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Optimal Capacitor Placement in the East part of Kabul Distribution System using Black Widow Optimization (BWO) Algorithm

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Abstract: *In this paper, for determining the optimal size and allocation of capacitors for the East part of Kabul distribution system (EKDS) a new metaheuristic algorithm is used. The objective of this work is to reduce the power loss, minimize the installation cost of capacitors and improve the nodes' voltage profile. The study is performed in three steps. First, the mathematical model of distribution network is made and power flow and losses of the network are obtained by Newton – Raphson load flow analysis method in MATLAB – R2017a environment. Then, the Black Widow Optimization (BWO) algorithm is used to obtain the optimal capacity of capacitor banks and the appropriate locations for the capacitors are determined with the help of real power loss sensitivity coefficient. At the end, the east distribution network of KDS that contains 9 main feeders and 183 buses is analyzed for different operating points (50%, 75%, 100% loads and changing of 6.25 % load over 50% light load) and obtained results are compared with the present network (without capacitor banks). The result shows that the optimized system can reduce the annual losses and also can enhance the stability of the system.*

Keywords: Capacitor placement and voltage profile improvement; Active power Losses, Black Widow Optimization Algorithm

2 Introduction

In all the developing countries the power system network is spreading, because the energy demand is increasing progressively. In the developing countries such as Afghanistan it is a big challenge to meet the energy demand that is increasing day by day. Mainly, a power system is consist of the three parts i.e. generation, transmission

and distribution. Commonly, at least 13% of generated power is wasted in distributing system only. Due to the power losses the voltage drops in the network and cause to reduces the voltage of distribution system. To reduce the power losses and improve the voltage profile of the distribution system, one of the best way is to use the optimal size and placement of the capacitor banks.

So far, due to the importance of the capacitor banks placement in distribution systems, the researchers are carried out several investigations and proposed various meta-heuristic algorithms. (Abass & D. A. Pavlyuchenko and Z. S. Hussain, Oct. 2020) used genetic algorithm (GA), imperialist competitive algorithm (ICA), and moth flame optimization (MFO) approaches to minimize total power losses and energy cost of radial distribution networks. They modeled the section of 214 buses system of an industrial area in southern Iraq. (Neelima & Subramanyam, 2011) proposed Genetic algorithm to optimize the size and location of capacitor banks for IEEE 69 bus system. For the enhancement of the voltage profile and minimization of the power losses of the system they used the software of ETAP. (Su, Chang, & Chiou, 2005), (Filho, Lacerda, & Junior, 8-12 November,2009). (Chang & Chung, Dec 2008) for the solution of shunt capacitor banks placement problem used an ant colony optimization (ACO) method. (Ghiasi & Javad, December 2016) for reduction of power losses, improvement of voltage profile and enhancement of power factor of Tehran Metro line-2 power system proposed capacitor placement solution methodology. They used the software of ETAP for power system real time implementation. (S., Sudhakara, & Vara Prasad, Nov 2018) for obtaining optimal VARs capacity and locations of capacitors for large and medium scales radial distribution systems used Ant lion optimizer. In the work of (Shwehdi, Raja Mohamed, & Devaraj, 2018) under steady and transient conditions the performance analysis of new planned 380 kV West – East inter-tie in Saudi Arabia transmission line is done. They also outlined and used GA approach to dynamically solve the problem of capacitor placement. This paper (Farzad, Ebrahim, & Sadikoglu, 2019) is about finding optimal places for adding capacitors in a typical radial network by using PSO. In calculation process they considered the harmonic distortion calculation.

There are active and reactive components in any power system. It is an effective and a common way to use capacitor banks for minimizing reactive component of the system. In (Sarkar, Chatterjee, & Ray, 2013) Roy Brillinton test system (RBTS) of 60 bus distribution is taken into account for rating and allocation of capacitors. This work is for reducing the power losses and voltage drop of the power system.

In (Tahir, Bakar, Alam, & Mazlihum, August 2019) presents the problem solution of optimal capacitors sizing and placement for IEEE four bus system, 33 bus system and real time grid station of NTDC 220 kV using GA. Branch current flow with reactive power compensation limitations is tabulated; the objective function of cost minimization for the mention system is define.

In this paper, the network of the system is mathematically modeled and using Newton – Raphson load flow analysis method to perform power flow analysis. The BWO is proposed to determine the optimal rating and allocation of capacitor banks

with the help of real power loss sensitivity coefficient in east part of Kabul distribution system to minimize power losses and to improve voltage profile of the system. the east part of KDS that contains 9 feeders and 183 buses is analyzed for different operating points (50%, 75%, 100% loads and changing of 6.25 % load over 50% load) and obtained results are compared with the present network (without capacitor banks). At the end, conclusion is presented.

2 Problem Formulation

To obtain optimal rating and placement of capacitors the following process can be done.

1. Modelling the system
2. Load flow analysis
3. Problem Optimization according to power flow constraints.

2.1 Kabul Distribution System

The network of Kabul distribution system is a complex radial network that has about tens of the main feeders and hundreds of sub – branches. A lot of the main feeders of KDS are operate without the reactive power compensation. Therefore, the network power losses and voltage drop are in high level and the power quality of the network is poor. KDS has eight sub – stations with 110 / (20 or 15) kV voltage levels.

The east – substation of the KDS has three power transformers. The capacities of transformers are 40 MVA, 25 MVA and 20 MVA and their voltage level is 110 / (20, 15) kV. In figure 1 the single line diagram of the network is shown. The necessary data of the network is obtained from the site, Afghan energy information center (AEIC), and DABS.

2.2 Load Flow

Because of its quadratic convergence and less prone to divergence with ill-conditioned problems, the Newton-Raphson power flow solution is widely used (Saadat, 2010). Due to its simplicity and accuracy, it is used in this paper for calculation of power flow analysis of Kabul distribution system.

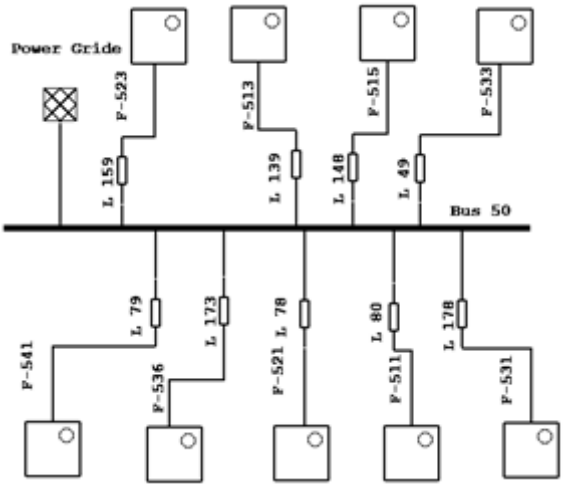


Figure 1: Under investigation distribution system

For the bus of the power system that is shown in Figure 2, the current entering bus i is given in the term of the bus admittance matrix as follow:

$$I_i = \sum_{j=1}^{n} Y_{ij} V_j \quad (1)$$

The polar form of equation (1) is as

$$I_i = \sum_{j=1}^{n} \left|Y_{ij}\right| \left|V_j\right| \angle\theta_{ij} + \delta_j \quad (2)$$

At bus i complex power is

$$P_i - jQ_i = V_i^* I_i \quad (3)$$

Substituting form (2) for I_i in (3),

$$P_i - jQ_i = V_i \angle - \delta_i \times \sum_{j=1}^{n} \left|Y_{ij}\right| \left|V_j\right| \angle\theta_{ij} + \delta_j \quad (4)$$

Separating the active and reactive parts of (4),

$$P_i = \sum_{j=1}^{n} |V_i| \left|V_j\right| \left|Y_{ij}\right| \cos(\theta_{ij} + \delta_j - \delta_i) \quad (5)$$

$$Q_i = -\sum_{j=1}^{n} |V_i| \left|V_j\right| \left|Y_{ij}\right| \sin(\theta_{ij} + \delta_j - \delta_i) \quad (6)$$

The equations (5) and (6) constitute the nonlinear algebraic equations set in terms of the independent variables, voltage magnitude in p.u. and phase angle in radians.

For each load bus, we have two equations, given by (5) and (6), and for voltage-controlled bus one equation, given by (5). Expanding (5) and (6) in series of Taylor about the initial estimate and neglecting all higher order terms results in the following linear equation set (Saadat, 2010).

$$\begin{bmatrix} \Delta P_2^{(k)} \\ \vdots \\ \Delta P_n^{(k)} \\ \Delta Q_2^{(k)} \\ \vdots \\ \Delta Q_n^{(k)} \end{bmatrix} = \begin{bmatrix} \frac{\partial P_2^{(k)}}{\partial \delta_2} & \cdots & \frac{\partial P_2^{(k)}}{\partial \delta_n} & \frac{\partial P_2^{(k)}}{\partial |V_2|} & \cdots & \frac{\partial P_2^{(k)}}{\partial |V_n|} \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ \frac{\partial P_n^{(k)}}{\partial \delta_2} & \cdots & \frac{\partial P_n^{(k)}}{\partial \delta_n} & \frac{\partial P_n^{(k)}}{\partial |V_2|} & \cdots & \frac{\partial P_n^{(k)}}{\partial |V_n|} \\ \frac{\partial Q_2^{(k)}}{\partial \delta_2} & \cdots & \frac{\partial Q_2^{(k)}}{\partial \delta_n} & \frac{\partial Q_2^{(k)}}{\partial |V_2|} & \cdots & \frac{\partial P_2^{(k)}}{\partial |V_n|} \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ \frac{\partial Q_n^{(k)}}{\partial \delta_2} & \cdots & \frac{\partial Q_n^{(k)}}{\partial \delta_n} & \frac{\partial Q_n^{(k)}}{\partial |V_2|} & \cdots & \frac{\partial Q_n^{(k)}}{\partial |V_n|} \end{bmatrix} \begin{bmatrix} \Delta \delta_2^{(k)} \\ \vdots \\ \Delta \delta_n^{(k)} \\ \Delta |V|_2^{(k)} \\ \vdots \\ \Delta |V|_n^{(k)} \end{bmatrix} \quad (7)$$

In equation (7), bus 1 is assumed as the slack bus. Jacobian matrix elements are the partial derivatives of (6) and (7), evaluated at $\Delta\delta_i^{(k)}$and $\Delta|V_i^{(k)}|$. It can be written in short form as

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_1 & J_2 \\ J_1 & J_4 \end{bmatrix} \begin{bmatrix} \Delta \delta \\ \Delta |V| \end{bmatrix} \quad (8)$$

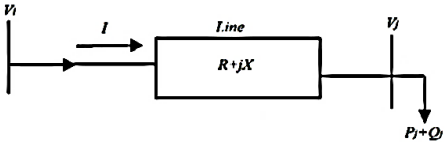


Figure 2: the single line diagram of simplified network

2.3 Objective Function

In this work, the objective function is subject to minimize the operating cost and the power losses. Mathematically, the objective function can be written as:

$OF = Minimize\ (F_1, F_2)$

F_1 and F_2 are power losses and operating cost in power system in order.

$F_1 = Minimize\ P_{i,loss} = \sum_{i=1}^{n-1} I_i^2 \times R_i$ (9)

$F_2 = Minimize\ S = K_e(P_{L,bc} - P_{L,ac})T - \alpha[K_c \sum_{i=1}^{Nc} Q_{c,i} + K_{o,m}N_c]$ (10)

In (9) and (10), $P_{i,loss}$ is real power loss in kW; I_i is line current in Ampere; R is line resistance in ohm; S is annual cost in Afg. $P_{L,bc}\ and\ P_{L,ac}$ are real power loss before capacitor banks and after capacitor banks respectively; K_e is energy cost Afg/kW; α is a depreciation coefficient; T is period of time in hour (h); K_c is the cost of capacitor banks in Afg/kVAr; $K_{o,m}$ is annual installation and operation cost in Afg; $Q_{c,i}$ is the

compensated reactive power in kVAr; and N_c is the number of compensated busses with capacitor banks. The energy losses of the system of eq. (9) subjected to system power flow constraints must become as low as possible and also the annual cost of eq. (10) must be minimized. The system constraints are as follow:

Power balance:

$$P = \sum_{i=2}^{n} P_D + \sum_{i=1}^{n} P_{i,loss} \quad (11)$$

Bus voltage limits:

$$V_{i,min} \leq V_i \leq V_{i,max} \quad (12)$$

Compensated reactive power:

$$Q_{c,min} \leq Q_{c,i} \leq Q_{c,max} \quad (13)$$

3 The Proposed Black Widow Optimization Algorithm

Black Widow Optimization (BWO) Algorithm is developed by (Hayyolalam & Kazem, 2020). The flowchart of the BWO algorithm is shown in Fig. 3. Like other meth heuristic algorithms, the proposed algorithm also starts with an initial population of spiders, therefore each spider represents a potential solution. These initial spiders try to reproduce the new generation in pairs. The male black widow is eaten by the female one during mating or after. Then she carries stored sperms in her sperm thecae and releases them into egg sacs. As least 11 days being laid, after spider lings come out from the egg sacs. They live together on the maternal web for a number of days to a week, during that time sibling anthropophagy is appeared. They are then carried away from each other in the wind. Some young spiders are even eaten by mother during that brief period. Other young spiders from the net are considered the fittest young spiders. Based on this concept different Pseudo - Code of BWO Algorithm is developed and the flowchart of the black widow optimization algorithm is shown in figure 3.

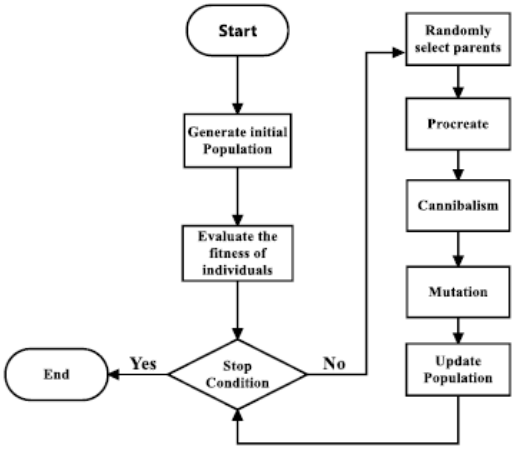


Figure 3: Flowchart of the black widow optimization algorithm.

3.1 Initial Population

For solving an optimization problem, an appropriate values structure of the problem variables must be formed as for the solution of the issue. This structure is named ''Chromosome'' in GA and ''Particle position'' in PSO terminologies, respectively, but here in black widow optimization (BWO) algorithm it is called ''widow''. In Black widow Optimization (BWO) Algorithm, the probable solution to any problem has been assumed as a Black widow spider. The values of the problem variables are shown by each Black widow spider. In this study, for solving benchmark functions, the structure is assumed as an array.

In N_{var} – dimensional optimization problem, an array of $1 \times N_{var}$ is a widow that representing solution of the problem, and defined as follows:

$Widow = [x_1, x_2, \dots, x_{N_{var}}]$

The values of each variable $(x_1, x_2, \dots, x_{N_{var}})$ is floating-point number. The widow fitness is obtained with fitness function f evaluating at a widow of$(x_1, x_2, \dots, x_{N_{var}})$. So

$Fitness = f(widow) = f(x_1, x_2, \dots, x_{N_{var}})$.

To start the optimization algorithm, $N_{pop} \times N_{var}$ size matrix of a candidate widow is generated with an initial population of spiders. Then parents pairs randomly are chosen to accomplish the procreating step by mating, in which the female black widow eats the male on during or after that.

3.2 Procreate

In this algorithm, to reproduce, an array called alpha and must be created as long as widow array that contains random numbers, then using α offspring is produced by the following equation (eq.14) in which x_1 and x_2 are parents, y_1 and y_2 are offspring.

$$\begin{cases} y_1 = \alpha \times x_1 + (1-\alpha) \times x_2 \\ y_2 = \alpha \times x_2 + (1-\alpha) \times x_1 \end{cases} \quad (14)$$

4 Simulations And Results

The system under consideration shown in figure (1) consists of F-511, F-513, F-515, F-521, F-523, F-531, F-533, F-536 and F-541 main feeders and 183 busses. In this system, transformers are taken as busses. Active and reactive loads of the system during peak are 83.27 MW and 31.99 MVAr and operating voltage of the system is 20 kV. From the obtained results of Newton-Raphson load flow analysis the real power loss is 6.928 MW, the annual lost energy is $60692.1\ \mathrm{MW \cdot h}$ and the voltages of different busses are varied from 0.77 p.u to 1 p.u. These conditions cause the system to have poor energy quality and be unstable.

Table 1. The specification of constant parameters for economical calculation

Description	**cost**
The electric energy average cost	*8 Afs/kWh*
Depreciation coefficient	*٢٠ %*
The cost of capacitor bank	*1875 Afs/kVAr*
Installation cost for one location	*120000 Afs/Location*
Annual operational cost	*22500 Afs/Location*
The number of hours in one year	*8760*

There are selected 24 busses for the placement of capacitor banks in east substation network of distribution system by using power loss sensitivity factor.

In this work, the system is studies for different operational conditions (50 %, 75 %, 100 % and 6.25 % changes over 50% light load). The specifications of the constant parameters for the economical calculations are given in table 1. The life time of each capacitor bank is assumed to 10 years.

4.1 First Operating Condition

In this operating condition the system load is assumed to be 50%. From the result obtained by Newton-Raphson load flow solution, without using capacitor banks the real power losses are 1448.7 kW (12690.7 MWh annual energy losses). In various busses of the system, the maximum and minimum voltage magnitudes are varying from to 0.9036 p.u. to 1p.u. and the power factor of all system is 0.934.

After injection of calculated capacity (the placement of capacitor banks) the power flow analysis reveal that the real power losses are decreased to 1298.6 kW (annual energy losses to 11375.83 MWh) and the maximum and minimum voltage magnitudes in various busses of the system are 1 p.u. to 0.93 p.u. and all system power factor is 0.998. The obtain results from simulation are shown in table 2 and the maximum and minimum voltage magnitudes of all busses are shown graphically in figure 4. The data in table 2 shows that the annual saving is 7.212 million Afghanis.

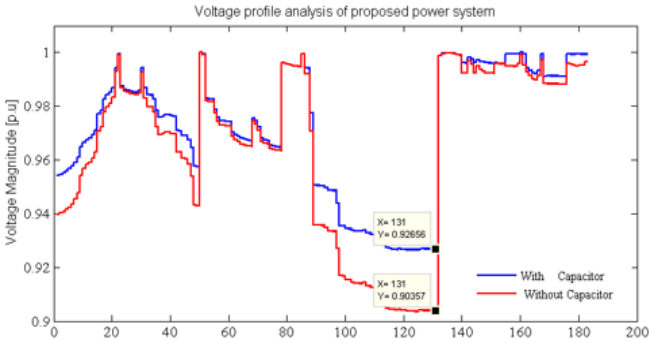


Figure 4: Voltage magnitudes of all busses

Table 2: The obtained results from the simulation of first operating case

Items	Real power loss (kW)	
	Uncompensated	Compensated
Total losses (kW)	1498.711	1298.611
Minimum voltage (p.u)	0.9036	0.93
Optimal location and size of capacitor (kVAr)	6(1000),8(839),13(396),15(462),19(595),25(740),52(136),57(387),64(370),89(1142),101(109),103(260),114(446),123(385),126(983),133(1029),136(715),141(1036),153(5),157(250),169(430),172(367),179(315),180(290)	
Total kVAr	12728	
Annual cost (Af/year)	3307000	
Annual energy saving [MWh]	1314.871	
Net saving (Af/year)	7211968	

4.2 Second Operating Condition

In this operating condition the system load is assumed to be 75%. From the result obtained by Newton-Raphson load flow solution, without capacitor banks in network

the real power losses are 3528.25 kW (30907.5 MWh annual energy losses). In various busses of the system, the maximum and minimum voltage magnitudes are varying from 1 p.u. to 0.9036 p.u. and the power factor of all system is 0.934.

After the compensation of appropriate capacity of reactive power (the placement of capacitor banks) from the power flow analysis obtained that the real power losses are decreased to 3194.192 kW (annual energy losses 27981.12 MWh), the maximum and minimum voltage magnitudes of busses are improved 0.85 p.u. to 1 p.u, and the power factor of all system is 0.987. The obtain results from simulation, the maximum and minimum voltage magnitudes of all busses are shown graphically in figure 5.

4.3 Third Operating Condition

In this operating condition the system load is assumed to be 100%. Without capacitor banks 6928.32 kW real power losses (60692.1 MWh annual energy losses) obtained. In various busses of the system, the maximum and minimum voltage magnitudes are varying from 1 p.u. to 0.77 p.u. and the power factor of all system is 0.934.

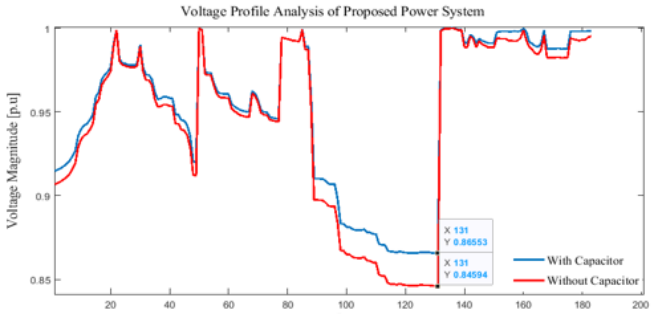


Figure 5: Voltage magnitudes of all busses

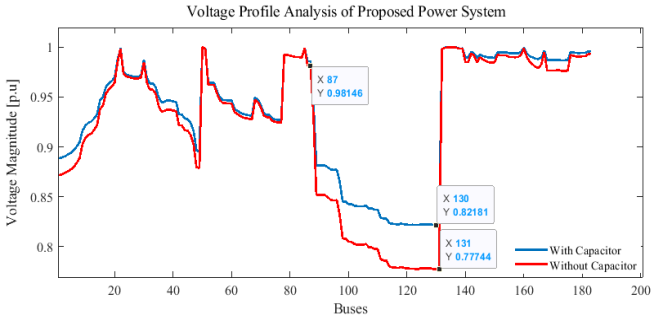


Figure 6: Voltage magnitudes of all busses

After the injection of optimized capacity of reactive power, the real power losses are decreased to 5894.75 kW (annual energy losses 51638.01 MWh), the maximum and minimum voltage magnitudes of busses are varying from 1 p.u. to 0.83 p.u., and

the power factor of all system is 0.982. The obtain results from simulation are in table 3 and the maximum and minimum voltage magnitudes of all busses are shown graphically in figure 6. The data in table 3 shows that the saving in one year is 62.762 million Afghanis.

Table 3: The obtained results from the simulation of third operating case

Items	Real power loss (kW)	
	Uncompensated	Compensated
Total losses (kW)	6927.5	5984.7
Minimum voltage (p.u)	0.77	0.934
Optimal location and size of capacitor (kVAr)	6(1317),8(90.4),13(1041),15(593),19(25),25(1030),52(237),57(513),64(135),89(846),101(74.4),103(991),114(656),123(343),126(1024),133(1252),136(45),141(862),153(1365),157(651),169(1399),172(693),179(68),180(937)	
Total kVAr	16189	
Annual cost (Af/year)	3310000	
Annual energy saving [MWh]	8258,928	
Net saving (Af/year)	62761424	

4.4 Fourth Operating Condition

Due to the system load changes, the voltage at the terminals of consumers also changes. To keep the system voltage profile within prescribed limits, one of the methods is to compensate reactive power. In this case, over 50 % the load changes of 6.25 % is considered. During the light load condition, the power losses level is lesser. In all busses of the power system, the voltage magnitudes will become higher. So, the control of voltage is necessary. During full load, because of higher line current flows, the energy losses become maximum and voltage in each bus drops.

In this operating condition, according to the load changes, optimal capacitor banks are selected. For all system busses the voltage amplitudes variations are shown in figure 7. Figure 7 reveals that the voltage reduced too much in the case of full load.

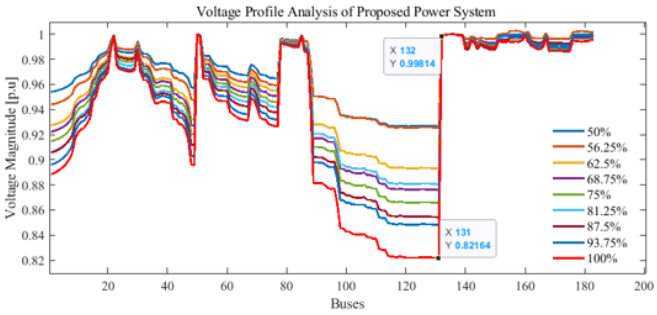


Figure 7: Voltage magnitudes of all busses

5 Conclusion

In this paper, to reduction of power loss in the east part of Kabul distribution system, the capacitor optimal size and locations are determined. East part of Kabul distribution system consists of 9 main feeders and 183 busses. The most connected loads to this system are industrial and a lot of them are inductive loads. The network of the system is mathematically modeled and using Newton – Raphson load flow analysis method to perform power flow analysis. The BWO is proposed to determine the optimal rating and allocation of capacitor. 24 busses are hired for the placement of capacitor banks with the help of real power loss sensitivity co-efficient. In the case of 50% load, for the compensation of all 100 kVAr capacity, 134 capacitor banks are proposed to install. That will cause to save 1314.9 MWh electrical energy annually which costs 7.212 million Afghani, the voltage amplitude increased from 0.9 p.u. to 0.93 p.u., and 150 kW capacity of the power flow of line is increased. In the case of 75% load, 334 kW additional power is increased to the power flow of lines, annually 2926.4 MWh energy which costs 22.324 million Afghani is saved, and the voltage profile of all busses is improved. In 100% load condition, from the simulation results obtained annual electrical saved energy is 8288.99 MWh, increased power flow of lines is 942.8 kW, and annual saved amount is 62.761 million Afghani. In 6.25 percent load changing over 50% load condition, the optimum sizes of capacitor banks and places are determined.

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Authors Profile



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