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Optimal placement of IPFC for solving optimal power flow problems using Hybrid Sine-Cosine Algorithm

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Abstract: This study presents an effective approach for solving the optimal power flow problem in power system. A novel algorithm Sine-Cosine Algorithm (SCA) which is based on population is being hybridized it with the arithmetic crossover operation, this proposed algorithm named as Hybrid Sine-Cosine Algorithm (HSCA) aims to reduce the computation time and make it more effective in achieving the global solution with the avoidance of local optima. Furthermore, for controlling and improving the power system parameters a novel FACTS Controller namely, Interline power flow controller (IPFC) is placed optimally in power system. For incorporating IPFC in Newton-Raphson load flow, it is mathematically modeled using current injection modeling (CIM). The performance of proposed algorithm is tested on some benchmark test functions to prove its superiority through convergence characteristics. The capability and performance of the proposed idea is implemented on IEEE-30 bus system for solving Optimal Power Flow problems. Generation fuel cost, emission and transmission losses are considered as single objectives of optimal power flow problem are being solved. The obtained results are compared with the existing literature to justify the supremacy and potential of the proposed idea.

Article Highlights

Implication of hybrid sine-cosine algorithm yields to better global optimum solution.

FACTS controllers help in controlling power flow capability.

Solution of Optimal Power Flow problem helps in utilizing the existing system more efficiently and effectively.

Keywords Current Injection modeling (CIM); Emission; Generation fuel cost; Hybrid Sine-Cosine Algorithm (HSCA); Interline power flow controller ; Optimal Power Flow (OPF); Power Injection modeling (PIM); Transmission losses.

I. Introduction

In recent years, demand of electricity is increasing spontaneously, but development of new power networks stresses the environment and economics limits. Therefore there is a need to utilize the existing system to its level best. Thus, as the power electronics based FACTS controllers are emerging as a best solution to utilize the existing system more efficiently. The FACTS devices like STATCOM, SSSC, IPFC and UPFC have the better operating performance as compare to SVC, TCSC and TCPS [1]. IPFC is a latest controller which can control real and reactive power of multiple lines simultaneously, which helps to share the load of overloaded line to unloaded line [2].

Power flow control capability of the interline power flow controller is detailed in [3]. FACTS devices can be modeled by many techniques, generally Power Injection Modeling (PIM) and Current Injection Modeling (CIM) is preferred for the analysis. PIM includes nodal equations which are referred in terms of voltages and impedances of the device, thus they are known as voltage source models (VSC). As research depicts that with the VSC model is not efficient in modeling series FACTS

devices [4]. Further, it has been observed that CIM gives more efficient response when modeling series compensating devices as it yields a faster and wider spectrum of convergence. In comparison to the modeling of UPFC [5] and SSSC [6], research is limited on the modeling of IPFC.

Power injection modeling (PIM) of IPFC is detailed in [7], which focuses on study the effect of IPFC parameters on bus voltages, real and reactive power flows in transmission lines. Some current based model of IPFC [1] is also derived but this current injection modeling is followed a different approach. The existing literature of current injection modelling of OUPFC gives a scope to model the CIM of IPFC using simple technique [8].

For placing IPFC in power network, an optimal location must be identified. In Ref. [9], line outages has been analysed to optimally place the FACTS device. A novel fault- location algorithm is used to identify the location in [10]. So there are different approaches to identify the location to place the FACTS controllers.

OPF helps in utilizing the existing system more effectively, it helps to identify the control variables values which are automatically adjusted to minimize the objectives functions such as generation fuel cost, emission and transmission losses with those values of control variables power system can be operated and effectively utilized. For solving the OPF problems, a number of classical and heuristics optimization techniques have been proposed by researchers in past decades. In classical techniques, researches were done by using gradient methods [16], linear programming [17], nonlinear programming [18], quadratic programming [19], and interior point [20], but these are not suitable for large-scale power systems and sometimes it led the solution to be stuck in local minima. In heuristic optimization techniques many intelligent algorithms were develop which helps to overcome the problem faced in classical approaches. In this paper a novel population based algorithm proposed by Seyedali Mirjalil [21] is used for solving the optimal power flow problems named as Sine- cosine algorithm. It also being modified and Levy operator is applied to it in [22] and used for solving the optimal power flow problems.

In this paper, Sine Cosine algorithm is hybridized with arithmetic crossover operation [23] to reduce the convergence time and get the best global optimum solution. Its effectiveness has been validated on benchmark test functions and IEEE- 30 bus system. It also includes the Current injection modeling of IPFC and its optimal allocation using severity function [24], this also being justified on IEEE- 30 bus system with comparison to the existing literature. Also, without any FACTS device and with IPFC results are compared to identify the effectiveness of the proposed idea.

This paper is structured as follows: Mathematical Modeling of IPFC is detailed in Section 2. Then in Section 3 problem formulation is mathematically presented. Further in Section 4, explanation of proposed Hybrid Sine Cosine algorithm is detailed. For incorporating the IPFC its optimal location is need to be identify, methodology adapted is detailed in Section 5. Section 6 of the paper is reserved to provide the experimental results along with a detailed comparison of HSCA algorithm with some existing algorithms. Finally, Section 7 presents the conclusion of this paper.

II. MATHEMATICAL MODELING OF IPFC

IPFC has the capability to control both active and reactive powers between the transmission lines. Basically it consists of two or more series connected converters (SSSC) which is supplied through a common DC voltage link, due to which IPFC can compensate multiple transmission lines simultaneously. A basic configuration of IPFC is shown in Fig. 1, which has two back-to-back dc-to-ac converters. The two converters are connected in series with the transmission and coupled via a common DC link.

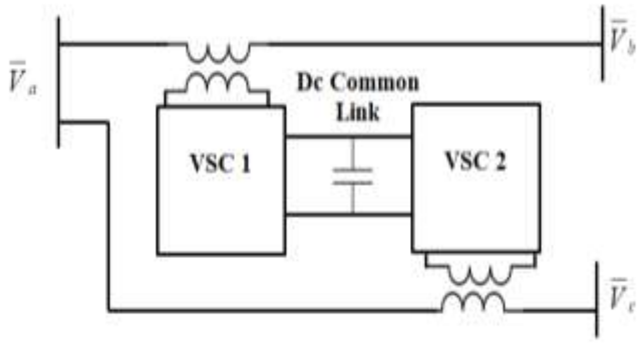

Fig. 1 Basic configuration of IPFC

2.1 Current injection modeling of IPFC

Let us consider that the IPFC is connected between buses a, b and c. The equivalent current source model of IPFC is shown in Fig. 2.

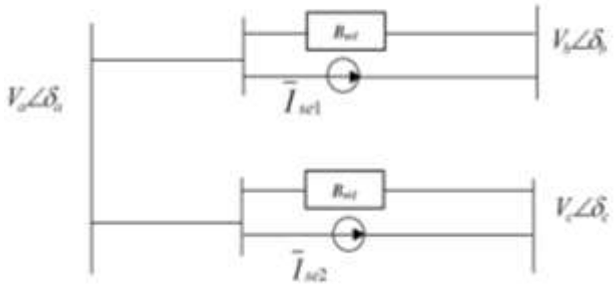

Fig. 2 Current source model of IPFC

The injected current in transmission line is given by

$$\overline{I} = \overline{I}_{se1} + \overline{I}_{se2} = (V_a\angle\delta_a + r_1V_a\angle(\delta_a+\gamma_1) - V_b\angle\delta_b)\times(jB_{se1}) + (V_a\angle\delta_a + r_2V_a\angle(\delta_a+\gamma_2) - V_c\angle\delta_c)\times(jB_{se2}) \quad (1)$$

IPFC injecting power at the bus-a

$$\overline{S}_a = P_{sa} + jQ_{sa} = \overline{V_a}(\overline{I})^* \quad (2)$$

On solving we get the real power and reactive power as

$$P_{sa} = V_aV_bB_{se1}\sin\delta_{ab} - r_1V_a^2B_{se1}\sin\gamma_1 + V_aV_cB_{se2}\sin\delta_{ac} - r_2V_a^2B_{se2}\sin\gamma_2 \quad (3)$$

$$Q_{sa} = -V_a^2B_{se1} + V_aV_bB_{se1}\cos\delta_{ab} - r_1V_a^2B_{se1}\cos\gamma_1 - V_a^2B_{se2} + V_aV_cB_{se2}\cos\delta_{ac} - r_2V_a^2B_{se2}\cos\gamma_2 \quad (4)$$

IPFC injecting power at the bus-b

$$\overline{S}_b = P_{sb} + jQ_{sb} = \overline{V_b}(\overline{I_{se1}})^* \quad (5)$$

On solving we get the real power and reactive power as

$$P_{sb} = -V_aV_bB_{se1}\sin\delta_{ab} - r_1V_aV_bB_{se1}\sin(\delta_{ab}+\gamma_1) \quad (6)$$

$$Q_{sb} = V_b^2B_{se1} - V_aV_bB_{se1}\cos\delta_{ab} - r_1V_aV_bB_{se1}\cos(\delta_{ab}+\gamma_1) \quad (7)$$

IPFC injecting power at the bus-c

$$\overline{S}_c = P_{sc} + jQ_{sc} = \overline{Vc}(\overline{I_{se2}})^* \quad (8)$$

On solving we get the real power and reactive power as

$$P_{sc} = -V_a V_c B_{se2} \sin \delta_{ac} - r_2 V_a V_c B_{se2} \sin(\delta_{ac} + \gamma_2) \quad (9)$$

$$Q_{sc} = V_c^2 B_{se2} - V_a V_c B_{se2} \cos \delta_{ac} - r_2 V_a V_c B_{se2} \cos(\delta_{ac} + \gamma_2) \quad (10)$$

2.2 Power mismatches equations of IPFC

By incorporating the device in NR load flow problem, its impact can be analyzed and with the modification of Jacobian elements and power mismatched equations, it can easily be incorporated. The final steady state network equation in NR load flow when IPFC is incorporated can be expressed as:

$$\left(\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} + \begin{bmatrix} P^{IPFC} \\ Q^{IPFC} \end{bmatrix}\right) = \left(\begin{bmatrix} H & N \\ J & L \end{bmatrix} + \begin{bmatrix} H^{IPFC} & N^{IPFC} \\ J^{IPFC} & L^{IPFC} \end{bmatrix}\right) \begin{bmatrix} \Delta\delta \\ \frac{\Delta V}{|V|} \end{bmatrix} \quad (11)$$

$P_a^{IPFC} = P_{sa}$, $P_b^{IPFC} = P_{sb}$, $P_c^{IPFC} = P_{sc}$

$Q_a^{IPFC} = Q_{sa}$, $Q_b^{IPFC} = Q_{sb}$, $Q_c^{IPFC} = Q_{sc}$

The Jacobian elements can be modified in the Newton-Raphson iterative process which has been explained in detail in appendix.

III. MATHEMATICAL PROBLEM FORMULATION

Optimal Power Flow (OPF) deals to solve the steady state problem of electric power system through minimizing the objective functions with the consideration of constraints simultaneously. Mathematically OPF is represented by:

Min $F_p(a,b) \qquad \forall p = 1,2,......t$

Subject to : $m(a,b) = 0$, $n(a,b) \le 0$

where, 'm' and 'n' are the equality and inequality constraints respectively, 'a' is the state vector of dependent variables and 'b' is the control vector of system and t is the total number of objectives functions.

The state vector may be represented by:

$$a^T = [P_{G,1}, V_{L,1} \dots V_{L,NLINE}, Q_{G,1} \dots Q_{G,NGB}, S_{L,1} \dots S_{L,NTL}]$$

The control vector may be represented by:

$$b^T = [P_{G,2} \dots\dots P_{G,NGB}, V_{G,1} \dots V_{G,NGB}, Q_{SH,1} \dots Q_{SH,NC}, T_1 \dots T_{NT}]$$

3.1 Objective Functions

In this paper, three single objective functions are minimized, which are mathematically expressed below:

a. Generation fuel cost minimization

$$F_1 = \min(F_c(P_{g_m})) = \sum_{m=1}^{NPV} x_m P_{g_m}^2 + y_m P_{g_m} + z_m \$/h \quad (12)$$

where, x_m, y_m and z_m are the fuel cost coefficients of m^{th} unit.

b. Emission minimization

$$F_2 = \min(E(P_{g_m})) = \sum_{m=1}^{NPV} \alpha_m + \beta_m P_{g_m} + \gamma_m P_{g_m}^2 \quad (13)$$
$$+ \xi_m \exp(\lambda_m P_{g_m}) ton/h$$

where, α_m, β_m, γ_m, λ_m and ξ_m are the emission coefficients of m^{th} unit.

c. Total power loss minimization

$$F_3 = \min(P_{loss})) = \sum_{m=1}^{NTL} P_{loss_m} MW \quad (14)$$

where, P_{loss_m} is the real power loss in m^{th} line.

3.2 Constraints

The equality and in-equality constraints are as follows:

a. Equality constraints

$$\sum_{m=1}^{NPV} P_{g_m} - P_d - P_l = 0 \quad , \quad \sum_{m=1}^{NPV} Q_{g_m} - Q_d - Q_l = 0$$

where, P_d, Q_d and P_l , Q_l are the real and reactive demands and losses respectively.

b. Inequality Constraints

These constraints represent power system operating limits.

(i). Generator constraints

All the buses with generators including slack bus are bounded by the voltages, real and reactive powers limits as expressed below:

$$V_{g_m}^{\min} \le V_{g_m} \le V_{g_m}^{\max} ,$$

$$P_{g_m}^{\min} \le P_{g_m} \le P_{g_m}^{\max} \quad \text{and}$$

$$Q_{g_m}^{\min} \le Q_{g_m} \le Q_{g_m}^{\max} \quad \forall m \in NGB$$

(ii). Tap changing transformers constraints

Tap changing of transformers are specified within limits.

$$T_{t_m}^{\min} \le T_{t_m} \le T_{t_m}^{\max} \quad \forall m \in NT$$

(iii). Shunt compensators constraints

Reactive power output of shunt compensators are specified within its upper and lower limits.

$$S_{sh_m}^{\min} \le S_{sh_m} \le S_{sh_m}^{\max} \quad \forall m \in NTL$$

(vi). IPFC limits

$$0 \le r_1, r_2 \le 0.1 , \quad 0 \le \gamma_1, \gamma_2 \le 2\pi$$

IV. HYBRID SINE-COSINE ALGORITHM (HSCA)

In this paper, we proposed an algorithm which is developed with the hybridization of existing SCA and arithmetic crossover operation.

4.1 Existing Sine-cosine Algorithm (SCA)

SCA is an optimization technique which is basically based on population, it initiates with a set of randomly generated solutions [21]. The core principle of the optimization techniques is to evaluate the randomly generated set of solutions iteratively by an objective function, and as the number of iterations increases the probability of achieving the global optima increases. Basically, in SCA exploration and exploitation are the main modes which took place with the Sine-cosine functions; mathematically position can be updated for both the modes by following equations:

$$A_i^{k+1} = A_i^k + r_a \times \sin(r_b) \times | r_c P_i^k - A_i^k | \qquad (15)$$

$$A_i^{k+1} = A_i^k + r_a \times \cos(r_b) \times | r_c P_i^k - A_i^k | \qquad (16)$$

Fig. 3 depicts the impact of sine-cosine equations on Eq. (15) and (16). The exploitation can be achieved between two solutions as sine and cosine functions possess a cyclic shape which forces a solution to get repositioned near to another solution present. The exploration can be achieved when solutions explores the outer spaces also, it can be made possible by changing the range of sine- cosine functions. Thus this algorithm able to manage equilibrium among exploration and exploitation modes to find the best search spaces and led to converge to the best solution.

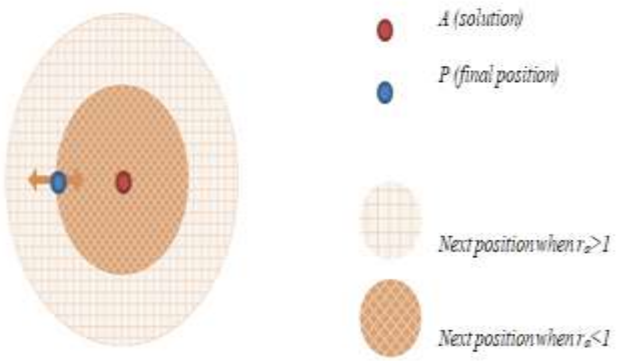

Fig. 3 Impact of Sine and cosine on next movement in Eq. (15) and (16)

4.2 Proposed Hybrid Sine-cosine Algorithm

This proposed algorithm took place in three stages, which are explained below:

4.2.1 Random initialization

Initially a set of search agents are generated randomly in the range of lower and upper bounds, it can be expressed as:

$$A_i = A_{lb} + R(0,1) \times (A_{ub} - A_{lb}) \qquad (17)$$

where, A_i is an initial set of solutions, lb and ub are the lower and upper bounds respectively and R(0,1) generates the random values between 0 and 1.

4.2.2 Exploration and exploitation

For exploration and exploitation modes above both equations (15) and (16) are combined as follows:

$$A_i^{k+1} = \begin{cases} A_i^k + r_a \times \sin(r_b) \times |r_c P_i^k - A_i^k| & r_d < 0.5 \\ A_i^k + r_a \times \cos(r_b) \times |r_c P_i^k - A_i^k| & r_d \geq 0.5 \end{cases} \quad (18)$$

$$r_a = \alpha - \frac{k\alpha}{K} \quad (19)$$

The variable r_a directs the next movement, which can be nearby to the solution and at final position or outside the region. To maintain equilibrium between the exploration and exploitation modes, the r_a changes its value adaptively by using Eq. (19) and changes the range of sine and cosine in Eq. (18). In Eq. (19) α is a constant, k is the current iteration and K is the maximum number of iterations. The variable r_b suggests how far the movements can be toward or outward the final position. r_c is a random variable and r_d is shifting parameters which causes a transition between the sine and cosine in Eq. (18). When r_d < 0.5 then exploration mode occurs and when $r_d \geq 0.5$ then exploitation mode get processed.

4.2.3 Arithmetic crossover operation

As in existing method the exploitation and exploration are control through sine-cosine function but it take time to achieve the best result, so this arithmetic crossover operation is implemented to achieve the global solution efficiently in less iteration. As arithmetic crossover operation [23] updates the generated locations and thus convergence occurs faster. Thus, the hybridization helps to get the optimum values quickly. Mathematically arithmetic crossover operation can be expressed as [23]:

$$A_i^{k+1} = (1-\xi) \times A_i^k + \xi \times A_i^{k+1} \quad (20)$$

where, ξ is a random number between 0 and 1.

4.3 Flowchart of HSCA

Sequential implementation of proposed algorithm is presented in Fig.4 by a flowchart.

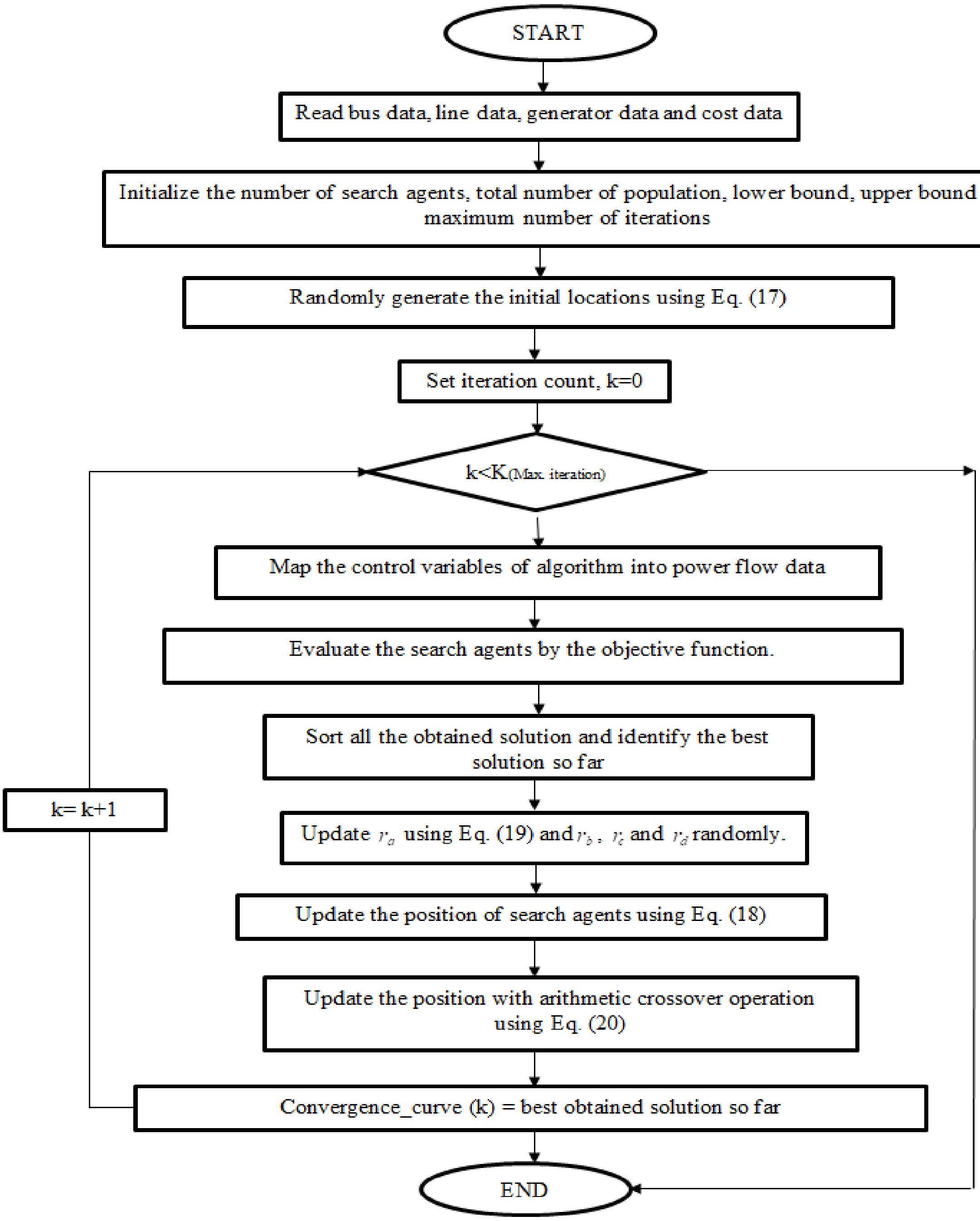

Fig. 4 Flowchart of proposed HSCA

4.4 Step by step procedure of proposed Hybrid Sine-cosine Algorithm (HSCA)

The step by step procedure of proposed method is described below:

1. Read bus data, line data, generator data and cost data for the given electric system.
2. Initialize the parameters of HSCA i.e., number of search agents, lower and upper bounds and maximum number of iterations.
3. Initially generate the random set of search agents using Eq. (17).

while (k ≤ Maximum number of iterations)

4. Map the algorithm variables with the load flow data and then evaluate them for obtaining the solution of the single objective problems.
5. Sort them in ascending order to obtain the best solution obtained so far (P).
6. Update the parameter r_a using Eq. (19).
7. Update r_b, r_c and r_d randomly.
8. Update the position of search agents using Eq. (18).
9. Update the position of search agents with arithmetic crossover operation using Eq. (20).
end

10. The best solution obtained so far will consider as the global solution for the objective function.

V. OPTIMAL ALLOCATION OF FACTS DEVICE

Under contingency conditions to secure the power system, the FACTS devices play a vital role as they minimize the line-loadings and avoid violation of bus voltage limits. Severity function can be expressed as [23]:

$$F_{SEVERITY} = \sum_{m=1}^{NTL} \left(\frac{S_m}{S_m^{\max}}\right)^{2x} + \sum_{n=1}^{NB} \left(\frac{V_{n,ref} - V_n}{V_{n,ref}}\right)^{2y} \quad (21)$$

where, $S_m^{\max}$ and S_m are the maximum and current apparent powers respectively of m^{th} line, $V_{n,ref}$ and V_n are the reference and current voltage of n^{th} bus and x and y is equal to 2.

Some heuristic rules are considered to reduce the number of locations for placing IPFC, which are discussed below:

1. It should not be placed between PV buses.
2. There should not be any shunt compensating device present.
3. Lines in which T changing transformers are already present should be avoided.
4. Only those buses will be consider which are interconnected with two or more buses.

Considering above four rules, 21 possible locations are determined to place IPFC in IEEE- 30 bus system. At all the identified location, severity function is being minimized with consideration of all the equality and inequality constraints, then the location at which severity function value is minimum will be considered as the optimal location for placing the IPFC.

VI. RESULTS AND DISCUSSION

6.1 Illustrative Example- 1

In this section we validated our proposed algorithm on two benchmark functions, which are mentioned below:

1. Step function, $f(x) = \sum_{i=1}^{D} (|x_i + 0.5|)^2$

It is a unimodal, discontinuous, non-differentiable, separable, and scalable function.

2. Ackley function, $f(x,y) = -20e(-0.2\sqrt{\frac{1}{n}\sum_{i=1}^{n} x_i^2}) - e(\frac{1}{n}\sum_{i=1}^{n}\cos(2\Pi x_i)) + 20 + e$

It is a multimodal, continuous, differentiable, non-separable and scalable function.

Table 1 Comparison results of optimal value of benchmark test functions

Function Name	GSA[17]	PSO[19]	ALO[19]	SCA[17]	HSCA
Step function	0.0002	0.0004	0.0002	0.0002	0.000
Ackley's function	0.0079	0.1045	0.0073	0.3804	0.0059

For the analysis, the maximum number of iteration considered are 100 with number of search agents equal to 30. The optimal values for both the functions are tabulated in Table 1 for the proposed algorithm and it is also being compared with the existing algorithms. It can be seen that for step function 0.000 is obtained as the minimum value in case of proposed algorithm while for the existing SCA, the function's optimal value is obtained as 0.0002 and for Ackley's function proposed algorithm gives optimal solution to 0.0059 which is less in comparison to the existing SCA. From the convergence curve in Fig. 5-6, it can be justified that with the hybridization of SCA and arithmetic operator leads to reduce the convergence time as it got its final value in less iteration as compared to SCA. Therefore, we can justify the effectiveness and performance of the proposed algorithm.

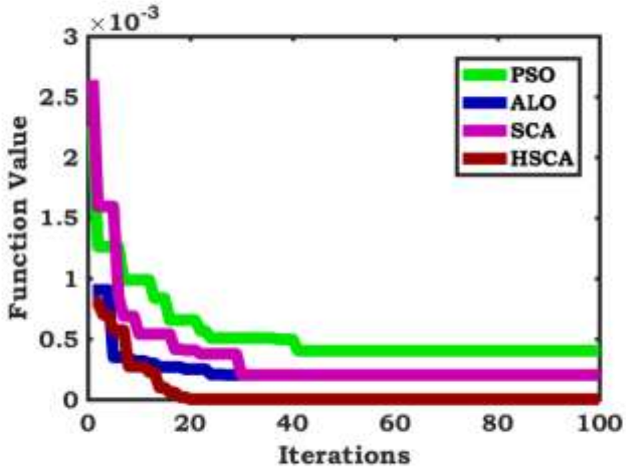

Fig. 5 Convergence curve for step function

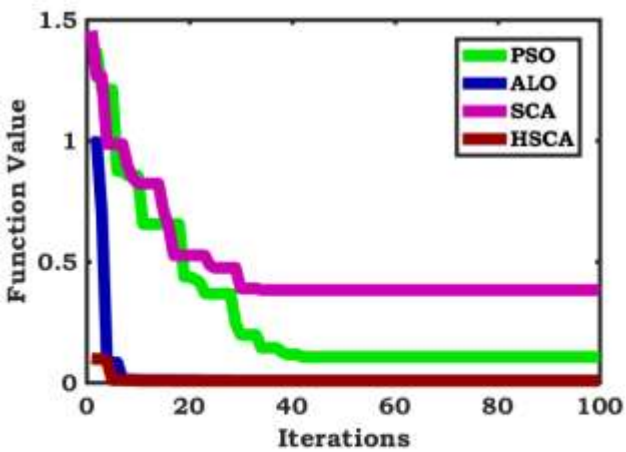

Fig. 6 Convergence curve for Ackley's function

6.2 Illustrative Example-2

The proposed HSCA has been verified on IEEE-30 bus system by solving the OPF problems. Generally, IEEE- 30 bus system consists of 6 generators placed on buses 1, 2, 5, 8, 11 and 13, four off-nominal T ratio transformers placed between the buses 6-9,6-10, 4-12, 27-28 and two shunt capacitors at buses 10 and 24. For each objective, proposed algorithm has run up to 100 iterations. The result obtained for proposed algorithm has been compared with the existing literature values.

Table 2 Comparison results of optimal value for generation fuel cost $/h for IEEE-30 bus system

Variables	PSO [23]	HCSA [23]	HFFA[20]	MSCA[23]	HSCA
PG1, MW	178.5558	176.87	179.3122	177.401	175.782
PG2, MW	48.6032	49.8862	48.26495	48.632	49.529
PG5, MW	21.6697	21.6135	20.9265	21.2376	21.611
PG8, MW	20.7414	20.8796	19.86292	20.8615	21.071
PG11, MW	11.7702	11.6168	23.3402	11.9385	12.186
PG13, MW	12	12	12	12	12
V1, p.u.	1.1	1.057	1.1	1.1	1.1
V2, p.u.	0.9	1.0456	1.057	1.0867	1.061
V5, p.u.	0.9642	1.0184	1.067	1.0604	1.064
V8, p.u.	0.9887	1.0265	1.07	1.0923	1.07
V11, p.u.	0.9403	1.057	1.025229	1.1	1.098
V13, p.u.	0.9284	1.057	1.092478	1.1	1.1
T 6-9, p.u.	0.9848	1.0254	1.045322	1.0439	1.054
T 6-10, p.u.	1.0299	0.9726	0.980038	0.9144	0.929
T 4-12, p.u.	0.9794	1.006	1.096105	1.03	1.019
T 28-27	1.0406	0.9644	10.2131	0.9913	0.979
Qc 10, p.u.	9.0931	25.3591	5	0.0246	8.496
Qc 24, p.u.	21.665	10.6424	29.67086	2.56	14.082
Generation fuel cost $/h	**802.41**	**802.034**	**800.9964**	**799.31**	**799.189**

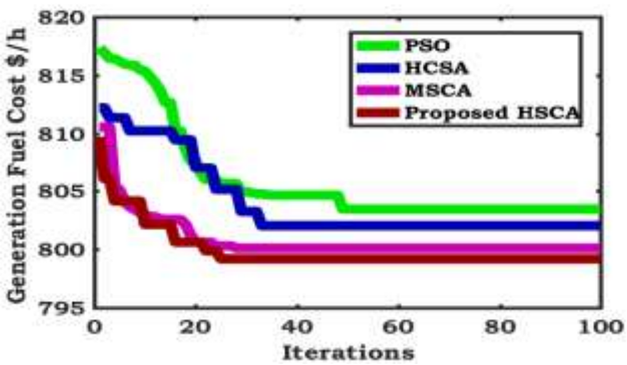

Fig. 7 Convergence curve for generation fuel cost

Generation fuel cost is minimized by proposed algorithm and from Table 2, it can easily be justified that the proposed algorithm minimizes the objective to the best minimum value as compare to other existing algorithms. It can be seen from Table 2 that generation fuel cost achieved is 799.189$/h which is less as compared to existing SCA. Thus, the proposed algorithm gives the better result. Fig. 7 shows the convergence curve for generation fuel cost, from which we can conclude that proposed algorithm helps the convergence to reach the best final value in less iteration as compared to other existing algorithms. Hence, the robustness and efficiency is justified and for further analysis HSCA will be preferred.

6.3 Optimal Location of IPFC

As discussed in Section 5, 21 possible locations are identified in accordance to the four heuristic rules assumed.

Table 3 Severity function value at 21 different locations

S.NO.	IPFC SEND	IPFC RECE1	IPFC RECE2	SEVERITY FUNCTION VALUE
1	4	3	6	1.525
2	6	7	4	2.05
3	6	7	28	1.554
4	6	28	4	2.747
5	12	14	15	1.385
6	12	14	16	1.427
7	12	15	16	1.337
8	14	12	15	1.406
9	15	12	18	1.362
10	15	14	18	1.413
11	15	23	18	1.388
12	15	23	12	1.839
13	15	23	14	1.402
14	15	12	14	1.361
15	16	12	17	1.425
16	18	15	19	1.38
17	19	20	18	1.704
18	25	26	27	1.406
19	27	30	29	1.419
20	29	30	27	1.68
21	**30**	**27**	**29**	**1.234**

For each location severity function is calculated, tabulated in Table 4. It can be observed that IPFC can be optimally placed among the buses 30, 27 and 29, as at this location severity function is minimum as compared to other locations.

6.4 Incorporation of IPFC in IEEE-30 bus system

In this section, current injection modelling of IPFC is incorporated in Newton-Raphson load flow method for solving OPF problems for IEEE-30 bus system at optimal location identified in section 6.3. Comparison of solutions for considered objectives is tabulated in Table 5, with and without IPFC and it can be seen that the objectives get further minimized and better solutions has been obtained. Comparison between the existing PIM of IPFC and proposed CIM of IPFC is also tabulated, in which by latter approach generation fuel cost obtained is 799.095 $/h, emission is 0.203128 ton/h, total power loss is 3.2762 MW, which justifies that the proposed modelling yields for better solutions for considered objectives.

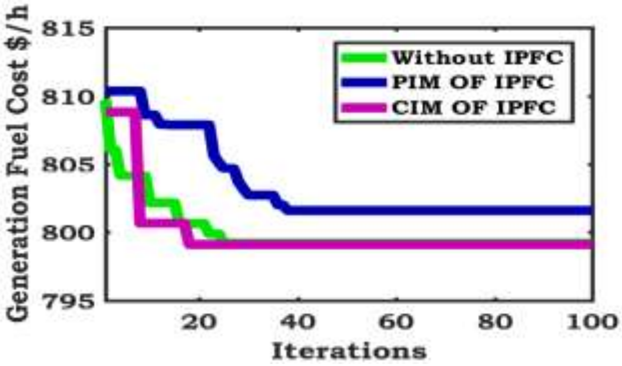

Fig. 8 Convergence curve for generation fuel cost

Table 4 Comparison of OPF solution with and without IPFC for IEEE-30 bus system

Variables	**Generation fuel cost $/h**			**Emission ton/h**			**Total real power loss MW**		
	Without IPFC	PIM OF IPFC [18]	CIM OF IPFC	Without IPFC	PIM OF IPFC [18]	CIM OF IPFC	Without IPFC	PIM OF IPFC [18]	CIM OF IPFC
PG1, MW	175.782	158.750	122.206	64.370	63.410	79.986	68.130	65.420	65.701
PG2, MW	49.529	46.410	60.000	67.519	68.998	53.551	74.774	71.093	72.084
PG5, MW	21.611	20.130	30.000	50.000	50.000	21.095	47.245	50.000	50.000
PG8, MW	21.071	25.000	25.000	35.000	35.000	48.871	35.000	35.000	35.000
PG11, MW	12.186	24.199	13.721	30.000	30.000	21.075	28.188	30.000	30.000
PG13, MW	12.000	15.213	30.000	40.000	40.000	38.441	33.529	35.312	34.234
V1, p.u.	1.100	1.004	1.048	1.088	0.991	1.088	1.094	1.100	1.093
V2, p.u.	1.061	0.956	0.953	0.994	0.950	1.068	1.093	1.100	0.996
V5, p.u.	1.064	1.012	1.066	1.060	0.985	0.983	1.069	1.068	1.045
V8, p.u.	1.070	0.992	0.973	1.077	1.039	0.900	1.076	1.100	1.075
V11, p.u.	1.098	1.087	0.971	0.905	1.100	0.963	0.971	1.009	1.028
V13, p.u.	1.100	1.100	1.058	1.052	0.951	0.983	1.087	1.040	1.049
T 6-9, p.u.	1.054	0.957	1.059	1.023	0.996	1.071	0.958	1.100	0.994
T 6-10, p.u.	0.929	0.910	1.025	0.976	0.907	1.011	0.995	1.014	0.961
T 4-12, p.u.	1.019	0.900	1.065	0.938	0.900	1.011	1.004	1.100	0.979
T 28-27,	0.979	1.055	0.956	1.024	1.100	1.099	1.018	1.027	0.962
Qc 10, p.u.	8.496	8.994	26.233	28.417	27.029	7.005	18.471	30.000	5.503
Qc 24, p.u.	14.082	6.935	14.329	10.920	16.981	18.037	13.651	5.000	17.723
r1, p.u.	NA	NA	0.036	NA	NA	0.035	NA	NA	0.027
r2, p.u.	NA	NA	0.045	NA	NA	0.033	NA	NA	0.076
γ1, deg	NA	NA	219.287	NA	NA	302.725	NA	NA	91.938
γ 2, deg	NA	NA	245.469	NA	NA	91.056	NA	NA	328.188
Xse1, p.u.	NA	0.094	0.078	NA	0.100	0.071	NA	0.100	0.098
Xse1, p.u.	NA	0.091	0.028	NA	0.954	0.081	NA	0.100	0.031
Generation fuel cost $/h	**799.189**	**801.577**	**799.095**	951.432	948.682	739.846	917.654	929.586	938.230
Emission, ton/h	0.363	0.318	0.955	**0.205**	**0.205**	**0.203**	0.210	0.207	0.208
Total real power loss, MW	8.779	6.326	8.745	3.587	4.011	6.019	**3.4667**	**3.429**	**3.276**

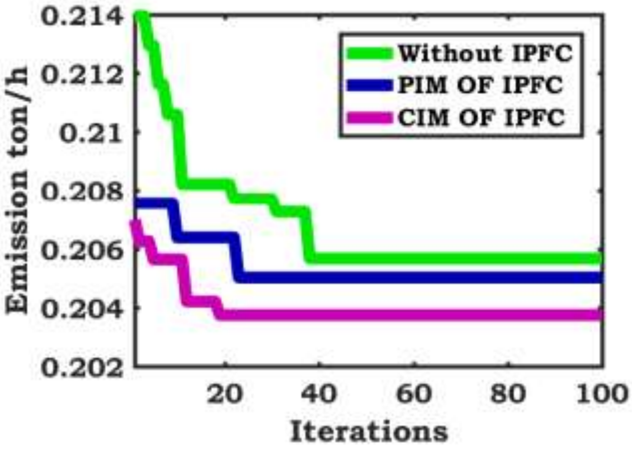

Fig. 9 Convergence curve for emission

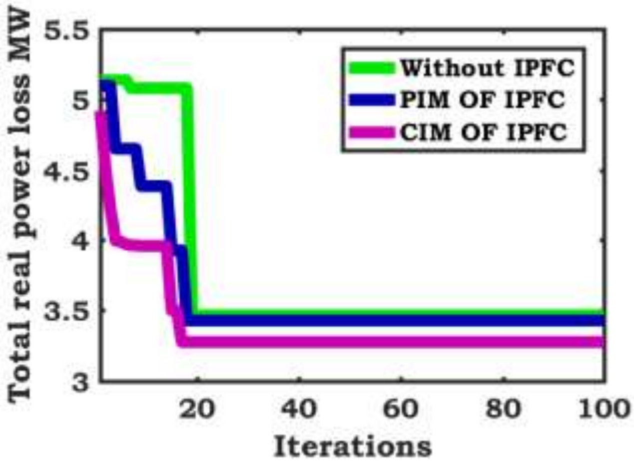

Fig. 10 Convergence curve for total power loss

Convergence curves for considered objectives are illustrated from Fig. 8-10, which validate the effectiveness and performance of proposed approach. So, incorporation of CIM of IPFC for solving OPF problem using the proposed HSCA enhances overall system performance.

This work helps in identifying the solution of optimal power flow problems which help in determining the values of control variables at which power system can be operated efficiently and economically. The implementation of proposed algorithm results in faster response thus for the large bus system convergence can be expected to occur earlier as observed when implemented for IEEE-30 bus system. Furthermore, this work also shows the impact of incorporating IPFC, power flow in power system can be controlled more effectively in the presence of IPFC. The proposed current injection modeling also results in improving the response as number of control variables are more in comparison to the power injection modeling, thus it helps in controlling the system more efficiently. Thus, overall the proposed idea focuses on finding the best optimal solution for the power system problems at steady state so that it can be operated economically.

VII. CONCLUSION

A novel ameliorated algorithm is proposed with the hybridization of arithmetic crossover operation and SCA, named as Hybrid Sine-cosine algorithm. Its superiority is justified in terms of achieving the better global solutions for the considered objectives in less iteration. The proposed algorithm is validated on unimodal and multimodal test functions , then it is implemented on IEEE- 30 bus system to minimize the considered objectives i.e., generation fuel cost, emission and total power loss. OPF results shows that the proposed algorithm enhances the capability of existing SCA and yields the better solutions as compared to the existing algorithms.

In this IPFC had been incorporated in IEEE- 30 bus system, for which its optimal location is identified with minimizing the severity function, which is an effective approach to secure the power system from the contingencies. Current injection modeling of IPFC is mathematically modeled is an easiest approach and it is being justified that incorporation of IPFC improves the system parameters and helps to minimize the considered objectives more efficiently. Thus, the proposed approach for solving OPF problem using the proposed HSCA with the incorporation of CIM of IPFC at an optimal location is more effective and feasible approach.

Abbreviations and symbols

SCA	Sine-Cosine Algorithm
HSCA	Hybrid Sine-Cosine Algorithm
FACTS	Flexible AC Transmission Systems
IPFC	Interline Power Flow Controller
CIM	Current Injection Modeling
IEEE	Institute of Electrical and Electronics Engineers
OPF	Optimal Power Flow
PIM	Power Injection modeling
ΔP	Real power mismatches
ΔQ	Reactive power mismatches
Δδ	Incremental changes in angles
ΔV	Incremental changes in voltages
H, N, J, L	Partial derivatives of P and Q w.r.to δ and V
NLINE	Total number of PQ buses
NGB	Total number of PV buses
NTL	Total number of transmission lines
NC	Total number of shunt compensators
NT	Total number of off-nominal taps transformers
PSO	Particle Swarm Optimization
HCSA	Hybrid Cuckoo Search Algorithm
HFFA	Hybrid Fruit Fly Algorithm
MSCA	Modified Sine-cosine Algorithm

REFERENCES

[1] S.Kamel, F. Jurado, "Power flow analysis with easy modelling of interline power flow controller", Electric Power Systems Research Volume 108, (2014), Pages 234-244. https://doi.org/10.1016/j.epsr.2013.11.017

[2] X.P. Zhang, "Modelling of the interline power flow controller and the generalized unified power flow controller in Newton power flow", IEE Proceedings, Generation, Transmission and Distribution 150 (May (3)) (2003) 268-274. DOI: 10.1049/ip-gtd:20030093

[3] Jun Zhang, Akihiko Yokoyama, Toshiro Ide, "Use of IPFC Detailed Dynamic Model for Analysis of Power Flow Control and Small-Signal Stability Enhancement", IEEJ, Trans. on electrical and electronic engineering, John Wiley & Sons, Inc., (2009).
https://doi.org/10.1002/tee.20442

[4] A.Vinkovic, R. Mihalic, "A current-based model of the static synchronous series compensator (SSSC) for Newton-Raphson Power Flow", Electric Power Systems Research 78(October (10)) (2008) 1806-1813. https://doi.org/10.1016/j.epsr.2008.03.006

[5] K.S.Smith L. Ran J. Penman, "Dynamic modelling of a unified power flow controller", IEE Proc Gener. Transm. Distrib.,Vol. 144, No. I, (1997). DOI: 10.1049/ip-gtd:19970680

[6] L. Gyqyi T. R Rietman A. Edris C. D. Schauda s. L. willirms, "the unified power flow controller: a new

approach to power transmission control", IEEE Transactions on Power Delivery, Vol. 10, No. 2, (1995). DOI: 10.1109/61.400878

[7] D. Srilatha, S. Sivanagaraju, "Analyzing Power flow solution with Optimal Unified Power Flow Controller", IJET, vol.9, No.3, (2017).http://www.enggjournals.com/ijet/docs/IJET17-09-03-341.pdf

[8] Mohammad Rafee Shaik, Dr. A. Srinivasula Reddy, "Optimal Placement and sizing of FACTS Device to Overcome Contingencies in Power Systems", International conference on Signal Processing, Communication, Power and Embedded System(SCOPES)-(2016). DOI: 10.1109/SCOPES.2016.7955559

[9] Mahdi Ghazizadeh Ahsaee and Javad Sadeh, "A Novel Fault-Location Algorithm for Long Transmission Lines Compensated by Series FACTS", IEEE transactions on power delivery, vol 26, no.4, (2011). DOI: 10.1109/TPWRD.2011.2166410

[10] Hermann W. Dommel, William F. Tinney, "Optimal Power Flow Solutions", IEEE transactions on power apparatus and systems, VOL. PAS-87, (1968) No. 10. DOI: 10.1109/TPAS.1968.292150

[11] A Sharma, G Rai, M Jain, P Kumawat , Performance study of recent swarm optimization techniques with standard test functions, Imperial Journal of Interdisciplinary Research, 2017

[12] MK Saini, MK Jain, GR Goyal, P Kumawat , "Load Frequency Control of Multi Area Hydro Thermal Power System using Hybrid Controllers"- Published in IJIREEICE, 2017

[13] GD Sen, J Sharma, GR Goyal, AK Singh, "A multi-objective PSO (MOPSO) algorithm for optimal active power dispatch with pollution control", Mathematical Modelling of Engineering Problems, 2017,

[14] Ansil Sharma, Govind R. Goyal, "Solution of an ELD problem with valve-point effect using artificial intelligence techniques", Mathematical Modelling of Engineering Problems, 2017

[15] MK Saini, MK Jain, GR Goyal, P Kumawat, "Load Frequency Control of Multi Area Hydro Thermal Power System using 2DOF Controllers", "Imperial Journal of Interdisciplinary Research (IJIR) · July 2017

[16] Xie, K., Song, Y.H, "Dynamic optimal power flow by interior point methods", IET Proceedings Generation, Transmission and Distribution, 148(1), (2002) 76–84. DOI: 10.1049/ip-gtd:20010026

[17] Javad Lavei, Anders Rantzer, Stephen Low, "Power flow optimization using positive quadratic programming", (2011), 18th IFAC (Italy). https://doi.org/10.3182/20110828-6-IT-1002.02588

[18] El-Hawary, J.A.M.M.E., Adapa, R, "A review of selected optimal power flow literature to 1993. part i: nonlinear and quadratic programming approaches", IEEE transactions on power systems, Vol. 14, (1999A), No. 1. DOI: 10.1109/59.744492

[19] El-Hawary, J.A.M.M.E., Adapa, R., "A review of selected optimal power flow literature to 1993. part ii: newton, linear programming and interior point methods" . IEEE Transactions on Power Systems, 14(1), (1999b), 105–111. DOI: 10.1109/59.744495

[20] O. Alsac, B. Stott, "Optimal load flow with steady-state security", IEEE Transactions on Power Systems, (1973), T73 484-3. DOI: 10.1109/TPAS.1974.293972

[21] Seyedali Mirjalil, "SCA: A Sine Cosine Algorithm for Solving Optimization Problems", Knowledge-Based Systems, S0950-7051, (2015), 00504-3. https://doi.org/10.1016/j.knosys.2015.12.022

[22] Abdel-Fattah Attia, Raga A. El Sehiemy, Hany M. Hasanien, "Optimal power flow solution in power systems using a novel Sine-Cosine algorithm', Electrical power and energy systems 99, (2018), 331-343. https://doi.org/10.1016/j.ijepes.2018.01.024

[23] M. Balasubba Reddy, "A solution to the Multi Objective Optimization problems with FACTS devices using NSHCSA including practical constraints", IEEE International Conference on Power, Control, Signals and Instrumentation Engineering, (2017). DOI: 10.1109/ICPCSI.2017.8392190

[24] Souhil Mouassaa, Tarek Bouktira, Ahmed. Salhib, "Ant lion optimizer for solving optimal reactive power dispatch problem in powersystems",Elsevier,2017.

https://doi.org/10.1016/j.jestch.2017.03.006
[25] M. Balasubba Reddy, "Multi-objective optimization in the presence of ramp-rate limits using non-dominated sorting hybrid fruit fly algorithm", Ain Shams Engineering Journal, (2016), 895-90. https://doi.org/10.1016/j.asej.2016.01.005