A NOVEL HYBRID AGWO-PSO ALGORITHM IN MITIGATION OF POWER NETWORK OSCILLATIONS WITH STATCOM

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ABSTRACT. The assimilation of flexible AC transmission (FACTS) controllers to the existing power network outweigh the numerous alternatives in enhancing the damping behavior for the inter-area/intra-area system oscillations of a power network. This paper provides a rigorous analysis in damping of oscillations in a power network. It utilizes a shunt connected voltage source converter (VSC) based FACTS device to enhance the system operating characteristics. A comprehensive system mathematical modelling has been developed for demonstrating the system behavior under different loading conditions. A novel hybrid augmented grey wolf optimization-particle swarm optimization (AGWO-PSO) is proposed for the coordinated design of controllers static synchronous compensator (STATCOM) and power system stabilizers (PSSs). A multi-objective function, comprising damping ratio improvement and drifting the real part to the left-hand side of S-plane of the system poles, has been developed to achieve the objective and the effectiveness of the proposed algorithms have been analyzed by monitoring the system performance under different loading conditions. Eigenvalue analysis and damping nature of the system states under perturbation have been presented for the proposed algorithms under different loading conditions, and the performance evaluation of the proposed algorithms have been done by means of time of execution and the convergence characteristics.

Nomenclature: Abbreviations
ABC : artificial bee colony
AFSA : Artificial Fish Swarm Algorithm
ALO : Ant lion optimization
AVR : automatic voltage regulator
BBO : bio-geography-based optimization
DA : Dragonfly algorithm
DE : differential evolution
EP : evolutionary programming
GWO : grey wolf optimization
HAS : harmony search algorithm
HHO : Harris hawks optimizer
IA : Immune algorithm

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1. **Introduction.** The application of metaheuristic algorithm is growing in finding the optimal solutions to the complex engineering problems [33], [19]. There are numerous benefits of these algorithms in terms of their creation and applicability. These algorithms are created by the general observation from the different paradigms in the universe and can be modified or hybridized, indicating its simplicity. The application of these algorithms also provides excellent flexibility in adopting a wide variety of engineering problems. As the popularity of these algorithms increasing corresponding to the increase in its application, it is found that no particular algorithm can give the best solution for all the problems [36]. An algorithm, which offers promising results, may not result in the best optimal values in the other research problem. Hence, as per the requirement of the given research problem, a specific algorithm can be chosen. It provides a broad scope for engineers in both the creation and application of the metaheuristics.

As the electric power system advanced, they are operated ever near to their operating limits. Hence, the controller parameter setting in the field of the electrical power system is very crucial and deterministic [25]. This made a necessity of tuning the controller parameters efficiently, thereby need for the application of efficient algorithms. For an instant, the application of different metaheuristic algorithms in the field of electrical power system have been listed in Table 1.

From the literature, it found that the application of metaheuristic algorithms is suitable, and it is necessary for finding the optimal controller parameter settings in a power system. The conventional PSS limited by critical stability gain and experience enormous stress in maintaining stability due to the forced oscillations [16]. Modified PSSs such as a nonlinear synergetic PSS [38], PSS with proportional-resonant controller [16] have been proposed to extend the stability limits by incorporating the design modifications. The analytical mechanics for the realization of the power system has been introduced, and stability analysis has been done [35]. The transient stability assessment has been done using a coverage-based stability assessment for a significant advantage in reliability [31]. The severity of uncoordinated PSSs in different areas of power network has been explained and a Hyper-Spherical Search (HSS) optimization algorithm employed to incorporate efficient system operating conditions [28]. The concept of reducing multiple machine control into multiple single machine control has been introduced by decentralized nonlinear model pred-
### Table 1. Application of different meta-heuristic techniques for research problems in the electric power system

| Suggested Algorithm | Performance comparison with algorithm | Problem solution | Considered Test system | Ref. |
|---------------------|--------------------------------------|------------------|------------------------|------|
| SCA                 | ZN, DE, ABC, BBO, MS, DE, MDE, PSO, TSA | controller parameters of AVR system | Sample test system | [17] |
| SSA                 | GWO, PSO, DE, EP, ALO, DA | OPF problem with voltage stability objective | IEEE 57- and 118-bus | [15] |
| Variant of HSA      | Other variants of HSA | Economic Emission problem | 5, 6, 10, 14- test systems | [21] |
| SSOA                | GWO, PSO, DE, EP | MRCHPED problem | three region test system | [3]  |
| SCA                 | ALO, DA | Power system oscillation damping | 2 machine with STATCOM | [10] |
| Hybrid PSO-AFSA     | PSO, AFSA | ELD problem | 5, 10 Units system | [37] |
| ALO                 | PSO | PSS parameter tuning | SMIB with STATCOM | [11] |
| IA                  | Algorithms from literature | Economic Dispatch problem | 8 test systems | [2]  |
| HHO modified        | GWO, WOA, ALO | Stabilizers coordination | SMIB with STATCOM | [6, 8] |
ictive control approach, and power system oscillation damping has been achieved [26]. A framework for the design of H-inf controller has been suggested in [7] for damping power oscillation, but the proposed technique suffers from a drawback of steady-state error in the deviation of its system states. A two-level strategy in blending local proportional-integral power system stabilizer (PI-PSS) and central controllers have been proposed for damping the low-frequency oscillations in power system [30]. Moth flame optimization (MFO) algorithm has been employed in obtaining the optimal parameter settings of a power system with FACTS controllers [14,32]. Recently, various metaheuristic algorithms [10] and their hybrid forms [12,13] have been tested for the controller parameter tuning of PSS. GWO is a recently developed population-based swarm intelligence technique which has already shown its popularity in providing superior quality results for ample types of optimization problems. The hunting strategy and position updating strategy of the wolves balanced by some crucial mathematical parameters provides a rich diversification and intensification methodology in mapping the search space for the best possible solution. Moreover, GWO eliminates the possible demerits of getting stuck in local minima and a larger number of tuning parameters. Particle swarm optimization (PSO) is a very old state of the art optimization tool used to solve numerous optimization problems. In hybrid GWOPSO, the inertia weight of PSO is implemented to modify the equations evaluating lambda. Further, the position updating procedure of GWO is changed by first evaluating the velocity update and then the position update of the wolves, as in PSO. Therefore hybrid GWOPSO exhibits the nature of both PSO and GWO in yielding better quality solutions for the fitness function.

From the literature presented above, the appropriate controller parameters are necessary for the stable running of a complex power system. In this regard, the contribution of metaheuristics in tuning the controller settings also tremendous. Based on this motivation, in the present work, the evaluation of different algorithms has been presented on a test power system. The main contribution of the paper is listed as follows:

- A two-machine power system connected with STATCOM has been modelled as a test power system.
- A multi-objective function is formulated for achieving the coordination among the PSSs and STATCOM of the test system.
- The objective function comprises of improvement in the damping ratio and finest location of the system eigenvalues for the controller parameter tuning with the proposed algorithms.
- The grey wolf optimization (GWO) is described, and the modified and hybridized versions of GWO are proposed.
- An augmented GWO (AGWO) is suggested for the considered research problem, and it is further improved by hybridizing with the particle swarm optimization (PSO). Hence, this paper proposes a novel hybrid AGWO-PSO algorithm to damp the power oscillations.
- For the considered test system, eigenvalue analysis and damping nature under system perturbation are analyzed with the proposed algorithms. The complete study is presented under different loading conditions.

The paper is organized as follows: Section 2 presents the detailed mathematical model of the test system to carry the system performance analysis. Different algorithms considered are described and detailed statistical analysis has been presented.
on the benchmark test functions in section 3. In section 4, proposed algorithms have been employed for the considered system and statistical tests have been presented. The rigorous analysis on the system performance characteristics have been presented in section 5. The conclusion and future scope of the proposed work are presented in section 6.

2. Problem Formulation and Objective function. A STATCOM provides desired reactive power generation/absorption by means of Voltage Source Converter (VSC) which is supported by an energy storage device. The reactive power generation/absorption can be controlled by means of modulation ratio (me) of PWM and phase angle (de) of VSC. The direction of reactive power depends on the direction of STATCOM current between the utility bus and converter terminal bus, which further depends on the voltage difference between the converter terminal and utility bus [34].

2.1. Mathematical Modeling of power system with STATCOM. The block diagram of the considered power network has been shown in Figure 1. It consists of a two-machine system where two areas having its local generation and load connected with an equivalent reactance value of the transmission lines and a STATCOM is connected in the middle of the transmission line.

![Figure 1. Schematic of the mathematically modelled System to coordinate STATCOM and PSS controllers](image)

In figure 1, terminal voltages at each generator are $V_{1i}$&$V_{12}$, $I_{1L}$&$I_{2L}$ armature current, $x_{1L}$&$x_{2L}$ are the transmission impedance which is connected between two terminal. $\delta_i$ is the torque angle between $E_{qi}$ and $V_{ti}$. STATCOM is connected between two generators. $V_i$ is the voltage at the bus where the STATCOM is connected, $V_0$ is the STATCOM voltage bus after step down transformer where $x_e$ is the step-down transformer reactance, $I_{L0}$ is STATCOM current.

The mathematical relationships of the test system can be derived as follows:
For an $i_{th}$ generator,

$$I_{iL} = I_{iLd} + jI_{iLq} \quad (1)$$

$$V_{ij} = V_{ijd} + jV_{ijq} = V_{ij}(\sin\delta_j + j\cos\delta_j) \quad (2)$$
\[ \delta_i = \angle(E'_{qi}, V_{ti}E'_{qi}) = V_{tiq} + x_{di}I_{Ld} \]  
(3)

\[ E'_{qi} : \text{Generator Internal voltage}; \quad x_{di}, x_{dq} \text{ : d-axis transient, steady state reactance; } \]

\[ i : \text{generator number}; \quad x_{qi} : \text{q-axis steady state reactance}; \quad P_{ei}, Q_{ei} : \text{Active and reactive power delivered from } \]

\[ \text{area } i \text{th area.} \]

\[ V_{tid} = \frac{P_{ei}V_{ti}}{\sqrt{P_{ei}^2 + Q_{ei}^2 + (V_{tiq}'V_{tiq})^2}} \]  
(4)

\[ V_{tiq} = \sqrt{V_{ti}^2 - V_{tid}^2} \]

\[ I_{Ld} = \frac{P_{ei} - I_{Lq}V_{tiq}}{V_{tid}} \]  
(5)

\[ I_{Lq} = \frac{V_{tid}}{x_{qi}} \]

Hence, the currents in equation 1 can be expressed for both generators as follows:

\[ I_{1Ld} = \frac{E'_{q1} - V_{1q2}\cos(\delta_1 - \delta_2) - \frac{x_{di}V_{de}\sin\delta}{x_e}}{(x_{1L} + x_{2L} + x_{1L'}\frac{V_{de}}{x_e}) + (1 + \frac{x_{di}'}{x_e})x_{d1}} \]  
(6)

\[ I_{1Lq} = \frac{V_{1q2}\sin(\delta_1 - \delta_2) + \frac{x_{di}V_{de}\cos\delta}{x_e}}{(x_{1L} + x_{2L} + x_{1L'}\frac{V_{de}}{x_e}) + (1 + \frac{x_{di}'}{x_e})x_{q1}} \]  
(7)

Similarly, for the second generator

\[ I_{2Ld} = \frac{E'_{q2} - V_{1q2}\cos(\delta_2 - \delta_1) - \frac{x_{di}V_{de}\sin\delta}{x_e}}{(x_{1L} + x_{2L} + x_{2L'}\frac{V_{de}}{x_e}) + (1 + \frac{x_{di}'}{x_e})x_{d2}} \]  
(8)

\[ I_{2Lq} = \frac{V_{1q2}\sin(\delta_2 - \delta_1) + \frac{x_{di}V_{de}\cos\delta}{x_e}}{(x_{1L} + x_{2L} + x_{2L'}\frac{V_{de}}{x_e}) + (1 + \frac{x_{di}'}{x_e})x_{q2}} \]  
(9)

The initial torque angle at the utility bus of area 1, 2 can be determined by

\[ \delta_1 = \sin^{-1}((I_{1Lq}x_{qei1} - m_eV_{de}x_{2L}\cos(d_e))/(x_eV_{1q2})) \]  
(10)

\[ \delta_2 = \sin^{-1}((I_{2Lq}x_{qei2} - m_eV_{de}x_{1L}\cos(d_e))/(x_eV_{1q1})) \]  
(11)

where, \( V_{de} \) is the STATCOM voltage on the dc side of the converter; and

\[ x_{qei} = (x_{qi} + x_{iL} + x_{e})x_{iL} + x_{e}(x_{qi} + x_{iL}) \]

\[ x_{deci} = (x_{di} + x_{iL} + x_{e})x_{iL} + x_{e}(x_{di} + x_{iL}) \]  
(12)

From the figure 1, the current at STATCOM can be derived using equations 6-9 as,

\[ I_{L0d} = x_e\left[\frac{E'_{q1}}{x_{deci}} + \frac{E'_{q2}}{x_{dec2}} - m_eV_{de}\sin\delta\left(\frac{x_{2L}}{x_{deci}} + \frac{x_{1L}}{x_{dec2}}\right)\right] \]

\[ + x_e\left[\frac{V_{1d}\cos(\delta_1 - \delta_2)}{x_{deci}} + \frac{V_{1q}\cos(\delta_2 - \delta_1)}{x_{dec2}}\right] \]  
(13)

\[ I_{L0q} = m_eV_{de}\cos\delta\left[\frac{x_{2L}}{x_{qei1}} + \frac{x_{1L}}{x_{qei2}}\right] + x_e\left[\frac{V_{1d}\sin(\delta_2 - \delta_1)}{x_{qei2}} + \frac{V_{1q}\sin(\delta_1 - \delta_2)}{x_{qei1}}\right] \]  
(14)

From equation 13 and 14, the magnitude of STATCOM current can be controlled by controlling the modulation index and phase angle of voltage source converter, which further controls the reactive power supplied/absorbed at utility bus of a power
system. By considering the variation in the system states around the operating point, the state space representation of the test system can be derived. For the system stability studies, the dynamics of synchronous machine and exciter \[20\] can be considered as follows

\[
\Delta \dot{\delta} = \omega_b \Delta \omega \tag{15}
\]

\[
\Delta \dot{\omega} = \frac{(-\Delta P_e - D \Delta \omega)}{M} \tag{16}
\]

\[
\Delta \dot{E}_q' = \frac{(-\Delta E_q + \Delta E_{fd})}{T_{d0}} \tag{17}
\]

\[
\Delta E_{fd} = -\frac{1}{T_A} \Delta E_{fd} - \frac{K_A}{T_A} \Delta V_t \tag{18}
\]

where \(\Delta \omega = (\omega - \omega_0)/\omega_0\).

For the STATCOM installed in a two-machine power network, without supplementary control, the state equations can be written as,

\[
\dot{X} = AX + BU \tag{19}
\]

The complete system model with the power system stabilizer is explained in the subsequent sections.

2.2. Power system stabilizer. PSS can be represented as a combination of two effects, namely, compensation and reset by which the field excitation can be controlled for the low-frequency oscillation. Figure 2 shows the block diagram of PSS, which consists of a compensation block and reset block. The control action for the field excitation by PSS depends on the speed variation in the synchronous machine due to the change in the system operating conditions. PSS will provide \(u_{E1}\) and \(u_{E2}\) for the generator 1 and 2 respectively based on the parameters of compensation block of generator 1 and 2 \((T_{11}, T_{21}, K_{c11} and T_{12}, T_{22}, K_{c12})\) and \(T_w\) represents the washout time constant.

\[
\Delta \omega \xrightarrow{\text{Reset Block}} \frac{ST_w}{1+ST_w} \xrightarrow{\text{Compensation Block}} Kc(1+ST_1)(1+ST_2) \xrightarrow{\text{u_e}}
\]

**Figure 2.** Power System Stabilizer block diagram representation

For the system with supplementary control \(u_{E1}\) and \(u_{E2}\) the state space representation can be given as,

\[
\dot{X} = AX + BU + B_E u_E = A_c X + B_c U \tag{20}
\]

where \(A\) is system state matrix, \(B\) is the STATCOM control input matrix, and \(B_E\) is a supplementary control matrix. The consolidated system matrixes with corresponding constants are explained in Appendix B.
2.3. Objective function and constraints. The detailed system model with STATCOM has been explained in the previous section. The complete model has been presented in the form of state-space representation with state variables and control variables mentioned above. The objective function considered for the optimal parameter tuning is given in Equation 21.

\[ J = \sum_{i=1}^{s} (\sigma_0 - \text{Re}[\text{eig}])^2 + \alpha \sum_{i=1}^{s} (\zeta_0 - \zeta_i)^2 \]  

(21)

From Figure 2, it has been observed that the controlling action by PSS is produced through a compensation block, based on the generator speed variation. The magnitude of the control signal is based on the tuning of gain and time constants in the compensation transfer function. Whereas, STATCOM will offer damping nature to the system oscillations by providing adequate reactive power at the utility bus based on the magnitude of STATCOM current. From equation 13 and 14, the reactive power is controlled by tuning modulation index and phase angle of voltage source converter. The constrains while tuning the parameters are given in equation (22) where maximum and minimum limits of time constant, gain, modulation index, and phase angle are given as, 0.01 and 2, 0.1 and 50, and 0 and 1 respectively.

\[
\begin{align*}
T_{1i,\text{min}} & \leq T_{1i} \leq T_{1i,\text{max}} \\
T_{2i,\text{min}} & \leq T_{2i} \leq T_{2i,\text{max}} \\
K_{c_{1i,\text{min}}} & \leq K_{c_{1i}} \leq K_{c_{1i,\text{max}}} \\
m_{e,\text{min}} & \leq m_{e} \leq m_{e,\text{max}} \\
d_{e,\text{min}} & \leq d_{e} \leq d_{e,\text{max}}
\end{align*}
\]  

(22)

The objective function \( J \) represented in equation (21) for controller parameter tuning, improves the system stability by opting the eigenvalue to be located in the common portion, as shown in figure 4. In equation 21, \( s \) is the total number of system states; \( \zeta \) and \( \text{Re}[\text{eig}] \) denotes the damping ratio and real part of the system eigenvalues, respectively. The decrement ratio \( \sigma_0 \) and damping factor \( \zeta_0 \) are shown in figure 4. The minimization of function \( J \) represents the improvement of damping ratios eigenvalues with lesser magnitudes and shifting of poles toward the left half of s-plane, which are the closer or right-hand side of the vertical axis. Practically, damping ratios more than 0.3 and eigenvalues left side of -3 are reasonable values to damp out the low-frequency oscillations. As the second term in the equation 21 is much lesser compared to the first term, the weightage factor \( \alpha \) is chosen as 1000 [9].

3. Proposed metaheuristic algorithms for damping power system oscillations. According to no free lunch (NFL) theorem, no optimization method can show the best characteristics for every problem even it is proved as an efficient algorithm [36]. In this paper, the latest and popular algorithms have been considered for the system analysis such that it will lead to the appropriate guidelines in the selection of optimization methods in the various applications in the power system.

3.1. Grey wolf optimization (GWO). Grey wolf optimization (GWO) [23] is a population-based and naturally inspired metaheuristic algorithm. It comes under the swarm intelligence based algorithm category and formulated based on the behaviour of grey wolves (GW) in catching the prey. In the pack of GW, based on the managing strength of the set of wolves, they behave as leaders, subordinates to the
leaders in decision-making, and the followers to the above. These characteristics are well-defined in the GWO algorithm by assuming $\alpha$-group as leaders, $\beta$-group as subordinate to the $\alpha$-group, $\delta$-group as followers to the $\alpha$ and $\beta$ groups and finally $\omega$-group as the rest of the GW involving in passing the information from the
boundaries to the other groups. This complete hierarchy is depicted, as shown in figure 4.

This strategy is formulated as a mathematical model for finding the optimal solution and formed the GWO algorithm. It considers encircling, hunting, attacking, and searching the prey as main phases and expressed as follows:

- Encircling prey: The mathematical model of encircling the prey by GW can be derived from figure 5. From figure 5, it has been observed that the proper adjustment of distances between the prey and wolf will result in the position update of the wolves within the search space. This can be derived from equations 23, 24.

\[
\vec{\lambda} = |\vec{C}.\vec{\chi}(t) - \vec{\chi}(t)| (23)
\]

\[
\vec{\chi}(t+1) = \vec{\chi}_p(t) - \vec{\rho}.\vec{\lambda} (24)
\]

where present iteration denoted by ‘t’, \(\vec{\rho}\) and \(\vec{C}\) are regulation vectors, \(\vec{\lambda}\) gives the distance between the GW and prey, and \(\vec{\chi}_p\) and \(\vec{\chi}\) are the position vectors of prey and GW respectively.

![Figure 5. Regulation vectors adjustment for catching the prey.](image)

The values of the regulation vectors depend on the distance between the GW and the prey, as shown in figure 5. These can be expressed as in 25, 26.

\[
\vec{\rho} = 2\vec{a}.\vec{i}_1 - \vec{a} (25)
\]

\[
\vec{C} = 2.\vec{i}_2 (26)
\]

where \(\vec{i}_1\) and \(\vec{i}_2\) are the incidental vectors in \([0, 1]\) and \(\vec{a}\) decreases from 2 to 0 linearly. The incidental vector provides the flexibility in moving the GW randomly using equations 23, 24 within the search space.

- Searching (Exploration) and Attacking (Exploitation) the prey: The searching and attacking strategy of GWs is depicted in figure 6. The value of \(\vec{\rho}\) in equation 25 determines the searching or attacking nature of the GWs. As \(\vec{A}\)
decreases from 2 to 0 linearly, range of $\vec{\rho}$ in the range of $[-2a, 2a]$. Hence, $\vec{\rho}_1$ characterizes the GW converges towards the prey and diverges to explore for the prey if $\vec{\rho}_1 < 1$. The exploration phase further considers a function $\vec{C}$ as given in equation 26 to emphasize/deemphasize the prey position due to the environmental effects. This factor improves the avoidance for the local optima, and exploration ability even in the final iterations of the GWO algorithm. In the entire process described above, the GWO algorithm follows the governance hierarchy as shown in figure 4. In exploration phase, $\alpha$, $\beta$ and $\delta$ GWs diverge from each other and they will converge towards the prey in exploitation phase. Hence, the hunting nature of different wolf groups can be found as follows:

$$\vec{\chi}_1 = \vec{\chi}_\alpha(t) - \vec{\rho}_1 \vec{\lambda}_\alpha$$

$$\vec{\chi}_2 = \vec{\chi}_\beta(t) - \vec{\rho}_2 \vec{\lambda}_\beta$$

$$\vec{\chi}_3 = \vec{\chi}_\delta(t) - \vec{\rho}_3 \vec{\lambda}_\delta$$

$$\vec{\chi}(t + 1) = \frac{\vec{\chi}_1 + \vec{\chi}_2 + \vec{\chi}_3}{3}$$

Where $\vec{\lambda}_\alpha$, $\vec{\lambda}_\beta$, and $\vec{\lambda}_\delta$ are the distance between the $\alpha$, $\beta$ and $\delta$ wolf group and the prey as shown in figure 6. These can be calculated using 23 as follows:

$$\vec{\lambda}_\alpha = |\vec{C}_1 \cdot \vec{\chi}_\alpha - \vec{\chi}|$$

$$\vec{\lambda}_\beta = |\vec{C}_2 \cdot \vec{\chi}_\beta - \vec{\chi}|$$

$$\vec{\lambda}_\delta = |\vec{C}_3 \cdot \vec{\chi}_\delta - \vec{\chi}|$$

Therefore, in GWO algorithm, $\alpha$, $\beta$ and $\delta$ groups update their positions using equation 27-29 and update the position of the prey using 30.

Figure 6. Attacking and searching strategy of GWs.
3.2. **Augmented GWO (AGWO):** For the research problems with lesser number of search agents, the GWO algorithm can be modified by considering the top two groups for the hunting process [27]. Further, the exploration capability within the search space is improved by updating the $\vec{a}$ vector. This modified GWO is termed as augmented GWO (AGWO) [27]. It considers only alpha and beta wolf groups and calculates the prey location as in 32.

$$\vec{\chi}(t + 1) = \frac{\vec{\chi}_1 + \vec{\chi}_2}{2}$$

(32)

where $\vec{\chi}_1$ and $\vec{\chi}_2$ can be found using equations 27 and 28.

The linearly decreasing $\vec{a}$ vector is replaced with 33 to improve the exploration capability.

$$\vec{a} = 2 - \cos(i_3) \frac{t}{t_{max}}$$

(33)

Where $i_3$ is the incidental value in radians.

The modified function in 33 helps in increasing in more exploration for searching the optimal solution in the search space.

3.3. **Hybrid Augmented GWO-Particle Swarm Optimization (AGWO-PSO):** The reduction in the GW groups in the hunting process may lead to the stuck in the local optima for the AGWO algorithm. Even though the exploration phase strengthened with proper adjustment, it needs better position update paradigm for the better claim of benefits of AGWO. This can be achieved with the application of the velocity function of the particle swarm optimization (PSO) in the position update of GWs in finding the prey [18]. Hence the AGWO prey position update can be modified as follows,

$$\lambda_\alpha = |C_1 \cdot \vec{\chi}_\alpha - \gamma \vec{\chi}|$$

$$\lambda_\beta = |C_2 \cdot \vec{\chi}_\beta - \gamma \vec{\chi}|$$

(34)

where, inertia weight

$$\gamma = \gamma_{max} - (\gamma_{max} - \gamma_{min}) * \frac{t}{t_{max}}$$

(35)

The position update of wolves with the hybrid AGWO-PSO technique can be found by 36.

$$\vec{\chi}(t + 1) = \vec{\chi} + \vec{V}(t + 1)$$

(36)

Where the velocity function is defined as,

$$\vec{V}(t + 1) = \gamma \ast (\vec{V} + C_1 \cdot i_4 \cdot (\vec{\chi}_{\alpha} - \vec{\chi}) + C_2 \cdot i_5 \cdot (\vec{\chi}_{\beta} - \vec{\chi}))$$

(37)

Where, $i_4$ and $i_5$ are the incidental vector in [0, 1].

3.4. **Moth Flame Optimization (MFO):** MFO Algorithm [22] is based on the fact that moths have the tendency to move in transverse motion. It is observed that moths move in a straight path for long distances at night by maintaining a fixed angle with respect to the moon. However, when an artificial light source is present in the vicinity, then they tend to move in a spiral path maintaining a fixed angle with respect to the light source. This strategy has been considered for the design of the MFO algorithm.
The variable position of the moths in the search space can be represented by matrix $M$;

$$M = \begin{bmatrix} m_{1,1} & \ldots & m_{1,d} \\ \vdots & \ddots & \vdots \\ \vdots & \ldots & \vdots \\ m_{n,1} & \ldots & m_{n,d} \end{bmatrix}$$ (38)

Where ‘n’ represents the number of moths, ‘d’ is the number of variables and ‘m’ is the corresponding moth in equation 38. The objective function or fitness value can be represented as in equation 39.

$$OM = [OM_1 OM_2 \ldots \ldots OM_n]^T$$ (39)

The set of solution matrix which represent the flame is as follows:

$$P = \begin{bmatrix} p_{1,1} & \ldots & p_{1,d} \\ \vdots & \ddots & \vdots \\ \vdots & \ldots & \vdots \\ p_{n,1} & \ldots & p_{n,d} \end{bmatrix}$$ (40)

where ‘P’ is the flame coordinate variables.

The logarithmic spiral function defined for MFOA is;

$$Q(M_i, P_j) = D_i e^{bt} \cos(2\pi K) + P_j$$ (42)

$$D_i = |P_i - M_i|$$ (43)

Here, ‘k’ is a random number which varies from $[r, 1]$, where ‘r’ is defined as

$$r = -1 + \left( \frac{-t}{t_{max}} \right)$$ (44)

Where $D_i$ is the distance of $i^{th}$ moth from $j^{th}$ flame, $b$ is the shape of a logarithmic spiral, $Q$ is a spiral function, $M_i$ represents $i^{th}$ moth position, $P_j$ represents $j^{th}$ flame position, N is the maximum number of flames.

The searching process is further enhanced by reducing the ‘Flame number’ with an increase in the number of iterations.

$$Flamenumber = round(N - t \times \frac{N - 1}{T})$$ (45)

3.5. Statistical test on the proposed algorithms: For the validation of the proposed algorithm for the implementation on the research problem, a statistical analysis in Table 2 has been presented on the well-known 23 benchmark functions [11, 24]. The statistical analysis is presented by executing the proposed algorithm for 30 times by considering maximum number of iterations as 500.
| Function | Mean | SD     | Best | Worst |
|----------|------|--------|------|-------|
| F1: Sphere | 1.21E-27 | 1.26E-25 | 1.81E-05 | 2.74E-25 |
| F2: Schwefel 2.22 | 1.18E-16 | 1.45E-15 | 1.63E-03 | 1.76E-15 |
| F3: Schwefel 1.2 | 1.30E-05 | 2.32E-04 | 4.84E-01 | 1.49E-05 |
| F4: Schwefel 2.21 | 1.16E-06 | 2.19E-06 | 3.30E-01 | 1.93E-06 |
| F5: Rosenbrock | 2.95E+01 | 2.95E+01 | 3.11E+01 | 2.97E+01 |
| F6: Step | 8.33E-01 | 8.07E-01 | 4.48E+00 | 1.15E+00 |
| F7: Quartic | 1.67E-03 | 2.11E-03 | 3.53E-02 | 2.60E-03 |
| F8: Schwefel | -6.58E+03 | -6.33E+03 | -5.72E+03 | -1.21E+04 |
| F9: Rastrigin | -7.98E-01 | -8.08E-01 | -6.25E+01 | -9.26E+01 |
| F10: Ackley | 2.20E+00 | 3.31E+00 | 5.81E+01 | 5.17E+01 |
| F11: Griewank | -6.82E-03 | -7.45E-03 | -7.64E-03 | -8.56E-03 |
| F12: Penalized | 4.72E+02 | 4.72E+02 | 4.97E+02 | 6.52E+02 |
| F13: Penalize 2 | 9.89E+02 | 9.89E+02 | 9.38E+02 | 9.12E+02 |
| F14: Foxholes | 6.63E+00 | 7.34E+00 | 1.11E+01 | 6.73E+00 |
| F15: Kowalik | 9.79E-03 | 9.36E-03 | 5.66E-03 | 3.21E-04 |
| F16: Six-hump Camel-Back | -1.13E+00 | -1.13E+00 | -1.12E+00 | -1.13E+00 |
| F17: Branin | 3.48E-03 | 3.48E-03 | 5.22E-01 | 4.34E-01 |
| F18: Goldstein | 3.27E+00 | 3.27E+00 | 3.27E+00 | 3.27E+00 |
From the statistical data in table 2, it has been perceived that the suggested AGWOPSO resulted in acceptable performance in different types of functions. Further, the statistical analysis in the table 2 can be extended by the characteristics obtained by different algorithms for different environments as shown in figure 7.

4. Performance of suggested algorithms. For the modelled power system and objective functions considered in Section 2, the coordination among the controllers has been achieved by tuning the controller parameters. For the considered test system, MFO, GWO, PSO, AGWO, and AGWO-PSO algorithms have been implemented under the similar environment to find the optimal controller settings. The tuned values of the controller parameters achieved using the proposed metaheuristic algorithms are within the inequality constraints as mentioned in 22 and these are listed in Table 4. The tuned parameters have been given for different loading conditions where ‘TOE’ represents the time of execution of the respective algorithm, and ‘\( J_{\text{min}} \)’ represents the minimized value of the objective function. The whole system analysis presented in this article has been performed in the identical hardware environment with a realistic configuration. Total search agents of 30 are considered for 500 iterations, and all the values obtained are the mean values of 30 individual runs. And the simulation process is done in MatLab 2016b version with the PC configuration of intel i7 8th gen processor and 16 GB RAM.

The convergence characteristics of the proposed algorithms under different loading conditions have been presented in figure 8. It represents the pattern of the minimization of the objective function over the number of iterations by proper tuning of controller parameters. The convergence to the minimized value in less number of iterations is always preferred for an efficient algorithm. The complexity of the GWO algorithm has been reduced in the proposed methods. However, this reduction in the number of wolf groups deteriorates the performance in achieving the minimum values, but the proposed algorithms resulted in faster convergence in different loading conditions.
Figure 7. (a) 2D representation of F1-F23, (b) Search space, (c) Average fitness obtained over the iterations, (d) box and whisker plot, (e) Convergence curves.

Table 3. Wilcoxon paired signed ranks test for the test system

| Algorithm               | p-value  |
|-------------------------|----------|
| Light Load              |          |
| AGWO-PSO Versus MFO     | 1.7344e-06 + |
| AGWO-PSO Versus GWO     | 1.7344e-06 + |
| AGWO-PSO Versus PSO     | 1.7344e-06 + |
| AGWO-PSO Versus AGWO    | 1.7344e-06 + |
| Nominal Load            |          |
| AGWO-PSO Versus MFO     | 1.7344e-06 + |
| AGWO-PSO Versus GWO     | 1.7344e-06 + |
| AGWO-PSO Versus PSO     | 1.7344e-06 + |
| AGWO-PSO Versus AGWO    | 1.7344e-06 + |
| Heavy Load              |          |
| AGWO-PSO Versus MFO     | 1.7344e-06 + |
| AGWO-PSO Versus GWO     | 1.7344e-06 + |
| AGWO-PSO Versus PSO     | 1.7344e-06 + |
| AGWO-PSO Versus AGWO    | 7.7122e-04 + |
| Table 4. Tuned parameters of controller parameters with the proposed metaheuristic optimization algorithms |
|---------------------------------|--------|--------|--------|--------|--------|--------|--------|
|                                | T11    | T21    | K1     | T12    | T22    | K2     | me     | de     | TOE    | Jmin    |
| Light Load                     |        |        |        |        |        |        |        |        |        |         |
| MFO                            | 2      | 0.353621 | 17.1851 | 0.896599 | 2      | 50     | 0.877263 | 0      | 21.1012 | 20634.638 |
| GWO                            | 1.99226 | 0.631084 | 20.0048 | 2      | 0.408557 | 7.68251 | 1      | 0.553048 | 19.8576 | 19744.427 |
| Pe1=Pe2=0.3&                   |        |        |        |        |        |        |        |        |        |         |
| PSO                            | 1.99616 | 0.531169 | 17.1061 | 1.99706 | 0.376092 | 7.67036 | 0.93685 | 0.471697 | 22.568  | 19790.2423 |
| AgWO                           | 2      | 0.814356 | 20.0335 | 2      | 0.349201 | 0.145617 | 1      | 0.606624 | 20.511  | 19749.174 |
| Qe1=Qe2=0.1                    | 1.91829 | 0.315199 | 16.476  | 2      | 0.367394 | 7.72613 | 0.759916 | 0      | 21.5609 | 19657.1023 |
| Nominal Load                   |        |        |        |        |        |        |        |        |        |         |
| MFO                            | 2      | 0.34587 | 6.5268  | 2      | 0.23173 | 4.0409 | 0.71636 | 1      | 25.2134 | 20699.6872 |
| GWO                            | 2      | 0.20802 | 4.8299  | 2      | 0.18249 | 4.344  | 1      | 0.00080834 | 21.9609 | 19897.141 |
| Pe1=Pe2=0.8&                   |        |        |        |        |        |        |        |        |        |         |
| PSO                            | 2      | 0.34586 | 6.5267  | 2      | 0.23173 | 4.0409 | 0.71631 | 0.99996 | 23.2164 | 19918.5198 |
| AgWO                           | 2      | 0.30786 | 5.9268  | 2      | 0.22043 | 2.9841 | 0.71539 | 1      | 20.9591 | 19457.3614 |
| Qe1=Qe2=0.6                    | 2      | 0.21304 | 5.271   | 2      | 0.20313 | 5.4271 | 1      | 0      | 20.5927 | 19425.0108 |
| Heavy Load                     |        |        |        |        |        |        |        |        |        |         |
| MFO                            | 2      | 0.12956 | 3.698   | 2      | 0.1436 | 5.036  | 1      | 0      | 21.3626 | 20880.619 |
| GWO                            | 2      | 0.12949 | 3.7016  | 2      | 0.14394 | 5.0545 | 1      | 0.00074374 | 20.4907 | 20388.983 |
| Pe1=Pe2=1.3&                   | 0.709342 | 0.168539 | 19.6737 | 0.69435 | 0.171915 | 19.1828 | 0.235767 | 0      | 22.1254 | 20396.0086 |
| Qe1=Qe2=1.0                    | 0.13122 | 3.7291  | 2      | 0.13306 | 4.9783 | 1      | 0      | 20.5043 | 20387.3276 |
| AGWO                           | 2      | 0.12329 | 3.5156  | 2      | 0.14564 | 5.9558 | 1      | 0      | 22.1768 | 20387.1437 |
The time of execution (TOE) of the proposed algorithms has been represented under different loading conditions in figure 9. The comparison of TOE (in seconds) shows that the proposed AGWO and AGWO-PSO resulted in the faster optimal solution for the tuned parameters. However, GWO performance relatively good, but due to the minimization of wolf groups in the base algorithm, the complexity has been reduced in the proposed algorithms.

Table 5. ANOVA test for the test system under different loading conditions

| Source of variation | Sum of square | degrees of freedom | Mean square |
|---------------------|--------------|--------------------|-------------|
| Light Load (Pe1=Pe2=0.3 & Qe1=Qe2=0.1) | 2.0661e+07 | 5-1 = 4 | 5.1651e+06 |
| Within techniques | 1.7391e+04 | 30-5 = 25 | 695.8936 |
| Nominal Load (Pe1=Pe2=0.8 & Qe1=Qe2=0.6) | 1.0308e+07 | 5-1 = 4 | 2.5770e+06 |
| Between techniques | 55.6981 | 30-5 = 25 | 2.2279 |
| Within techniques | 2.3453e+09 | 30-5 = 25 | 9.3812e+07 |
| Heavy Load (Pe1=Pe2=1.3 & Qe1=Qe2=1.0) | 1.1328e+09 | 5-1 = 4 | 2.8320e+08 |
| Between techniques | 2.3453e+09 | 30-5 = 25 | 9.3812e+07 |

| Source of variation | F-ratio |  5% F-limit [1] |
|---------------------|---------|----------------|
| Light Load (Pe1=Pe2=0.3 & Qe1=Qe2=0.1) | 7.4225e+03 | F(4,25) = 2.7587 |
| Within techniques | 3.0188 | F(4,25) = 2.7587 |
| Nominal Load (Pe1=Pe2=0.8 & Qe1=Qe2=0.6) | 1.1567e+06 | F(4,25) = 2.7587 |
| Within techniques | 1.1567e+06 | F(4,25) = 2.7587 |
| Heavy Load (Pe1=Pe2=1.3 & Qe1=Qe2=1.0) | 1.1567e+06 | F(4,25) = 2.7587 |
| Between techniques | 3.0188 | F(4,25) = 2.7587 |

- Statistical tests with the proposed algorithm on the test system: The advantages of the proposed AGWO-PSO algorithm over other algorithms can be assessed with the help of few statistical tests. The authors in [5] and [4] suggested some nonparametric and parametric statistical tests respectively. Wilcoxon’s signed-rank test and ANOVA test has been performed with the proposed algorithm on the considered test system under different loading conditions. The mentioned tests have been performed by executing the algorithms for 30 times. Table 4 is depiction of the p-values generated after performing Wilcoxon’s paired sign rank test. The defining criteria is considering two alternative hypothesis such that H0 be a hypothesis that affirms there exist no difference between the four methods, and H1 is the alternative hypothesis confirming the methods to be different. The significance level, \( \alpha \) is chosen as 0.05 and the symbols +/-/ indicates that the value yielded by the proposed AGWO-PSO is better than/worse than/approximately equal to the algorithms with which paired contrasting is executed. Considering a ‘p-value’ less than 0.05 for all the test systems the null hypothesis is contradicted and proves the Wilcoxon’s signed rank test [5] true for the proposed algorithm.
Figure 8. Convergence characteristics of the proposed optimization algorithms under (a) Light Load, (b) Nominal Load and (c) Heavy Load condition
The ANOVA test [4], [29] is performed by the coding method. In the proposed work, ANOVA test is performed between five optimization techniques namely, MFO, GWO, PSO, AGWO, and AGWO-PSO (i.e., $k=5$) The table 4 also shows that the calculated value of F for both the systems are less than the tabulated value of F at 5% level of significance with degrees of freedom being 4 and 25. We may therefore conclude that the difference in the minimized cost by the techniques is significant and is not just a matter of chance.

5. Results and Analysis. The performance of various optimization methods varies from case to case. In such a scenario, different analysis has to be performed for the metaheuristic algorithms on the modelled system under different operating conditions to comment on the suitability. In this section, an eigenvalue analysis and damping nature of the system states under perturbation has been presented for the considered system under different loading conditions.

Table 5 represents the system eigenvalues and their corresponding damping ratios with different techniques under different loading conditions. Corresponding to the considered objective function, the system eigenvalues had higher negative real parts and positive damping ratios. From the magnitudes presented, it has been observed that the proposed AGWO-PSO algorithm has shown better magnitudes in respect of damping ratios and expected to be more stable under the different operating environment in comparison with the other proposed controller techniques. The key benefit of AGWO for reducing the algorithm complexity resulted in more oscillating modes under the nominal condition for the test system. This has been improved with the proposed hybrid method, and the system performance has been improved. The analysis of the system performance characteristics further extended to the damping nature offered by the system states for the perturbations occurred in system operating environment. For the study, a 10% perturbation is assumed at $t=0$ sec., and damping nature obtained with the tuned controller parameters has been presented in figure 10 to 12 under light load, nominal load and heavy load conditions respectively. For the analysis purpose, variations in rotor torque angle ($\delta$), angular velocity ($\omega$), internal generator voltage ($E_q$), and excitation voltages ($E_{fd}$)
Table 6. System Eigenvalues & Damping ratios under various loading conditions with the proposed optimization algorithms

|                  | Light Load |                  | Nominal Load |                  | Heavy Load |                  |
|------------------|------------|------------------|--------------|------------------|------------|------------------|
|                  | Eigenvalues | Damping Ratios   | Eigenvalues  | Damping Ratios   | Eigenvalues | Damping Ratios   |
|                  |            |                  |              |                  |            |                  |
| MFO              | -0.0078±0.0188i | 0.3827         | -0.7480±1.8259i | 0.3791         | -1.9085±2.4671i | 0.6119         |
|                  | -0.9740±0.5584i | 0.8675         | -1.2802±2.6786i | 0.4312         | -2.0760±2.4939i | 0.6398         |
|                  | -1.1434±1.7995i | 0.5363         | -2.8197±6.1449i | 0.4171         | -3.6275±9.2904i | 0.3637         |
|                  | -0.8615±3.6316i | 0.2308         | -2.9734±6.3771i | 0.4226         | -3.2760±10.3411i | 0.3020         |
|                  | -3.2999±7.4141i | 0.4066         |                  |                  |            |                  |
| GWO              | -0.4185±1.0616i | 0.3668         | -1.1920±1.9198i | 0.5275         | -1.9079±2.4615i | 0.6126         |
|                  | -0.4371±1.1238i | 0.3625         | -1.1982±1.9436i | 0.5248         | -2.0721±2.4946i | 0.6391         |
|                  | -2.6004±5.4552i | 0.4303         | -2.9651±7.9998i | 0.3475         | -3.6312±9.2956i | 0.3639         |
|                  | -2.6500±5.9959i | 0.4042         | -3.4152±8.2929i | 0.3808         | -3.2705±10.3508i | 0.3013         |
| PSO              | -0.4699±1.1627i | 0.3747         | -0.7481±1.8259i | 0.3791         | 0.0904±0.1394i | -0.5443         |
|                  | -0.4865±1.2265i | 0.3687         | -1.2802±2.6786i | 0.4312         | -2.0095±1.4211i | 0.8165         |
|                  | -2.6526±5.6651i | 0.4240         | -2.8198±6.1450i | 0.4171         | -2.1101±1.4246i | 0.8288         |
|                  | -2.7110±6.1662i | 0.4025         | -2.9734±6.3772i | 0.4226         | -1.0158±5.2287i | 0.1907         |
|                  |                  |                  |              |                  |            |                  |
| AGWO             | -0.4699±1.1627i | 0.3747         | -0.7481±1.8259i | 0.3791         | 0.0904±0.1394i | -0.5443         |
|                  | -0.4865±1.2265i | 0.3687         | -1.2802±2.6786i | 0.4312         | -2.0095±1.4211i | 0.8165         |
|                  | -2.6526±5.6651i | 0.4240         | -2.8198±6.1450i | 0.4171         | -2.1101±1.4246i | 0.8288         |
|                  | -2.7110±6.1662i | 0.4025         | -2.9734±6.3772i | 0.4226         | -1.0158±5.2287i | 0.1907         |
|                  |                  |                  |              |                  |            |                  |
| AGWO-PSO         | -0.3352±0.9516i | 0.3322         | -2.9867±5.1894i | 0.4988         | 0.4900±2.5140i | 0.5940         |
|                  | -0.5279±2.9215i | 0.1778         | -2.9863±5.1862i | 0.4990         | -2.1206±2.4898i | 0.6484         |
|                  | -2.2861±5.4747i | 0.3853         | -2.9946±6.1582i | 0.4373         | -3.5667±9.2841i | 0.3586         |
|                  |                  |                  |              |                  |            |                  |
| AGWO-PSO         | -0.6870±1.3777i | 0.4463         | -1.1504±1.7145i | 0.5572         | -1.7398±2.2605i | 0.6099         |
|                  | -0.6182±1.6901i | 0.3435         | -1.0548±1.9079i | 0.4838         | -2.1183±2.6682i | 0.6218         |
|                  | -2.5066±5.7174i | 0.4015         | -3.0003±8.3249i | 0.3391         | -3.7652±9.1415i | 0.3808         |
|                  | -3.0112±8.0047i | 0.3521         | -3.1771±8.7298i | 0.3420         | -3.3353±11.0972i | 0.2878         |

are considered under the perturbation conditions. Figure 10 represents the variations in the system states after encountering a perturbation at t=0 Sec under light load conditions. A comparative analysis of different metaheuristic algorithms can be observed and found that the proposed AGWO-PSO resulting in less magnitude of fluctuation and fast damping nature in system states. The tuned parameters by the MFO algorithm not able to damp the oscillations in the considered loading condition. GWO and AGWO algorithms also showing satisfactory damping characteristics but with more settling time and peak magnitudes compared to the proposed hybrid algorithm.

The system characteristics under nominal load condition have been represented in figure 11. In this loading conditions, all the considered algorithms are resulting in satisfactory performance, but GWO, MFO algorithms are suffering from some steady-state error in the system states. In a similar manner, during the heavy load conditions, the characteristics have been shown in figure 12 for 10% perturbation...
Figure 10. Damping behavior of system states for 10% perturbation under light load with different algorithms.
Figure 11. Damping behavior of system states for 10% perturbation under light load with different algorithms.
Figure 12. Damping behavior of system states for 10% perturbation under heavy load with different algorithms.
in system states. Under this loading condition, all the considered algorithms are performing in satisfactory operation. So from figure 10 to 12, it has been observed that GWO metaheuristic method and its variants are resulting in satisfying damping nature in the system operating environment. And from the eigenvalue analysis, TOE performance and convergence characteristics, it is found that GWO is efficiently tuning the system control parameters for the coordination of STATCOM with PSSs. However, GWO resulting in some steady-state error in the nominal load condition for the deviation of system states. The AGWO and hybrid AGWO-PSO methods overcome this. Whereas the proposed AGWO-PSO algorithm resulting in the lesser peak values compared to AGWO for the considered test system.

6. Conclusion & Future scope. This paper presents a rigorous analysis of power system oscillations damping by the coordinated design of STATCOM and PSSs using meta-heuristic optimization algorithms. A two-area system with STATCOM connected in the middle of the transmission line has been modelled to perform the analysis on damping characteristics achieved with the proposed methods. For the selection of an appropriate tuning method from the proposed metaheuristic algorithms, the system study has been performed under different system loading conditions. The various analyses are performed based on the proposed technique convergence characteristics, the execution time for the considered system and the tuned parameters within the limits of the constraints. The system performances are analyzed by means of system eigenvalue location, damping ratios and damping nature offered to the system perturbations. By considering all the system analysis, the proposed AGWO-PSO algorithm has been shown satisfactory performance characteristics and suggested over other techniques for various system operating conditions.

The analysis can be further extended with the different FACTS devices considering the larger size of the power system. However, the proposed test system model can be further extended by including more realistic environment by including PI and PLL for the facts controllers. Hence the proposed algorithm has a full scope of applying in the different power system research problems.

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**Appendix A:**

Power system parameters:

\[ M_1 = M_2 = 6; D_1 = D_2 = 0 \]

\[ V t_1 = 1.0; V t_2 = 0.89; \]

\[ K a_1 = K a_2 = 50; T a_1 = T a_2 = 0.01; T d_0_{11} = T d_0_{12} = 6.3; \]

\[ x_e = 0.15; x_{1L} = 0.3; x_{2L} = 0.3; \]

**Appendix B:**

System matrices are:

\[
A_{13,13} = \begin{bmatrix}
A_{1,1} & A_{1,2} & \cdots & A_{1,13} \\
A_{2,1} & A_{2,2} & \cdots & A_{2,n} \\
\vdots & \vdots & \ddots & \vdots \\
A_{13,1} & A_{13,2} & \cdots & A_{13,13}
\end{bmatrix}
\]

(46)

and

\[
B_{13,2} = \begin{bmatrix}
0 & 0 & 0 \\
B_{2,1} & B_{2,2} \\
B_{3,1} & B_{3,2} \\
B_{4,1} & B_{4,2} \\
B_{5,1} & B_{5,2} \\
B_{6,1} & B_{6,2} \\
B_{7,1} & B_{7,2} \\
0 & 0 & 0 \\
B_{9,1} & B_{9,2} \\
\vdots & B_{10,1} & B_{10,2} \\
B_{11,1} & B_{11,2} \\
B_{12,1} & B_{12,2} \\
B_{13,1} & B_{13,2}
\end{bmatrix}
\]

(47)
where

\[ A_{1,2} = w_0; \quad A_{2,1} = -K_{11}; \quad A_{2,2} = -D_1; \quad A_{2,3} = -K_{21}; \]

\[ A_{2,5} = -\frac{K_{pd1}}{M_1}; \quad A_{3,1} = -\frac{K_{41}}{T_d0_1}; \quad A_{3,3} = -\frac{K_{41} * K_{51}}{T_d0_1}; \quad A_{3,4} = \frac{T_d0_1}{T_d0_1}; \]

\[ A_{4,5} = -\frac{K_{pd1}}{T_d0_1}; \quad A_{4,1} = -\frac{K_{41} * K_{51}}{T_d0_1}; \quad A_{4,4} = -\frac{K_{41}}{T_0_1}; \]

\[ A_{4,4} = -\frac{1}{T_0_1}; \quad A_{4,5} = -\frac{K_{41} * K_{pd1}}{T_0_1}; \quad A_{4,6} = K_{0_1}; \quad A_{5,1} = K_{7_1}; \]

\[ A_{5,3} = K_{9_1}; \quad A_{5,5} = -K_{9_1}; \quad A_{5,8} = K_{7_2}; \quad A_{5,10} = K_{8_2}; \]

\[ A_{6,1} = \frac{1}{M_1}; \quad A_{6,2} = \frac{D_1}{M_1}; \quad A_{6,3} = -\frac{K_{21}}{M_1}; \quad A_{6,5} = -\frac{K_{pd1}}{M_1}; \]

\[ A_{6,6} = \frac{1}{T_{w_1}}; \quad A_{7,1} = \frac{K_{A_{11}} * K_{11} * T_{11}}{M_1 * T_{21}}; \]

\[ A_{7,2} = -\frac{D_1 * K_{A_{11}} * T_{11}}{M_1 * T_{21}}; \quad A_{7,3} = \frac{K_{A_{11}} * T_{11} * K_{21}}{M_1 * T_{21}}; \]

\[ A_{7,5} = -\frac{K_{pd1} * K_{A_{11}} * T_{11}}{(M_1 * T_{21})}; \quad A_{7,6} = \frac{K_{A_{11}}}{T_{w_1}} * \left(1 - \frac{T_{11}}{T_{w_1}}\right); \]

\[ A_{7,7} = \frac{1}{T_{w_1}}; \quad A_{8,9} = w_0; \quad A_{9,5} = -\frac{K_{pd2}}{M_2}; \]

\[ A_{9,8} = \frac{M_2}{K_{12}}; \quad A_{9,9} = -\frac{D_2}{M_2}; \quad A_{9,10} = \frac{M_2}{K_{22}}; \]

\[ A_{10,5} = \frac{K_{pd2}}{T_d0_2}; \quad A_{10,8} = \frac{K_{42}}{T_d0_2}; \quad A_{10,10} = \frac{T_d0_2}{T_d0_1}; \]

\[ A_{10,11} = \frac{T_d0_2}{T_0_2}; \quad A_{11,5} = \frac{K_{a_2} * K_{pd2}}{T_0_2}; \quad A_{11,8} = \frac{K_{a_2} * K_{52}}{T_0_2}; \]

\[ A_{11,10} = \frac{K_{a_2} * K_{62}}{T_0_2}; \quad A_{11,11} = -\frac{1}{T_{w_2}}; \quad A_{11,13} = \frac{K_{a_2}}{T_{w_2}}; \]

\[ A_{12,5} = -\frac{K_{pd2}}{M_2}; \quad A_{12,8} = -\frac{K_{12}}{M_2}; \quad A_{12,9} = -\frac{D_2}{M_2}; \]

\[ A_{12,10} = -\frac{K_{pd2}}{K_{22}}; \quad A_{12,12} = \frac{1}{T_{w_2}}; \]

\[ A_{13,5} = -\frac{K_{pd2} * K_{A_{12}} * T_{12}}{(M_2 * T_{22})}; \quad A_{13,8} = -\frac{K_{A_{12}} * K_{12} * T_{12}}{(M_2 * T_{22})}; \]

\[ A_{13,9} = -\frac{D_2 * K_{A_{12}} * T_{12}}{(M_2 * T_{22})}; \quad A_{13,10} = -\frac{K_{A_{12}} * T_{12} * K_{22}}{(M_2 * T_{22})}; \]

\[ A_{13,12} = \frac{K_{A_{12}}}{T_{22}} * \left(1 - \frac{T_{12}}{T_{w_2}}\right); \quad A_{13,13} = -\frac{1}{T_{22}}; \]

and zero for the remaining elements.
\[ B_{13,2} = \frac{-K A_{12} * T_{12} * K_{pde2}}{(M_2 * T_{22})} \]

System constants:

\[
K_{11} = \frac{(V_{1d} - x'_d I_{1Lq})(x_{dc1} - x_{dt1})V_{i2} \sin(\delta_1 - \delta_2)}{x_{dec1}} \\
+ \frac{(V_{1q} - x_q I_{1Ld})(x_{qc1} - x_{qe1})V_{i2} \cos(\delta_1 - \delta_2)}{x_{qce1}}
\]

\[
K_{21} = \left( I_{1Lq} + \frac{V_{1d}(x_{2L} + x_e)}{x_{dec1}} \right)
\]

\[
K_{31} = 1 + \frac{(x'_{d1} - x_{d1})(x_{2L} + x_e)}{x_{dec1}}
\]

\[
K_{41} = \frac{-(x'_{d1} - x_{d1})(x_{dec1} - x_{dt1})V_{i2} \sin(\delta_1 - \delta_2)}{x_{dec1}}
\]

\[
K_{pe1} = \frac{(V_{1d} - x'_d I_{1Lq})(x_{bd1} - x_{de1})V_{dc} \sin de}{2x_{dec1}} \\
+ \frac{(V_{1q} - x_q I_{1Ld})(x_{bd1} - x_{qe1})V_{dc} \cos de}{2x_{qce1}}
\]

\[
K_{pde1} = \frac{(V_{1d} - x'_d I_{1Lq})(x_{bd1} - x_{de1})meV_{dc} \cos de}{2x_{dec1}} \\
+ \frac{(V_{1q} - x_q I_{1Ld})(-x_{q1} + x_{qe1})meV_{dc} \sin de}{2x_{qce1}}
\]

\[
K_{pd1} = \frac{(V_{1d} - x'_d I_{1Lq})(x_{bd1} - x_{de1})me \sin de}{2x_{dec1}} \\
+ \frac{(V_{1q} - x_q I_{1Ld})(x_{q1} - x_{qe1})me \cos de}{2x_{qce1}}
\]

\[
K_{51} = \frac{(V_{1d} / V_{11})x_q I_{1Ld}(x_{q1} - x_{qe1})V_{i2} \cos(\delta_1 - \delta_2)}{x_{qce1}} \\
- \frac{(V_{1q} / V_{11})x'_q I_{1Ld}(x_{de1} - x_{dt1})V_{i2} \cos(\delta_1 - \delta_2)}{x_{dec1}}
\]

\[
K_{61} = \frac{(V_{1q} / V_{11})(x_{dec1} + x'_{d1}(x_{2L} - x_e))}{x_{dec1}}
\]

\[
K_{71} = \left( \frac{3}{4C_{dc}} \right) \left\{ \frac{meV_{i2} \sin(\delta_1 - \delta_2)(\cos de)x_{dec1}}{x_{dec1}} \\
- \frac{meV_{i2} \cos(\delta_1 - \delta_2)(\sin de)x_{qce1}}{x_{qce1}} \right\}
\]

\[
K_{81} = \left( \frac{-3}{4C_{dc}'} \right) \frac{x_{2l} me \cos de}{x_{dec1}} \\
+ \frac{me \cos de(x_{bd1})x_{q1}}{2x_{dec1}} \\
+ \frac{me \sin de(x_{bd1})x_{q1}}{2x_{dec1}}
\]

Similarly, constants with respective to generator 2 can also be written.
\[ K_{ze} = \left( \frac{3}{4C_{dc}} \right) \left\{ \frac{V_{dc} \sin de (me \cos de) x_{bd1}}{2x_{dec1}} + \frac{V_{dc} \cos de (me \sin de) x_{bq1}}{2x_{dec1}} \right. \]
\[ \left. + \frac{V_{dc} \sin de (me \cos de) x_{bd2}}{2x_{dec2}} + \frac{V_{dc} \cos de (me \sin de) x_{bq2}}{2x_{dec2}} \right\} \]
\[ K_{ze} = \left( \frac{3me}{4C_{dc}} \right) (I_{Ldq} \cos de - I_{Ldq} \sin de) \]
\[ + \left( \frac{3}{4C_{dc}} \right) \left\{ \frac{meV_{dc} \cos de (me \cos de) x_{bd1}}{2x_{dec1}} - \frac{meV_{dc} \sin de (me \sin de) x_{bq1}}{2x_{qec1}} \right. \]
\[ \left. + \frac{meV_{dc} \cos de (me \cos de) x_{bd2}}{2x_{dec2}} - \frac{meV_{dc} \sin de (me \sin de) x_{bq2}}{2x_{qec2}} \right\} \]

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