International Journal on
"Technical and Physical Problems of Engineering"
(IJTPE)
Published by International Organization of IOTPE

ISSN 2077-3528
IJTPE Journal
www.iotpe.com
ijtpe@iotpe.com

September 2016	Issue 28	Volume 8	Number 3	Pages 1-8

REACTIVE POWER OPTIMIZATION USING INTELLIGENT SEARCH ALGORITHMS CONSIDERING VOLTAGE STABILITY INDEX

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Abstract- The ever-increasing demand for the electric power has caused speeding up expansion of power systems to be able to fulfil costumers' needs for reliable, cheap, and high quality electric power. Active power losses reduction in transmission system is known as an important respect which is raising among popularity of specialists and usually it is very important from the economical point of view in which the needs of power systems and high-tech approaches combine together to achieve remarkable objectives. This paper investigates the subject of reactive power optimization in order to decrease active power losses considering voltage stability index and voltage deviation reduction. In addition, simulation of reactive power optimization problem and analyzing data of performed methods including Genetic Algorithm, Particle Swarm Optimization, Pattern Search and their combinations on IEEE 6-Bus and 14-Bus system are approached using DIgSILENT and MATLAB software. Finally, the mixture as PSO with Pattern Search algorithm are introduced as the best optimization approach for the purposes of reactive power optimization.

Keywords: Reactive Power Optimization, Active Power Loss Reduction, Voltage Stability, Reactive Power Compensation, Intelligent Algorithms, Voltage Deviation.

I. INTRODUCTION

Optimizing reactive power in power networks is of high significance in order to boost stability and power quality of the whole grid. The manner reactive power is being controlled in order to achieve the quality of voltage and decline system losses is of importance principally and practically simultaneously. The modification of control variables as generators voltages, transformers tap settings, and the output power of reactive power compensators will handle supplying of reactive power and impact voltage profiles, and active power losses as a result. Reactive power optimization problem is aimed at finding appropriate tunings of adjustable variables that will aid power network operators leading a grid with lesser amount of active power losses. The objective function of reactive power optimization problem is a complex non-differentiable nonlinear constrained optimization problem [1, 8-11].

Plenty of optimization methods have been applied to reactive power optimization problem in order to assess their performances in online and offline uses, roughly categorized in two main groups as conventional, such as Newton's technique, linear programming and successive quadratic programming and heuristic approaches. Nevertheless, conventional algorithms require some mathematical properties in one way or another, such as derivatives of objective function, which is not readily accessible in discrete variable problem area, and high chances there are that the algorithm will get stuck in local optimal rather than global one due to gradient-based nature of the algorithms, whereas power system optimal power flow formulations consists of various continuous variables such as generators voltages, and discrete control variables, like transformer taps and switching shunt capacitor banks [1, 9].

Heuristic exploration approaches like the ones which are grounded on genetic algorithm (GA) are recognized to be the most appropriate global searching methods because of their capability of concurrently multidimensional exploration for the global optimum solution. On the other hand, current works have illustrated some deficiencies of GA-based methods, whereas particle swarm optimization (PSO) has presented better performance on the same ilk of optimization problems. PSO algorithm technique has mixed communal psychology inspiring the performance of creatures such as fish, birds, etc. founded on a simile of societal collaboration which has led to enhanced convergence performances than GAs. It works based on regulating the routes of solitary sets of variable values (vectors), called "particles" of the swarm, as they have been considered as moving opinions in the space of the problem [2, 9-13].

Pattern and direct search approaches are of the utmost common classes of techniques to minimalize functions without the usage of derivatives or of estimates to derivatives. They are built on producing examination paths, which positively search the exploration space. Direct search is theoretically simple and natural for parallelization. These approaches can be intended to thoroughly recognize opinions fulfilling stationarity for local minimization (from random initial positions).

Furthermore, their adjustability can be used to be combined with procedures or artificial intelligence for global optimization, in a means that the consequential direct or pattern search technique receives some of the properties of the incorporated global optimization method, without risking the convergence for local stationarity stated before [3, 11-13].

Heuristic algorithms such as genetic algorithm and particle swarm optimization algorithm have some operators, which are the most important tools of these algorithms for performing optimization. Many articles are about discovering a new methods and formulas to improve performance of the optimization algorithms to pinpoint global optimum. This paper suggests a new hybrid algorithm containing PSO and Pattern search algorithm as well as GA and Pattern search algorithm. The algorithms PSO and GA have very good performance to find an answer in accurate answers neighborhood, although they have some drawbacks to pinpoint answer. The performances of suggested algorithms are investigated on two IEEE test systems and simulation results can be found simulation results section.

II. PROBLEM DEFINITION

Reactive power (VAR) optimization is to lessen system active power losses, increase voltage profile, stability considerations and to specify optimum VAR compensators operational settings in several functioning circumstances. To accomplish these aims, there are several regulative measures which power system operators can take, such as adjusting tap setting of transformers, excitation of generators, reactive power output of shunt capacitors, and SVC etc. On the other hand, there are some state variables, which is needed to calculate active power loss, to obtain the value of state variables there is need to power flow calculations. Therefore, reactive power flow optimization is a non-convex, high dimensional, and having lots of local optimums due to nonlinear behavior of the grid [4, 8, 9].

The complexity level of the power grid, the number of enormous parameters and their codependency, and dominant restrictions make power system operators confront with vigorous conditions adjusting voltage violations at a specific period of time, especially under failure conditions. In such dominantly changing and indeterminate computational atmosphere cases, the requirement for making fast, reliable and comprehensive decisions comes to a critical importance. The attention through getting these operational measures via reactive power optimization has been growing among the popularity of electrical engineers over the last decade. So, there is a desperate need to find accurate and fast algorithm to be applied in reactive power optimization problem, which will be introduced in this paper as particle swarm pattern search algorithm [4].

III. PROBLEM FORMULATION

The optimum reactive power flow (ORPF) formulation comprises the objective functions, variables restraint circumstances and the constraint equations corresponding to load flow [12]. The objective function of reactive power optimization must fulfil some practical objectives as well as a number of economic goals. The financial goal is essentially to minimalize the active power transmission losses of the network. The practical objectives are to lessen voltage deviation of buses from the best designed operational voltage point and to improve the index of voltage stability appropriately chosen for the purpose [5].

A. Active Power Loss Objective Function

The main objective of reactive power optimization is to reduce active power losses in power grid. Active power losses in transmission lines between buses can be calculated by the following equation:

$$\min F_{loss} = \sum_{k=1}^{N_L} G_k \left[V_{1,k}^2 + V_{2,k}^2 - 2V_{1,k}V_{2,k}\cos\left(\theta_{1,k} - \theta_{2,k}\right) \right] \quad (1)$$

where, F_{loss} is real power losses in aggregate, V is buses voltage, and θ is angle the buses voltage.

B. Voltage Deviation Objective Function

There are lots of different forms of objective functions can be considered for voltage deviation reduction, one can be as the following [5]:

$$\text{minimize } F_{VD} = \sum_{j=1}^{N_{load}} \left| V_j - V_j^{ref} \right| \quad (2)$$

where, V_j is the actual voltage of the system load buses, V_j^{ref} is the best operational voltage point of the load bus j.

C. System Voltage Stability Margin

A fairly simple index to describe and calculate voltage stability margin is the ratio V/V_0. V is the bus voltage rate, of which can be gauged by load flow calculations or state-estimation related studies having system working on its operational condition, and V_0 can be measured resolving load flow equations for the power network at the equal state having all loads fixed at zero. The ratio V/V_0 at each node provides power system operators with an index availing discovery of fragile spots. There is a problem with this indicator, which is that it offers a very nonlinear profile with regard to alterations on the system parameters, not availing for precise forecasts of proximity to failure [6].

$$\text{minimize } VSI = \sum_{i=1}^{N_l} \left| 1 - \frac{V_i}{V_{i0}} \right| \quad (3)$$

where, N_l is number of load buses.

D. System Variable Constraint Conditions

Variable constriction circumstances contain two major groups of the variables as control and state variable restraint settings which should be met during optimization procedure. The first group consists of generators bus voltages, transformers tap settings and reactive power compensators output power, while the second group comprises buses voltage and reactive power output of all generators. Therefore, the variable constrictions can be written as [5]:

$$\begin{cases} V_{gk\min} < V_{gk} < V_{gk\max} \\ T_{i\min} < T_i < T_{i\max} \\ C_{j\min} < C_j < C_{j\max} \end{cases} \quad (4)$$

$$\begin{cases} Q_{gk\min} < Q_{gk} < Q_{gk\max} \\ V_{l\min} < V_l < V_{l\max} \end{cases} \quad (5)$$

where, V_{gk} is generators bus voltage, T_i is transformers tap setting, C_j is output power of compensators, Q_{gk} is reactive power output of generators and V_l is non-PV buses voltage [5, 8-13].

It should be noted that, the state variables constraints would be satisfied by power flow and control variables constraints would be satisfied by optimization algorithm. Therefore, there is no need to input them into penalty function.

E. System Power Flow Constriction Equations

The optimal reactive power flow must fulfil the system power flow equations, which are written as:

$$P_{Gi} - P_{Li} - V_i \sum_{j=1}^{n} V_j \left(G_{ij} \cos\delta_{ij} + B_{ij} \sin\delta_{ij} \right) = 0 \quad (6)$$

$$Q_{Gi} - Q_{Li} - V_i \sum_{j=1}^{n} V_j \left(G_{ij} \sin\delta_{ij} - B_{ij} \cos\delta_{ij} \right) = 0 \quad (7)$$

where, n is the total number of buses, P_{Gi} and Q_{Gi} refer to the active power and reactive power of the generator in bus i, respectively. P_{Li} and Q_{Li} are correspondent to the load active power and reactive power in bus i. V_i and V_j represent voltages of buses i and j. G_{ij}, B_{ij}, and δ_{ij} indicate the conductance characteristics and phase angle between the voltages of bus i and j, respectively [5, 8-13].

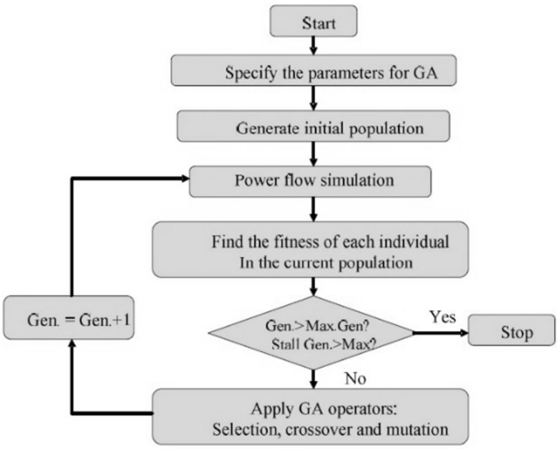

Figure 1. Flow chart of reactive power optimization using GA algorithm [2]

F. General Objective Function

To gather all objective functions into just one, which makes it easy to use when it comes to using intelligent algorithms in reactive power optimization, the penalty function approach can be used. The importance and penetrating of each objective function can be controlled using penalty factors as well.

$$F_{loss} = \underbrace{\sum_{k=1}^{N_{Bus}} G_k \left[V_{1,k}^2 + V_{2,k}^2 - 2V_{1,k}V_{2,k} \cos\left(\theta_{1,k} - \theta_{2,k}\right) \right]}_{P_{loss}} + \quad (8)$$
$$+ k_v \underbrace{\left[\sum_{j=1}^{N_{load}} \left| V_j - V_j^{ref} \right| \right]}_{\text{Voltage Deviation}} + k_s \underbrace{\sum_{i=1}^{N_l} \left| 1 - \frac{V_i}{V_{i0}} \right|}_{\text{Voltage Stability}}$$

where, k_v and k_s are penalty factors.

System power flow constraints would be satisfied by power flow process and there is no need to input them in the general objective function. In addition, control variables constraint would be satisfied by algorithm itself and no need to include them to objective function.

IV. REACTIVE POWER OPTIMIZATION USING INTELLIGENT ALGORITHMS

In this paper, four different algorithms will be implemented on reactive power optimization in order to figure out which one has the best performance and best optimization result in given time.

A. Genetic Algorithm

The global exploration algorithm known as Genetic Algorithm (GA) is an optimization method which is inspired by the notion of natural evolution happening for million years. GA consists of members which has made up a population that signify candidate answers of the given optimization problem. Each member makes their contribution of providing some useful information about the area they have explored through helping the whole algorithm to get the most optimum solution. In Each generation numbers which are the most suitable candidates are chosen and the operators of GA algorithm are applied on them so that the next generation is created. There are two main operators, of which genetic algorithm does optimization procedure applying them to individual chromosomes as crossover and mutation.

Generally, crossover is considered to combine genetic information together from selected chromosomes. Mutation is used in order to facilitate the GA algorithm being able to explore more random locations in each generation to make sure that enough of the solution space has been examined. Figure 1 illustrates how genetic algorithm has been scheduled to optimize reactive power in power system [7].

B. Particle Swarm Optimization Algorithm

Kennedy and Eberhart established a particle swarm optimization algorithm founded on the manners of members (i.e., particles or agents) of a swarm. It is inspired from the strategy of individuals' movements of the group they are living in. Sharing information between the members of the group has been discovered to be the main approach which leads the whole swarm to the goal it is off to. The particle swarm optimization algorithm uses parallel computational approach by means of a group of alike mates and iterative improvement through getting the best solution possible.

Each member indicates a candidate answer to the problem in each iteration, while the determining factors which lead each individual to a better position in the next iteration is current speed, earlier experience, and the knowledge of its neighbors. The velocity vectors characterize location and pace of single participant *i* in an *n*-dimensional problem space. Figure 2 illustrates the procedure of the basic particle swarm optimization algorithm.

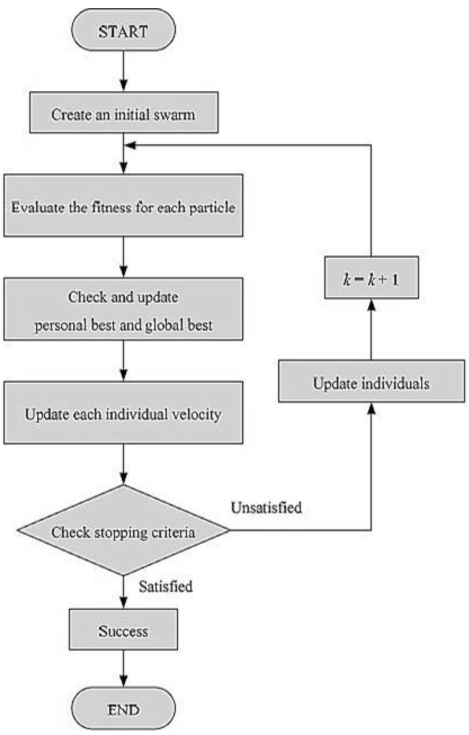

Figure 2. Flow chart of reactive power optimization using PSO algorithm [2]

C. Hybrid Genetic Algorithm / Particle Swarm Optimization and Pattern Search Algorithm

Direct search approaches are local techniques in the sense that they are intended to attain convergence (from random initial points) to positions that fulfil essential circumstances for local optimality. Some arithmetical experiences have revealed cases in which pattern search has managed to find global optimum solutions for some specific classes of problems. Certain factors selections can allow pattern search to get out of one basin of magnetism of a local minimum into another (that is with any luck a better one). This paper is making an effort to attain this inclination using a global heuristic in the exploration step.

In addition, the election step can thoroughly assure convergence to stationary solution. The hybrid technique presented in this paper is a pattern search method that joins a genetic algorithm or particle swarm optimization search in the global exploration step. The idea is to start through a preliminary population and to put particle swarm or genetic algorithm into practice to optimize reactive power. The intelligent algorithms usually can reach the neighborhood of global optimum in appropriate time. Besides, the pattern search algorithm has very good performance to finding local minimum very fast.

However, the pattern search outcome strongly depend on start position. Therefore, it seem to could to pinpoint optimal point using hybrid intelligent and a direct search method and the combination of a global optimizer and a local one can be very sane choice. The start point of pattern search would be specified with an intelligent algorithm and pattern search would continue the optimization process.

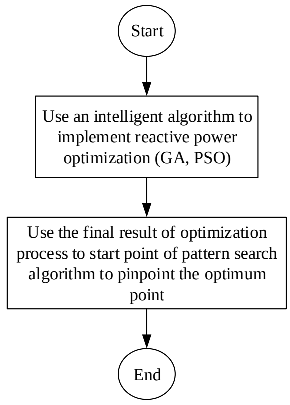

Figure 3. Proposed algorithm to reactive power optimization

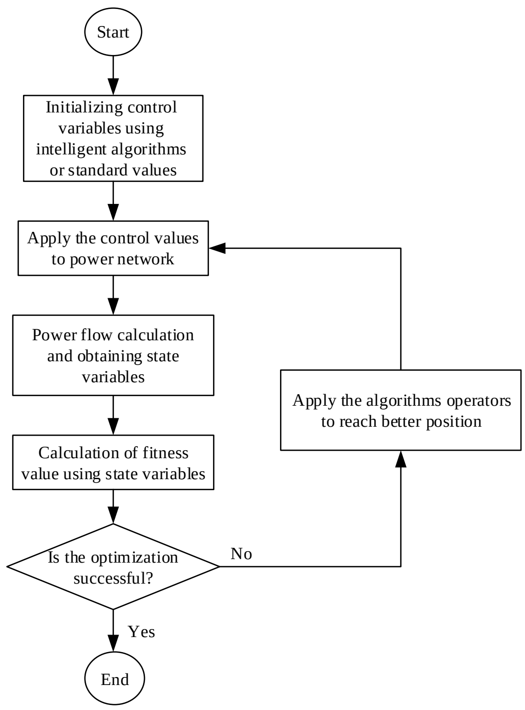

Figure 4. General trend of reactive power optimization

V. SIMULATION RESULTS

This paper uses an effective connection between MATLAB and DIgSILENT software to implement reactive power optimization. The general trend of reactive power optimization is shown in Figure 4. In addition, the procedure of reactive power optimization problem using MATLAB and DIgSILENT software is shown in Figure 5. This paper investigates four optimization algorithm on reactive power optimization problem as GA, PSO, GA+PS, PSO+PS. All algorithms are tested on two IEEE test system, which could be found on the following.

A. Case Study 1, IEEE 6-Bus Standard System

In this section, four proposed algorithms are implemented on IEEE 6-bus standard system and results are shown on Figures 6 to 9 and Table 1.

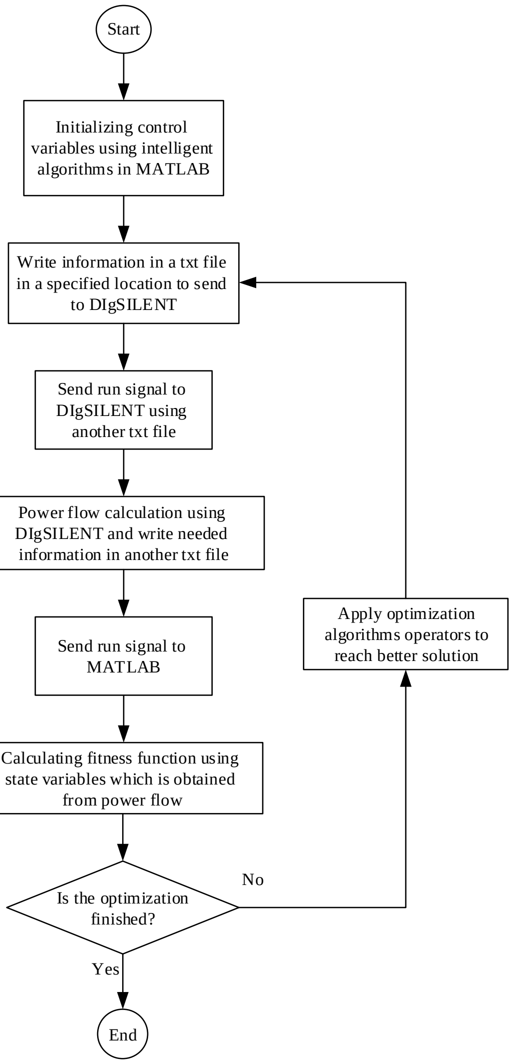

Figure 5. The procedure of reactive power optimization problem using MATLAB and DIgSILENT software

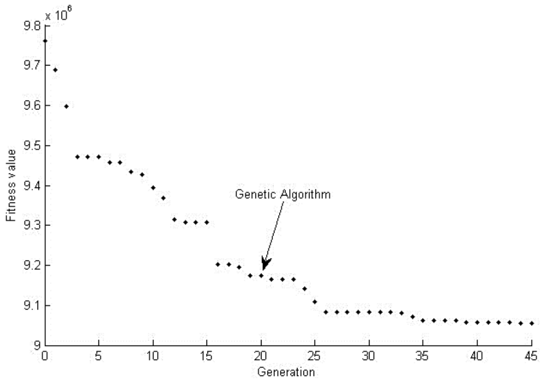

Figure 6. Optimization trend using GA for IEEE 6-bus system

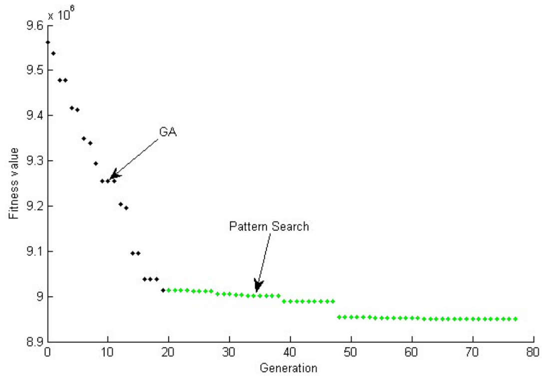

Figure 7. Optimization trend using GA+PS for IEEE 6-bus system

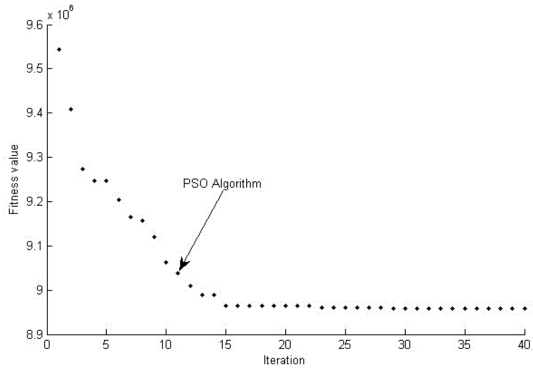

Figure 8. Optimization trend using PSO for IEEE 6-bus system

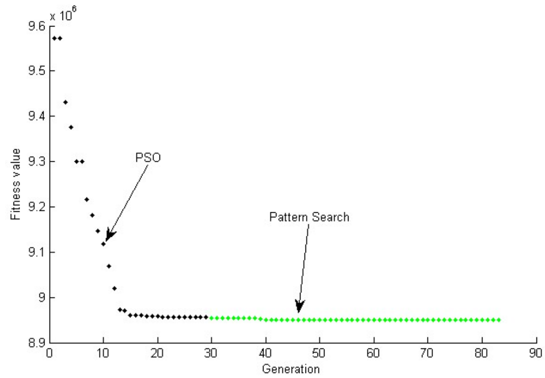

Figure 9. Optimization trend using PSO+PS for IEEE 6-bus system

Table 1. Reactive power optimization results using proposed algorithms for IEEE 6-bus system

	IEEE	GA	GA+PS	PSO	PSO+PS
Active Power Loss (W)	10778370	9055178	8950550	8958107	**8950232**
Reduction percent (%)	-	15.98754	16.95826	16.88814	**16.96121**
Voltage stability index	2.665148	2.712660	2.712409	**2.715128**	2.715127
Voltage deviation (kV)	15.65904	2.006784	2.127879	1.185444	**1.185288**

Table 2. Control variable values after optimization using PSO+PS for IEEE 6-bus system

	V_{G2} p.u.	V_{G6} p.u.	T_{35}	T_{14}	Q_3 MVar	Q_4 MVar
IEEE	1.1	1.05	9725	9100	0	0
After optimization	1.15	1.1	11100	11100	5	5

Considering Table 1, the active power losses reduced from 10778370 W to 8959232 W (16.96%) using PSO+PS algorithm, which is the best solution among other approaches. In addition, Voltage stability index raised from 2.665148 to 2.715127, which is very good improvement in voltage stability respect. The voltage deviation also reduced from 15.65904 kV to 1.185288 kV that can be considered as a great promotion for network utilization. Therefore reactive power optimization has very good effects on power network as cost-effective and reliability aspects. The control variables after optimization also presented in Table 2.

B. Case Study 2, IEEE 14-Bus Standard System

In this section, four proposed algorithms are implemented on IEEE 14-bus standard system and results are shown on Figures 10 to 11 and Table 2.

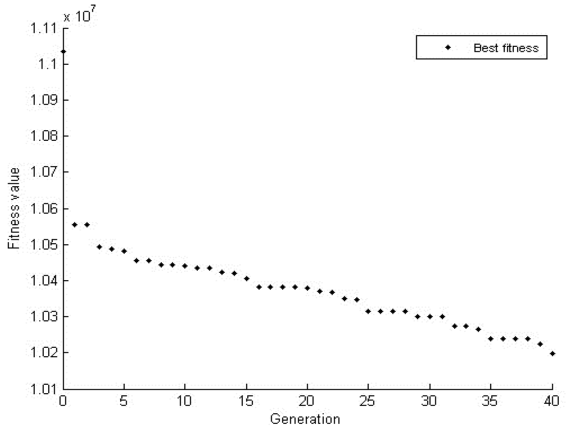

Figure 10. Optimization trend using GA for IEEE 14-bus system

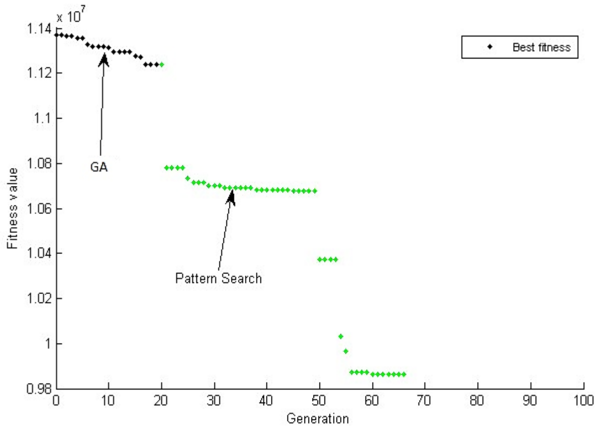

Figure 11. Optimization trend using GA+PS for IEEE 14-bus system

Table 3. Control variable values after optimization using PSO+PS for IEEE 14-bus system

	V_{G1} p.u.	V_{G2} p.u.	T_{47}	T_{49}	T_{56}	Q_3 MVar	Q_6 MVar	Q_8 MVar
IEEE	1	1	9780	9690	9320	0	0	0
After optimization	1.139790	1.100000	10264	10146	10664	7.436791	2.399997	3.129134

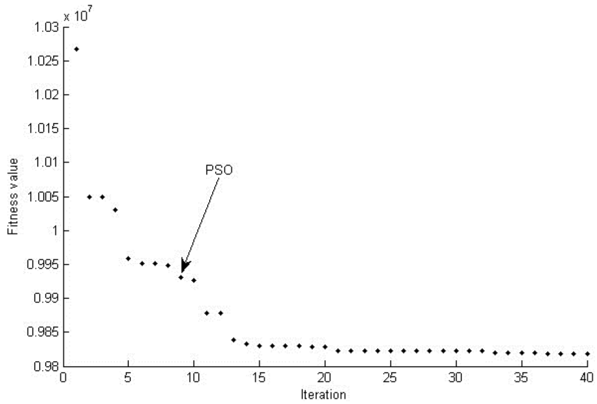

Figure 12. Optimization trend using PSO for IEEE 14-bus system

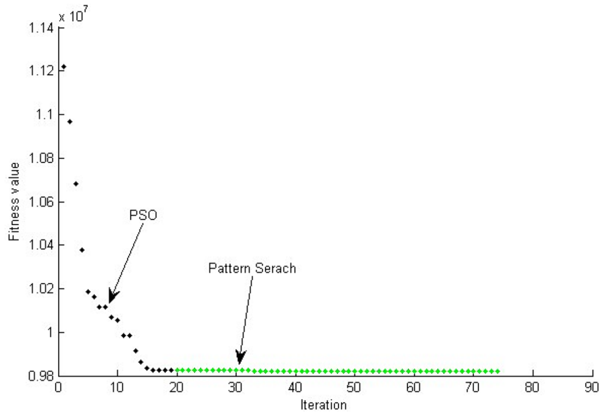

Figure 13. Optimization trend using PSO+PS for IEEE 14-bus system

Table 4. Reactive power optimization results using proposed algorithms for IEEE 14-bus system

	IEEE	GA	GA+PS	PSO	PSO+PS
Active Power Loss (W)	16710700	10199360	9862619	9835300	**9823200**
Reduction percent (%)	-	38.96510	40.98023	41.14370	**41.21612**
Voltage stabilty index	8.953467	9.619730	9.655891	9.687009	**9.708002**
Voltage deviation (kV)	219.7092	**56.17259**	57.82206	58.63506	**56.17259**

Considering Table 4, the active power losses reduced from 16710700 W to 9823200 W (41.22%) using PSO+PS algorithm, which is the best solution among other approaches. In addition, Voltage stability index raised from 8.953467 to 9.708002, which is very good improvement in voltage stability respect. The voltage deviation also reduced from 219.7092 kV to 56.17259 kV that can be considered as a great promotion for network utilization. Therefore reactive power optimization has very good effects on power network as cost-effective and reliability aspects. The control variables after optimization also presented in Table 3.

VI. CONCLUSIONS

In this paper, a GA, PSO, GA+PS, PSO+PS solutions to the optimal reactive power flow (ORPF) problem has been presented for purpose of the global or near-global optimal answers. The offered algorithms have been examined on the IEEE 6-bus and IEEE 14-bus power networks to minimize the active power losses.

The best adjustment of control variables is achieved in both continuous and discrete values. The results were compared with each other and it has been recognized that a hybrid algorithm consist of one global optimizer and the other a direct search algorithm can reach a better position considering the same period of time.

In this paper, the hybrid algorithm containing PSO algorithm and Pattern search algorithm is the best optimization algorithm among the algorithms, which are used for reactive power optimization problem. In addition, the reactive power optimization has great impact on other utilization as voltage stability index and voltage deviation, although the main purpose of that is the active power loss reduction.

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BIOGRAPHIES

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Narges Sadat Boushehri was born in Iran. She received her B.Sc. degree in Control Engineering from Sharif University of Technology (Tehran, Iran), and Electronic Engineering from Central Tehran Branch, Islamic Azad University, (Tehran, Iran), in 1991 and 1996, respectively. She received the M.Sc. degree in Electronic Engineering from International Ecocenergy Academy, in 2009. She is the member of Scientific and Executive Committees of International Conference of ICTPE and also the Scientific and Executive Secretary of International Journal of IJTPE supported by International Organization of IOTPE (www.iotpe.com). Her research interests are in the area of power system control and artificial intelligent algorithms.