Performance of static synchronous series compensator and superconducting magnetic energy storage controllers for frequency regulation in two area hybrid wind-thermal power system using Cuckoo Search Algorithm

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Abstract
To improve the management of limited real power resources, the controller parameters of flexible alternating current transmission systems (FACTs) and energy storage systems (ESS) may be simultaneously tuned to optimize the frequency regulation in a two-area thermal power system penetrated by wind power. In this regard, superconducting magnetic energy storage (SMES) and static synchronous series compensator (SSSC), are operated together in different combinations in a two-area power system. The controller parameters of SMES and SSSC placed in the system are optimized by means of Cuckoo Search Algorithm (CSA). Among the two, SMES is found to provide the best dynamic performance. The performance of coordinated controllers of SMES in both the areas supported by wind power from a double-fed induction generator (DFIG), is also tested. In the event of any load perturbation, the dynamic performance of the controllers is analyzed with the sole participation of the DFIG and with the simultaneous operation of DFIG and SMES in both areas. Finally, time and frequency domain performance indices are reported and discussed.

KEYWORDS
automatic generation control, CSA, DFIG, SMES, SSSC, wind-thermal

1 | INTRODUCTION
With ever increasing power demands and constraints of operation, the capacity expansion by integrating Renewable Energy Resources with conventional power grid has been a better alternative in recent times. A power system operator faces many challenges in secure operation of power system, and similar problems are expected to increase with greater penetration of the renewable generation. Greater penetration of wind generation into the system has resulted in an urgent need for the assessment of their impact on frequency control of power systems. In this regard, it may be beneficial to introduce energy storage devices to alleviate power fluctuations and ensure more reliable and stable power system operation.

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It is important to note that, most of the solutions proposed so far for Automatic Generation Control (AGC) have not been implemented due to the operational constraints associated with thermal power plants. The main reason being the non-availability of required stored energy capacity other than the inertia of the generator rotors. Moreover, in many practical scenarios, due to the persistent deviations in the system frequency and tie-line power, the governor system may no longer be able to absorb the frequency fluctuations due to its slower response. Therefore, the study of AGC of power system in presence of energy storage device and Flexible alternating current transmission systems (FACTs) devices is an interesting topic that has received much attention in literature.

Due to high energy density, discharge rate, and capacity, Superconducting Magnetic Energy Storage (SMES) has been widely applied in the frequency control of power systems.\(^1\)\(^,\)\(^2\) Within the FACTs family, the use of supplementary control can be applied for devices connected in series with power flow line of two area systems to regulate power flow and to decrease inter-area fluctuation.\(^3\)-\(^5\) As FACTs devices give faster response, many in this category like Thyristor Controlled Phase Shifter (TCPS),\(^6\) Static Synchronous Series Compensator (SSSC),\(^7\) and Thyristor controlled series capacitor\(^8\) have been employed in power system to regulate frequency and inter line power variations. In References 9,10, TCPS utilized as an ancillary service, has been applied for stabilizing the frequency oscillations of an interconnected power system.

In conventional system, the integration of wind power generation driven by Double-Fed Induction Generator (DFIG) causes higher frequency variation during decreased or increased load demand. The system dynamic performance enhancement in interconnected power systems utilizing DFIG-based wind turbines were discussed in References 11-14. Further, with considerable wind power penetration in the system, the inertial control may not be sufficient to regulate the frequency deviation effectively due to the limited ramp rate capacities and reduced real and reactive power reserves. The inertial support by wind turbines are limited by their speed, power ratings, and period of recovery.\(^15\)-\(^17\) In addition, the nature of randomness and uncertainty in the availability of renewable resources also require extra storage system for grid reliability. With these conditions of system operation, energy storage systems (ESS) offer an aided support capability to the system.

In larger interconnected systems, simultaneous use of ESS and FACTs devices has been found to give faster response in AGC domain.\(^18\) In these families, some devices like SMES and SSSC are expected to be the most effective stabilizers in power systems,\(^19\)-\(^22\) because of their capability to control active and reactive powers simultaneously. In a similar work, the frequency regulation capability of DFIG is examined on two area conventional system in the presence of SMES and TCPS.\(^23\),\(^24\) Similarly, real power support from the DFIG in the presence of SMES and TCPS has resulted in optimal transient performance.\(^25\) However, approximation of original model may work within certain specific operating ranges, and therefore demand improved models or better tuned control parameters during changed operating conditions. To address that, some works have applied intelligent optimization techniques for the frequency regulation issues in the power systems with the presence of wind power units.\(^26\),\(^27\) In this category, Teaching-learning based optimization algorithm,\(^28\) quasi-oppositional harmony search algorithm\(^29\) are also applied for optimizing controller gains in AGC. However, most of the papers only optimize the integral controller gains of the two area thermal system but not along with those of ESS and FACTs devices simultaneously. Moreover, very few literature probes into relative merit of using SMES and SSSC when the system is penetrated by wind power.

In this regard, the present paper is focused to investigate the following issues.

1. In the problem of AGC, a comparative analysis of a coordinated operation of controllers of SSSC and SMES is carried out. They are placed in different combinations in the two area thermal system (ie, T-T system).
2. By optimizing the controller gains using Cuckoo Search Algorithm (CSA), the work probes into the optimum utilization of SMES and SSSC to improve regulation of system frequency with load variation.
3. The work also aims to test the performance of controllers of SMES in both the areas of the T-T system, when it is augmented and supported by wind power from DFIGs.

The main contributions of the work can be summarized as follows,

1. Proper design of objective function in Equation (1), which includes both time as well as frequency domain performance indices (PFIs), makes the algorithm converge faster.
2. Selection of an efficient optimization algorithm like CSA, has resulted in fast convergence to an optimal solution. The dynamic performance of optimized controllers is tested with the help of both time domain simulations and eigen value modal analysis.
3. The paper also probes into the relative merit of using identical sizes of SMES and SSSC. Details are explained in Section 5.4, by studying participation factors of states in a key electromechanical value.
4. The impact of penetration of DFIG-based wind energy system in the presence of ESS systems like SMES is also verified.

The planning of the paper is as follows. Section 2 illustrates and introduces the models of T-T system along with the controller structures of SSSC, SMES, and DFIG. Section 3 discusses about the different objective functions, methodology, and chosen system parameters. A brief overview of the CSA is presented in Section 4. The simulation and results are discussed in Section 5. At the end, conclusions are presented in Section 6.

2 | MODELS OF TWO AREA THERMAL POWER SYSTEM, SMES, SSSC, AND DFIG CONTROLLERS

The well accepted two area interconnected power system model used in the problem of AGC is shown in Figure 1. SMES connected in the system provides fast control in the frequency during deficit or excess of active power, by utilizing the energy stored in a bulk inductor. Figure 2 illustrates the transfer function model of the SMES control scheme. A detailed discussion about the model in terms of the fundamentals of physics behind the same, is elaborated in References 21, 22, 30.

Conventionally, SSSC is applied in series with interconnected line in power systems for power flow control and also for frequency stabilization.30,31 The capability of SSSC to regulate the characteristic reactance within two extremes from capacitive to inductive, makes it very effective in controlling power flow. It employs self-commutated voltage-source converters to synthesize a three-phase voltage in quadrature with the line current, thereby emulating an inductive/capacitive
reactance to influence the power flow in the transmission lines. The compensation levels can be controlled dynamically by changing the magnitude and phase angle of injected voltage. For frequency regulation studies, SSSC is used in coordination with a second order lead-lag structure as shown in Figure 3.

Among the family of wind power sources, DFIG can supply and regulate real power both via the stator and rotor circuits of induction machine due to the presence of the back to back converters. To make DFIG capable of providing frequency support, additional active power can be derived from the kinetic energy of the turbine’s rotating mass. To achieve the same, an additional auxiliary signal is added as shown in Figure 4, which shows the structure of the controller used in the present work as elaborated in References 32, 33.

3 | FORMULATION OF OBJECTIVE FUNCTION

The operating conditions and system data related to T-T and wind system are described in References 32, 34 and mentioned in Appendix A for understanding of readers. In this work, both the control areas are assumed to have identical integral controllers whose gains ($K_{11}, K_{12}$) are $K_{11} = K_{12} = K_1$ denoted as $K_1$. The units/values used in SMES device are provided in Reference 21.

The objective function is designed to be a single objective, by combining the performances indices obtained from both time and frequency domain responses of the integrated system. The objective function $J$, is formulated by using the values of Integral Time Square Error (ITSE), total settling time $T_s$ of both the area frequencies, tie line power deviation ($\Delta f_1$, $\Delta f_2$, and $\Delta P_{tie}$), and the minimum damping ratio (MDR) of the eigenvalues of the system, as defined below.

$$J = \omega_1(\text{ITSE}) + \omega_2\left(\frac{1}{X}\right) + \omega_3(T_s).$$

where the error is that of the frequency deviations of both the areas and tie line power deviation ($\Delta f_1$, $\Delta f_2$, and $\Delta P_{tie}$), from their respective pre disturbance nominal values.

$$T_s = \text{Sum of total settling times of } \Delta f_1, \Delta f_2, \text{and } \Delta P_{tie}.$$  

$\Delta f_1$ and $\Delta f_2 = \text{frequency deviations of area 1 and 2 respectively,}$

$\Delta P_{tie} = \text{tie line power deviation.}$

$X = \text{MDR, which is the damping ratio of the most lightly damped eigen value mode of the system.}$
\( \omega_1, \omega_2, \) and \( \omega_3 \) are the suitably chosen weighing factors.

\[
ITSE = \sum_{k=1}^{k=n} [(\Delta f_1 k)^2 + (\Delta f_2 k)^2 + (\Delta P_{\text{tie}} k)^2] \ast (t_k - t_{k-1})
\]  

(2)

\[
Ts = Ts_f + Ts_f_2 + Ts_{\Delta \text{P}_{\text{tie}}}
\]  

(3)

\( Ts_{\Delta \text{P}_{\text{tie}}}, Ts_f, Ts_f_2 \) = Settling times of tie line power and frequency deviations.

4 | CUCKOO SEARCH ALGORITHM: A BRIEF OVERVIEW

The algorithm CSA, was originally proposed in References 21,33. The basic philosophy of search procedure adopted by the algorithm is influenced and therefore based on the principle of egg laying by Cuckoos. However, in its optimization application the algorithm steps assume three simplifying assumptions described below.

1. Each cuckoo lays one egg at a time which it dumps in a randomly selected nest.
2. The better nests having better quality eggs, are retained for subsequent generations.
3. Keeping the total numbers of host nests as constant, an egg laid by a cuckoo could be detected by the host bird with a probability \( P_a \) of 0.1 \( (0, 1) \).

The need of specifying probability \( P_a \) is from the fact that, the host bird can either throw the egg away or abandon the nest and instead build a completely new one. Therefore, by specifying \( P_a \), the same fraction of total \( n \) numbers of nests can be replaced by new nests randomly generated afresh. In terms of application methodology for optimization problems, each egg in a nest represents a set of potential random value of optimizing variables with its corresponding fitness value of the objective function. During the course of optimization, the aim is to find cuckoos with better solutions in place of the existing solution in the nests. Even though, the algorithm can be extended to a more complicated case where each nest has multiple eggs representing a set of values, one egg per nest is considered in this work for simplicity. The basic steps of the CSA can be summarized by the flow chart shown in Figure 5. For detail of the algorithm, the readers are advised to follow.33 As far as applying the algorithm is concerned, it has also been applied in References 21,33 to verify the optimization efficiency and the results were found to be promising. In this work, the parameters of the controllers of AGC, SSSC, and SMES are optimized with CSA.

5 | SIMULATION AND RESULTS

For the problem of AGC, the two area T-T system, SMES and SSSC nominal operating conditions and parameters are selected as mentioned in the Appendix A. The two area and other controller models are designed and simulated using MATLAB/SIMULINK. Three different scenarios with different combinations of devices are considered for comparison, where the integral gains of AGC of both the areas are optimized simultaneously along with the controller parameters of these devices. They will be denoted as following cases.

- **SSSC**: In this case, only one SSSC is assumed to be present in the tie-line.
- **SMES-SSSC**: In this case, one SMES is placed in the first area along with the SSSC operating in the tie-line.
- **SMES-SMES**: Both the areas are assumed to be having one SMES each, without SSSC in the tie-line.

For the purpose of optimization, disturbance in the form of 1% step load perturbation (SLP) \( \Delta P_d \) from the nominal load is considered in the first area. Under this scenario, the controller gains of integral controller in AGC loop \( (K_i) \), SMES \( (K_{\text{SMES}}, K_{d}) \), and SSSC \( (K_{\text{SSSC}}, T_1, \) and \( T_3) \) are to be optimized with an objective to minimize the objective function defined in Equation (1) with the help of CSA. In the simulation, a sampling time of 0.01 second is chosen. The dynamic performances of all these cases are analyzed and compared. In all the time domain response figures, the dynamic performances of the system are obtained with the same SLP for which the controllers were optimized.
5.1 Dynamic performance of SSSC

At the outset, suitable gains are optimized when only SSSC is present in the T-T system. The optimized values of controller parameters and the objective function are presented in Table 1. The dynamic responses obtained for the given SLP, with and without SSSC are comparatively depicted in Figure 6. It is observed that the presence of SSSC with suitably optimized controller gains has significantly improved the damping of the system with better PFIs in terms of $T_s$, peak overshoot, and undershoot.

| Controller parameters | Controller parameters | Optimized value of $J$ |
|-----------------------|-----------------------|------------------------|
| SSSC                  | 0.7026                | 49.8825                |
| SMES(first)-SSSC      | 1.7399 50.8156 22.2465 5.7902 32.2239 1.6682 41.7909 |
| SMES-SMES             | 4.7118 99.1703 14.3716 | 14.8430 |
| T-T only              | 0.4986                | 76.3698                |

**TABLE 1** The CSA optimized values of controller parameters and objective function $J$ obtained for different schemes of SSSC and SMES
5.2 Dynamic performance of SMES-SSSC

Proceeding as above, all the controller gains of SSSC and SMES are again optimized simultaneously along with $K_i$ of AGC. The respective optimized controller gains and the value of objective function $J$, is shown in Table 1 and the dynamic performance of the optimized controllers are shown in Figure 7. It is seen as expected that, with the inclusion of SMES, the time domain PFIs improved as compared to when SSSC was operating alone.
5.3 Dynamic performance of SMES-SMES

At last, the controller parameters two numbers of SMES were optimized along with $K_i$ of AGC, so that a comparative understanding of the system dynamic behavior can be compared with SMES-SSSC. As shown in Figure 7, the results improved compared to SMES-SSSC, which is also reflected in the time domain PFIs in Table 2.

It is observed that the coordinated operation of SMES-SMES and SSSC-SMES, with simultaneous optimization of their controller gains can suppress the variations in area frequencies and the tie-line power flow variations. Between the two cases, it is more beneficial to operate with SMES in both the areas, as lower under/overshoots in frequency fluctuations as well as inter-line power flow were obtained compared to SMES-SSSC. Further, these deviations take lesser time $T_s$ to settle. Some other established time domain PFIs, that is, integral absolute error (IAE), ITSE, integral square error (ISE), and integral time absolute error (ITAE) obtained for all the schemes were also compared as shown in Table 2. With these results, further study of these systems with the help of eigen value modal analysis were carried out as elaborated in Section 5.4. This was done to further verify and understand the relative merits of using these devices.
### Table 2: PFIs and MDR of the system used

| Performance indices | T-T DFIG with SMES | T-T DFIG | T-T with SMES | T-T with SSSC-SMES |
|---------------------|-------------------|----------|---------------|-------------------|
| ITSE                | 2.2352 × 10^{-4}  | 0.0069   | 3.5042 × 10^{-4} | 9.7620 × 10^{-4}  |
| IAE                 | 0.0270            | 0.0034   | 0.0324        | 0.0634            |
| ITAE                | 0.0533            | 0.8994   | 0.0484        | 0.1193            |
| ISE                 | 2.1331 × 10^{-4}  | 0.2285   | 3.1536 × 10^{-4} | 8.4152 × 10^{-4}  |
| MDR                 | 0.5055            | 0.2963   | 0.6954        | 0.6350            |
| Total $T_S$         | 21.49             | 70.90    | 13.22         | 30.31             |
| $T_S$ (s)           | Δf$_1$            | 6.0300   | 24.5300       | 4.9000            |
|                     | Δf$_2$            | 9.0100   | 25.5600       | 4.3400            |
|                     | Δ$P_{tie}$        | 6.4500   | 20.8100       | 3.9800            |

**Eigenvalues**

|                | $-6.93 \pm 11.83i$ | $-6.03 \pm 3.79i$ | $-12.5000$ | $-30.3751$ |
|----------------|---------------------|-------------------|------------|------------|
|                | $-8.40 \pm 11.27i$  | $-6.37 \pm 4.11i$ | $-24.2947$ | $-7.80 \pm 10.10i$ |
|                | $-3.91 \pm 0.34i$   | $-1.34 \pm 2.16i$ | $-3.83 + 3.96i$ | $-1.91 \pm 3.15i$ |
|                | $-0.78 \pm 1.23i$   | $-2.43 \pm 0.71i$ | $-3.83 - 3.96i$ |

### 5.4 Eigen value analysis of the T-T system with and without SSSC with SMES

In order to understand comparative influence of SSSC and SMES in the system, a study of their participation in eigen value modes was carried out. Keeping the optimized controller gains, a modal analysis of the T-T system is done.

At the outset, the system eigen values were obtained without any of these two devices. The MATLAB model of the system is linearized using the `linmod` command, which gives the state matrices of the model. The normalized participation factors, of all the system states (in eigen value mode) are then obtained using participation matrix from eigen vectors. A prominent electromechanical eigen value of the T-T system with low damping is shown in Table 3, for all the cases of operation. The damping factor of this mode gets improved when the devices are connected in different combinations, and the pattern of improvement is similar to the results obtained with time domain PFIs. Further, the generalized participation factors of each prominent participating state in the given eigen value, are evaluated as summarized in brief. It was observed that, when SSSC is present in the system, the extent of its participation is higher compared to that of SMES (see T-T with SMES-SSSC). Alternatively, their respective participation factors are similar when they are operating individually.

Further, the SMES-SMES scheme has a total of 16% participation in the chosen eigen value mode, which is far lesser compared to when SSSC is also present in the system. The combined participation of SMES (in area 1) and SSSC was around 60%. The results show that, SMES alone in both the areas gives better dynamic performance in terms of damping factor improvement compared to SMES-SSSC case, even though the total participation is small. The same result can also be seen from Table 3, where the value of the X (MDR) obtained in SMES-SMES case is better than others. A similar trend in performance was also present at higher levels of SLP. Looking at all the results, two clear inferences may be derived regarding relative merit of using SMES and/or SSSC.

1. Compared to SSSC, SMES has given better dynamic damping performance both in terms of time domain and eigen value modal analysis even with smaller levels of participation in a prominent electromechanical mode, compared to the former.

### Table 3: Participation in eigen value of different systems

| Description | Modal analysis of two area system with different subsystems | T-T (11 states) | SSSC (14 states) | SMES-SSSC (16 states) | SMES-SMES (15 states) |
|-------------|-----------------------------------------------------------|-----------------|-----------------|-----------------------|-----------------------|
| Dominant electromechanical eigen value model | $-0.196 \pm 2.96i$ | $-3.81 \pm 4.05i$ | $-1.91 \pm 3.15i$ | $-3.83 \pm 3.96i$ |
| Damping ratio | 0.0661 | 0.685 | 0.635 | 0.6954 |
| Participation factors of prominent states of different systems | T-T Syst: 60%(2) | T-T Syst: 60%(4) | T-T Syst: 42%(4) | T-T Syst: 55%(4) |
| | SSSC: 35%(2) | SMES: 16%(2) |
| | SSSC: 17%(2) | SMES: 25%(2) |

Note: The number shown within bracket of participation factor denotes number of prominent participating states, i.e., 60%(2).
2. As the combined ratings of SMES in both areas is 60 (30 × 2) MW compared to SSSC of 100 MW. Therefore, it may be more beneficial also to use SMES instead of SSSC.

### 5.5 T-T DFIG with SMES-SMES coordination

When the system is penetrated by DFIG-based wind generators, the role of SMES may be even more important, as wind power output is uncertain due to nature of wind flow. Therefore, the work intends 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 reported in References 32,34 is considered. The penetration level of wind power $L_p$ is assumed to be 20% to that of total generating capacity of the area. Using CSA, the parameters $K_i$, $K_{df}$, $K_{pf}$, $K_{SMES}$, and $K_{ld}$ are optimized, keeping identical values in both the areas. $K_{11} = K_{12} = K_1$. As followed previously, a 1% SLP in the first control area is simulated to derive the objective function $J$.

The CSA optimized system parameters are presented in Table 4. Figure 8 shows that a coordinated operation of two SMES improves the dynamic response of $\Delta f_1$, $\Delta f_2$, and $\Delta P_{tie}$ to even greater extent, with the availability of frequency

| Controller parameters | $K_i$ | $K_{df}$ | $K_{pf}$ | $K_{SMES}$ | $K_{ld}$ | Value of $J$ |
|-----------------------|-------|----------|----------|------------|----------|--------------|
| T–T DFIG              | 0.7218| 0.2512   | 0.0975   | —          | —        | 70.8711      |
| T–T DFIG with SMES    | 9.6818| 1.0697   | 0.2431   | 124.6332   | 18.3503  | 23.6018      |
| T–T with SMES         | 4.7118| —        | —        | 99.1703    | 14.3716  | 14.8430      |

**TABLE 4** Optimized parameters for the T-T DFIG systems with SMES

![Figure 8](image-url)  
**FIGURE 8** $\Delta f_1$, $\Delta f_2$, and $\Delta P_{tie}$ obtained for the T-T-DFIG system comparing with and without SMES and T-T with SMES having 1% SLP in area-1
support from DFIG. Moreover, to study the importance of SMES in a W-T system, the corresponding PFI values are compared with those without SMES in the W-T system, as depicted in Table 2. Even though the settling time and MDR values with DFIG-SMES has reduced marginally compared to SMES operating alone, but the overall dynamic response has improved as witnessed in the waveforms in Figure 8.

6 | CONCLUSION

The thermal power plants operate with large numbers of operational constraints, particularly in an integrated system. The level of real and reactive power reserve with only contribution from rotor inertia of generators provides a very small margin of maneuverability in system operation. The use of ESS and FACTs devices solves the problem to a large extent particularly in larger interconnected system. Further, the nature of randomness and uncertainty in the availability of renewable resources also require extra storage system for grid reliability. In these operating scenarios the following concluding remarks are drawn from this work

1. With CSA tuned controllers in all the cases of SSSC, SMES-SSSC, and SMES-SMES, the dynamic performance of the system has improved, with both time and frequency domain PFIs improving in that order.
2. When SMES is operating alone vis-à-vis operating with SSSC, its participation in a key electromechanical mode is smaller compared to the latter case. But, even with lesser participation in the eigen value mode, the SMES imparts greater damping into the system and therefore may be more effective.
3. Further, with SMES operating alone in both areas the tie line power deviations are lesser compared to when both SMES and SSSC are operating together.
4. A coordinated operation of CSA optimized controllers of SMES along with active power support from DFIG-based WECS in both the areas, further improves the dynamic response of the T-T systems during load fluctuations. Even though the settling time and MDR values with DFIG-SMES has reduced marginally compared to SMES alone, but the overall dynamic response has improved as witnessed in the waveforms.

However, more studies of these devices operating in an actual or test multi-machine power system may be required with greater details of system and device modeling and advancements. The Mantegna Algorithm suggested in the search process of CSA, may not be an accurate model in predicting Levy flight, and more research may hence be needed in that direction. A mathematical proof may indeed be beneficial in this regard.

PEER REVIEW INFORMATION

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CONFLICT OF INTEREST

The authors declare no potential conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings are included in the paper. Additional information is available from the corresponding author upon request.

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APPENDIX A

Nominal parameter of system investigated

\[ H_1 = H_2 = 5, D_i = \Delta P_d / \Delta f_i = 8.33 \times 10^{-3} \text{p.u.MW/Hz} \]

\[ R_1 = R_2 = 2.4 \text{ (Hz/p.u.MW)}, T_{g1} = T_{g2} = 0.08 \text{second} \]

\[ K_{r1} = K_{r2} = 0.5, T_{r1} = T_{r2} = 10 \text{seconds}, T_{11} = T_{12} = 0.3 \text{second} \]

\[ \beta_i = \left( D_i + \frac{1}{R_i} \right), \beta_1 = \beta_2 = 0.425, f_1 = f_2 = 60 \text{Hz.} \]

\[ T_{p1} = T_{p2} = 20 \text{seconds} \left( T_p = \frac{2H}{fD} \right), K_{p1} = K_{p2} = 120 \text{Hz/p.u.MW} \]

\[ T_{12} = 0.0867 \text{second}, P_{r1} = P_{r2} = 2000 \text{MW}, a_{12} = \frac{P_{r1}}{P_{r2}} \]

SMES system data

\[ T_{dc1} = T_{dc2} = 0.03 \text{second} \]

\[ S_B = \text{base power of the system} = 2000 \text{MW} \]

Assuming base value of \( E_d = 10 \text{kV} \) \( E_d = 10 \text{kV} \) and \( I_d = 200 \text{kA} \) \( I_d = 200 \text{kA} \)

Base impedance \( (Z_{\text{Base}}) = 0.05 \Omega L_{\text{Base}} = Z_{\text{Base}}/(2 \times \pi \times f) = 0.0001326 \)

\[ L_1 = L_2 = 2.65 \text{H} \text{(Absolute value)} = L_1/L_{\text{Base}} = 19970 \text{ p.u.} \]

\[ I_{do} = 4.5 \text{ kA} = 0.02 \text{ p.u.} \Delta p_d = 20 \text{MW} = 0.01 \text{ p.u.} \]

Nominal parameter of system with DFIG

\[ L_p = 20\%, \beta_1 = \beta_2 = 0.3417, T_{p1} = T_{p2} = 18.8415 \text{seconds} \]

\[ H_e = 3.5 \text{seconds}, T_w = 6 \text{seconds}, T_R = 0.1 \text{second}, T_A = 0.2 \text{second}, K_{pw} = 1.5, K_{iw} = 0.15 \]

\[ P_{\text{min}}^{\text{NC}} / P_{\text{max}}^{\text{NC}} = 0/1.2 \text{p.u.,} T_X = 1.55 \text{seconds} \]

SSSC lead-lag controller

SSSC capacity : 100 MW, \( T_{\text{SSSC}} = 0.05 \text{second}, T_2 = 0.5 \text{second}, \) and \( T_4 = 0.5 \text{second}. \)