

Reactive Power Planning for Enhancement of Power System Performances at Margin of Stability

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Abstract-- The continuing increase in demand for electric power has resulted in operation closer to the limit of stability with inadequate voltage profile and unacceptable total active losses. Flexible Alternative Current Transmission Systems (FACTS) devices can provide the possibility to enhance Static Voltage Stability based on Reactive Power Planning (RPP). In this paper, The Static Var Compensator SVC which is considered as a control device together with generators and transformers are used for increasing Loading Margin (LM) referred to Voltage Stability Index (VSI) L-index of load buses, minimization of active total losses and to improve voltage profile described by minimization of voltage deviations. Each problem is treated through the best locations of different SVC equipments at the Stability Margin. This assumption is based on the optimization problem by Genetic Algorithms (GA) for one objective function and Non-dominated Sorting Genetic Algorithm-II (NSGA-II) for two objectives mentioned above. The Algorithm is applied on IEEE 30 Bus test system.

Keywords: Loading Margin, Genetic Algorithm, Reactive Power Planning, Non Dominated Sorting Genetic Algorithm II, Static Var Compensator, Voltage profile, Static Voltage Stability.

I. INTRODUCTION

Electric power utilities today are facing many challenges due to ever-increasing complexity in their operation and structure. One of the challenges that receive wide attention is the voltage instability [1]. An open-access market with poorly scheduled generation for the competitive bidding is one of many reasons for voltage instability problem in the deregulated electricity environment. Thus, in order to relieve or at least minimize the system from the voltage instability problem, many electric utilities and researchers have devoted a great effort of studies related to static voltage stability [2]-[4].

The continuing increase in demand for electric power has resulted in an increasingly complex interconnected system, forced to operate closer to the limits of stability with unacceptable voltage profile and important total losses. According to this problem, secure and economic operation of power system requires appropriate planning and control

actions to avoid problems cited above. Flexible Alternative Current Transmission Systems (FACTS) devices can provide the possibility of controlling the power flow and Voltage profile in electric power system without new generation rescheduling or topological changes, with the improvement of the performances considerably [5]. The well-known FACTS device for voltage support in power system is the Static Var compensator (SVC), his location and other types of shunt compensation devices is an important practical question to enhance voltage stability [6]. Due to the complexity of installation and control related to FACTS devices, there is a great need for minimizing the number of SVCs in power system. Moreover, the high costs of FACTS devices impose to the exploiters of electrical networks to reduce the size of such elements. Further to this issue, Reactive Power Planning problem (RPP) is considered to overcome such conflicts [7].

In this paper, RPP is analyzed after driving the electrical power system to the margin of stability to improve the power system performances at such state. Continuation Power Flow (CPF) is used to determine the loading margin (LM) [4].

The purpose of RPP is to improve the margin of static voltage stability or LM; this approach is based on, minimization of Voltage Stability Index (VSI), minimize the network real power loss and improve the voltage profile by regulating the unit active power outputs, generator bus voltage magnitudes, switching on/off SVCs (with optimal locations) and changing transformer tap-settings. Therefore, the problem of the RPP can be optimized to solve these three problems previously evoked. The above given problem can be deal with Single Objective Optimization Algorithm and it provides a unique optimal solution. However, there are many situations where Decision Makers have multiple objectives; in these situations a group of conflicting objectives may be optimized, Multi Objective Optimization Problem (MOOP) is used [8]. In this case, the solution requires a multi-objective algorithm such Non-dominated Sorting Genetic Algorithm- NSGA. Srinivas and Deb developed NSGA in which a ranking selection method emphasizes current non-dominated solutions and a niching method maintains diversity in the population [9]. Multi-objective evolutionary algorithms including NSGA that use non-dominated sorting and sharing have been criticized mainly for i) computational complexity, ii) non-elitism approach and iii) the need for specifying a sharing parameter. K. Deb alleviated these difficulties in NSGA-II [10].

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This article is organized as follows: Section 2 is devoted to Static Voltage Stability methods and CPF concepts; Section 3 describes the modelling of SVC, a proposed simulation approach has been briefly exposed in Section 5 and Simulation with results is focused on Section 6. Finally, we finished with discussions and conclusion.

II. STATIC VOLTAGE STABILITY

1) Overview:

Voltage Stability is defined as the ability of a power system to maintain steady voltages at all buses in the system after being subjected to a disturbance from a given initial operating condition. Increase in load demand, causes a progressive and uncontrollable decline in voltage, the system enters a state of instability after reaching Voltage Collapse and instability leads to a blackout or abnormally low voltages in a significant part of the power system. Many analytical methodologies have been proposed and are currently used for the study of this problem:

- Static voltage stability analysis tools such as P-V and V-Q curve analysis. [11]
- Continuation Power Flow (CPF). [11]
- Voltage collapse index based on normal load flow solution (L-index) [12].
- Minimum singular Value (MSV) of the power flow related to Jacobian matrices [13].

2) Continuation Power Flow:

Continuation Power Flow presents a way to plot complete PV curves, by automatically changing the value of Loading Factor LF (). It involves predictor and corrector steps to guarantee a well behaved numerical solution of the related following vector equations:

$$F(x, \lambda) = 0 \quad (1)$$

x denotes the state variables consisting of system buses phase angles and load buses voltage magnitudes.

F : functional vector including the system nonlinear real and reactive power injections balance equations.

The solution of the system equations at base case state of power flow is insured with $\lambda = 1$. The increase of uncontrollable parameter λ , that, associated with a loading level, would drive the system from one stable equilibrium point to another, until obtaining critical value of LF, where $\lambda_{critical}$ being the maximum value of λ in LM.

III. MODELING OF STATIC VAR COMPENSATOR

Advances in power electronics technology together with sophisticated control methods made possible the development of fast SVC's in the early 1970's. The SVC consists of a group of shunt-connected capacitors and reactors banks with fast control action by means of thyristor switching [14]. From the operational point of view, The SVC is taken to be a continuous, variable-shunt susceptance B_{SVC} ; Fig. 1, which is adjusted in order to achieve a specified voltage magnitude while satisfying constraint conditions. The susceptance model applied in this paper take into account upper and lower limits

of total susceptance. The characteristics of SVC are summarized in [15] and the model is as follows:

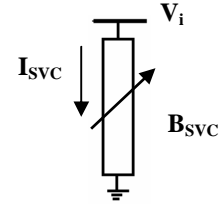


Fig. 1 Variable shunt susceptance

- Within control range ($B_{min} \leq B \leq B_{max}$)

$$V = V_{ref} - X_{SL} I_{SVC}$$

- Inductive limit ($B < B_{min}$)

$$B = B_{min} \quad (2)$$

- Capacitive limit ($B > B_{max}$)

$$B = B_{max}$$

Where:

V_{ref} : reference voltage magnitude of SVC.

X_{SL} : characteristic impedance of the control system.

IV. PROPOSED SIMULATION APPROACH

In this paper, our goal is to get the optimal adjustments of control devices in power system (unit active power outputs, transformer tap settings, generator voltage magnitudes and susceptances of SVCs) to correct our system so that it can carry the load at the margin of stability. The proposed simulation approach is based on MOOP involves the simultaneous optimization of Active Total Losses (ATL), LM described by Voltage Stability Index (VSI) and load bus voltage deviations drawn by Voltage Profile Index (VPI) at the margin of stability. The problem can be formulated as follows:

A. Objective Functions:

1) Voltage Stability Index:

Different methods are used to indicate a general picture of the proximity of the system to voltage collapse, the index proposed in Reference [16] gives a scalar number to each load bus, called L -index. This index value ranges from 0 (no load system) to 1 (voltage collapse). The bus with the highest L -index value will be the most vulnerable bus in the system and hence this method helps in identifying the weak areas in the system which critical reactive power needs support. Using the load flow results, L -index is computed as:

$$L_j = \left| 1 - \sum_{i=1}^{ng} \bar{F}_{ji} \frac{\bar{V}_i}{\bar{V}_j} \right| \quad (3)$$

\bar{V}_i : is the complex voltage at generator bus.

\bar{V}_j : is the complex voltage at load bus.

$i=1,2,\dots,ng$. ng : is the total number of generators.

$j=ng+1,\dots,nb$. nb : is the total number of buses.

\bar{F}_{ji} : is complex quantity obtained from \bar{Y}_{bus} matrix [16] as flows:

$$\begin{bmatrix} I_G \\ I_L \end{bmatrix} = \begin{bmatrix} Y_{GG} & Y_{GL} \\ Y_{LG} & Y_{LL} \end{bmatrix} \begin{bmatrix} V_G \\ V_L \end{bmatrix} \quad (4)$$

where I_G, I_L, V_G, V_L represent the currents and voltages at the generator nodes and load nodes. Rearranging Eq. (4) we get:

$$\begin{bmatrix} V_L \\ I_G \end{bmatrix} = \begin{bmatrix} Z_{LL} & F_{LG} \\ K_{GL} & Y_{GG} \end{bmatrix} \begin{bmatrix} I_L \\ V_G \end{bmatrix} \quad (5)$$

Where $F_{LG} = -[Y_{LL}]^{-1}[Y_{LG}]$ are required values.

2) Voltage Profile Index:

Best security of the power system is described by the flatter voltage profile. The voltage magnitude deviation from the desired value at each load bus must be as small as possible. The deviation of voltage magnitude from 1 p.u is given as follows:

$$f_{VPI} = \sqrt{\sum_{i=1}^{N_{pq}} (V_i - 1)^2} \quad (6)$$

V_i : Voltage magnitude at PQ bus i .

N_{pq} : Number of PQ buses.

3) Active Total Losses:

The classical reactive power optimization problem of minimizing the real power loss in the transmission lines can be mathematically expressed as follows:

$$ATL = \sum_{k=1}^{nl} g_k [V_i^2 + V_j^2 - 2V_i V_j \cos(\delta_i - \delta_j)] \quad (7)$$

nl is the number of transmission lines in the system, g_k is the conductance of k^{th} transmission line between buses i and j ; V_i and V_j are magnitude voltages at bus i and j respectively. δ_i and δ_j are voltage angles.

B. Multi-Objective Formulation:

$$\min[\max(L_{-index}, f_{VPI}, ATL)] \quad (8)$$

$$\text{Subject to: } \begin{aligned} g(x) &= 0 \\ h(x) &\leq 0 \end{aligned}$$

Where:

$g(x)$: represents equality constrains described as below :

$$P_{Ti} + \lambda P_{Li} - \lambda P_{Gi} = 0 \quad (9)$$

$$Q_{Ti} + \lambda Q_{Li} - Q_{Gi} - B_{SVC(i)} V_i^2 = 0 \quad (10)$$

P_{Gi}, P_{Li} and P_{Ti} indicate active power generation, load, and injection respectively.

Q_{Gi}, Q_{Li} and Q_{Ti} indicate reactive power generation, load, and injection respectively.

$B_{SVC(i)}$: susceptance of SVC located at bus i .

$$P_{Ti} = \sum_{j=1}^N |V_i| |V_j| |Y_{ij}| \cos(\delta_i - \delta_j - \theta_{ij}) \quad (11)$$

$$Q_{Ti} = \sum_{j=1}^N |V_i| |V_j| |Y_{ij}| \sin(\delta_i - \delta_j - \theta_{ij}) \quad (12)$$

$h(x)$: represents inequality constrains described as below :

$$\begin{aligned} P_{Gi}(\min) &\leq P_{Gi} \leq P_{Gi}(\max) & i = 1, 2, \dots, ng \\ Q_{Gi}(\min) &\leq Q_{Gi} \leq Q_{Gi}(\max) & i = 1, 2, \dots, ng \\ T_i(\min) &\leq T_i \leq T_i(\max) & i = 1, 2, \dots, nt \\ V_{Gi}(\min) &\leq V_{Gi} \leq V_{Gi}(\max) & i = 2, \dots, ng \\ B_{SVC(i)(\min)} &\leq B_{SVC(i)} \leq B_{SVC(i)(\max)} & i = 1, 2, \dots, n_{svc} \end{aligned} \quad (13)$$

ng : number of total units for power generation.

nt : number of transformer tap settings.

n_{svc} : number of Static Var Compensators.

u : is the vector of control variables.

$$u^T = [P_{Gi_i \in ng}, T_{j_j \in nt}, V_{Gk_k \in ng}, B_{m_m \in n_{svc}}] \quad (14)$$

At the margin of stability $\lambda = \lambda_{critical}$, with active and reactive power load:

$$\begin{aligned} P_L &= \lambda_{critical} P_{Lo} \\ Q_L &= \lambda_{critical} Q_{Lo} \end{aligned} \quad (15)$$

P_{Lo}, Q_{Lo} : signified active and reactive power at base case.

The optimization problem is implemented with SVCs locations at a variety of PQ selected buses (they become PV buses). In such case, the power flow program is performed and objective functions are calculated.

V. SIMULATION AND RESULTS

Simulation is applied on IEEE 30 bus test system, under MATLAB environment. The system consists of 6 generators buses, 24 load buses, 41 transmission lines of which four branches are in-phase transformers with assumed tapping ranges of 10% and 2 installed shunt capacitor banks at bus 10 and bus 24. The candidate buses for SVCs locations are 12, 15, 17, 18, 19, 21, 23, 24, 25, 26, 29 and 30 witch are loaded buses (most loaded buses with reactive power and they have the highest L-index values).

LF for IEEE30 Bus test system =1.832 is obtained with PSAT program. The voltage profile of the base case and LM is illustrated in Fig. 2.

At base case, the total active load is 283.4 MW and total reactive load is 126.2 MVAR. At the margin of stability ($\lambda_{critical}=1.832$), active total load is 519.18 MW and the reactive total load is 231.19 MVAR. For these two cases, ATL and Reactive Total Losses (RTL), minimal Voltage magnitude $V_{M(\min)}$ and generated reactive powers are given in Table. I.

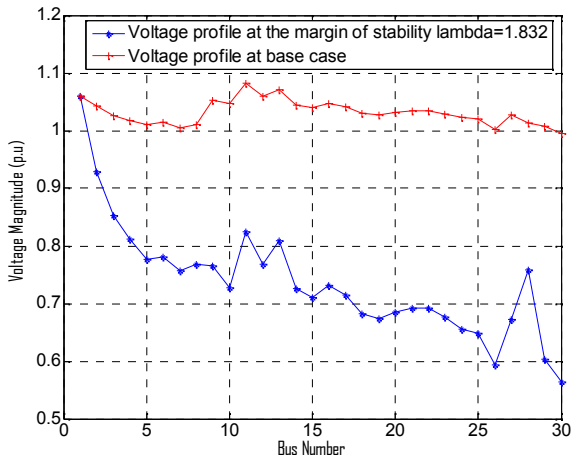


Fig. 2 Voltage profile at base case and LM

At the margin of stability and at PV buses, generators operate at their upper limits to supply reactive power for electrical network and then they turn to PQ generators buses. Great voltage drop and ATL are assigned to refer to Fig. 2. and Table. I.

Calculation of L-index at base case and at the margin of stability is illustrated in the Figure. 3. Maximum values of L-index are remarked to bus 30 for two cases which are 0.1362 ($\lambda = 1$) and 0.7440 ($\lambda_{critical}=1.832$).

At the LM, the electrical power system is in the worst state, then to get better voltage profile, minimal ATL and the wide margin of stability, several locations of SVC are optimized and the best emplacement is selected (with active power outputs, generators voltage magnitudes and tap setting transformers adjustments). Two SVC are chosen where each SVC have $V_{ref}=1.05$ p.u, $B_{SVC(min)}=-0.92$ p.u and $B_{SVC(max)}=0.92$ p.u.

TABLE. I
GENERATED REACTIVE POWER AND LOSSES AT BASE CASE AND AT THE MARGIN OF STABILITY

State Variables	Base Case	Loading Margin
Qg(1) (MVAR)	-1.3619	262.86
Qg(2) (MVAR)	29.5031	50.00
Qg(5) (MVAR)	26.1590	40.00
Qg(8) (MVAR)	16.6277	40.00
Qg(11)(MVAR)	15.2326	24.00
Qg(13)(MVAR)	8.5443	24.00
ATL (MW)	9.4920	64.64
RTL (MVAR)	-8.1953	232.97
VM(min) (p.u)	0.9957	0.5639

A. Optimization of each objective function independently to Another one:

Genetic Algorithm is used to optimize each objective function independently to another one with crossover probability 0.7, mutation probability 0.061, population size 60 and the maximum number of generations 250.

Simulation results for this case are shown in Table. II. Reactive power generations are illustrated in Table. III.

Voltage magnitude at all buses for each case of optimization is indicated in Fig. 4.

The optimization results in case of ATL minimization are closer to results of max(L-index) minimization case than in the VPI minimization case due to improvement of voltage magnitude in the two first cases. On the other hand, VPI minimization needs to set the voltage magnitude to 1 p.u.

Voltage magnitude for ATL and max(L-index) optimization are relatively close, it appears in Fig. 4. Voltage magnitudes are between upper and lower limits. Reactive power reserves are 184.34 MVAR, 188.19 MVAR and 186.49 MVAR for optimization of ATL, L-max and VPI respectively.

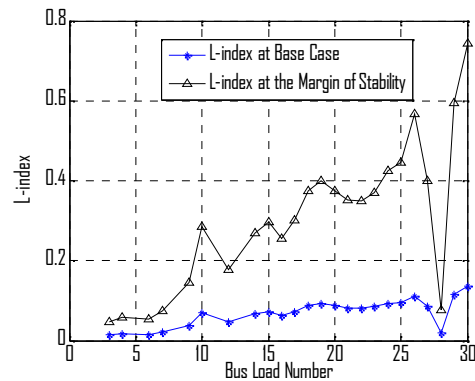


Fig. 3 L-index for each load bus at two cases $\lambda = 1$ and $\lambda_{critical}=1.832$

TABLE. II
OPTIMIZATION OF EACH OBJECTIVE FUNCTION INDEPENDENTLY TO ANOTHER ONE

Control variables & Objectives	Minimization ATL	Minimization VPI	Minimization max(L-index)
Pg (1) (MW)	101.1447	231.0578	106.0300
Pg (2) (MW)	146.4696	111.4859	145.1931
Pg (5) (MW)	91.1740	90.9454	90.8751
Pg (8) (MW)	63.4772	32.2821	63.1928
Pg(11) (MW)	54.8857	54.6881	54.9232
Pg(13) (MW)	73.2114	22.2701	73.2595
T ₁	1.0143	1.0130	0.9020
T ₂	0.9974	0.9052	0.9005
T ₃	0.9871	1.0997	1.0994
T ₄	0.9001	0.9855	1.0288
Vg ₂ (p.u)	1.0928	1.0420	1.0646
Vg ₅ (p.u)	1.0168	1.0879	1.0201
Vg ₈ (p.u)	1.0264	1.0123	0.9583
Vg ₁₁ (p.u)	1.0956	1.0299	1.0988
Vg ₁₃ (p.u)	1.0920	0.9831	1.0899
SVC-Bus-Locations	21 15	15 29	12 30
BSVC(p.u)	0.3454 0.1981	0.9200 0.2029	0.5931 0.2743
Total Losses(MW)	11.1738	23.5406	14.285
Voltage profile(p.u)	0.1979	0.0952	0.1349
max(L-index)	0.1493	0.2148	0.133

B. Optimization of two objective functions:

The NSGA-II Algorithm is used to optimize two objective functions simultaneously for each case, the population size is 60, the Pareto fraction is 0.7 and crossover fraction is 0.8.

TABLE III
REACTIVE POWER GENERATIONS FOR EACH CASE OF OPTIMIZATION

Reactive Power Generation	min VPI	min ATL	min max(L-index)
Qg(1)(MVAR)	0.9371	-20.7168	15.6236
Qg(2)(MVAR)	50.0000	50.0000	50.0000
Qg(5)(MVAR)	40.0000	40.0000	40.0000
Qg(8)(MVAR)	40.0000	40.0000	-10.0000
Qg(11)(MVAR)	16.5683	24.0000	20.1787
Qg(13)(MVAR)	-6.0000	23.8960	24.0000

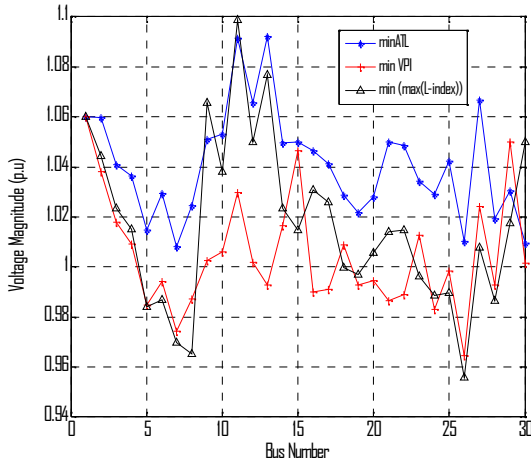


Fig. 4 Voltage profile at each case of optimization

a. VPI and ATL minimization:

For this case, the NSGA-II Algorithm is used to minimize the real power loss and the load bus voltage deviations simultaneously. The Pareto-optimal front (trade-off curve) obtained is shown in Fig. 5.

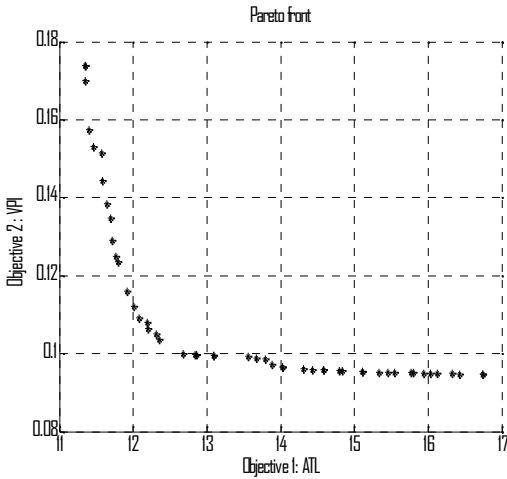


Fig. 5 Pareto front for Optimization of VPI and ATL simultaneously

b. VPI and max(L-index) minimization:

In such case VPI and max(L-index) are optimized simultaneously the Pareto front is extracted after simulation results. Optimal front (trade-off curve) is exposed at Fig. 6.

According to Fig. 5 and Fig. 6, the best solutions are obtained for the optimal adjustments of control variables and

best locations of two SVCs. There is an important improvement of performances of power system with such Pareto fronts compared with the situation before optimization. The set of solutions is reserved for the Decision Maker to choose the appropriate one.

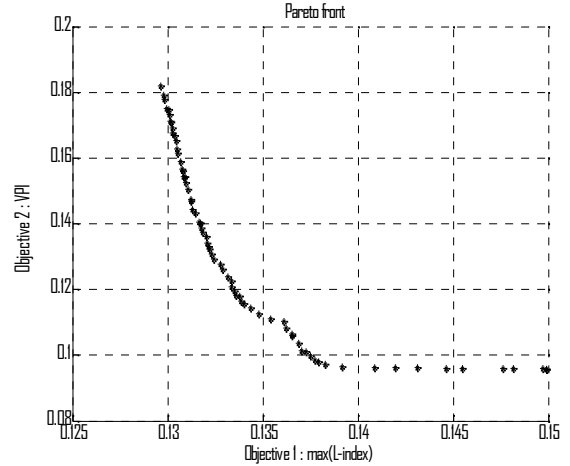


Fig. 6 Pareto front for Optimization of VPI and Max(L-index) simultaneously

C. Best compromise solution:

Best compromise solution is obtained using Fuzzy Logic theory indicated in [17]. This theory is based on the maximisation of degree of satisfaction for all membership functions related to objective functions. The optimization of three functions simultaneously involves results in Table. IV. Best compromise solution is observed with optimal control variables.

TABLE IV
CONTROL VARIABLES AND OBJECTIVES FOR MAXIMISATION OF SATISFACTION DEGREE

Control variables & Objectives	Maximisation DS
Pg (1) (MW)	104.7179
Pg (2) (MW)	146.0171
Pg (5) (MW)	91.3725
Pg (8) (MW)	63.5809
Pg(11) (MW)	53.7664
Pg(13) (MW)	72.4996
T ₁	0.9555
T ₂	0.9247
T ₃	1.0141
T ₄	0.9862
Vg ₂ (p.u)	1.0421
Vg ₅ (p.u)	1.0783
Vg ₈ (p.u)	0.9945
Vg ₁₁ (p.u)	1.0635
Vg ₁₃ (p.u)	1.0899
SVC-Bus-Locations	12 29
BSVC(p.u)	0.3610 0.2051
Total Losses(MW)	12.7657
Voltage Profile(p.u)	0.1088
max(L-index)	0.1439
Degree of Satisfaction	0.8673

VI. CONCLUSION

The electrical power system IEEE 30 bus test system is loaded at loading margin. With the aim to have a stable electrical network, we are forced to describe the optimal adjustments of different electrical equipments with the best locations and settings of Static VAR compensators. The most important indices for static voltage stability are voltage deviation, active total losses and voltage stability index.

The previous functions are optimized independently and simultaneously with reactive power planning analysis to get best operating situation of power system. For each type of optimization, voltage magnitudes are in the range of upper and lower limits ($0.95 \text{ p.u.} < V_M < 1.1 \text{ p.u.}$). Pareto fronts are obtained and discussed for more stable situation.

Fuzzy logic theory is employed to extract the best compromise solution over the trade-off curves obtained.

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