

# Optimal Placement of D-STATCOMs into the Radial Distribution Networks in the Presence of Distributed Generations

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**Abstract** This paper proposes a combination of Discrete Imperialistic Competition and Nelder-Mead algorithms to solve D-STATCOMs placement optimization problem. It is assumed that optimal number, locations and sizes of D-STATCOMs are determined in radial distribution network while Distributed Generations are previously installed in it. Indeed, we focus on voltage control and concept of reactive power management in annual scheduling time interval. Objective function is defined in terms of network active power losses and voltage stability characteristic at different load levels by appropriate weighting factors. Voltage Stability Index (VSI) is applied to identify the weak buses in radial distribution network. To validate performance and effectiveness of proposed DICA-NM hybrid algorithm, simulation studies are applied on the 30-bus IEEE radial distribution test feeder. Finally, numerical results for some important network variables have been compared in three different case studies.

**Keywords:** *Discrete Imperialistic Competition Algorithm and Nelder-Mead (DICA-NM), Distributed Generations (DGs), location and Size of D-STATCOM, Forward and Backward Power Flow, Voltage Stability Index (VSI)*

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## 1. Introduction

In recent years, restructuring process in power system, demand side competition promotion, in addition to generation side and deregulation into the power system management causes distribution networks to play an important role in power system planning. For above challenging situation, the important subjects in optimal planning and operation planning of electrical distribution system are loss reduction, voltage and current profile improvement which are related to voltage control and reactive power management concept. This concept includes all planning and actions to improve voltage profile and voltage stability. It consists of two steps: first step is reactive power resources planning and second step is reactive power dispatch on reactive power resources that have up to now been installed on networks. Reactors, capacitor banks and transformer equipped to Under Load Tap Changer (ULTC) are available reactive power resources in distribution network. Main goal of voltage control and reactive power management are indeed correct coordination and setting between available controlling devices in sub-transmission substation and distribution feeders. Nowadays, DG resources, because of high importance in energy generation process, are vastly applied in the electrical distribution systems. Synchronous generators are one of the most applicable types of DGs

that are installed in the medium voltage systems. DGs can affect the voltage control devices and reactive power especially on Under Load Tap Changer because of its operation ability in two different modes including power factor control (PQ) and voltage control (PV) and also installation ability on different locations in distribution network. Therefore, for reliable voltage regulation in system, DG unit connections should be coordinated with other system devices. During reactive power management studies with high penetration of DGs in networks, high flexibility of DGs reactive power related to network should be considered. In spite of these, power system operators cannot use all available reactive abilities of DGs up to now due to lack of optimal management, thus distribution systems with large capacity of DGs are faced with major issues such as voltage stability and voltage collapse. To cover this gap, recently, D-FACTS devices due to control ability of voltage profile and power flow are proposed as an applicable option for voltage stability improvement. By development in modern control techniques and power electronic devices technology, use of these devices would be inevitable to improve the quality of distribution network operation. Desirable controlling methods for improvement in distribution network operation have been achieved by Custom Power Devices (CPD) application. These elements are used in distribution networks for voltage profile and power quality improvement, and loss reduction, which consist of devices such as Solid State Transfer Switch (SSTS), Distribution

Static Compensator (D-STATCOM) and Unified Power Flow Controller (UPFC). D-STATCOM as a Voltage Source Converter (VSC) with shunt connection is more applied for power quality concerns. Under voltage sag conditions or lines overload, bus voltage to which D-STATCOM is connected can be regulated with proper compensation current injection. Injected current to voltage balance/regulation in desired level is estimated by bus voltage and requested reactive power. Optimal use of these devices is achieved via finding out its optimal numbers, locations, and sizing. Ref. [1] pays attention to the optimal placement of D-STATCOM in electrical distribution systems by use of particle swarm optimization (PSO) method. Ref. [2] proposes Immune Algorithm (IA) for finding the optimal location of unified power flow controller (UPFC) for the optimal power flow determination and congestion management. Ref. [3] presents a method for optimal placement of D-STATCOM using the firefly algorithm (FA) by goal of power quality enhancement in distribution network and obtained results are also compared with the particle swarm optimization and genetic algorithm. In ref. [4], optimal location and sizing of DSTATCOM for the sake of power loss reduction, and improvement of current and voltage profile in distribution networks are investigated using Immune Algorithm while considering voltage and current profile improvement, minimum cost of installation of DSTATCOM and maximum power loss reduction are integrated into an objective function through appropriate weighting factors. This paper proposes an application of DICA-NM hybrid algorithm to determine the optimal numbers, locations and sizing of D-STATCOMs in radial distribution networks in presence of Distributed Generation (DGs). Objective function is defined in two terms by appropriate weighting factors: summation of active power losses, D-STATCOMs devices' installation costs after normalization and reverse value of normalized voltage stability index (VSI) for system critical bus at three different load levels. Problem constraints consist of under/over current and voltage limits, minimum and maximum active and reactive power generation of DGs, number and size of D-STATCOMs, Voltage Stability Index (VSI). Rest of the paper is organized as follows: In section.2, Forward-Backward power flow is reviewed as an efficient study method in radial distribution network and then entering procedure of DGs and D-STATCOM into the Forward-Backward distribution load flow is presented. In section.3, Voltage Stability Index (VSI) formulation is performed. In section.4, Optimal Placement of D-STATCOMs as an optimization problem is modeled by an objective function and system constraints. In section.5, proposed DICA-NM hybrid algorithm is illustrated. Simulation studies and numerical analysis have been performed in section.6 and concluding remarks appear in the last part of paper.

## 2. Forward-Backward Power Flow

Because of high  $\frac{r}{x}$  ratio and vast changing range of  $r$  &  $x$  in distribution systems, especially, in radial type, common power flow methods hardly converge. Therefore in this paper forward-backward load flow is used for power flow study of radial distribution systems [5]. It is assumed that,

substation bus of radial feeder is slack bus with known voltage magnitude and angle, under initial conditions that other buses' voltages are equal to slack bus, and power losses of all branches are equal to zero. Forward-backward power flow repetitive algorithm is composed of four stages: these four stages in  $k_{th}$  repetition are as below:

### A) Nodes Power Calculation

Considering this point that the absorbed power with constant current and impedance loads and also injected reactive power by capacitors due to change in nodes voltages will be changed during algorithm repetition, all aforementioned values should be calculated during performing  $k_{th}$  repetition of algorithm, again. Only, absorbed power with constant power loads will be unchanged during sequential repetitions.

### B) Backward Sweep for Summing Over All Branches

With starting from end-bus and move toward the slack bus, branches' powers are calculated according to relation (1):

$$S_{ij}(n) = S_j(n) + \sum_{\substack{m \in M \\ k \in N}} S_{jk}(m) + Loss_{ij}(n) \quad (1)$$

Indexes  $i$  and  $j$  are sending and receiving nodes of branch  $n$ , respectively;  $M$  is a set of branches which from one side are connected to the receiving node  $j$  of branch  $n$  and from the other side are connected to sending node  $k$  of branch  $m$ . Index  $N$  is a set of sending end nodes  $k$  of branches in set  $M$ . Index  $S_j(n)$  is absorbed power by the load which is connected to receiving node  $j$  of branch  $n$ . Index  $S_{ij}(n)$  is power flow from node  $i$  toward node  $j$  through branch  $n$  and  $Loss_{ij}(n)$  is power losses in branch  $n$  which is connected to nodes  $i$  and  $j$  and also it is assumed in first iteration equal to zero.

### C) Forward Sweep to Update Nodes Voltages

With starting from the branch which is connected to slack bus and move toward the end branches, currents in sending bus of branch  $n$ , voltages in receiving bus of branch  $n$  and active and reactive losses are calculated by relations (2), (3) and (4):

$$I_{ij}(n) = \left( \frac{S_{ij}(n)}{V_i(n)} \right)^* \quad (2)$$

$$V_j(n) = V_i(n) - Z_{ij}(n) \cdot I_{ij}(n) \quad (3)$$

$$Loss_{ij}(n) = (V_i(n) - V_j(n)) \cdot I_{ij}^*(n) \quad (4)$$

Index  $I_{ij}(n)$  is the current flow from node  $i$  toward node  $j$  through branch  $n$ , and  $Z_{ij}(n)$  is series impedance  $r_{ij}(n) + jx_{ij}(n)$  of branch  $n$  between nodes  $i$  and  $j$ . Indexes  $V_i(n)$  and  $V_j(n)$  are nodes voltages  $i$  and  $j$  of branch  $n$  and  $Loss_{ij}(n)$  is power losses of branch  $n$  between nodes  $i$  and  $j$ .

### D) Voltage Miss match

After performing previous stages in each repetition, voltage miss match is calculated for all buses by relation (5):

$$V_i^k(n) = \left| V_i^k(n) \right| - \left| V_i^{k-1}(n) \right| \quad (5)$$

Even if one of miss match values is greater than convergence criteria, all stages of algorithm should be repeated until convergence condition is achieved.

### 2.1. DGs Model in Forward-Backward Power Flow

One of the most common DG types is synchronous generators which are installed in the medium voltage of distribution system and it has the capability of direct connection to network. DGs, depending on operation of excitation system, can be modeled as voltage control (PV) and power factor control (PQ) [6,7]. Aforementioned types of DGs used in this paper have been modeled as power factor control (PQ). Active and reactive power generation limits in synchronous generators are determined with regard to operational curve, which considers mechanical limit of turbine, thermal limit of armature winding, etc. for generator at working set point. DG units that are controlled in form of PQ buses, as a negative load, enter the forward-backward load flow model, but DG units that are controlled in form of PV buses need additional process in power flow solution [8].

### 2.2. D-STATCOM Model in Forward-Backward Power Flow

A D-STATCOM can work as synchronize voltage source with variable amplitude and phase angle. Therefore, it has a capability to control its bus voltage and correct power factor. In steady state operation with heavy load or some types of short circuit, usually, D-STATCOM injects appropriate current to Point of Common Coupling (PCC) and regulates bus voltage to nominal rating or predetermined value. Generally, D-STATCOM can transfer active and reactive powers to network, simultaneously [9]. As can be seen, Figure 1 shows D-STATCOM installation in bus j of radial distribution feeder. In this paper, we consider D-STATCOM application only for transferring reactive power. Many of distribution systems have a radial structure that is fed through one side. It is assumed that three phase radial distribution feeder has a balance condition.

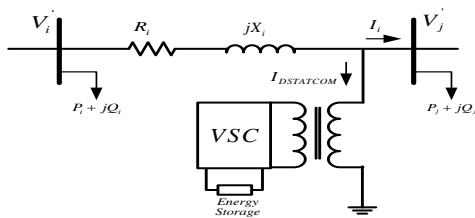


Figure 1. D-STATCOM installation in bus j of radial distribution feeder

In this investigation, D-STATCOM device is used for compensating voltage of bus j of radial distribution feeder to desirable value as can be seen in Figure 1; Phasordigram is available in Figure 2. Considering the system voltage, consequently,  $I_{DSTATCOM}$  should be kept in quarter.

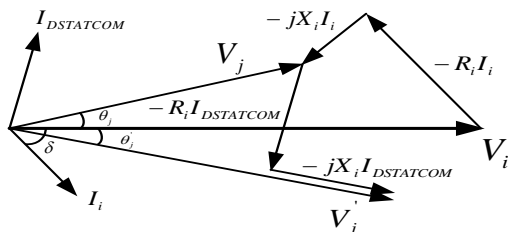


Figure 2. Phasor diagram of voltage and current of system in Figure 1 after D-STATCOM installation

According to the Figure 1 with D-STATCOM installation in bus j, currents  $I_i$  and  $I_{DSTATCOM}$  flow in branch, simultaneously and based on Phasor diagram in Figure 2, we have:

$$\angle I_{DSTATCOM} = \frac{\pi}{2} + \theta'_{i+1} \quad (6)$$

$$V'_j \angle \theta'_j = V'_i \angle \theta'_i - \left( \begin{matrix} R_{ij}(n) \\ +jX_{ij}(n) \end{matrix} \right) \cdot \left( \begin{matrix} I_i \angle \delta \\ +I_{DSTATCOM} \angle (\frac{\pi}{2} + \theta'_j) \end{matrix} \right) \quad (7)$$

By separating real and imaginary parts of equation 7 and some calculations, we have:

$$x = \frac{-B \pm \sqrt{\Delta}}{2A} \quad (8)$$

$$x = \sin \theta'_j \quad (9)$$

$$x = \frac{-B \pm \sqrt{\Delta}}{2A}$$

$$x = \sin \theta'_j$$

$$A = (a_1 a_3 - a_2 a_4)^2 + (a_1 a_4 + a_2 a_3)^2$$

$$B = 2(a_1 a_3 - a_2 a_4) \cdot (V'_j) \cdot (-R_{ij}(n))$$

$$C = (V'_j \cdot R_{ij}(n))^2 - (a_1 a_4 + a_2 a_3)^2$$

$$a_1 = \text{Real}(V'_i \angle \theta'_i) - \text{Real}\left(\begin{matrix} R_{ij}(n) \\ +jX_{ij}(n) \end{matrix}\right) \cdot (I_i \angle \delta)$$

$$a_2 = \text{Imag}(V'_i \angle \theta'_i) - \text{Imag}\left(\begin{matrix} R_{ij}(n) \\ +jX_{ij}(n) \end{matrix}\right) \cdot (I_i \angle \delta)$$

$$a_3 = -X_{ij}(n) \quad a_4 = -R_{ij}(n)$$

As can be found from equation block9, there are two roots for variable x and therefore two values for  $\angle I_{DSTATCOM}$  and  $|I_{DSTATCOM}|$  are calculated. To determine the correct solution, boundary conditions in these roots have been tested as (10).

$$V'_j = V_j \rightarrow \left\{ \begin{matrix} I_{DSTATCOM} = 0 \\ \theta'_j = \theta_j \end{matrix} \right\} \quad (10)$$

The results show that the correct answer to equation 7 for  $|I_{DSTATCOM}|$  and  $\angle I_{DSTATCOM}$  are calculated with appropriate separated real and imaginary equations as below (11) and (12):

$$\angle I_{DSTATCOM} = \frac{\pi}{2} + \theta'_j = \frac{\pi}{2} + \sin^{-1} x_{ij}(n) \quad (11)$$

$$|I_{DSTATCOM}| = \frac{V'_j \cos \theta'_j - a_1}{-a_4 \sin \theta'_j - a_3 \cos \theta'_j} \quad (12)$$

Therefore, current and voltage Phasors of D-STATCOM in the point of common coupling with network can be calculated by relations (10), (11) and (12). Finally, injected reactive power to network by D-STATCOM to recover bus voltage to desire value  $V'_j$  can be express as below relation (13) which “\*” is conjugation mark.

$$jQ_{DSTATCOM} = \left( V_j' \angle \theta_j' \right) \cdot \left( I_{DSTATCOM} \angle \frac{\pi}{2} + \theta_j' \right)^* \quad (13)$$

To evaluate network power flow considering D-STATCOM in distribution system for any iteration of forward sweep, the magnitude of compensated bus voltage can be assumed equal to desirable value (1 P. U.), phase angle of compensated bus, reactive power and size of D-STATCOM can currently be calculated by above equations. Voltages are up to dated and reactive power injection by D-STATCOM is applied to continue the forward sweep and with goal of determining load current in the next backward sweep. This process is repeated until power flow can converge [10].

### 3. Voltage Stability Index (VSI)

Based on voltage level, electrical power systems can be divided in generation, transmission and distribution systems. Modern distribution networks are faced with load demand increment, and also, experience significant changes in load demand from low to high levels during a day. In different industrial areas of distribution network, voltage collapse has been observed under critical load demand. In ref. [11], real occurrence of these phenomena have been reported which system voltage periodically collapsed and to avoid the repetition of voltage collapse, fast reactive compensation has been required. Up to now, a few investigations have been carried out about voltage stability in radial distribution networks, unlike transmission systems. In this paper, voltage stability index (VSI) proposed in ref. [12] is applied to identify weak buses of radial distribution networks due to its simplicity and enough accuracy. The node in which VSI value is minimum, related to other nodes, is more susceptible to voltage collapse. Consider Figure 3 and Figure 4 for mathematical formulation of voltage stability index. After forward-backward power flow study, voltage and current of all branches and nodes are known, therefore the values of  $P_j^{\text{total}}(n)$  and  $Q_j^{\text{total}}(n)$  for node  $j = 2, 3, \dots, \text{NB}$  can be easily calculated and then  $VSI_j(n)$  will be determined.

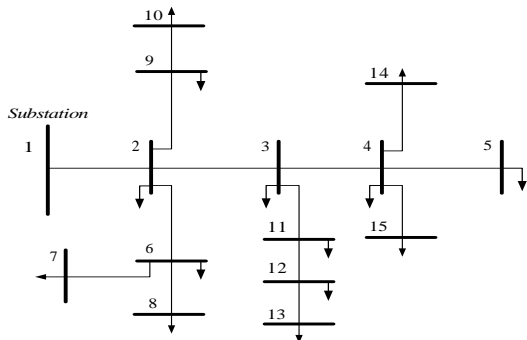


Figure 3. single line diagram of 15-bus radial distribution feeder

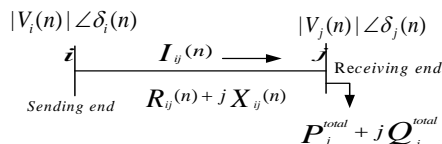


Figure 4. equivalent circuit of radial distribution feeder for Figure 3

From ref. [6] voltage stability index can be formulated as below relation (14):

$$VSI_j(n) = |V_i(n)|^4 - 4.0 \left\{ \begin{array}{l} P_j^{\text{total}}(n) \cdot x_{ij}(n) \\ -Q_j^{\text{total}}(n) \cdot R_{ij}(n) \end{array} \right\}^2 - 4.0 \left\{ \begin{array}{l} P_j^{\text{total}}(n) \cdot R_{ij}(n) \\ +Q_j^{\text{total}}(n) \cdot x_{ij}(n) \end{array} \right\} |V_i(n)|^2 \quad (14)$$

Indexes  $P_j^{\text{total}}(n)$  and  $Q_j^{\text{total}}(n)$  are total active and reactive powers fed to load and branches which are connected to receiving node  $j$  of branch  $n$  ( $j = 2, 3$  to  $\text{NB}$ ). For steady state operation of radial distribution networks,  $VSI_j(n)$  should be greater than zero and lower than one, for all nodes of the network. By use of voltage stability index calculation, stability level of radial distribution network can be measured and consequently if VSI is weak, then, proper operation should be performed.

### 4. Problem Formulation

By development in management system and distribution automation, the load demands among feeders and secondary bus of sub-transmission substation can be estimated for a day to one year via short-term and long-term forecasting methods. Therefore, by determining annual load profile which consists of load levels and its durations, D-STATCOM placement optimization problem in radial distribution network in presence of DGs can be formulated and solved by the goal of loss reduction and voltage stability improvement.

#### 4.1. Objective Function of D-STATCOMs Placement in Radial Distribution Feeders

In this paper, optimal number, location and size of DSTATCOMs are determined, considering DGs presence in radial distribution networks. Objective Function (OF) is minimizing the sum of two important terms with appropriate weighting factor. First one  $\text{Cost}'$  is total normalization value of active power losses cost and D-STATCOMs installation and operation costs. Second term is reverse value of normalized critical bus voltage stability index  $VSI'_{\text{CrT}}$  in three low, medium and peak load-levels. Indeed, objective function is implicitly a cost-benefit analysis between total saving in active losses cost against D-STATCOMs installation and operation costs and simultaneously improve voltage stability characteristic of network buses whose mathematical formulation has been expressed as relation (15).

$$\text{OF} = \left[ W_1 * \text{Cost}' + W_2 * \left( \frac{1}{VSI'_{\text{CrT}}} \right) \right] \quad (15)$$

Weighting factor  $W_1$  and  $W_2$  can be selected based on priorities of decrease in network costs and voltage stability characteristic of radial distribution system. Index  $\text{Cost}'$  is defined as relation (16).

$$\text{Cost}' = \frac{\text{Cost}}{\text{Cost}_{\text{max}}} \quad (16)$$



In above relation  $Cost_{max}$  can be calculated by summation of distribution network losses cost without D-STATCOM presence ( $P_{LOSS_i}$ ) and annual investment cost of D-STATCOM including installation and operation with regard to three low, medium and peak load levels. So, index cost is defined as follow relation (17). Index  $K_e$  shows the cost of energy losses and  $T_i$  is time duration of  $i$ th load level and  $K_{ci}$  is the ratio of time duration of  $i$ th load level to total time period [13]. Index  $P_{lossi}^{With DSTATCOM}$  is active power losses of distribution network in  $i$ th load level after D-STATCOM installation and operation.

$$Cost = \left[ \begin{aligned} &K_e \cdot \sum_{Li=1}^{nLi} (T_i \cdot P_{lossi}^{With DSTATCOM}) \\ &+ \sum_{Li=1}^{nLi} (K_{ci} \cdot cost_{DSTATCOM-year_i}) \end{aligned} \right] \quad (17)$$

Investment cost of D-STATCOM can be extracted by mathematical formulation as relation (18).

$$\begin{aligned} &cost_{DSTATCOM-year_i} \\ &= cost_{DSTATCOM_i} \cdot \left( \frac{(1+B)^{n_{DSTATCOM}} \times B}{(1+B)^{n_{DSTATCOM}} - 1} \right) \end{aligned} \quad (18)$$

Index  $cost_{DSTATCOM-year_i}$  shows the annual cost of D-STATCOM in  $i$ th load level,  $Cost_{DSTATCOM_i}$  is investment cost assigned to  $i$ th load level,  $B$  is the asset rate of return and  $n_{DSTATCOM}$  is longevity of D-STATCOM [14]. Total cost saving (TCS) is the difference between total energy losses cost before installation and total energy losses cost and annual cost of D-STATCOM after installation in different load levels which is calculated by relation (19).

$$\begin{aligned} TCS &= K_e \cdot \sum_{Li=1}^{nLi} T_i \cdot P_{LOSS_i} \\ &- K_e \cdot \sum_{Li=1}^{nLi} T_i \cdot P_{lossi}^{With DSTATCOM} \\ &- \sum_{Li=1}^{nLi} K_{ci} \cdot cost_{DSTATCOM-year_i} \end{aligned} \quad (19)$$

Index  $VSI'_{Crt}$  in OF is defined as relation (20) by dividing  $VSI_{crt}$  to  $VSI_{max}$ .

$$VSI'_{Crt} = \frac{VSI_{crt}}{VSI_{max}} \quad (20)$$

Indexes  $VSI_{crt}$  and  $VSI_{max}$  show respectively the weakest and the strongest network buses as voltage stability characteristic in three load levels by performing forward-backward power flow study during solution of D-STATCOM placement optimization problem.

## 4.2. Technical Constraints in Radial Distribution Feeders

Usually, voltage control and reactive power management in long-term scheduling have been performed via optimal placement of D-STATCOM and other reactive resources in radial distribution network to maintain network in static

safe operation limits and improve voltage stability profile. The limits that should be satisfied for the optimal placement of D-STATCOM in presence of DGs in radial distribution system are as follows:

### 4.2.1. Permissible Range of Bus Voltage and line Current Magnitude

In steady state conditions, buses voltages and lines currents magnitude of radial distribution feeder should be in permissible range.

$$|V_{i-min}| \leq |V_i| \leq |V_{i-max}| \quad (21)$$

$$|I_{ij-min}| \leq |I_{ij}| \leq |I_{ij-max}| \quad (22)$$

### 4.2.2. Reactive Power Injection Limit of D-STATCOMs

In steady state conditions, D-STATCOM reactive power injection should be in allowable range to the bus to which it is connected.

$$0 \leq Q_{DSTATCOM} \leq Q_{DSTATCOM max} \quad (23)$$

### 4.2.3. Active and Reactive Power Generation Limit of DGs

In steady state conditions, active and reactive power generation constraints of DGs are modeled as relations (24), (25) and (26).

$$P_{DG min} \leq P_{DG} \leq P_{DG max} \quad (24)$$

$$Q_{DG min} \leq Q_{DG} \leq Q_{DG max} \quad (25)$$

$$P_{DG}^2 + Q_{DG}^2 \leq S_{DG max}^2 \quad (26)$$

Indexes  $P_{DG}$  and  $Q_{DG}$  are active and reactive power generation of DG units, respectively. Indexes  $P_{DG min}$  and  $P_{DG max}$  are minimum and maximum active power generation of DGs units, respectively. Index  $Q_{DG min}$  and  $Q_{DG max}$  are minimum and maximum reactive power generation of DGs respectively. Index  $S_{DG max}$  is maximum apparent power of DGs.

## 5. Proposed DICA-NM Hybrid Algorithm

Imperialistic Competition Algorithm (ICA) is a new method in evolutionary computations that helps to find optimal solution to different optimization problems. This algorithm presents a solution to different problems by mathematical model of political-social human evolution process. From application viewpoint, this algorithm is categorized in optimization evolutionary algorithms like Genetic Algorithm (GA), Particle Swarm Optimization (PSO), Ant Colony Optimization (ACO), Simulated Annealing (SA), which lead to global optimal solution. Similar to other algorithms in this category, ICA provides a primary set of probabilistic solutions. The assimilation policy, imperialistic competition and revolution construct the basis of this algorithm. This algorithm presents the operators in a regular form as an algorithm which can help to solve complex optimization problems by imitation of social evolution, economic and political processes in countries and mathematical modeling of parts of these processes. Indeed, Algorithm sees the optimization

problem' solutions in form of a country and, tries to gradually improve these solutions during repetitive process and finally get to optimal solution. Similar to other evolutionary algorithms, this algorithm also begins with a number of primary random populations which each of them has been called a country. Some of the best population elements (equal to genes in genetic algorithm) are selected as imperialist. The rest of the populations are called colonies. Imperialists, depending on their power draw these colonies to their side with a special procedure that is explained later. Total power of each empire depends on both imperialist country (as central core) and its colonies. In mathematical form, this dependency is modeled by imperial power definition as summation of total power of imperial country and a percentage of its colonies' average power. After forming primary empires, their imperialistic competitions begin between them. Each empire which cannot be success in imperial competition and increase itself power (or at least maintains its power), will be removed from imperialistic competition scene. Therefore, an imperial survival would be in absorbing and seizing the territory of adversary empires. Thus, during imperialistic competitions, gradually bigger empires gain more power and the weaker ones will be eliminated. Empires to increase their power will have to expand their territories [15]. Imperialistic competition repetitively continues and in different populations until just one empire remains that is the global optimal solution of problem [16,17]. NelderMeadalgorithm is one of the best known algorithms and also a very fast method for finding local optima in multi-dimensional unconstrained optimization problems. Unlike gradient method, this method does not use function derivatives for finding optimal solution. Nelder mead algorithm converges to local optima by constructing a unique structure. By use of this unique structure, search in different directions with high potential has been performed to optimize the objective function. Unique structure in NelderMead method is defined as a geometrical figure which is composed of  $N + 1$  points that are considered as the vertices of a working simplex which  $N$  is the number of variables of objective function in optimization problem. In each iteration NM algorithm starts calculating the reflection of worst point (vertex with maximum value in objective function) along the central point (vertex with mid value in objective function). Based on the calculated value in first step, NM algorithm performs expansion and contraction actions in new structure. In other words, values of objective function in each iteration has been evaluated for all vertices of created structure and highest value of objective function for each vertex of structure in each iteration replaces the worst value calculated from previous step and otherwise structure is contracted in along the best point (vertex with lowest value of objective function). This process will be repeated until desired error is achieved. Convergence speed is affected by tree parameters:  $\alpha$ ,  $\beta$  and  $\gamma$  which are coefficients of reflection, contraction and expansion, respectively [18]. It should be noted that ICA-NM hybrid algorithm operation is based on real numbers. With regard to structure of problem variables, solution is categorized in two parts: in first part with regard to maximum permissible number of D-STATCOMs, the buses numbers which D-STATCOMs should be installed on determined locations and in second

part the size of D-STATCOM and DGs generation in three load levels are determined. Figure 5 shows flowchart of DICA-NM hybrid algorithm. Because buses' numbers as problem variables of D-STATCOM placement in first part are discrete types, here ICA algorithm cannot be directly used in problem solution and therefore DICA-NMHybrid Algorithm is applied for aforementioned problem solution. Under these conditions, DICA-NM search space for problem variables in first part will be according to relation (27) for  $j \leq n_{\max}$  and ICA-NM search space in second part will be as relation (28) for  $j > n_{\max}$ .

$$x_{ij} = x_j^{\min} + \text{fix} \left( \text{rand}(0,1) \left( x_j^{\max} - x_j^{\min} \right) \right) \quad (27)$$

$$x_{ij} = x_j^{\min} + \text{rand}(0,1) \left( x_j^{\max} - x_j^{\min} \right) \quad (28)$$

That  $\text{fix}(\cdot)$  is used to get to the integer part and also  $x_{ij}$  should be limited as follows (29):

$$\left\{ \begin{array}{ll} 0 \leq x_{ij}(\text{new}) \leq nb & \text{if } j \leq n_{\max} \\ P_{\text{DG.min}} \leq x_{ij}(\text{new}) \leq P_{\text{DG.max}} & \text{if } j > n_{\max} \end{array} \right\} \quad (29)$$

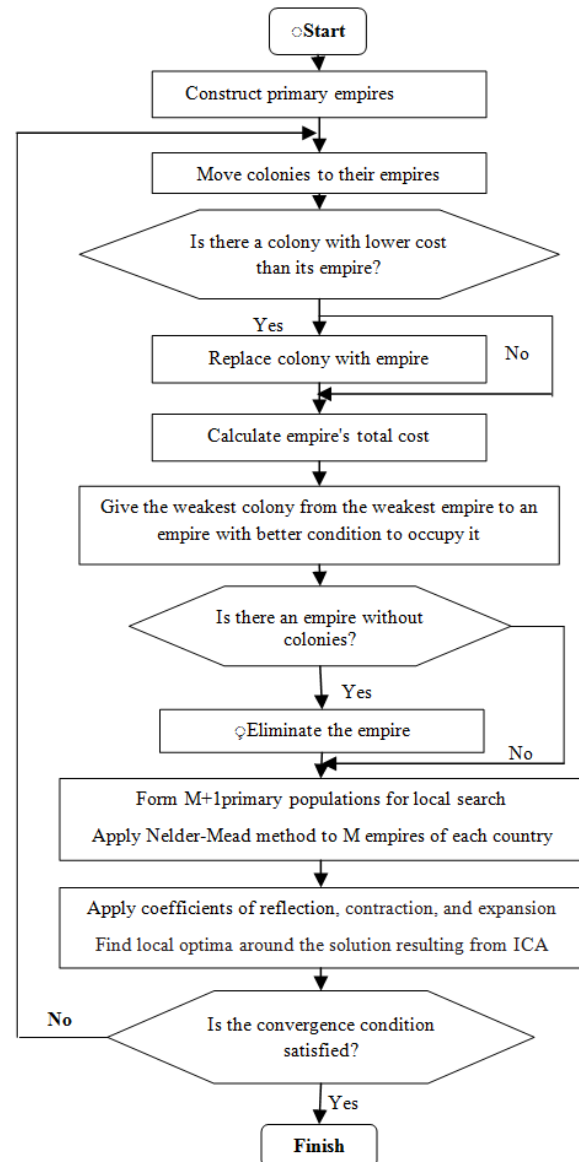


Figure 5. flowchart of DICA-NM hybrid algorithm for D-STATCOM placement

Indexes  $n_b$  and  $n_{max}$  are the number of network buses and maximum permissible number of D-STATCOMs for installation, respectively.

## 6. Simulation Studies

In this section to validate the effectiveness and performance of proposed DICA-NM hybrid algorithm, optimization problem of D-STATCOM placement in presence of DGs has been solved for 30-IEEE radial test feeder [19]. As can be seen in Figure 6, there is a sub-transmission substation 63kv/20kv, therefore voltage level of radial feeder is 20kv, and apparent power of substation transformer is 500KVA. It is assumed that optimal location of Distributed Generation (DG) was determined on bus8 based on previous network studies and its nominal rating is 4.5MVA with the power factor of 0.9.

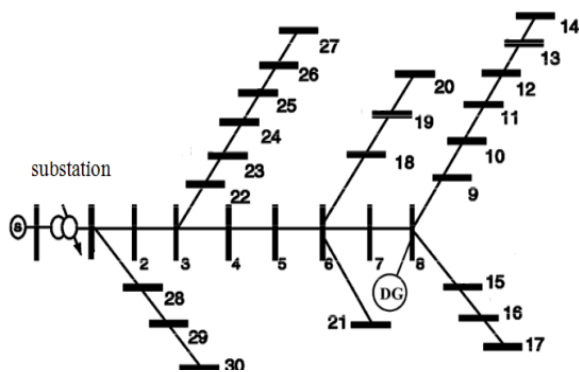


Figure 6. Single line diagram of 30-bus IEEE radial test feeder

Branches' maximum current limit is 520A. Allowable range for bus voltage magnitude is considered from 0.9 to 1.10p.u. It is assumed maximum number of D-STATCOMs which can be installed on 30-bus radial feeder is equal to 3. In addition, maximum reactive capacity of D-STATCOM ( $Q_{DSTATCOM\ max}$ ) is assumed 5000kvar. Load demands along the feeder are modeled as constant power type which can cause the worst case of voltage stability for radial distribution network. Table 1 shows investment parameters of D-STATCOMs and values of three load levels including light, medium and peak and their durations in a year. In addition, network load demand on each bus is available in ref. [20]. Proposed approach has been implemented on computer ASUS (Intel) with CPU processor 2.4GHz. Three different case studies have been considered on IEEE 30-bus radial test feeder as follow:

- 1) Radial distribution test feeder without DGs and D-STATCOM presence.
- 2) Radial distribution test feeder without DGs and with D-STATCOM presence.
- 3) Radial distribution test feeder with DGs and D-STATCOM presence.

Table 1. D-STATCOMs investment parameters in IEEE 30-bus radial test feeder

$Cost_{DSTATCOMi}$ US(\$/Kvar)	$n_{DSTATCOM}$ (year)	B	$k_e$ US(\$/KWh)
50	30	0.1	0.06
Total Demand	light	medium	peak
Duration(h)	2000	5260	1500
Load-level	0.625	0.8125	1

Achievement results and conclusion remarks related to bellow subjects for three different case studies are validated and compared: Voltage profile in each load-level, network losses costs of active power, D-STATCOM installation and operation costs in network, reactive power injection by D-STATCOM, active and reactive power injections by DGs, economic benefit of D-STATCOM installation and coordination between DG and D-STATCOMs belong to the radial feeder due to network losses reduction, and improvement in voltage stability characteristic of radial distribution feeder.

### 6.1. Case 1: Base case (Radial Distribution Feeder without D-STATCOM and DGs)

In base case study, there are no DGs and D-STATCOMs in radial test feeder. Branches power flows, active and reactive power losses and also buses voltages are determined by use of forward-backward power flow method. Total active power loss in each load-level, and critical bus which is susceptible to voltage instability have been shown in Table 2. Total active power losses cost of distribution network is equal to 109919.79 \$ in a year. In addition, simulation results show that Bus14 has the lowest VSI values among all network buses in three load levels and therefore, it is more susceptible to voltage collapse than other buses along the radial distribution feeder.

Table 2. Simulation results for base case study

Base Case	Three Load Levels		
	Light	Medium	peak
$P_{Loss_i}$ (KW)	132.68	209.65	309.24
Critical Bus	Bus14	Bus14	Bus14
$VSI_{crt}$	0.7379	0.6875	0.6447

### 6.2. Case2: D-STATCOM Placement in Radial Distribution Feeder without DGs

In second case study, it is assumed that all information as compared to base case study remains unchanged. In new case study optimization problem of D-STATCOM placement without DGs in radial distribution test feeder is solved again by DICA-NM hybrid algorithm. From simulation results in case2, Bus6 is selected as optimal location of a D-STATCOM installation in the 30-bus radial distribution feeder. It is expected that optimal amount of reactive power is injected to network by D-STATCOM and thus, as compared to case1 not only network voltage and current profiles are improved but also total active power losses cost in radial distribution network is decreased. According to our expectation, in case2 the total active power losses cost is equal to 103040.89\$ which shows 6879\$ decrement in annual cost as compared to base case study. From simulation result in case2, Total Cost Saving (TCS) in a year is equal to 4757.1\$ due to only a D-STATCOM presence in radial distribution feeder. Network active power losses, D-STATCOM reactive power injection, D-STATCOM current magnitude and its phase angle and also annual cost of D-STATCOM in ith load level have been shown in Table 3.

**Table 3. Simulation results for Case2**

Case 2	Three Load Levels		
	Light	Medium	peak
$P_{lossi}^{WithDSTATCOM}$ (KW)	127.37	193.63	296.03
$Q_{DSTATCOM}$ (KVAR)	1215	785	1842
$ I_{DSTATCOM} $ (P. U.)	2.70	1.59	3.81
$\angle I_{DSTATCOM}$ (Radian)	-1.550	-1.616	-1.623
$cost_{DSTATCOM-year1}$ (\$)	1470.55	2497.64	1672.16

From simulation result in case2,the lowest voltage stability index ( $VSI_{crit}$ ) is calculated in three load levels for **Bus14** similar to base case, but, VSI values show little increment as compared to base case study.

### 6.3. Case 3: D-STATCOM Placement in Radial Distribution Feeder with DGs

In third case study, D-STATCOM placement optimization problem is solved again in presence of DGs. In case3 similar to case2 all network information remains unchanged as compared to case1.It is assumed that one DG is installed on Bus8 in radial distribution test feeder. Now, optimization problem of D-STATCOM placement in presence of DGs can be solved again with proposed DICA-NM hybrid algorithm. It can be seen from simulation results that **Bus6** is selected again as optimal location of D-STATCOM installation and its optimal

number is one similar to previous case study (case2).Under new condition total active power losses cost of distribution network is equal to 85211.11 \$, and we can see 24708.68 \$ and 17829.78 \$ decrements as compared to case 1 and case 2, respectively, due to reactive power management coordination between D-STATCOM and DGs. From simulation result in case3, Total Cost Saving (TCS) in a year is equal to 22393 \$, due to simultaneous presence of DG and D-STATCOM in radial distribution feeder. In case 3, we can calculate the values of network active power losses, D-STATCOM reactive power injection, D-STATCOM current magnitude and its phase angle, annual cost of D-STATCOM and also DGs active and reactive power injections in three load-level as the [Table 4](#).

**Table 4. Simulation results for Case3**

Case 3	Three Load Levels		
	Light	Medium	peak
$P_{lossi}^{WithDSTATCOM}$ (KW)	120.23	154.47	244.77
$Q_{DSTATCOM}$ (Kvar)	1275	885	1735
$ I_{DSTATCOM} $ (P. U.)	3.05	1.80	3.58
$\angle I_{DSTATCOM}$ (Radian)	-1.547	-1.620	-1.624
$cost_{DSTATCOM-year1}$ (\$)	1548.03	2818.75	1574.71
$P_{DG}$ (KW)	1500	2568	4000
$Q_{DG}$ (Kvar)	376	645	1005

**Table 5. The comparison of all buses voltage magnitude in test feeder**

Magnitude of Bus Voltage ( IEEE 30-bus Radial Test Feeder )									
Case studies	Without D-STATCOM and DGs			With D-STATCOM and without DGs			With D-STATCOM and DGs		
Load-level	light	medium	peak	light	medium	peak	light	medium	peak
Bus1	0.9805	0.9782	0.9767	0.9923	0.9853	0.9927	0.9926	0.9861	0.9934
Bus2	0.9753	0.9722	0.9701	0.9894	0.9807	0.9890	0.9898	0.9816	0.9899
Bus3	0.9724	0.9685	0.9655	0.9865	0.9771	0.9846	0.9868	0.9780	0.9855
Bus4	0.9694	0.9648	0.9612	0.9851	0.9744	0.9824	0.9852	0.9755	0.9834
Bus5	0.9639	0.9580	0.9531	0.9821	0.9692	0.9780	0.9829	0.9705	0.9830
Bus6	0.9598	0.9528	0.9470	0.9806	0.9656	0.9754	0.9812	0.9671	0.9826
Bus7	0.9524	0.9432	0.9354	0.9731	0.9562	0.9653	0.9780	0.9661	0.9814
Bus8	0.9450	0.9337	0.9239	0.9655	0.9469	0.9540	0.9759	0.9656	0.9804
Bus9	0.9410	0.9286	0.9178	0.9613	0.9419	0.9479	0.9714	0.9642	0.9795
Bus10	0.9370	0.9235	0.9116	0.9571	0.9369	0.9419	0.9668	0.9593	0.9736
Bus11	0.9333	0.9189	0.9061	0.9534	0.9324	0.9364	0.9628	0.9548	0.9683
Bus12	0.9297	0.9143	0.9005	0.9496	0.9279	0.9310	0.9587	0.9503	0.9630
Bus13	0.9268	0.9106	0.8960	0.9467	0.9242	0.9265	0.9554	0.9467	0.9586
Bus14	0.9252	0.9085	0.8936	0.9451	0.9222	0.9241	0.9534	0.9447	0.9563
Bus15	0.9416	0.9292	0.9185	0.9621	0.9425	0.9487	0.9716	0.9648	0.9802
Bus16	0.9402	0.9274	0.9164	0.9607	0.9407	0.9465	0.9700	0.9630	0.9782
Bus17	0.9391	0.9260	0.9147	0.9596	0.9393	0.9449	0.9688	0.9617	0.9766
Bus18	0.9549	0.9465	0.9394	0.9746	0.9594	0.9681	0.9756	0.9610	0.9692
Bus19	0.9533	0.9446	0.9371	0.9728	0.9576	0.9659	0.9733	0.9591	0.9670
Bus20	0.9524	0.9434	0.9357	0.9717	0.9564	0.9646	0.9727	0.9580	0.9656
Bus21	0.9589	0.9516	0.9455	0.9790	0.9644	0.9740	0.9797	0.9659	0.9752
Bus22	0.9662	0.9610	0.9567	0.9804	0.9697	0.9759	0.9805	0.9707	0.9768
Bus23	0.9630	0.9572	0.9523	0.9773	0.9660	0.9715	0.9773	0.9669	0.9724
Bus24	0.9603	0.9539	0.9484	0.9746	0.9627	0.9677	0.9746	0.9637	0.9686
Bus25	0.9578	0.9510	0.9450	0.9720	0.9599	0.9643	0.9723	0.9608	0.9652
Bus26	0.9554	0.9481	0.9416	0.9693	0.9570	0.9618	0.9699	0.9580	0.9620
Bus27	0.9546	0.9472	0.9405	0.9683	0.9561	0.9605	0.9691	0.9570	0.9609
Bus28	0.9753	0.9719	0.9692	0.9865	0.9791	0.9860	0.9871	0.9799	0.9862
Bus29	0.9747	0.9711	0.9683	0.9857	0.9783	0.9843	0.9865	0.9792	0.9851
Bus30	0.9727	0.9690	0.9657	0.9836	0.9762	0.9825	0.9848	0.9770	0.9827



Results show that total network active power losses in three load-level is decreased as compared to previous case studies using coordinated reactive power management of DGs and D-STATCOM. In three case studies values of all bus voltage magnitude are in desirable ranges between 0.9 and 1.1 p. u. while their comparison comes into the Table 5. In case3 again **Bus14** is identified with the lowest VSI values in three load-level as critical network bus which shows that this bus is more susceptible to voltage instability relative to other buses of radial distribution test feeder. Change of voltage stability index (VSI) for critical network bus (**Bus14**) in each network load-level conditions including light, medium and peak have been shown in Figure 7 and for three case studies are compared. This comparison shows that VSI index for case 2 and case 3 are significantly affected in each three load-level, and these effects on VSI values are ascending especially in peak loading condition of distribution network.

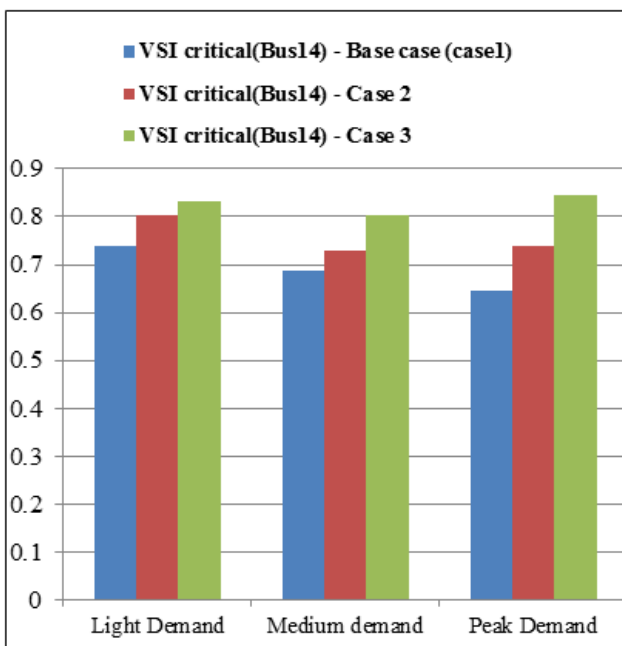


Figure 7. voltage stability index comparison between three case studies

## 7. Conclusion

In this paper a new DICA-NM hybrid algorithm is proposed for solving optimization problem of the annual D-STATCOM placement when distributed generations have been previously installed on distribution network. Objective function is minimizing the sum of normalized active power losses, D-STATCOM installation cost and the reverse value of normalized voltage stability index. Forward-Backward method is applied for power flow study in radial distribution network. Simulation analyses are applied for three case studies. Numerical results show that utilizing coordinated D-STATCOMs and DGs as voltage control and reactive power management resources cause more reduction in active power losses and more improvement in voltage profile of network buses than conditions that D-STATCOMs have been applied without DGs presence in distribution feeder. Therefore, it can be concluded that new DICA-NM hybrid algorithm that converges to optimal solution of D-STATCOM placement problem with appropriate accuracy would be comparable

to other evolutionary methods such as GA, PSO, ACO and etc.

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