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Optimal power flow with SVC devices by using the artificial bee colony algorithm

Kadir ABACI, Volkan YAMAÇLI, Ali AKDAĞLI[*]
Electrical and Electronics Engineering Department, Mersin University, Mersin, Turkey

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Abstract: In this paper a simple and efficient heuristic search method based on the artificial bee colony (ABC) algorithm is presented and used for the optimal power flow (OPF) problem in power systems with static VAR compensator (SVC) devices. The total generation cost of a power system with SVC devices (which improve the voltage stability at load buses) is optimally minimized with the use of ABC. The ABC, which is based on the foraging behavior of honey bees searching for the best food source, is a recently proposed optimization algorithm. The performance of the presented ABC algorithm was tested and verified on the IEEE 11-bus and IEEE 30-bus power systems by comparing it with several other optimization methods. Furthermore, ABC is used not only for optimizing the total generation cost and active power loss, but also for improving the voltage stability of the 22-bus power system in Turkey. Our results illustrate that ABC can successfully be used to solve nonlinear problems related to power systems.

Key words: Optimal power flow, SVC, voltage stability, optimization, artificial bee colony

1. Introduction

Since electricity plays a vital role in the economy and industrial activity of a country, electric power systems have extensively expanded in the past decades. Electricity is generated in stations, transmitted by high voltage transmission networks, and delivered to consumers. With the ever-growing energy demand, power systems become more complex and difficult to control because the systems are being operated under highly stressed conditions such as unscheduled power flows and higher losses. It has been a challenging task to operate a power system efficiently because the modern electrical system needs to be able to compensate for the continually changing load demand and provide high quality energy. In addition, the power system should overcome the voltage instability problem so that it would be able to insure desired voltage values at all load buses in the system. Generally, voltage collapse and instability occur once the power system is not able to cope with the increasing reactive power demand [1]. Therefore, increasing the voltage stability margin is of crucial importance for a power system. In order to overcome the problems mentioned above and to operate the power system equipment effectively, the flexible AC transmission system (FACTS) was presented by Hingorani [2] in 1988. The voltage magnitude and phase angle at selected buses of the transmission system can be controlled with the use of FACTS devices [3]. Thanks to FACTS devices, power can flow through the chosen routes with a considerable increase in transmission line capability and the security of the power system is enhanced. The static VAR compensator (SVC) is a well-known FACTS device that improves voltage stability; it maintains a desired voltage value by generating or absorbing reactive power at the bus in which it is installed.

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[*] Correspondence: akdagli@mersin.edu.tr

Optimal power flow (OPF) (which optimizes a certain objective function while satisfying the physical, operational, and security constraints) is a very important issue in the management and control of power systems. In general, OPF can be defined as a nonlinear, multidimensional, and large-scale numerical problem depending on line and bus data; it becomes even more complicated with the inclusion of variable constraints and FACTS device parameters. Many analytical techniques and classical optimization methods such as the quadratic programming method [4], the generalized reduced gradient method [5], the Newton–Raphson method [6], the linear programming method [7], the P–Q decomposition method [8], and the interior point method [9] have been used to handle the convergence to the optimal solution. The classical optimization methods require an initial point that is acceptably close to the solution in order not to be stuck in local minima. When the number of parameters of the problem increases, the quality of solutions highly depends on the initial starting values. Due to the disadvantages of these classical methods and with the development of computer technologies, the interest in using heuristic optimization methods for solving power system problems has rapidly grown during the past decades. The heuristic optimization algorithms use random transition rules rather than deterministic ones, do not employ derivative information, have the ability to not get stuck in a local minimum, and cope with large-scale nonlinear problems. The most popular heuristics such as differential evolution [10], particle swarm optimization [11], and genetic algorithm [12] have recently been applied to minimize the total generation cost and to keep the load bus voltages within the constraints by optimally determining the locations and parameter values of SVC devices. Both classical optimization methods and heuristic optimization algorithms have been used with their respective benefits and limitations in power systems.

In the current work a recently presented heuristic optimization method, the artificial bee colony (ABC) algorithm (inspired by the foraging behavior of honey bee swarms), is proposed for resolving the OPF problem. In addition, the power system is considered to be integrated with the SVC susceptance model and solved by ABC based OPF. The total generation cost is chosen to be minimized within the given maximum power constraints, generation limits of active power values, and limits of bus voltages; the parameter values of FACTS are determined for the OPF problem by using ABC for IEEE 11-bus and IEEE 30-bus systems. ABC has also been applied to the 22-bus power system in Turkey by allocating SVC devices to critical buses (determined by using the sensitivity analysis) so as to optimize the total generation cost, voltage profile, and active power losses. The performance of this method is evaluated by comparing it with several other optimization methods such as differential evolution, the reduced Hessian method, and the second order gradient method.

This paper is organized as follows: Section 2 indicates the problem formulation of OPF and explains the power system modeling. The ABC algorithm and its implementation to OPF are addressed in Section 3. Section 4 shows the results achieved, and conclusions are given in Section 5.

2. Problem formulation of OPF with a SVC controller

2.1. SVC model

The SVC susceptance model, considered as reactive power injection at the load buses [13] implemented for the OPF used in this work, is shown in Figure 1. It is a shunt connected SVC; the output is designed to switch the capacitive or inductive current in terms of maintaining the stability of the electrical power system by controlling parameters such as load bus voltages.

The reactive power absorbed by the SVC (Q_{svc}) for the bus $k(Q_k)$ can be written as:

$$Q_{SVC} = Q_k = -V_k^2 B_{SVC}, \tag{1}$$

where V_k and B_{SVC} are the voltage of bus k and the equivalent susceptance value of the SVC device, respectively.

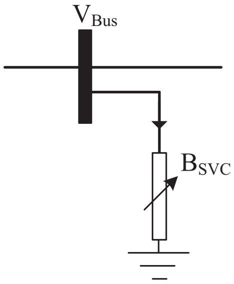

Figure 1. Susceptance model of SVC.

2.2. Optimal power flow

In the OPF problem considered in this study the main objective is optimizing the total generation cost by determining the dispatched power values of generation units and the parameters of the SVC devices. Basically, the OPF problem is stated as:

Optimize: $f(x, u)$

With subject of: $g(x, u) = 0 and h(x, u) \leq 0$

In accordance with:

$$\begin{array}{l} x = [P_{Gslack} V_L Q_G] \\ u = [P_G V_G Q_{SVC}] \end{array},$$

where $x$indicates the state variables, including the real power value of the slack bus P_{Gslack}, the voltage of the load bus V_L, and the generation of reactive power Q_{G0}; u represents the vector of the control variables, including the real power P_G, the generator voltage V_G, and the reactive power of the SVC Q_{SVC}; f represents the objective function; g represents the load flow equations; and h indicates the parameter limits of the system.

For an optimal active power dispatch, the total generation cost $f(x, u)$to be minimized, in US dollars per hour (\$/h), is expressed as:

$$f = \sum_{i=1}^{Ng} a_i + b_i P_{Gi} + c_i P_{Gi}^2 (\$/h), \tag{2}$$

where N_g is the generator number;P_{Gi} is the generation of real power at bus$i$; a_i, b_i, and c_i are the weighting factors of the generating unit i.

The equality constraints and typical load flow equations $g(x, u)$ are given as [14]:

$$P_{Gi} - P_{Di} - \sum_{j=1}^{Nb} |V_i| |V_j| |Y_{ij}| \cos(\theta_{ij} + \delta_i - \delta_j) + P_{injSVCi} = 0 \tag{3a}$$

$$Q_{Gi} - Q_{Di} - \sum_{j=1}^{Nb} |V_i| |V_j| |Y_{ij}| \sin(\theta_{ij} + \delta_i - \delta_j) + Q_{injSVCi} = 0, 3. \tag{3b}$$

where Q_{Gi} is the reactive generation power, P_{Di} and Q_{Di} are the active load and reactive load demand of bus i, respectively; Y_{ij} is the bus admittance value of buses i and j; $P_{injSVCi}$ and $Q_{injSVCi}$ are the active power and reactive power injected to bus i, respectively.

The parameter constraint limits, $h(x,u)$, including the typical load flow constraints are given as:

$$V_{Gi}^{\min} \leq V_{Gi} \leq V_{Gi}^{\max} i = 1, ..., N_g \tag{4a}$$

$$P_{Gi}^{\min} \leq P_{Gi} \leq P_{Gi}^{\max} i = 1, ..., N_g \tag{4b}$$

$$Q_{Gi}^{\min} \leq Q_{Gi} \leq Q_{Gi}^{\max} i = 1, ..., N_g \tag{4c}$$

$$Q_{SVCi}^{\min} \leq Q_{SVCi} \leq Q_{SVCi}^{\max} i = 1, ..., N_{SVC} \tag{4d}$$

where N_{SVC} is the number of the SVC devices.

2.3. Sensitivity analysis

A sensitivity analysis was applied to the power system with the purpose of determining the bus number with highest sensitivity to changes in reactive power in order to establish SVC devices in the best locations. Shunt compensation is effective in improving voltage stability and a $V-Q$ sensitivity analysis is required to specify the location of SVC devices in order to achieve the best efficiency.

The power system Jacobian matrix was used in the sensitivity analysis [15]. The diagonal elements of the matrix represent the steady state stability indices, while the diagonal elements of the inverse reduced Jacobian matrix represent the sensitivities of the bus voltages. The sensitivity analysis was applied only to load buses and a positive sensitivity index indicated a reduced stability margin; a negative sensitivity indicated instability. The voltage value differentiation is described as an equation of the J matrix and the variation of reactive power:

$$\Delta V = J_R^{-1} \Delta Q, \tag{5}$$

where $J_R = \left[J_4 - J_3 . J_1^{-1} . J_2 \right]$ is the reduced Jacobian matrix of the system.

3. Artificial bee colony (ABC) algorithm

In recent years optimization methods based on swarm intelligence have generated much interest in science and engineering for solving optimization problems, which are multidimensional and nonlinear. The artificial bee colony [16–20] is a recently proposed heuristic optimization algorithm used to find the best converged solutions of optimization problems by using the foraging behavior of honey bee swarms. In swarm intelligence labor division and self-organization are two basic and necessary notions.

In the ABC algorithm the labor is divided among three groups: employed, onlookers, and scout bees. The foraging behavior, food sources, and nectar amount represent the problem, the possible solutions, and the solution quality, respectively. ABC starts with the initial food sources generated randomly by the scouts; then employed and onlooker bees exploit the nectar of the located sources until the food sources that are being exploited become exhausted. Following exhaustion the employed bees turn into scout bees in order to look for farther food sources, and the algorithm continues until finding the best quality solution within the limits.

The procedure of the algorithm considered in this work is given below:

Step 1. Define the parameters of the ABC algorithm and the constraints of the parent vector, which includes real power generation values of generating units except slack bus, voltage magnitude values of system buses, and the SVC susceptance values.

Step 2. Randomly generate initial parent vectors by (6):

$$P_{ij} = P_{j\,\min} + rand \times (P_{j\,\max} - P_{j\,\min}) \qquad (6)$$
$$i\text{=index number, } j\text{=dimension number}$$

Step 3. Evaluate the fuel cost values by optimal power flow and fitness values by Eq. (7):

$$fitness_i = \left\{ \begin{array}{l} 1/(1+f_i), 0 \le f_i \\ 1 + abs(f_i), 0 > f_i \end{array} \right\} \qquad (7)$$

Step 4. Generate a new target vector corresponding to Eq. (8). Evaluate the fuel cost values and fitness values for each target vector by optimal power flow. Select and save the best vector with respect to its fitness value.

$$P_{ijnew} = P_{ij} + \phi \times (P_{ij} - P_{kj})(i \ne k, \phi = rand[-1,1]) \qquad (8)$$

Step 5. Evaluate probabilities of the fuel cost values for each food source corresponding to a given rule. Generate a new vector corresponding to equation (9); evaluate fitness and select the best ones for each food source.

$$p_i = \frac{fitness_i}{\sum\limits_{i=1}^{SN} fitness_i} \qquad (9)$$

Step 6. If the target vector cannot be improved after trying up to the trial limit defined by the user, abandon that vector and create a new target vector by Step 2.

Step 7. Save the best solution achieved up to the current iteration and increase the iteration counter by one. Stop the iteration process if stop criteria are met. Otherwise jump to Step 4 and continue the iteration process until stop criteria are met or the iteration counter exceeds the maximum cycle number defined by the user.

The parameters of ABC such as the number of employed bees, the source number, and the maximum iteration limit are selected as 20, 20, and 500, respectively.

4. Test results and discussion

4.1. Case.1 IEEE 11-bus and 30-bus test systems

The IEEE 11-bus power system, comprising 5 generators and 17 transmission lines, is chosen as the test system. The system shown in Figure 2 and the fuel cost weighting coefficients of the generators can be found in the references [21].

The ABC algorithm is applied to that of the IEEE 11-bus test power system. In order to assess the ABC algorithm, differential evolution (DE) (a robust heuristic optimization algorithm introduced by Storn) [22] is also applied to the same problem. The optimization results are given in Table 1. This table also contains the results of the reduced Hessian method (RHM) reported in the literature [21] for comparison. As seen from Table 1, both ABC and DE give better results than RHM; the results of ABC are slightly better than those of DE. The generation cost value of the IEEE 11-bus test system is optimized to 1253.66 ($/h) by using the ABC for the OPF problem.

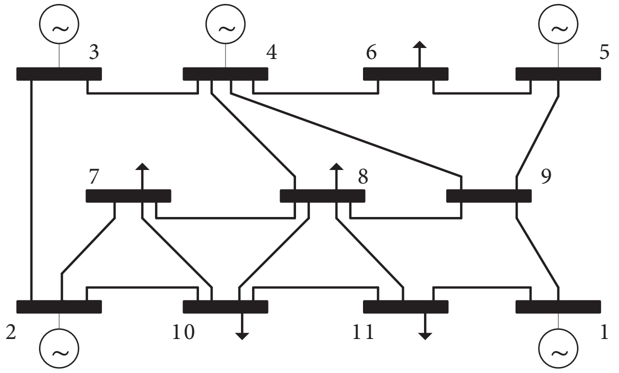

Figure 2. A single line diagram of the IEEE 11-bus test system.

Table 1. Optimization results of the ABC, DE, and RHM for the IEEE 11-bus power system.

	System parameters	ABC	DE	RHM [21]
Active power (MW)	P_1	47.33	47.61	47.40
	P_2	74.68	74.63	74.70
	P_3	48.49	48.51	48.50
	P_4	47.55	47.56	47.60
	P_5	52.17	52.16	52.10
Reactive power (MVAR)	Q_1	26.10	26.10	26.30
	Q_2	43.60	43.80	43.70
	Q_3	0.00	0.04	0.10
	Q_4	14.48	14.49	14.20
	Q_5	13.44	13.44	13.40
Voltage angle (deg.)	δ_2	1.39	1.39	1.39
	δ_2	6.10	6.10	6.11
	δ_3	2.80	2.80	2.81
	δ_4	2.04	2.04	2.04
	δ_5	1.65	1.65	1.65
TGC ($/h)	C_{gen}	1253.66	1254.53	1263.84

The convergence cycles of the ABC and DE based OPF solutions for the IEEE 11-bus system were also investigated. The results given in Figure 3 show that ABC converges in 24 iterations while DE converges in 60 iterations to achieve the best solution.

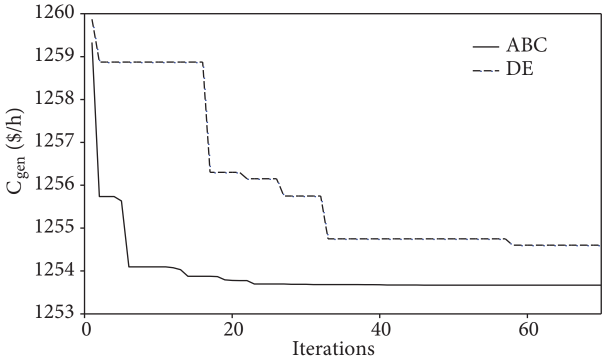

Figure 3. Convergence of ABC and DE methods on the IEEE 11-bus system.

The IEEE 30-bus system [10] was used to show the effectiveness of the ABC algorithm. The system has six generators at buses 1, 2, 5, 8, 11, and 13 and four transformers with off-nominal tap ratio at lines 6–9, 6–10, 4–12, and 28–27. In addition, buses 10, 12, 15, 17, 20, 21, 23, 24, and 29 have been selected as shunt VAR compensation buses. The convergence results are given in Figure 4. Also, the optimization results are given in Table 2 in order to compare with [10].

Table 2. Optimization results of the ABC and DE for the IEEE 30-bus power system.

	System parameter	ABC	DE [10]
Active power (MW)	P_1	176.476	176.259
	P_2	48.907	48.560
	P_5	22.222	21.340
	P_8	21.125	22.055
	P_{11}	12.307	11.778
	P_{13}	12.000	12.021
Bus voltage (pu)	V_1	1.100	1.099
	V_2	1.090	1.089
	V_5	1.096	1.065
	V_8	1.070	1.069
	V_{11}	1.100	1.096
	V_{13}	1.098	1.099
LTC ratio (t)	T_{11} T_{12} T_{15} T_{36}	1.021 0.946 1.011 0.972	1.042 0.917 1.019 0.989
Q_c (MVAR)	Q_{12}	4.978	4.545
	Q_{15}	4.999	4.415
	Q_{15}	4.290	4.173
	Q_{17}	4.730	2.517
	Q_{20}	4.999	2.091
	Q_{21}	4.949	4.199
	Q_{23}	4.418	2.552
	Q_{24}	4.999	4.381
	Q_{29}	2.090	2.750
TGC ($/h)	C_{gen}	799.264	799.289

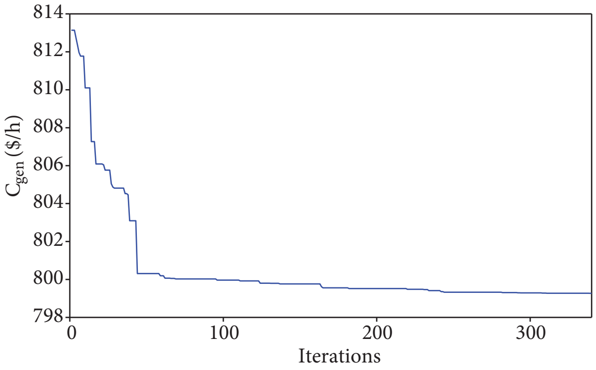

Figure 4. Convergence of ABC optimization on the IEEE 30-bus system.

4.2. Case.2 22-bus power system in Turkey

In order to further inspect the robustness and effectiveness of the ABC algorithm on a real-world problem, it was implemented to the 22-bus power system in Turkey [23]. This system consists of 8 generators, 14 load buses, and 26 transmission lines. The single line diagram of the power system is given in Figure 5. To show the effects of the SVC devices on the system, some scenarios containing one, two, and no SVC devices were considered. A sensitivity analysis was performed so as to determine the best locations of the SVC devices. The sensitivity analysis results are listed in Table 3.

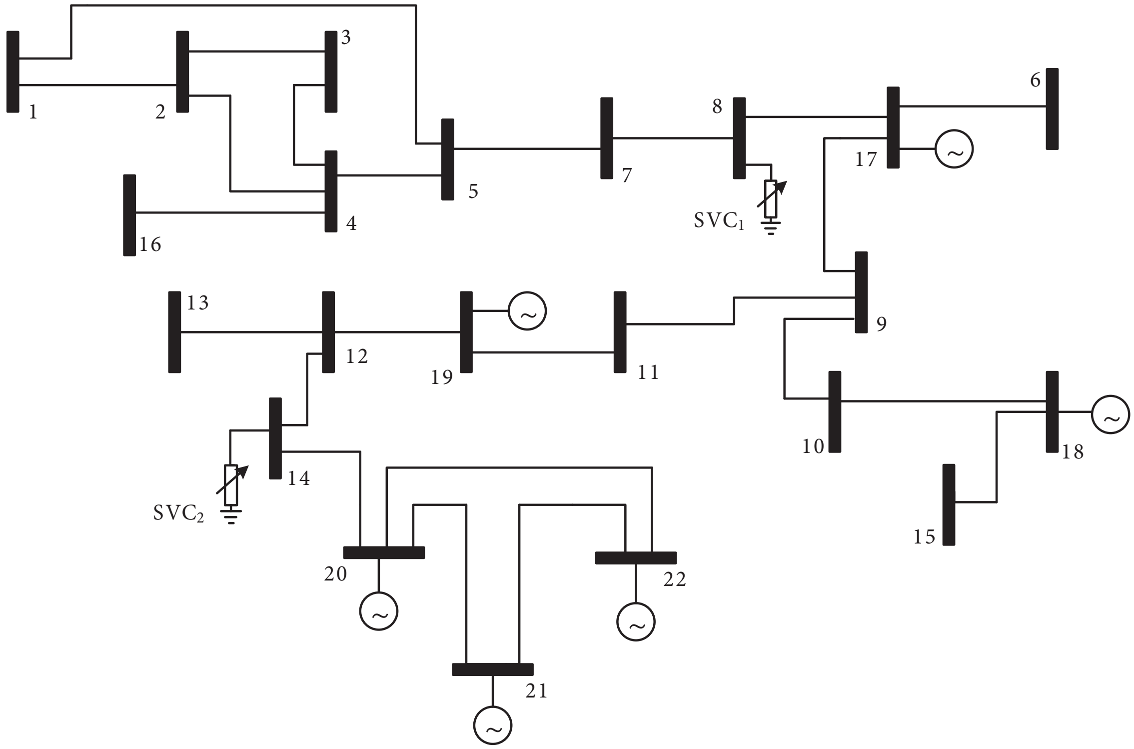

Figure 5. A single line diagram of the 22-bus system in Turkey.

Table 3. Results of the sensitivity analysis of the 22-bus system in Turkey.

Bus number	J_R	$\frac{\partial V_L}{\partial Q_L}$
2	163.272	0.00835
3	258.681	0.00741
4	690.128	0.00365
5	402.443	0.00599
6	30.634	0.03264
7	405.017	0.01115
8	296.774	0.01288
9	372.084	0.00294
10	158.540	0.00662
11	109.112	0.00958
12	6965.484	0.00980
13	6743.341	0.00996
14	105.720	0.01456
15	142.106	0.01120

4.2.1. Sensitivity analysis and determining the locations of SVC devices

Buses 8 and 14 were chosen for the installation of SVC devices because they had the two highest sensitivity values. It should be noted that bus 6, despite having the highest sensitivity value, was not chosen because it demands no reactive load.

The optimization results obtained by using the ABC algorithm for the 22-bus power system in Turkey with two SVC and without SVC devices, and the results of the second order gradient method reported elsewhere [24] are given in Table 4. As seen from Table 4, the ABC based OPF optimization algorithm implemented with SVC devices decreased the total generation cost, improved the voltage stability, and minimized the active power loss on transmission lines, while the system without SVC devices could only decrease the total generation cost and the power loss. It is also shown that the results of the ABC algorithm with or without SVC devices are better than those of the second order gradient method [24].

Table 4. Optimal settings of system parameters for the 22-bus power system in Turkey.

	System parameter	ABC		Second order gradient method [24]
		Without SVC	With SVC at buses 8 and 14	Without SVC
Active power (MW)	P_1	354.091	361.900	456.609
	P_{16}	549.567	517.838	569.120
	P_{17}	659.277	667.321	584.335
	P_{18}	578.028	584.204	573.390
	P_{19}	401.343	398.783	378.541
	P_{20}	377.125	375.324	417.253
	P_{21}	575.712	583.869	564.935
	P_{22}	534.259	539.050	574.162
Reactive power (MVAR)	Q_1	21.670	26.309	–13.577
	Q_{16}	411.393	258.469	238.636
	Q_{17}	187.578	59.008	316.779
	Q_{18}	101.887	139.596	128.164
	Q_{19}	410.385	145.380	47.693
	Q_{20}	206.180	183.395	–2.403
	Q_{21}	–80.651	28.005	5.294
	Q_{22}	346.601	195.202	12.553
Bus voltage (pu)	V_1	1.0150	1.0150	1.031
	V_{16}	1.0230	1.0120	1.029
	V_{17}	1.0365	1.0174	1.030
	V_{18}	1.0258	1.0250	1.033
	V_{19}	1.0320	1.0064	1.039
	V_{20}	1.0202	1.0326	1.022
	V_{21}	1.0206	1.0342	1.030
	V_{22}	1.0237	1.0307	1.015
Power loss (MW)	P_{loss}	30.076	27.962	118.318
TGC ($/h)	C_{gen}	81,421	81,354	83,258

The convergence curves versus the iterations for the four scenarios handled in this work are given in Figure 6. As expected, the optimization by using ABC with two SVC devices was the best, while the optimization without SVC model was the worst in terms of the convergence of the total generation cost (TGC) to the optimal one.

By providing 1.424 pu and 1.542 pu of reactive power, the voltage values of load buses 8 and 14 (installed with SVC by sensitivity analysis) were increased to 1 pu as seen in Figure 7, respectively. Moreover, the increment in the voltage values of the SVC buses improved the voltage profile of the other load buses as well. The results of the ABC optimization with SVC devices are given in Figure 8. Susceptance constraint values of the SVC devices were set between 0 pu and 2 pu, and the voltage magnitudes of the critical buses were fixed to 1 pu by converging to the best susceptance values of the SVC devices.

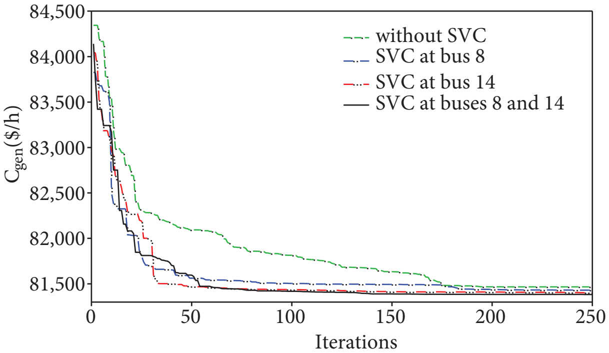

Figure 6. Convergence of ABC for the 22-bus system.

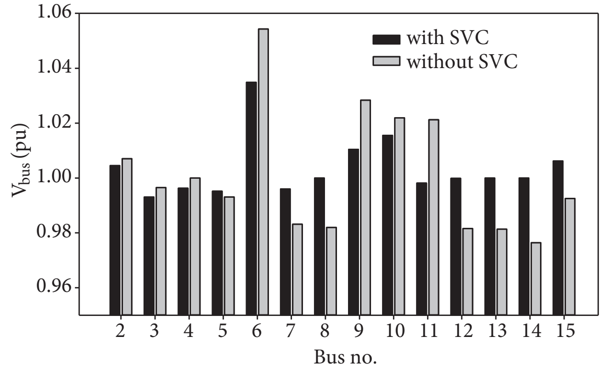

Figure 7. Voltage profile chart of the 22-bus power system.

The continuation power flow algorithm was also applied to the system with the purpose of calculating the maximum loading point (MLP) by using the ABC based OPF algorithm. A voltage stability analysis was applied to the system, beginning with an initial power value and increasing the load values by the element of λ until the OPF continued up to its respective singular point. The flowchart of the continuation power flow is given in Figure 9. The load increment equations for the critical buses are given below:

$$P_L = P_{L0}\lambda \tag{10a}$$

$$Q_L = Q_{L0}\lambda \tag{10b}$$

The active base load and reactive base load of the system are given by P_{L0} and Q_{L0}; the calculated active and reactive load of the bus L are given by P_L and Q_L, respectively. The improvement in MLP can be seen in Table 5 and Figure 10. Critical voltage collapse values of buses are increased by installing SVC and using the proposed ABC optimization method.

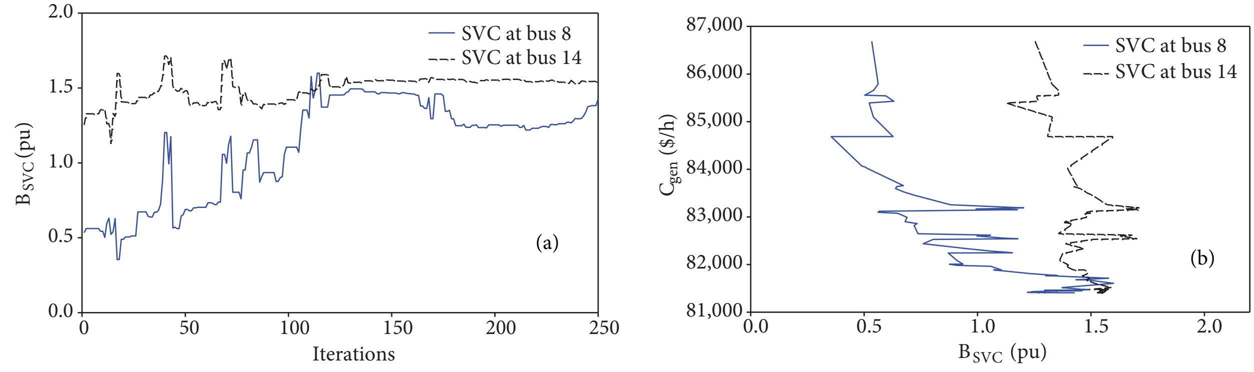

Figure 8. Convergence of SVC susceptance values by using the ABC method. a) Bus 8: and b) Bus 14.

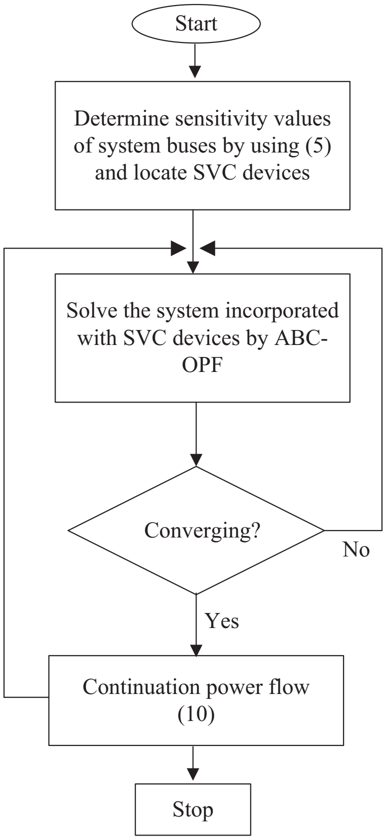

Figure 9. Flowchart of continuation power flow with SVC and ABC-OPF.

Table 5. Maximum loading point values of the SVC buses.

		Without optimization	ABC optimization
		MLP λ (pu)	
Bus 8	Without SVC	7.537	7.579
	With SVC	8.005	8.270
Bus 14	Without SVC	6.309	6.337
	With SVC	6.678	6.884

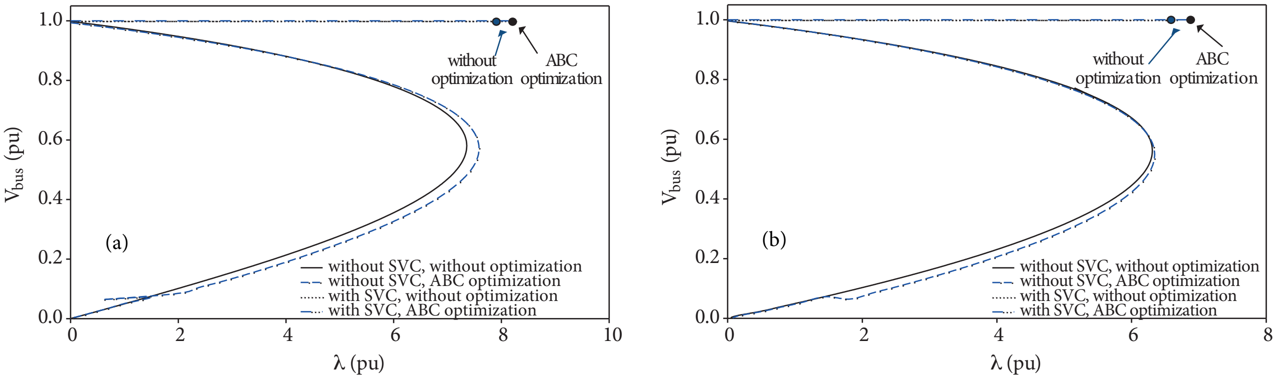

Figure 10. Voltage profile and magnitude improvement at critical buses: Bus 8; and b) Bus 14.

5. Conclusions

The current paper presents a study of the ABC optimization algorithm with the purpose of improving voltage stability and minimizing generator fuel costs in OPF control of a power system including SVC devices. The proposed approach based on ABC was tested on IEEE 11-bus and 30-bus test systems, and was applied to the 22-bus power system in Turkey. Sensitivity and continuation power flow analyses were applied to the 22-bus power system. The best SVC locations were determined by sensitivity analysis. By using the SVC susceptance model, voltage magnitude values of critical buses were fixed to 1 pu. Furthermore, voltage stability was improved in the critical load buses by the ABC-OPF; the voltage stability margin was calculated by the continuation power flow. The performance achieved in the current work was evaluated by comparing it with those of other heuristic and classical optimization methods reported in the literature. In conclusion, ABC can effectively be used to address the difficult nonlinear problems of power systems because of its superiority and fast converging in a short runtime.

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