OPEN ACCESS
International Journal of Engineering and Advanced Technology (IJEAT)
ISSN: 2249-8958 (Online), Volume-12 Issue-6, August 2023

Differential Evolution Algorithm for Coordination of SVC Modules in MV Distribution Systems

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Abstract: ***This paper proposes a new strategy based on the differential evolution algorithm to optimize the performance of distribution networks through the optimal coordination of Static VAR Compensator modules (SVCs). Installation costs minimization and savings maximization due to reducing power losses are merged in one multi-objective function. In order to investigate the influences of varying loading conditions, various regular loadings are further combined. This framework implemented on a 37-bus real feeder connected to the Egyptian Unified Network (EUN). The findings of the simulation reveal evident technical and economical characteristics of the proposed algorithm. The reactive power compensation using SVCs based on the pro-posed scheme leads to major quality improvements of the entire nodes' voltage with variations of loads. Especially, in light loading condition, the SVCs control their performance characteristics according to the reactive power demands in the adjacent nodes.***

Keywords: ***Differential Evolution, Coordination of SVC Modules, Distribution Systems.***

I. INTRODUCTION

Any distribution network's performance faces several technological challenges. excessive power losses, excessive voltage variation, poor power factor, reactive power shortage, and congested lines are a few examples [1]. These negative consequences are caused by several characteristics of distribution grid planning and design methods, such as network architecture, long distance distribution lines, lower X/R percentage, and use of non-linear loads. In addition, the passiveness of traditional distribution networks with unidirectional power flow contributes to other power quality concerns [2],[3].

Several technological approaches have been suggested for solving the abovementioned issues. Conventionally, shunt capacitors are one of the most effectual power system compensators because of their cheapness, installation simplicity and efficient performance. Nevertheless, in light load conditions they may lead to some negative impacts such as voltage violations [4], [5]. Also, automatic voltage regulators [6], distributed generations coordinated with fault limiters [7], renewable energies integration [8] and etc. are other advanced devices to enhance the power system performance. Additionally, optimal power flow is an operational system framework with great impacts on fuel costs, power losses and voltages profile [9], [10]. Nowadays, numerous sophisticated solutions were developed to maximize the potential performance of distribution networks with the tremendous progression in the electrical field. In particular, DESs are introduced to be an eco-friendly appropriate alternative for compensating power losses in distribution networks. Furthermore, they can exchange active and reactive powers depending on their types and design. Unfortunately, these units have intermittent nature depending on the climate changes. This leads to a major hurdle for installing them in large capacities [11]. In this context, the synchronized combination between capacitors and DESs was the best way for enhancing the distribution network performance.

Today, the power electronics sector is undergoing an evolutionary transition in the area of electric energy. Specifically, Flexible Alternating Current Transmission systems (FACTs) which represents a category of instantaneous response power electronic converters. These devices have been used to maximize the power delivery efficacy, enhance voltage and network stability in a very short time. Moreover, some of them can be used with distribution systems to mitigate any power quality issues that these systems may have. For instance, SVCs modules that can be used for both transmission and distribution systems. It can generate / consume reactive power when attached to the distribution network nodes. This reactive power exchange between the SVCs and the network is helpful for introducing accelerated and smooth voltage control compared to any conventional devices. So, the best sizes and locations of SVCs have also been mentioned for optimizing the distribution grids voltage profile using various methodologies [12], [13], [14]. A diverse array of strategies have been proposed to solve the allocation issue of shunt capacitors and distributed resources such as analytical, heuristic and artificial intelligence (AI).

From another point of view, the inclusion of SVCs creates more beneficial impacts and challenges for the distribution networks. This research presents an innovative approach based on the differential evolution algorithm for optimising distribution network performance through optimum coordination of SVCs. Minimising installation costs and increasing savings by decreasing power losses are combined into a single multi-objective function. Various regular loadings are further mixed to study the effects of varied loading situations. This framework was built around a 37-bus actual feeder that was linked to the Egyptian Unified Network (EUN).

Manuscript received on 12 July 2023 | Revised Manuscript received on 23 July 2023 | Manuscript Accepted on 15 August 2023 | Manuscript published on 30 August 2023.
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The simulation results show that the suggested algorithm has obvious technical and economic properties. The proposed technique for reactive power correction utilising SVCs results in significant quality improvements of the whole node voltage with fluctuations in loads.

II. PROBLEM FORMULATION

A. Multi-objective function

Installation costs minimization and savings maximization due to reducing power losses are merged in one multi-objective function. They can be achieved by formulating the coordination among SVCs. Costs minimization function has the primacy to be minified as it includes the purchase, installation, operation and maintenance costs of the new equipment in addition to the savings resulted from installing them. This can be expressed as in Eq. (1)

$$Maximize\,(F) = f_1^{Savings} - f_1^{Expenses} \quad (1)$$

Where, F represents the total annual costs ($/year), $f_1^{Expenses}$ represents the annual expenses for the new equipments ($/year) and $f_1^{Savings}$ represents the annual savings related to installing these equipment's ($/year) [15].

B. System constraints

In order to achieve a proper performance for a specified distribution network, it must be governed by some restrictions. These restrictions judge the system performance. So that, the amount of power generated using DESs should be maintained within the range specified to prevent the system from overvoltage issues [16], [17].

$$\sum_{i=1}^{N_{DES}} P_{DES}^{i} \leq P.R_{DES} * \sum_{i=1}^{N_{bus}} P_i^{load} \quad (2)$$

Where; $P.R_{DES}$ is the DES integration ratio, P_i^{load} is the network total active demand, N_{DES} represents the number of DES units. The capacity of the SVCs modules must not exceed their allowable limits as:

$$-Q_{SVCs,i}^{max} \leq Q_{SVCs} \leq Q_{SVCs,i}^{max};\ (i = 1,2, \ldots, N_{SVCs}) \quad (3)$$

Where; $-Q_{SVCs}^{max}$ and Q_{SVCs}^{max} represent the maximum inductive and the maximum capacitive limits of the SVCs modules. While, N_{SVCs} refers to the SVCs modules number.

Additionally, the network voltage must be kept to their allowable limits as [18]:

$$V_j^{min} \leq V_{Loading} \leq V_j^{max} \quad (4)$$

Each line power flow must not exceed the maximum thermal capacity for each loading condition as [19]:

$$|S_l^{i:j}| \leq S_{max}^{i:j} \quad (5)$$

III. METHODOLOGY

Differential evolution is a population-based stochastic search algorithm [20]. major stages of this algorithm can be described as follow:

A. Initialization

The control variables are initialized to construct a population P of size NP, by randomizing individuals within their feasible numerical range. At initial generation (G=0), the jth variable of the ith population member (X) could be initialized as [21]:

$$X_{i,j}(0) = X_j^{min} + \text{rand}(0,1).\,(X_j^{max} - X_j^{min})$$
$$i = 1, \ldots, NP \text{ and } j = 1, \ldots, D \quad (6)$$

where, the superscripts min and max are lower and upper bounds of the jth variable, rand (0,1) is a random number between 0 and 1, and D is the number of variables of each individual i.

B. Mutation

After that, the mutation process generates mutant vectors (V_i) at every generation G. The proposed mutation strategy selects the best individual and perturbs it with the difference of two other randomly selected vectors as [22]:

$$V_{i,j}(G+1) = X_{r3,j}(G) + F.\,(X_{r1,j}(G) - X_{r2,j}(G)) \quad (7)$$

Where, r1, r2 and r3 are randomly integers chosen from the range [1, NP], and they are different from the individual i. X_{best} is the individual with best fitness of the current generation. F is the scale factor which is usually in the range of [0.4–1].

C. Crossover

Then, the crossover operation creates trial vectors (U_i) by exchanging the components of the mutant vectors (V_i) and the target vectors (X_i) as [23]:

$$U_{i,j}(G+1) = \begin{cases} V_{i,j}(G+1) & \text{if } \text{rand}(0,1) < C_r \\ X_{i,j}(G) & \text{else} \end{cases} \quad (8)$$

Where, C_r is the crossover probability, which is usually selected within the range [0, 1].

D. 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 will survive in the next generation which provides the best solution as follows:

$$X_{i,j}(G+1) = \begin{cases} U_{i,j}(G+1) & \text{if } f(U_{i,j}(G+1)) \leq f(X_{i,j}(G)) \\ X_{i,j}(G) & \text{else} \end{cases} \quad (9)$$

Where, f (.) is the function to be minimized. Then, these stages are repeated across generations and stopped whenever maximum number of generations is reached or other stopping criterion is satisfied.

IV. APPLICATIONS AND RESULTS

The proposed differential evolution is applied on a real distribution feeder from Egypt. This feeder consists of 37 nodes with 36 branches. Its single line diagram is depicted in Fig. 1. Its branch and load data are taken from reference [15]. Table 1 tabulates its base information.

Retrieval Number:100.1/ijeat.F42550812623
DOI: 10.35940/ijeat.F4255.0812623
Journal Website: www.ijeat.org

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The parameters of differential evolution are set with population size of 50 and maximum iteration number ($iter^{max}$) of 200.

Table 1. Data of 37-Node Case Study Feeder

Total load active power	4801.9 kW
Total load reactive power	2975.9 kVAr
Rated line voltage	11 kV

The network voltage regulation is set to ±10%. Three cases are investigated based on the number of SVC devices. Maximum locations of SVCs are set to one, two and three. In the first case, one SVC device is allocated. Two SVC devices are allocated in the second case while three SVC devices are considered in the third cases. For all considered cases, the proposed technique is applied where Fig. 2 dis-plays the regarding convergence characteristics. As well, Table 2 tabulates the locations, sizes and the operational values of the SVC devices for the light, medium and peak operating load level.

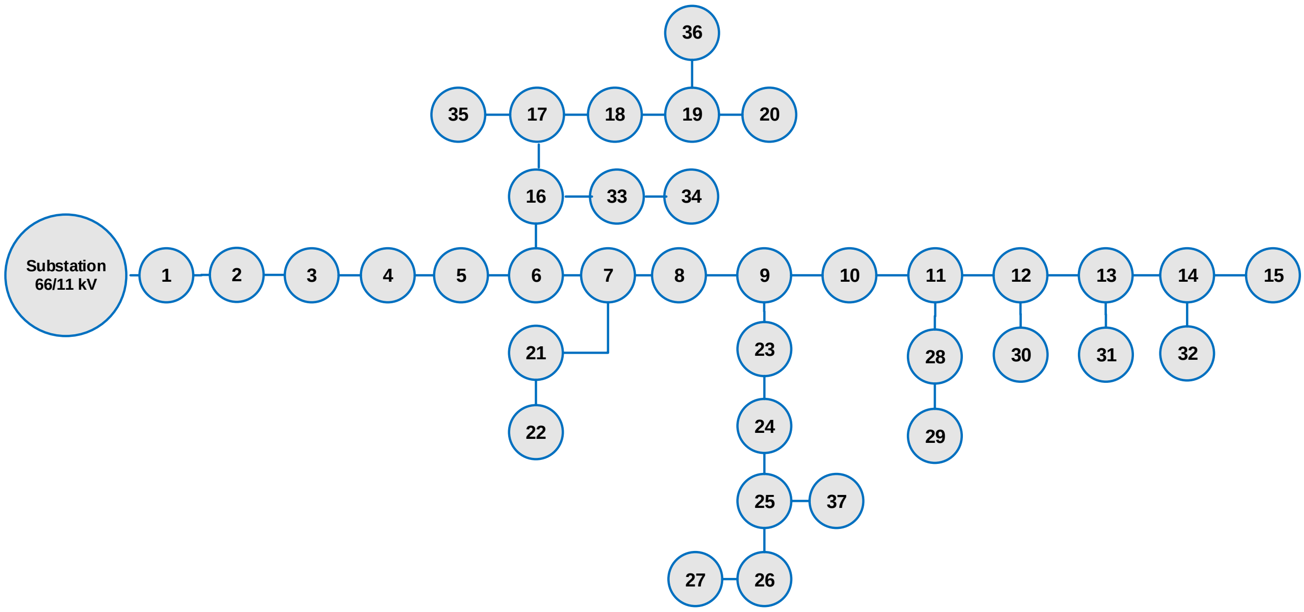

Fig. 1. Single line diagram of 37-node feeder

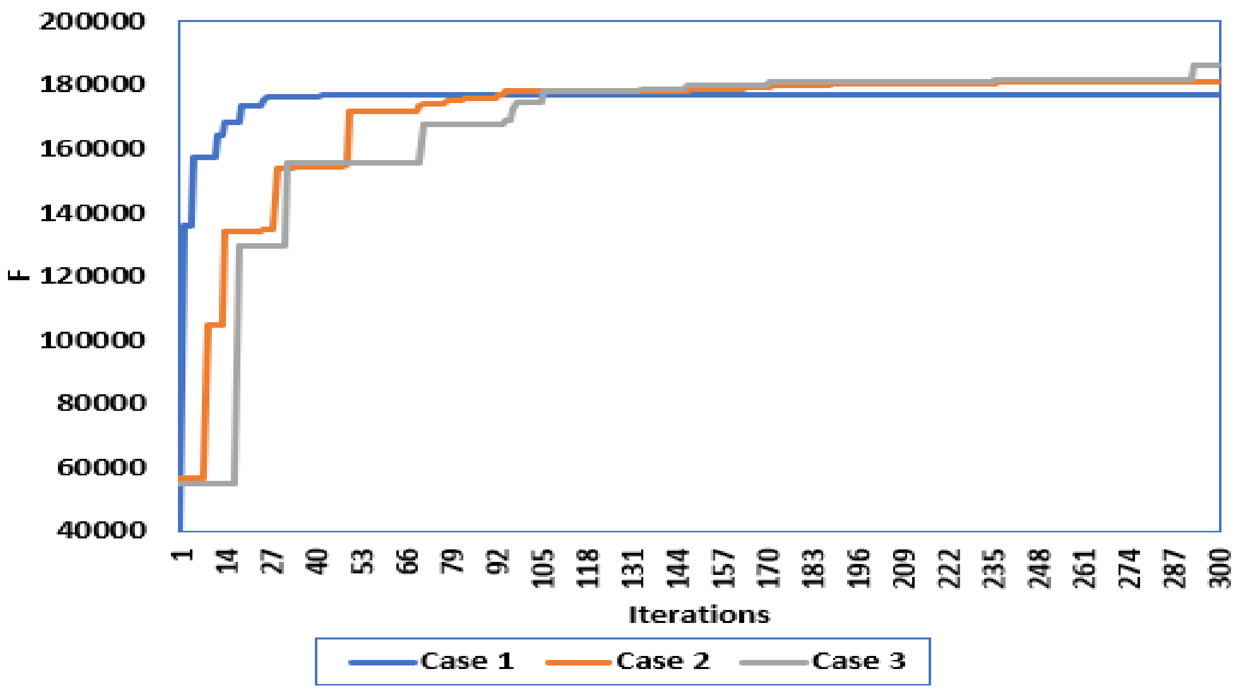

Fig. 2. Convergence characteristics of the differential evolution for the three cases studied.

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Table 2. Allocation of SVCs (Site and Size)

	Site	Size	Light	Medium	Peak
Case 1	7	3913	2836	3150	3913
Case 2	5	5000	1552	2355	-5000
	11	2934	1327	1593	2934
Case 3	5	1217	805	1217	-111
	6	5000	930	1617	5000
	9	3994	1205	641	3994

Regarding to the attained SVS allocations in Table 2, power losses and objectives are illustrated in Table 3. From this table, the costs saving is maximized through the three cases recording objective values of 176831.83, 180834.375 and 186216.659 $, respectively. The power losses are greatly reduced from 1.3621 MW in the initial peak loading with 82.6%, 82.8% and 82.6% for the three cases, respectively. Similarly, the power losses are greatly reduced from 1.3621 MW in the initial medium loading with 41.3%, 42.3% and 47.6% for the three cases, respectively

Table 3. Power losses and objectives regarding the cases studied.

		Initial case	Case 1	Case 2	Case 3
P^{loss} (MW)	Peak	1.3621	0.236599	0.233617	0.237292
	Medium	0.7075	0.41515	0.40792	0.370668
	Light	0.3432	0.700508	0.687625	0.688444
F	-	0	176831.83	180834.375	186216.659

In this context, the boundary voltages regarding the cases studied are illustrated in Table 4. From this table, all the boundary voltages are improved at the peak, medium and light loading levels for the three cases studied. Added to that, Figures 3, 4 and 5 displays the great enhancement of the voltages profile at all loading levels for the three cases studied.

Table 4. Boundary voltages regarding the cases studied.

		Initial case	Case 1	Case 2	Case 3
Maximum Voltage (P.U)	Peak	0.7370 (bus 27)	0.999273	1.000712	1.003683
	Medium	0.8258 (bus 27)	0.946182	0.945893	0.999306
	Light	0.8946 (bus 27)	0.90002	0.900326	0.90575
Minimum Voltage (P.U)	Peak	1.05 (bus 1)	1.05	1.05	1.05
	Medium	1.05 (bus 1)	1.05	1.05	1.05
	Light	1.05 (bus 1)	1.05	1.05	1.05

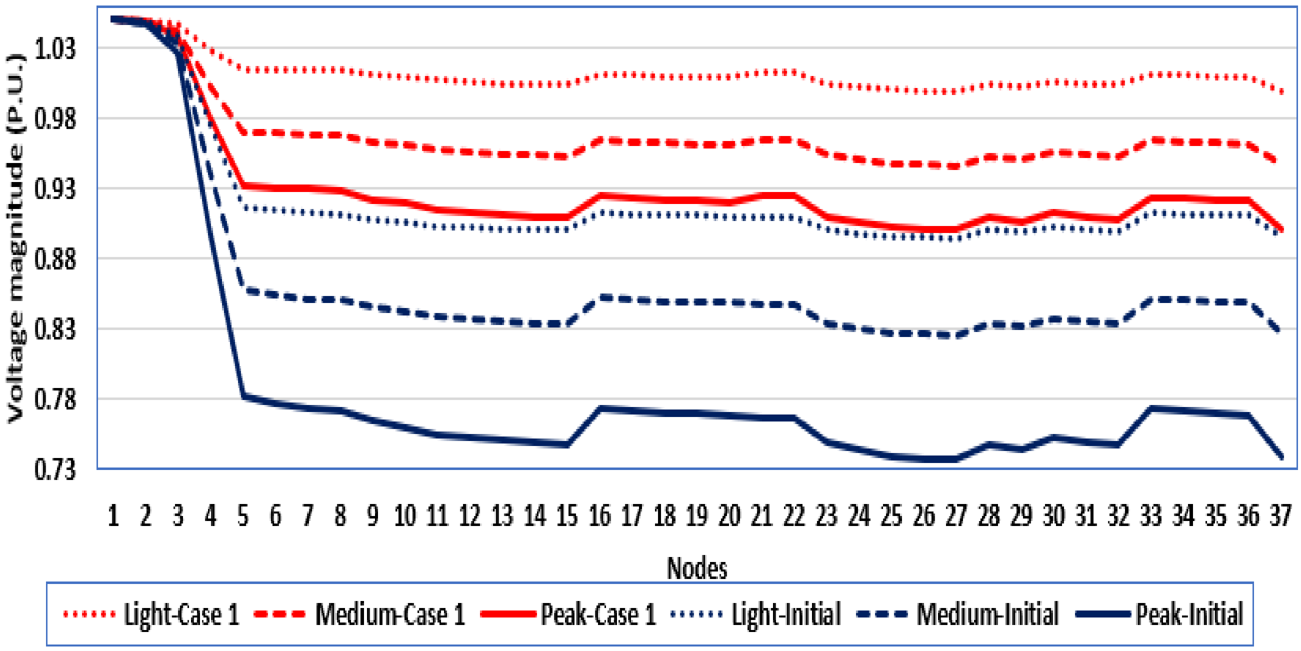

Fig. 3. Voltage profile of 37-nodes feeder for the three loadings for Case 1.

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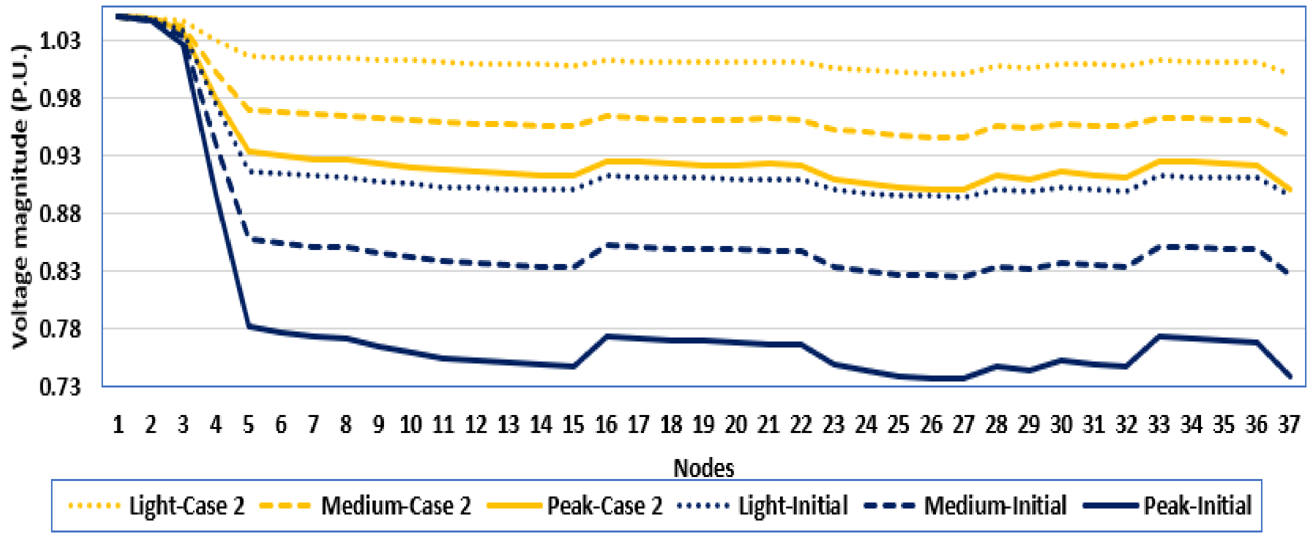

Fig. 4. Voltage profile of 37-nodes feeder for the three loadings for Case 2.

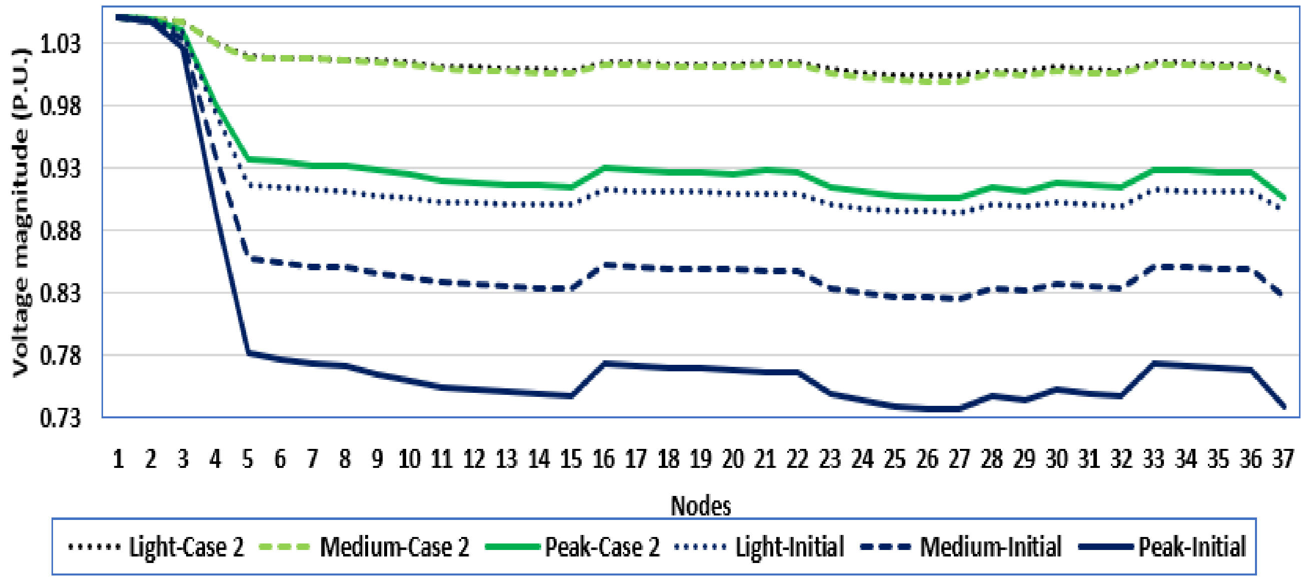

Fig. 5. Voltage profile of 37-nodes feeder for the three loadings for Case 3.

V. CONCLUSION

This research provides a new technique based on the differential evolution algorithm for optimising distribution network performance by coordinating Static VAR Compensator modules (SVCs) optimally. Minimising installation costs and increasing savings by decreasing power losses are combined into a single multi-objective function. Various regular loadings are further mixed to study the effects of varied loading situations. This framework was built around a 37-bus actual feeder that was linked to the Egyptian Unified Network (EUN). The simulation results show that the suggested algorithm has obvious technical and economic properties. The suggested technique for reactive power correction utilising SVCs results in significant quality improvements of the whole node voltage with fluctuations in loads. SVCs are especially important in low-load conditions. The SVCs control their performance characteristics according to the reactive power demands in the adjacent nodes. Moreover, the boundary voltages for the different loading levels for the three scenarios analysed are improved. Not only that, but also, significant improvements in the voltage profile are achieved at all loading levels for the three examples analysed.

DECLARATION

Funding/ Grants/ Financial Support	No, I did not receive.
Conflicts of Interest/ Competing Interests	No conflicts of interest to the best of our knowledge.
Ethical Approval and Consent to Participate	No, the article does not require ethical approval and consent to participate with evidence.
Availability of Data and Material/ Data Access Statement	Not relevant.
Authors Contributions	I am only the sole author of the article.

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