Optimal Scheduling of Hybrid Pumped Hydro Storage System using Linear Programming

B. Shyam, B. Harini Krishna, P. Kanakasabapathy

Abstract— This paper presents optimal scheduling of a grid-connected microgrid with grid, solar PV system, and wind energy system acting as sources and a local water reservoir acting as a storage system. Using mathematical models of solar PV, wind energy system, load profile, and pumped storage system, the optimization problem is formulated to minimize the daily operating cost taking into account all the constraints. Using a modified linear programming algorithm based on varying price weight, an optimum schedule is obtained and the minimum operating cost is determined. Comparison of operating cost is carried out based on all possible combinations of available sources and storage system. Cases of maximum initial reservoir volume and minimum initial reservoir volume were considered for each combination of sources and storage system. Finally, by analyzing the simulation results and cost calculations, share of different renewable energy sources, grid, and storage system in meeting the load is isolated.

Index Terms— Scheduling, Pumped Hydro Storage, Renewable Energy Sources, Solar PV, Wind Energy.

I. INTRODUCTION

India’s energy sector has significantly grown over the last decades. It is the third largest consumer and 3rd largest producer of electricity. It is due to the rapid growth of the economy, increase in exports, developing infrastructure and increment in household income [1]. The shares of fossil fuels in the energy sector of India is 81.9% and the renewable share 15.3% [2]. Since three fourth of the electricity of India is produced by fossil fuel, particularly coal, there is a major impact on the environment and also the fossil fuels are depleting rapidly, which poses a major problem to the energy sector. Renewable energy resources provide a solution to this threat. Wind and Solar are the major renewable energy resources that are widely available in our country. It is the fourth largest wind power producer in the world with 49.3% contribution to the renewable energy field whereas solar contributes 31.4%.

[3] Though there is abundant availability of renewable energy resources in our country, the intermittent nature of the renewable energy resources poses a hitch in merging them with our existing power system [4]. The existing solution for the problem is the storage system [5]. The effect on the grid due to the fluctuating nature of renewable energy generation can be nullified by connecting energy storage system between the RES and grid which act as a buffer between them [6].

Using pumped hydro storage along with available renewable energy resources, clean energy can be generated [7]. The fuel cost and emission can be reduced by using hydro-thermal co-ordinations. At peak hours the pumped hydro storage meets the load demand and at low peak hours, the water is pumped back to the upper reservoir. [8] In India, the plan of integrating pumped hydro storage with nuclear plant started in the 1970s. The country’s first pumped hydro storage, Nagarjuna Sagar pumped hydro storage plant was commissioned in the year 1985. Presently 11 pumped hydro plants are under operation and 56 new sites were identified as suitable for a pumped hydro scheme by CEA [9].

In this paper, a modified linear programming method is used to obtain an optimal schedule for a hybrid pumped hydro storage system. The solar PV, wind and pumped hydro storage system are mathematically modelled. An objective function is formulated for the system and the different constraints and boundaries of the system are identified. The system is simulated for different cases and a comparative study for various cases is done.

II. SYSTEM DESCRIPTION

In the proposed system as shown in figure 1, the load is supplied by the available renewable energy resources and grid. The pumped hydro storage acts as either a load or an energy source based on the hour of operation and the volume of the upper reservoir. There is no power exported to the grid from renewable energy sources and pumped hydro storage.

At off-peak hours, if the volume of the upper reservoirs less than the maximum volume the pumped hydro storage will be in pumping mode and will act as a load. The grid and renewable energy sources supply the load and pumped hydro storage. During peak hours, the operation of the grid is restricted. The pumped hydro storage acts as a source i.e. it will be in generating mode. The load demand is met by pumped hydro storage along with renewable energy sources. The renewable energy sources participate in meeting the load demand only when they are available. During the availability of renewable energy sources, they are dedicated to the load. Based on the volume of the upper reservoir, the excess renewable energy will be given to the pumped hydro storage. For a small scale, pumped hydro storage is not economical [10].

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Optimal Scheduling of Hybrid Pumped Hydro Storage System using Linear Programming

So, a locally available dam is used as upper reservoir and a nearby canal is used as the lower reservoir storage is not economical [10]. So, a locally available dam is used as upper reservoir and a nearby canal is used as the lower reservoir.

Fig. 1: Proposed System Block Diagram

III. MODELLING

Modelling of Solar PV
The solar PV can be calculated by knowing the area of the panel and the PV system efficiency.

\[ P(kW) = A \times \eta \times I \]

where
- \( A \): area of the PV array
- \( \eta \): Efficiency of the PV system
- \( I \): Solar Irradiation

The solar irradiation data for a location can be collected and the output PV power can be calculated. [11].

Modelling of Wind Power
For a given rotor swept area the output power from the wind turbine can be calculated by

\[ P(kW) = C_p \times \frac{1}{2} \times \rho \times A \times V^3 \]

where
- \( C_p \): Maximum power coefficient
- \( A \): Swept area of the rotor
- \( V \): Wind Velocity
- \( k \): Constant to convert power into KW
- \( \rho \): Density of air

The wind turbine gives an output power only when the velocity of the wind is between the cut-in and cut-out velocity. The output power of the wind plant can be calculated by knowing the wind velocity of the location. [12]

Modelling of Pumped Hydro Storage
The capacity of pumped hydro storage in the upper reservoir can be calculated as,

\[ P(W) = \frac{\rho \times V_i \times g \times h \times \eta}{t \times 3.6 \times 10^6} \]

The power required to pump the water from the upper reservoir to the lower reservoir during the pumping mode is given by

\[ P(W) = \frac{\rho \times g \times h \times Q_p}{\eta_{p} \times t} \]

The power obtained by the pumped hydro storage during generating mode is given by [13]

\[ P(W) = \frac{\rho \times g \times h \times \eta_{g} \times Q_g}{t} \]

where
- \( \rho \): Density of water
- \( g \): Gravitational constant
- \( h \): water head
- \( Q_p \): Water flow rate during pumping
- \( Q_g \): Water flow rate during generation
- \( \eta_{p} \): Pumping Efficiency
- \( \eta_{g} \): generating efficiency
- \( t \): time period of operation
- \( V_i \): Volume of the upper reservoir

Grid energy pricing
The grid energy pricing depends on the time of usage. An approximate energy pricing for peak, standard and off-peak hour are assumed for different intervals of time as shown in the table.

<table>
<thead>
<tr>
<th>TIME(h)</th>
<th>Hour of usage</th>
<th>cost/kW</th>
</tr>
</thead>
<tbody>
<tr>
<td>(0, 7) U (22, 23)</td>
<td>Off-peak hour</td>
<td>5Rs</td>
</tr>
<tr>
<td>(11, 17) U (20, 21)</td>
<td>Standard hour</td>
<td>7.5Rs</td>
</tr>
<tr>
<td>(8, 10) U (18, 19)</td>
<td>Peak hour</td>
<td>15Rs</td>
</tr>
</tbody>
</table>

Load Curve
The daily load curve is shown in figure 2 [14]

Solar Data
The PV profile shown in figure 3 is obtained collecting a locations irradiation data for each hour and calculating the output power of solar PV using equation 1.

Wind Data
The wind profile as shown in figure 4 is plotted by obtaining the wind velocity of a location on hourly basis. Using equation 2 the power output for for different wind velocities is calculated.
IV. FORMULATION OF OPTIMIZATION PROBLEM

Objective Function

This work focuses mainly on the reduction of the usage of grid power. This can be written as

\[
F = \sum_{j=1}^{n} (P_{gph} + P_{gl}) \times R \times s \times \Delta t
\]

(6)

The minimization function is subjected to different constraints based on the system.

Variable Constrains

The instantaneous power from the wind farm to meet the load or pumped hydro storage interval \( i \) should not exceed the total power generated by wind farm at interval \( i \).

\[
P_{wph}(i) + P_{wl}(i) \leq P_{w}(i)
\]

(7)

The sum of power drawn from Solar PV in any interval to meet the load or pumped hydro demand should be less than or equal to the total power generated by solar PV at the particular interval.

\[
P_{pvph}(i) + P_{pvl}(i) \leq P_{pv}(i)
\]

(8)

The total allowable power that can be drawn from the grid at any interval should be equal to or greater than the sum of power drawn from the grid to meet the load or supply pumped hydrostorage.

\[
P_{gpl}(i) + P_{gph}(i) \leq P_{g}(i)
\]

(9)

Equality Constrains

The sum of power from renewable energy sources, storage unit, and the grid should be equal to the total load demand at any interval of time.

\[
P_{gl}(i) + P_{pv}(i) + P_{w}(i) + P_{ph}(i) = P_{l}(i)
\]

(10)

D. Variable Boundaries

The boundaries of the variable parameters of the system can be set by a lower and upper limit so that the parameter does not violate any of the constraints of the system. The limits are as given below.

\[
0 \leq P_{gl}(i) \leq P_{gmin}
\]

(11)

\[
0 \leq P_{wl}(i) \leq P_{wmax}
\]

(12)

\[
0 \leq P_{ph}(i) \leq P_{pmax}
\]

(13)

\[
V_{rmin} \leq V_{r}(i) \leq V_{rmax}
\]

(14)

where

- \( \cdot : 1,2,..,24 \)
- \( PVph: \) Power from PV to PHS
- \( Pwph: \) Power from Windfarm to PHS
- \( Pv: \) Power from Windfarm to load
- \( Ppv: \) Power from PV to load
- \( Pgph: \) Power from grid to PHS
- \( Pgl: \) Power from grid to load
- \( Vr: \) Volume of upper reservoir
- \( Rs: \) Grid Pricing

Modes of Pumped Hydro Storage

The pumped hydro storage acts in two modes of operation

1) Pumping Mode: When the hour is an off-peak hour or if the renewable energy sources exceed the load demand, based on the volume of the reservoir the pumping action takes place. The amount of water available in the upper reservoir at any instant of time is given by

\[
V_{r}(i) = V_{r}(i-1) + (V_{pvph}(i) + V_{wph}(i) + V_{w}(i))
\]

(15)

2) Generating Mode: if the hour is of peak hour and the renewable are not enough to meet the load, the pumped hydro storage acts as an energy source to meet the load. The status of the water availability in the upper reservoir is given by

\[
V_{r}(i) = V_{r}(i-1) - (V_{ph}(i))
\]

(16)

The current volume of the upper reservoir at the end of any interval can be calculated by combining equations 15 and 16, that is

\[
V_{r}(i) = V_{r}(i-1) + ((V_{pvph}(i) + V_{wph}(i) + V_{w}(i))(V_{ph}(i))
\]

(17)
Optimal Scheduling of Hybrid Pumped Hydro Storage System using Linear Programming

Where
- \( V_r(i-1) \): Volume of reservoir at the end of previous hour
- \( V_{pvph} \): Volume filled by PV
- \( V_{gph} \): Volume filled by grid
- \( V_{wph} \): Volume filled by Windfarm
- \( V_{phl} \): Decrease in volume during generating mode

**Modified Linear Programming Algorithm**

Figure 5 represents an approach to optimization using modified linear programming. The data of load, power from solar PV and wind, the volume of the reservoir and the grid pricing is read and the present volume is checked. If the present volume is less than the maximum volume, the hour of operation is checked or else the default pumping and generating cost weightage is taken. If the hour of operation is an off-peak hour, the generating cost weightage is increased and the pumping cost weightage is reduced so that the pumping action does not take place at peak hours. The linear programming optimization is run for the defined condition. If all the constraints are satisfied the volume is updated. At the end of all iterations, a 24 hours schedule is printed.

\[
\text{Minimize } F = \sum_{j=1}^{\infty} \left( (W_p P_{gph} + P_{w}) \times R \times \Delta t + (W_g P_{phl}) \right) 
\]

\[
A_x \leq b 
\]
\[
A_{eq} = b_{eq} 
\]
\[
l_b \leq x \leq u_b 
\]

where \( f \) represents the objective function, equation 20 represents the equality constraint parameters, equation 19 represent the inequality constraint parameters and equation 21 represent the lower and upper limits of the variables. The linear programming method can be used using an inbuilt function as given below

\[
y = \text{linprog}(f, A, b, A_{eq}, b_{eq}, l_b, u_b) 
\]

At peak hour rating, based on the availability of the renewable energy sources, the use of pumped hydro will be maximum, avoiding the use of grid the cost of the power can be reduced. During the off-peak hour, the grid will be used to supply the load and some part of the pumped hydro plant.

**V. OPTIMAL SCHEDULING OF PROPOSED SYSTEM & RESULTS**

**Input Data and System Specifications**

The load demand for 24 hours time period. The scheduling in this work is done for the load in figure 2 with an interval of one hour for a day. The system parameters used in the simulation are given in Table II.

<table>
<thead>
<tr>
<th>System Specifications</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Load</td>
<td>5 kW</td>
</tr>
<tr>
<td>Solar PV</td>
<td></td>
</tr>
<tr>
<td>Area</td>
<td>22.22 m²</td>
</tr>
<tr>
<td>( \eta )</td>
<td>18 %</td>
</tr>
<tr>
<td>Wind Energy System</td>
<td></td>
</tr>
<tr>
<td>Wind turbine rating</td>
<td>3.3 kW</td>
</tr>
<tr>
<td>Swept area</td>
<td>175 sq.m</td>
</tr>
<tr>
<td>cut-in velocity</td>
<td>6 m/sec</td>
</tr>
<tr>
<td>cut-out velocity</td>
<td>18 m/sec</td>
</tr>
<tr>
<td>Pumped Hydro Storage</td>
<td></td>
</tr>
<tr>
<td>Volume of upper reservoir</td>
<td>816 m³</td>
</tr>
<tr>
<td>Rate of charge</td>
<td>0.009 m³/sec</td>
</tr>
<tr>
<td>Rate of discharge</td>
<td>0.11 m³/sec</td>
</tr>
<tr>
<td>Height</td>
<td>10 m</td>
</tr>
</tbody>
</table>

**Simulation Results and Discussion**

The simulation is carried out with minimum initial reservoir level. During the off-peak hours which is from 0\(^{th}\) to 7\(^{th}\) hour and 22\(^{nd}\) to 24\(^{th}\) hour the load is supplied by the grid.
The grid also supplies during standard hours which are from 17th to 18th hour and 21st to 22nd hour where the renewable energy sources are not capable to handle the load. Figure 6 shows the participation of the grid to serve the load in a day.

The pumped hydro storage acts as a load on the grid only when there is an occurrence of the low peak hour. The figure 7 refers to the power drawn from the grid to supply the pumped hydro storage. During the off-peak period 1st to 2nd hour and 23rd to 24th the grid power is utilized to fill the upper reservoir of pumped hydrostorage.

When solar energy is available, the PV is dedicated to meet the load demand. If the PV is excess than load, based on the volume of the reservoir, the excess power is used to meet the demand of pumped hydrostorage.

At 1st to 3rd hour and 9th to 10th hour, the power from wind energy system is given to pumped hydro system. The figure 10 shows the power flow profile from wind energy system to pumped hydrostorage. When wind energy is available, wind energy system supports the other energy sources to meet the load. The figure 11 shows the role of wind energy system in meeting a part of the load in a day.

The pumped hydro storage supports the system to meet the demand at the first peak hour. During the peak hours at 8th to 9th hour, the first peak hour of the day occurs. The available renewable energy sources are not enough to meet the load.

The pumped hydro storage during these hours. The figure 12 shows the amount of power drawn from pumped hydro storage to meet the load during peak hours. Due to the involvement of pumped hydro storage in the system, the burden on the grid is reduced at peak hours and the operational cost of the grid is reduced.
The change in the volume of the reservoir is shown in figure 13. At peak hours, that is from 6\(^{th}\) to 10\(^{th}\) hour and 19\(^{th}\) to 21\(^{st}\) hour, the pumped hydro acts as a source, so the volume in the upper reservoir comes down and at off peak hours, 1\(^{st}\) to 3\(^{rd}\) hour and 23\(^{rd}\) to 24\(^{th}\) hour, the pumped hydro acts as a load. It draws power from the other sources to pump the water back into the upper reservoir.

Fig. 13: Change in volume of upper reservoir

Table III: Participation of Energy Sources in Meeting the Load Demand without PHS

<table>
<thead>
<tr>
<th>Source</th>
<th>Grid Alone</th>
<th>Grid+PV</th>
<th>Grid+Wind</th>
<th>Hybrid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grid</td>
<td>59,950 Units</td>
<td>31,717 Units</td>
<td>50,520 Units</td>
<td>27,588 Units</td>
</tr>
<tr>
<td>PV</td>
<td>–</td>
<td>28,233 Units</td>
<td>–</td>
<td>28,182 Units</td>
</tr>
<tr>
<td>Wind</td>
<td>–</td>
<td>–</td>
<td>9,430 Units</td>
<td>4,180 Units</td>
</tr>
<tr>
<td>Load</td>
<td>–</td>
<td>59,950 Units</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

Table IV: Participation of Energy Sources in Meeting the Load Demand with PHS

<table>
<thead>
<tr>
<th>Source</th>
<th>Grid+PV</th>
<th>Grid+Wind</th>
<th>Hybrid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grid</td>
<td>22,361 Units</td>
<td>36,267 Units</td>
<td>19,329 Units</td>
</tr>
<tr>
<td>PV</td>
<td>28,233 Units</td>
<td>–</td>
<td>22,771 Units</td>
</tr>
<tr>
<td>Wind</td>
<td>–</td>
<td>9,761 Units</td>
<td>8,076 Units</td>
</tr>
<tr>
<td>PHS (as energy source)</td>
<td>9,356 Units</td>
<td>13,982 Units</td>
<td>9,574 Units</td>
</tr>
<tr>
<td>Load</td>
<td>–</td>
<td>59,950 Units</td>
<td>–</td>
</tr>
</tbody>
</table>

Table V: Cost Comparison

<table>
<thead>
<tr>
<th>System</th>
<th>Cost (in Rs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grid Alone</td>
<td>531</td>
</tr>
<tr>
<td>Grid + PV</td>
<td>229</td>
</tr>
<tr>
<td>Grid + Wind</td>
<td>471</td>
</tr>
<tr>
<td>Grid + PV + Wind</td>
<td>281 (Opt)</td>
</tr>
<tr>
<td>Reservoir initial volume</td>
<td></td>
</tr>
<tr>
<td>Zero</td>
<td>240</td>
</tr>
<tr>
<td>Maximum</td>
<td>196</td>
</tr>
<tr>
<td>Grid + Wind</td>
<td>432</td>
</tr>
<tr>
<td>Maximum</td>
<td>383</td>
</tr>
<tr>
<td>Grid + PV + Wind</td>
<td>306</td>
</tr>
<tr>
<td>Maximum</td>
<td>156</td>
</tr>
</tbody>
</table>

VI. CONCLUSION

In this paper, a novel method to minimize the operational cost of a system is proposed. The system consists of a PV system and Wind system with pumped hydro storage. The total operational cost of the grid for a day is reduced using modified linear programming. From the obtained results, it can be inferred that the pumped hydro storage plays a major role in supporting the system. Pumped hydro storage provides an effective integration between the renewable energy sources and the load. Due to the addition of pumped hydro storage, the burden on the grid is reduced. The daily operational cost of the system is dependent on the initial volume of the upper reservoir. The system can further be studied by accounting for various losses associated to it and also the pumped hydro storage can be used as a source during few standard hours.

REFERENCES