IMPROVEMENT OF FREQUENCY REGULATION SUPPORT IN DFIG BASED WIND INTEGRATED HYDRO THERMAL POWER SYSTEM

3.1. INTRODUCTION

Interconnected power system comprises of thermal, hydro, and nuclear power generation. Nuclear units cannot participate in AGC due to their high efficiency and usually operate at base load close to their maximum output [36]. However, plants utilizing gas or diesel as the energy source do not play very significant role in AGC of a large power system, as these plants constitute smaller percentage of total system generation and generally their primary role is to meet peak demands only. Therefore, the responsibility of frequency control is primarily shared either by thermal or hydro based generating units [36]. The characteristics of hydro turbines differ from those of steam turbines in many respects [36]. To analyze the operational issues of a hydro-thermal integrated system, some literatures related to research work in the area of AGC [161-163] have studied two equal area of widely different characteristics. Further, the impact of wind power based generators in frequency regulation behavior of a hydro-thermal system becomes another area of interest particularly when the penetration of WECS becomes substantially high and comparable with the other two resources. In this scenario, it may become necessary to comprehensively examine about the methodologies with which wind units may efficiently participate in the process of system frequency support [8, 9, 164].

The VSWTs are designed to be able to vary their rotational speed in some ranges during normal operations, making them capable to utilize their kinetic energy stored in the turbine-generator. In this manner, it may provide active power support in
a short term basis in the event of frequency deviations in the system [8]. The research work in [9] focuses on the dynamic participation of DFIG to system frequency responses of two-area interconnected hydro-thermal power system. The work probes into the impact of varying levels of active power support from the wind farm on frequency control mechanism of the system.

In another work [54], it has been found that the response of conventional generator is considerably slower than that of the equivalent generation from wind resources, as the later can deliver the deficient real power into the system in a faster manner compared to the conventional units. In the event of any frequency disturbance, the conventional units are found to provide frequency support only after the frequency transient is over. In all the above discussed literatures, the impacts of wind power penetration in different areas of hydro-thermal power stations have not been extensively analysed from different perspectives. Therefore, the work here is motivated to look into the same with the following primary objectives of research in a hydro-thermal-wind system environment.

1. Comparison of mechanical governor and electrical governor in hydro area of two area hydro-thermal system.
2. Response of hydro-thermal system and thermal-thermal system for step load change in different area.
3. The performances of wind power penetration in a hydro thermal power system in terms of its frequency regulating characteristics.

The preliminary literatures related to thermal and wind systems are discussed in the previous two chapters. For discussing wind integrated hydro-thermal system only hydro systems are elaborated in this chapter. In this regard, a fundamental overview of different types of governor in a hydro system needs to be discussed here.
3.2. HYDRAULIC GOVERNING SYSTEM

The primary objective of a governor for a hydraulic unit is to control the speed and load. The performance of hydraulic turbines is influenced by the characteristics of the water column feeding the turbine. In the hydro turbine system, the changes in the flow lag behind the corresponding changes in the gate openings, owing to the inertia of water [3]. The turbine and the penstock characteristics are determined as follows.

Velocity of water (U) = K \times G \times \sqrt{H} \quad (3.1)

Where, G = The position of gate opening

H= Hydraulic head at the gate

K= A proportionality constant

For small displacements about an operating point,

\[ \Delta U = \frac{\partial U}{\partial H} \Delta H + \frac{\partial U}{\partial G} \Delta G \quad (3.2) \]

Replacing the appropriate expression for the partial derivatives and dividing through

U_0 = K \times G_0 \times \sqrt{H_0} \quad \text{gives}

\[ \frac{\Delta U}{U_0} = \frac{1}{2} \frac{\Delta H}{H_0} + \frac{\Delta G}{G_0} \quad (3.3) \]

The subscript ‘0’ and ‘\Delta’ denote initial steady-state value and small deviations respectively. In normalized form equation 3.3 can be written as,

\[ \Delta \bar{U} = \frac{1}{2} \Delta \bar{H} + \Delta \bar{G} \quad (3.4) \]

Turbine mechanical power (P_m) = K' \times H \times U \quad (3.5)

Linearizing by considering small displacement and normalizing by dividing both sides by $P_{m0} = K'H_0U_0$ the (3.5) can be written as,
According to the Newton’s second law of motion, acceleration of water column due to change in head at the turbine, may be written as,

\[
(pLA) \frac{d\Delta U}{dt} = -A (\rho a_g) \Delta H
\]  

(3.8)

Where; \( L \) = Length of the conduit
\( a_g \) = Acceleration due to gravity,
\( \rho \) = mass density,
\( A \) = area of the pipe

Expressing equation (3.8) in normalized form by dividing \( A \rho a_g H_0 U_0 \) it becomes,

\[
T_w \times \frac{d\overline{U}}{dt} = - \Delta \overline{H}
\]  

(3.9)

Where, \( T_w = \frac{LU_0}{a_g H_0} \).

Here, \( T_w \) = Water starting time, that represents the time required for a head \( H_0 \) to accelerate the water in the pen stock from stand still to the velocity \( U_0 \). \( T_w \) varies with load. Its value typically at full load lies between 0.5 sec and 4 sec [3]. Equation (3.9) explains an important characteristic of hydraulic plant that, if back pressure is applied at the end of the pen stock by closing the gate then, the water in the pen stock will decelerate.

From (3.4) and (3.9), the relationship between change in velocity and change in gate position can be expressed as;

\[
T_w \times \frac{d\overline{U}}{dt} = 2(\Delta \overline{G} - \Delta \overline{U})
\]  

(3.10)
Substituting Laplace operator $s$, (3.10) can be written as:

$$T_w \times s \Delta \bar{U} = 2(\Delta \bar{G} - \Delta \bar{U}) \quad (3.11)$$

$$\Delta \bar{U} = \frac{1}{1 + \frac{1}{2} T_w s} \Delta \bar{G} \quad (3.12)$$

Replacing $\Delta \bar{U}$ by using (3.4) and (3.7) and rearranging we can express

$$\frac{\Delta P_m}{\Delta G} = \frac{1 - T_w S}{1 + 0.5 T_w S} \quad (3.13)$$

Equation (3.13) represents transfer function of hydraulic turbine. It reveals the response of turbine power output changes to a change in gate opening for an ideal turbine. It can be observed that, the hydro turbine is a non-minimum phase linear time-invariant (LTI) system which has unstable zeros (i.e., open-loop zeros in the right half of the $s$ - plane are defined as non-minimum phase systems [3, 8]). A change in the gate position at the foot of the penstock causes the reduced pressure across the turbine. However, the flow does not change immediately due to high water inertia causing the power of the turbine to reduce temporarily. Therefore, the initial power surge of a hydro turbine is opposite to that is desired [3].

Due to this non-minimum phase characteristic, the governor of a hydro turbine does not have a simple steady-state droop characteristic. Therefore, for a stable operation a large transient (short-term) droop (smaller gain) is needed [3]. This is accomplished by providing a rate feedback or transient droop compensating term as shown in Fig. 3.1. The rate of feedback retards or limits gate movement until the water flow and power output has time to catch up, resulting governor with a high droop (low gain) for fast speed deviation and the normal low droop (high gain) during its steady state operation.
In the above figure $R_p$ and $R_T$ represent hydraulic governor permanent droop and temporary droop. $T_{Rw}$ is hydraulic governor reset time constant. The hydro power stations are equipped with mechanical hydraulic governors but modern hydro units are normally equipped with electro hydraulic governors in which the electronic apparatus is used to perform low power functions associated with speed sensing and droop compensation [165]. The comparison of performances of mechanical hydraulic and electro hydraulic governor can be critically analyzed if a mechanical hydraulic governor is replaced by an electro hydraulic governing system. The details about the mechanical hydraulic governor and electro hydraulic governor [166] are described below.

### 3.2.1. Mechanical hydraulic governor

The transfer function model of mechanical hydraulic governor [36, 167] is shown in Fig. 3.2. The $R_T$ in mechanical governor plays a very important role in the stability of the system than $R_p$ because, during transient conditions by utilizing a transient droop compensation function, the valve movement becomes slower during transients [3]. The initial opposite power surge lasts for 1 to 2 s depending on the water starting time and the load step. Because of this phenomenon, the decelerating
power (energy) is higher for a hydro turbine compared to a steam turbine with/without the reheat [36] during a generation deficit situation.

\[
\Delta f(s) \rightarrow \frac{-1}{R} \rightarrow \frac{1}{1 + sT_1} \rightarrow \frac{1+sT_{Rw}}{1+sT_2} \rightarrow \Delta P(s)
\]

**Fig. 3.2.** Transfer function model of mechanical governor.

### 3.2.2. Electro-hydraulic governor

Modern speed governors for hydraulic turbines use electro-hydraulic systems. Functionally, their operation is very similar to that of mechanical hydraulic governor. Speed sensing, permanent droop, temporary droop and other measuring and computing functions are performed electrically. The electric components provide greater flexibility and improved performance with regard to dead bands and time lags. The dynamic characteristics of electric governors are usually adjusted to be essentially similar to those of the mechanical hydraulic governor [3]. The electro-hydraulic governors are provided with three-term controllers with proportional-integral-derivative (PID) action as shown in Fig. 3.3.

**Fig. 3.3.** Electro-hydraulic governors with PID action.

### 3.3. TWO AREA HYDRO THERMAL SYSTEM WITH DFIG

The Linearized model of two-area interconnected power system for the load frequency control is a mixture of conventional hydro and thermal power generating
systems [3] along with DFIG-based wind turbine generators shown in Fig. 3.4. The model of a two area hydro-thermal system for a load-frequency analysis is an established model that can be referred from [3]. The system consists of two generating areas of equal size, the first area comprising a thermal system with reheat turbine and the second area comprising a hydro system. Thermal and hydro generating units are represented by traditional units’ blocks [9] with 20% penetration of wind power. As highlighted in the Fig. 3.4 the generators for wind power in both the areas are considered as DFIGs which can feed real power through both the stator and rotor of the induction generator interfacing through two back to back power electronics converters. The contribution of DFIG for frequency support is described in chapter 2 with greater detail.

Hydro-thermal system with penetration of DFIG based wind power after step load perturbation has been analyzed numerically in MATLAB/Simulink. The presence of DFIG in linearized model of the test system as shown in Fig. 3.4 has an effect of modifying the values of $R$ and $H$, with these changed values directly dependent on the $L_p$. Therefore, an equivalent modified system is replaced by estimating the changes in $R$ and $H$ for different $L_p$. The effect of varying wind power penetration, in terms of percentage of total power generation, on the values of equivalent $R$ and $H$ are discussed in the next section.

### 3.3.1. Estimation of $R$ and $H$ with increased penetration of wind power by DFIG

**without/with frequency support in hydro system**

The equivalent hydro thermal system with wind penetration is developed by augmenting the wind contribution with the following assumptions [8].

- The percentage (%) wind penetration means a % reduction in the existing generating units, i.e., a $w$% increase in wind penetration will reduce $w$%
system inertia. The steady state load balance is maintained by the \( w \) % wind generation.

- The droop settings \( (R) \) of the individual generators remain the same. Because, there is an increase in the equivalent droop (decrease in the equivalent gain) with increasing \( L_p \).
- The existing hydro generating units have enough spinning reserves to take up any generation mismatch.
- Calculation of change in \( R \) in the hydro system with increasing \( L_p \) is same as that of thermal system. Similarly, the changes in \( H \) without frequency support are same as that of thermal system [9] as explained earlier in section 2.6. However, for estimating the system inertia constant \( H \) in presence of \( L_p \) wind penetration level with frequency support, \( T_d \) as given in (2.4) and (2.6) can be calculated by putting \( \frac{t_{G,ss}}{2} \) as given below for hydraulic turbine.

\[
\frac{t_{G,ss}}{2} = H_{eq} R_T \left( 1 - \frac{D}{\frac{1}{R} + D} \right)
\] (3.14)

It may be noticed that, while calculating the delay involved in governor valve position for hydraulic unit, temporary droop \( R_T \) is used because during transient conditions, the effect of \( R_T \) prevails for a hydro governor. The estimated values of \( R \) and \( H \) for integrated operation of thermal-hydro and DFIG based wind power system for different levels of wind penetration are shown in Table 3.1.
Table 3.1 Changes in $R$ and $H$ for thermal-hydro generating units with different levels of wind power.

<table>
<thead>
<tr>
<th></th>
<th>With frequency support ($H_{eq,Lp}$)</th>
<th>Without frequency support ($H_{Lp}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$L_p$ 0%</td>
<td>10%</td>
</tr>
<tr>
<td>Thermal-wind</td>
<td>2.4</td>
<td>2.6667</td>
</tr>
<tr>
<td>Hydro-wind</td>
<td>5</td>
<td>4.8669</td>
</tr>
</tbody>
</table>

Fig. 3.4. Two area interconnected hydro thermal power system with DFIG.

3.4. RESULTS ANALYSIS

Before examining the effect of wind power penetration in a hydro-thermal system, it is necessary to analyze the hydro thermal system without wind power support. In this context, a comparative study of the characteristics of hydro thermal system towards the frequency regulation capabilities may be required at the outset.
3.4.1. Hydro-thermal (H-T) system comparing electrical and mechanical governor

As shown in Fig. 3.4, the AGC model of the interconnected two area hydro-thermal system has the first area comprising of single stage reheat thermal system and the second hydro area assumed to be having electrical governor. The two area system does not have wind penetration in the system. For a preliminary analysis of the system, data related to H-T system, which are reported in [3, 5], are considered and the same is given in the Appendix A.6. For the system, 1% SLP has been considered either in thermal or hydro area. Proceeding similar to the approach discussed in earlier chapter (in section 2.8), the objective function $J$ is defined by considering the same performance indices as before. The controller parameters ($K_{1i}$, $K_{2i}$) in both the areas are optimized using CSA. The brief overview of CSA is given in section 2.10.3. The simulations are performed using MATLAB/Simulink.

To compare the action of hydro governors in an interconnected two area hydro-thermal system mechanical governor as shown in Fig. 3.2 is placed in place of electrical governor shown in Fig. 3.4. Optimization of the same objective function $J$ is carried out with the help of CSA. Table 3.2, depicts the optimized controller gains in both the areas when mechanical and electrical governors are operating. Considering their respective optimized gains, the dynamic performance obtained with mechanical and electrical governors are compared, for cases of load variation in different areas. The response of $\Delta f_1$, $\Delta f_2$, and $\Delta P_{tie}$ are shown in Fig. 3.5 and Fig. 3.6 when loads are varied in the two different areas respectively.

Fig. 3.5 reveals the response of $\Delta f_1$, $\Delta f_2$, and $\Delta P_{tie}$, for 1% SLP in thermal area. Similarly when the same amount of perturbation is introduced in the hydro area the responses obtained, are depicted in Fig. 3.6.
Fig. 3.5. Performance of H-T in terms of $\Delta f_1$, $\Delta f_2$ and $\Delta P_{tie}$ comparing mechanical and electrical governor with 1% SLP in thermal area.
Fig. 3.6. Performance of H-T in terms of $\Delta f_1$, $\Delta f_2$ and $\Delta P_{tie}$ deviation comparing mechanical and electrical governor with 1% SLP in hydro area.
It can be seen from both the Fig. 3.5 and Fig. 3.6 that, the system settles down the transient perturbation at a faster rate with better dynamic characteristics when an electrical governor is operating compared to the case of utilizing the mechanical governor. Both in terms of maximum peak deviations (undershoot/overshoot) and settling time, the electrical governor stabilizes the oscillation faster than the mechanical governor. Further, it is observed that with load perturbation occurring in the hydro area, the system oscillations are greater than the case when equivalent perturbation occurs in the thermal area. For clear comparison about the impact of load variation in a two area hydro-thermal system with electrical governor 1% SLP is done in individual areas and also in both areas. The dynamic responses of $\Delta f_1$, $\Delta f_2$ and $\Delta P_{tie}$, for 1% SLP in area-1, area-2 and in both the areas are shown in Fig. 3.7.

### 3.4.2. Comparison of hydro-thermal system with thermal-thermal system

The response of hydro-thermal and thermal-thermal interconnected two area power system with load variation in either area are compared to show the efficiency towards frequency regulation. With tuned integral controller $K_{i1}$ and $K_{i2}$ considered as per the optimized values given in Table 3.2, responses of $\Delta f_1$, $\Delta f_2$ and $\Delta P_{tie}$ for 1% SLP in thermal area are depicted in Fig. 3.8. Further, the responses of $\Delta f_1$, $\Delta f_2$ and $\Delta P_{tie}$ for 1% SLP in hydro area in the interconnected hydro-thermal system is shown in Fig. 3.9.

<table>
<thead>
<tr>
<th>Nature of the Two areas</th>
<th>Type of Governing System in Hydro area</th>
<th>Area in which load is perturbed</th>
<th>$K_{i1}$</th>
<th>$K_{i2}$</th>
<th>$J$</th>
</tr>
</thead>
<tbody>
<tr>
<td>T-T</td>
<td>---</td>
<td>First Area</td>
<td>-0.4986</td>
<td>-0.4986</td>
<td>96.5328</td>
</tr>
<tr>
<td>H-T</td>
<td>Electrical</td>
<td>First Area</td>
<td>-2.2467</td>
<td>0.0093</td>
<td>62.7130</td>
</tr>
<tr>
<td>H-T</td>
<td>Electrical</td>
<td>Second Area</td>
<td>-2.2824</td>
<td>-0.0973</td>
<td>78.0820</td>
</tr>
<tr>
<td>H-T</td>
<td>Mechanical</td>
<td>First Area</td>
<td>-0.3734</td>
<td>0.0152</td>
<td>151.4583</td>
</tr>
<tr>
<td>H-T</td>
<td>Mechanical</td>
<td>Second Area</td>
<td>0.0109</td>
<td>-0.8424</td>
<td>184.4648</td>
</tr>
</tbody>
</table>
Fig. 3.8 reveals that, the response of the steam turbine governing system is significantly slower than that of hydro turbine governing system. Due to high water inertia in hydro system, it arrests the frequency deviation earlier than thermal system.

Fig. 3.7. Responses of H-T in terms of $\Delta f_1$, $\Delta f_2$ and $\Delta P_{tie}$, for 1% SLP in area-1, area-2 and in both area.
**Fig. 3.8.** Responses of $\Delta f_1$, $\Delta f_2$ and $\Delta P_{\text{tie}}$ in comparison between interconnected H-T and T-T, for 1% SLP in thermal area.
Fig. 3.9. Responses of $\Delta f_1$, $\Delta f_2$ and $\Delta P_{tie}$ in comparison between interconnected H-T and T-T, for 1% SLP in hydro area.
Examining the responses it is also observed that thermal-thermal (T-T) take more settling time than the H-T with 1% SLP in area-1. The performance indices $MDR$ and $T_S$ of H-T as given in Table 3.4, are better compared to their corresponding values in T-T system.

However, when the same load perturbation occurs in hydro area with separately tuned controllers, more amount of maximum peak overshoot is observed in Fig. 3.9. This may be due to the presence of initial power surge caused by inertia of the hydro system. Due to the presence of non minimum phase transfer function of the hydro governing system, the real power generation reduces initially when it is desired to increase the same during load increase. However, because of larger inertia the steady state performance is better.

3.4.3. **Hydro-thermal with DFIG based WECS in different areas**

The relative performance of wind power penetration in the same hydro thermal power system in terms of the ability of the system to improve frequency regulation, needs to be verified here. Simulations are carried out by considering H-T interconnections of traditional plants after the integration of DFIG in different areas of hydro or thermal types and then in both H-T areas. Regulation and system inertia constants are calculated and adjusted considering a 20% of $L_p$.

Considering identical DFIGs, their converters, wind characteristics and other local factors in both the area as done in previous chapter, the values of the controller parameters $K_{i1}$, $K_{i2}$, $K_{df}$, $K_{pf}$ are optimized using CSA with objective function $J$. The optimal values are depicted in Table 3.3. The responses of $\Delta f_1$, $\Delta f_2$ and $\Delta P_{tie}$ for 1% SLP in thermal area with wind integration in each separate area and in both H-T areas are depicted in Fig. 3.10. Similarly, the responses of $\Delta f_1$, $\Delta f_2$ and $\Delta P_{tie}$ as obtained with 1% SLP in hydro area are depicted in Fig. 3.11. From the figures it may be
noticed that, power generation contributed by wind resources in the same area where SLP has occurred, improves the frequency regulation, compared to the case when SLP is done in other area. Another difference noticed that with the support from wind power in the hydro area along with SLP in the same area, the $\Delta f_1$, $\Delta f_2$ and $\Delta P_{tie}$ are less compared to other case as shown in Fig. 3.11.

### 3.4.4. Hydro-thermal with/without DFIG

The behaviour of the $\Delta f_1$, $\Delta f_2$ and $\Delta P_{tie}$ as obtained for the H-T system, when the same is perturbed with 1% SLP, with frequency support from DFIG and without WECS in two separate cases. The active power supports by DFIG can improve the frequency profile as compared to the case when the same is not integrated to the system as depicted in Fig. 3.12. The decreased value of performance indices as shown in Table 3.4 proves the effective contribution of DFIG for frequency control. It is observed from the figure that, frequency peak excursion is reduced when DFIG participation is considered.

<table>
<thead>
<tr>
<th>Table 3.3</th>
<th>Optimized parameters for the wind integrated H-T systems.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optimized parameters</td>
<td>$K_1$</td>
</tr>
<tr>
<td>H-T with DFIG in area-1 and SLP in area-1</td>
<td>-2.9241</td>
</tr>
<tr>
<td>H-T with DFIG in area-1 and SLP in area-2</td>
<td>-2.2649</td>
</tr>
<tr>
<td>H-T with DFIG in area-2 and SLP in area-1</td>
<td>-2.0930</td>
</tr>
<tr>
<td>H-T with DFIG in area-2 and SLP in area-2</td>
<td>-1.2609</td>
</tr>
<tr>
<td>H-T with DFIG in both area and SLP in area-1</td>
<td>-1.8368</td>
</tr>
<tr>
<td>H-T with DFIG in both area and SLP in area-2</td>
<td>-0.9097</td>
</tr>
<tr>
<td>T-T with DFIG in both area and SLP in area-1</td>
<td>0.7218</td>
</tr>
</tbody>
</table>
Fig. 3.10. $\Delta f_1$, $\Delta f_2$ and $\Delta P_{tie}$ for the H-T system with DFIG in area 1, 2 & both for 1% SLP in area-1.
Fig. 3.11. $\Delta f_1$, $\Delta f_2$ and $\Delta P_{\text{tie}}$ for the H-T system with DFIG in area 1, 2 & both for 1% SLP in area-2.
Fig. 3.12. $\Delta f_1$, $\Delta f_2$ and $\Delta P_{tie}$ are obtained for the H-T system with or without DFIG for 1% SLP in area-1.
Fig. 3.13. $\Delta f_1$, $\Delta f_2$ and $\Delta P_{tie}$ are obtained for the H-T system with or without DFIG for 1% SLP in area-2.
The responses of $\Delta f_1$, $\Delta f_2$ and $\Delta P_{tie}$ as obtained with 1% SLP in hydro area are depicted in Fig. 3.13. Irrespective of load variation in hydro or thermal system, the frequency regulation is improved with wind penetration.

3.5. DISCUSSION

Analyzing all the results above, the following issues may be highlighted

i) The electrical governor of hydro- generators in a hydro-thermal system has an advantage of providing initial real power surge in the case increased power demand. Therefore, the frequency regulation performance improves. Because of sluggish response, the mechanical governor of hydro generators fails to improve the frequency regulation as effectively as the electrical governor.

ii) Due to high water inertia of hydro system, it arrest the frequency fall dominantly when SLP occurs in hydro area, even though the frequency deviations during initial periods remain higher compared to the thermal area load disturbance.

iii) The change in system inertia with different wind penetration levels are calculated in the presence of active power support from DFIG in hydro and thermal areas.

<table>
<thead>
<tr>
<th>Performance indices</th>
<th>H-T DFIG</th>
<th>T-T DFIG</th>
<th>H-T</th>
<th>T-T</th>
</tr>
</thead>
<tbody>
<tr>
<td>ITSE</td>
<td>0.0046</td>
<td>0.0069</td>
<td>0.036</td>
<td>0.031</td>
</tr>
<tr>
<td>ISE</td>
<td>0.0017</td>
<td>0.0034</td>
<td>0.018</td>
<td>0.017</td>
</tr>
<tr>
<td>ITAE</td>
<td>0.1903</td>
<td>0.8994</td>
<td>0.3816</td>
<td>0.4542</td>
</tr>
<tr>
<td>IAE</td>
<td>0.0438</td>
<td>0.2285</td>
<td>0.1176</td>
<td>0.1253</td>
</tr>
<tr>
<td>MDR</td>
<td>0.0762</td>
<td>0.2963</td>
<td>0.1247</td>
<td>0.0098</td>
</tr>
<tr>
<td>$T_s$ (sec)</td>
<td>39.19</td>
<td>70.90</td>
<td>51.29</td>
<td>76.04</td>
</tr>
<tr>
<td>$\Delta f_1$</td>
<td>13.30</td>
<td>24.5300</td>
<td>18.38</td>
<td>25.49</td>
</tr>
<tr>
<td>$\Delta f_2$</td>
<td>13.41</td>
<td>25.5600</td>
<td>18.92</td>
<td>26.57</td>
</tr>
<tr>
<td>$\Delta P_{tie}$</td>
<td>12.48</td>
<td>20.8100</td>
<td>13.99</td>
<td>23.98</td>
</tr>
<tr>
<td>Dominant Eigen values</td>
<td>-12.9119</td>
<td>-6.03 ± 3.79i</td>
<td>-12.8492</td>
<td>-12.50</td>
</tr>
<tr>
<td></td>
<td>-0.209 ± 2.742i</td>
<td>-6.37 ± 4.11i</td>
<td>-1.104 ± 3.56i</td>
<td>-3.3333</td>
</tr>
<tr>
<td></td>
<td>-0.257 ± 0.346i</td>
<td>-1.34 ± 2.16i</td>
<td>-0.366 ± 2.92i</td>
<td>-12.5000</td>
</tr>
<tr>
<td></td>
<td>-0.187 ± 0.089i</td>
<td>-2.43 ± 0.71i</td>
<td>-0.301 ± 1.098i</td>
<td>-0.025 ± 2.55i</td>
</tr>
</tbody>
</table>

Table 3.4 Comparison of several PFI's and MDR of the system with controllers tuned with CSA.
The participation of DFIG in hydro area or thermal area or in both areas is analyzed separately for SLP in either area. The, wind power penetration in Hydro power system improves the frequency regulation characteristics, when the controller parameters of PD controllers of wind generators and integral controllers of both hydro and thermal system are optimized simultaneously to improve frequency regulation.

iv) The fast response capability associated with electronically-controlled PD control loop of DFIG based WECS is utilized to improve the transient performance of frequency regulation of power system. Integrated with hydro thermal systems, a coordinated tuning of the PD controllers along with those of integral controllers of AGC in a two area is found to be beneficial. The improvement of frequency regulation is observed in wind integrated H-T system than the case of only H-T. The CSA optimization technique has effectively tuned the controller gain parameters resulting in improved dynamic performances.