4.1. INTRODUCTION

Deregulated electricity market introduces a competitive environment for power producers resulting in high capital cost requirement to meet peak demands and volatile electricity prices. It has imposed technical, economic and environmental challenges for secure supply of electricity. Power systems are on the threshold of a new transformation by the confluence of deploying variable RES and free electricity markets. High share of variable RES signifies the variability and intermittency of the power supply, disrupting the optimal operation of conventional power systems and grid reliability. The nature of randomness and uncertainty in availability of renewable resources, like variable wind speed and solar radiation, makes it difficult to schedule of generated power from generators with different resources (including conventional). Therefore, the power system operator faces ever increasing challenges in secure operation of power system, and similar problems are expected to increase with increasing penetration of the renewable generation. In this regard, to ensure more reliable and stable power system operation, it may be beneficial to introduce energy storage devices to alleviate power fluctuations. Generally, the ESS is connected in the output side of the renewable system to stabilize the generated power directly. When connected at the output side, it has been shown to reduce the uncertainty, which leads to better scheduling of its generation [168-173]. Moreover, energy storage may prove to be beneficial for stabilizing high prices of power generation during peak demand periods.
Apart from the problem of scheduling in competitive electricity market, Independent Power Producers (IPPs) with various kinds of large capacity and fast power consuming apparatus [174] do not possess sufficient frequency control capabilities and may cause a serious problem of frequency oscillations, when the share of renewable energy based generation increases. Under this situation, the conventional frequency control, i.e. a governor, may no longer be able to absorb large frequency oscillations due to its slower response. Therefore, newer methodologies of stabilization of frequency oscillations may become a necessary component in future. The work aims to analyze the impact of coordinated control of different storage devices to improve the frequency regulation capability of power system.

In another similar domain of devices, the benefits of utilizing FACTs devices in overall improvement of power system operation and control has already been established [175, 100-103]. The co-ordination of ESS and FACT devices facilitates extra storage source, permits independent adjustment of certain system variables and therefore makes the system more controllable and secure. The work probes into the optimum utilization of ESS and FACTs devices to enhance controllability of system frequency, with load variation.

4.2. BASIC TYPES OF ESS AND FACTS CONTROLLERS

Energy storage has been used in various applications. Examples of some primary applications are in traction and transportation systems [176], FACTs devices [177], uninterruptible power supplies (UPS) [178] and many more. The main benefits of ESS can be summarized as;

- Capability of instantaneous exchange of real power with the system using power electronic interface.
- Enables both storage and supply of energy, as it behaves both as source and sink.
- Short term supply prevents multiple switching of back-up generators.
- Further improvement in transient stability [179], by utilizing an ESS integrated FACTs devices.
- Smoothing of the output power from non-dispatchable energy sources.

The several types of ESS, such as BESS, SCESS, flywheel energy storage system (FESS) [180] and SMES [181], used in power system applications are introduced (in section 1.5.3). Various factors need to be considered during the selection of a particular type of ESS, which include their size, rating, speed and cost. Some storage devices are better suited for larger ratings and their relative performance in terms of speed of exchange of energy to compensate for any real power demand, differs from each other. Table 4.1 summarizes the principle of their energy storage, ranges of energy and power, charging time, power density and cost. It may be noticed that each of these parameters are different for each of them [182, 183].

**Table 4.1 Summary of ESS characteristics.**

<table>
<thead>
<tr>
<th>Type of ESS</th>
<th>Power Range</th>
<th>Energy Range (MJ)</th>
<th>Charging Time</th>
<th>Power Density (W/Kg)</th>
<th>Cost (US$/kJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BESS</td>
<td>5kW-10MW</td>
<td>0.1-600</td>
<td>Hours</td>
<td>10-300</td>
<td>0.2-1.5</td>
</tr>
<tr>
<td>SC</td>
<td>5-100kW</td>
<td>0.001-10</td>
<td>Sec-min</td>
<td>2000-10000</td>
<td>5-20</td>
</tr>
<tr>
<td>SMES</td>
<td>1-50MW</td>
<td>1-100</td>
<td>Sec</td>
<td>300-1000</td>
<td>30-50</td>
</tr>
<tr>
<td>FESS</td>
<td>1kW-10MW</td>
<td>1-15</td>
<td>Min</td>
<td>1000-10000</td>
<td>0.3-2</td>
</tr>
</tbody>
</table>

Due to high energy density, discharge rate and capacity, SMES has been widely applied in the frequency control of the electric power systems [172]. The increased penetration of wind power by DFIG in power system results in higher frequency excursion and increased rate of change of frequency in the event of generation loss or increased load demand. The frequency regulation capability of DFIG by incorporating SMES-TCPS is tested on an interconnected two-area power
system [184]. In addition to the dynamic active power support from the DFIG, the presence of SMES and TCPS results in optimal transient performance [113]. The sole participation of the DFIG and also the coordinated actions of DFIG and SMES in both the areas gives optimal dynamic performance of the area frequencies and tie-line power deviations, in the event of any load perturbation.

Among some more prevalent devices in the FACTs family, the use of supplementary control can be applied for devices connected in series with tie-line of interconnected power systems to control power flow and to damp the inter-area oscillations [185]. Due to quick dynamic responses, series FACTs devices such as TCPS [186], SSSC and thyristor controlled series capacitor (TCSC) [187] have been employed in power system to reduce the area frequency and tie-line power oscillations. In [188, 189], the TCPS utilized in the form of an ancillary service, has been applied for stabilizing the frequency oscillations of an interconnected power system.

In this regard, the application of coordinated controllers for SMES in both the areas of the system may be tested in a T-T system, supported by wind power from DFIGs. The present chapter is discussed as follows;

1. To investigate the capability of the TCPS damping controller in series with the tie-line for a two-area reheat thermal (T-T) power system considering Generation Rate Constraint (GRC) nonlinearities.
2. To compare the transient responses for coordination of TCPS in series with the tie-line along with SMES located in one area and SMES located at the terminal of each area.
3. To study the impact of SSSC in series with the tie-line for the same T-T system.
4. To investigate the impacts of coordinated controllers SMES–SMES and SSSC–SMES on dynamic response of the test system under load perturbation.
5. To examine the robustness of designed controllers for any changes in parameter and/or operating conditions in power system.

4.3. AGC IN A TWO AREA THERMAL POWER SYSTEM WITH THE PRESENCE OF SMES AND SERIES FACTS DEVICES

Many problems in AGC, within two interconnected areas of power system, have utilized a widely accepted model [160] in Fig. 4.1 in order to examine the response of power system towards several factors like changes in system parameter, model parameters, operating condition, gains of controllers etc. A detail discussion related to each of the components of AGC is elaborated in section 1.2. However, brief highlights on the characteristics and/or requirement of generation rate constraint (GRC), SMES, TCPS and SSSC in LFC are enumerated below. Before, discussing about the impact of series FACTs devices in the two area system, the importance of generation rate constraint in the process of modeling is highlighted first.

4.3.1. Generation Rate Constraint (GRC)

In power system having thermal units, power generation can change only at a specified maximum rate. When the real power generation of thermal generator units increase or decrease in order to control the change in frequency with varying load demand, they can do so within fixed limits based on their ramp up or down capacities. Defined as GRC, such limit on the real power generation of individual units, is introduced in the model of AGC in order to achieve realistic results. Investigations reveal that optimum parameters of the AGC obtained ignoring the effects of GRC are sometimes not acceptable. It is therefore necessary to account for a realistic value of GRC for large reheat steam turbines while optimizing the parameters of AGC [190].
The model of the two area system including GRC in its simplified version is depicted in Fig. 4.1. The generation rate limitation of 3% per minute for both the areas of the two-equal-area system may be a realistic limit [34] to assume.

### 4.3.2. The role of SMES, TCPS and SSSC in the problem of AGC

The presence of SMES in the control of frequency in an AGC framework provides rapid control over requirement of deficit or surplus real power, by deriving the same from a large inductor or reactor. As per the need of the power system, the power delivered or recovered from the reactor can be controlled by suitably designed controller dedicated for the SMES. A detail overview behind the fundamental physics and some elementary modeling issues shall be covered in the following section 4.4.

With proper control of TCPS, the real power flow can be regulated to improve damping and mitigate the low frequency oscillations (which persist after any disturbance in the system) so that the transient stability of power system can be enhanced. The device can swiftly control the real power as it can modify the relative phase angle between system voltages [186, 191], at the two ends of a transmission line. An elaborated discussion shall be covered in the following section 4.5.

![Figure 4.1. Two area interconnected power system with SMES unit considering GRC.](image-url)
SSSC is one of the important members of FACTs family [109] which can be installed in series with the transmission lines. With the capability to change its reactance characteristic within two extremes from being capacitive to inductive, the SSSC can prove to be very effective in controlling power flow [104]. Ngamroo et al. [105] proposed the application of SSSC for frequency stabilization by locating SSSC in series with the tie-line between interconnected two-area power systems with thermal units. A SSSC employs self-commutated voltage-source switching converters to synthesize a three-phase voltage in quadrature with the line current, thereby emulating an inductive or a capacitive reactance so as to influence the power flow in the transmission lines [104]. The compensation levels can be controlled dynamically by changing the magnitude and polarity of injected voltage. Greater detail of the same is given in section 4.6.

4.4. SUPER CONDUCTING MAGNETIC ENERGY STORAGE (SMES) SYSTEM: BRIEF OVERVIEW

4.4.1. Fundamental principle of SMES

As depicted in Fig. 4.2, the SMES system has a DC magnetic coil that is connected to the ac grid through a power conversion system (PCS) which includes two numbers of power electronic converters for inversion and rectification purposes. The coil is maintained at extremely low temperature with the help of liquid helium that makes it behave like a superconducting lossless coil, which can be charged to a set point from the utility grid during normal operation. The superconducting nature of SMES and its capability to absorb or release energy from or to the grid as per the load demand makes it unique for its utilization in AGC. The most important advantages of SMES include:

- High power and energy density with excellent conversion efficiency
Fast and independent power response in all four quadrants.

High critical temperature ceramic superconductors are commercially available. Therefore, it makes SMES units more economic to construct and operate. The cryogenic (refrigeration) system and helium vessel keep the conductor cold in order to maintain the coil in the superconducting state. SMES systems store energy in the magnetic field created by the flow of direct current in a superconducting coil which has been cryogenically cooled to a temperature below its superconducting critical temperature [192-193].

A typical SMES system includes three parts. They are the superconducting coil, power conditioning system and cryogenically cooled refrigerator system. Once the superconducting coil is charged, the current will not decay and the magnetic energy can be stored indefinitely. The stored energy can be released back to the network by discharging the energy stored in the coil. The power conditioning system uses an inverter/rectifier to transform alternating current (AC) power to direct current or convert DC back to AC power. The inverter/rectifier accounts for about 2–3% energy loss in each direction. SMES loses the least amount of electricity in the energy storage process compared to other methods of storing energy. SMES systems are highly efficient as the round-trip efficiency is greater than 95% [194].

Due to the energy requirements of refrigeration and the high cost of superconducting wire, SMES is currently used for short duration energy storage. Therefore, SMES is most commonly devoted to improving power quality [195]. It has been established that, if SMES were to be used for utilities it would be a diurnal storage device, charged from base load power at night and meeting peak loads during the day [196]. Large diurnal or spinning reserve applications, the SMES has been found to be cost-effective [197].
4.4.2. Operation and control of SMES in AGC

The control of the operation of SMES during its charging, discharging, steady state modes and the power modulating dynamic oscillatory period are achieved by the application of adequate positive or negative voltage to the inductor, through the control of firing angle of the converter bridges.

![Fig. 4.2. Schematic diagram of SMES connected to electric AC grid.](image)

In (4.1), \( T_{dc} \) is the converter time delay in Sec; \( K_{SMES} \) is the gain of the SMES control loop for ACE signal in kV/unit ACE, \( K_{ld} \) is the gain of the inductor current deviation feedback loop in kV/kA and \( s \) is the Laplace operator.

\[
\Delta E_{di} = \frac{1}{1 + sT_{dc}} [K_{SMES} (\beta_i \Delta f_i + \Delta P_{ij}) - K_{ld} \Delta I_{di}] 
\]
Since the amount of stored energy is finite, the inductor current falls. The deviation in the inductor current $\Delta I_d$ is expressed as follows in (4.2).

$$\Delta I_d = \frac{\Delta E_d}{PL}$$  \hspace{1cm} (4.2)

Where, $P$ is the differential operator with respect to time and $L$ is the inductor. The deviation in the inductor power flow $\Delta P_{SMES}$ is given by the expression as follows in (4.3).

$$\Delta P_{SMES} = I_{d0} \cdot \Delta E_d + \Delta E_d \cdot \Delta I_d$$  \hspace{1cm} (4.3)

![Fig. 4.3. Transfer function model of SMES units.](image)

The inductor is initially charged to its rated current $I_{d0}$ by applying a small positive voltage. Once the current has attained the rated value, it is held constant by reducing the voltage ideally to zero since the coil is superconducting. However, a very small voltage may be required to overcome the commutating resistance. A brief idea about the systems parameters may be necessary here.

The voltage $\Delta E_d$ across the inductor and the current deviation $\Delta I_d$ during the disturbance should be within specified values of upper and lower bounds. In actual practice, the inductor current $I_d$ should not be allowed to reach zero to prevent the possibility of discontinuous conduction in the presence of large disturbances. Therefore, the lower limit to inductor current is to set at 30% of the nominal rated
value \( I_{d0} \), which is set in such a manner that the maximum allowable energy to be absorbed by the inductor should remain equal to the maximum allowable energy to be discharged by it [198]. This is done to provide effective damping introduced by SMES, when it responds to rapid increase and decrease in load [89].

4.5. TCPS AND ITS MODELING FOR THE STUDY OF LFC

Fig. 4.4 shows the two-area interconnected reheat thermal power system with TCPS in series with tie line. The power flow in the interconnected tie-line from area 1 to area 2, without considering TCPS can be expressed as

\[
\Delta P_{\text{tie}12} = \frac{2 \pi T_{12}}{s} \left[ \Delta f_1 - \Delta f_2 \right]
\]

(4.4)

Where \( T_{12} \) is synchronizing coefficients, \( \Delta f_1 \) and \( \Delta f_2 \) are frequency deviation in area 1 and 2.

Fig. 4.4. Two area interconnected power system with SMES and TCPS units.
The complex power can be written as

\[ P_{tie} = jQ_{tie} = \left| V_1 \right| \angle (\delta_1 + \phi) \frac{\left| V_1 \right| \angle \delta_2}{jX_{12}} \]  \hspace{2cm} (4.5)

Separating the real part of tie-line power

\[ P_{tie} = \frac{\left| V_1 \right| \left| V_2 \right|}{X_{12}} \sin(\delta_1 - \delta_2 + \phi) \]  \hspace{2cm} (4.6)

In (4.6) perturbing \( \delta_1 \), \( \delta_2 \) and \( \phi \) from their nominal values \( \delta_1^0 \), \( \delta_2^0 \) and \( \phi^0 \) respectively, the tie line power deviation can be obtained as;

\[ \Delta P_{tie} = T_{12} (\Delta \delta_1 - \Delta \delta_2) + T_{12} \Delta \phi \]  \hspace{2cm} (4.7)

It is known that

\[ \Delta \delta_1 = 2\pi \int \Delta f_1 \, dt \quad \text{and} \quad \Delta \delta_2 = 2\pi \int \Delta f_2 \, dt \]

Putting the value of \( \Delta \delta_1 \) and \( \Delta \delta_2 \) in (4.7) and applying Laplace transform

\[ \Delta P_{tie}(s) = \frac{2\pi T_{12}}{s} [\Delta F_1(s) - \Delta F_2(s)] + T_{12} \Delta \phi(s) \]  \hspace{2cm} (4.8)

As per (4.8), it can be observed that the tie-line power flow can be controlled by controlling the phase shifter angle \( \Delta \phi \). It can be written as

\[ \Delta \phi(s) = \frac{K_{TCPS}}{1 + sT_{TCPS}} \Delta \text{Error}_1(s) \]  \hspace{2cm} (4.9)

Where \( K_{TCPS} \) and \( T_{TCPS} \) are the gain and time constants of the TCPS and \( \Delta \text{Error}_1(s) \) is the control signal which controls the phase angle of the phase shifter. \( \Delta \text{Error}_1 \) can be any signal such as the frequency deviation or ACE to the TCPS unit to control the TCPS phase shifter angle which in turn controls the tie-line.
power flow. However, as TCPS is placed near Area 1, measurement of $\Delta f_1$ will be practically easier rather than ACE$_1$, which requires measurement of tie-power also. Hence, the frequency deviation of the area-1 $f_1$ may be chosen as the control signal i.e with $\Delta Error_j=\Delta f_j$ the phase shifter angle deviation $\Delta \phi$ can be written as

$$\Delta \phi(s) = \frac{K_{TCPS}}{1+st_{TCPS}} \Delta f_1(s)$$  \hspace{1cm} (4.10)

The structure of TCPS as frequency stabilizer is shown in Fig. 4.6.

\[\text{Fig. 4.6. Structures of TCPS as a frequency stabilizer.}\]

Frequencies and tie-power oscillations following sudden load disturbance in either of the areas can be suppressed by controlling the phase angle of TCPS [199]. Therefore, it may be concluded that, the control of tie-line power flow by a TCPS can be expected to be utilized as a new ancillary service for stabilization of frequencies and tie-line power oscillations in the power system. There are two parameters such as stabilization gain, $K_{TCPS}$ and time constant, $T_{TCPS}$ to be optimized for the optimal design of the frequency stabilizer.

4.6. STATIC SYNCHRONOUS SERIES COMPENSATOR (SSSC)

SSSC is a solid state voltage sourced based series compensator used for real power control over a transmission line. The SSSC is located in series with the tie line between two-area interconnected power systems. By utilizing the system interconnection as the channel of power flow control of SSSC, system frequency oscillations due to the inter-area mode can be stabilized effectively. The configuration SSSC is shown in Fig. 4.7. The response of SSSC is faster compared to the primary
control by the governor. However, the SSSC and the governing system may act coordinately to further improve the performance in terms of frequency stabilization.

In case of sudden load disturbance, the frequency oscillation in the transient period is quickly damped out by the response of SSSC [106]. From Fig. 4.7, power flow equation [100] can be written as:

\[ P + jQ = V_1 I^* \]  
\[ \text{(4.11)} \]

The real part of the power will be:

\[ P = \frac{V_1 V_2}{X_L \sin(\delta_1 - \delta_2)} - V_{SSSC} \frac{V_1 I^*}{X_L I} \]  
\[ \text{(4.12)} \]

Where, \( P_{SSSC} \) is the active power controlled by SSSC, \( P_{tie12} \) is the tie line power flowing between the two areas.

The incremental power is given by

\[ \Delta P = \Delta P_{tie12} + \Delta P_{SSSC} \]  
\[ \text{(4.14)} \]

The frequency stabilizer SSSC is used in coordination with a second order lead-lag structure as shown in Fig. 4.8. The frequency deviation of the concerned area is the input signal.

**Fig. 4.8.** Structure of SSSC as a frequency stabilizer.
Chapter 4

$T_{SSSC}$, $T_2$ and $T_4$ have been taken as 0.05 S, 0.5 S and 0.5 S respectively [106]. $K_{SSSC}$, $T_1$ and $T_3$ may be suitably tuned to obtain a desired performance in terms of frequency regulation.

4.7. METHODOLOGY AND SYSTEM PARAMETER CHOSEN

The two area thermal (T-T) system data has been obtained from [160] and wind system data from [11] are mentioned in appendix A1 and A2. In this work, both the control areas have been assumed to have identical integral controllers whose gains ($K_{i1}$, $K_{i2}$) are denoted as $K_i$. By obeying the criteria of equal rate of energy discharge and absorption, the upper inductor current limit, is set at 1.38 $I_{d0}$. The actual and per unit value of SMES device are given in appendix A.7 as per description in [87]. The SMES inductor voltage limit is considered at 1.3 kV and the initial current of inductor $I_{d0} = 4.5$ kA.

The parameters of the controllers of AGC, SSSC, TCPS and SMES are optimized with the help of the CSA, which has been already established in earlier chapters-2 to be giving better performance in optimization.

4.8. SIMULATION AND RESULTS

As done in the previous chapters, the model of AGC system is developed in MATLAB/SIMULINK to obtain dynamic response for a step load perturbation (SLP). As an interconnected power system is subjected to load disturbances, system frequency may get disturbed and oscillating, affecting the dynamic performance. To compensate for such load disturbances and stabilize the area frequency oscillations, the dynamic power flow control of SSSC or TCPS in coordination with SMES are examined in this work. A coordinated operation of SMES in both the areas, is also studied in a comparative manner. The effectiveness of frequency controllers are guaranteed by analyzing the transient performance of the system with varying load.
The gains \((K_i)\) of integral controller in AGC loop, SMES \((K_{SMES}, K_{Id})\), TCPS \((K_{TCPS}, T_{TCPS})\) and SSSC \((K_{SSSC}, T_1\) and \(T_3)\) are optimized in different cases with the help of CSA. At the outset, for the sake of obtaining the objective functions \(J\), the real power loads \((P_d)\) of the 1st control area is perturbed by 1 % SLP. It is to be noted that the objective functions are dependent on the time domain and eigenvalue based PFIs, which are evaluated at the end of simulation time of 30 seconds. Moreover, in order to take into account the smallest time constants, time-domain analysis of the continuous system is performed with a time step of 0.01 second with appropriate choice of sampling time intervals for the controllers. Optimum system response for a SLP and the impacts of SMES and TCPS, SSSC in that regard, have been explored and discussed in the following section.

4.8.1. The effect of CSA optimized controllers of TCPS in the T-T system

A TCPS is placed in series with the tie-line in the system as shown in Fig. 4.2. The \(K_i\) for the main AGC loop, \(K_{TCPS}\) and \(T_{TCPS}\) in TCPS control loop are obtained by optimizing the objective functions \(J\) using CSA. The optimized values are given in Table 4.2. The \(\Delta f_1, \Delta f_2\) and \(\Delta P_{tie}\) after 1% SLP are shown in Fig. 4.9. The deviations shown without TCPS, consider frequency response of the system for the same SLP, using an optimized value of integral gain \((K_i)\) in both the areas.

It may be seen that, even with the optimized integral gains, the area frequencies and the tie-line power oscillations exist for a longer period. Moreover, the overall dynamic performance of the \(\Delta f_1\) in terms of settling time, peak overshoot, and undershoot, without TCPS is inferior to the case when system is operating with the TCPS. But, peak overshoot and undershoot of \(\Delta f_2\) and \(\Delta P_{tie}\) is more, as additional real power is drawn from other area to compensate the load increase in area-1.
Fig. 4.9. $\Delta f_1, \Delta f_2$ and $\Delta P_{tie}$ obtained for the T-T system with and without TCPS with 1% SLP in area-1.
4.8.2. Coordination of TCPS with SMES in different areas for improvement of damping performance

The presence of a TCPS along with a SMES needs to be clearly understood, so that both the devices may be utilized simultaneously to improve the damping performance of the system. In this subsection, the relative performance of SMES along with TCPS is compared with only SMES. Two specific cases are examined as follows;

**TCPS-SMES:** In this case, the SMES is placed in area 1, where load is perturbed. Further, a TCPS is placed in the connected tie-line between the two areas.

**SMES–SMES:** In this case, the SMES is placed in both the areas, without the presence of TCPS in the tie-line.

The SMES in both the areas are assumed to be having capacities of 30 MJ. Simulation is carried out for 1 % SLP in area-1 by considering SMES-TCPS and SMES–SMES separately and also for the case when none of the either areas is operating with SMES and TCPS. As proceeded earlier, the integral gains $K_i$, and the gains ($K_{SMES}$, $K_{Id}$, $K_{TCPS}$) and time constants ($T_{TCPS}$) of SMES and TCPS controllers are obtained by optimizing the objective function $J$ using CSA. A tolerance of 2% is considered for evaluation of all the $PFI$s. The optimized gains, their corresponding values of objective function, for three different cases of operation including no SMES or TCPS, are elucidated in Table 4.2. It may be seen that, the optimized value of $J$, obtained for SMES-SMES has the least value compared to the other cases, and therefore the dynamic performance for the same should be the best among them.

The dynamic responses for the SMES–SMES coordinated operation against SMES-TCPS coordination is shown comparatively in Fig. 4.10. The results depict
The relative advantage of investing in two numbers of SMES compared to an SMES operating with TCPS in the tie-line.

**Fig. 4.10.** $\Delta f_1$, $\Delta f_2$ and $\Delta P_{tie}$ are obtained for the T-T system with comparing SMES and TCPS with 1% SLP in area-1.
Table 4.2 The CSA optimized values of controller parameters and objective function $J$ with different scheme of TCPS and SMES.

<table>
<thead>
<tr>
<th>Controller parameters</th>
<th>Controller parameters</th>
<th>Optimized value of $J$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$K_c$</td>
<td>$K_{SMES}$</td>
</tr>
<tr>
<td>TCPS</td>
<td>-0.9147</td>
<td>-</td>
</tr>
<tr>
<td>TCPS-SMES</td>
<td>-1.6658</td>
<td>47.1224</td>
</tr>
<tr>
<td>Only T-T</td>
<td>0.4986</td>
<td>-</td>
</tr>
</tbody>
</table>

4.8.3. Coordination of SSSC with SMES in different areas for improvement of damping performance

Proceeding in similar way as done in the previous sub-section for TCPS, the effectiveness of the SSSC in series with tie-line of T-T system, the responses are compared with those obtained with the case without SSSC in the same system. In this analysis, four different cases are considered.

SSSC: Only SSSC is assumed to be present in the tie-line. In this case, the gains of SSSC and integral gains of AGC in both the areas are to be optimized.

SMES-SSSC: In this case, an SMES is placed in the 1st area along with an SSSC operating in the tie-line.

SMES-SMES: Both the areas are assumed to be having one SMES each, without the presence of SSSC in the tie-line.

The gains of the controllers in each case are simultaneously optimized as done in the previous cases, when TCPS were assumed to be operating with the SMES. The optimized controller parameters and optimized value of objective function are presented in Table 4.3. The dynamic responses obtained are depicted in Fig. 4.11. It is observed that the SSSC coordination with T-T system has significantly improved the performance as expected compared to those obtained when SSSC is not operating in the system. The corresponding performance parameters in terms of $Ts$, peak overshoot and undershoot, as shown in the Fig. 4.11 have improved. However, when the relative
advantage of operating the system with two SMES or one SMES in area 1 and SSSC in the tie line is to be examined, their gains are accordingly tuned. In the case of SMES-SMES, the gains ($K_i, K_{SMES}, K_{Id}$) are optimized with CSA using objective function $J$ as done before. Similarly, for SMES-SSSC, their corresponding gains and time constants ($K_{SSSC}, T_I$ and $T_3$) are optimized, using CSA in all the cases, considering the same objective function $J$.

**Table 4.3** The CSA optimized values of controller parameters and objective function $J$ obtained for different schemes of SSSC and SMES.

<table>
<thead>
<tr>
<th>Controller parameters</th>
<th>Controller parameters</th>
<th>Optimized value of J</th>
</tr>
</thead>
<tbody>
<tr>
<td>SSSC</td>
<td>$K_i$ 0.7026, $K_{SMES}$ - , $K_{Id}$ - , $T_3$ 0.4273 , $T_1$ 3.1191 , $K_{SSSC}$ 5.0092</td>
<td>49.8825</td>
</tr>
<tr>
<td>SMES-SSSC</td>
<td>$K_i$ 1.7399, $K_{SMES}$ 50.8156 , $K_{Id}$ 22.2465 , $T_3$ 5.7902 , $T_1$ 32.2239 , $K_{SSSC}$ 1.6682</td>
<td>41.7909</td>
</tr>
<tr>
<td>SMES-SMES</td>
<td>$K_i$ 4.7118, $K_{SMES}$ 99.1703 , $K_{Id}$ 14.3716 , $T_3$ - , $T_1$ - , $K_{SSSC}$ -</td>
<td>14.8430</td>
</tr>
<tr>
<td>T-T only</td>
<td>$K_i$ 0.4986, $K_{SMES}$ - , $K_{Id}$ - , $T_3$ - , $T_1$ -</td>
<td>76.3698</td>
</tr>
</tbody>
</table>

The optimized controller parameters and objective function values are depicted in Tables 4.3. The dynamic responses of the systems with the SMES–SMES and SSSC–SMES coordinated operation are depicted in Fig. 4.12 after 1 % SLP in area 1. The results clearly indicate that the coordination of SMES–SMES and SSSC–SMES can be effectively employed to suppress the oscillations in area frequencies and the tie-line power exchange under load disturbance. It is observed that the system with SMES placed in both areas gives minimum undershoot and overshoot in frequency oscillations as well as tie-line power exchange, as compared to SSSC–SMES controllers. Further, the oscillations in frequencies and tie-line power take lesser time to settle.

Keeping the respective optimized gains for all the cases, the performance of each damping scheme is evaluated and compared in terms of several other established
time domain performance indices, i.e., $IAE$, $ITSE$, $ISE$ and $IAE$ and in terms of the values of the MDRs of their eigen values. All these data are elucidated in Tables 4.4, from which a clear idea about the efficacy of coordinated control and operation of SMES–SMES, SSSC–SMES and TCPS–SMES, can be obtained.

![Time domain performance indices graphs](image)

**Fig. 4.11.** $\Delta f_1$, $\Delta f_2$ and $\Delta P_{tie}$ in T-T system comparing with and without SSSC for 1% SLP in area-1.
Fig. 4.12. $\Delta f_1$, $\Delta f_2$ and $\Delta P_{tie}$ in T-T system with SMES and SSSC for 1% SLP in area-1.
From all the results it may be observed that, among all the schemes of damping controllers, the operation of two numbers of SMES in both the areas has provided the best dynamic response.

### 4.9. THE PERFORMANCE OF CSA OPTIMIZED SMES CONTROLLERS IN BOTH THE AREAS, FOR LOAD DISTURBANCES AT DIFFERENT LOCATIONS AND VARIATION IN PARAMETER VALUES

#### 4.9.1. Step load increase in area 1

The parameters $K_i$, $K_{SMES}$ and $K_{Id}$ are set at the values obtained by optimizing objective function $J$. The optimal values of $K_i$ found in the cases of system with and without SMES are given in Table 4.3. The first control area is subjected to a SLP of 1\% from its nominal value at time $t = 0$. Dynamic response of $\Delta f_1$, $\Delta f_2$ and $\Delta P_{tie}$ obtained for the perturbation is depicted in Fig. 4.13. From the figure it can be witnessed that, the frequency and tie line power oscillations tend to settle around 25 seconds without SMES, whereas the same value reduces to 5 seconds with the SMES operating.

### Table 4.4 Comparison of several PFIs and MDR of the system with different cases of coordinated controllers.

<table>
<thead>
<tr>
<th>Performance Indices</th>
<th>Different FACT devices with SMES.</th>
<th>T-T</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>TCP-SMES</td>
<td>SSSC-SMES</td>
</tr>
<tr>
<td>ISE</td>
<td>$7.4383 \times 10^4$</td>
<td>$8.4152 \times 10^4$</td>
</tr>
<tr>
<td>ITSE</td>
<td>$0.0015$</td>
<td>$9.7620 \times 10^4$</td>
</tr>
<tr>
<td>IAE</td>
<td>$0.0697$</td>
<td>$0.0634$</td>
</tr>
<tr>
<td>ITAE</td>
<td>$0.1965$</td>
<td>$0.1193$</td>
</tr>
<tr>
<td>$T_s$ (sec)</td>
<td>$\Delta f_1$</td>
<td>$12.24$</td>
</tr>
<tr>
<td></td>
<td>$\Delta f_2$</td>
<td>$14.71$</td>
</tr>
<tr>
<td></td>
<td>$\Delta P_{tie}$</td>
<td>$13.14$</td>
</tr>
<tr>
<td>MDR</td>
<td>$0.3472$</td>
<td>$0.6110$</td>
</tr>
<tr>
<td>Eigen values</td>
<td>$-12.5000$</td>
<td>$-30.3751$</td>
</tr>
<tr>
<td></td>
<td>$-30.0252$</td>
<td>$-7.80 \pm 10.10i$</td>
</tr>
<tr>
<td></td>
<td>$-1.04 \pm 2.82i$</td>
<td>$-1.77 \pm 0.29i$</td>
</tr>
</tbody>
</table>
4.9.2. Step load increase in area 2

Keeping the SMES placed in both areas, only 2\textsuperscript{nd} area is subjected to a SLP of 1\% from its nominal value at time $t = 0$. Dynamic response of $\Delta f_1$, $\Delta f_2$ and $\Delta P_{\text{Tie}}$ obtained for this perturbation is depicted in Fig. 4.14. Form the responses it is clear that system oscillations with the proposed controllers are reduced, improving system stability and settling time compared to those obtained without SMES. As reflected in Table 4.4 the system eigenvalues, the overall damping levels have improved when CSA optimized controllers were used with SMES then without SMES.

4.9.3. Step Load increase in both area 1 and 2

The load is varied by 1\% SLP in both the areas so that the dynamic performances of load increases in area 1 and 2 alone may be compared. The response of $\Delta f_1$, $\Delta f_2$ and $\Delta P_{\text{Tie}}$ obtained for these perturbations are depicted in Fig. 4.15, comparatively with the cases discussed in 4.9.1 and 4.9.2. It can be seen that both the area frequency deviations become more when loads in both of them are increased simultaneously. Moreover, it can be noticed that, when both the areas are subjected to same SLP, frequency deviations in both the areas have increased but no oscillation is noticed in tie line power deviation as equal disturbances given to two equal area having same inertia would not require any exchange through tie line. However, with perturbation in 2\textsuperscript{nd} area gives more pronounced overshoot compared to the disturbance occurring in the 1\textsuperscript{st} area. This may be due to the fact that the parameters are optimized with disturbance occurring in 1\textsuperscript{st} area.
Fig. 4.13. $\Delta f_1, \Delta f_2$ and $\Delta P_{ne}$ responses comparing with and without SMES for 1% SLP in area-1.
Fig. 4.14. $\Delta f_1$, $\Delta f_2$ and $\Delta P_{tie}$ responses comparing with and without SMES for 1% SLP in area-2.
Fig. 4.15. $\Delta f_1$, $\Delta f_2$ and $\Delta P_{tie}$ responses due to 1% SLP in 1<sup>st</sup>, 2<sup>nd</sup> and both areas in the presence of SMES in both areas.
4.9.4. Sensitivity analysis with variation in parameter

To study the robustness of the proposed controllers of SMES in the 1st area obtained by optimizing $J$ with CSA, the system parameters and operating conditions are deliberately varied in some ranges other than at which the controllers were optimized initially. For testing the controller performance with parameter variations, several numbers of time constants related to the governing system ($T_g$), turbines ($T_t$), the synchronizing power coefficient ($T_{12}$), reheater ($T_r$) are varied in the range of -50 % to + 50 % from their respective nominal values in separate events of perturbation cases. The oscillations in frequency deviations, which have remained stable even with variation in the above three time constant parameters, are depicted in Fig. 4.16 to Fig. 4.19. Moreover, as illustrated in Fig. 4.20 and Fig. 4.21, similar variations in the values of reheater gain ($K_r$) and inertia constant ($H$) have also not disturbed the oscillations keeping them stable.

![Image of Fig. 4.16. Change in frequency of 1st area with variation in Tg in the system with SMES.](image-url)
Fig. 4.17. Change in frequency of 1st area with variation in $T_1$ in the system with SMES.

Fig. 4.18. Change in frequency of 1st area with variation in $T_{12}$ in the system with SMES.

Fig. 4.19. Change in frequency of 1st area with variation in $T_r$ in the system with SMES.
Sensitivity analysis with variation in operating conditions

In actual operating scenario, the percentage share of frequency dependent loads may change, even though the total load demand in the system remains unchanged. In that case, the value of load damping factor (D) is varied in the range of -50% to +50%. Similar to the parameter variations, further 1% perturbation in load of area 1 is introduced. The frequency deviations obtained at these two new operating points are depicted in Fig. 4.22 and Fig. 4.23 respectively. It can be seen that even

Fig. 4.20. Change in frequency of 1st area with variation in $K_r$ in the system with SMES.

Fig. 4.21. Change in frequency of 1st area with variation in $H$ in the system with SMES.
with variation of nominal operating condition the dynamic performance of the proposed controller has not altered significantly.

Moreover, the numerical values of ITSE, $T_s$ of $\Delta f_1$, $\Delta f_2$ and $\Delta P_{tie}$ and MDR obtained with variations in system parameters and operating conditions are listed in Table 4.5. The values obtained corroborate the robustness of the proposed SMES-SMES controller with T-T for changed parameters and operating conditions.
An active power source with fast response such as SMES is expected to be the most effective stabilizer for frequency oscillations to compensate for the sudden load.
changes [69]. Furthermore, when the system is penetrated by wind energy based
generators, whose power generation output is always uncertain due to the nature of
wind flow, the role of SMES may be even more important. Therefore, the work has
directed its attention to verify the use of two SMES in wind energy penetrated thermal
power system. For the purpose of simulation, the wind integrated T-T power system
considered in chapter 2 is taken assuming $L_p$ of 20% to that of total generating
capacity of the area. It may be observed that, both the control areas have equal
capacities and are assumed to have identical model parameters. Therefore, the values
of the controller parameters $K_i$, $K_{df}$, $K_{pf}$, $K_{SMES}$, $K_{Id}$ to be optimized, are assumed to
be of identical values in both the areas. A 1% SLP of the 1st control area is simulated
to obtain the objective function.

The CSA optimized system parameters in T-T DFIG system with SMES in
both areas are presented in Table 4.6. Fig. 4.24 depicts that a coordinated operation of
two SMES successfully improve the dynamic response of $\Delta f_1$, $\Delta f_2$ and $\Delta P_{tie}$ with the
availability of frequency support from DFIG. The results corroborate the findings that
SMES and DFIG simultaneous operation imposes least regulation stress on
conventional unit.

<table>
<thead>
<tr>
<th>Controller parameters</th>
<th>$K_i$</th>
<th>$K_{pf}$</th>
<th>$K_{df}$</th>
<th>$K_{SMES}$</th>
<th>$K_{Id}$</th>
<th>Value of $J$</th>
</tr>
</thead>
<tbody>
<tr>
<td>T-T DFIG</td>
<td>0.7218</td>
<td>0.2512</td>
<td>0.0975</td>
<td>-</td>
<td>-</td>
<td>70.8711</td>
</tr>
<tr>
<td>T-T DFIG with SMES</td>
<td>9.6818</td>
<td>1.0697</td>
<td>0.2431</td>
<td>124.6332</td>
<td>18.3503</td>
<td>23.6018</td>
</tr>
</tbody>
</table>

Further, to have a comparison of all the performance indices are obtained for
comparing the effectiveness of SMES in a wind integrated thermal systems. The
performance indices values are compared with the case when no SMES is present in the system. They are presented in Table 4.7.

Fig. 4.24. $\Delta f_1$, $\Delta f_2$ and $\Delta P_{\text{tie}}$ obtained for the T-T-DFIG system comparing with and without SMES and T-T with SMES having 1% SLP in area-1.
Table 4.7 Comparison of several PFI$s$ and MDR of the system with controllers tuned with CSA.

<table>
<thead>
<tr>
<th>Performance Indices</th>
<th>T-T DFIG with SMES</th>
<th>T-T DFIG</th>
<th>T-T with SMES</th>
</tr>
</thead>
<tbody>
<tr>
<td>ITSE</td>
<td>2.2352×10^{-4}</td>
<td>0.0069</td>
<td>3.5042×10^{-4}</td>
</tr>
<tr>
<td>IAE</td>
<td>0.0270</td>
<td>0.0034</td>
<td>0.0324</td>
</tr>
<tr>
<td>ITAE</td>
<td>0.0533</td>
<td>0.8994</td>
<td>0.0484</td>
</tr>
<tr>
<td>ISE</td>
<td>2.1331×10^{-4}</td>
<td>0.2285</td>
<td>3.1536×10^{-4}</td>
</tr>
<tr>
<td>MDR</td>
<td>0.5055</td>
<td>0.2963</td>
<td>0.6954</td>
</tr>
<tr>
<td>Total $T_S$</td>
<td>21.49</td>
<td>70.90</td>
<td>13.22</td>
</tr>
<tr>
<td>$T_S$ (sec)</td>
<td>Δ$f_1$</td>
<td>6.0300</td>
<td>24.5300</td>
</tr>
<tr>
<td></td>
<td>Δ$f_2$</td>
<td>9.0100</td>
<td>25.5600</td>
</tr>
<tr>
<td></td>
<td>Δ$P_{tie}$</td>
<td>6.4500</td>
<td>20.8100</td>
</tr>
<tr>
<td>Eigen values</td>
<td>-6.93 ± 11.83i</td>
<td>-6.03 ± 3.79i</td>
<td>-12.5000</td>
</tr>
<tr>
<td></td>
<td>-8.40 ± 11.27i</td>
<td>-6.37 ± 4.11i</td>
<td>-24.2947</td>
</tr>
<tr>
<td></td>
<td>-3.91 ± 0.34i</td>
<td>-1.34 ± 2.16i</td>
<td>-3.8294 + 3.9570i</td>
</tr>
<tr>
<td></td>
<td>-0.78 ± 1.23i</td>
<td>-2.43 ± 0.71i</td>
<td>-3.8294 - 3.9570i</td>
</tr>
</tbody>
</table>

4.11. DISCUSSION

i) For a comparative analysis of FACTs devices along with ESS coordinated controllers SMES–SMES, SSSC–SMES and TCPS–SMES may be successfully implemented for load frequency stabilization of an interconnected two-area T-T system. The SMES–SMES scheme offers the least undershoot and overshoot in frequency deviations and tie-line power exchanges as compared to SSSC–SMES controller and TCPS–SMES controller. However, as far as coordinated operation of SMES with FACTs devices is concerned, SSSC is a preferred option compared to the TCPS, due to better dynamic performance.

ii) The integral gains of two area interconnected power system and SMES are tuned using CSA. From the simulation results it is observed that, effectively tuned controller gains of SMES along with those of the power system enables the later to operate in a more stable manner compared to the case when no SMES were present.
iii) Performances of the proposed controller towards changes in operating conditions and parameter values corroborate the robustness of the proposed controller for changes in parameter values and operating conditions.

iv) The consideration of coordinated control of SMES at the terminal of the both area along with the active power support from DFIG based wind power, significantly improves the dynamic response of the T-T systems. However, the settling time and damping levels with wind penetration remains poorer compared to SMES in thermal system alone. Therefore, in a wind integrated thermal power system with the uncertain nature of wind flow, investing in SMES in both the areas may be advantageous.

As far as optimization algorithm is concerned, the proposed CSA has relative smaller numbers of control variables and therefore it is suitable for different types of optimization problems in power system. However, any possible modification of the algorithm either through the process of hybridization with other similar evolutionary algorithms, or by altering the basic process for multi objective optimization problems may result in improving its efficiency. So, in the subsequent chapter multi objective optimization problems are considered for further improvement in wind integrated T-T power system.