Network Loadability Maximization by Changing the Reactance of Transmission Lines Applying Genetic Algorithm and Voltage Stability Considerations

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Abstract— **This paper proposed a new method for maximizing the loadability of power networks regardless to the transmission lines compensation types. The paper determines some of the network lines that by making change in the reactance of them, loadability of whole system could rise considerably. This optimized design of mentioned network is performed through Genetic Algorithm (GA) optimization technique. With GA technique, the paper is looking for drastic transmission lines and their compensational values in order to transmitting more power in considered network, provided that maximum loadability of voltage stability besides the minimization of costs is respected sufficiently. Numerical results are obtained applying IEEE-39 Bus test system as a case study for testing correctness and applicability of this new offered solution.**

Index Terms- Genetic Algorithm, Loadability, Reactance Reduction, Sensitivity Analysis, Transmission Lines, Voltage Stability.

I. Introduction

Nowadays applying unused capacity of transmission lines is one of the main issues in electrical power systems. In many cases, it is possible that the structure of network in power plants locations, load centers and transmission lines connections and also reactance characteristics points of view, may lead to impossible operation with complete capacity usage of lines. In this condition, some parts of capacity of lines remain actually unused. Thus, loadability of bus-bars and network decrease considerably.

If the reactance characteristics of some lines changes, this affair has a directional effect on network load flow and the value of network loadability that can increase/ decrease the transmittable power of lines. Therefore, this paper determines the number of lines, the lines and the value of reactance reduction of each line in order to maximize the loadability of system in steady state and voltage stability points of view. For reaching a secure network with acceptable voltage and higher stability level, numerous solutions have been proposed such as lost reduction, applying adequate reactive resources, supplying reactive power near to the loads, reducing reactive power transmitted by lines, proper using of on-load tap changing transformers, optimizing placement of generations, applying distributed generations, network structural modifications and creating the lines with lower resistance and reactance and etc.

Many researches have been done through calculating and optimizing the loadability of power systems considering different constraints [1-9]. Some of the offered methods in papers are relying on voltage stability and voltage collapse analysis [8], [9]. But most of the papers didn't attend to the role of reducing impedance of transmission lines as a separate factor of optimizing loadability of systems. On the other hand, in many papers, the loadability issue is being evaluated only in generation and load bus-bars and they didn't pay any attention to the role of unused capacity of transmission lines in optimizing the network structure and loadability maximization. Table I presents a brief overview of researches about loadability issue. The reactance reduction of transmission lines reduce the line power lost, so it can increase the transmittable power of lines. In this paper, a new method for achieving maximum loadability of system has been presented. This method can be applied in optimal planning for designing networks to improve the power in voltage stability point and the power in normal operational point of a power system. Thus, the paper assesses the roles of reducing impedance of transmission lines on voltage stability. Also, the paper determines how reducing impedance of lines can lead to higher voltage stability and safer operational modes.

The paper has offered the value of compensation, the number of lines that need compensation and the importance factors of each transmission line in increasing loadability of system. Although, reducing impedance of lines is being done through various methods such as: replacing conductors, applying shunt or series capacitors, using FACTS, using parallel lines for a transmission path and etc, but regardless to these methods, this paper has considered the impendence of lines as an independent factor that affects the voltage stability and has assessed these impacts on loadability of system. Converging conventional methods to the local optimal points is one of the problem difficulties.

TABLE I.
BRIEF LITERATURE REVIEW OF LOADABILITY ASSESSMENTS

Issue	Method	Line Considerations	Comp. Costs	Reactance Reduction Idea	Test System	Ref.
Trans. System Loadability Assessment	Saddle-Node bifurcation	Yes	No	No	IEEE 118 & 300	[1]
Transmission Lines Loadability Assessment	VAR Supply Capability	Yes	No	No	Very Simple	[5]
Power System Maximum Loadability	Probabilistic Analysis	No	No	No	WSCC-9	[9]
Improving Loadability with Voltage Stability	Neural Network	No	No	No	14 Bus	[10]
Transmission Loadability	Field Current Control	Yes	No	No	IEEE RTS	[12]
Power System Loadability Calc.	Analytical Function	No	No	No	Simple	[15]
Maximum Loadability Participation Factor calculations	Game Theory	No	Yes	No	Simple	[16]
Power System Maximum Loadability by reducing reactance of Lines	GA + Sensitivity Analysis	Yes	Yes	Yes	IEEE 39 Bus	This Paper

Therefore, the paper has applied Genetic Algorithm (GA) technique besides sensitivity analysis in order to find the best optimized solution for maximizing the loadability of system and dispel the mentioned problem. Numerical results are determined by studying IEEE-39 Bus test system [10] for testing accuracy and applicability of the presented solution.

II. VOLTAGE STABILITY OF POWER SYSTEMS

A. *Static Analysis Methods of Voltage Stability and Selecting a Criterion for Assessing it*

By expansion of integrated power systems, stability study of power systems became more important. On the other hand, the complicated characteristics of current power systems lead to engender new instability modes. Also, control and dynamic system progression, calculation methods development and new protection schemes, make identifying various aspects of stability issue more possible than ever. Therefore, it is important to recognize the voltage stability issues well to find the solutions for preventing the instability incidents. Voltage stability is one of the fundamental issues in future power systems. For static analysis of voltage stability, PV and QV curves can be applied. On the other hand, three loadabilities have been considered:

- Loadability of Voltage Stability (P^{VS}_{max}):
  Loadability of network that is corresponding to the total power of all network bus-bars or some of the bus-bars in voltage collapse point on the P-V curve.
- Normal Loadability of Voltage (P^{V}_{max}):
  Loadability of network that is corresponding to the total power of all network bus-bars or some of the bus-bars in a load level that at least one of the bus-bar's voltage gets over the normal limit (V<0.95 per units).
- Normal Loadability of Over-Load (P^{L}_{max}):
  Loadability of network that is corresponding to the total power of all network bus-bars or some of the bus-bars in a load level that at least one of the lines gets the over-load problem ($P>P_{Max\text{-}Line}$). In this case, the maximum transmittable power of each transmission line has been considered 1000 MVA.

Fig. 1 shows the PV curve and the mentioned loadabilities.

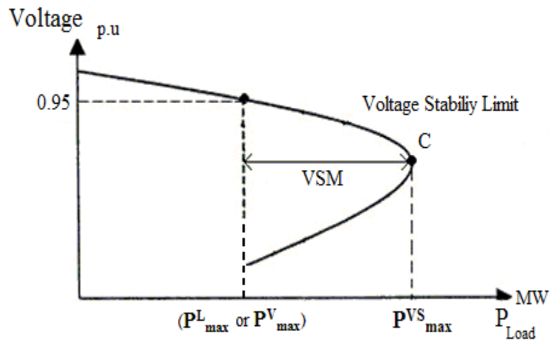

Figure 1. Considered PV Curve and Loadability Points.

B. *The Role of Network Structure on Voltage Stability*

Voltage instability is the result of operation in higher maximum power level of the system that can be caused by increasing demand or decreasing maximum deliverable power level of system or both. For assessing the maximum transmitted power of transmission lines to the loads, this concept can be seen as Thevnant equation of one of the system bursars. The Thevnant equivalent circuit of the system has shown in Fig. 2.

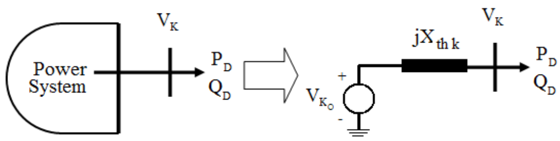

Figure 2. Thevnant Equivalent Model of Power System.

On the other hand, the relation between maximum absorbed power from the load and the reactance of transmission lines has presented in (1). As (1) shows, reducing reactance of transmission lines leads to release the transmittable power of network lines and increase the absorbed power from the loads.

$$P_D^{max} = \begin{cases} \dfrac{-2kX_{th} \pm \sqrt{4k^2X_{th}^2 + 4X_{th}^2V_{K_0}^4}}{4X_{th}^2} \\ = \dfrac{-k \pm \sqrt{k^2 + V_{K_0}^4}}{2X_{th}} \end{cases} \quad (1)$$

III. SENSITIVITY ANALYSIS OF POWER SYSTEM LINES

For sensitivity analysis, the paper has determined each line and the effects of them on Power-Voltage diagram of power system. As the first step, the reactance of each existence line reduced in 10 and 20 percent steps. After power flow calculation with continues iteration and detecting voltage collapse point, Fig. 1 has been obtained.

As it is shown in Fig. 1, the effect of each line is different from the other lines. In some lines, reducing reactance raised the loadability of the network but in some lines, reducing reactance didn't have any impact on loadability. Fig. 3 shows that in reducing 10 percent step of transmission line's reactance, some of the lines such as 1, 2, 14 and 15 have the most impact on loadability of voltage. In 20 percent step of transmission line's reactance reductions, the number of lines which have impacts on loadability point is get more. Also, these lines increase the transmitted power of the network. In 20 percent reduction step, lines 1, 2, 14 and 15 are the effective lines again, but in this case, they move the voltage collapse point more than 10 percent reduction step.

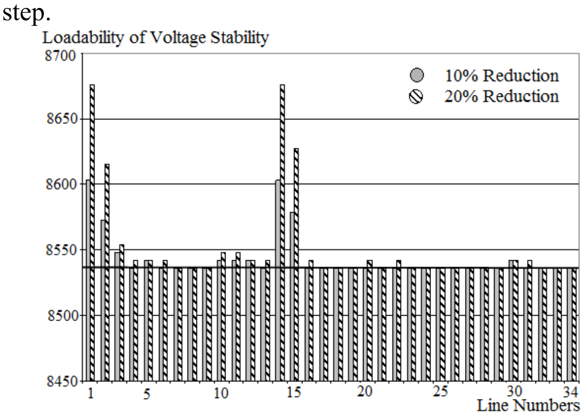

Figure 3. Loadability of voltage stability in 10 and 20 percent reactance reduction of lines.

This paper detects the effective lines of network on loadability point and the value of compensation for each line in order to find the highest voltage collapse point by applying GA. Also the paper assesses the impacts of this compensation on normal operational condition of considered power system network.

IV. Assessing The Imoacts of Simultaneous Reactance Reduction of All Lines

In the initial notion, it is expected that by reducing reactance of all transmission lines, the loadability of network increase considerably. For this reason, the reactance of all lines have been reduced in 10 percent steps in 9 step stages up to 10 percent of initial reactance of the network. The mentioned stages have been decreased until the power-voltage diagram collapse points, normal operational points, voltage limits and maximum power of the network have been obtained. Fig. 4 presents the P-V diagram of busbar-8 according to reactance changes of network lines.

In Fig. 4 the points which are marked with the star, determines the normal loadability level due to voltage limits and the point which are market with the square show the normal loadability level due to over-load limits of transmission lines. Fig. 5 represents the percentage of changes in loading of considered network. As Fig. 5 shows, by reducing reactance of all transmission lines, the voltage collapse point rises appropriately

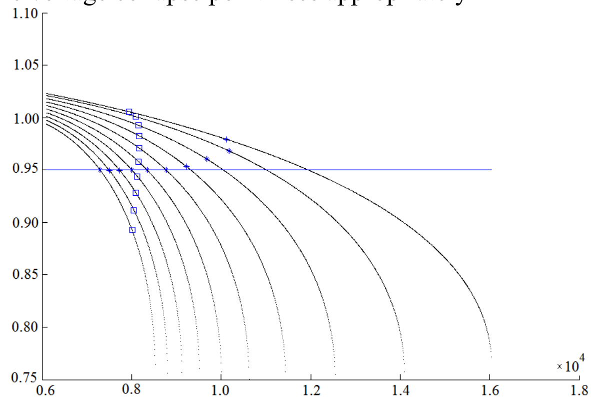

Figure 4. PV Curve changes of Bus-bar 8 according to reactance changes of network lines.

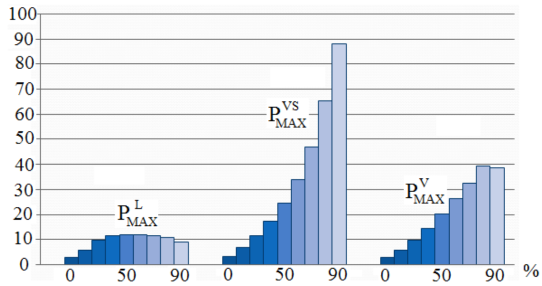

Figure 5. Percentage changes in loadabilities of Network.

For instance, when reactance of all lines reduced to 50 percent, the loadability of voltage stability increased 24 percent comparing to the base condition.

Even, this affair is conformable with a normal operational point without any over-load limitation of lines. As a result, integrated reactance reduction of all lines cannot always be an adequate method for maximizing loadability of transmission lines. Therefore, an optimization technique should be applied to detect the best strategy for transmission line's compensations.

V. Applying Genetic Algorithm for Network Loadability Maximization

In GA, each chromosome creates from reactance combination of network lines that demonstrates the specified structure of the network. The IEEE-39 Bus test system has 34 lines. Each chromosome has 34 genomes with real values in decimal system as presented in (2).

$$X^{(i)} = [X_1^i, X_2^i, X_3^i, ..., X_{34}^i] \quad (2)$$

Where,

$X^{(i)}$: Chromosome-i from a determined population that demonstrates the specified structure of the network.

$X_j^{(i)}$: Genome-i that demonstrates the reactance of line-j in chromosome-i and/or structure-i of a population.

The searching space of reactance of lines (genomes of chromosomes of each generation) has been selected due to an assumed method. For α percent compensation with GA, the stage of searching space of algorithm has been determined through (3) and (4).

$$UpperLimit \rightarrow X_0 = 0.3[\Omega / KM] \quad (3)$$

$$LowerLimit \rightarrow \begin{cases} X_0 - \alpha X_0 = X_0(1-\alpha) \\ = 0.3(1-\alpha) \end{cases} \quad (4)$$

The selected value in this stage has been determined randomly. After multiplying this value to the length of the line and divide it to the base impedance, the per-unit reactance of line has been calculated. IEEE-39 bus test system has 345 kV voltage transmission level with 100 MW base powers. Therefore, the base value of network impedance is gained from (5):

$$Z_b = \frac{(V_b)^2}{S_b} = \frac{345^2}{100} = 1190.25 \quad (5)$$

VI. The Network Compensation Cost Constraint

One of the main issues that could be considered besides maximizing the loadability of network is compensation costs minimization. For strengthen and compensating lines the maximization process could be written as (6):

Max (NLL – CC) (6)

Where,

NLL: Network Loadability & CC: Compensation Costs

For bringing compensation cost in the function of loadability, the objective function of optimization issue can be gained from the normalized value of network loadability and compensation cost. Thus, the objective function is being firmed as an integrated maximization goal (7) So that constraints and limitations of problems are being fulfilled:

$$MAX : ((\frac{P_{\max} - P_0}{P_0}) + (1 - \frac{\cos t}{\cos t_{\max}})) \quad (7)$$

Where,

P : Network loadability that can be obtained based on voltage stability, voltage constraints and over-loads of lines in normal operational conditions.

P_0 : Network loadability in basic structure and without compensating.

$\cos t$: Total Compensation Cost ($).

$\cos t_{\max}$: Maximum Compensation Cost for all lines compensating in desired amount.

With the assumption that compensation cost for reducing the reactance of each line is equal, the network compensation costs of transmission lines calculate from (8):

$$Cost = \sum_{i=1}^{n} c_i \Delta X_i \quad (8)$$

Where,

ΔX_i : The reactance compensation value of line-i.

c_i : Per-Unit compensation cost of each line.

n : The number of transmission lines in considered network. (9) presents the calculating of maximum compensation cost.

$$Cost_{\max} = \sum_{i=1}^{n} c_i \Delta X_{\max} \quad (9)$$

Where,

$\Delta X_{\max}$: Max. compensation value of considered lines.

Considering Fig. 5, by compensating lines up to 50 percent, all three loadabilities will be increased but compensating more than 50 percent leads to decrease normal loadability of network. Therefore, in this paper the maximum compensation value has been considered 50 percent. It could be mentioned that this value is based on IEEE-39 Bus test system structure and the method of loadability calculations. So, this value cannot be extended to other networks. If 50 percent compensation applies for all transmission lines, the total reactance changes will be equal to 0.3 per units. So, the proportion of compensation cost and maximum compensation cost can be formulated as (10):

$$\frac{Cost}{Cost_{\max}} = \frac{\sum c_i \Delta X_i}{\sum c_i \Delta X_{\max}} = \frac{c_i \sum \Delta X_i}{0.3c} = \frac{\sum \Delta X_i}{0.3} \quad (10)$$

VII. Numerical Results and Case Study

For executing the presented subjects, software has been provided in MATLAB that calculates: The electrical powers that are corresponding to voltage stability limit, normal voltage limitations and over-loads.

A. *Calculating the Power of Voltage Stability Point and Normal Operational Mode of Network*

For calculation of these values in IEEE-39 Bus test system, a load and a generation level have been considered as the based operational point. The generation and the load of system have been increased coordinately under the specific pattern until the system reached to voltage instability (divergent load flow). In a load level which one of the bus-bar's voltage of system drops below 0.95 p.u power of this condition determines as normal voltage loadability of system ($P^{V}_{\max}$). Also, in a load level which one of the transmission lines face with over-load problem, the power of this condition considered as normal over-load loadability ($P^{L}_{\max}$) of system. After calculations in divergent point of load flow, the load level of system defines as voltage stability loadability ($P^{VS}_{\max}$) of network. Therefore, for each structure of network and in the process of increasing the load, three loadability points will be obtained: the loadability in normal operational points of network with the voltage limitations constraints in bus-bars, loadability in normal operational points of network with power transmitting constraints from transmission lines and loadability in voltage collapse point.

B. *Finding the Best Structure for Maximizing Loadability of System*

Table. I presents the optimization results in comparison with all transmission lines in simultaneous compensation case. Fig. 6 compared the changes process of loadability of voltage stability of optimized compensation with all transmission lines simultaneous compensation case. As Fig. 6 shows, in optimization method a new structure will be gained which approximately has the same loadability value for voltage stability in comparison with all transmission lines simultaneous compensation case but in this method, only some of the lines have 50 percent reactance reduction and the other lines have the lower reduction steps. Thereupon, it is not necessary to reduce reactance of all transmission lines in order to increase the loadability of voltage stability of system. In other words, by recognizing more effective and sensitive lines of system, the maximization of loadability will be performed desirably.

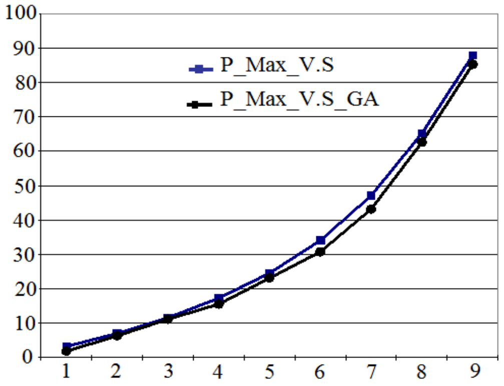

Figure 6. Comparison of Loadability of voltage stability in all lines reactance reduction case by GA optimization compensation.

As it is mentioned before, for a normal operational point of IEE-39 Bus test system, reducing reactance of lines in equal steps, at first leads to raise the voltage collapse point, but then it leads to reduce this value again. Thus, in this case study the best maximum compensation step will be 50 percent.

C. *Optimization of Network Structure by Maximizing Loadability of Voltage Stability* (P^{VS}_{max})

At first, the optimization process has been obtained without any cost constraints and then GA has assessed the optimization issue with cost considerations. Fig. 7 represents the information about loadability maximization of voltage stability with both cost and non-cost considerations. After assessing the values and find the offered structure by GA, the values of loadability in normal operational point of system have been obtained due to voltage and over-load limitation constraints. These values have shown in Table III.

D. *Sensitivity Analysis of Important Lines*

As it is shown in Fig. 7 some of transmission lines have less than 10 percent compensation. These mentioned compensations are negligible in comparison with the roles of other transmission lines on reducing reactance of whole system. In this case, compensating lines number 2, 11, 13, 14, 15, 18, 20, 21, 27, 28 and 32 are seems sufficient. Table III shows the voltage and normal loadability of system that they haven't any significant different with all transmission lines simultaneous compensation case.

TABLE II.
THREE NETWORK LOADABILITIES WITH AND WITHOUT COST CONSIDERATIONS

	Without Cost Considerations	With Cost Consideration
$\%P^{V}_{MAX}$	16.88	7.19
P^{V}_{MAX}	8529.80	7822.60
$\%P^{L}_{MAX}$	12.53	7.19
P^{L}_{MAX}	8212.80	7822.60
$\%P^{VS}_{MAX}$	24.29	11.64
P^{VS}_{MAX}	10609	9529.8

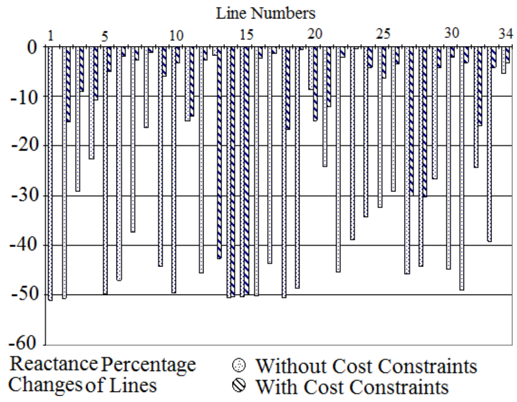

Figure 7. Loadability maximization of voltage stability with both cost and non-cost considerations (Obj.Function = P^{VS}max).

TABLE III.
THREE NETWORK LOADABILITIES IN ALL AND IMPORTANT LINES SCENARIOS

	Compensating all 34 lines with Cost Considerations by GA	Compensating Important 11 lines with Cost Considerations by GA
$\%P^{V}_{MAX}$	7.19	6.77
P^{V}_{MAX}	7822.60	7792.10
$\%P^{L}_{MAX}$	7.19	6.77
P^{L}_{MAX}	7822.60	7792.10
$\%P^{VS}_{MAX}$	11.64	11.43
P^{VS}_{MAX}	9529.80	9511.50

After detecting the lines of considered network that have effective impacts on voltage loadability, the sensitivity analysis of these lines has been performed. Reducing reactance of 11 mentioned lines leads to raise loadability up to 11.43 percent. The total value of reactance reduction of these lines is equal to 0.0696 per-units. For comprehensive assessment of the impacts of these lines, all lines have been deleted from the network one by one to find the loadability value in each case. Appendix I presents the sensitivity analysis of these effective lines. Considering the percentage changes in loadability in comparison with the base case, lines number 2, 14 and 15 are obtained as the most effective and sensitive lines between network lines. Therefore, Table IV compares the sensitivity analysis methods of IEEE-39 bus lines. In the first column of Table VI, the reactance of all lines reduces by GA and the total value of compensation is near 0.07 per-units. By disregarding the less 10 percent reactance reduction lines, 11 lines have been presented in the second column with 0.057 per-units compensation value. The loadability percentage changes of voltage stability with these 11 lines are lower than 0.05 percent in comparison with previous 34 line compensation case. This clearly shows the fact that it is not much necessary to compensate all transmission lines. After selecting 11 important lines, the paper has detected three major effective lines among these eleven by sensitivity analysis. By reducing reactance of these three lines that has gained from GA, the 3rd column has been presented the 11 percent growth in loadability. This value is equals to 0.03 per-units compensation for transmission lines. In the last step, the paper offers a case that these three lines have 50 percent compensation. This case leads to have 0.043 per-units compensation value but loadability rising percentage of voltage stability will be equal to 12.71 percent which this value is better than the offered strategy by GA in the third column.

TABLE IV.
SENSITIVITY ANALYSIS OF MENTIONED STRATEGIES

No. Compensated Lines according to GA	34	11	3	3 (Proposed)
Line Numbers	1:34	2, 11, 13, 14, 15, 18, 20, 21, 27, 28, 32	2, 14, 15	2, 14, 15
Total Compensation	0.070	0.057	0.035	0.043
Loadability of Voltage Stability	9529.80	9511.50	9474.90	9621.20
Normal Loadability	7822.60	7792.10	7731.10	7779.90
Loadability of Voltage Stability (%)	11.64	11.43	11.00	12.71
Normal Loadability (%)	7.19	6.77	5.93	6.60

Also the compensation value of this proposed strategy is better than GA three lines compensation strategy. As a result, if important lines of network detects by GA optimization and after that, sensitivity analysis executes comprehensively, the best strategy for maximizing loadability will be obtained. Therefore, in IEEE-39 bus test system, sensitivity analysis brings 11 important lines for GA optimization. Then, by GA the optimized strategy have gained with compensating these 11 lines. By selecting the most compensated lines and by performing sensitivity analysis on these lines gained from GA, the paper proposed a new strategy that has the best optimization results.

VIII. CONCLUSION

This paper offers a new comprehensive solution for maximizing the loadability of power networks regardless to the transmission lines compensation types. The paper offers a hybrid GA optimization-Sensitivity analysis method that maximizes the loadability of system by reducing reactance of targeted transmission lines. By GA technique, the paper is looking for drastic transmission lines and their compensational values in order to minimize the unused capacity of them besides the minimization of compensation costs sufficiently. For testing the correctness and the applicability of this mentioned solution, IEEE-39 Bus Test System has been studied thoroughly as a case study. In conclusion, the best efficient and comfortable strategy for network designed is gained through this new proposed method.

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APPENDIX I.
SENSITIVITY ANALYSIS OF 11 EFFECTIVE LINES

Lines	Bus1	Bus2	Offered Compensation Reactance by GA	Initial Reactance of line	Changes from the Base Case (%)	Total Compensation Loadability of Voltage Stability	Total Normal Compensation Loadability	Rising Loadability of Voltage Stability (%)	Rising Normal Loadability (%)
Base							7792.10	11.43	6.77
2	1	39	0.0212	0.0250	-15.20	9450.50	7773.80	10.71	6.52
11	6	7	0.0079	0.0092	-14.00	9499.30	7767.70	11.29	6.43
13	7	8	0.0026	0.0046	-42.63	9493.20	7767.70	11.21	6.43
14	8	9	0.0180	0.0363	-50.41	8877.40	7468.90	4.00	2.34
15	9	39	0.0125	0.0250	-50.04	9042.00	7615.30	5.93	4.34
18	13	14	0.0084	0.0101	-16.68	9511.50	7792.10	11.43	6.77
20	15	16	0.0080	0.0094	-14.92	9505.40	7786.00	11.36	6.68
21	16	17	0.0078	0.0089	-12.08	9511.50	7792.10	11.43	6.77
27	21	22	0.0098	0.0140	-30.17	9505.40	7786.00	11.36	6.68
28	22	23	0.0067	0.0096	-30.21	9511.50	7792.10	11.43	6.77
32	26	28	0.0399	0.0474	-15.93	9511.50	7792.10	11.43	6.77