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Full Length Article

A novel symbiotic organisms search algorithm for optimal power flow of power system with FACTS devices

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ABSTRACT

In this paper, symbiotic organisms search (SOS) algorithm is proposed for the solution of optimal power flow (OPF) problem of power system equipped with flexible ac transmission systems (FACTS) devices. Inspired by interaction between organisms in ecosystem, SOS algorithm is a recent population based algorithm which does not require any algorithm specific control parameters unlike other algorithms. The performance of the proposed SOS algorithm is tested on the modified IEEE-30 bus and IEEE-57 bus test systems incorporating two types of FACTS devices, namely, thyristor controlled series capacitor and thyristor controlled phase shifter at fixed locations. The OPF problem of the present work is formulated with four different objective functions viz. (a) fuel cost minimization, (b) transmission active power loss minimization, (c) emission reduction and (d) minimization of combined economic and environmental cost. The simulation results exhibit the potential of the proposed SOS algorithm and demonstrate its effectiveness for solving the OPF problem of power system incorporating FACTS devices over the other evolutionary optimization techniques that surfaced in the recent state-of-the-art literature.

1. Introduction

OPF has become one of the imperative tools for energy management in modern power systems [1]. The main purpose of OPF is the optimal adjustment of the power system control variables to optimize an objective function while satisfying a set of equality and inequality constraints [2–9]. Over the years, a wide range of conventional as well as evolutionary optimization techniques, such as quadratic programming [3], Newton method [4], interior point methods [4], genetic algorithm (GA) [5], particle swarm optimization (PSO) [6], biogeography-based optimization (BBO) [7,8], gravitational search algorithm (GSA) [9], etc., have been applied for solving OPF problem of power system.

In the recent past, energy, environment, right-of-way and increasing cost have delayed the construction of generation and transmission facilities. These problems have necessitated a much more intensive shared use of the existing transmission facilities [10,11]. By incorporating flexible ac transmission system (FACTS) devices such as thyristor controlled series capacitor (TCSC) and thyristor controlled phase shifter (TCPS) in the existing networks, it is possible to redistribute line power flow and regulate bus voltages and, hence, maximize the use of the existing transmission assets [12,13].

The conventional OPF algorithm needs to be modified in order to incorporate the FACTS devices in the power system structure [14]. In the recent past, various optimization algorithms such as hybrid GA [15], hybrid Tabu search and simulated annealing (TS/SA) [16], real coded GA (RCGA) [17], differential evolution (DE) [17,18], dynamic strategy based fast decomposed GA [19], craziness PSO [20] and turbulent crazy PSO [20], etc., have been proposed for solving the OPF problem of power system equipped with FACTS devices.

In the past, many researchers have implemented RCGA [17] and DE [17,18] most frequently to solve many complex engineering problems. Although those are found to be effective, they are also not free of limitations. DE [21] algorithm may not be able to solve optimal power flow (OPF) with non-smooth cost functions and exhibit unstable convergence in the last period and may be easily dropped into the regional optimum. Similarly, the conventional RCGA [22] causes loss of the genetic diversity, which means the number of base points in the searching space, because the lack of genetic diversity corresponds to loss of the base points. As a consequence, a drop in the genetic diversity leads to an ineffective search. The comparative analysis of the obtained results reflects superiority of the proposed SOS algorithm in finding global optimum values by eliminating the aforementioned limitations.

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Thus, literature survey reveals that a variety of evolutionary optimization techniques has been applied to solve the conventional OPF problem of power system. Literature survey also reveals that the solution of OPF problem of the power network along with FACTS devices require optimization techniques to solve these problems. Researchers over the globe are continuously searching for a better meta-heuristic for the solution of the optimization problems and the researchers, oriented toward the solution of engineering optimization task, are continuously searching for a better meta-heuristic to accomplish the same.

Cheng and Prayogo [23] introduced a novel optimization technique and named it as symbiotic organisms search (SOS) algorithm. It is based on the symbiotic interaction strategies that organisms use to survive in the ecosystem. A main advantage of the SOS algorithm over most other meta-heuristic algorithms is that the operation of this algorithm requires no algorithm specific parameters. SOS algorithm has been found to be very efficient in solving engineering field optimization problems with very fast convergence rate and less computational time [23,24].

In this work, SOS algorithm is applied for the solution of OPF problem of power system along with FACTS devices. IEEE standard power systems like modified IEEE-30 and IEEE-57 bus test systems are adopted and the OPF problem with FACTS devices of these test power systems are solved with different objectives such as (a) fuel cost minimization, (b) transmission active power loss (P_{Loss}) minimization, (c) emission reduction and (d) combined economic and environmental cost minimization, while maintaining power balance constraints, active and reactive power generation limits, voltage limits, transmission line limits and physical limits of FACTS devices, etc. In the current work, the strategic location of TCSC and TCPS are considered to be at fixed locations of the test power system and these locations are taken from the literature. Results obtained are compared to other computational intelligence-based meta-heuristic algorithms that surfaced in the recent state-of-the-art literature.

The rest of this paper is organized as follows. In Section 2, modeling of FACTS devices is presented. Mathematical problem of the OPF work with FACTS devices is discussed in Section 3. SOS algorithm is depicted in Section 4. In Section 5, application of SOS for the solution of OPF problem with FACTS is described. Simulation results are presented and discussed in Section 6. Finally, conclusions of the present paper are drawn in Section 7.

2. Modeling of FACTS devices

2.1. Modeling of TCSC

The effect of TCSC on a power network may be represented by a controllable reactance inserted in series to the related transmission line. Active power flow through the compensated transmission line may be maintained at a specified level under a wide range of operating conditions [12,14]. The static model of the network with TCSC connected between i-th and j-th bus is shown in Fig. 1. The power flow equations of the branch having TCSC are given by (1) and (2) [16]

$$P_{ij} = V_i^2 G_{ij} - V_i V_j G_{ij}\cos(\delta_i - \delta_j) - V_i V_j B_{ij}\sin(\delta_i - \delta_j) \quad (1)$$

$$Q_{ij} = -V_i^2 B_{ij} - V_i V_j G_{ij}\sin(\delta_i - \delta_j) + V_i V_j B_{ij}\cos(\delta_i - \delta_j) \quad (2)$$

Similarly, real and reactive power flows from j-th to i-th bus may be expressed by (3) and (4)

$$P_{ji} = V_j^2 G_{ij} - V_i V_j G_{ij}\cos(\delta_i - \delta_j) + V_i V_j B_{ij}\sin(\delta_i - \delta_j) \quad (3)$$

$$Q_{ji} = -V_j^2 B_{ij} + V_i V_j G_{ij}\sin(\delta_i - \delta_j) + V_{ij} V_j B_{ij}\cos(\delta_i - \delta_j) \quad (4)$$

where

Conductance of transmission line $(G_{ij}) = \dfrac{R_{ij}}{R_{ij}^2 + (X_{ij} - X_{C_{ij}})^2}$ and susceptance of transmission line $(B_{ij}) = \dfrac{X_{ij} - X_{C_{ij}}}{R_{ij}^2 + (X_{ij} - X_{C_{ij}})^2}$.

Also,

P_{ij}, Q_{ij}	: active and reactive power flows, respectively, between i-th and j-th bus;
V_i, V_j	: voltage magnitudes at i-th and j-th bus, respectively;
δ_i, δ_j	: angles at i-th and j-th bus, respectively;
R_{ij}, X_{ij}	: resistance and reactance, respectively, of transmission line connected between i-th and j-th bus; and
$X_{C_{ij}}$	: reactance of TCSC placed in the transmission line connected between i-th and j-th bus.

2.2. Modeling of TCPS

The static model of a TCPS connected between i-th and j-th bus, having a complex tapping ratio of $1:1\angle\phi$ and series admittance of $Y_{ij} = (G_{ij} - sqrt(-1)B_{ij})$ is shown in Fig. 2 [12,14]. Similar to TCSC, real and reactive power flows from i-th to j-th bus may be expressed by (5) and (6) [16]

$$P_{ij} = \frac{V_i^2 G_{ij}}{\cos^2\phi} - \frac{V_i V_j}{\cos\phi}[G_{ij}\cos(\delta_i - \delta_j + \phi) + B_{ij}\sin(\delta_i - \delta_j + \phi)] \quad (5)$$

$$Q_{ij} = -\frac{V_i^2 B_{ij}}{\cos^2\phi} - \frac{V_i V_j}{\cos\phi}[G_{ij}\sin(\delta_i - \delta_j + \phi) - B_{ij}\cos(\delta_i - \delta_j + \phi)] \quad (6)$$

Real and reactive power flows from j-th to i-th bus may be expressed by (7) and (8) [16]

$$P_{ji} = V_j^2 G_{ij} - \frac{V_i V_j}{\cos\phi}[G_{ij}\cos(\delta_i - \delta_j + \phi) - B_{ij}\sin(\delta_i - \delta_j + \phi)] \quad (7)$$

$$Q_{ji} = -V_j^2 B_{ij} + \frac{V_i V_j}{\cos\phi}[G_{ij}\sin(\delta_i - \delta_j + \phi) + B_{ij}\cos(\delta_i - \delta_j + \phi)] \quad (8)$$

The injected power model of TCPS is shown in Fig. 3 [12,14]. The injected real and reactive powers of TCPS at i-th and j-th bus may be represented by (9)–(12)

$$P_{is} = -G_{ij}V_i^2\tan^2\phi - V_m V_j\tan\phi[G_{ij}\sin(\delta_i - \delta_j) - B_{ij}\cos(\delta_i - \delta_j)] \quad (9)$$

$$Q_{is} = B_{ij}V_i^2\tan^2\phi + V_i V_j\tan\phi[G_{ij}\cos(\delta_i - \delta_j) + B_{ij}\sin(\delta_i - \delta_j)] \quad (10)$$

$$P_{js} = -V_i V_j\tan\phi[G_{ij}\sin(\delta_i - \delta_j) + B_{ij}\cos(\delta_i - \delta_j)] \quad (11)$$

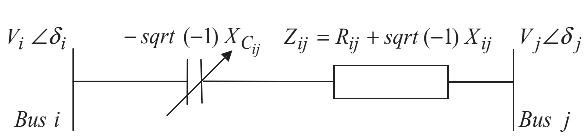

Fig. 1. Circuit model of TCSC connected between i-th bus and j-th bus.

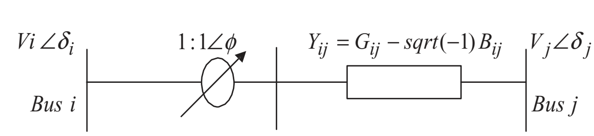

Fig. 2. Circuit model of TCPS connected between i-th and j-th bus.

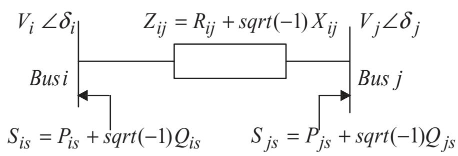

Fig. 3. Power injected model of TCPS connected between i-th and j-th bus.

$$Q_{js} = -V_i V_j \tan\phi\left[G_{ij}\cos(\delta_i - \delta_j) - B_{ij}\sin(\delta_i - \delta_j)\right] \tag{12}$$

3. Problem formulation of OPF with FACTS

The objective of OPF is to minimize an objective function while satisfying all the equality and inequality constraints of the power system. The OPF problem may be formulated by (13) and (14) [7–9]

$$\text{Minimize} \quad OF(\boldsymbol{x}, \boldsymbol{y}) \tag{13}$$

$$\text{Subject to:} \quad \begin{cases} e(\boldsymbol{x}, \boldsymbol{y}) = 0 \\ ie_l \le ie(\boldsymbol{x}, \boldsymbol{y}) \le ie_u \end{cases} \tag{14}$$

where

$OF(\boldsymbol{x}, \boldsymbol{y})$	: objective function;
$e(\boldsymbol{x}, \boldsymbol{y})$	: set of equality constraints;
$ie(\boldsymbol{x}, \boldsymbol{y})$	: set of inequality constraints;
ie_l, ie_u	: set of lower and upper limits of the inequality constraints, respectively;
$\boldsymbol{x}$	: vector of dependent variables consisting of slack bus active power, load voltages, generators' reactive powers and transmission lines' loadings; and
$\boldsymbol{y}$	: vector of independent variables consisting of continuous and discrete variables.

The continuous variables are generators' active powers except slack bus, generators' voltages and discrete variables are transformers' tap settings, reactive power injections of shunt regulators, reactance values of TCSC devices and phase shifting angles of TCPS devices. Hence, x and y may be expressed by (15) and (16), respectively,

$$\boldsymbol{x}^{\mathrm{T}} = [P_{G_1}, V_{L_1} \cdots V_{L_{NL}}, Q_{C_1} \cdots Q_{C_{NG}}, S_{l_1} \cdots S_{l_{NTL}}] \tag{15}$$

$$\boldsymbol{y}^{\mathrm{T}} = [P_{G_2} \cdots P_{G_{NG}}, V_{G_1} \cdots V_{G_{NG}}, T_1 \cdots T_{NT}, Q_{C_1} \cdots Q_{C_{NC}}] \tag{16}$$

where

NG	: number of generator buses;
NL	: number of load buses;
NTL	: number of transmission lines;
NT	: number of regulating transformers; and
NC	: number of shunt compensators.

3.1. Constraints

The OPF with TCSC and TCPS are subjected to the constraints mentioned in the next two sub-sections.

3.1.1. Equality constraints

These constraints represent the load flow equations as stated in (17) [16]

$$\left.\begin{aligned} \sum_{i=1}^{NB}(P_{Gi} - P_{Li}) + \sum_{i=1}^{NTCPS} P_{is} &= \sum_{i=1}^{NB}\sum_{j=1}^{NB}|V_i||V_j||Y_{ij}|cos(\theta_{ij} + \delta_i - \delta_j) \\ \sum_{i=1}^{NB}(Q_{Gi} - Q_{Li}) + \sum_{i=1}^{NTCPS} Q_{is} &= -\sum_{i=1}^{NB}\sum_{j=1}^{NB}|V_i||V_j||Y_{ij}|sin(\theta_{ij} + \delta_i - \delta_j) \end{aligned}\right\} \tag{17}$$

where

P_{Li}, Q_{Li}	: active and reactive power demands of i-th bus, respectively;
P_{Gi}, Q_{Gi}	: active and reactive power generations of i-th bus, respectively;
P_{is}, Q_{is}	: injected active and reactive powers of TCPS at i-th bus, respectively;
Y_{ij}	: admittance of transmission line connected between i-th and j-th bus;
θ_{ij}	: admittance angle of transmission line connected between i-th and j-th bus;
NB	: number of buses; and
$NTCPS$	: number of TCPS devices in the power network.

3.1.2. Inequality constraints

(i) *Generator constraints:* Generator voltage, active and reactive power of the i-th bus should lie between their respective maximum and minimum limits as given by (18)

$$\left.\begin{aligned} V_{Gi\,\min} \le V_i \le V_{Gi\,\max} \quad & i = 1, 2, \cdots, NG \\ P_{Gi\,\min} \le P_i \le P_{Gi\,\max} \quad & i = 1, 2, \cdots, NG \\ Q_{Gi\,\min} \le Q_i \le Q_{Gi\,\max} \quad & i = 1, 2, \cdots, NG \end{aligned}\right\} \tag{18}$$

where

$V_{Gi\,\min}$, $V_{Gi\,\max}$	: minimum and maximum generator voltage of the i-th generating unit, respectively;
$P_{Gi\,\min}$, $P_{Gi\,\max}$	: minimum and maximum active power of the i-th generating unit, respectively; and
$Q_{Gi\,\min}$, $Q_{Gi\,\max}$	: minimum and maximum reactive power of the i-th generating unit, respectively.

(ii) *Load bus constraints*: Load bus voltage should lie between its respective maximum and minimum limits and may be represented by (19)

$$V_{Li\,\min} \le V_i \le V_{Li\,\max}, \quad i = 1, 2, \cdots, NL \tag{19}$$

where $V_{Li\,\min}$ and $V_{Li\,\max}$ are minimum and maximum load voltage of i-th generating unit, respectively.

(iii) Transmission line constraints: Line flow for each transmission line must be within its capacity limits and these limits may be, mathematically, expressed by (20)

$$S_{l_i} \le S_{l_i\,\max} \quad i = 1, 2, \cdots, NTL \tag{20}$$

where

S_{l_i}	: apparent power flow of the i-th branch and
$S_{l_i\,\max}$	: maximum apparent power flow limit of the i-th branch.

(iv) *Transformer tap constraints:* Transformer tap settings are bounded between maximum and minimum limits by (21)

$$T_{i\,\min} \le T_i \le T_{i\,\max} \quad i = 1, 2, \cdots, NT \tag{21}$$

where $T_{i\,\min}$ and $T_{i\,\max}$ are minimum and maximum tap setting limits of the i-th transformer, respectively.

(v) *Shunt compensator constraints:* Shunt compensation are restricted by their maximum and minimum limits as in (22)

$$Q_{ci\,\min} \le Q_{ci} \le Q_{ci\,\max} \quad i = 1, 2, \cdots, NC \tag{22}$$

where $Q_{ci\,\min}$ and $Q_{ci\,\max}$ are minimum and maximum VAR injection limits of the i-th shunt capacitor, respectively.

(vi) *TCSC reactance constraints*: TCSC reactance are restricted by their maximum and minimum limits as in (23)

$$X_{ti\,min} \le X_{ci} \le X_{ti\,max}, \quad i = 1, 2, \cdots, NTCSC \tag{23}$$

where

$X_{ti\,min}$, $X_{ti\,max}$	: minimum and maximum reactance of the i-th TCSC, respectively, and
$NTCSC$	: number of TCSC devices installed in the power network.

(vii) *TCPS phase shift constraints*: TCPS phase shifts are restricted by their maximum and minimum limits as in (24)

$$\phi_{ti\,min} \le \phi_{ci} \le \phi_{ti\,max}, \quad i = 1, 2, \cdots, NTCPS \tag{24}$$

where $\phi_{ti\,min}$ and $\phi_{ti\,max}$ are minimum and maximum phase shift angle of the i-th TCPS, respectively.

3.2. Objective function

In this paper, four different objective functions are considered to determine the effectiveness of the proposed algorithm. These objective functions are as follows:

(i) *Minimization of fuel cost*: The aim of this type of problem is to minimize the total fuel cost while satisfying all the equality and inequality constraints and may be formulated by (25)

$$\text{Min FC}(P_G) \tag{25}$$

where $\text{FC}(P_G)$ is the total fuel cost in \$/hr.

(a) *Fuel cost with quadratic cost function*: Total fuel cost of generating units having quadratic cost function without valve point effect is given by (26) [25]

$$FC(P_G) = \left(\sum_{i=1}^{NG} F_i(P_{Gi})\right) = \left(\sum_{i=1}^{NG} a_i + b_i P_{Gi} + c_i P_{Gi}^2\right) \tag{26}$$

where a_i, b_i and c_i are cost coefficients of the i-th generator.

(b) *Fuel cost with valve point loading effect*: For more practical and accurate model of the cost function, multiple valve steam turbines are incorporated for flexible operational facilities. Total cost of generating units with valve point loading is given by (27) [25]

$$FC(P_G) = \left(\sum_{i=1}^{NG} F_i(P_{Gi})\right) = \sum_{i=1}^{NG} \left(a_i + b_i P_{Gi} + c_i P_{Gi}^2 + |d_i \times sin\{e_i \times (P_{Gi\,min} - P_{Gi})\}|\right) \tag{27}$$

where d_i and e_i are fuel cost coefficients of i-th unit with valve point effect.

(ii) *Minimization of transmission loss:* Mathematical formulation of this type of objective function is given by (28)

$$\text{Min } P_{Loss} \tag{28}$$

where P_{Loss} is the total power losses. Power losses may be, mathematically, formulated as by (29)

$$P_{Loss} = \sum_{k=1}^{NTL} G_k \left[V_i^2 + V_j^2 - 2|V_i||V_j| cos(\delta_i - \delta_j)\right] \tag{29}$$

where G_k is the conductance of the k-th line connected between i-th and j-th buses

(iii) *Minimization of emission*: Mathematical formulation for this type of objective function is given by (30) [26]

$$\text{Min } E(P_G) \tag{30}$$

where $E(P_G)$ is total emission.

In general, the atmospheric pollutants such as sulfur oxides (SO_x) and nitrogen oxides (NO_x) caused by thermal generating units can be modeled separately. However, for comparison purposes, the total emission of these pollutants which is the sum of a quadratic and an exponential function can be expressed by (31) [27]

$$E(P_G) = \sum_{i=1}^{NG} \left(\alpha_i + \beta_i P_{Gi} + \gamma_i P_{Gi}^2 + \eta_i \exp(\lambda_i P_{Gi})\right) \tag{31}$$

where α_i, β_i, γ_i, η_i and λ_i are emission coefficients of i-th generator

(iv) *Minimization of combined economic and environmental cost*: The combined economic environmental OPF considers both cost and emission objectives simultaneously. In this study, economic environmental OPF problem has been converted into a single objective optimization problem by introducing price penalty factor h [26] and may be formulated as

$$\text{Min } OF(FC, E) \tag{32}$$

where $OF(FC, E)$ is the combined economic environmental cost and is, mathematically, represented by (33) [17]

$$OF(FC, E) = FC + h \times E \tag{33}$$

The steps of calculating h may be found in [26].

4. Description of SOS algorithm

The SOS algorithm is inspired from the symbiotic interactions observed between two organisms in the ecosystem and it is recently developed by Cheng and Prayogo in 2014 [23]. The basic concept of symbiosis and the overview of SOS algorithm are discussed in the next two sub-sections.

4.1. Symbiosis: basic concept

The word ‘symbiosis’ is actually derived from a Greek word, which means ‘living together’. In 1869, German mycologist de Bary first used this word to define the relationship between two different species of organisms that are interdependent. Symbiotic relationships are broadly divided into two types, such as obligate and facultative. In obligate relationship, both organisms entirely depend on each other for their survival whereas in facultative relationship, the organisms may depend on each other but it is not mandatory.

Three types of symbiotic relationships are found in nature. These are mutualism, commensalism and parasitism. Mutualism refers to the relationship between two different species of organisms where both individuals get benefited. Commensalism describes the symbiotic relationship between two organisms in which one benefits and the other is, not significantly, affected. Parasitism is the kind of symbiotic relationship where one organism is benefited and the other is, effectively, harmed. Living organisms undergo symbiotic relationships in order to adapt themselves in the environment and, hence, they improve their fitness to survive in the ecosystem over the long-term.

4.2. SOS: features

Unlike other meta-heuristic algorithms like PSO, flower fly algorithm, flower pollination algorithm, bat algorithm, etc., which mimic natural phenomena, SOS algorithm replicates the symbiotic interactions between organisms that are used to find the fittest organism in the search space. Similar to other population based algorithms, SOS algorithm also employs a population of candidate solutions to seek the optimal global solution.

SOS algorithm commences with an initial population of organisms which is called the ecosystem. Each organism of the ecosystem is considered as a candidate solution to the corresponding problem and is correlated to a certain fitness value which imitates degree of adaptation to the desired objective. The new solutions are generated by simulating the symbiotic interactions between two organisms in the ecosystem which includes the mutualism, commensalism and parasitism phases. Each organism in the ecosystem randomly interacts with the other through all these three phases and this process of interaction is repeated until the termination criterion is fulfilled. The details of operation of these three phases of symbiotic interaction are provided in the next three sub-sections.

4.2.1. Mutualism phase

This phase of SOS algorithm mimics the mutualistic interaction between two organisms where both the organisms are benefited. One example of mutualism is the relation between oxpecker and zebra. Oxpeckers eat ticks and parasites from zebra's skin. In this way, oxpeckers get food and zebra gets pest control. Also, when danger comes, the oxpeckers fly and scream that helps zebra to be alert and escape.

In this phase, X_i is considered as *i*th organism in the ecosystem and another organism X_j is selected randomly to interact with X_i. Both the organisms exhibit a mutualistic relationship to increase their mutual survival advantage in the ecosystem and the new solutions for X_i and X_j are given by (34) and (35), respectively,

$$X_{inew} = X_i + rand(0,1) \times (X_{best} - Mutual\_Vector \times BF_1) \quad (34)$$

$$X_{jnew} = X_j + rand(0,1) \times (X_{best} - Mutual\_Vector \times BF_2) \quad (35)$$

In (34) and (35), $Mutual\_Vector$ is determined by (36)

$$Mutual\_Vector = \frac{X_i + X_j}{2} \quad (36)$$

and $rand(0,1)$ is a random number between 0 and 1. BF_1 and BF_2 are benefit factors and their values are either 1 or 2. These factors represent the level of benefit to each organism, as the organisms may get partially or fully benefited from the interaction. $Mutual\_Vector$ in (36) represents the relationship between X_i and X_j. The later parts of both (34) and (35) represent the mutualistic effort given by the organisms to increase their degree of adaptation to the ecosystem while X_{best} represents the highest degree of adaptation. The new solutions are only accepted if they give better fitness value compared to the previous solutions.

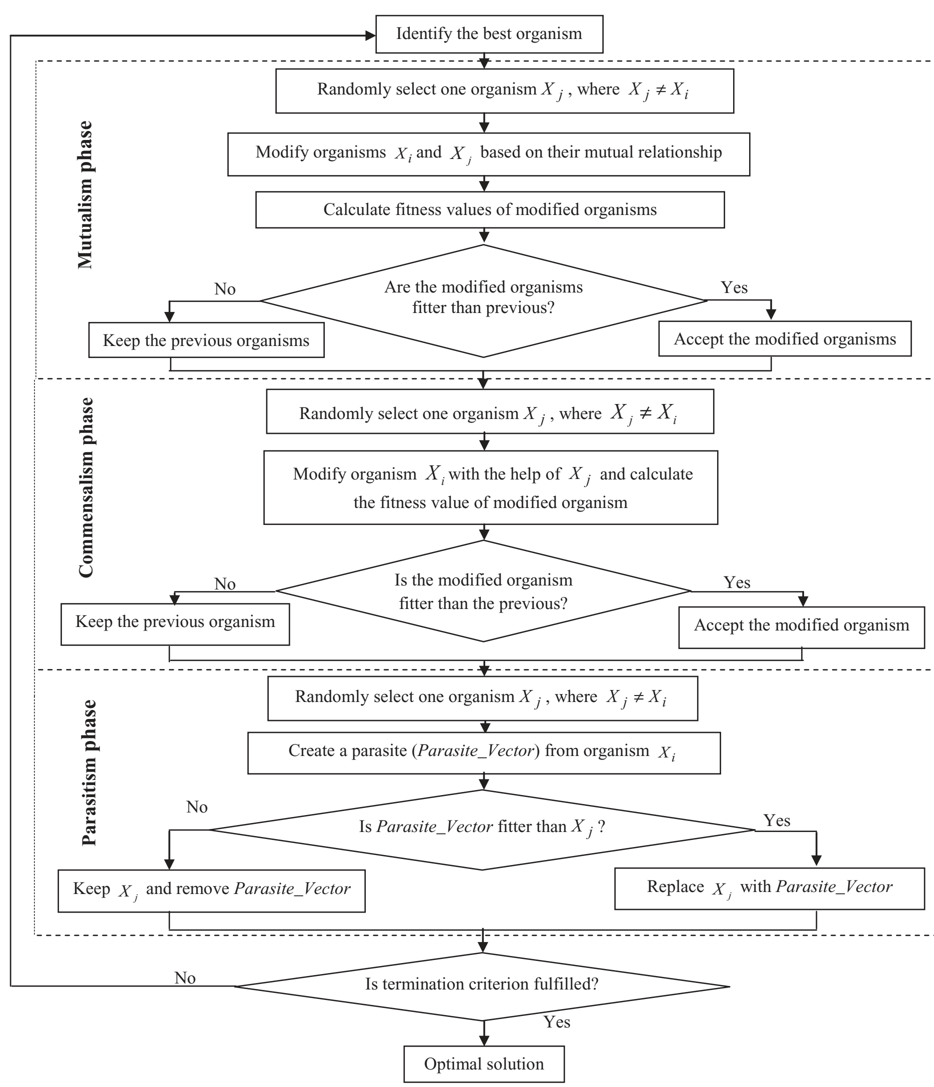

Fig. 4. Flowchart of the SOS algorithm.

4.2.2. Commensalism phase

The relationship between spider and trees or herbs is the example of commensalism. The spider makes net on the trees or herbs to trap insects. In this way, the spider gets food but the trees or herbs remain unaffected. In the SOS algorithm, to simulate this commensalism phase, an organism X_j is selected randomly from the ecosystem which is made to interact with the organism X_i. Now, the organism X_i tries to get benefited from the interaction while it does not benefit or harm the organism X_j. The new candidate solution of X_i, generated by the commensal interaction, is given by (37)

$$X_{inew} = X_i + rand(-1,1) \times (X_{best} - X_j) \tag{37}$$

where $(X_{best} - X_j)$ interprets the benefit provided by X_j to help X_i to increase its degree of adaptation so that it can survive in the ecosystem.

4.2.3. Parasitism phase

A very common example of parasitic relationship is the relation between plasmodium parasite and the human being. This parasite enters into human body through anopheles mosquitoes and it reproduces inside the host human body. As a result, the human host suffers from malaria and may also die.

In parasitism phase of SOS algorithm, an organism X_i is chosen, which is similar to the anopheles mosquito, and it creates an artificial parasite named *Parasite_Vector*. This *Parasite_Vector* is created by duplicating X_i and then its randomly selected dimensions are modified using a random number. Now, an organism X_j is selected randomly from the ecosystem which is treated as a host to the parasite. If the fitness value of *Parasite_Vector* is better than that of X_j, then it will kill the organism X_j and take over its position in the ecosystem. On the other hand, if the fitness value of X_j is better, then it builds immunity against the *Parasite_Vector* and the parasite will no longer exist in the ecosystem.

4.3. Computational procedure

The flow chart of the SOS algorithm is depicted in Fig. 4. The computational procedure for the algorithm may be summarized in Algorithm 1.

Algorithm 1: Pseudo-code of SOS algorithm

```
Define objective function f(x); x = (x_1, x_2, ..., x_d)          % d is dimension of the problem
Initialize an ecosystem of n organisms with random solutions
while (t < MaxGeneration)
    for i = 1: n                                                    % n is number of organisms
        Find the best organism X_best in the ecosystem
        % Mutualism Phase
        Randomly select one organism X_j, where X_j ≠ X_i
        Determine mutual relationship vector (Mutual_Vector) and benefit factor (BF)
        Modify organisms X_i and X_j using (34) and (35)
        If modified organisms give better fitness evaluation than previous, then update
        them in the ecosystem
        % Commensalism Phase
        Randomly select one organism X_j, where X_j ≠ X_i
        Modify organism X_i with the help of X_j using (37)
        If the modified organism gives better fitness evaluation, then update it in the
        ecosystem
        % Parasitism Phase
        Randomly select one organism X_j, where X_j ≠ X_i
        Generate Parasite_Vector from organism X_i
        If Parasite_Vector gives better fitness value than X_j, then replace it with
        Parasite_Vector
    end for
    The global best solution is saved as optimal solution
end while
```

5. Implementation of SOS for OPF problem with FACTS

The fitness value of each element is calculated by using the objective function of the problem. The real-value position of the organism consists of active power generation, reactive power generation, generator voltages, load bus voltages, transformer taps and shunt capacitors/inductors. The real-value position of the agents is changed into a mixed-variable vector which is used to calculate the objective function value of the problem based on Newton–Raphson power flow analysis [1].

6. Test systems vis-à-vis simulation results and discussions

In this paper, SOS algorithm is applied on modified IEEE-30 and IEEE-57 bus test power system with FACTS devices installed at fixed location [17] to comprehensively investigate the performance of the proposed approach in solving the OPF problem. The prototype systems are designed and simulated in MATLAB 2008a computing environment on a 2.63 GHz Pentium IV personal computer with 3 GB RAM. In this study, 30 test runs are performed for all the test cases and simulation results along with comparative discussion are presented below. To indicate the optimization capability of the SOS algorithm, the results of interest are **bold faced** in the respective tables.

6.1. Test system 1: modified IEEE-30 bus power system

The modified IEEE-30 bus test system consists of six generating units (at buses 1, 2, 5, 8, 11 and 13), interconnected with forty-one branches of a transmission network having four transformers with off-nominal tap ratios (at lines 6–9, 6–10, 4–12 and 28 and 27) and nine shunt VAR compensation devices (at buses 10, 12, 15, 17, 20, 21, 23, 24 and 29), taken as test system 1. The total system demand is 2.834 p.u. at 100 MVA base. The fuel cost coefficients, bus data, transmission line data and the rating of generators are taken from Reference 28. In this work, two TCSC are installed in the lines like {3, 4} and {19, 20} and two TCPS are installed in lines like {5, 7} and {10, 22}, respectively [17].

(a) *Minimization of fuel cost with valve point effect*: Fuel cost minimization objective is put on top priority in the industry houses, owing to the fact of involvement of money. Valve point loading effect makes the generator input–output characteristics non-linear. In the present work, SOS algorithm based solution of OPF problem with FACTS for fuel cost minimization objective of this test system is presented in Table 1.The same reported in recent literature like RCGA [17] and DE [17] are also featured in this table. It may be observed from the comparative analysis of the table that SOS algorithm yields a fuel cost of **824.21 $/h**, which signifies 2.33 $/h cheapness of fuels.This value of Table 1 clarifies a reduction of generation cost by **0.2819%** as compared to DE-based previous best result of 826.54 $/h reported in [17]. And, hence, this approach makes the system economically viable. SOS based convergence profile of fuel cost ($/h) for this test power system is presented in Fig. 5. The proposed SOS based convergence profile of fuel cost for this test system is found to be a promising one.

(b) *Minimization of transmission loss*: Transmission line loss causes substantial increase in operating cost of electricity and consequently results in increase in electricity tariff. Hence, it is

Table 1
Best control variable settings for fuel cost minimization objective (with valve point effect) of modified IEEE-30 bus test power system offered by different algorithms.

Control variables	RCGA [17]	DE [17]	SOS
P_{G1} (MW)	198.81	199.13	200.000
P_{G2} (MW)	38.96	38.32	45.000
P_{G5} (MW)	19.16	20.17	15.040
P_{G8} (MW)	10.64	11.43	10.000
P_{G11} (MW)	13.56	10.43	10.080
P_{G13} (MW)	12.03	12.66	12.000
Total P_G (MW)	293.16	292.14	292.120
Xc_{3-4} (p.u.)	0.0185	0.0123	0.0121
Xc_{19-20} (p.u.)	0.0247	0.0250	0.0252
ϕ_{5-7} (°)	–0.5713	–0.1891	–0.1824
ϕ_{10-22} (°)	–0.0281	0.2177	0.2157
Cost ($/h)	831.03	826.54	**824.21**
Emission (ton/h)	0.4366	0.4383	0.443694
P_{Loss} (MW)	9.76	8.74	8.72
CPU time (s)	714.8	505.6	500.71

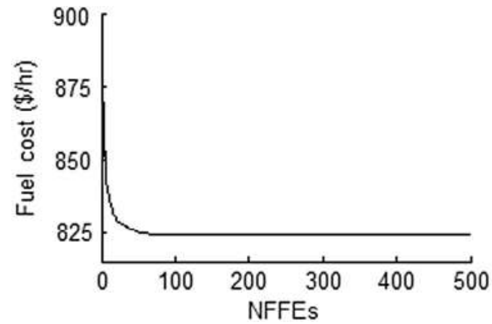

Fig. 5. Convergence profile of fuel cost for fuel cost minimization objective of modified IEEE-30 bus test power system.

Table 2
Best control variable settings for active power transmission loss minimization objective of modified IEEE-30 bus test power system offered by different algorithms.

Control variables	RCGA [17]	DE [17]	SOS
P_{G1} (MW)	77.58	74.59	74.685
P_{G2} (MW)	69.58	67.30	67.450
P_{G5} (MW)	49.98	50.00	50.000
P_{G8} (MW)	34.96	34.85	34.430
P_{G11} (MW)	23.69	27.04	27.180
P_{G13} (MW)	30.43	32.36	32.380
Total P_G (MW)	286.22	286.14	286.125
Xc_{3-4} (p.u.)	0.0193	0.0084	0.0082
Xc_{19-20} (p.u.)	0.0239	0.0045	0.0045
ϕ_{5-7} (°)	–0.5347	–0.5329	–0.5326
ϕ_{10-22} (°)	–0.0292	–0.4526	–0.4520
Cost ($/h)	985.21	992.30	992.24
Emission (ton/h)	0.2144	0.2109	0.210944
P_{Loss} (MW)	2.82	2.74	**2.725**
CPU time (s)	711.7	497.4	485.2

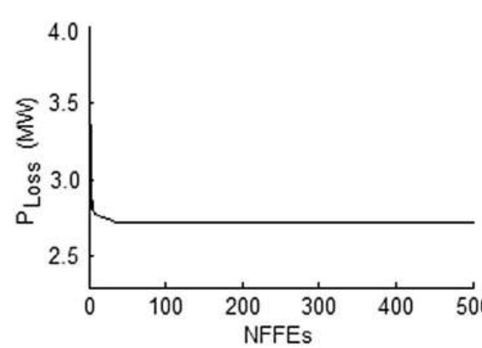

Fig. 6. Convergence profile of P_{Loss} for P_{Loss} minimization objective of modified IEEE-30 bus test power system.

Table 3
Best control variable settings for emission minimization objective of modified IEEE-30 bus test power system offered by different algorithms.

Control variables	RCGA [17]	DE [17]	SOS
P_{G1} (MW)	63.98	63.50	64.340
P_{G2} (MW)	67.75	67.92	67.080
P_{G5} (MW)	50.00	50.00	50.000
P_{G8} (MW)	35.00	35.00	35.000
P_{G11} (MW)	29.96	30.00	30.000
P_{G13} (MW)	40.00	40.00	40.000
Total P_G (MW)	286.69	286.42	286.420
Xc_{3-4} (p.u.)	0.0192	0.0187	0.0183
Xc_{19-20} (p.u.)	0.0246	0.0251	0.0248
ϕ_{5-7} (°)	–0.5518	–0.5478	–0.5417
ϕ_{10-22} (°)	–0.0288	0.0293	0.0285
Cost ($/h)	1015.80	1015.10	1014.40
Emission (ton/h)	0.2049	0.2048	**0.204756**
P_{Loss} (MW)	3.29	3.02	3.020
CPU time (s)	707.6	511.3	501.2

given prime importance, considering financial, economic and socio-economic aspects of service providers and utilities. The best control variable settings for transmission loss minimization objective function of this test system, as yielded by the proposed SOS algorithm, are tabulated in Table 2. In this table, SOS based results are compared to other optimization techniques recently reported in the literature like RCGA [17] and DE [17]. The obtained real power loss from the proposed approach is found to be **2.725 MW** as a near global minimum value, while satisfying all the system constraints. The value

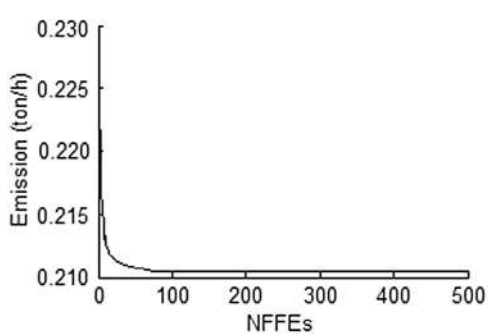

Fig. 7. Convergence profile of emission for emission minimization objective of modified IEEE-30 bus test power system.

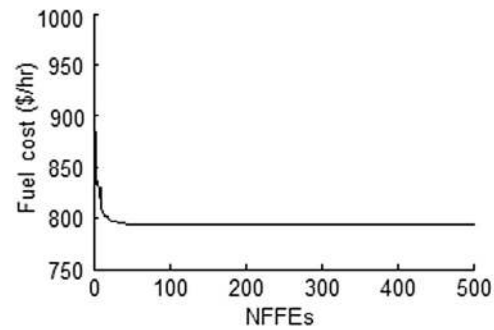

Fig. 8. Convergence profile of fuel cost (with quadratic cost function) for fuel cost minimization objective of modified IEEE-30 bus test power system.

of P_{Loss} (MW) yielded by SOS is **0.015 MW** less than DE-based best results of 2.74 MW reported in Reference 17. The outcome reveals enhancement in transmission line performance by **0. 5474%**. Promising convergence profile of P_{Loss} (MW), as yielded by SOS algorithm, for minimization of real power loss objective for this test power system may be noted from Fig. 6.

(c) *Minimization of emission*: The emission of pollutants (*i.e.*, CO_2, SO_x, NO_x, etc.) during power generation from fossil fuels causes severe impact on human health and the environment. Considering minimization of emission as one of the objective functions for this test power network, obtained optimal values of the control variables (as yielded by the SOS method) are presented in Table 3 along with those reported in in the literature like DE [17] and RCGA [17]. From this table, a curtailment in emission by **0.000044 ton/h** (*i.e.* an improvement of **0.0215%**) may be recorded by using the proposed SOS based algorithm (**0.204756 ton/h**) as compared to DE counterpart (0.2048 ton/h) reported in Reference 17. Fig. 7 shows the variation of emission (ton/h) against NFFEs for this test case yielded by SOS based approach. Better convergence profile of the proposed SOS approach may be noted from this figure by means of its ability to reach the near optimal solution.

(d) *Minimization of fuel cost without valve point effect*: The value of economical mode of power generation without valve point effect is presented in Table 4. And the best control variable settings for the solution of OPF problem with FACTS devices for fuel cost minimization objective (without valve point effect) of this test system, as yielded by the proposed SOS algorithm, along with those reported in literature like DE [17] and

Table 4
Best control variable settings for fuel cost (without valve point effect) minimization objective of modified IEEE-30 bus test power system offered by different algorithms.

Control variables	TS/SA [16]	DE [17]	SOS
P_{G1} (MW)	192.46	180.26	186.40
P_{G2} (MW)	48.38	49.32	46.23
P_{G5} (MW)	19.54	20.82	20.54
P_{G8} (MW)	11.60	17.61	14.34
P_{G11} (MW)	10.00	11.05	11.57
P_{G13} (MW)	12.00	12.69	12.68
Total P_G (MW)	294.00	291.75	291.76
Xc_{3-4} (p.u.)	0.0200	0.0190	0.0191
Xc_{19-20} (p.u.)	0.0200	0.0243	0.0240
ϕ_{5-7} (°)	1.9137	–0.5558	–0.5517
ϕ_{10-22} (°)	0.8251	–0.0286	–0.0276
Cost ($/h)	803.84	797.29	**796.74**
Emission (ton/h)	NR*	0.3756	0.393843
P_{Loss} (MW)	10.60	8.35	8.360
CPU time (s)	265.8	487.3	482.1

NR* means not reported in the referred literature.

Table 5
Best control variable settings for combined fuel cost and emission minimization objective of modified IEEE-30 bus test power system offered by different algorithms.

Control variable	DE [17]	SOS
P_{G1} (MW)	107.98	118.230
P_{G2} (MW)	58.57	55.570
P_{G5} (MW)	32.38	31.900
P_{G8} (MW)	27.61	26.540
P_{G11} (MW)	29.51	22.870
P_{G13} (MW)	33.27	34.210
Total P_G (MW)	289.32	289.320
Xc_{3-4} (p.u.)	0.0024	0.0022
Xc_{19-20} (p.u.)	0.0170	0.0165
ϕ_{5-7} (°)	0.6131	0.6129
ϕ_{10-22} (°)	–0.0745	–0.0741
OF($/h)	1238.099	**1233.805**
Cost ($/h)	922.36	901.65
Emission (ton/h)	0.2364	0.246647
P_{Loss} (MW)	5.92	5.920
CPU time (s)	521.9	510.7

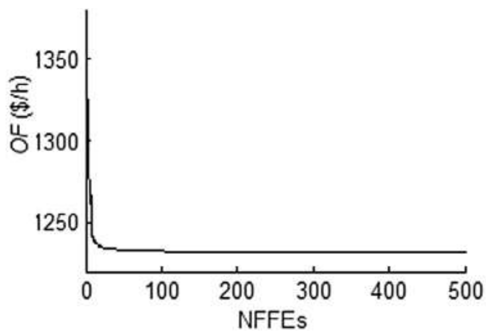

Fig. 9. Convergence profile of *OF* for combined economic and environmental cost minimization objective of modified IEEE-30 bus test power system.

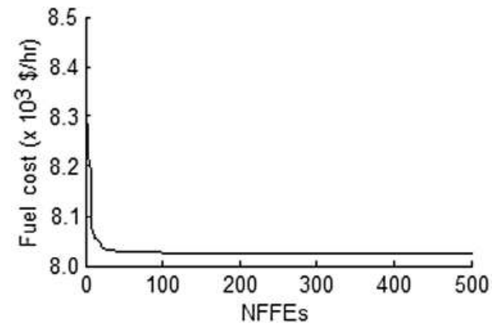

Fig. 10. Convergence profile of fuel cost for fuel cost minimization objective of standard IEEE-57 bus test power system.

TS/SA [16] are featured in the same table. This table demonstrates that a fuel cost reduction of **0.069%** (from previous best of 797.29 $/h (as reported by using DE in Reference 17) to **796.74 $/h**)) is accomplished by using the proposed SOS approach. Fig. 8 portrays the convergence profile of fuel cost for fuel cost minimization of objective without valve point effect and its nature is found to be a promising one.

(e) *Minimization of combined economic and environmental cost*: The pollutant emitted during power generation causes unquantifiable impact on the eco-system by the way of air pollution, water pollution, noise pollution, global warming, etc. The recovery from those effects may render involvement of additional cost and, in some cases, it might be irreparable. So during operation, fuel cost along with emission may be required to be minimized. The best solution of OPF problem with FACTS as yielded by the SOS and DE [17] algorithms for combined economic and environmental cost minimization objective (presented in (33)) for this test power system is tabulated in Table 5. This table indicates a reduction of **0.3468 %** in the value of objective function (i.e. reduction from 1238.099 $/h (previous best reported by DE [17]) to **1233.805** $/h**)** by using SOS algorithm. Good convergence profile of minimum objective function value, as obtained by SOS, may be noted from Fig. 9 by means of its ability to reach the near optimal solution.

6.2. Test system 2: IEEE-57 bus power system

The standard IEEE-57 bus system is taken as test system 2. The system consists of eighty transmission lines, seven generators (at the buses 1, 2, 3, 6, 8, 9, 12) and fifteen branches under load tap setting transformer branches. Three reactive power sources are considered at buses 18, 25 and 53. Line data, bus data, variable limits and the initial values of the control variables are given in References 29 and 30. The total system demand is 12.508 p.u. at 100 MVA base. In this work, five lines like {18, 19}, {31, 32}, {34, 32}, {40, 56} and {39, 57} are installed with TCSC and five lines like {4, 5}, {5, 6}, {26, 27}, {41, 43} and {53, 54} are installed with TCPS [17].

(a) *Minimization of fuel cost*: Table 6 depicts the optimal control variable settings for fuel cost minimization objective of test system 2 as yielded by RCGA [17], DE [17] and the proposed SOS algorithm. From the table, it may be observed that SOS based results yield minimum fuel cost of **8032.64** $/h (i.e. a reduction of **3.329**%) compared to previously reported best result of 8309.27 $/h using DE [17] for this power network. Promising convergence profile of fuel cost for minimization of fuel cost objective, as yielded by the proposed SOS algorithm, is found in Fig. 10.

(b) *Minimization of transmission loss*: The SOS based results for minimization of transmission loss objective is presented in

Table 6
Best control variable settings for fuel cost minimization objective of IEEE-57 bus test power system offered by different algorithms.

Control variables	RCGA [17]	DE [17]	SOS
P_{G1} (MW)	517.45	520.09	516.550
P_{G2} (MW)	0	0	0.000
P_{G3} (MW)	94.81	103.74	129.560
P_{G6} (MW)	0	0	0.000
P_{G8} (MW)	181.75	175.63	155.340
P_{G9} (MW)	0	0	0.000
P_{G12} (MW)	489.77	485.23	482.250
Total P_G (MW)	1283.78	1284.69	1283.700
Xc_{18-19} (p.u.)	0.0572	0.0604	0.0410
Xc_{31-32} (p.u.)	0.0832	0.0199	0.0245
Xc_{34-32} (p.u.)	0.0203	0.0015	0.0145
Xc_{40-56} (p.u.)	0.0480	0.0932	0.0789
Xc_{39-57} (p.u.)	0.0624	0.0466	0.0445
ϕ_{4-5} (°)	−0.7678	−0.6131	−0.5689
ϕ_{5-6} (°)	−0.7620	−0.6188	−0.5469
ϕ_{26-27} (°)	−0.3438	−0.4698	−0.5544
ϕ_{41-43} (°)	−0.3953	0.5099	0.1269
ϕ_{53-54} (°)	−0.4011	−0.1146	−0.1578
Cost ($/h)	8413.43	8309.27	**8032.64**
Emission (ton/h)	2.4331	2.4333	2.398740
P_{Loss} (MW)	32.98	33.89	32.9
CPU time (s)	874.9	689.9	675.19

Table 7
Best control variable settings for active power transmission loss minimization objective of IEEE-57 bus test power system offered by different algorithms.

Control variables	RCGA [17]	DE [17]	SOS
P_{G1} (MW)	303.24	318.58	311.320
P_{G2} (MW)	0	0	0.000
P_{G3} (MW)	63.19	45.90	60.560
P_{G6} (MW)	0	0	0.000
P_{G8} (MW)	400.75	407.65	400.180
P_{G9} (MW)	0	0	0.000
P_{G12} (MW)	500.00	495.03	495.090
Total P_G (MW)	1267.18	1267.16	1267.15
Xc_{18-19} (p.u.)	0.0593	0.0100	0.0245
Xc_{31-32} (p.u.)	0.0179	0.0004	0.0014
Xc_{34-32} (p.u.)	0.0189	0.0079	0.0019
Xc_{40-56} (p.u.)	0.0641	0.0819	0.0714
Xc_{39-57} (p.u.)	0.0055	0.0841	0.0258
ϕ_{4-5} (°)	−0.6532	−0.0745	−0.0789
ϕ_{5-6} (°)	−0.0917	−0.2807	−0.2458
ϕ_{26-27} (°)	−0.7620	−0.9798	−0.7978
ϕ_{41-43} (°)	0.6933	−0.9053	−0.9053
ϕ_{53-54} (°)	0.2406	0.9798	0.8479
Cost ($/h)	15423.88	15691.30	15353.32
Emission (ton/h)	1.906545	1.966905	1.917455
P_{Loss} (MW)	16.38	16.36	**16.35**
CPU time (s)	881.3	701.7	675.18

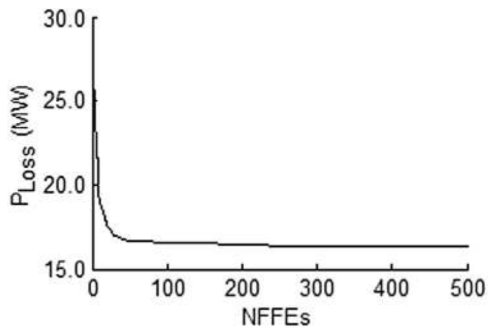

Fig. 11. Convergence profile of P_{Loss} for P_{Loss} minimization objective of standard IEEE-57 bus test power system.

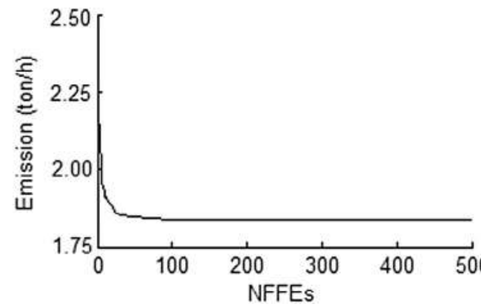

Fig. 12. Convergence profile of emission for emission minimization objective of standard IEEE-57 bus test power system.

Table 7. The results obtained by the proposed SOS algorithm are compared to those obtained by RCGA [17] and DE [17] as reported in literature. The minimum real power loss obtained from the proposed SOS approach is found to be **16.35 MW**. The value of P_{Loss} (MW) yielded by SOS is **0.01 MW** (i.e. 0.0611**%**) less than DE-based best result of 16.36 MW reported in Reference 17. The convergence profile as yielded by SOS of fuel cost for this test power system is portrayed in Fig. 11.

(c) *Minimization of emission:* The best solution of OPF problem along with FACTS devices for emission minimization objective of this test system as yielded by those reported in the literature like RCGA [17] and DE [17] and the proposed SOS algorithm are given in Table 8. This table demonstrates that an emission reduction of **1.259 %** (from the previous best result of 1.858705 ton/h (as reported for DE in Reference 17 to **1.835307 ton/h**)) is accomplished by using the proposed SOS approach. SOS based convergence profile of emission for emission minimization objective of this power system is presented in Fig. 12 which is found to be a promising one.

(d) *Minimization of combined economic and environmental cost:* The optimal values of control variables as yielded by the proposed SOS for combined economic and environmental cost minimization objective function (stated in (33)) of this test system are presented in Table 9. In this table, SOS based results are compared to the results obtained by DE in Reference 17. The value of objective function is found to be **12699.787** $/h (which is **3.669%** less than the DE-based best result of 13183.423 $/h reported in Reference 17). SOS based convergence profile of combined economic and environmental cost minimization for this test power system is presented in Fig. 13. The proposed SOS based convergence profile of objective function for this test system is found to be a promising one.

Table 8
Best control variable settings for emission minimization objective of IEEE-57 bus test power system offered by different algorithms.

Control variable	RCGA [17]	DE [17]	SOS
P_{G1} (MW)	341.91	298.12	294.120
P_{G2} (MW)	0	0	0.000
P_{G3} (MW)	91.90	83.24	92.340
P_{G6} (MW)	0	0	0.000
P_{G8} (MW)	419.25	413.63	411.310
P_{G9} (MW)	0	0	0.000
P_{G12} (MW)	418.45	474.14	472.100
Total P_G (MW)	1271.51	1269.13	1269.870
$Xc_{18\text{-}19}$ (p.u.)	0.0830	0.0830	0.0459
$Xc_{31\text{-}32}$ (p.u.)	0.0672	0.0672	0.0569
$Xc_{34\text{-}32}$ (p.u.)	0.0009	0.0009	0.0007
$Xc_{40\text{-}56}$ (p.u.)	0.0437	0.0437	0.0546
$Xc_{39\text{-}57}$ (p.u.)	0.0772	0.0772	0.0697
$\phi_{4\text{-}5}$ (°)	–0.8995	–0.8995	–0.8975
$\phi_{5\text{-}6}$ (°)	0.4297	0.4297	0.5478
$\phi_{26\text{-}27}$ (°)	–0.8079	–0.8079	–0.8134
$\phi_{41\text{-}43}$ (°)	–0.1375	–0.1375	–0.2564
$\phi_{53\text{-}54}$ (°)	–1.0313	–1.0313	–1.0459
Cost ($/h)	15856.14	15914.38	15824.39
Emission (ton/h)	1.889188	1.858705	**1.835307**
P_{Loss} (MW)	20.71	18.33	19.07
CPU time (s)	878.7	694.2	670.45

Table 9
Best control variable settings for combined economic and environmental cost minimization objective of IEEE-57 bus test power system offered by different algorithms.

Control variable	DE [17]	SOS
P_{G1} (MW)	475.68	485.72
P_{G2} (MW)	0.00	0.00
P_{G3} (MW)	80.64	92.67
P_{G6} (MW)	0.00	0.00
P_{G8} (MW)	276.03	258.78
P_{G9} (MW)	0.00	0.00
P_{G12} (MW)	447.20	442.35
Total P_G (MW)	1279.55	1279.52
$Xc_{18–19}$ (p.u.)	0.0077	0.0069
$Xc_{31–32}$ (p.u.)	0.0360	0.0459
$Xc_{34–32}$ (p.u.)	0.0832	0.0789
$Xc_{40–56}$ (p.u.)	0.0221	0.0369
$Xc_{39–57}$ (p.u.)	0.0521	0.0489
$\phi_{4–5}$ (°)	0.8308	0.8937
$\phi_{5–6}$ (°)	–0.4526	–0.3458
$\phi_{26–27}$ (°)	–0.5500	–0.4951
$\phi_{41–43}$ (°)	–0.7277	–0.6557
$\phi_{53–54}$ (°)	0.8136	0.8231
OF ($/h)	13183.423	**12699.787**
Cost ($/h)	10408.49	9906.38
Emission (ton/h)	2.211635	2.226356
P_{Loss} (MW)	28.750	28.720
CPU time (s)	702.9	699.8

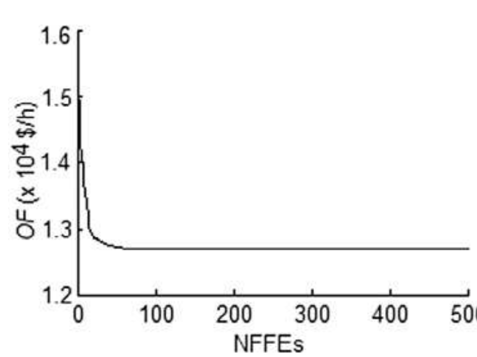

Fig. 13. Convergence profile of *OF* for combined economic and environmental cost minimization objective of standard IEEE-57 bus test power system.

7. Conclusion

In this work, a recently developed meta-heuristic algorithm like SOS is proposed to solve the OPF problem of power system equipped with FACTS devices. The problem of the present work is formulated as a nonlinear optimization problem with equality and inequality constraints of the power network. In this study, fuel cost minimization with different cost curves, transmission loss minimization, emission minimization and combined economic and emission cost minimization objectives are considered individually. The feasibility of the proposed SOS method for solving OPF problems is demonstrated by using modified IEEE-30 and IEEE-57 bus systems with TCSC and TCPS installed at fixed locations. Results obtained are compared to those other well established techniques reported in the literature recently. It is revealed that among all the techniques, SOS gives better results for all the test cases of the OPF problem with FACTS devices. Thus, the proposed SOS may be recommended as a very promising algorithm for solving some more complex engineering optimization problems for the future researchers.

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