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Optimal Placement of Unified Power Flow Controller via Chronological Sine Cosine Algorithm

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Abstract: The Unified Power Flow Controller (UPFC) is one of the most promising Flexible AC Transmission Systems (FACTS) devices for the load flow control. Optimizing the size and allocation for UPFCs is of noteworthy concern for increasing the loading capability of the system. So far, numerous optimization models were developed for resolving the issues in UPFC. Thereby, this work uses the Chronological Sine Cosine Algorithm (SCA) model for optimal allocation of UPFC to attain Optimal Power Flow (OPF). The algorithm is the enhanced version of the conventional SCA algorithm. In addition, the overall cost function given for resolving the placement issue comprises the reduction of cost and power loss. Finally, the superiority of the adopted scheme is evaluated over traditional models in terms of varied measures.

Keywords: UPFC; FACTS; Optimal Flow Control; Optimization; Power Quality; Cost Function.

Nomenclature

Abbreviations	Descriptions
ABC	Artificial Bee Colony
APLFs	Active Power Loop Flows
CPS-SPWM	Carrier Phase Shifted Sinusoidal Pulse Width Modulation
DG	Distribution Generation
DE	Differential Evolutionary
EP	Evolutionary Programming
FACTS	Flexible AC Transmission Systems
GSA	Gravitational Search Algorithm
GU	Generation Unit
GA	Genetic Algorithm
HBC	Half-Bridge Converter
HICA-PS	Hybrid Imperialist Competitive Algorithm-Pattern Search
ITLBO	Improved Teaching Learning Based Optimization
IPM	Interior Point Method
MMC	Modular Multilevel Converter
OPF	Optimal Power Flow
OKHA	Oppositional Krill Herd Algorithm
PQ	Power Quality
RA	Resul Accuracy
SCA	Sine Cosine Algorithm
TCR	Thyristor Controlled Reactor
UPFC	Unified Power Flow Controller

1. Introduction

In these days, the acceptable level of PQ is a primary challenge in a DG system for various nonlinear loads. "PQ [1] [2] [3] is termed as the quality of electric power distributed to customers, which includes generation, distribution and transmission systems". Amongst them, the distribution system is a foremost feature that holds a vital role in power utilization. The distribution system [6] [7] divides up the

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electrical and power utilities to consumers. An optimal power system aims to share out electricity to its clients in a well-organized and reliable manner [8] [9] [10].

The power factor, voltage distortion, harmonics reliability, and continuity of service are certain computational indices that describe the efficacy of the intellect PQ system [11] [12]. Yet, the issues like impedance and resonance make the system performance more defective and multifaceted [13] [14] [1]. Consequently, for overcoming these problems, the FACTS devices like TCR, UPFC [1] [2] are deployed that achieves enhanced electrical power quality. It also offers diverse harmonic orders and recompenses for reactive power [5]. Furthermore, the source currents are assessed when the loads are unstable and stable [3].

Several FACTS controllers were modeled for controlling the power system at normal states and contingency conditions [19] [20]. Amongst them, UPFC shows the fine characters in aiding the power system to function reliably and securely [3]. UPFC [7] is an adjustable device that plays a primary role in regulating the whole power system. The chief task of UPFC [6] is to control the OPF of load in the electrical system. Also, the optimal allotment of UPFC [5] is crucial to accomplish better cost-efficacy and system performance. There are several strategies and approaches in the literature for solving the issues on UPFC allotment. Commonly exploited techniques involve "sensitivity-based analysis and optimization and index calculation method". Certain familiar heuristic techniques for determining the optimal allocation of UPFC devices take account of IPM, GA, EP model, and DE algorithms.

The arrangement of the paper is: Section 2 portrays the review. Section 3 gives a short portrayal of modeling of the UPFC system; section 4 defines the chronological SCA based optimization for optimal flow control of UPFC. Section 5 portrays the outcomes and the paper is concluded by section 6.

2. Literature review

2.1 Related works

In 2019, Vural and Emile [1] developed an inclusive model of an MMC oriented UPFC. In addition, a high switching frequency technique known as CPS-SPWM was developed for balancing the capacitor voltage in the sub-modules of HBC. The introduced balancing scheme was further evaluated and the investigational outcomes have shown the advantage of the established method over the other existing methods through case studies.

In 2017, Ravindra et al. [2] have adopted an ITLBO model for analyzing the security of the system under contingency conditions. For improving the security, the UPFC device was optimally positioned in the system. For this reason, the power injection model and optimal location detection models were introduced. In the end, the presented scheme was examined in terms of security, and optimal outcomes were obtained.

In 2016, Majid et al. [3] have suggested a new UPFC allocation method with load shedding coordination design for preventing the collapse of voltage. Moreover, the contingency state was computed via the HICA-PS model, which holds a major role in fine-tuning the ICA outcomes. For demonstrating the effectiveness of the presented scheme, it was evaluated over the conventional schemes regarding voltage collapse. In this work, the adopted scheme chiefly focused on the diminution of voltage fall down, load shedding, and constancy of energy supply.

In 2016, Dutta et al. [4] have modeled a technique for accomplishing optimal steady-state power system based on the OKHA scheme. This work has analyzed the impact of UPFC allocation using steady-state analysis and it furthermore established the abilities of UPFC in balancing the reactive and active flows of power in the system. For validating the efficacy of the developed method, improvement of voltage and diminution of real power losses were taken into consideration and their outcomes were found to be viable and proficient.

In 2020, Li et al. [5] have analyzed the active power levels of UPFC for avoiding the APLFs. The sensitivity amongst the active power of UPFC was resolved for accomplishing zero active power flow of the critical branch. Moreover, the coordination among the converters was established for portraying the controllable ranges for diverse voltage settings. The coordination of several UPFCs was offered for deciding the active power of different UPFCs. In the end, the outcomes have confirmed the development of the adopted model in terms of its viability.

3. A short portrayal of Modeling of UPFC System

Fig. 1 demonstrates the modeling of the UPFC system, in which the generator Ge is related to the buses n and m. Consequently, the converters are related by the transformer. It entails the load and converter impedance indicated by Z_H and Z_L correspondingly. The converters are related to voltage V_{dc} capacity with the DC link capacitor C_{dc}. It is integrated with the UPFC power flow formulations [14], which is essential for resolving the issues such as, inequality and equality constraints. It may take place owing to the outage of generators present in the power system since the requirements should be satisfied continually. The inequality and equality constraints are briefly explained in the below section.

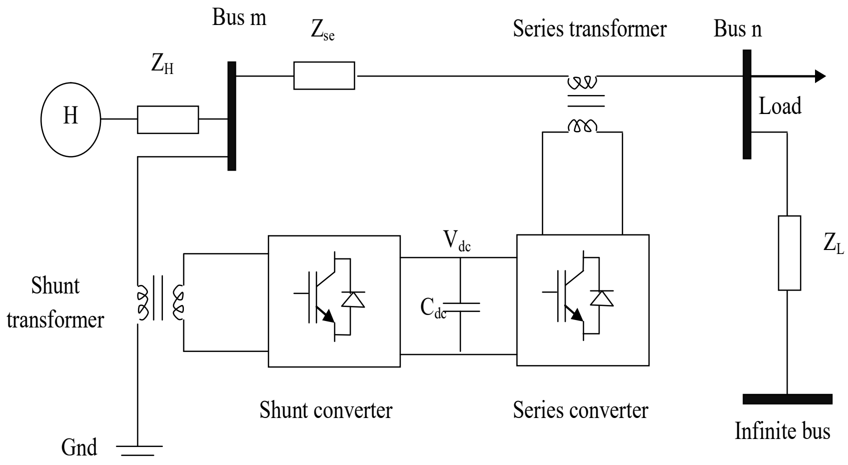

Fig. 1. *Modelling of UPFC*

Equality constraints: The major contribution of the power system relies on the accomplishment of the total demand of utility [15]. In this context, Ge have to satisfy the entire demand of the clientele and it is supposed to satisfy the loss of power in transmission lines. This is identified as the power balance state or equality constraints of the power system. The needed equality constraints are depicted as per Eq. (1).

$$\sum_{a=1}^{M_H} P_H^a = P_B + \sum_{b=1}^{M_H}\left(P_L^b + bQ_L^b\right) \tag{1}$$

In Eq. (1), P_H^a refers to the power produced in a^{th} bus, P_B specifies the demand, Q_L^b and P_L^b denotes the reactive and real power losses of b^{th} bus that are evaluated as per Eq. (2) and Eq. (3).

$$Q_L^b = |V_a||V_b||X_{ab}|\sum_{n=1}^{M}\sin(\delta_{ab} - \alpha_a - \alpha_b) \tag{2}$$

$$P_L^b = |V_a||V_b||X_{ab}|\sum_{n=1}^{M}\cos(\delta_{ab} - \alpha_a - \alpha_b) \tag{3}$$

In Eq. (2) and Eq. (3), V_b and V_a indicates the voltage of the buses b and a, X_{ab} signify the matrix of bus admittance, δ_{ab} represents the angle among buses a and b, α_b and α_a symbolizes the load angles of b and a.

Inequality constraints: The inequality parameters namely, reactive and real power flows and voltage are affected because of the protest of the GU. The dynamic stability of the power system mainly focuses on the voltage stability of every node. For a stable flow of power, the voltage of every bus has to lie among 0.95–1.05 pu. The deviation in voltage is specified by Eq. (4). where V_a^k is computed as per Eq. (5).

$$\Delta V_i = \frac{1}{\sqrt{l}}\sqrt{\sum_{a=1}^{l}\left(V_a^k\right)^2} \tag{4}$$

$$V_a^k = V_{slack} - \sum_{a=1}^{n} Z_a\left(\frac{P_a - bQ_a}{V_a}\right) \tag{5}$$

In Eq. (4), V_{slack} denotes the slack bus voltage, ΔV_a specifies the voltage stability index of a^{th} bus, where $a = 1, 2, \ldots.n,$, Z_a point out the impedance of a^{th} bus, Q_a and P_a the reactive and real powers of bus a, and the count of nodes is specified by b. The bus voltage relies on amongst the bounds, i.e. $V_a^{min} \le V_a \le V_a^{max}$: The reactive and real powers of the specific bus are known by Eq. (6) and Eq. (7).

$$Q_a = |V_a||V_b| \sum_{n=1}^{M_D} \left(H_{ab} \sin \alpha_{ab} - D_{ab} \cos \alpha_{ab} \right) \quad (6)$$

$$P_a = |V_a||V_b| \sum_{n=1}^{M_D} \left(H_{ab} \cos \alpha_{ab} + D_{ab} \sin \alpha_{ab} \right) \quad (7)$$

In the above equations, M_D signify the total count of buses α_{ab} represent the angle among buses a and b in that order, D_{ab} and H_{ab} represent the susceptance and conductance values, respectively.

4. Chronological SCA for Optimal Allocation of UPFC

4.1 Solution Encoding and Objective Function

The adopted model handles the optimal flow control by optimizing the angle, compensation, tap setting, and location of UPFC. For this, an algorithm termed as Chronological SCA is used in this work. The input solution given to the chronological SCA model is illustrated in Fig. 2, where L symbolize the location, C represent the compensation whose limits lay among17 to 0.17, TS indicate the tap setting whose limits lie among 0 to 1 and α denotes the angle whose limits lie among 0 to 2π.

Furthermore, a single objective function (OF) is portrayed in this work that encompasses the reduction of cost and power loss, which is described as in Eq. (10). In Eq. (10) f_1 and f_2 are computed as shown in Eq. (8) and (9), where u_1 and u_2 holds a value of 0.8, PV points out penalty voltage, P_L specifies the power loss, and C represents the cost.

$$f_1 = u_1 * C + (1 - u_1) * PV \quad (8)$$

$$f_2 = u_2 * f_1 + (1 - u_2) * P_L \quad (9)$$

$$OF = \min(f_2) \quad (10)$$

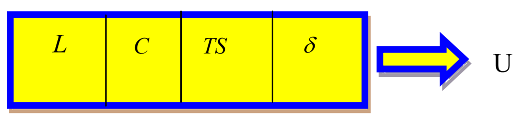

Fig. 2. *Solution encoding*

4.2 Chronological SCA Algorithm

The chronological SCA algorithm [16] includes the characteristics of SCA, however here, the update comprises of the previous solutions. The steps of chronological SCA are specified below:

Initialization: At first, the population size is initialized by the chronological SCA algorithm.

Fitness: For evaluating the fitness of the chronological SCA algorithm, the reduction of cost and diminution of power loss is considered.

The modification of the deployed SCA model is carried out by including the previous solutions, and the approach is termed as the chronological SCA. In the traditional SCA, the solution gets updated depending on the cosine and sine functions as shown in Eq. (11) and Eq. (12).

$$U_P^{t+1} = U_P^t + S_1 \times \sin(S_2) \times \left| S_3 \times T_P^t - U_P^t \right| \ ; S_4 < 0.5 \quad (11)$$

$$U_P^{t+1} = U_P^t + S_1 \times \cos(S_2) \times \left| S_3 \times T_P^t - U_P^t \right| \ ; S_4 \geq 0.5 \quad (12)$$

The aforesaid position update is done based on an arbitrary value S_4. After taking account of the previous solutions in Eq. (11) and Eq. (12), the position is updated as shown in Eq. (13) and Eq. (14) respectively.

$$U_P^{t+1} = \frac{1}{2} \begin{bmatrix} U_P^t \times (1 - S_1 \times \sin(S_2)) + U_P^{t-1} \times \\ (1 - S_1 \times \sin(S_2))(1 - S_1 \times \sin(S_2)) + \\ S_1 \times \sin(S_2) \times S_3 \times T_P^{t-1} (1 - S_1 \times \sin(S_2)) + \\ 2 \times S_1 \times \sin(S_2) \times S_3 \times T_P^t \end{bmatrix} ; S_4 < 0.5 \quad (13)$$

$$U_P^{t+1} = \frac{1}{2} \times \begin{bmatrix} U_P^t \times (1 - S_1 \times \cos(S_2)) + U_P^{t-1} \\ \times (1 - S_1 \times \cos(S_2))^2 + \\ Z_1 \times \cos(S_2) \times S_3 \times T_P^{t-1} (1 - S_1 \times \cos(S_2)) + \\ 2 \times S_1 \times \cos(S_2) \times S_3 \times T_P^t \end{bmatrix} ; S_4 \geq 0.5 \tag{14}$$

According to the aforesaid formulation, the chronological SCA carries out the position update of the searching agent.

Determining the optimal solutions based on fitness: During this phase, the fitness of the solution is portrayed and the better solution is discovered via the fitness function. Accordingly, the current solution is replaced by the best solution and the iteration is continued.

Termination: Following the specific iteration limit, the search agent position gets stabilized and offers the optimum final solution.

5. Results and Discussion

5.1 Simulation Procedure

The developed optimal allocation of UPFC using Chronological SCA was implemented in Matlab and the resultants were observed. The deployed chronological SCA model was compared over the conventional schemes like ABC [17] and GSA [18] models. The analysis was performed on the IEEE 30 bus system that includes "six generator bus, 21 load bus, and 42 transmission lines". Moreover, the examination was carried out concerning loss and result accuracy.

5.2 Performance Analysis

The performance analysis of the Chronological SCA scheme over conventional schemes is given in Fig. 3 for the IEEE 30 bus system. The analysis was done concerning RA, which is computed as $RA = (BP - NP)/NP \times 100$, where BP denotes the best minimal loss of power and N denotes the normal loss of power. From the observed outcomes, the RA of the chronological SCA is found to be higher than the compared schemes. That is, the chronological SCA is 54.79% and 39.76% better than the compared ABC and GSA models. Thus, the betterment of the adopted chronological SCA scheme is proved from the simulation outcomes.

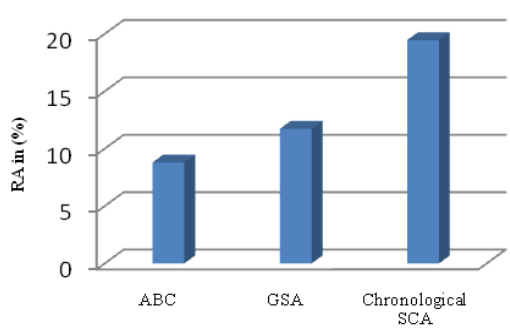

Fig. 3. *Performance evaluation of chronological SCA over the existing works with respect to RA*

5.3 Analysis of Power Loss

The power loss (MW) attained by chronological SCA over the conventional models for a single generator issue is represented in Fig. 4. On noticing the outcomes, the chronological SCA model has accomplished minimal power loss when compared to the existing models. Here, from Fig. 4, the chronological SCA has achieved a reduced power loss of 9.498 MW, which is 3.65% and 0.46% better than existing ABC and GSA models, when the generator bus number is 2. This shows the enhancement of the chronological SCA framework over the existing models.

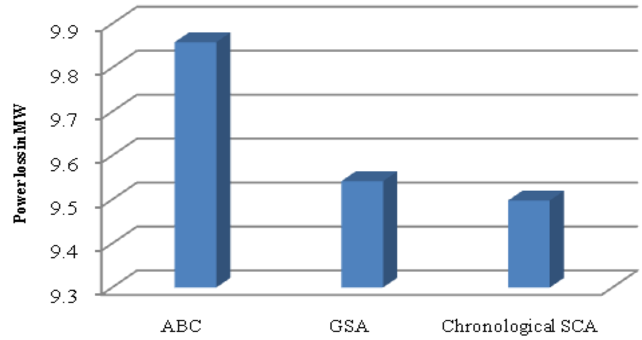

Fig. 4. *Power loss analysis of chronological SCA over the existing works when the generator bus number=2*

5.4 Power Loss of Double Generator Issue

Table 1 show the power loss information attained by means of the chronological SCA model for the IEEE 30 bus system. The examination was carried out by varying the generator bus numbers from 2 and 6, 2 and 13, 6 and 13, 22 and 27 and 13 and 27. From the analysis, power loss attained using the chronological SCA model at normal condition is 10.809 MW, whereas, during a fault condition, 14.73 MW, 15.017 MW, 14.833 MW, 13.051 MW, and 14.005 MW are attained for varied generator bus numbers from 2 and 6, 2 and 13, 6 and 13, 22 and 27 and 13 and 27 in that order.

Table 1: *Power loss of double generator issue attained by the chronological SCA model*

Generator bus no.	Best location		Power loss in MW		
	From bus	To bus	Normal	During fault	With UPFC
13 and 27	10	22	10.809	14.005	9.901
22 and 27	12	15		13.051	8.706
6 and 13	10	22		14.833	9.602
2 and 13	5	7		15.017	8.999
2 and 6	12	15		14.73	9.212

6. Conclusion

This paper has introduced a chronological SCA model for solving the placement issues of UPFC, by which load flow control can be enhanced. In addition, the adopted model intended to solve two diverse problems namely, minimization of power loss and UPFC cost. Accordingly, the analysis primarily focused on the loss and result from the accuracy of the chronological SCA over the traditional models. On observing the outcomes, the RA of the chronological SCA was found to be higher than the compared schemes. That is, the chronological SCA was 54.79% and 39.76% better than the compared ABC and GSA models. Thus, the enhancement of the adopted model was confirmed from the analysis.

Compliance with Ethical Standards

Conflicts of interest: Authors declared that they have no conflict of interest.

Human participants: The conducted research follows the ethical standards and the authors ensured that they have not conducted any studies with human participants or animals.

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