*

Revue des Sciences et Sciences de l'ingénieur
Journal of sciences and engineering sciences

ISSN 2170-0737 EISSN: 2600-7029

https://www.asjp.cerist.dz/en/PresentationRevue/303


Revue des Sciences
et Sciences de l'Ingénieur

Model Order Reduction of External Power Systems

*O. Benmiloud[1], S. Arif[1]
[1]University Amar Telidji of Laghouat, LACoSERE laboratory.

Article history
Received: 2018-03-29
Accepted: 2020-01-30
DOI: 10.34118/rssi.v9i1.1693

Abstract

Model order reduction of external power systems remains a useful technique to reduce the computational efforts introduced by transient stability studies. In this paper, the equivalent of the 10-machine power system is build. By preserving the electrical power of those generators in the internal system following a disturbance, the problem is formulated as a single objective function solved by the novel Salp Swarm Algorithm (SSA). Furthermore, to fit the dynamic characteristics of the external system, the equivalent generator is expressed by the six-order model with excitation system. The results show the capability of the proposed methodology to imitate the dynamics of the external system. Quality of the estimated model is confirmed by several transient stability studies and the equivalent was able to preserve the dynamic properties of the original system with accuracy.

Key words: Dynamic equivalents; parameter estimation; power systems; transient stability.

Résumé

La réduction d'ordre relative aux modèles des systèmes électriques externes reste une technique utile pour réduire les efforts de calcul introduits par les études de stabilité transitoire. Dans cet article, l'équivalent du système de 10 machines est construit. En préservant la puissance électrique de ces générateurs dans le système interne suite à une perturbation, le problème est formulé comme une fonction mono-objective résolue par l'algorithme Essaim Salpidae (ES). De plus, pour s'adapter aux caractéristiques dynamiques du système externe, le générateur équivalent est exprimé par un modèle du sixième ordre avec un système d'excitation. Les résultats montrent la capacité de la méthodologie proposée à imiter la dynamique du système externe. La qualité du modèle estimé est confirmée par plusieurs études de stabilité transitoire et l'équivalent a pu préserver les propriétés dynamiques du système initial avec précision.

Mots-clés : Équivalents dynamiques ; estimation des paramètres ; systèmes électriques de puissance ; stabilité transitoire.

---

* Corresponding author. Tel./fax: +213 662520509.
E-mail address: o.benmiloud@lagh-univ.dz.

1. Introduction

As a result of the crucial demand of electricity, modern power systems become larger than ever. Generally, when dealing the stability analysis we partitioned the electric power system into internal system, external system and a group of boundary buses; (see Fig.1). The internal system represents the area of interest while the external system is often a large system with certain electrical distant or geographical extent and only its influence on the internal system is the interest. Thus, the whole system can be simplified and the computation burden of analyzing large systems can be reduced if the external system is replaced by an equivalent, the equivalent (usually synchronous generator) must keep the dynamics of the external system with reasonable accuracy. The methods by which dynamic equivalent of external power systems are created can be divided into three main categories, Modal [1; 2], Coherency [3-7], and estimation based equivalents [8-19].

In modal and coherency based equivalents the knowledge of information such as configuration and parameters of the external system itself are essential. This is rarely available in power market environments in which the power system belongs to different utilities each with its own control center [14]. Nevertheless, system identification based drives the equivalent following the steps listed below:

- Perform a disturbance in the internal system,
- Record the system responses (e.g. voltages, powers, angular speeds),
- Estimate the parameters of the external system based on the recorded signals.

Hence, the parameters and topology of the external system are not required to be known in advance. To solve the dynamic equivalent problem using estimation techniques variety of optimization algorithms were employed in the past [9-10; 14]. In [13], the second and third order models were used to equivalent a 13 machine system. In [14], the detail model was used and the parameters where identified using two population of Particle Swarm Optimization (PSO) with a mutation operator, the method appear to be time consuming due to the time required to evaluate two populations. Despite several attempts, the detailed model did not gain much attention from the researchers. In this paper, the six-order model with an equivalent excitation system is used to replace the external system. This model offers considerable accuracy compared to the classical model when representing dynamics equivalents. However, the model requires more parameters to be identified. The only concern when using the detailed model is the need for fast and accurate optimization algorithm to identify the large number of parameters. This paper employ the recently introduced Salp Swarm Algorithm (SSA) to tackle this problem.

The remainder of this paper is organized as follows: section 2 outlines the problem formulation, section 3 introduced the reader to the Salp Swarm Algorithm (SSA), simulation results are presented in section 4 and finally, section 5 draws conclusions for this work.

2. Methodology

2.1 Generator Model

In this paper, the six-order detailed model of synchronous generator that describes the transient and sub-transient dynamics on the d and q axes is used. The state variables are δ, ω, e'_d, e'_q, e''_q and e''_d. The differential equations describing the generator are given in eq.(1):

$$\begin{aligned}
&\frac{d\delta}{dt} = \omega_0(\omega - 1)\\
&2H\frac{d\omega}{dt} = P_m - P_e - D(\omega - 1)\\
&T'_{d0}\frac{de'_q}{dt} = -e'_q - (x_d - x'_d - \frac{T''_{d0}}{T'_{d0}}\frac{x''_d}{x'_d}(x_d - x'_d))i_d + e_{fd}\\
&T'_{q0}\frac{de'_d}{dt} = -e'_d + (x_q - x'_q - \frac{T''_{q0}}{T'_{q0}}\frac{x''_q}{x'_q}(x_q - x'_q))i_q\\
&T''_{d0}\frac{de''_q}{dt} = -e''_q + e'_q - (x'_d - x''_d + \frac{T''_{d0}}{T'_{d0}}\frac{x''_d}{x'_d}(x_d - x'_d))i_d\\
&T''_{q0}\frac{de''_d}{dt} = -e''_d + e'_d - (x'_q - x''_q + \frac{T''_{q0}}{T'_{q0}}\frac{x''_q}{x'_q}(x_q - x'_q))i_q
\end{aligned} \tag{1}$$

With:

$$P_e = e''_q i_q + e''_d i_d - (x''_d - x''_q)i_d i_q \tag{2}$$

Where δ and ω are the angular position and angular velocity, respectively. P_e, P_m, H and D are the electrical power, mechanical power, inertia and damping coefficient, respectively. e'_d, e'_q, e''_d, e''_q, T'_{d0}, T'_{q0}, T''_{d0} and T''_{q0} are the transient and sub-transient voltages and time constants, on the d and q axes, respectively. x_d, x_q, x'_d, x'_q, x''_d and x''_q are the steady state transient and sub-transient reactance respectively on the d and q axes; i_d and i_q are direct and quadrature currents and e_{fd} is the excitation voltage.

Furthermore, the fictitious generators are equipped with an equivalent static exciter IEEE type II described by eq.(3):

$$T_a \frac{de'_{fd}}{dt} = K_a\left(V_{ref} - V_t + V_s\right) - e_{fd} \qquad (3)$$

Where K_a and T_a are the excitation gain and time constant, V_{ref} and V_t are the reference and terminal voltages, respectively. V_s represents the PSS output (if installed).

From eq.(1) and eq.(3), it can be seen that there are 14 parameters to be estimated for each equivalent generator (see eq.(4)).

$$\vec{\alpha} = \left[x_d, x'_d, x''_d, x_q, x'_q, x''_q, T'_{d0}, T''_{d0}, T'_{q0}, T''_{q0}, H, D, K_a, T_a\right]^T \qquad (4)$$

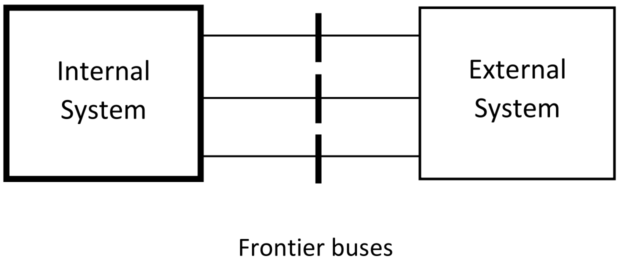

Figure 1. Partitioning power systems into external and study areas

2.2 *Objective Function*

In this paper, the fictitious generator parameters are estimated by optimization, given the objective function in eq.(5), the task is to find the vector $\vec{\alpha}^*$ that preserves as close as possible the behaviors of those generators in the internal system.

$$f = Minimize\left(\sum_{i=1}^{N-gen}\left|P_{e_i}^{ori}(t) - P_{e_i}^{equiv}(t,\alpha)\right|\right) \qquad (5)$$

With $t \in [t_0, t_f]$

Where $P_{e_i}^{ori}$ is the electrical transient behavior of the i^{th} generator within the internal area in the original system; $P_{e_i}^{equiv}$ is the electrical transient behavior of the i^{th} generator within the internal area in the equivalent system; N-gen is the total number of generators in the internal system.

3. Salp Swarm Algorithm (SSA)

One of the most interesting and least known creatures of the ocean are sea salps. These ocean creatures pump water through their bodies in order to move, breath and to catch food. They usually travel in colonies in the form huge chains called salp chains (see Fig.2).

This behavior motivated the authors in [20], to propose the Salp Swarm Algorithm (SSA). It is a novel optimization algorithm designed to solve single and multi-objective problems.

In order to simulate, the salp chain, the swarm is split into two groups:

- Leader salp: the salp in the front of the chain;
- Followers: the rest of salps in the chain.

The leader guides the swarm and the remaining salps follow each other and their leader. As in other optimization techniques, the first population is randomly generated in the slap swarm algorithm. The position of the leader salp is

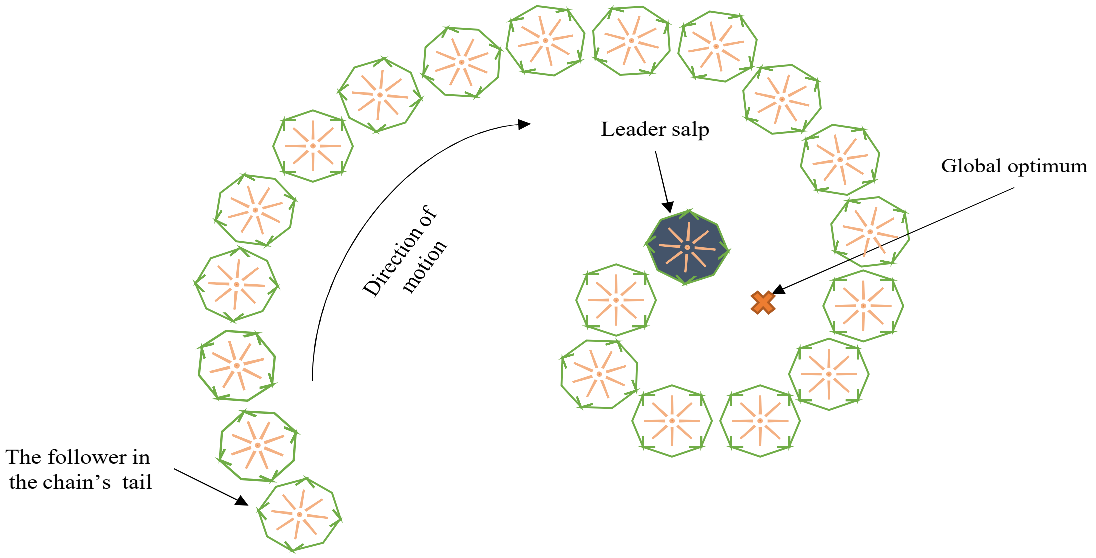

Figure 2. The chain of salps

updated in by the expression defined in eq.(6).

$$Pos_j^1 = \begin{cases} Food_j + C_1((Ub_j - Lb_j)C_2 + Lb_j) & \forall\ C_3 < 0.5 \\ Food_j - C_1((Ub_j - Lb_j)C_2 + Lb_j) & otherwise \end{cases} \qquad (6)$$

Where Pos_j^1 is of the leader's position in the j^{th} dimension, $Food_j$ is the position of the swarm's target (food source), Ub_j and Lb_j are the upper and lower bounds, respectively; and the coefficients C_1, C_2 and C_3 are random numbers $\in [0,1]$.

From eq.(6), one can observe that the leader salp only updates its position with respect to the food source [20]. Additionally, the coefficient C_1 is the key parameter in the SSA because it controls the balance between diversification and intensification, C_1 is calculated as:

$$C_1 = 2.\exp\left(-\left(\frac{4 \times Ite}{MaxIte}\right)^2\right) \qquad (7)$$

Where Ite is the current iteration and $MaxIte$ is the maximum number of iterations.

To update the position of the followers, Newton's law of motion as depicted in eq.(8) is applied.

$$Pos_j^i = \frac{1}{2}at^2 + v_0 t\ \ \forall\ i \geq 2 \qquad (8)$$

Where Pos_j^i is the position in the i^{th} salp follower in the j^{th} dimension. t is time and since time samples in optimization are simply iterations, the discrepancy between two successive times is equal to 1, Therefore, eq.(8) can be reformulated as:

$$Pos_j^i = \frac{1}{2}(Pos_j^i + Pos_j^{i-1})\ \ \forall\ i \geq 2 \qquad (9)$$

Now with mentioned steps, the chain of salp is simulated, it can be noted that the salp numbers (i.e. the population) and the maximum number of iterations $MaxIte$ are the exclusively the two parameters to adjust by the user in order to tune the characteristics of the SSA [20].

SSA algorithm has been utilized in [20] to estimate the optimal parameters of polymer electrolyte membrane fuel cells (PEMFCs). In [20] the algorithm proves its efficiency to handle real-world problems (e.g. airfoil design and marine propeller design). The algorithm appears to be simple and easy to implement. Furthermore, SSA has only two control parameters and strong optimization capacity as shown in [20; 21]. Therefore, SSA will be employed in this work to solve the objective function in eq.(5).

4. Applications

The following simulations were completed in a MATLAB environment running on Intel® Core™ i7-7500 CPU, 2.70 GHz processing speed, and physique memory of 8GB DDR4. As a case study of the proposed methodology, the 10 machines New England system presented in Fig .3 is used. Descriptions of the system are given in Tab.1. Furthermore, all generators in the original system are equipped with static exciter IEEE type 2 and turbine governing system. Power system stabilizers (PSSs) are included for generators 2 to 10. Fig.4 shows the system with the equivalent generator whose parameters are to be estimated, this generator is located at bus 16 (the frontier bus).

To initiate the transient behavior, a load variation of 25% is applied for all load buses in the internal system. The transient lasts 500 ms and the signals from the original and equivalent system are compared over 5 s interval.

Table 1. Comparison between the original and equivalent system

New England System		
	Original	Equivalent
Buses	39	29
Generators	10	7
Transformers	12	7
Transmission lines	34	28
Dynamic Order	154	103

In this paper and after several attempts the SSA settings are granted in Tab.2.

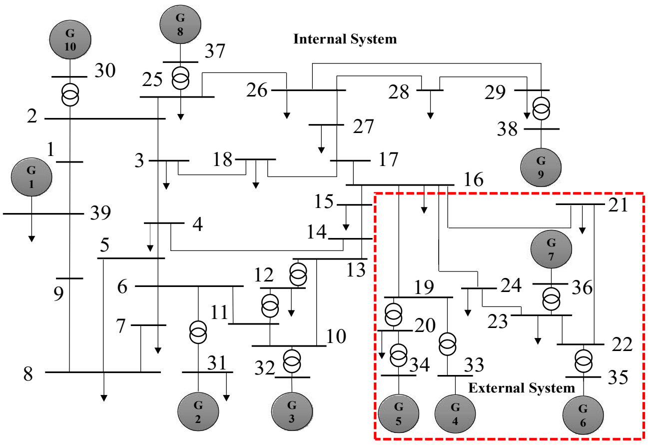

Figure 3. New England original system

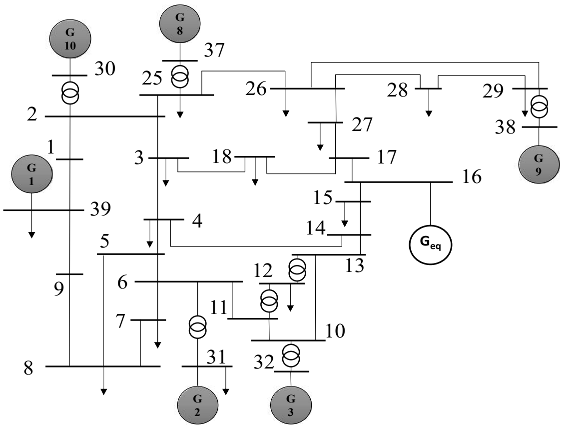

Figure 4. New England equivalent system

Table 2. Salp swarm algorithm settings

Control Parameters of SSA	
Parameters	Values
Number of Salps	20
Maximum iteration	20
Objective function	11.3436

Table 3. Optimized parameters of the equivalent generator

Parameters	Values	Parameters	Values
$x_d(pu)$	0.005	$T''_{d0}(s)$	0.2804
$x'_d(pu)$	0.005	$T'_{q0}(s)$	0.0647
$x''_d(pu)$	0.001	$T''_{q0}(s)$	0.0128
$x_q(pu)$	0.01	$H(\mathrm{kWs/KVA})$	0.1750
$x'_q(pu)$	0.01	$D(-)$	0.0233
$x''_q(pu)$	0.001	$K_a(pu/pu)$	0.0073
$T'_{d0}(s)$	2	$T_a(s)$	5.3867

The estimated parameters of the equivalent generator are given in Tab.3. To confirm the quality of the estimated parameters, the dynamic responses of the original and equivalent systems subjected to three different contingencies are shown in Figs. 5-10.

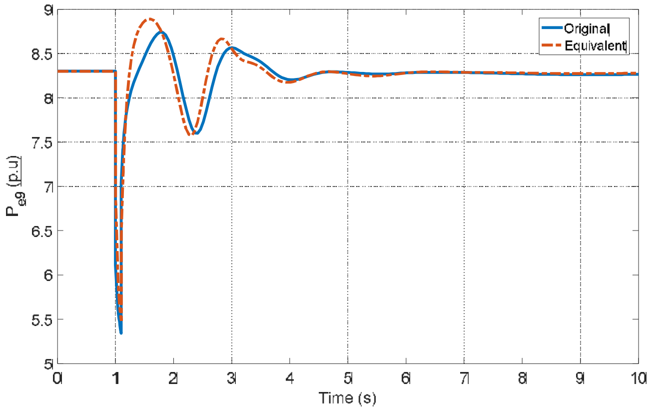

Figure 5. Electrical power of generator 9 for a fault at bus 14

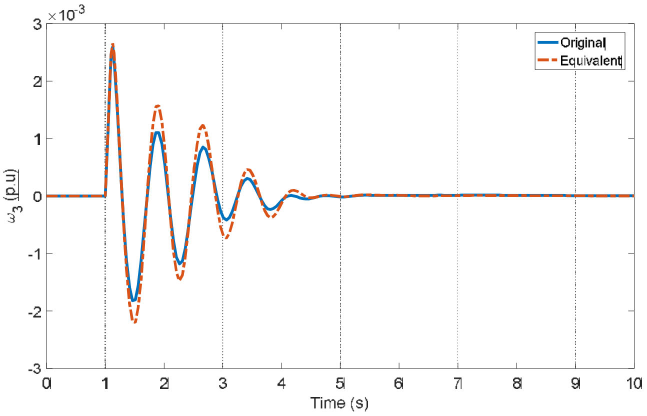

Figure 6. Rotor speed of generator 3 for a fault at bus 14

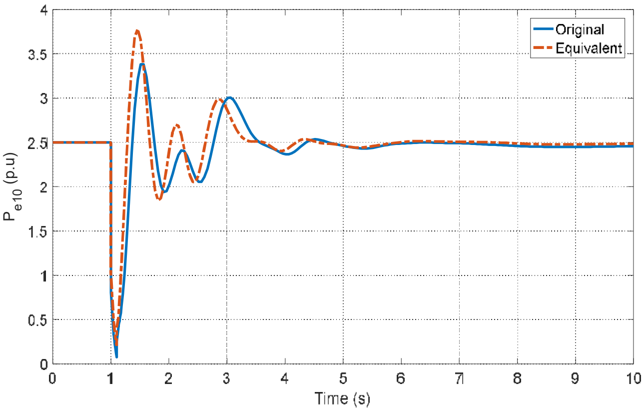

Figure 7. Electrical power of generator 10 for a fault at bus 17

Figs. 5-10 show the electrical power, angular position and speed of generators along with voltages, for three phase faults at bus 14, 17 and 9, respectively. Each fault is provoked at $t = 1\,s$ and lasts 6 cycles; the fault is then eliminated by assuming the disconnection of the associated branch. The evolution of the quantities mentioned before are observed in a closed interval of 10 seconds. From the above figures, it can be seen that the equivalent model is able to predict the dynamics of the original model and the responses are perfectly consistent.

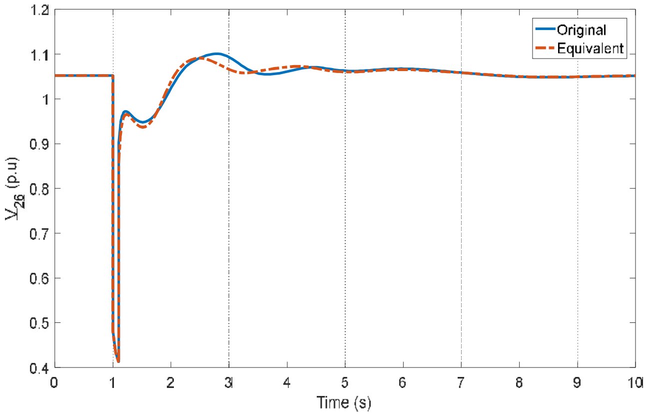

Figure 8. Voltage magnitude of bus 26 for a fault at bus 17

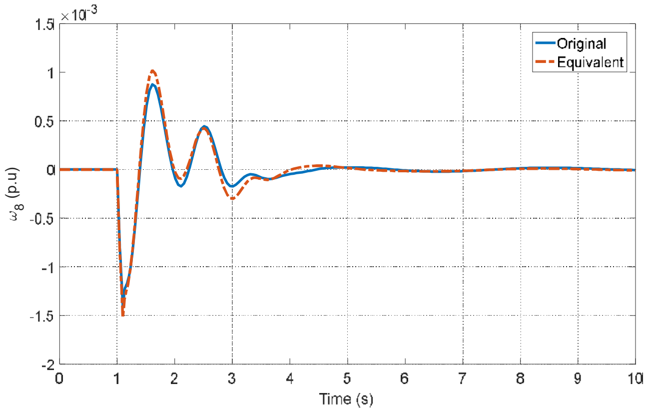

Figure 9. Rotor speed of generator 8 for a fault at bus 9

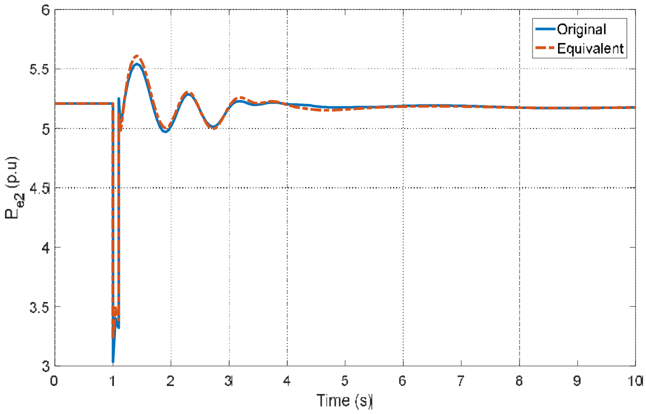

Figure 10. Electrical power of generator 2 for a fault at bus 9

To demonstrate the superiority of the SSA. A comparative study with the Genetic Algorithm (GA) and the Harris Hawks Optimization (HHO) is carried. Based on the sitting reported in appendix, Tab.4. shows the performance of the optimization algorithms in terms of objective function minimization and elapsed time.

Table 4. Performance of compared optimization algorithms

	SSA	GA	HHO [22]
Objective function	**8.6255**	11.1732	13.1083
Elapsed time (s)	**6386**	6420	15622

As can be seen, SSA proved its efficiency to handle the dynamic equivalencing problem. Due to its simplicity, the CPU time for SSA is less than the other algorithms which is required when fast equivalencing is needed.

5. Conclusions

This paper presented a single objective formulation, aim to construct dynamic equivalents of external power systems. In this method, information on the external system is not required, using only measurements within the internal system the salp swarm algorithm was employed to estimate the parameters of the fictitious generator placed at the frontier bus. The six-order model of synchronous generators with an equivalent excitation system was used for a better representation of the external system. The quality of the estimated parameters was validated using several contingencies in various locations in the internal system. The transient responses of both systems showed a perfect agreement where the equivalent system was able to preserve the dynamics of the original system with a good accuracy.

Appendix

- SSA: 20 salps, 100 iterations.
- GA: 20 particles, 100 generations, $Cr = 0.8$.
- HHO: 20 harris hawks, 100 iterations.

References

[1] Undrill J, Turner AE. Construction of power system electromechanical equivalents by modal analysis. IEEE Transactions on Power Systems 1971, PAS-90(5):2049–2059.

[2] Price WW, Roth BA. Large-scale implementation of modal dynamic equivalents. IEEE Transactions on Power Systems 1981. PAS-100 (8):3811–3817.

[3] Kyriakidis T, Cherkaoui R, Kayal M. Generator coherency identification algorithm using modal and time-domain information IEEE International Conference EUROCON 2013.

[4] Ariff MAM, Pal BC. Coherency identification in interconnected power system - an independent component analysis approach. IEEE Transactions on Power Systems 2013;28(2):1747–1755.

[5] Wang MH, Chang HC. Novel clustering method for coherency identification using an artificial neural network. IEEE Transactions on Power Systems 1994;9(4):2056–2062.

[6] Joo SK, Liu CC, Jones LE, Choe JW. Coherency and aggregation techniques incorporating rotor and voltage dynamics. IEEE Transactions on Power Systems 2004;19(2):1068-1075.

[7] Vahidnia A, Ledwich G, Palmer E, Ghosh A dynamic equivalent state estimation for multi-area power systems with synchronized phasor measurement units. Electric Power Systems Research 2013; 96:170–176.

[8] Kim DE, El-Sharkawi M. Dynamic equivalent model of wind power plant using parameter identification. IEEE Transactions on Energy Conversion 2016;3(1):34–45.

[9] Ramirez JM. Obtaining dynamic equivalents through the minimization of a line flows function. International Journal of Electrical Power and Energy Systems 1999:21(5): 365–373.

[10] Ramirez JM, Hernández BV, Correa RE. Dynamic equivalence by an optimal strategy. Electric Power Systems Research.2012;84(1):58–64.

[11] Rueda JL, Cepeda J, Erlich I, Echeverría D, Argüellob G. Heuristic optimization based approach for identification of power system dynamic equivalents. 2015;64:185–193.

[12] Gueddouche R, Boudour M. Nonlinear estimation of external power system dynamic equivalent parameters. Global Journal of Researches in Engineering Electrical and Electronics Engineering 2012, 12(7).

[13] Yu YN, El-Sharkawi MA. Estimation of external dynamic equivalents of a thirteen-machine system. IEEE Transactions on Power Apparatus and Systems 1981, PAS-100(3):1324–1332.

[14] Yang J, Zhang J, Pan W. Dynamic equivalents of power system based on extended two particle swarm optimization. 3rd International Conference on Natural Computation 2007.

[15] Benmiloud O, Arif S. Model order reduction of power systems preserving tie line flows. International Conference on Applied Smart Systems (ICASS) 2018.

[16] Annakkage UD et al. Dynamic system equivalents : a survey of available techniques .IEEE Transactions on Power Delivery 2012;27(1)411–420.

[17] Gueddouche R, Boudour M. Intelligent non-linear dynamic equivalent approach applied to Algerian power system. IET Generation, Transmission & Distribution 2019;13(14):2919–2929.

[18] Benmiloud O, Arif S. Optimal dynamic equivalence based on multi-objective formulation. 3rd International Conference on Electrical Sciences and Technologies in Maghreb (CISTEM) 2018.

[19] Benmiloud O, Arif S. A novel measurement-based procedure for dynamic equivalents of electric power systems for stability studies using improved sine cosine algorithm. Journal of Electrical Engineering 2019;70(6):454-464.

[20] Mirjalili S et al., Salp swarm algorithm: a bio-inspired optimizer for engineering design problems. Advances in Engineering Software 2017; 163–191.

[21] El-Fergany AA, Extracting optimal parameters of PEM fuel cells using Salp Swarm Optimizer. Renewable Energy 2018;119:641–648.

[22] Heidari AA et al., Harris hawks optimization: algorithm and applications. Future Generation Computer Systems 2019;97:849-872.