Differential Evolution Algorithm for Voltage Stability Enhancement in Electric Power Systems

Abdullah Mohammad Abusorrah

Electrical and Computer Engineering Department, College of Engineering,
King Abdulaziz University, Jeddah, Saudi Arabia
aabusorrah@kau.edu.sa

Abstract: This study introduces two modern optimization techniques for voltage stability enhancement in series-compensated transmission lines. These optimization tools have been successfully applied to the IEEE 14-bus and IEEE 30-bus power systems. Series capacitors are implemented and used as control variables to minimize the total reactive power loss in the network. The proposed approaches employ Differential Evolution Algorithm (DEA) and a Classical Optimization Technique (COT) for optimal settings of control variables. Outputs of the systems under investigation are validated and compared with earlier published study, to verify the impact of the proposed techniques. The results offer more effective and reliable performance than other published optimization algorithms.
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1. Introduction

Reactive power transfer in a power system network from source areas to consumption areas can be considered as a major risk for voltage stability issues. The risk of voltage instability is normally raised if the load demand increases or a major disturbance affect the system voltages (Kundur, 2000) and (Miller, 1983). Enhancing the voltage stability can be achieved by arranging different solutions by the network engineers. These solutions include load shedding on load areas, on-load tap changers or reactive power compensations (shunt and/or series). Moreover, violation of reactive power in the power network will lead to system voltage collapse and progressive loss of system voltage control (Yokoyama et al., 1994). In the literature, various systematic studies were developed to locate series reactive power devices in a power system (Tare and Bijwe, 1997) and (Chebbo et al., 1992). Earlier, (Chang and Saha, 2010), developed a mixed integer linear programming technique to maximize the power system loadability and to enhance the system stability. While (Memaripour et al., 2012) used the Particle Swarm Optimization (PSO) as an optimization tool for optimal reactive power planning of Electric Network. They used the Static Var Compensator (SVC) to minimize several objective functions including system voltage profile and power system losses. On the other hand, (Hamzaoglu and Makram, 1999) introduced an efficient strategy to minimize the total series reactive power loss of a power system network by detecting the best location of series capacitors in the transmission lines. They examined their technique in the IEEE 14-bus system. The technique introduced a newly defined indicator that measures the effect of series compensation in total reactive power loss. The technique offered good results on the systems under investigation. Moreover, (Kowsalya et al., 2008) modified the previous methodology with the help of modern optimization techniques. They applied Genetic Algorithm (GA) and Particle Swarm Optimization (PSO) techniques in the IEEE 14-bus and the IEEE 30-bus systems to investigate the effect of series compensation on total reactive power loss (RPL). The authors suggested an implementation of controlled series capacitors installed in specific lines of the networks. They concluded that their method was effective and efficient.

This study is intended to take the advantages of the previous researches done by Hamzaoglu and Makram (1999), and Kowsalya et al. (2008) to conduct this work. DEA will be used as an optimization technique to explore the effect of series reactive power compensation, in specific locations, on the total reactive power loss (RPL) of the networks under investigation. Additionally, the same process will be conducted again using a MATLAB© constrained nonlinear optimization routine (COT) to verify the results of DEA. After that, both optimization techniques will be compared with previously published results in (Kowsalya et al., 2008). The paper is organized in five sections. Section 2 expresses the problem under investigation, whereas, the suggested DEA is briefly described in section 3. Section 4 presents the application of DEA to voltage stability enhancement, simulation results are illustrated and discussed in this section. Section 5 concludes the study.

2. Formulation of the Problem

The effect of series compensation on total reactive power loss (RPL) will be investigated and considered as an optimization problem with specific constraints.

2.1 Objective function

The problem under investigation is discussed based on specific mathematical features which represent the formulation of the objective function and network structure. The optimization goal is to minimize the total series reactive power loss of a power system, which in turn will minimize the total reactive power loss (RPL). Moreover, Hamzaoglu and Makram (1999), and Kowsalya et al. (2008), demonstrated and explained the essential idea of series reactive power loss (SRPL) effect on power system performance.

Consider SRPL as an objective function to be minimized and subjected to a set of equality and inequality constraints. Therefore, the reactances of the compensated lines will be considered as control variables. Mathematically, SRPL of a power system is a function of system voltages, phase angles and line impedance. Hence, SRPL measured across the transmission line can be articulated as:

$$Q_{Loss}=\sum^{N_{TL}}\frac{X_L}{R_L^2+X_L^2}\{V_i^2+V_j^2-2V_iV_j\,Cos(\theta_i-\theta_j)\} \qquad (1)$$

where, N_{TL} is the number of transmission lines with an impedance $Z_L = R_L + j\,K_S.X_L$ and K_S is the degree of compensation, and $V_i\angle\theta_i$ and $V_j\angle\theta_j$ are the voltage at end buses i and j. Controlling X_L in Equation 1 will enhance the system voltage profile and lessen the reactive power loss. Hamzaoglu and Makram (1999), and Kowsalya et al. (2008) concluded that the most suitable lines for compensations can be found by searching for maximum change in SRPL in transmission lines as follows:

$$\left(\frac{X_{org}}{X_L}\right)*\sum^{N_{TL}}\frac{dQ_{Loss}}{dK_S} \qquad (2)$$

where the original reactance of the compensated line is denoted as X_{org}. Moreover, Hamzaoglu and Makram (1999), and Kowsalya et al. (2008) found that a small incremental step of 1% in compensation factor K_S at each iteration will result in small error at bus voltage values.

2.2 Network Performance Constraints

In order to maximize the loadability of a power system, the maximum load should be served by the power network without violating voltage and line flow constraints. Therefore, minimizing Equation 1 will be subjected to these constraints which can be categorized as follows:

Equality constraints

Given that the summation of the active and reactive powers at any bus is equal to zero, the equality constraints of the tested systems will be:

$$P_{Gi} - P_{Li} - P_{Ti} = 0 \qquad (3)$$

$$Q_{Gi} - Q_{Li} - Q_{Ti} = 0 \qquad (4)$$

Where, P_{Gi} , P_{Li} and P_{Ti}: generation, loads and injected active powers of the *ith* bus respectively, and Q_{Gi}, Q_{Li} and Q_{Ti}: generation, loads and injected reactive powers of the *ith* bus respectively.

Inequality constraints

The inequality constraints represent the system security limits which are described by the compensation factor, apparent power and voltage limits of the generation units, load bus voltage (V_{Li}) and transmission line flow (S_{TLi}) limit as shown:

$$K_S^{\min} \le K_S \le K_S^{\max} \qquad i=1,\ldots,N_C \qquad (5)$$

where N_C represents the number of compensated capacitance. Hamzaoglu and Makram (1999), and Kowsalya et al. (2008) recommended practical limits for the compensation value which varies between 0.3 X_L to 0.9 X_L. This constraint is very important to be considered, since it plays an important role to avoid any overcompensation might occurs in the system.

$$P_{Gi}^{\min} \le P_{Gi} \le P_{Gi}^{\max} \qquad i=1,\ldots, N_{PV} \qquad (6)$$

$$Q_{Gi}^{\min} \le Q_{Gi} \le Q_{Gi}^{\max} \qquad i=1,\ldots,N_{PV} \qquad (7)$$

where N_{PV} represents the number of generation units in the network which lays between their lower and upper limits.

$$V_{Lmin} \le V_{Li} \le V_{Lmax} \qquad i=1,\ldots,N_L \qquad (8)$$

where V_{Lmax} and V_{Lmin} are minimum and maximum load voltages of *ith* bus, practically (V_L = 1.0 p.u. ± 5%). while, N_L represents the number of load buses.

$$S_{TLi} \le S_{TLimax} \qquad i=1,\ldots,N_{TL} \qquad (9)$$

where N_{TL} denotes the number of transmission lines.

2.3 The IEEE Test Systems

In this study, a MATLAB simulation algorithm is carried out to minimize the SRPL in the IEEE 14-bus and IEEE 30-bus systems in specific locations recommended by (Hamzaoglu and Makram, 1999) and (Kowsalya et al., 2008). To investigate the computational efficiency of the proposed technique, DEA is tested and verified with COT. After that, both optimization techniques are compared with previously published results by Kowsalya et al. (2008). For the purpose of illustration and simplicity, the IEEE 14-bus system of Figure 1 is investigated first and the optimal locations of the compensated lines were found by Hamzaoglu and Makram (1999) and Kowsalya et al. (2008) to be lines 1-2, 1-5 and 2-3. In comparison, the IEEE 30-bus system has five generators and 9 load nodes (Zimmerman et al., 2011). Four of the generator nodes are PV-buses and one is taken as a slack bus and the optimal locations of the compensated lines were suggested by Kowsalya et al. (2008) to be lines 1-2, 1-3 and 2-5.

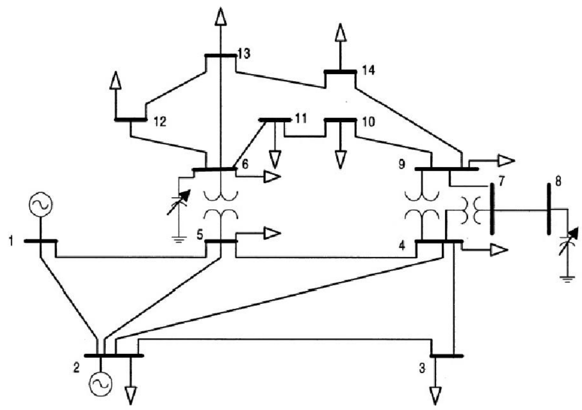

Figure 1: IEEE 14-Bus system (Hamzaoglu and Makram, 1999)

3. The Differential Evolution Algorithm (DEA)

3.1 Overview

The Differential Evolution Algorithm (DEA) was initiated by R. Storn and K. Price in 1995, and it was derived from the philosophy of natural evolution. They introduced DEA as an efficient optimization tool that resolves nonlinear problems and non-differentiable objective functions. It has the advantage of simplicity, effectiveness, fast convergence and few control variables. Moreover, DEA has the same concepts that the genetic algorithm (GA) has, such as selection, mutation and crossover operators (Abido and Al-Ali, 2012). On the other hand, the main difference between the GA and DEA techniques is the application of these operators. Therefore, the selection procedure and the differential scheme introduce DEA as a self-adaptive algorithm (Attia, 2011).

3.2 Implementation of Differential Evolution Algorithm for Voltage Stability Enhancement:

In this study, DEA is executed using prewritten MATLAB© routine. Historically, adaptation of the DEA key parameters such as mutation and crossover appropriately were one of the major problems of DEA (Choi et al., 2013). Therefore, in this study, they were adjusted with a maximum number of iteration as a stopping criteria (Attia, 2011) and (Rashed et al., 2012). The individual position vector in DEA consists of vector of control variables (K_S).The whole process of the proposed DEA is shown in Figure 2. Moreover, the following steps explain the optimal elements (Attia, 2011):

Step 1: System data and parameters of DEA are read (F, CR, NP…).

Step 2: The positions of individuals (vectors) in the searching space are initialized randomly and uniformly. Set the iteration counter; iter = 0.

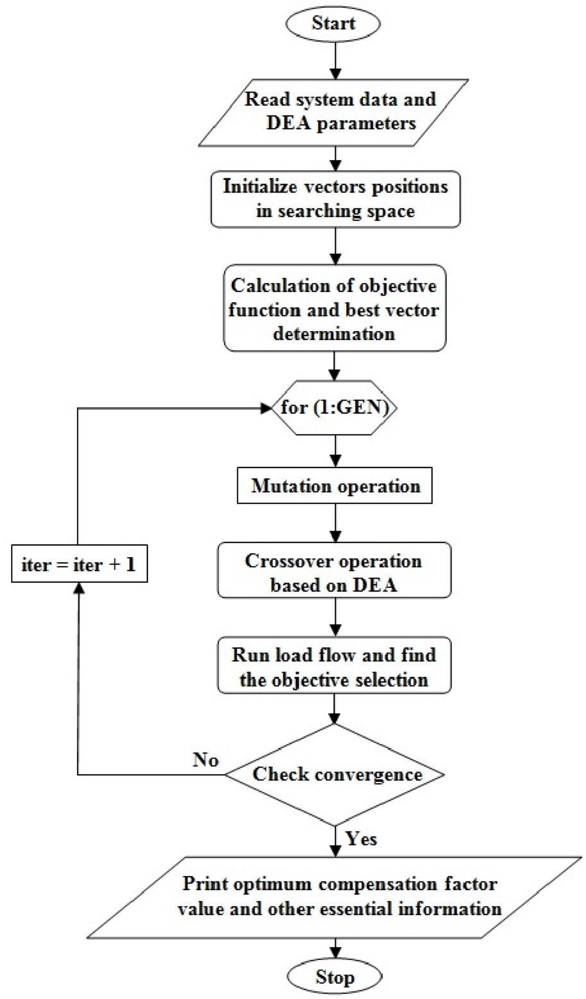

Figure 2: Flowchart of DEA for determining the optimal compensation factor

Step 3:Run the load power flow program, then from Equations 1 and (3-9) the fitness value of the initial individual can be calculated. Additionally, the objective function evaluates the initial position of each individual. This means that the variables K_S in vector x are used to determine the best fitness function. Then , the preliminary best individual between the population is attained.

Step 4: Let iter = iter + 1

Step 5:The following updating scenario is applied to update each individual position.

For every vector in the population, find a mutation difference vector based on mutation operation. Form crossover vector based on crossover operation, get trail vector based on DEA.

Step 6: Use the objective function to calculate the evaluation values of the new individuals (control variables).

Step 7: The current best individual is updated with the best individual of the last iteration.

Step 8: If a criterion is met go to step 4, typically a suitable accepted value or a maximum number of iterations is achieved.
The flowchart of DEA in Figure 2 illustrates the optimal compensation parameter.

In this study, the following values of DEA parameters are chosen for the simultaneous optimization of the objective function (Q_{Loss}), F = 0.7, CR = 0.8, NP = 50 and GEN = 2000.

4. Simulation Results

The aim of this section is to validate the performance and effectiveness of the proposed techniques. The problem is simulated to find out the optimal values of compensation degree (K_S) for the selected transmission lines in each test system. This will be achieved by conducting DEA and COT for each system under investigation to minimize the objective function (Q_{loss}) in the selected lines with optimal value of K_S.

4.1 Simulation results for the IEEE 14-bus system

The proposed approaches have been tested in the IEEE 14-bus system with satisfactory results. The system data, conditions, and limits used in the analysis are the same as those used by Kowsalya et al. (2008). The results depicted in Table 1 presents the SRPL of the three lines calculated by the four optimization tools, DEA, COT and GA, PSO (Kowsalya et al., 2008). The initial system state is presented as well, to make the comparison between the optimization techniques more feasible. In addition, Table 1 clarifies the massive difference in performance and computation accuracy between both DEA and COT on one side and the early published results, GA and PSO performed by Kowsalya et al. (2008) on the other side. Figure 3 illuminates the difference in Q_{loss} before and after the computations take place. The Figure demonstrates the COT as a powerful optimization tool as well, in fact it gives promising results compared to DEA. This proves that COT can still be considered as a primary choice in the optimization problems and one can rely on it. On the other hand, the choice of using advance optimization techniques such as DEA, GA or DEA will be essential and give significant results if the optimization problems are more complicated. Figure 4 shows the amount of compensated reactive power that can be achieved, this in turn will improve power transmission capacity and increase system stability margin. In comparison, the total reactive power loss of the system has decreased significantly to more than 44% after the optimization process, as shown in Figure 5. Furthermore, bus 5 is one of the most sensitive bus in the tested system (Hamzaoglu and Makram, 1999) and (Kowsalya et al., 2008). Therefore, Figure 6 shows the V-P curve for bus 5 which gain better stability enhancement after the optimization. Figure 6 and Figure 7 demonstrate better voltage profiles for bus 5, which conclude that minimization of SRPL results in a better stability margin and improves the system loadability. Figure 8 illustrates the voltage profiles of the tested system, all bus voltages are within the specified security limits except the slack bus which was adjusted at 1.06 p.u.

Table 1: Results of different optimization techniques for the IEEE 14-bus power system

Line	SRPL (MVAR) Initial system state	SRPL (MVAR) DEA	SRPL (MVAR) COT	SRPL (MVAR) GA [9]	SRPL (MVAR) PSO [9]
1 - 2	12.963	4.044	3.061	5.735	4.828
1 - 5	11.643	5.675	5.296	7.132	6.774
2 - 3	9.599	5.785	5.209	6.774	6.664

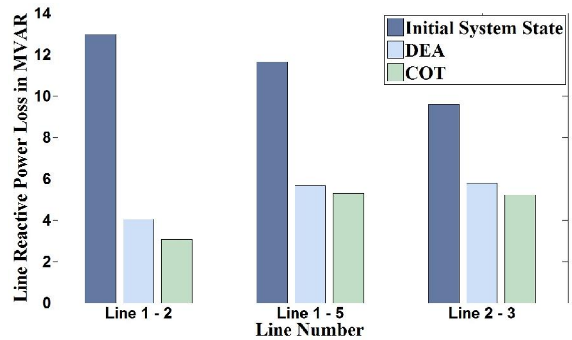

Figure 3: Reactive power losses profile with DEA and COT

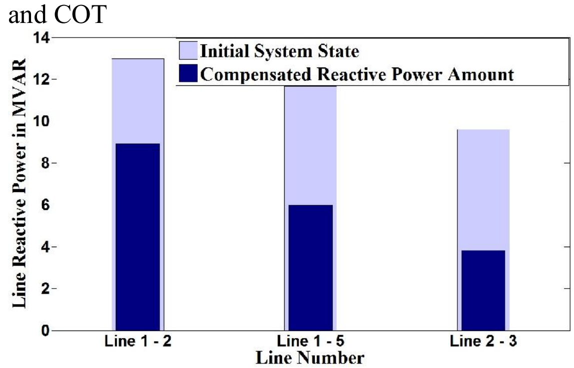

Figure 4: The amount of compensated reactive power

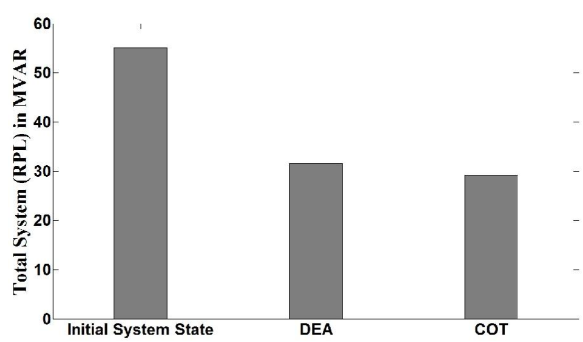

Figure 5: The total reactive power loss of the system

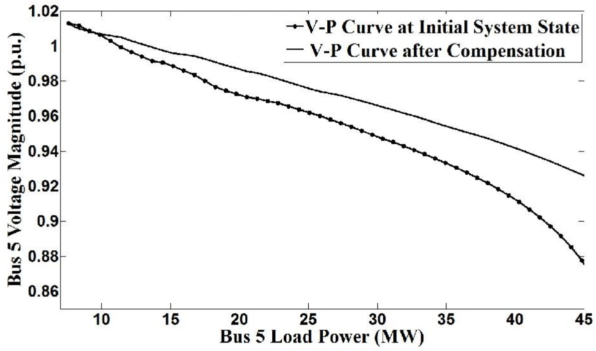

Figure 6: V-P curve for Bus 5

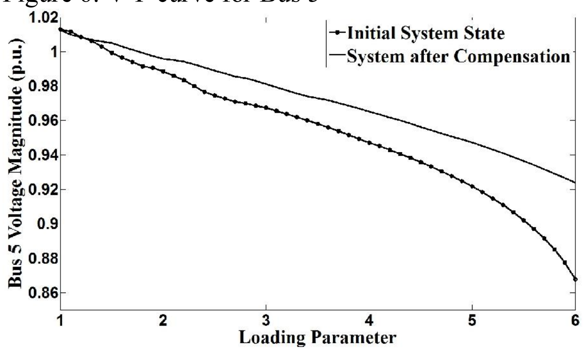

Figure 7: V-Loading Parameter for Bus 5

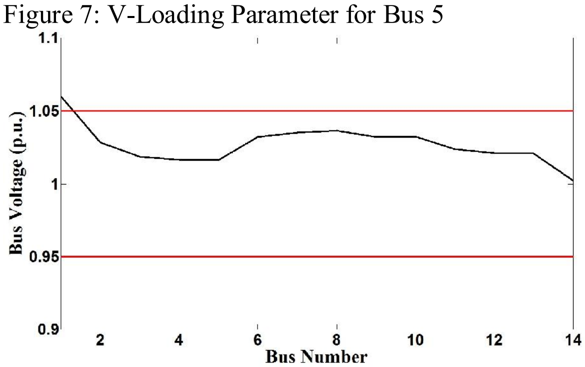

Figure 8: Voltage profiles of IEEE 14-Bus model

4.2 Simulation results for the IEEE 30-bus system

In the second test, DEA and COT are successfully applied to the IEEE 30-bus system. The comparative results from Table 2 clarify the obtained solution by DEA and COT. It presents the SRPL of the three lines calculated by the four optimization tools, DEA, COT and GA, PSO (Kowsalya et al., 2008). Demonstrating the initial system state shows the remarkable reduction in SRPL in the tested system as a result of the optimization process. Moreover, Table 2 simplifies the considerable difference in the performance of the four techniques. Figure 9 illustrates the reactive power loss profiles for the system before and after the optimization process. The Figure once more introduces comparable results between DEA and COT. Figure 10 gives us an idea about the amount of reactive power the network can compensate. Whereas, Figure 11 shows a significant reduction of 45% in total reactive power loss of the system. Therefore, the network stability margin will increase and the system loadability will improve. Figure 12 shows the voltage profiles of the tested system, all bus voltages are within the permissible security limits except the slack bus which was adjusted at 1.06 p.u.

Table 2: Results of different optimization techniques for the IEEE 30-bus power system

Line	SRPL (MVAR) Initial system state	SRPL (MVAR) DEA	SRPL (MVAR) COT	SRPL (MVAR) GA [9]	SRPL (MVAR) PSO [9]
1 - 2	10.485	4.743	4.745	6.479	4.43291
1 - 3	7.071	4.371	4.361	7.056	5.50063
2 - 5	8.151	6.912	6.986	— —	— —

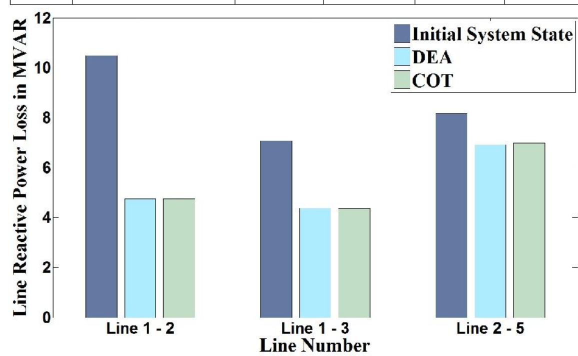

Figure 9: Reactive power losses profile with DEA and COT for the 30-bus system

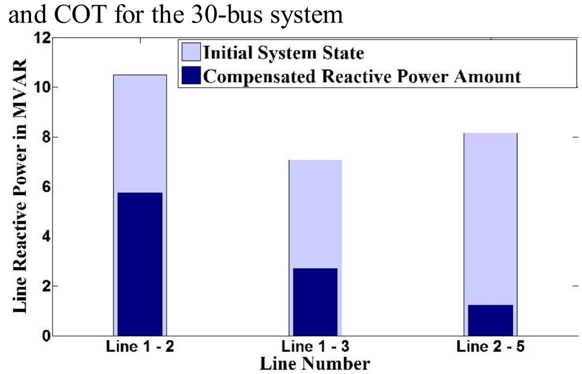

Figure 10: The amount of compensated reactive power

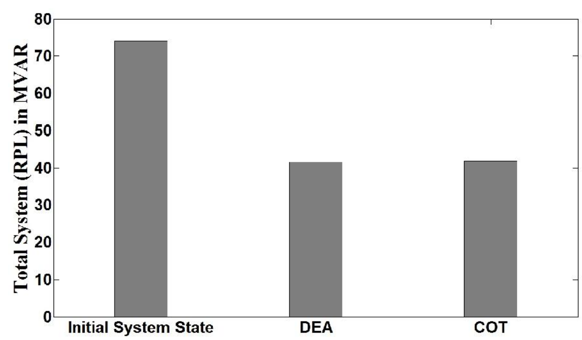

Figure 11: The total reactive power loss of the system

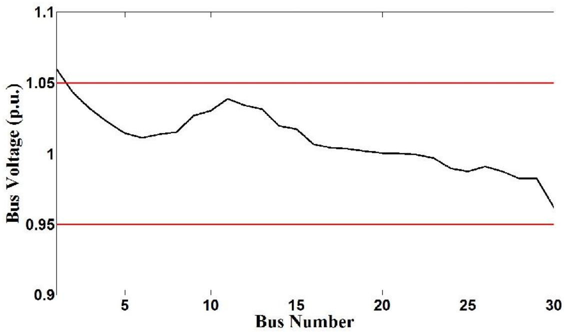

Figure 12: Voltage profiles of IEEE 30-Bus model

5. Conclusions

This paper offers a comparison study between different optimization techniques in terms of accuracy and reliability. The DEA approach is used to investigate the Voltage Stability Enhancement of two power system networks. Results of the optimization technique present DEA as an efficient and well suited tool. It offers accurate results so that RPL of the tested systems were minimized. A comparison between DEA and other optimization techniques validates the computational efficiency of it. Moreover, the study introduced the MATLAB© constrained nonlinear optimization routine (COT) as a powerful optimization tool as well. It presents promising results compared to DEA and better than GA and PSO. This proves that COT can still be considered as a primary choice in the optimization problems. On the other hand, the choice of using advanced optimization techniques such as GA, PSO or DEA will be essential and give significant results if the optimization problems are more complex or complicated. Moreover, it should be highlighted that, the scope of the current study is concentrating on the effect of series compensation on the voltage support of the power network. In a later stage, more investigation about the effect of sub-synchronous resonance to the power system network will be considered and investigated.

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Corresponding Author:
Dr. Abdullah M. Abusorrah
Department of Electrical and Computer Engineering
King Abdulaziz University
Jeddah, Saudi Arabia
E-mail: aabusorrah@kau.edu.sa

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