Chapter 12
Optimal Allocation of Compensators

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Abstract Electric distribution networks mainly deliver the electric power from the high-voltage transmission system to the consumers. In these networks, the R/X ratio is significantly high compared to transmission systems hence power loss is high (about 10–13% of the generated power). Moreover, poor quality of power including the voltage profile and voltage stability issues may arise. The inclusion of shunt capacitors and distributed Flexible ac transmission system (D-FACTS) devices can significantly enhance the performance of distribution networks by providing the required reactive power. D-FACTS include different members such as; distributed static compensator (DSTATCOM), Distribution Static Var Compensator (D-SVC) and unified power quality conditioner (UPQC). Optimal allocation of these controllers in the distribution networks is an important task for researchers for power loss minimizing, voltage profile improvement, voltage stability enhancement, reducing the overall system costs and maximizing the system load ability and reliability. Several analytical and optimization methods have been presented to find the optimal siting and sizing of capacitors and shunt compensators in electric distribution networks. This chapter presents a survey of new optimization techniques which are used to find the optimal sizes and locations of such devices. This chapter also presents an application of new optimization technique called

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Grasshopper Optimization Algorithm (GOA) to determine the optimal locations and sizes of capacitor banks and DSTATCOMs. The obtained results are compared with different algorithms such as; Grey Wolf Optimizer (GWO), Sine Cosine Algorithm (SCA).

Keywords D-FACTS · UPQC · Capacitor · DSTATCOM · Optimization

12.1 Introduction

Reactive power compensation can be used for enhancing system power quality, reducing power loss, improving voltage profile, increasing power factor and network capacity and reliability, reducing power flow in feeder lines, and enhancing the network's loadability and stability, as well as minimizing energy cost.

The most conventional devices that have been applied for reactive power compensation are capacitor banks which include the switched and fixed types, in addition to phase shifters and shunt reactor. D-FACTS devices have been incorporated in the distribution network for reactive power compensation. The main advantages of D-FACTS devices are fast response, fine controllable and continuous adjustment compared to conventional devices. Several types of D-FACTS devices have been presented for enhancing the performance of distribution networks such as DSTATCOM [1], UPQC [2] and Distribution Static Synchronous Series Compensator (DSSSC) [3].

Optimal allocation of such compensation devices is an important issue to maximize the benefits of these devices. Several techniques have been presented for solving the optimal allocation problem of compensation devices in distribution networks such as analytical techniques, numerical programming techniques, heuristic techniques and artificial intelligence techniques [4]. The analytical methods are based on calculus analytical approaches to determine the maximum of a certain objective function, and the shortage of these methods is the obtained capacitor sizes aren't matched with the standard sizes hence the solution is rounded up to standard capacitor sizes which may lead to overvoltage or less loss saving [5–7]. The numerical programming techniques are iterative optimization approach that can be applied to determine the optimal size and locations of compensation devices [8–11]. It should point out that the obtained results using these methods are more accurate compared to the analytical methods, but these techniques could be trapped in local optimal solution. Heuristic techniques are applied for minimizing the search space of optimization techniques where heuristic techniques are based on determining the most candidate nodes for reactive power compensation using sensitivity analysis [12]. Recently, artificial intelligence (AI) techniques are widely used for solving the allocation problem of compensation devices in distribution networks. Most of AI techniques are inspired from the natural phenomena behaviors. The AI methods can be applied to the nonlinear and complex problems.

This chapter introduces an application of Grasshopper Optimization Algorithm (GOA) for solving problem allocation of compensators in distribution network where GOA is employed to determine the optimal placement of shunt capacitor banks for minimizing the total cost (energy loss cost along with capacitor cost) moreover GOA is applied for assigning the optimal location and size of DSTATCOM for minimizing the total loss, improving the voltage profile and enhancing the voltage stability simultaneously.

12.2 Operation Principles of Distributed Compensators

The fixed and switched capacitor types are the most common devices that have been incorporated for reactive power compensation. Different FACTS devices are implemented for changing the parameters of network such as; transmission line impedance, the bus voltage, the active and reactive power through networks for enhancing the performance of electric systems [13, 14]. FACTS devices can be classified as: (a) series members such as Thyristor Controlled Series Capacitor (TCSC) and Static Synchronous Series Compensator (SSSC) (b) Shunt connected devices include Static VAR Compensator (SVC), Static Synchronous Compensator (STATCOM) and (c) Combined shunt-series controllers like Interline Power Flow Controller (IPFC) and Generalized Unified Power Flow Controller (GUPFC) [15–18].

12.2.1 Shunt Capacitor

The power flow equations of distribution system can be obtained from Fig. 12.1 as

$$P_{n+1} = P_n - P_{L,n+1} - R_n\left(\frac{P_n^2 + jQ_n^2}{|V_n|^2}\right) \tag{12.1}$$

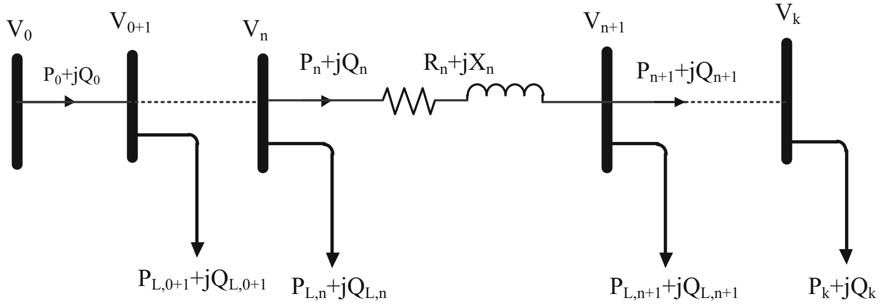

Fig. 12.1 Single line diagram of a radial distribution network

$$Q_{n+1} = Q_n - Q_{Ln+1} - X_n \left(\frac{P_n^2 + jQ_n^2}{|V_n|^2} \right) \quad (12.2)$$

$$V_{n+1}^2 = V_n^2 - 2(R_n P_n + X_n Q_n) + \left(R_n^2 + X_n^2\right) \left(\frac{P_n^2 + jQ_n^2}{|V_n|^2} \right) \quad (12.3)$$

where

P_n, Q_n Real and reactive power flows into the receiving end of branch *n + 1* connecting bus *n* and node *n + 1*.
R_n, X_n Resistance and reactance of the line section between buses *n* and *n* + 1.
V_n The bus voltage magnitude at bus *n*

The active and reactive power loss of the *n*th line between buses *n* and *n + 1* are given as

$$P_{loss(n,n+1)} = R_n \left(\frac{P_n^2 + jQ_n^2}{|V_n|^2} \right) \quad (12.4)$$

$$Q_{loss(n,n+1)} = X_n \left(\frac{P_n^2 + jQ_n^2}{|V_n|^2} \right) \quad (12.5)$$

The system security level can be realized using the voltage stability index [19] as

$$VSI_{(n+1)} = |V_n|^4 - 4(P_{n+1} X_n - Q_{n+1} R_n)^2 - 4(P_{n+1} X_n + Q_{n+1} R_n)|V_n|^2 \quad (12.6)$$

where $VSI_{(n+1)}$ is the voltage stability index at bus *n + 1*. Enhancing the voltage profile depends upon minimizing the voltage deviations as

$$VD = \sum_{n=1}^{k} \left(V_n - V_{ref}\right)^2 \quad (12.7)$$

where k is a number of buses and V_{ref} is the reference voltage that commonly equals to 1 pu.

The capacitor banks are included in distribution systems for enhancing the power quality and minimizing the total cost by injecting reactive power into the systems. Figure 12.2 illustrates a shunt capacitor that is incorporated at bus *n + 1* and the reactive power through the transmission line is given as

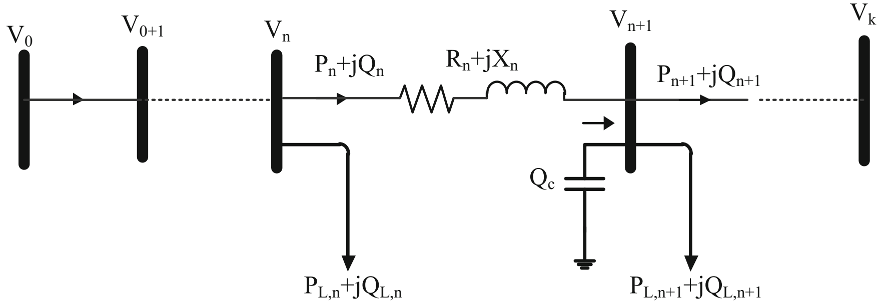

Fig. 12.2 Radial distribution system with a shunt capacitor

$$Q_{n+1} = Q_n - Q_{Ln+1} - X_n\left(\frac{P_n^2 + jQ_n^2}{|V_n|^2}\right) + Q_{C,n+1} \tag{12.8}$$

12.2.2 Distributed Static Compensator (DSTATCOM)

New members of FACTS controllers have been emerged due to progress of power electronic devices. DSTATCOM is a developed controller based on voltage source converter (VSC). DSTATCOM can inject or absorb both active and reactive power at a point of coupling connection (PCC) by injecting a variable magnitude and phase angle voltage at PCC. DSTATCOM is incorporated in electric systems for enhancing the power quality, improving the power factor, balancing the loading, mitigating the harmonic, reactive power compensation, reducing the power fluctuations of photovoltaic units minimizing the voltage sag, mitigating the flicker in the electric system and minimizing the power loss [20–23].

DSTATCOM consists of voltage source converter, dc bus capacitor, ripple filter and coupling transformer as shown in Fig. 12.3. VSC is constructed by using insulated gate bipolar transistors (IGBT) and MOSFET where the switching of component is based on pulse-width modulation (PWM) sequences. The coupling transformer is utilized for matching the inverter voltage with the bus voltage. The DSTATCOM topologies are categorized based on three-phase three-wire (3P3 W) and three-phase four-wire (3P4 W) as illustrated in [24].

DSTATCOM has an ability to exchange active and reactive current with the network. A steady state modeling DSTATCOM has been presented in [25].

Figure 12.4 shows DSTATCOM controller which included in the radial distribution system at bus $n + 1$ where DSTATCOM inject or absorb I_D at this bus. By applying KVL, the voltage at bus $n + 1$ can be obtained as

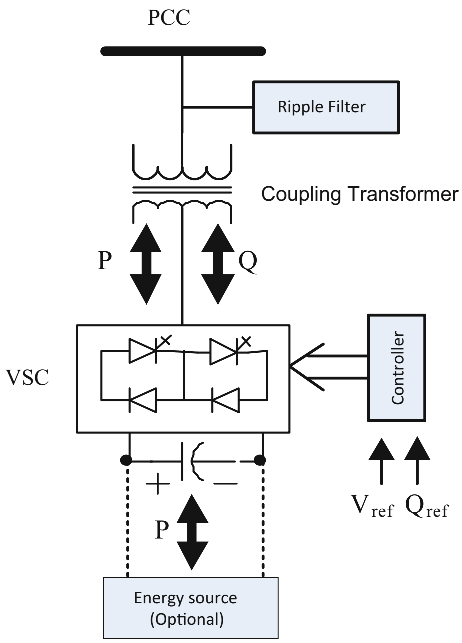

Fig. 12.3 Schematic diagram of DSTATCOM device

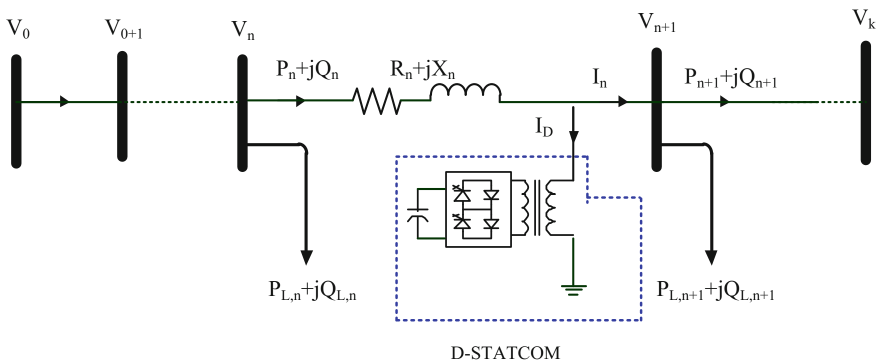

Fig. 12.4 Radial distribution system with DSTATCOM

$$V_{n+1}\angle\theta_{n+1} = V_n\angle\theta_n - (R_n + jX_n)\left(I_n\angle\delta + I_D\angle\left(\theta_{n+1} + \frac{\pi}{2}\right)\right) \tag{12.9}$$

where

$V_{n+1}\angle\theta_{n+1}$	Voltage of bus *n + 1* after inclusion DSTATCOM.
I_D	The injected current by DSTATCOM.
I_n	The line current after inclusion of DSTATCOM

Equation (12.9) represents the essential idea for modeling DSTATCOM which can be solved by separating it to real and imaginary terms as

$$\begin{aligned} V_{n+1}\mathrm{Cos}(\theta_{n+1}) = {} & Re(V_n\angle\theta_n) - Re(I_n\angle\delta(R_n + jX_n)) + X_n I_D \mathrm{Sin}\left(\theta_{n+1} + \frac{\pi}{2}\right) \\ & - R_n I_D \mathrm{Cos}\left(\theta_{n+1} + \frac{\pi}{2}\right) \end{aligned} \tag{12.10}$$

$$\begin{aligned} V_{n+1}\mathrm{Sin}(\theta_{n+1}) = {} & Im(V_n\angle\theta_n) - Im(I_n\angle\delta(R_n + jX_n)) - X_n I_D \mathrm{Cos}\left(\theta_{n+1} + \frac{\pi}{2}\right) \\ & - R_n I_D Sin\left(\theta_{n+1} + \frac{\pi}{2}\right) \end{aligned} \tag{12.11}$$

Equations (12.10) and (12.11) can be simplified as

$$a\mathrm{Cos}x_2 = k_1 - b_1 x_1 \mathrm{Sin}x_2 - b_2 x_1 \mathrm{Cos}x_2 \tag{12.12}$$

$$a\mathrm{Sin}x_2 = k_2 - b_2 x_1 \mathrm{Sin}x_2 + b_1 x_1 \mathrm{Cos}x_2 \tag{12.13}$$

where

$$k_1 = Re(V_n\angle\theta_n) - Re(I_n\angle\delta(R_n + jX_n))$$

$$k_2 = Im(V_n\angle\theta_n) - Im(I_n\angle\delta(R_n + jX_n))$$

$$a = V_{n+1}$$

$$b_1 = -R_n$$

$$b_2 = -X_n$$

$$x_1 = I_D$$

$$x_2 = \theta_{n+1}$$

Equations (12.12) and (12.13) can be rewritten as

$$x_1 = \frac{a\text{Cos}x_2 - k_1}{-b_1\text{Sin}x_2 - b_2\text{Cos}x_2} \tag{12.14}$$

$$x_1 = \frac{a\text{Sin}x_2 - k_2}{-b_2\text{Sin}x_2 + b_1\text{Cos}x_2} \tag{12.15}$$

Solving (12.14) and (12.15) yields

$$(k_1b_2 - k_2b_1)\text{Sin}x_2 + (-k_1b_1 - k_2b_2)\text{Cos}x_2 + ab_1 = 0 \tag{12.16}$$

The previous equation can be simplified as

$$\left(d_1^2 + d_2^2\right)x^2 + (2d_1ab_1)x + \left(a^2b_1^2 - d_2^2\right) = 0 \tag{12.17}$$

where

$$x = Sin(x_2)$$

$$d_1 = (k_1b_2 - k_2b_1)$$

$$d_2 = (-k_1b_1 - k_2b_2)$$

Hence, (12.17) can be solved as

$$x = \frac{-B \pm \sqrt{B^2 - 4AC}}{2A} \tag{12.18}$$

where

$$A = \left(d_1^2 + d_2^2\right)$$

$$B = (2d_1ab_1)$$

$$C = \left(a^2b_1^2 - d_2^2\right)$$

Hence

$$\theta_{n+1} = \text{Sin}^{-1}(x) \tag{12.19}$$

The value of I_D can be obtained from (12.14) or (12.15). The voltage at PCC, the DSTATCOM current and injected reactive power by DSTATCOM can be found as

$$\overrightarrow{V_{n+1}} = V_{n+1}\angle\theta_{n+1} \tag{12.20}$$

$$\overrightarrow{I_D} = I_D\angle\left(\theta_{n+1} + \frac{\pi}{2}\right) \tag{12.21}$$

$$Q_D = Im\left(V_{n+1}\angle\theta_{n+1}\left(I_D\angle\left(\theta_{n+1} + \frac{\pi}{2}\right)\right)^*\right) \tag{12.22}$$

12.2.3 Unified Power Quality Conditioner (UPQC)

UPQC is a powerful controller that has applied for enhancing the power quality of the electric system where it has the ability to minimize the voltage sags, balance the system, mitigate the existed harmonics and minimizing the power loss, etc.

UPQC consists of two inverters on of these inverters is connected in series with a certain transmission line while the other converter is connected in shunt to the common bus. These inverters are combined thought dc linked bus. The inverters are connected to the network by coupling transformers as shown in as shown in Fig. 12.5 [26–28]. The main purpose of the series inverter is injecting an ac series voltage to system to mitigate the supply voltage flickers or imbalance from the load and forces the shunt branch to absorb harmonics generated by the nonlinear loads. The shunt converter is employed for delivering the reactive power compensation for improving the power factor correction in addition the shunt converter is used to mitigate of current distortions and adjusting the dc bus voltage. In other words, the series converter regulates the load voltage to be balanced and sinusoidal while the shunt converter ensures the balancing of system current and become sinusoidal (harmonic free). Several types of UPQC have produced which can be classified based on the converter topology or the supply system or UPQC configuration [28].

Figure 12.5 shows the UPQC controller which included in the radial distribution system where the series controller is included between buses n, $n + 1$ while the shunt converter is connected at bus $n + 1$. It should highlight that the series injected

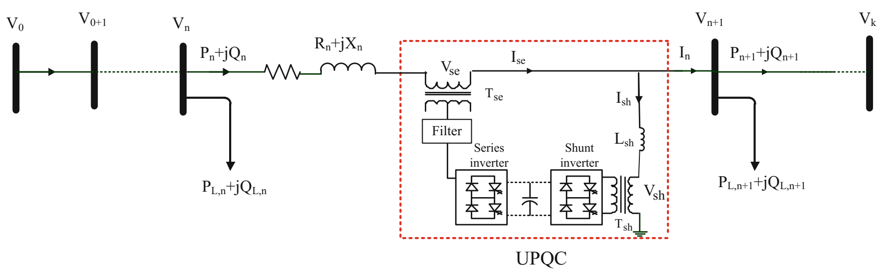

Fig. 12.5 Schematic diagram of UPQC controller

voltage is kept in quadrature with current flow. In other words, the series and shunt current are kept in quadrature with the voltage of bus $n + 1$ [29]. Referring to Fig. 12.5, the voltage at bus $n + 1$ can be given as

$$V_{n+1}\angle\theta_{n+1} = V_n\angle\theta_n - (R_n + jX_n)\left(I_n\angle\delta + I_{sh}\angle\left(\theta_{n+1} + \frac{\pi}{2}\right)\right) + V_{se}\angle\theta_{se} \tag{12.23}$$

where

V_{se}	The magnitude of the series injected voltage.
θ_{se}	The phase angle of the injected voltage.
I_n	The current flow through the transmission line.
$I_{sh}\angle\left(\theta_{n+1} + \frac{\pi}{2}\right)$	The injected current of the shunt converter

The injected current of the series converter can be found as

$$\overrightarrow{I_{se}} = \overrightarrow{I_n} + \overrightarrow{I_{sh}} \tag{12.24}$$

However, two equations are obtained by separating the real and imaginary part of (12.23). Three quantities are unknown $(V_{se}, \theta_{n+1}, I_{sh})$. For solving this problem, it is assumed that the reactive shunt power by shunt converter is represented as the negative reactive load at bus *n + 1* as shown in Fig. 12.6 [28].

Referring to Fig. 12.6, the injected series voltage can be found as

$$V_{se}\angle\theta_{se} = V_{n+1}\angle\theta_{n+1} + Z_n\left(\acute{I}_n\angle\acute{\delta}\right) - V_n\angle\theta_n \tag{12.25}$$

where

$$\theta_{se} = \acute{\delta} + \frac{\pi}{2} \quad \acute{\delta} \le 0 \tag{12.26}$$

$$\theta_{se} = \acute{\delta} - \frac{\pi}{2} \quad \acute{\delta} > 0 \tag{12.27}$$

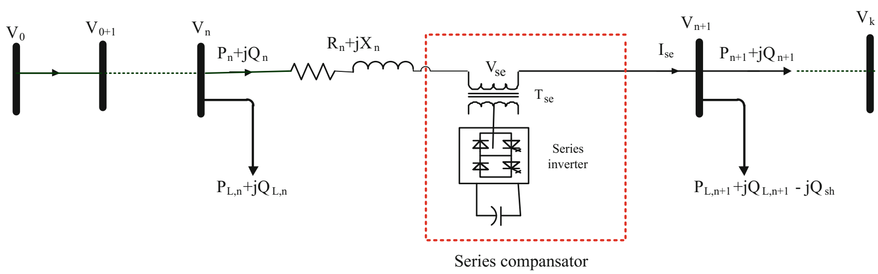

Fig. 12.6 Representation of UPQC in a distribution system

By separating the real and imaginary terms of (12.25) as

$$V_{se}\cos(\theta_{se}) = V_{n+1}\cos(\theta_{n+1}) + Re\left(Z_n\left(\acute{I}_n\angle\acute{\delta}\right)\right) - Re(V_n\angle\theta_n) \tag{12.28}$$

$$V_{se}\sin(\theta_{se}) = V_{n+1}\sin(\theta_{n+1}) + Im\left(Z_n\left(\acute{I}_n\angle\acute{\delta}\right)\right) - Im(V_n\angle\theta_n) \tag{12.29}$$

Equations (12.28) and (12.29) can be simplified as

$$V_{se}K_1 = b_3\cos(\theta_{n+1}) + b_1 \tag{12.30}$$

$$V_{se}K_2 = b_3\sin(\theta_{n+1}) + b_2 \tag{12.31}$$

where

$$x_1 = V_{se}$$

$$x_2 = \theta_{n+1}$$

$$K_1 = \cos\ (\theta_{se})$$

$$K_2 = \sin\ (\theta_{se})$$

$$b_1 = Re\left(Z_n\left(\acute{I}_n\angle\acute{\delta}\right)\right) - Re(V_n\angle\theta_n)$$

$$b_2 = Im\left(Z_n\left(\acute{I}_n\angle\acute{\delta}\right)\right) - Im(V_n\angle\theta_n)$$

$$b_3 = V_{n+1}$$

Solving (12.30) and (12.31), the value of V_{se} can be given as

$$V_{se} = \frac{-B \pm \sqrt{B^2 - 4AC}}{2A} \tag{12.32}$$

where

$$A = \frac{k_1^2 + k_2^2}{b_3}$$

$$B = -2 \times \frac{K_1 b_1 + K_2 b_2}{b_3}$$

$$C = \frac{b_1^2 + b_2^2}{b_3}$$

The value of θ_{n+1} can be obtained from (12.30) or (12.31) as

$$\theta_{n+1} = \cos^{-1}\left(\frac{K_1 x_1 - b_1}{b_3}\right) \tag{12.33}$$

$$\theta_{n+1} = \sin^{-1}\left(\frac{K_2 x_1 - b_2}{b_3}\right) \tag{12.34}$$

The reactive power of series compensator can be found as

$$Q_{series} = Im\left(V_{n+1}\angle\theta_{n+1}\left(\acute{I}_n\angle\acute{\delta}\right)^*\right) \tag{12.35}$$

12.3 Optimization Techniques

Recently, the several optimization techniques are widely applied to determine the optimal sizes and locations of compensation device in distribution networks. Variety of optimization techniques have been proposed based on nature-swarm inspired methods, human-inspired methods, physics inspired methods and evolutionary inspired algorithms. In this section, a survey including the previous techniques for solving the allocation problem of compensation devices is presented. Table 12.1 shows an overview of application the optimization techniques in radial distribution systems.

12.4 Problem Formulation

12.4.1 Capacitor Allocation Problem Formulation

The objective of optimal capacitor placement problem of the radial distribution system is minimizing the total cost including the energy loss cost along with capacitor cost. The objective function can be formulated as

$$Minimize \quad Cost = K_p P_{loss} + \sum_{i=1}^{nc} K_{c,i} Q_{c,i} \tag{12.36}$$

Table 12.1 Summary of the literature review regarding compensation devices placement problem

	Algorithm	Objective function	Controller	Sensitivity using?	Year	Refs.
Nature inspired	Ant Colony	P_{loss}	Reconfiguration and capacitor	No	2008	[30]
	Bacterial Foraging	P_{loss} and Cost	Capacitor	Yes	2015	[31]
	Particle Swarm Optimization	Cost	Capacitor	No	2010	[32]
	Cuckoo Search Algorithm	Cost	Capacitor	Yes	2013	[33]
	Artificial Bee Colony Algorithm	Cost and VSI	Capacitor	Yes	2014	[34]
	Ant Colony Optimization	P_{loss} and Cost and VD	Capacitor	Yes	2016	[35]
	Crow Search Algorithm	P_{loss} and Cost	Capacitor	No	2016	[36]
	Flower Pollination Algorithm		Capacitor		2016	[37]
	Bat and Cuckoo Search Algorithms	P_{loss} and Cost	Capacitor	No	2015	[38]
	Oppositional Krill Herd Algorithm	P_{loss}	Reconfiguration and capacitor	No	2016	[39]
	Monkey Search Optimization	P_{loss} and Cost and VD and emission	Capacitor	No	2016	[40]
	MOPSO	P_{loss} and VSI and VD and current balancing	Capacitor and DG	No	2015	[41]
	Firefly Algorithm	SAIFI and SAIDI and AENS and Cost	Capacitor	No	2014	[42]
	Particle Swarm Optimization	Cost	Capacitor	Yes	2014	[43]
	Genetic Algorithm	Loadability and total cost	DSTATCOM and DG	No	2016	[44]
	Fuzzy system and Expanded Invasive Weed Optimization	P_{loss} and VSI and VD	DSTATCOM and DG	No	2016	[45]
	Particle Swarm Optimization	P_{loss} and VD	DSTATCOM	No	2014	[46]
				No	2015	[47]

(continued)

Table 12.1 (continued)

	Algorithm	Objective function	Controller	Sensitivity using?	Year	Refs.
	Fuzzy Multiobjective Approach and Ant Colony Optimization	P_{loss} and VD and feeder load balancing	Reconfiguration and DSTATCOM and Photovoltc arry			
	Bacterial Foraging Optimization Algorithm	P_{loss} and VD and Cost	DSTATCOM and DG		2016	[48]
	Bat algorithm	P_{loss} and VSI and Cost	DSTATCOM	Yes	2015	[49]
	Improved Cat Swarm Optimization	P_{loss} and VD	DSTATCOM and DG	No		
	Cuckoo Optimization Algorithm	P_{loss} and VD and Cost and harmonic	UPQC	No	2016	[50]
	Particle Swarm Optimization	P_{loss} and VD and UPQC rating	UPQC	No	2014	[51]
	Plant Growth Simulation Algorithm	P_{loss} and Cost	Capacitor	Yes	2011	[52]
Human-inspired methods	Tabu Search	Cost	Capacitor	Yes	1996	[53]
	Improved Harmony Search	Cost	Capacitor		2016	[54]
	Harmony Search and the Particle Artificial Bee Colony	P_{loss} and VD	DG and Capacitor	Yes	2016	[55]
	Modified Cultural Algorithm	Cost	Capacitor	No	2013	[56]
	Imperialist Competitive Algorithm and Genetic Algorithm	P_{loss} and VSI and VD and load balancing	DG and Capacitor	No	2014	[57]
	Teaching Learning Based Optimization	P_{loss} and Cost	Capacitor	No	2014	[58]
	Harmony Search (HS) Algorithm	P_{loss} and VD	UPQC	No	2015	[59]

(continued)

Table 12.1 (continued)

	Algorithm	Objective function	Controller	Sensitivity using?	Year	Refs.
Physics inspired methods	Gravitational Search Algorithm	Cost	Capacitor	yes	2015	[60]
	Simulated Annealing and Greedy Search	Cost	Capacitor	No	1995	[61]
	Biogeography Based optimization (BBO)	P_{loss}	Capacitor and DG	No	2016	[62]
	Big bang-big Crunch Optimization	P_{loss}	Capacitor	No	2011	[63]
	Simulated Annealing	Cost	Capacitor	No	1990	[64]
Evolutionary inspired algorithms	Integrated Evolutionary Algorithms	Cost	Capacitor	yes	2013	[65]
	Penalty Free Genetic Algorithm	Cost	Capacitor	No	2016	[66]
	Differential Evolutionary	Cost	Capacitor	No	2015	[67]
	Fuzzy GA Genetic Algorithm	VSI and VD	Capacitor	Yes	2014	[68]
	Genetic Algorithms	Cost	Capacitor and voltage regulators	No	2012	[69]
	Genetic Algorithms	Cost	Capacitor	Yes	1994	[61]
	Immune Algorithm	Cost	DSTATCOM	No	2014	[1]
	Differential Evolution	P_{loss} and VD	DSTATCOM	No	2011	[70]
	Differential Evolution	P_{loss}	DSTATCOM	No	2016	[71]

SAIFI System average interruption frequency index
SAIDI System average interruption duration index
AENS Average energy not supplied index

where

Cost	The total cost
P_{loss}	The total active power loss (kW)
Q_c	The capacitor reactive power (kVar)
K_p	The annual cost of energy losses
K_c	The cost of capacitor per kVar

12.4.2 DSTATCOM Allocation Problem Formulation

The objective of optimal placement problem of DSTATCOM in the radial distribution system is minimizing the total loss, improving the voltage profile and enhancing the voltage stability index simultaneously as

$$f_1 = \frac{\sum_{i=1}^{nl} (P_{loss}(i))_{after\,DSTATCOM}}{\sum_{i=1}^{nl} (P_{loss}(i))_{before\,DSTATCOM}} \tag{12.37}$$

$$f_2 = \frac{\sum_{i=1}^{nb} \left(\left|V(i) - V_{ref}\right|\right)_{after\,DSTATCOM}}{\sum_{i=1}^{nl} \left(\left|V(i) - V_{ref}\right|\right)_{before\,DSTATCOM}} \tag{12.38}$$

$$f_3 = \frac{1}{\sum_{i=1}^{nb} (|VSI(i)|)_{after\,DSTATCOM}} \tag{12.39}$$

where *nl* is the number of branches in electric distribution network while *nb* is the number of buses in the network.

12.4.3 System Constraints

The required objective functions are subjected to equality and inequality constraints related to electric distribution network which can be represented as

- **Equality constraints**

The equality constraints of the system are the active and reactive power flow constraints which can be obtained as

$$P_{slack} = \sum_{i=1}^{n} P_L(i) + \sum_{j=1}^{nb} P_{loss}(j) \tag{12.40}$$

$$Q_{slack} + \sum_{i=1}^{nc} Q_c(i) = \sum_{i=1}^{n} Q_L(i) + \sum_{j=1}^{nb} Q_{loss}(j) \tag{12.41}$$

where P_{slack} and Q_{slack} are active power and reactive powers supplied from the slack bus, respectively. P_L and Q_L are the active and reactive load demands respectively. *nb* is the number of branches in the network while *nc* is the number of compensation units.

– **Inequality constraints**

I. Bus voltage constraints

$$V_{min} \leq V_i \leq V_{max} \tag{12.42}$$

where V_{min} and V_{max} are the minimum and the maximum allowable bus voltage limit.

II. Total reactive power constraint

Practically, the total injected reactive power using compensation devices is equal to or less than the reactive load demand.

$$\sum_{i=1}^{nc} Q_c(i) \leq \sum_{i=1}^{n} Q_L(i) \tag{12.43}$$

where Q_L is the reactive load at a certain bus and Q_c is compensator reactive power.

III. Thermal limit

The current flow through network branches must be within their allowable limits as

$$I_{n,i} \leq I_{max,i} \quad i = 1, 2, 3 \ldots Nb \tag{12.44}$$

Nb is the number of branches in the distribution system.

12.5 Overview of Grasshopper Optimization Algorithm (GOA)

GOA is a new optimization technique that is inspired form the movement and migration of grasshopper in natural. The adult insects of grasshopper travel together over long distance which mimics exploration of optimization technique while the

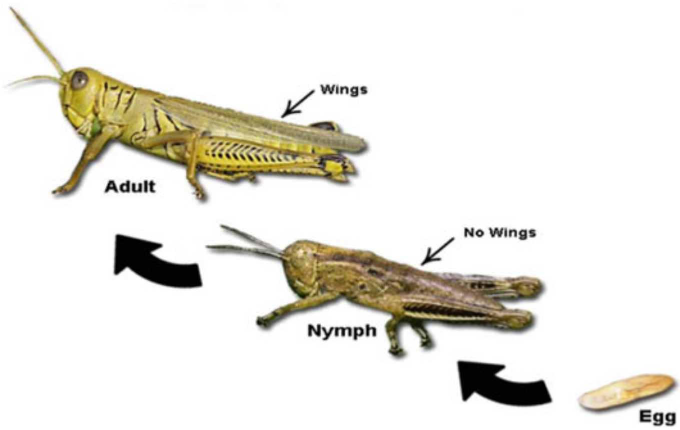

Fig. 12.7 The life cycle of grasshopper

nymphs have no wings, so it move in small area which mimics the exploitation of optimization technique [72].

Grasshoppers are harmful insects that can destroy a wide area of the agriculture and crops where the grasshoppers swarm consist of million members which can cover a wide area up to 1000 km. The life cycle of Grasshopper consists of three stages as depicted in Fig. 12.7. The grasshopper can be found in two phases. In the first phase the individual of grasshoppers avoids interaction together (solitary phase) while in the other phase (gregarious phase), grasshoppers became sociable and form a swarm. The swarm became a flying swarm depends upon environmental consideration such as air temperature, sunshine and wind speed [73].

The swarm of grasshopper moves in rolling motion where groups are formed in ground firstly by a collection of individuals of insects which move in the ground or locally and short flight then these groups became coordinated together, and the insects share a common spatial orientation. The behavior of grasshopper swarm can be summarized as

(1) The swarm flies with downwind.
(2) The grasshoppers in front of swarm settle on the ground.
(3) The settled insects start eating and resting.
(4) The swarm starts taking of gain to altitude.

The grasshopper swarm navigation behavior aligned the wind is depicted in Fig. 12.8.

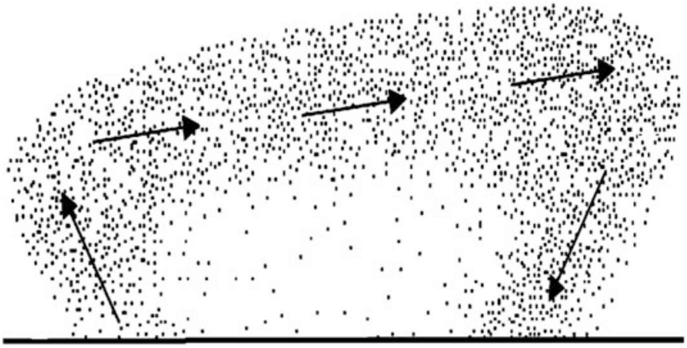

Fig. 12.8 Motion of grasshopper swarm aligned with wind

The grasshopper swarm behavior depends upon the social interaction between a grasshopper, the gravity force and the downwind advection. Hence mathematical behavior can be represented as [74]:

$$X_i = r_1 A_i + r_2 B_i + r_3 C_i \tag{12.45}$$

where

X_i	The position of *i*th grasshopper
A_i	The social interaction
B_i	The gravity force on the *i*th grasshopper
C_i	Wind advection
r_1, r_2, r_3	Random numbers

A social forced between two grasshoppers is established biologically where the repulsion forces are existed in order to prevent collisions over a short length scale and attraction force is existed for aggregation. The social interaction between grasshoppers can define as

$$A_i = \sum_{\substack{j=1 \\ i \neq j}}^{N} s\left(Dis_{ij}\right)\left(\frac{x_i - x_j}{Dis_{ij}}\right) \tag{12.46}$$

where Dis_{ij} is the distance between i and j grasshoppers that equals to $Dis_{ij} = \left|\mathrm{x_i} - \mathrm{x_j}\right|$ and the s function represents the social forces which can be represented as

$$s\left(Dis_{ij}\right) = Fe^{\frac{Dis_{ij}}{l}} - e^{Dis_{ij}} \tag{12.47}$$

where F is the intensity of attractive force and l is the attractive length scale. The swarm motion is directly affected by the gravity force which can be found as

$$B_i = -g\overrightarrow{e_g} \tag{12.48}$$

where g is the gravitational constant and $\overrightarrow{e_g}$ the unity vector towards the center of earth. The wind advection effect on the motion swarm

$$C_i = u\overrightarrow{e_w} \tag{12.49}$$

Substituting the value of A_i, B_i and C_i from (12.46), (12.48) and (12.49) in (12.45) yields

$$X_i = \sum_{\substack{j=1 \\ i \neq j}}^{N} s(Dis_{ij})\left(\frac{x_i - x_j}{Dis_{ij}}\right) - g\overrightarrow{e_g} + u\overrightarrow{e_w} \tag{12.50}$$

The previous equation is modified to be implemented for optimization problems and for enhancing the capability global searching of the algorithm it can be modified as

$$X_i^m = C\left(\sum_{\substack{j=1 \\ i \neq j}}^{N} C\left(\frac{Upper(m) - Lower(m)}{2}\right)s(Dis_{ij})\left(\frac{x_i - x_j}{Dis_{ij}}\right)\right) + P_{best}^m \tag{12.51}$$

where $Upper(.)$ and $Lower(.)$ are the upper and lower limits of the control variable, respectively. P_{best}^m is the best position (the target position). C is an adaptive coefficient that decrease linearly for enhancing the search capability of GOA which can be represented as

$$C = C_{max} - T\frac{C_{max} - C_{min}}{T_{max}} \tag{12.52}$$

where C_{max}, C_{min} are the maximum and the minimum values of C, respectivly. T and T_{max} are the current iterations and the maximum iteration, respectively.

Step 1: Determine the input data of GOA algorithm including number of the search agents (N), maximum number of iterations,C_{min}, C_{max}, F, L and the upper and lower boundaries of control variables.
Step 2: Initialize the population of GOA algorithm as

$$P_i^m = Lower(i, m) + rand * (Upper(i, m) - Lower(i, m)) \tag{12.53}$$

Step 3: Calculate the fitness functions for each search agent.
Step 4: Determine the best position (target position) in term of the best fitness function.
Step 5: Update the position of search agent according to (12.51).
Step 6: Check the boundaries of the updated agents and bring the violated variable to accepted limit.
Step 7: Calculate the fitness function for the updated positions and determine the target position.
Step 8: Repeat steps form (12.5) to (12.7) until the stopping criterion is achieved (current iteration equals to maximum iteration).
Step 9: Obtain the optimal solution by capture the target position and the related fitness function.

12.6 Numerical Examples

In this section the grasshopper optimization technique is employed to determine the optimal locations and sizes of shunt capacitors and DSTATCOM in the 69-bus radial distribution network. The line diagram of the network is shown in Fig. 12.9. The network data are given in [75] which are also tabulated in Table 12.7. A program code for optimal allocation of compensators is written using MATLAB 2009a and run on a PC with core i5 processor, 2.50 GHz and 4 GB RAM. The selected parameters of GOA technique are listed in Table 12.2. The parameters required for implementation of the proposed algorithm are adjusted by 50 times running of this algorithm. The obtained results using the GOA algorithm are compared with compared with other well-known optimization algorithms such as; Grey Wolf Optimizer (GWO) [76], Sine Cosine Algorithm (SCA) [77] and other meta-heuristics techniques. The studied cases are presented as

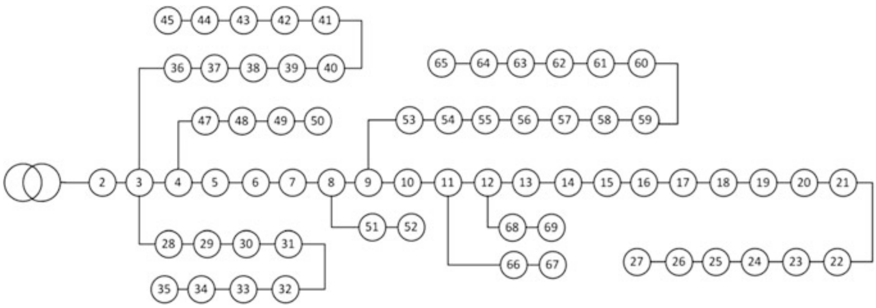

Fig. 12.9 The line diagram of the 69-bus system

Table 12.2 The selected parameters of GOA

Parameter	T_{max}	Search agents NO.	C_{max}	C_{min}	F	L
Value	100	30	1	0.00001	0.5	1.5

12.6.1 Case 1

The GOA technique is applied for optimal allocation of the capacitor in the 69-bus network to minimize the total cost as described in (12.36). The sizes of capacitors are selected to be standard with the available industrial market. The available sizes and costs of capacitors are listed in Table 12.3. The Total active and reactive load demands are 3801.89 kW and 2694.1 kVar respectively. The substation voltage is 12.66 kV and the single line diagram. The system power loss without inclusion compensation devices equal to 225 kW and the total cost for the system without any capacitor is found to be 37,800.0 $. The optimal size of capacitors, their locations and the impact of optimal placement and sizing of capacitors on the energy loss cost, capacitor cost and total cost of the system by 50 run trials are given in Table 12.4. Moreover, the best, worst and mean obtained results by GOA also are listed in Table 12.4. The power loss decreased to 145.405 MW with incorporating capacitor banks optimally using GOA. Moreover, the value of total cost is enhanced to 24,820.84 $. From Table 12.5 it can also be found that the objective value found by the GOA technique is better than those obtained by the CSA [33], DSA [78], TLBO [58], GSA [2], GWO and SCA. This demonstrates that the GOA successfully achieves better simulation results than other techniques. The voltage profiles of all system buses are enhanced significantly with incorporating capacitor banks optimally using GOA as shown in Fig. 12.10. The average computational time taken by the GOA technique and the other techniques are reported in Table 12.4. It can be obvious that GOA needs less computational time compared with other reported techniques. The convergence characteristic of the GOA, GWO

Table 12.3 Available capacitor size and related cost ($/kVar)

Size (kVar)	150	300	450	600	750	900	1050	1200	1350
Cost ($/kVar)	0.5	0.35	0.253	0.22	0.276	0.183	0.228	0.170	0.207
Size (kVar)	1500	1650	1800	1950	2100	2250	2400	2550	2700
Cost $/kVar	0.201	0.193	0.187	0.211	0.176	0.197	0.170	0.189	0.187
Size (kVar)	2850	3000	3150	3300	3450	3600	3750	3900	4050
Cost ($/kVar)	0.183	0.180	0.195	0.174	0.188	0.170	0.183	0.182	0.179

Table 12.4 Obtained results for the 69-bus test system using different optimization techniques

	Base case	CSA [33]	DSA [78]	TLBO [58]	GSA [2]	GWO	SCA	GOA
$V_{min}(p.u)$	0.9092	0.930	0.9318	0.9321	0.9519	0.93079	0.93145	0.93079
$P_{loss}(kW)$	225.00	147.95	147	146.35	145.9	145.569	145.440	145.405
Capacitor location (kVar)	–	21 (250) 62 (1200)	61 (900) 15 (450) 60 (450)	22 (300) 61 (1050) 62 (300)	26 (150) 13 (150) 15 (1050)	61 (1200) 12 (450) 26 (150)	61 (1200) 9 (450) 17 (350)	61 (1200) 12 (450) 21 (150)
Total (kVar)	–	1450	1800	1650	1350	1800	2000	1800
Capacitors cost ($)	–	291.5	392.4	446.4	451.5	392.85	440.35	392.85
Energy cost ($)	37,800.0	24,855.6	24,696	24,586.8	24,511.2	24,455.51	24,433.98	24,427.99
Total annual cost ($)	37,800.0	25,147.1	25,088.4	25,033.2	24,962.7	24,848.36	24,874.33	24,820.84
Net savings ($)	–	12,652.9	12,711.6	12,766.8	12,837.3	12,951.6	12,925.7	12,979.1
Best annual cost ($)	37,800.0	25,147.1	25,088.4	25,033.2	24,962.7	24,848.36	24,874.33	24,820.84
Worst annual cost ($)		NA	NA	NA	NA	25,093.56	25,040.17	25,040.17
Mean annual cost ($)		NA	NA	NA	NA	24,938.10	24,930.81	24,930.81
Average CPU time (S)		125.80	NA	36.87	NA	23.66	24.15	21.30

and SCA are depicted in Fig. 12.11. From the convergence graph, it may be observed that the objective value (total cost) converges and smoothly rapidly at the 15th iteration compared to GWO and SCA. This confirms the convergence reliability of the proposed GWO algorithm.

12.6.2 Case2

In this case, GOA technique is employed to determine the optimal locations and sizes of DSTATCOMs in the 69-bus network for minimizing the total loss, improving the voltage profile and enhancing the voltage stability index simultaneously as described in (12.37), (12.38) and (12.39). Hence, in this case, the objective function is a multi-objective function which can be formulated as

$$f_t = w_1 f_1 + w_2 f_2 + w_3 f_3 \quad (12.54)$$

where w_1, $w2$ and $w3$ are weighting factors. The value of any weighting factor is selected based on the relative important on its related objective function with others objective functions. The sum of the absolute values of the weight factors in (12.54) assigned to all impacts should add up to one as [79]

$$|w_1| + |w_2| + |w_3| = 1 \quad (12.55)$$

In this chapter, w_1 is set as 0.5 while w_2 and w_3 equal 0.25.It should point out that the constraint of injected reactive power of DSTATCOM is restricted as [1]

$$0 \le Q_{STATCOM} \le 10,000 KVAR \quad (12.56)$$

$$\sum_{i=1}^{nc} Q_{STATCOM}(i) \le \sum_{i=1}^{n} Q_L(i) \quad (12.57)$$

In this case, three DSTATCOM devices are included in the 69-bus system. The optimal locations and sizes of DSTATCOMs that have been determined using GOA, GWO and SCA, are listed in Table 12.5. It is obvious that the power loss is reduced to 145.146 and the summation of voltage deviations is also reduced from 1.8374 to 1.3872 p.u with incorporating of the DSTATCOMs optimally using GOA. Moreover, the voltage stability is also enhanced to 62.7759 p.u with inclusion of DSTATCOMs. From Table 12.6, it is clear that the obtained results by GOA are better than those obtained by GWO and SCA.

Table 12.5 Simulation results of the 69-bus system at different loadings

Loading		Base case	GWO	SCA	GOA
100%	Minimum voltage	0.9092	0.93079	0.93145	0.93079
	Total active loss kW	225.00	145.569	145.440	145.405
	Annual cost $/year	37,800.0	24,848.36	24,874.33	24,820.84
	Location and size	–	61 (1200) 12 (450) 26 (150)	61 (1200) 9 (450) 17 (350)	61 (1200) 12 (450) 21 (150)
75%	Minimum voltage	0.93353	0.94874	0.94873	0.94874
	Total active loss kW	121.030	79.971	81.383	79.971
	Annual cost $/year	20,333.04	13,722.35	13,959.48	13,722.35
	Location and size	–	61 (900) 12 (350)	61 (900) 9 (350)	61 (900) 12 (350)
50%	Minimum voltage	0.95668	0.96569	0.96569	0.96569
	Total active loss kW	51.606	35.757	35.757	35.757
	Annual cost $/year	8669.808	6139.1694	6139.1694	6139.1694
	Location and size	–	61 (600)	61 (600)	61 (600)
Net injected kVar			Fixed 600 at bus 61 Switched 600 at bus 61 Switched 450 at bus 12 Switched 350 at bus 26	Fixed 600 at bus 61 Switched 600 at bus 61 Switched 450 at bus 9 Switched 350 at bus 17	Fixed 600 at bus 61 Switched 600 at bus 61 Switched 450 at bus 12 Switched 350 at bus 21

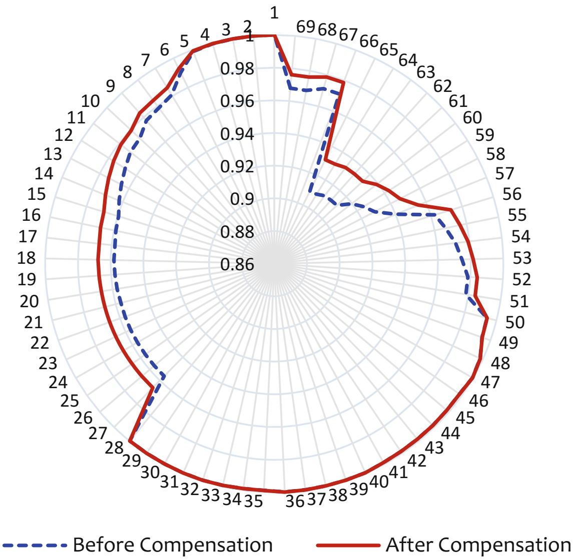

Fig. 12.10 Effect of compensation on system voltages for the 69-bus system

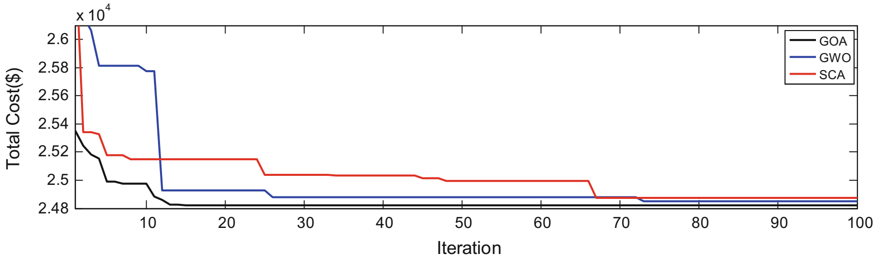

Fig. 12.11 Change of total cost with iterations for the 69-bus using GOA, GWO and SCA

Table 12.6 Obtained results for optimal allocation of DSTATCOM using different optimization techniques

	Base case	GWO	SCA	GOA
$V_{min}(p.u)$	0.90919	0.93093	0.93132	0.93121
$V_{max}(p.u)$	0.99997	0.9999	0.99998	0.99998
$VSI_{min}(p.u)$	0.6833	0.7511	0.7523	0.7520
$VSI_{max}(p.u)$	0.9999	1.0000	0.9999	0.9999
$\sum VSI$	61.2181	62.6904	62.7154	62.7759
$P_{loss}(KW)$	225.00	146.453	145.840	145.146
$VD(p.u)$	1.8374	1.4105	1.4046	1.3872
Optimal locations and size of DSTATCOM (kVar)	–	61 (1264.5) 17 (346.9973) 36 (687.7078)	12 (548.01) 61 (1245.6) 49 (562.84)	11 (374.71) 61 (1224.21) 18 (242.430)

Appendix

See Table 12.7.

Table 12.7 Data of the 69-bus test systems

S. NO.	From bus	To bus	R (Ω)	X (Ω)	PL (kW)	QL (kVar)
1	1	2	0.0005	0.0012	0	0
2	2	3	0.0005	0.0012	0	0
3	3	4	0.0015	0.0036	0	0
4	4	5	0.0251	0.0294	0	0
5	5	6	0.366	0.1864	2.60	2.20
6	6	7	0.3811	0.1941	40.40	30
7	7	8	0.0922	0.0470	75	54
8	8	9	0.0493	0.0251	30	22
9	9	10	0.819	0.2707	28	19
10	10	11	0.1872	0.0619	145	104
11	11	12	0.7114	0.2350	145	104
12	12	13	1.0300	0.3400	8	5
13	13	14	1.0440	0.3450	8	5.50
14	14	15	1.0580	0.3496	0	0
15	15	16	0.1966	0.0650	45.50	30
16	16	17	0.3744	0.1238	60	35
17	17	18	0.0047	0.0016	60	35
18	18	19	0.3276	0.1083	0	0

(continued)

Table 12.7 (continued)

S. NO.	From bus	To bus	R (Ω)	X (Ω)	PL (kW)	QL (kVar)
19	19	20	0.2106	0.0690	1	0.60
20	20	21	0.3416	0.1129	114	81
21	21	22	0.0140	0.0046	5	3.50
22	22	23	0.1591	0.0526	0	0
23	23	24	0.3463	0.1145	28	20
24	24	25	0.7488	0.2475	0	0
25	25	26	0.3089	0.1021	14	10
26	26	27	0.1732	0.0572	14	10
27	27	28	0.0044	0.0108	26	18.60
28	28	29	0.0640	0.15650	26	18.60
29	29	30	0.3978	0.1315	0	0
30	30	31	0.0702	0.0232	0	0
31	31	32	0.3510	0.1160	0	0
32	32	33	0.8390	0.2816	14	10
33	33	34	1.7080	0.5646	9.50	14
34	34	35	1.4740	0.4873	6	4
35	35	6	0.0044	0.0108	26	18.55
36	36	37	0.0640	0.1565	26	18.55
37	37	38	0.1053	0.1230	0	0
38	38	39	0.0304	0.0355	24	17
39	39	40	0.0018	0.0021	24	17
40	40	41	0.7283	0.8509	1.20	1
41	41	42	0.3100	0.3623	0	0
42	42	43	0.0410	0.0478	6	4.30
43	43	44	0.0092	0.0116	0	0
44	44	45	0.1089	0.1373	39.22	26.30
45	45	46	0.0009	0.0012	39.22	26.30
46	4	47	0.0034	0.0084	0	0
47	47	48	0.0851	0.2083	79	56.40
48	48	49	0.2898	0.7091	384.70	274.50
49	49	50	0.0822	0.2011	384.70	274.50
50	8	51	0.0928	0.0473	40.50	28.30
51	51	52	0.3319	0.1114	3.60	2.70
52	9	53	0.1740	0.0886	4.35	3.50
53	53	54	0.2030	0.1034	26.40	19
54	54	55	0.2842	0.1447	24	17.20
55	55	56	0.2813	0.1433	0	0
56	56	57	1.5900	0.5337	0	0
57	57	58	0.7837	0.2630	0	0
58	58	59	0.3042	0.1006	100	72

(continued)

Table 12.7 (continued)

S. NO.	From bus	To bus	R (Ω)	X (Ω)	PL (kW)	QL (kVar)
59	59	60	0.3861	0.1172	0	0
60	60	61	0.5075	0.2585	1244	888
61	61	62	0.0974	0.0496	32	23
62	62	63	0.1450	0.0738	0	0
63	63	64	0.7105	0.3619	227	162
64	64	65	1.0410	0.5302	59	42
65	11	66	0.2012	0.0611	18	13
66	66	67	0.0047	0.0014	18	13
67	12	68	0.7394	0.2444	28	20
68	68	69	0.0047	0.0016	28	20
Tie lines						
69	11	43	0.5	0.5	6.0	4.30
70	13	21	0.5	0.5	5.00	3.50
71	15	46	1.0	1.0	39.22	26.30
72	50	59	2.0	2.0	100.0	72
73	27	65	1.0	1.0	59.0	42.0

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