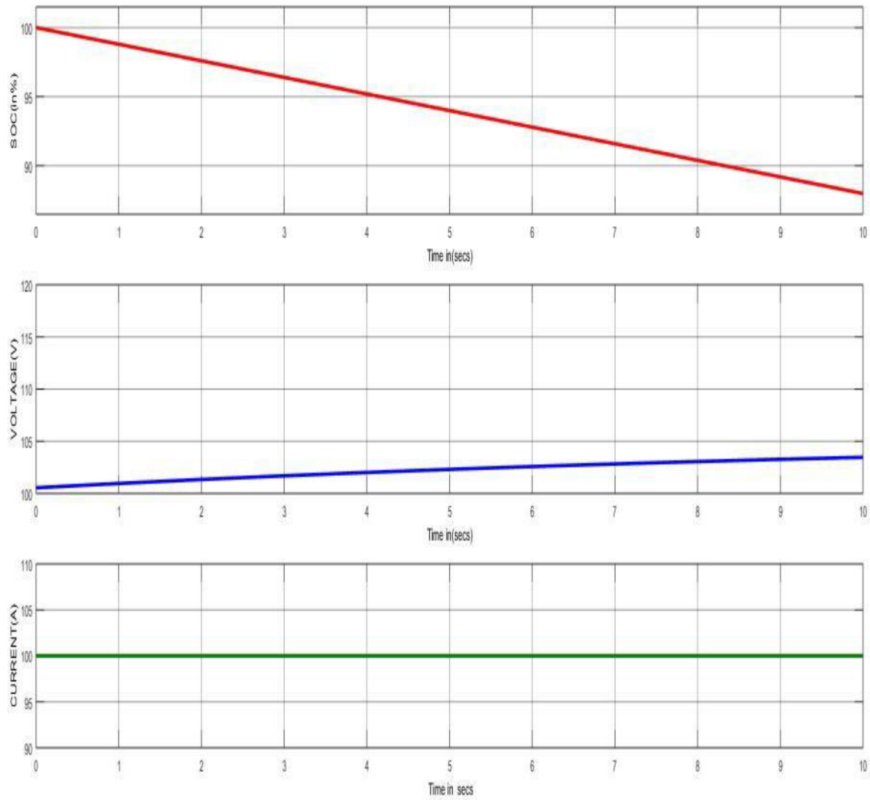


**Figure-15.** Output response of zinc bromide battery during discharging.

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Discharging characteristics of zinc bromide battery for simulation period of 10 secs is shown in Figure-15.In which there is steady decline in SOC characteristics from 100 % to 0% at end of test period. The current waveform is positive depicting the current is drawn out from the battery. From the experimental data and results of the charging and discharge characteristics of the zinc bromide battery the voltaic efficiency and columbic efficiency is

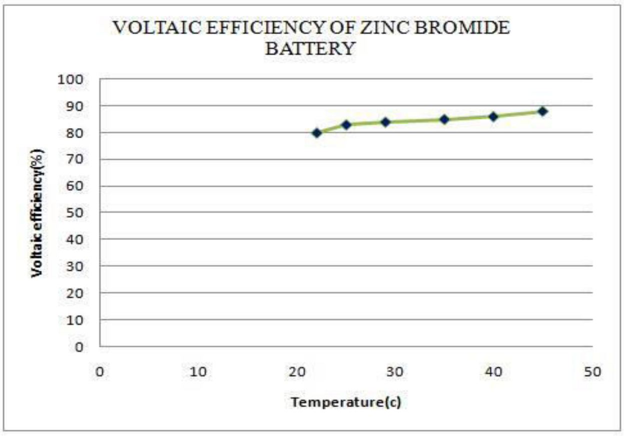


**Figure-16.** Voltaic efficiency of zinc bromide battery.

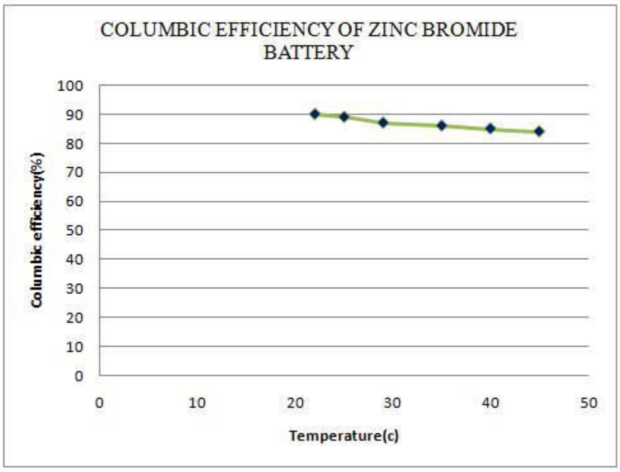


**Figure-17.** Columbic efficiency of zinc bromide battery.

From the graph it is inferred that at low temperatures the electrolyte resistivity increases, leads to lower voltaic efficiency, this is offset by slow bromine transportation which results in higher columbic efficiency in zinc bromide battery.

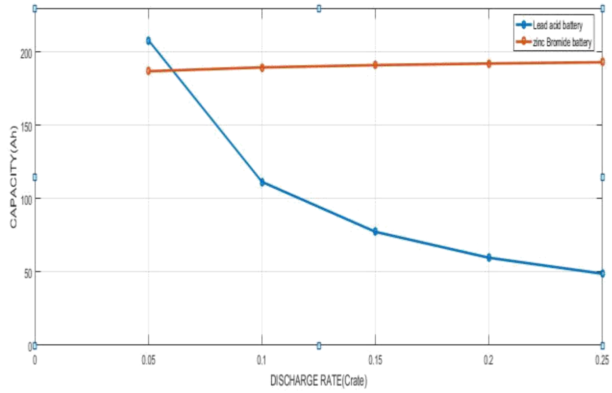


**Figure-18.** Capacity vs crate of ZBr and lead acid battery.

Form Figure-18 it is concluded that capacity of the lead acid battery declines as the discharge rate (Crate) is increased, whereas in case of zinc bromide battery the capacity of the battery is maintained constant to the initial value.

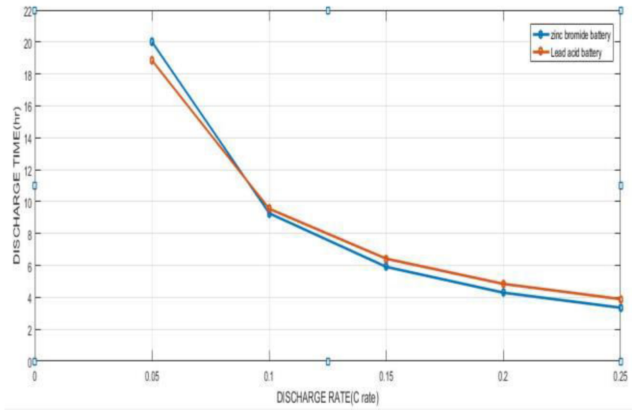


**Figure-19.** Capacity vs crate of ZBr and lead acid battery.

Discharge timeVs Crate for lead acid and zinc bromide battery is shown in Figure-19. Discharge time decreases as the discharge (Crate) is increased for both the batteries, and both have similar slope in the simulation period.

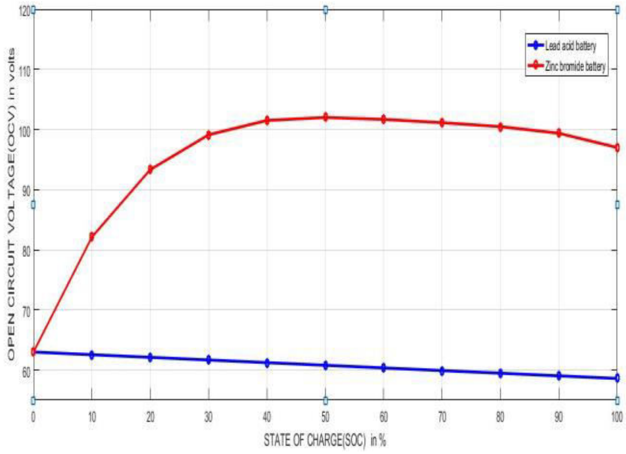


**Figure-20.** Open circuit voltage vs SOC of ZBr and lead acid battery.

In Figure-20 OCV VS SOC of lead acid and zinc bromide battery is shown in which the zinc bromide battery there is a gradual increase in voltage as SOC is increased and it gets saturated at fully charged condition of the battery (SOC=100%).But in the case of lead acid battery, even then SOC increases there is a very slight decline in the open circuit voltage.

From Figures 18, 19, 20, 21 it is inferred that Zinc bromide battery has better discharging and charging characteristics compared to lead acid battery, which makes it more suitable for Energy storage requirement (ES) in hybrid system than its conventional counterpart.

### 7.2. Comparison on economic grounds

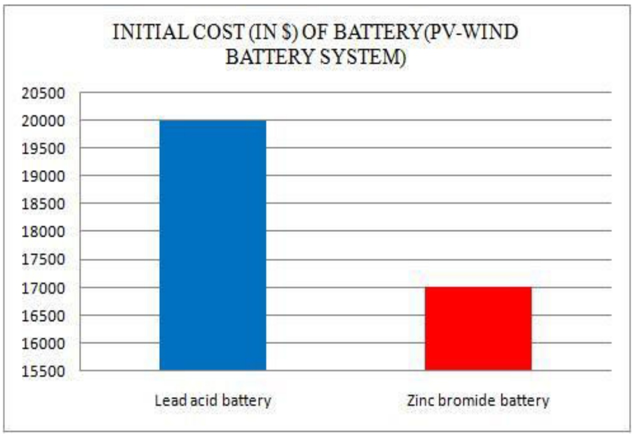


**Figure-21.** Initial cost of batteries.

From Figure-21 it is seen that initial cost of lead acid battery is around 2000$ whereas in case of zinc bromide battery is around 17000$.which shows the cost effectiveness of the zinc bromide battery over lead acid battery.

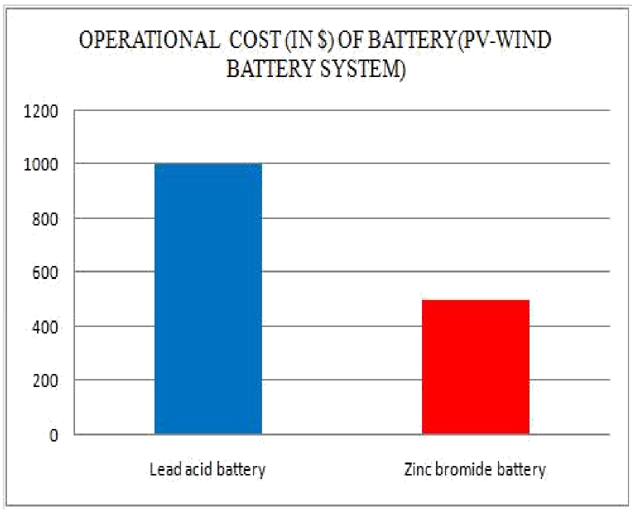


**Figure-22.** Net Present cost of batteries.

Similarly operational cost of lead acid battery is around 1000$,but in the case of zinc bromide battery it is around 500$,which shows that zinc bromide battery requires very less maintenance compared to lead acid battery during its life time.

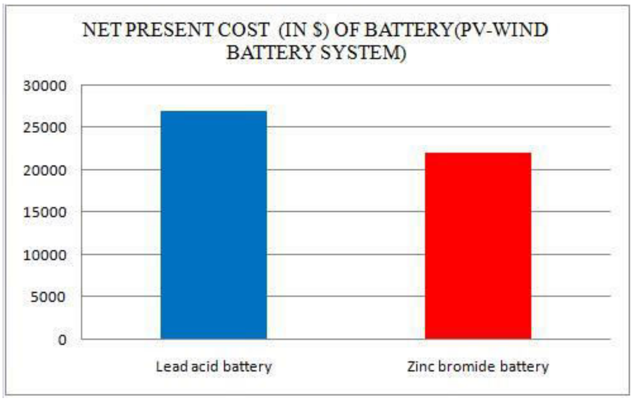


**Figure-23.** Net present cost of batteries.

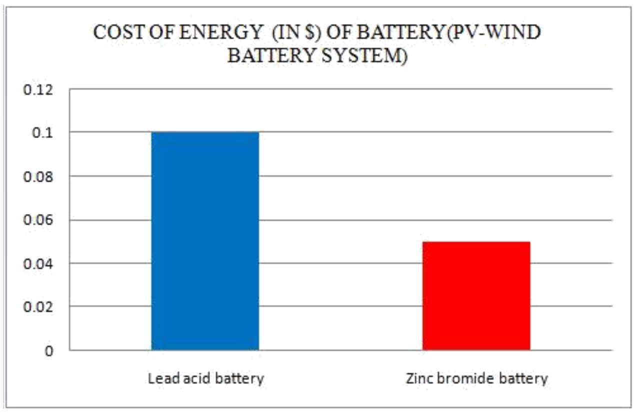


**Figure-24.** COE (cost of energy) of batteries.

Net present cost and cost of energy of zinc bromide battery is comparatively lesser than that of lead acid battery, making it more economical in hybrid systems. Similarly zinc bromide battery has one more added advantage than lead acid battery, that is it can undergo 10,000 plus cycles during its lifetime whereas the lead acid battery have it around 4500 cycles, which makes the zinc bromide battery more appropriate for hybrid PV-wind system where the sources are intermittent.

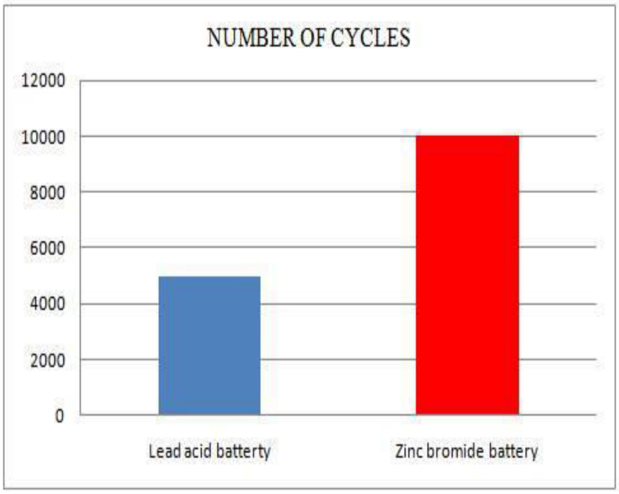


**Figure-25.** Life cycles of batteries

**Table-1.** Comparison between lead acid and zinc bromide battery.

| | Lead-acid battery | Zinc-bromide battery |
|---|---|---|
| Initial cost | 20000$ | 17000$ |
| Operational cost | 1000$ | 500$ |
| Net present cost | 26000$ | 22000$ |
| Cost of energy | 0.1$ | 0.05$ |
| Life cycles | 4500 | 10000 |

Comparing and analysing the above graphs the Net present cost (NPC), Initial cost(IC), Cost of energy (COE), and Operating cost of zinc bromide battery is much lesser than the Lead acid battery .Hence using Zinc bromide batteries gives better performance and found to be economically optimal one than lead acid battery.

**8. CONCLUSIONS**

From the proposed design in MATLAB simulink the storage requirement of the hybrid power plant and Battery parameters of the two batteries are studied under different cases, found that Zinc bromide batteries are better than Lead acid batteries on the basis of SOC. In addition to that bromide batteries can undergo ten thousand plus charging and discharging cycles during its operational lifetime whereas, the conventional lead acid batteries undergoes only five thousand cycles (approx). Zinc batteries can undergo full discharge without causing any deterioration to the battery's operation. It can exhibit good operating characteristics for broad range of temperatures without getting damaged. Thereby zinc bromide battery becomes the optimal one for hybrid system and assures zero LPSP at different environmental conditions.

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