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REACTIVE POWER PLANNING CONSIDERING TRANSFORMER CAPACITY RELEASE USING DIFFERENTIAL EVOLUTION

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Abstract

This paper proposes a new formulation of the reactive power planning (RPP) problem. Objectives are: achieving the minimum investment cost of new injected shunt power capacitors (SPCs), maximizing the savings due to release MVA transformers capacity through transmission network, and minimizing the operation costs of power losses. These three objectives are handled as a multi-objective RPP problem using the mathematical sum approach while satisfying the equality and inequality constraints. For solving this RPP formulation, the proposed approach employs a new variant of differential evolution algorithm (DEA) (DE/best/1) which has a high capability of global search exploitation and fast convergence. The proposed approach is examined and tested on the West Delta region (WDN) system as a part of the Egyptian Unified network with different objective functions. The simulation results demonstrate the potential implementation of the proposed DE variant and show its effectiveness to solve the RPP problem.

يتناول البحث عمل نمذجه جديده لتخطيط القدره غير الفعاله فى نظم القوى الكهربيه من أجل تحقيق أقل تكاليف إستثمار لمكثفات القدره الجديده مع أقصى توفير للقدره المحرره من سعة المحولات خلال منظومة النقل وكذلك أمثل خفض لمفاقيد نقل القدره. يتم التعامل مع دوال الهدف الثلاثة بصياغة متعددة الهدف لمشكلة التخطيط للقدره غير الفعاله باستخدام طريقة الجمع الرياضي مع تلبية قيود المساواة وعدم المساواة المناظرة. ومن أجل حل هذه الصيغة فإن المقترح يستخدم نهجية مختلفة وجديده من خوارزمية التطور التفاضلي والتي لديها قدرة عالية لاستغلال البحث الشامل وسرعة تقارب نحو الحل. وقد تم فحص النهج المقترح واختباره من خلال تطبيقه على المنظومة الكهربية لمنطقة غرب الدلتا كجزء من الشبكة الموحدة المصرية. وقد أظهرت النتائج قدرةالطريقة المقترحة وفعاليتها في حل مشكلة التخطيط للقدره غير الفعاله.

Keywords: reactive power planning, transformer capacity release, losses minimization, differential evolution.

List of Symbols

I_C	The investment cost of new VAR supplies
O_C	The operational costs of power losses
e_i	Fixed VAR installation cost at bus i
C_{c_i}	Purchase cost of new VAR supplies
N_c	The reactive compensator buses
P^L_{Loss}	Power losses during the period of load level L
h	The per unit energy cost (60 $/mwhr)
d_L	duration of load level (hours)
N_L	Number of load level duration
g_{ij}	Conductance of branch between buses i and j
θ_{ij}	Voltage angle difference between buses i and j
V_i	Voltage magnitude at bus i
Q_{g_i}	Reactive power generated at bus i
N_{pv}	Number of voltage-controlled buses
T_k	The tapping change of a transformer k
N_t	Number of on-load tap changing transformers
S^{flow}	Apparent power flow
S^{max}	Maximum MVA rating of the transmission lines and transformers
N_L	Number of transmission lines in the system
Q_{c_e}	Reactive power output of existing VAR source at bus e
Q_c^{max}	Maximum capacity of VAR source
N_C	Number of existing VAR sources
$Q^n_{C_i}$	The capacitive or inductive power of new VAR source installed at bus i
P_s	Active power output at slack bus
P_s^{min}	Mainimum limit at slack bus
P_s^{max}	Maximum limit at slack bus
f_1	The operational costs of real losses in $/hr
ΔPg_s	The increasing increment of slack generated power to match the losses ($\Delta pg_s = P_{losses}$)
a_s, b_s, and c_s	The cost coefficients of slack power generation
f_2	The investment costs of new SPCs in $/hr
f_3 or S_{TR}	The savings of released MVA transformer capacities in $/hr due to new SPCs installation

MVA_1 & MVA_2	The apparent power demand before and after the additional VAR compensations
C_{TR}	The charge on the released transformer capacity in $ per MVA per hour
NP	Number of populations
F	Mutation scale
CR	Crossover rate

1.Introduction

Reactive power sources are planned and disseminated throughout the power systems to meet the future demands and ensure system performance. It is known as reactive power planning (RPP) problem. Minimization of VAR investment cost and system operational costs of real power losses, improvement of voltage profile, and enhancement of voltage stability are several objective functions with different modeling that have been utilized in the RPP problem [1]. It is a nonlinear multi-objective constrained mixed discrete optimization problem which has been handled using various conventional optimization algorithms [1 and 2].

Recently, meta-heuristic optimization algorithms (MOAs) have been widely applied to solve this problem such as simple genetic algorithm (SGA) [3 and 4], real coded GA (RGA) [5], modified non-dominated sorting genetic algorithm II (MNSGA-II) [6], covariance matrix adaptation evolution strategy (CMAES) [7], multi-objective fuzzy linear programming (MFLP) [8 and 9], particle swarm optimization (PSO) [10 and 11], and evolutionary programming [12].

Nonetheless, DEA has been used in [13] in order to solve the RPP problem for minimizing both the injected VARs as well as energy loss costs. In [14], DEA has been performed for solving the contingency constrained optimal RPP problem. In [15], fast voltage stability index has been used to identify the weak buses for the RPP problem which has been solved using DEA. In [16 and 17], DEA has been applied to solve the RPP problem after identifying the candidate buses using L-index. DE/randSF/1/bin scheme has been implemented in [15-17] which modified the commonly used strategy (DE/rand/1/bin) of DE with a self-tuned mutation parameter. Although most references executed the DEA [13-17], the only applied DE strategy is DE/rand/1/bin.

DEA has a great concern in current use due to its simplicity, efficiency and robustness. DE has been utilized in various applications in power system optimization [18]. However, DE/rand/1/bin is the most executed DE strategy. DE/best/1 has been successfully applied to the RPP problem with faster convergence characteristics and high robustness and consistence features [19].

Installation of new SPCs through transmission networks releases a significant MVA capacity of transformers which has high impact on transmission and distribution systems especially for high loaded transformers [20]. This important benefit is suggested to be incorporated in a new formulation of reactive power planning (RPP) problem. Also, a new DE variant (DE/best/1) is proposed for solving the RPP problem. This variant is distinguished with a high capability of global search exploitation and faster convergence.

2.Formulation of the RPP Problem

2.1Traditional Formulation of the RPP

Conventionally, the classical objective of the RPP is to minimize the investment cost of additional reactive power supplies and minimize the system operation costs [5-7, 13, and 14]. The formulation of the RPP model can be traditionally modeled as:

$$\text{Min } F = \text{Min } (O_C + I_C)$$
$$\text{where, } O_C = h\sum_{i=1}^{N_L} d_L P_{loss}^L \textit{ and } I_C = \sum_{i=1}^{N_c}(e_i + C_{c_i}\left|Q_{c_i}\right|) \quad (1)$$

$$P_{loss} = \sum_{i,j\in N_b} g_{ij}\left(V_i^2 + V_j^2 - V_iV_j\cos\theta_{ij}\right) \quad (2)$$

$$Q_{gi}^{min} \le Q_{gi} \le Q_{gi}^{max},\ i = 1, 2, \ldots\ldots. N_{pv} \quad (3)$$

$$V_i^{min} \le V_i \le V_i^{max},\ i = 1, 2, \ldots\ldots. N_b \quad (4)$$

$$T_k^{min} \le T_k \le T_k^{max},\ k = 1, 2, \ldots\ldots. N_t \quad (5)$$

$$\left|S_L^{flow}\right| \le S_L^{max},\ L = 1, 2, \ldots\ldots. N_L \quad (6)$$

$$0 \le Q_{Ce} \le Q_{Ce}^{max},\ e = 1, 2, \ldots\ldots. N_C \quad (7)$$

$$0 \le Q_{Cj}^{n} \le Q_{Cj}^{max(n)},\ j \in \text{candidate buses} \quad (8)$$

$$P_s^{min} \le P_s \le P_s^{max} \quad (9)$$

is the fixed VAR source installation cost (e_i) and is its corresponding purchase cost (C_{ci}) are taken equal to 1000 $, and 30,000 $/Mvar, respectively as considered in most researches [5-7, 13, and 14]. The load flow balance equations are also satisfied as equality constraints.

2.2 Proposed RPP formulation

The formulation of RPP problem can take into considerations a lot of practical aspects of installing and operating the additional SPCs into the power system so different modifications are proposed. Firstly, the model of O_C (Eq. 1) uses a linear relationship between the losses and its corresponding operational costs but, the real losses are usually matched from slack generation. Thus, it is suggested to handle the operational costs of losses regarding the fuel cost function of active power generation at slack bus which is traditionally modeled as polynomial function as follows:

$$\mathrm{Min}\, f_1 = a_s \Delta Pg_s^{\,2} + b_s \Delta Pg_s + c_s \qquad (10)$$

Secondly, the model of I_C (Eq. 1) considers only the capital purchase costs of the new SPCs while the loss in value resulting from the use of these devices during its lifetime isn't taken into account. For accurate modeling of this function, it can be expressed in terms of depreciation rate considering the actual lifetime of the VAR source, and its average working rate as follows:

$$\mathrm{Min}\, f_2 = \frac{\sum_{i=1}^{N_c} (e_i + C_{c_i} |Q_{c_i}|)}{\text{Average working rate} * \text{lifetime} * 8760} \qquad (11)$$

Where, Average working rate is usually 2/3 where lifetime is considered 15 years.

Thirdly, installing additional SPCs through power system releases a significant MVA capacity of transformers which has high impact on transmission and distribution systems especially for high loaded transformers. This important benefit is proposed to be incorporated in the RPP formulation to maximize the savings due to release MVA transformer capacities as follows:

$$\mathrm{Max}\, f_3 = S_{TR} = \sum_{i=1}^{Nc} (MVA_1 - MVA_2)_i . C_{TR} \qquad (12)$$

Where, the charge on the released transformer capacity (C_{TR}) is assumed 0.25 $/MVAhr.

Finally, these three objective functions have similar unit which is $/hr. Thus, they can be handled as multi-objective RPP optimization problem by simply converting them into one objective as follows:

$$\mathrm{Min}\, F = f_1 + f_2 - f_3 \qquad (13)$$

3.Proposed Differential Evolution Variant

DEA is a population-based stochastic search algorithm which runs through consecutive computational steps. The major stages of DEA can be described as follow:

Initialization: The DE control variables are represented as floating point numbers in the DE population of the problem. They are initialized to construct an initial population, by randomizing individuals within their feasible numerical range.

Mutation: The proposed mutation strategy selects the best individual and perturbs it with the difference of two other randomly selected vectors. This proposed variant of mutation is called DE/best/1, where DE refers to differential evolution, ("/best/") refers to a best chosen base vector and the mutation process is executed by the addition of a single ("/1/") scaled and randomly chosen difference vector [18 and 19].

Crossover: The crossover operation is then carried out to increase the diversity of the population using the binomial crossover which performed on each of the control variables.

Selection: The selection process is carried out in the last stage to compare the fitness of the trial vector and the corresponding target vector and select the parent which will survive in the next generation. Therefore, the population either gets better objective values or remains constant. Then, these stages are repeated across generations and stopped whenever maximum number of generations is reached or other stopping criterion is satisfied.

However, the control variables of RPP problem will be initialized satisfying their constraints. They might be violated during generations. In this paper, random re-initialization is used to replace the exceeded variable. For the other constraints of dependent variables, the fitness of the individual, which violates any constraint, is set to a very high value. So, the infeasible solutions, which violate the constraints, have a little chance to be transferred to the next generation.

3.1Discrete Variable Handling

Generally, the DEA solves optimization problems over continuous spaces. However, the existing and new SPCs, and tap ratio of transformers are discrete in nature. So the DE code is adjusted to handle this discrete variables with the use of an operator which rounds the variable value to the nearest integer value when it lies between two integer values. This operator is involved after the initialization and mutation process. Each individual (X) in the dimension (D) is divided into two parts as follows:

$$X_{1,.,...,D} = [Y_{1,.,.....,k}, \mathrm{round}(Z_{k+1,.,...,D})]^T \qquad (14)$$

where, Y is the continuous variables with k dimension and Z is the discrete variables with (D − k) dimension. Discrete variables with fixed step sizes Δ can be converted from integer values to discrete values as follows:

$$Z_j = Z_j^{min} + n.\Delta \quad j = 1,....., (D - k) \qquad (15)$$

where n is an integer that varies from zero to the corresponding maximum integer (n^{max}) which is determined as follows:

$$n^{max} = \frac{Z_j^{max} - Z_j^{min}}{\Delta} \qquad (16)$$

4.Simulation Results

To evaluate the performance and effectiveness of the proposed DE variant to solve the RPP problem, the WDN system as a real part of the Egyptian Unified Network is used. It consists of 52-bus and 8 generation buses, connected by 108 lines. The complete data of buses, lines, and generation are taken from Ref. [21]. The WDN system active and reactive loads equal 889.75 MW and 539.98 Mvar. The initial transmission active and reactive power losses are 19.015 MW and 64.07 Mvar, respectively. There are four violated bus voltages at buses 18 and 20-22.

Two on load tap-changer (OLTC) are considered between buses 4-25 and 11-28 while, the compensation buses are identified using the proposed iterative heuristic method (IHM) [19] which are 18, 19, 20, 21, 24, 32, 33, 35, 49 and 50 and their corresponding maximum are determined as 13.7, 0.8, 24.2, 12.7, 0.1, 10, 26.5, 3, 4.2 and 4.7 Mvar, respectively. In this system, 20 control variables are optimized and different cases are considered as follows:

Case 1: Minimization of active power losses as single objective function.

Case 2: Minimization of the investment cost and the system operational costs of active power losses (Eq. 1) as traditional formulation.

Case 3: Minimization of the investment cost (Eq. 10) and the system operational costs of power losses (Eq. 11) using the proposed RPP as follows:

$$\operatorname{Min} F = f_1 + f_2 \qquad \$/\text{hr} \qquad (17)$$

Case 4: Minimization of the investment cost, the system operational costs of power losses, and the savings of transformer capacity release as in Eq. 13.

To test the capability of the proposed DE variant for solving the mixed discrete RPP problem, the transformers taps and SPCs are modeled as discrete variables. SPCs are available in a variety of voltage ratings (240 V to 24940V) and sizes (2.5 kvar to about 1000 kvar) [22] so the capacitor banks steps were chosen to be of 0.1 Mvar. 32 steps of on-load tap changers are considered as they generally provide ±10% automatic adjustment regulation in approximately 0.625 % steps [23 and 24]. The simulation was performed using the proposed DE variant (DE/best/1) with NP = 50, F = 0.6, CR = 0.9 and a maximum of 300 iterations.

4.1 Case 1: Power losses minimization

The proposed DE variant has been implemented for Case 1 and the optimal settings of the control variables and their corresponding results are shown in Table 1. It is clear from this table that the proposed DE variant reduced the active power losses from 19.015 MW to 14.5886 MW and consequently the corresponding operational costs are reduced from 9994300 $ to 7667800 $ compared with the initial case (Case 0). This reduction is equivalent to 23.28 %. Also, the convergence characteristics of minimizing the losses over iterations are shown in Fig. 1. As shown, the proposed DE variant reaches the minimum active power losses very quickly.

4.2 Case 2: Costs minimization of the investment and the power losses: traditional formulation

The optimal settings of the control variables for Case 2 are shown in Table 1. The convergence characteristic of the DE variant for this case is shown in Fig. 2. As shown, the total costs of investment and operational losses (O_C+ I_C) are reduced from 9994300 $ to 8459900 $ with reduction of 15.34 % compared with the initial case. On the other side, it is remarked that the traditional model of O_C and I_C pushes the optimal solution towards reducing the operational costs of real losses based on controlling the existing RPP variables only without installing new SPCs.

4.3 Case 3: Costs minimization of the investment and the power losses: Proposed formulation

Table 1 shows the optimal settings of the control variables for Case 3. The convergence characteristics of the DE variant for this case is shown in Fig. 3.

Table 1 Results of different objectives for the West Delta region system

	Min	Max	Initial	Case 1	Case 2	Case 3	Case 4
Vg_1	0.94	1.06	1	1.06	1.06	1.06	1.06
Vg_2	0.94	1.06	1	1.06	1.06	1.06	1.06
Vg_3	0.94	1.06	1	1.06	1.06	1.06	1.06
Vg_4	0.94	1.06	1	1.0594	1.0595	1.0594	1.0594
Vg_5	0.94	1.06	1	1.0591	1.0591	1.0591	1.0591
Vg_6	0.94	1.06	1	1.0337	1.0339	1.034	1.034
Vg_7	0.94	1.06	1	1.0262	1.0264	1.0266	1.0266
Vg_8	0.94	1.06	1	1.0402	1.0406	1.0408	1.0407
Tap_{4-7}	0.9	1.1	1	1	1.0063	1	1
Tap_{4-9}	0.9	1.1	1	0.9938	0.9938	0.9938	0.9938
Qc_{18}	0	13.7	0	13.7	0	0.2	8.6
Qc_{19}	0	0.8	0	0.8	0	0.2	0.2
Qc_{20}	0	24.2	0	20.4	0	15.5	10.7
Qc_{21}	0	12.7	0	10.7	0	3	6.5
Qc_{24}	0	0.1	0	0	0	0	0.1
Qc_{32}	0	10	0	10.1	0	0	1.1
Qc_{33}	0	26.5	0	26.5	0	14	18.5
Qc_{35}	0	3	0	3	0	0	1.4
Qc_{49}	0	4.2	0	4.2	0	0	0.7
Qc_{50}	0	4.7	0	4.2	0	0.9	0.9
P_{losses} (Mw)	-	-	19.0151	**14.5886**	16.0957	15.2107	14.9747
O_C ($)	-	-	9994300	7667800	8459900	7994700	7870700
I_C ($)	-	-	0	2817000	0	1020000	1471000
O_C+ I_C ($)	-	-	9994300	10485000	**8459900**	9014700	9341700
f_1 ($/hr)	-	-	345.6013	32.1575	0	11.6438	16.7922
f_2 ($/hr)	-	-	0	264.5552	292.1082	275.9232	271.6095
f_1+f_2 ($/hr)	-	-	345.6013	296.7127	292.1082	**287.567**	288.4017
f_3 ($/hr)	-	-	0	11.3351	0	4.2821	6.1034
f_1+f_2 -f_3 ($/hr)	-	-	345.6013	285.3776	292.1082	283.2849	**282.2983**

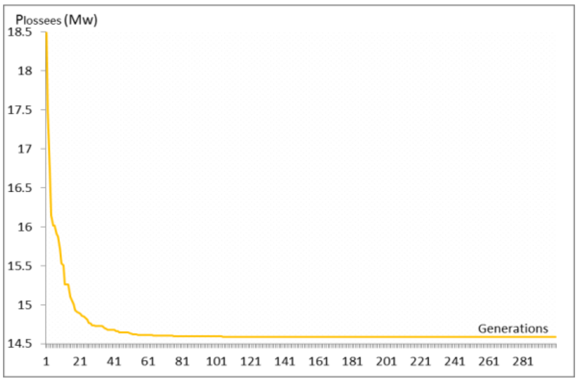

Figure 1 Convergence characteristics of power losses minimization (Case 1)

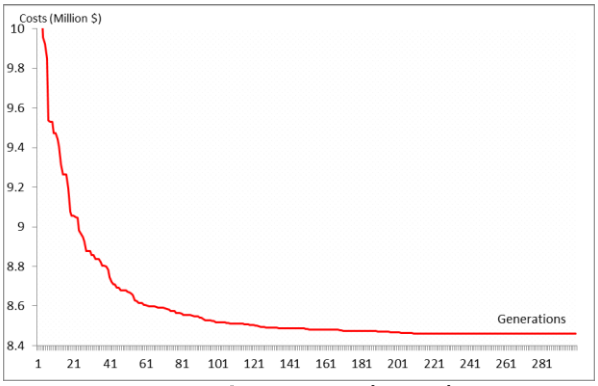

Figure 2 Convergence characteristics of costs of investment and real losses minimization (Case 2)

With aid of Table 1 and Fig. 3, the total costs of proposed investment and operational losses (f_1+ f_2) are reduced from 345.6013 $/hr to 287.567 $/hr compared with the initial case. In comparison with Case 2, it is remarked that the proposed model (f_1+ f_2) gains more reduction to the real losses to 15.2107 MW compared to 16.0957 MW with making use of the possibility for installing new SPCs. Moreover, the savings due to the capacity released from transformers are increased to 4.2821 $/hr which are nonexistent in the traditional formulation (Case 2).

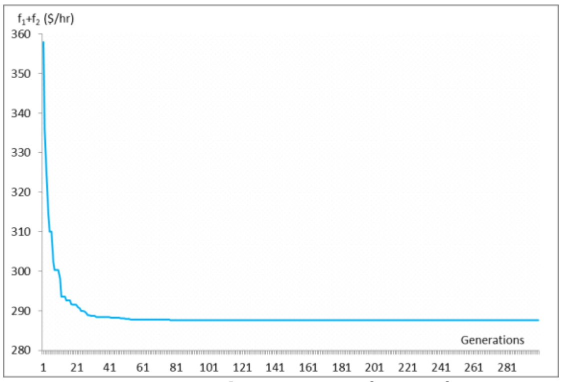

Figure 3 Convergence characteristics of costs of investment and real losses minimization (Case 3)

4.4 Case 4: Minimization of the investment cost, system operational costs of losses, and the savings of transformer capacity release: Proposed formulation

To encourage releasing more capacity from transformers, maximization of the corresponding savings is incorporated in this case with minimization of both the investment cost and the system operational costs of active power losses. The considered objective is modeled in Eq. 13. The optimal settings of the optimized variables for Case 4 are tabulated in Table 1. The considered objective (f_1+ f_2- f_3) are reduced from 345.6013 $/hr to 282.2983 $/hr compared with the initial case. It gains more reduction of the real losses as 14.9747 MW compared with 19.015, 16.0957, and 15.2107 MW in the Initial, Case 1, and Case 2, respectively. Moreover, the savings due to the capacity release from transformers are increased to 6.1034 $/hr. The convergence of this objective is shown in Fig. 4 which confirms that the proposed DE variant has excellent convergence characteristics to obtain the minimum objective value with faster convergence.

The system voltage profile obtained by the proposed DE variant in all Cases 1-4 compared to the initial case is shown in Fig. 5. It is evident that the voltage profile is greatly improved compared to that of case 0. Also, the four violated bus voltages at buses 18 and 20-22 are corrected.

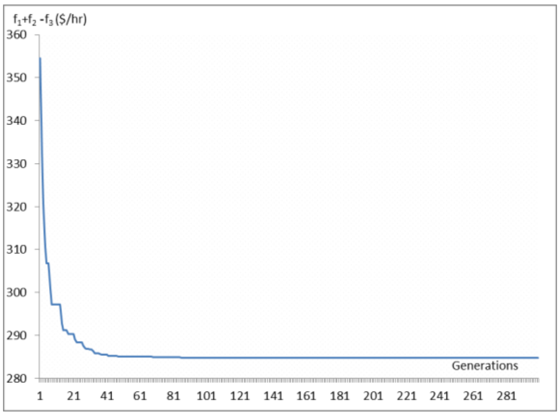

Figure 4 Convergence characteristics of the proposed objective in Case 4

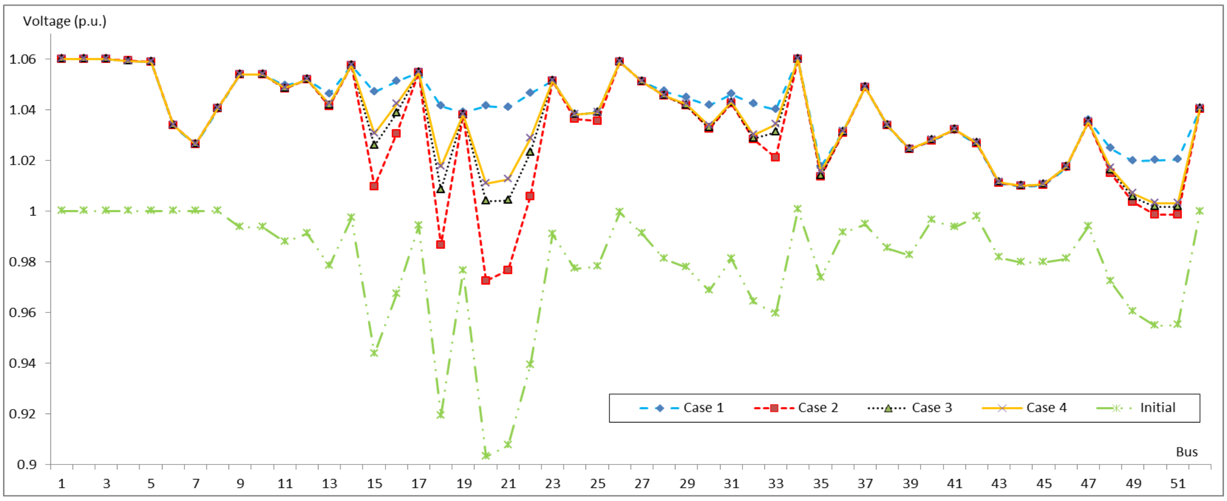

Figure 5 Voltage profile obtained by the DE variant for all studied Cases

5.Conclusions

In this paper, different modifications are introduced to the RPP problem formulation, which reveals the accurate practical considerations in handling the RPP problem. Firstly, the operational costs of active power losses is counted regarding to the fuel cost function of active power generation at slack bus. Secondly, the investment cost of new SPCs is modeled considering the loss in value resulting from its utilization during the lifetime. Thirdly, maximizing the savings due to released MVA transformers capacities through transmission network is incorporated which is highly beneficial on transmission and distribution systems especially in cases of over-loading systems. Fourthly, the RPP problem is handled as multi-objective optimization problem and mixed discrete with practical steps of SPCs and tap changers. Last but not least, a new variant of DEA, which is called DE/best/1, is proposed as a promised solution tool. It has been successfully implemented and tested on the West Delta region system as a part of the Egyptian Unified network. Not only the proposed DE variant is able to obtain the least objective values, but also it has faster convergence characteristics which confirm the high capability to explore the global minimum. This demonstrates the effectiveness and the superiority of the proposed DE variant to solve the RPP problem.

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