CHAPTER 5

OPTIMAL POWER FLOW SOLUTION FOR HYDRO-
THERMAL-WIND GENERATION SYSTEM

5.1. INTRODUCTION

The integration of wind power with conventional fossil fuel based generation system (Thermal generating units) has several benefits in terms of environmental friendliness and security in system operation. But the unpredictability and intermittency of actual available wind power has the ability of making the power system operation vulnerable. Moreover, as there is only the thermal power generation systems to compensate for meeting the deficit of wind power in wind-thermal (WT) system operation during the over prediction of wind power, the system operator does not have any other options for generating resources. But this in turn may be a threat to environment due to increased emission. Therefore, some other forms of renewable energy resources may be considered for their integration into the power system. In this context, the hydro-electric energy is the most conventional form of renewable source which has already been widely used worldwide. Further, apart from the power generating potential of hydro storage systems, it has several other contributions to the general development, economic progress and welfare of the society. Some of the more general advantages of properly harnessing and utilizing hydro resources are as follows

1. Flood and draught control.
2. Irrigation requirement in farming.
3. Cater to the needs of portable water and industrial consumption.

In addition to the above, hydro resources, when used for power generation, provide many benefits. Three most prominent reasons for their use are as follows.

1. No air pollution due to absence of combustible fuel, and therefore no fuel cost.
2. Hydro power generators have the unique ability to ramp up its power output at a faster rate compared to an equivalent capacity thermal unit. Therefore, it is more efficient in meeting changing demands for electricity.

3. Safer power plants compared to thermal, diesel and nuclear power plants.

4. Good potential of their use in distributed generation scenario, as hydro power from micro to mega range is possible.

The proposed hydro-thermal-wind (HTW) power scheduling aims at determining optimal hydro, thermal and wind generations in order to meet the load demands over a scheduled horizon of one day, satisfying various constraints on the hydraulic and wind-thermal power system network. The goal is to minimize total operation costs of the hybrid (HTW) system. The problem therefore becomes an optimization problem with highly nonlinear characteristics.

The extent to which large scale integration of wind energy in electric power systems will affect system costs and reliability may depend greatly on the availability of sources that can rapidly change the electricity output [134-136]. Due to their capacity for energy storage, low marginal costs, and fast ramp rates, hydroelectric systems are often regarded as an ideal resource for mitigating problematic issues related to wind's intermittency and unpredictability [137]. In recent years, researchers have investigated a wide range of topics concerning the coordinated use of wind and hydropower. However, the development of wind-hydro models remain a limiting factor in addressing numbers of unanswered questions in the area of voltage security and cost beneficial operation of hybrid power systems. Previous researches of wind-hydro projects presented a conceptual classification of the system in terms of pair-wise and system-based studies [137]. Pair-wise classification evaluates the benefits of operating the wind-hydro projects in isolated environment [138]. Advanced pair-wise studies have represented the incorporation wind-hydro projects' to larger electric power systems using
historical market prices. These include the value of energy storage in wind-hydro systems [139,140]; the pecuniary and environmental costs of dams' providing a wind firming service [141]; using dams to enhance wind market penetration [142]; and the use of multipurpose dams to integrate wind energy [143]. However, the pair-wise studies are generally less capable of capturing the more complex, endogenous economic and operational consequences of large scale wind integration for generators and consumers [137].

More comprehensive system-based models simulate the effect of integration of wind power on the operation of entire electric power systems. The power system may be consisting of many different sizes and types of generators. Thus they offer the significant advantage of being able to simulate changes in system costs that may occur as a result of wind power integration. Thus the way these changes could influence the working of hydroelectric system can be analyzed. Some of the instances of system-based studies incorporate investigations of the impacts of wind-hydro ventures on: the value of wind energy [144]; and the cost of reducing CO₂ emissions [145].

Considering the system-based wind-hydro approach, considerable gaps in analysis remain as to what is the impact of wind-thermal integration on hydropower resources. For example: in some of the states of USA, less than 10% of total annual electricity demand is fulfilled by hydro resources. Therefore, consideration of hydro dominant system-based wind-hydro studies where hydropower meets a larger percentage of total system generation may not be prolific. As per the knowledge of the authors, no system-based study has yet addressed the potential of increased wind penetration on security, reliability and operational economy of HTW system. Investigation of these topics require models that can simulate the effects of wind power integration on hydro-thermal power system under a variety of operating conditions, while also satisfying the constraints of HTW generation system.
Many researchers have focussed on modelling and solving the short term hydro-thermal (HT) scheduling problem using intelligent optimization techniques [146-153]. A few researchers have investigated the optimal operation of (i) wind-thermal (WT) generation system [23-27] and (ii) thermal generation system [29-37] in OPF/ED/UC framework. It is found by the authors that no work exists especially in the area of analysing combined operation of hydro-thermal-wind (HTW) generation system and determining the optimal generation scheduling at which the system will operate most economically. Thus, in this work an attempt is taken to model and demonstrate the above issue in an optimal power flow framework while optimizing the suitably formulated operational objectives with MBFA, GA, and HA algorithms. The optimized generating schedules are tested for their competence in obtaining a secure power system operation, when the system is subjected to numbers of (N-1) contingencies in the form of line outages, load increase. Simulations are carried out in MATLAB/SIMULINK environment.

The primary contributions of this work are given as follows

- Formulation, modeling and optimal scheduling of hydro-thermal generation system in the presence of wind power.
- Implementation of MBFA, HA and GA algorithm and their validation in an existing IEEE30 bus power network in a multi objective OPF framework with wind integration. The existing thermal units in the test system are replaced with wind and hydro units with proper modifications in the power flow models, wherever necessary.
- The real power generation schedules of all types of units are optimized using MBFA, HA and GA. The operating efficiencies and voltage profiles given by different optimal schedules are then evaluated and compared under different operating scenarios.
Apart from considering the modeling aspects of wind power uncertainty in the OPF formulation, the focus is also towards the necessity of the inclusion of shunt FACTS devices into the OPF framework, to improve the overall system voltage profile.

5.2. PROBLEM STATEMENT AND FORMULATION OF OBJECTIVE FUNCTION

The random behaviour of wind power generation makes the scheduling problem more complex, making the system vulnerable to insecure voltage conditions. In this context, to mitigate the power imbalance, additional costs are added to the objective function to manage the power imbalance during the UE and OE scenarios. However, during a condition of OE additional reserve units of the thermal systems may have to be summoned due to shortage in the available wind power from its original scheduled value. To reduce the dependency on thermal generating units and simultaneously to aim for emission reduction, hydro powered units may be incorporated to fulfil the demand.

The objective of the hydro-thermal-wind scheduling problem is to minimize the total system operational cost to meet the load demands during the intervals of the generation scheduling. The optimal schedules from all the three types of units should not violate any of the operating constraints and be able to operate the system in a secured manner even with some changes in the operating conditions. Fig.5.1 depicts the schematic diagram of the hydro-thermal-wind generation system.
Optimal power flow solution for hydro-thermal-wind generation system

5.2.1 Methodology of solving the scheduling problem

The prime objective of the HTW scheduling problem is to minimize the total system operation cost such that the load demand supplied from hydro plant, thermal plant and wind powered units in the intervals of the generation scheduling horizon can be met and simultaneously, all the equality and inequality operational constraints are satisfied.

The HTW scheduling approach may be described as

- The hydro discharge of $k^{th}$ unit at $j^{th}$ scheduling horizon $q_{kj}$ is calculated by using the hydraulic continuity equation (5.12). During this, the spillage is assumed to be zero.
- Knowing the amount of water discharge, the reservoir volumes at different intervals are determined and hydro power generation is calculated using (5.13).
- After finding the hydro power, the wind power available is evaluated.
- Finally after obtaining the hydro and wind power generation for satisfying the load demand, the thermal power generation is evaluated using (5.2).
5.2.2 Formulation of objective function

Mathematically, the objective function may be represented as

Minimize

\[ F_S = F_T + F_W + pf_c \]  \hspace{1cm} (5.1)

In the above expression, \( F_S \) is the total system operation cost.

\( F_T \) is the cost of thermal power generation.

\( F_W \) is the cost of wind power generation.

\( pf_c \) is the penalty function for penalizing any constraint violation.

Subject to constraints:

\[ \sum_{t}^{N_t} P_{gt} + \sum_{k}^{N_h} P_{gh} + \sum_{r}^{N_w} P_{wr} = P_{\text{loss}} + P_{\text{load}} \]  \hspace{1cm} (5.2)

\[ \sum_{t}^{N_t} Q_{gt} + \sum_{r}^{N_w} Q_{wr} = Q_{\text{loss}} + Q_{\text{load}} \]  \hspace{1cm} (5.3)

\[ p_{gt}^{\text{min}} \leq P_{gt} \leq p_{gt}^{\text{max}} \]  \hspace{1cm} (5.4)

\[ q_{gt}^{\text{min}} \leq Q_{gt} \leq q_{gt}^{\text{max}} \]  \hspace{1cm} (5.5)

\[ V_t^{\text{min}} \leq V_t \leq V_t^{\text{max}} \]  \hspace{1cm} (5.6)

\[ P_{wr} \leq P_{wr}^{\text{max}} \]  \hspace{1cm} (5.7)

\[ Q_{wr}^{\text{min}} \leq Q_{wr} \leq Q_{wr}^{\text{max}} \]  \hspace{1cm} (5.8)

Equations (5.2) and (5.3) denote the load balance equation for both real and reactive powers respectively. Equations (5.4) and (5.5) refer to the limiting values (min and max) of real and reactive power limits of thermal generating units. Further, (5.6) explains the limits within which the system voltage magnitude varies. Variations of real and reactive power output of wind powered units are indicated by (5.7) and (5.8).

Further, the equations explaining the hydro system operation and its constraints are given as follows. In all these equations, the subscript \( k \) refers to the \( k^{\text{th}} \) hydro unit, and \( j \) refers to the \( j^{\text{th}} \) interval in the scheduling horizon. Therefore, all the limiting values constraints for the hydro system are specified for the \( k^{\text{th}} \) hydro unit during the \( j^{\text{th}} \) time interval.
Optimal power flow solution for hydro-thermal-wind generation system

\[ \begin{align*}
    P_{Hk}^{\text{min}} & \leq P_{Hkj} \leq P_{Hk}^{\text{max}} \\
    V_k^{\text{min}} & \leq V_{kj} \leq V_k^{\text{max}} \\
    q_k^{\text{min}} & \leq q_{kj} \leq q_k^{\text{max}}
\end{align*} \quad (5.9, 5.10, 5.11)

The operating limits of hydro powered units during the specified interval are restricted by lower and upper bounds as given in (5.9). Similarly reservoir capacity constraint and water discharge constraint of equivalent hydro powered units are considered in (5.10) and (5.11). Finally, the hydraulic continuity constraint and hydro power generation constraints are depicted by (5.12) and (5.13) respectively.

\[ V_{k(j+1)} = V_{kj} + \sum_{u=1}^{R_u} [q_{u(j-r)} + S_{u(j-r)}] - q_{k(j+1)} - S_{k(j+1)} + r_{k(j+1)} \quad (5.12) \]

\[ P_{Hkj} = c_{1k} V_{kj}^2 + c_{2k} q_{kj}^2 + c_{3k} (V_{kj} q_{kj}) + c_{4k} V_{kj} + c_{5k} q_{kj} + c_{6k} \quad (5.13) \]

The spillage rate for the hydraulic system is not taken in to account (for simplicity) and further, the electric loss from the hydro plant to the load is taken to be negligibly small.

Mathematical expressions of the terms described in (5.1) are discussed as below.

5.2.2.1. Cost of thermal power generation \((F_T)\):

The quadratic cost function representing the cost of thermal power generation for the thermal generators are considered the same with (2.3).

5.2.2.2. Cost of intermittent wind generation \((F_W)\):

This cost consists of three components.

\[ F_W = F_D + F_P + F_R \quad (5.15) \]

First one deals with cost of wind power purchase from wind power producer (WPP), second one deals with expected availability of surplus wind power during \(UE\) scenario, third one deals with expected availability of deficit wind power during \(OE\) scenario. These components
are named as direct cost, penalty cost and reserve cost respectively. Mathematical expression of $F_D, F_P, F_R$ are kept same as (2.4), (2.5) and (2.6) respectively.

5.2.2.3. Incorporation of Penalty functions for constraint violation

Principally in an optimization procedure, only those solutions are considered to be optimal which are obtained without violating any of the constraints. To ensure that the variable has not violated the limits during the optimization process, penalty functions are added to the objective function. The penalty functions try to force the unconstrained optimum towards the feasibility boundary by incorporating penalty terms into the fitness function that violate the constraints. In this work to achieve the above facts, the inequality constraints for real power line flow and bus voltage limits are incorporated as penalty functions represented as $P_{f_{c1}}$ and $P_{f_{c2}}$, which can be defined by the mathematical expressions (5.16) and (5.17). The functioning of the penalty factors can be explained as follows. As long as any variable $L_k$ remains within its defined minimum and maximum limits of $L_{min}$ and $L_{max}$, the penalty factor $P_{f_k}$ for the same shall become zero, else it will take a high value proportional to $pf$ [7].

\[
P_{f_{c1}} = \text{abs} [\text{sign}(P_{max} - P_k) - 1] \ast pf + \text{abs} [\text{sign}(P_{min} - P_k) + 1] \ast pf
\]  
(5.16)

\[
P_{f_{c2}} = \text{abs} [1 + \text{sign}(V_k - V_{max})] \ast pf + \text{abs} [1 - \text{sign}(V_k - V_{min})] \ast pf
\]  
(5.17)

5.3. TEST SYSTEM UNDER CONSIDERATION

IEEE-30 bus has been considered as the system under study. Bus one is the slack bus which is connected to the largest generating unit (Thermal). Generator at bus 2 is a thermal generating unit while that installed at 8th bus is modelled as an equivalent size hydro powered unit assumed to have replaced the existing thermal system with an installed capacity of 40 MW. The test system is further modified by replacing thermal units with same capacity wind farms located at fifth, eleventh and thirteenth buses. Each wind farm (WF) consists of several wind turbine generators (WTG) equipped with DFIGs. In this work, WF at bus number 5
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consists of ten WTG (each of 3 MW) having a total capacity of 30 MW. Similarly WF at bus numbers 11 and 13 each consist of eight WTG of 3 MW capacities with total capacities of 24 MW each.

5.4. OVERVIEW OF OPTIMIZATION METHODOLOGIES

For the purpose of optimization MBFA, GA and HA are employed to optimize both the objective function and their respective performances are compared. Brief overviews of the algorithms are discussed below.

5.4.1. Genetic Algorithm

Genetic Algorithm (GA) [100] is an established parallel search algorithm, which has been applied in varieties of optimization problems in power systems. In GA, the initial set of randomly generated population evolves through several generations to reproduce fitter candidate solutions using crossover and mutation operators. As the algorithm is based on idea of the survival of the fittest, the weaker off-springs get eliminated. During the search process, as there is no restriction on the search space, it enhances the robustness of GA. Details of the processes may be referred from Section 2.7.1.

5.4.2. Hybrid Algorithm

The Hybrid Algorithm (HA) is synthesized by implementing the mutation strategies of GA along with the BFA. The steps involved in HA can be referred from section 4.4.2.

5.4.3. Modified Bacteria foraging algorithm

The details of steps and flow chart used in MBFA can be referred from previously mentioned section 2.8.3.
5.5. SIMULATION AND RESULTS

The simulation for the proposed objective function is carried out in MATLAB/SIMULINK environment. The program was run on a 2.30 GHz, Intel(R) Core-i3, with 4 GB RAM notebook configuration. The analysis of system behaviour and optimal operating configuration is evaluated under different cases as described below.

5.5.1. Cost effective system operation

In this case the objective function (5.1) is optimized for the considered test system with three optimization techniques at the nominal operating conditions. The optimization algorithms are MBFA, GA and HA as discussed in sections 2.8.3, 2.8.1 and 4.4.2 respectively. In order to determine the best operating conditions in terms of operational economy, voltage security and fastness in operation a comparative analysis is carried out with the three above mentioned techniques. The details of parameters chosen for these algorithms are mentioned in the appendix.

Fig.5.2 and Fig.5.3 represent the convergence characteristics found with the three different algorithms plotted at 10000 and 20000 generations respectively. In Fig.5.2 the GA optimized curve converges at 3396.76 $/h and HA optimized curve converges approximately at 3389.42 $/h. But the MBFA optimized scenario provides the superior characteristics with a final solution of 3386.92 $/h. In order to find any further improvement in the characteristics, the number of generations during the optimization process is continued till $2\times10^4$ generations. However, MBFA retained its superiority over GA and HA in providing the most economic solution.
This is depicted in Fig.5.2 and presented in Table.5.1. It may be seen that when GA and HA converged at 3395.24$/h and 3389.34$/h respectively, MBFA converged at 3386.25$/h. Different components of the final optimized solution obtained with the three algorithms are tabulated in Table 5.1.

Table-5.1. Optimized generation schedule of the Hydro-Thermal-Wind system in \( p.u. \) with MBFA, HA and GA during normal operation.

<table>
<thead>
<tr>
<th>Generator Number</th>
<th>MBFA</th>
<th>HA</th>
<th>GA</th>
</tr>
</thead>
<tbody>
<tr>
<td>( P_g )</td>
<td>( Q )</td>
<td>( P_g )</td>
<td>( Q )</td>
</tr>
<tr>
<td>1</td>
<td>1.2010</td>
<td>0.9372</td>
<td>1.2640</td>
</tr>
<tr>
<td>2</td>
<td>0.6184</td>
<td>-0.3270</td>
<td>0.6200</td>
</tr>
<tr>
<td>5</td>
<td>0.3000</td>
<td>0.1100</td>
<td>0.3000</td>
</tr>
<tr>
<td>8</td>
<td>0.3686</td>
<td>-0.4500</td>
<td>0.3100</td>
</tr>
<tr>
<td>11</td>
<td>0.2210</td>
<td>0.3000</td>
<td>0.2200</td>
</tr>
<tr>
<td>13</td>
<td>0.2096</td>
<td>0.3000</td>
<td>0.2100</td>
</tr>
<tr>
<td>( P_{L(p.u.)} )</td>
<td>0.0854</td>
<td>0.0900</td>
<td>0.0922</td>
</tr>
<tr>
<td>( TC($/h) )</td>
<td>3386.25</td>
<td>3389.34</td>
<td>3395.24</td>
</tr>
</tbody>
</table>
Optimal power flow solution for hydro-thermal-wind generation system

Fig. 5.2. Convergence characteristics of HTW system with GA, HA and MBFA techniques after $10^4$ generations

Fig. 5.3. Convergence characteristics of HTW system with GA, HA and MBFA techniques after $2\times10^4$ generations
In the above Table 5.1, \( P_L \) represents the real power transmission loss and \( TC \) is the total system operational cost. As seen from the table, the loss is minimum (0.0854 \( p.u. \)) with MBFA optimized schedule while it is maximum (0.0922 \( p.u. \)) with GA optimized schedule. The loss comes within these values i.e. 0.0900 \( p.u. \) with HA optimized schedule.

Further, as depicted in Fig.5.4, the computational time of convergence expressed in minutes is also least with MBFA.

![CPU run time](Image)

Fig.5.4. Time elapsed during the different optimization processes.

The above findings presented by Table.5.1 and Fig.5.1-.5.3, depicts the superiority of MBFA optimized schedule over GA and HA in terms of

- Minimum operating cost of the HTW generation system.
- Operating the power system with minimum transmission loss.
- Obtaining the optimal convergence characteristics within minimum time.
At the outset, the wind power penetration (WPPN) level was kept at 25%, for which the results have already been discussed above. The impact of increasing the WPPN level on the overall system operation was decided to be studied, by increasing the same to 45%.

In this context, MBFA is used to optimize the objective function (5.1) and the cost convergence characteristic of the modified system with 45% WPPN is depicted in Fig.5.5.

Comparing the characteristics presented by MBFA technique for the HTW system with two different WPPN levels as depicted in Fig.5.2. and Fig.5.5, a notion may be drawn that with 20% increment in WPPN the system operation cost is decremented approximately by 15%. The real power transmission loss with 45% WPPN reduces to 0.0544 p.u. which was 0.0854 p.u. with 25% WPPN. Fig. 5.6 depicts hourly hydro discharge from the reservoir. After knowing the water discharges, the reservoir volumes at different scheduling intervals are found out. Then, the hydro generations are calculated using (5.13). Fig.5.7 depicts the trajectories of the reservoir storage volume during different scheduling stages.
Optimal power flow solution for hydro-thermal-wind generation system

Fig. 5.6. Hourly discharge (×10⁴ m³) of plant during different stages.

Fig. 5.7. Variation of reservoir volume during the scheduling horizon.
5.5.2. Voltage secure system operation

In order to test the competence of MBFA optimized generation schedule in providing an improved voltage response during normal and stressed operating condition, a comparison is made between the three optimization techniques. This is presented as

Case 1: Normal operating Condition

Case 2: Stressed operating Condition

Case 1:

The system voltage response during Case 1 is depicted in Fig. 5.8. It shows that though a minor improvement in bus voltage is shown by HA schedule over GA, remarkable enhancement in voltage in most of the buses is presented by MBFA optimized schedule. The numerical analysis of this fact is depicted in Table 5.2.

![Fig. 5.8. HTW System voltage profile during normal operating condition.](image-url)
As seen from the Table-5.2, the minimum and mean voltage magnitude obtained with MBFA is 0.9098 p.u. and 0.9510 p.u. respectively. These are higher than the corresponding voltages obtained with HA and GA. Moreover, comparing the standard deviations (SD) obtained with the three techniques, MBFA presents the minimum value i.e. 0.0323 p.u. as compared to SD obtained with HA and GA which are 0.0328 p.u. and 0.0330 p.u. From these findings, the superiority of MBFA optimized schedule in depicting a superior voltage during normal system operation is established.

**Case-2:**

In this case, the operational competency of MBFA is tested with HA and GA during stressed operating conditions. To verify this, the system operation is subjected to stress situation by intentionally introducing load increase (LI) scenario in one of the randomly chosen bus in the power network. At the outset load is increased in bus number 12 in steps of 20% from its nominal condition load. Thus bus-12 is gradually subjected increase of load at 20%, 40%, 60%, 80% and 120% steps. These are depicted in Fig.5.9 - Fig.5.13. From the figures it may be seen that in every load increase scenario, the voltage obtained with MBFA schedule provides relatively superior performance. The mathematical analysis of the voltage improvement is presented in Table-5.3.

<table>
<thead>
<tr>
<th>Case 1</th>
<th>Optimization Algorithm</th>
<th>Statistical properties of Bus voltage during normal Operating Conditions (p.u.)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Mean</td>
</tr>
<tr>
<td>MBFA</td>
<td>0.9510</td>
<td>0.9098</td>
</tr>
<tr>
<td>HA</td>
<td>0.9485</td>
<td>0.9068</td>
</tr>
<tr>
<td>GA</td>
<td>0.9474</td>
<td>0.9055</td>
</tr>
</tbody>
</table>
Fig. 5.9. System voltage response when bus-12 is subjected to 20% LI.

Fig. 5.10. System voltage response when bus-12 is subjected to 40% LI.
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Fig. 5.11. System voltage response when bus-12 is subjected to 60\% LI.

Fig. 5.12. System voltage response when bus-12 is subjected to 80\% LI.
Table 5.3: Relative system voltage improvement analysis during LI condition.

<table>
<thead>
<tr>
<th>Sr No</th>
<th>Bus voltage characteristics</th>
<th>Voltage during stressed (Load increased)</th>
<th>operating Conditions (p.u.)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>20%</td>
<td>40%</td>
</tr>
<tr>
<td></td>
<td>MBFA</td>
<td>Mean</td>
<td>0.9660</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Min</td>
<td>0.9294</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Max</td>
<td>1.0500</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SD</td>
<td>0.0292</td>
</tr>
<tr>
<td></td>
<td>HA</td>
<td>Mean</td>
<td>0.9642</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Min</td>
<td>0.9271</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Max</td>
<td>1.0500</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SD</td>
<td>0.0296</td>
</tr>
<tr>
<td></td>
<td>GA</td>
<td>Mean</td>
<td>0.9633</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Min</td>
<td>0.9261</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Max</td>
<td>1.0500</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SD</td>
<td>0.0297</td>
</tr>
</tbody>
</table>

Fig 5.13: Comparative analysis between 20% and 120% LI.
From the Table-5.3, it may be summarized that..

- For 20% load increase, the mean and minimum system voltage as found from MBFA schedule is 0.9660 p.u. and 0.9294 p.u. while those with HA optimized schedule is 0.9642 p.u. and 0.9271 p.u. respectively and from GA optimized schedule 0.9633 p.u. and 0.9261 p.u.

- Besides these findings, the standard deviation (SD) with 20% LI for MBFA, HA, GA optimized schedule is 0.0292 p.u, 0.0296 p.u and 0.0297 p.u. respectively.

- Thus the voltage deviation is minimum with MBFA case while it is moderate with HA and maximum with GA, though the difference is not significant.

- For each LI case, the mean and minimum system as depicted from Table.5.3. bus voltage with MBFA optimized schedule is higher than that of the HA and GA schedule and the SD is consistently less in magnitude in MBFA case as compared to HA and GA even during severe stressed situation of 120% LI.

- Comparing the other parameters in LI percentages up-to 120%, it clearly demonstrates the superiority of MBFA in providing a relatively robust system voltage performance.

5.5.3. Comparative assessment of system Voltage of HTW system versus WT system

In this scenario, the operational efficiency of Hydro-Thermal-Wind (HTW) generation system with respect to Wind-Thermal (WT) system is compared in terms of achieving voltage secure system operation.

The analysis is carried out in four operational environments as mentioned below.

**Scenario1:** With 25% wind power penetration

**Scenario2:** With 45% wind power penetration

**Scenario3:** With 25% wind power penetration in the presence of STATCOM.

**Scenario4:** With 45% wind power penetration in the presence of STATCOM.
5.5.3.1. Scenario 1:

In this case the optimized generation schedule with MBFA for both WT and HTW generation system is obtained. Taking this into consideration, the system voltage during normal operating condition is evaluated and the comparative analysis is presented in Figure 5.14.

![Figure 5.14. System voltage response with 25% wind penetration. (Scenario1)](image)

From the above figure, it may be pointed out that WT generation system with 25% wind penetration has provided a relatively better voltage response as compared to HTW system though the improvement in voltage at majority of buses is very minor. Statistical analyses of these results are enumerated in Table 5.4. Therefore, to study the performance of both the systems (WT and HTW) in the presence of increased wind penetration, contribution of wind power to the overall generation system is increased to 45%. This leads to the next section.
5.5.3.2. Scenario 2:

Figure 5.15 demonstrates the impact of increased wind penetration on the system voltage. The numerical analysis of voltage improvement is tabulated in Table 5.4.

![Graph showing system voltage response with 45% wind penetration (scenario 2)](image)

**Table 5.4. Comparative analysis of system voltage with different wind penetration.**

<table>
<thead>
<tr>
<th>Sr No</th>
<th>Bus voltage characteristics</th>
<th>Analysis of system voltage (p.u.) in the presence of 25% wind penetration</th>
<th>Analysis of system voltage (p.u.) in the presence of 45% wind penetration</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>WT</td>
<td>HTW</td>
</tr>
<tr>
<td>1</td>
<td>MBFA</td>
<td>Mean 0.9523</td>
<td>0.9510</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Min 0.9113</td>
<td>0.9098</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Max 1.0500</td>
<td>1.0500</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SD 0.0320</td>
<td>0.0323</td>
</tr>
</tbody>
</table>
From the above results it may be depicted that

- With 25% wind penetration, the mean and minimum WT system voltage is 0.9523 \( p.u \) and 0.9113 \( p.u \) respectively whereas for HTW system these are 0.9510 \( p.u \) and 0.9098 \( p.u \) respectively.
- SD as found with 25% wind penetration is 0.0320 for WT system while that is 0.0323 \( p.u \) for HTW system.
- Thus, in mean voltage evaluation, WT system shows 0.13% improvement over HTW system.
- In minimum voltage evaluation, WT system shows 0.15% improvement over HTW system.
- It is observed that for less wind penetration, marginal improvement in system response can be shown by WT system over HTW system.
- For 45% wind penetration, the percentage of mean voltage improvement for WT system increases up to 0.31% over HTW system.
- Similarly, the percentage of improvement in the magnitude of minimum voltage for WT system increases by 0.38% over HTW system.
- The SD of WT system is found to be less than that of the HTW system.
- Also, while increasing the wind penetration levels it is found that
  - The mean system voltage increases from 0.9523 \( p.u \) to 0.9679 \( p.u \) for WT system while that increases from 0.9510 \( p.u \) to 0.9648 \( p.u \) for HTW system.
  - The minimum system voltage increases from 0.9113 \( p.u \) to 0.9278 \( p.u \) for WT system while that increases from 0.9098 \( p.u \) to 0.9240 \( p.u \) for HTW system.
  - The SD in voltage reduces from 0.0320 \( p.u \) to 0.0296 \( p.u \) for WT system while that reduces from 0.0323 \( p.u \) to 0.0302 \( p.u \) for HTW system. In order to figure out any further improvement in the system voltage for both the system
as discussed above, STATCOM is incorporated at the weakest bus in the network. This is depicted in the next section.

5.5.3.3. Scenario 3:

In this scenario, relative performance of both the WT and HTW system in terms of maintaining a secure voltage in the presence of STATCOM is analysed when wind power penetration level is 25% of system generation capacity.

![System voltage response with 25% wind penetration with STATCOM.](image)

From Fig.5.16, it may be depicted that significant improvement in the voltage magnitude is observed for both the systems after the incorporation of STATCOM in the system. But, here also the WT system shows marginal improvement in voltage as compared to HTW system.
5.5.3.4. Scenario 4:

In this scenario, relative performance of both the WT and HTW system in terms of maintaining a secure voltage in the presence of STATCOM is analysed when wind power penetration level is increased from 25% in Scenario 2 to 45% in Scenario 4.

![Graph showing system voltage response with 45% wind penetration with STATCOM.](image)

Similar to previous results as illustrated by Fig. 5.16, WT system with STATCOM, considerably improves the system voltage as compared to WT system without STATCOM and HTW system with STATCOM. The statistical analyses of the above findings are enumerated in Table. 5.5.
Table-5.5. Comparative analysis of system voltage with different wind penetration level in the presence of STATCOM.

<table>
<thead>
<tr>
<th>Bus voltage characteristics</th>
<th>Analysis of system voltage (p.u.) with STATCOM for 25% wind penetration</th>
<th>Analysis of system voltage (p.u.) with STATCOM for 45% wind penetration</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>WT</td>
<td>HTW</td>
</tr>
<tr>
<td>MBFA</td>
<td>Mean</td>
<td>0.9734</td>
</tr>
<tr>
<td></td>
<td>Min</td>
<td>0.9440</td>
</tr>
<tr>
<td></td>
<td>Max</td>
<td>1.0500</td>
</tr>
<tr>
<td></td>
<td>SD</td>
<td>0.0272</td>
</tr>
</tbody>
</table>

On comparison between the data obtained from Table.5.4. and Table.5.5., the salient findings may be summarized as below.

The presence of STATCOM for 25% wind penetration has

- Enhanced the mean WT system voltage by 0.0211 p.u. and minimum system voltage by 0.0327 p.u.
- Reduced the standard deviation of voltage by 0.0048 p.u.
- Similarly upgraded the mean HTW system voltage by 0.0215 p.u. and minimum voltage by 0.0332 p.u.
- Decreased the SD for HTW system by 0.005 p.u.

Similar conclusions may be drawn for incorporation of STATCOM with 45% of wind penetration.

- It is important to note that, even after the installation of STATCOM in both the systems i.e. WT and HTW, the evaluating parameters have significantly shown improvement.
but still the superiority of maintaining a relatively enhanced system voltage is presented by WT system compared to HTW generation system.

- Considering all the scenarios, it may be summarized that with less wind penetration, approximately 20%-25%, WT system behaves almost similar to HTW system in terms of maintaining a voltage secure operation.

- But with enhancement in wind power penetration level nearly 45%, considerable improvement in the system voltage may be observed compared to HTW system.

In order to further evaluate the robustness of the optimization techniques on improving the relative system voltage performances of the previously mentioned scenarios during stressed operating conditions, a comparative analysis is conducted between them. In this context, stressed operating conditions are created in the system by intentionally introducing line outages (LO) at few of the randomly chosen lines one at a time. This is presented in Fig.5.18 – Fig.5.19.

From Fig.5.18 and Fig.5.19 it may be depicted that MBFA optimized schedule presents relatively superior voltage performance during different LO conditions as compared to GA and HA optimized schedules. Therefore, MBFA is selected for evaluating and finding the best operating performance in terms of maintaining an improved system voltage among all the four above mentioned scenarios during LO situations. This is applied for the HTW system. In this context, two separate LO events are created in the HTW system one after another in the form of outage of line 15-18 and 10-20. This is depicted in Fig. 5.20 and Fig.5.21 respectively. It may be clearly pointed out that scenario 4 presents a significant improvement in the system voltage even during different stressed operating conditions.
Fig. 5.18. Comparative analysis of HTW system voltage response during Scenario-1 for outage of line 8-28 with GA, HA and MBFA optimized schedule.

Fig. 5.19. Comparative analysis of HTW system voltage response during Scenario-3 for outage of line 10-20 with GA, HA and MBFA optimized schedule.
Fig. 5.20. Comparative analysis of HTW system voltage response during different Scenarios for outage of line 15-18 with MBFA.

Fig. 5.21. Comparative analysis of HTW system voltage response during different Scenarios for outage of line 10-20 with MBFA.
It is already demonstrated from Fig.5.13- Fig.5.16 that during normal operating condition, the WT system portrayed superior voltage profile than HTW system in all the four scenarios. Therefore, to validate the occurrence of similar consequences, both WT and HTW system behaviour is tested during LO conditions. The findings of this analysis are presented in Fig.5.22 - Fig.5.24. It may be concluded that for all the four earlier stated scenarios WT system depicts a superior system voltage performance even during stressed operating conditions. Though the improvement is not significant for low wind penetration but it is remarkable during high wind penetration scenarios.

Fig.5.22. Comparative analysis of WT and HTW system voltage response during Scenario-1 and Scenario-2 for outage of line 27-30 with MBFA.
Fig. 5.23. Comparative analysis of WT and HTW system voltage response during Scenario-3 and Scenario-4 for outage of line 14-15 with MBFA.

Fig. 5.24. Comparative analysis of WT and HTW system voltage response during Scenario-3 and Scenario-4 for outage of line 25-27 with MBFA.
The salient findings drawn from Fig.5.22 - Fig.5.24 is enumerated below

- During stressed operating condition (i.e. outage of line 27-30), HTW system for Scenario-2 depicts an improved voltage response than Scenario-1 (as shown in Fig.5.22).
- But the voltage response as shown by WT system for Scenario-2 during the above mentioned LO condition is superior to HTW system (as shown in Fig.5.22).
- Thus a notion may be drawn that even in the absence of shunt FACTs devices, WT system presents comparatively a better voltage secure operation than HTW system under stressed operating environment.
- In the presence of STATCOM, a comparison is made between HTW system operation under Scenario-3 and Scenario- 4 during outage of randomly chosen lines (14-15) and line (25-27). This is shown in Fig.5.23 and Fig.5.24 respectively.
- It is found that HTW system while operating in Scenario- 4 presents an improved voltage response than Scenario-3. But as previously found for Scenario-2, WT system in Scenario-4 depicts a superior voltage performance compared to HTW system though the improvement is marginal.
- Therefore it may be concluded that, as far as maintaining the voltage security issue is concerned, WT operation may be a preferred option than HTW operation during substantial wind penetration.

5.6. DISCUSSION

The primary objective of this chapter is find out the optimal generating and operating conditions to minimize the cost of hydro-thermal-wind generation system, reduce the real power loss. The optimum schedule should be able to operate the system in a voltage secure manner. All the multiple numbers of objectives are combined to form a single suitable
objective function with the help of penalty functions. The proposed MBFA is utilized to solve the problem. Some of the thermal units of IEEE-30 bus system are replaced with equivalent capacity hydro and wind farms. A STATCOM is also placed at the weak bus in the system. The objective function was proposed which take several operational constraints into consideration. The efficiency of MBFA schedule is compared with the GA and HA optimized schedules. The optimal schedules for the objective functions are then tested for their operating efficiencies with various types and levels of stressed conditions. MBFA is found to have not only given a better solution than other mentioned optimization algorithms, but the optimum schedule has also operated the system in a more secure manner. Different levels of wind power penetration are considered, so that its effect on varying hydro and thermal power generation levels may be seen and the optimum total generation cost may be evaluated. The problem basically seeks the most optimum thermal power generation cost with the extent of availability of hydro and wind powers, during the scheduling horizon.

Though this work mainly concentrates on the steady state operational aspects like cost, loss and voltage security, the dynamic and transient stability constraints can also be incorporated into the multi-objective optimization problem and may be taken up as future work.