# VOLTAGE SECURITY IMPROVEMENT USING FUZZY LOGIC SYSTEMS

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## ABSTRACT

*This paper presents a new approach using fuzzy bet theory for voltage and reactive power control of power systems. The predication of steady state voltage stability conditions in a transmission network. The voltage stability is checked by formulating an L and the corresponding uncertainties input parameters are efficiently modeled in terms of fuzzy sets by using triangular membership function. The proposed technique will be highly useful to ensure voltage security of power system by predicting the nearness of voltage collapse with respect to the existing load condition. The approach translates violation level of buses voltage and controlling ability of controlling devices into fuzzy set notations using linearized model. A modified IEEE 30-bus test system is used to demonstrate the application of the proposed approach. Simulation result shows that the approach is efficient and has good flexibility and adaptability for voltage-reactive power control.*

***KEYWORDS:*** *Fuzzy sets, membership functions, voltage-reactive power control voltage violation level, Power system enhancement, Stability, Voltage Stability.*

## I. INTRODUCTION

Power system throughout the world is undergoing tremendous changes and developments due to rapid Restructuring, Deregulation and Open-access policies. Greater liberalization, larger market and increasing dependency on the electricity lead to the system operators to work on limited spinning reserve and to operate on vicinities to maximize the economy compromising on the reliability and security of the system for greater profits, which lead to establishment of a monitoring authority and accurate electronic system to prevent any untoward incidents like Blackouts. Optimal Power Flow (OPF) study plays an important role in the Energy Management System (EMS), where the whole operation of the system is supervised in each conceivable real time intervals. Optimal Power flow is the assessment of the finest settings of the control variables viz. the Active Power and Voltages of Generators, Discrete variables like Transformer taps, Continuous variables like the Shunt reactors and Capacitors and other continuous and discrete variables so as to attain a common objective such as minimization of operating cost or Social Welfare while respecting all the system limits for safe operation. This greater dependency on Electric Power has brought in the stage where the consumer depends not only on the availability of the electricity, but also looks for Reliable, Secure, Quality and Uninterrupted supply. In order to enhance the voltage security; power systems are equipped with a lot of voltage controlling devices such as generators, tap changing transformers, shunt capacitors/reactors, synchronous condensers, and static VAR compensators etc. Either by the variations of load or by the changes of network configuration, a real time control employing those controlling devices is required to fast alleviate the problems caused by the perturbations. For voltage security problems, linear programming (LP) [1]–[4] utilized linearized models to attain an objective function and constraints to formulate the problem. The LP results may not represent the optimal solution for inherently nonlinear objective functions; also, the approach requires a great deal of computation. In the other way, rule-based approach [5] and expert systems [6], [7] as well as hybrid (heuristic and algorithmic) systems [8]–[10] proposed rigorous mathematical models and numerical approaches to solving the problems. Fuzzy set theory [11], [12] was also applied to solve the problems [13]–[17], in this application, objectives and constraints were first translated into fuzzy set notations, then LP was employed to find the optimal solution. In [18], an approximate reasoning based on a flexible model which employed an expert system and fuzzy sets to solve the VAR control problems was proposed. In [19], a new fuzzy control approach which repeatedly uses fuzzy operations to effectively enhance voltage profile was presented. In this paper, we introduce a new voltage/reactive power control model which uses fuzzy sets to formulate the problem, such that the voltage security improvement is achieved while loss reduction is also attained. In this modeling, bus voltage violation level and controlling ability of controlling device are first translated into fuzzy set notations, and then max–min operation is employed to find a feasible solution set which enhances the voltage security. Final solution is attained using min-operation aiming at further reducing the power loss. The method is very simple and straightforward. The proposed method has been applied to a modified IEEE 30-bus test system. Results show that the approach is effective for improving voltage security and simultaneously lowering power loss. In this paper, we introduce a new voltage-reactive power control model using fuzzy sets, which aims at the enhancement of voltage security. In this modeling, two linguistic variables are applied to measure the proximity of a given quantity to a certain condition to be satisfied. Both bus voltage violation level and controlling ability of controlling devices are first translated into fuzzy set notations, and then through fuzzy operations it could fast found the answer for the realistic question. The proposed approach is simple and straightforward, which defines the membership functions of the two linguistic variables ingeniously, so that the merits of fuzzy technique are brought into play. The proposed method has been applied to a modified IEEE 30-bus and the simulation results has got.

# II. MATHEMATICAL MODELLING OF LINE VOLTAGE STABILITY

The proposed line voltage stability is capable of yielding accurate, consistent and reliable results as demonstrated in the case studies carried out under this paper.

$$L_i = \frac{2\frac{B}{A}\sqrt{(P_m{}^2 + Q_m{}^2}}{\frac{V_K{}^2}{A^2} - 2\frac{B}{A}P_m\cos(\beta-\alpha) - 2\frac{B}{A}Q_m\sin(\beta-\alpha)} \le 1$$

----- (1)

where,
Pm – Receiving end real power in p.u
Qm – Receiving end reactive power in p.u
Vk – Sending magnitude voltage in p.u
As long as above is less than unity, the system is stable. Li is termed as voltage stability of the line. At collapse point, the value of Li will be unity. Based on voltage stability indices, voltage collapse can be accurately be predicted. The lines having high value of the can be predicted as the critical lines, which contribute to voltage collapse. This method is used to assess the voltage stability.

# III. FUZZY BASED LOAD FLOW ANALYSIS

In Newton-Raphson load flow method the repetitive solution is obtained by the equations (1). By using these equations "δ" and "V" is updated in each iteration. In fuzzy load flow problem "Fuzzy Logic" is used to update "δ" and "V".

$$\begin{bmatrix}\Delta P\\ \Delta Q\end{bmatrix} = \begin{bmatrix}H & N\\ M & L\end{bmatrix}\begin{bmatrix}\Delta\delta\\ \Delta|V|\end{bmatrix}$$

------- (2)

## A. Main Idea of Fuzzy Load Flow (FLF) Algorithm

The Equation (1) given by Newton-Raphson can be expressed as for the proposed Fuzzy by the equation (**2**) the above equation denotes that the correction of state vector ΔX at each node of the system is directly proportional to vector ΔF. The proposed fuzzy load flow algorithm is based on the previous Newton – Raphson load flow equation but the repeated update of the state vector of the system will be performed via expressed by, ΔF [J]ΔX The above equation denotes that the correction of state vector ΔX at each node of the system is directly proportional to vector ΔF. The proposed fuzzy load flow algorithm is based on the previous Newton – Raphson load flow equation but the repeated update of the state vector of the system will be performed via expressed by ΔX = fuzzy[ ΔF]

## B. Fuzzy Logic Load Flow Algorithm

In Figure 1 the power parameters such as real power (ΔFp ) and reactive power (ΔFq ) are calculated and introduced to the p- and q-v fuzzy logic controller (FLC) respectively. The FLCs algorithm executes the state vector ΔX namely, the correction of voltage magnitude Δδ for the p-q cycle and the voltage magnitude ΔV for the q-v cycle.

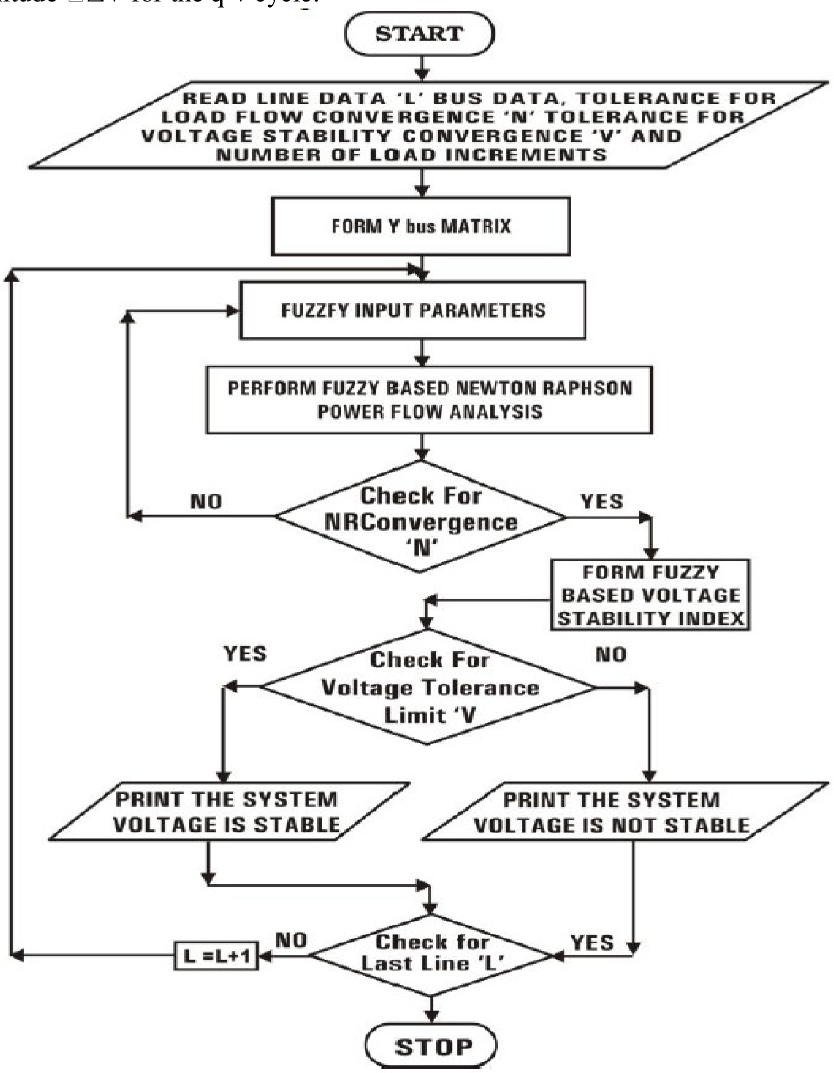


Figure1. Flow Chart for the Proposed Fuzzy

The described computational procedures iii the solution process of the proposed control are given as follows:

Step 1: Input data of network configuration, line impedance, bus power, bus voltage limits and controlling margin.
Step 2: Perform a base case load flow by Newton-Raphson method.
Step 3: Find the sensitivity coefficients.
Step 4: Calculate the controlling ability.
Step ***5:*** Find the membership value of bus voltage violation and controlling ability.
Step 6: Evaluate the optimal control solution.

Step *7:* Modify the value of the control variables.
Step 8: If all buses are enhanced to the desired voltage level, go to nest step; otherwise, go to step 4.
Step 9: Perform the load flow study and output the results.

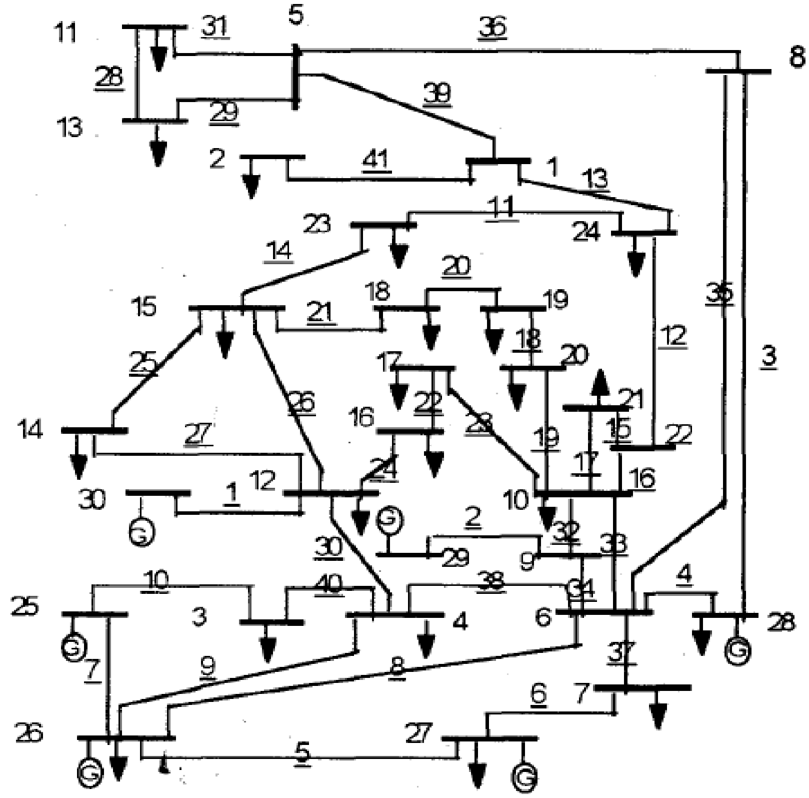

Figure 2: A modified IEEE 30-bus test system

# IV. REACTIVE POWER COMPENSATION

We need to release the power flow in transmission lines for partially solving of problem of losses as well as other problems. We can't do anything with active power flow, but we could supply the reactive power locally where it is highly consumed in a system. In this way the loading of lines would decrease. It would decrease the losses also and with this action the problem of voltage drops could be solved also. By means of reactive power compensation transmission system losses can be reduced as shown in many papers in the literature, see e.g., [20]-[22]. It has also been widely known that the maximum power transfer of the transmission system can be increased by shunt reactive power compensation, typically by capacitors banks placed at the end of the transmission lines or a the load terminals [23]. Therefore, planning of reactive power supports would give benefits to the users of the transmission systems, in terms of loss reduction, among other technical benefits, such as improving steady-state and dynamic stability, improve system voltage profiles, etc. which are documented in [24]. The reactive power planning problem involves optimal allocation and sizing of reactive power sources at load centers to improve the system voltage profile and reduce losses. However, cost considerations generally limit the extent to which this can be applied. The transmission of active power requires a difference in *angular phase* between voltages at the sending and receiving points (which is feasible within wide limits), whereas the transmission of reactive power requires a difference in *magnitude* of these same voltages (which is feasible only within very narrow limits). But why should we want to transmit reactive power anyway? Is it not just a troublesome concept, invented by the theoreticians, that is best disregarded? The answer is that reactive power is consumed not only by most of the network elements, but also by most of the consumer loads, so it must be supplied somewhere. If we can't transmit it very easily, then it ought to be generated where is needed. Reactive power is needed to form magnetic fields in motors and other equipment, but it cannot perform any actual work itself. The more reactive power that is distributed in the electrical system, the less space is left for productive or active power. By generating reactive power as close as possible to the machine which is to use it, there is less need to waste valuable resources in transporting it in the power network. This is known as reactive power compensation improvement in the power factor - the efficiency rating - of the plant. The best part is, everyone is a winner.

Shunt capacitors are employed at substation level for the following reasons:

***1. Voltage regulation***: The main reason that shunt capacitors are installed at substations is to control the voltage within required levels. Load varies over the day, with very low load from midnight to early morning and peak values occurring in the evening between 4 PM and 7 PM. Shape of the load curve also varies from weekday to weekend, with weekend load typically low. As the load varies, voltage at the substation bus and at the load bus varies. Since the load power factor is always lagging, a shunt connected capacitor bank at the substation can raise voltage when the load is high. The shunt capacitor banks can be permanently connected to the bus (fixed capacitor bank) or can be switched as needed. Switching can be based on time, if load variation is predictable, or can be based on voltage, power factor, or line current.

***2. Reducing power losses***: Compensating the load lagging power factor with the bus connected shunt capacitor bank improves the power factor and reduces current flow through the transmission lines, transformers, generators, etc. This will reduce power losses (I2R losses) in this equipment.

***3. Increased utilization of equipment*****:** Shunt compensation with capacitor banks reduces KVA loading of lines, transformers, and generators, which means with compensation they can be used for delivering more power without overloading the equipment. Reactive power compensation in a power system is of two types—shunt and series. Shunt compensation can be installed near the load, in a distribution substation, along the distribution feeder, or in a transmission substation. Each application has different purposes. Shunt reactive compensation can be inductive or capacitive. At load level, at the distribution substation, and along the distribution feeder, compensation is usually capacitive. In a transmission substation, both inductive and capacitive reactive compensation are installed [16].

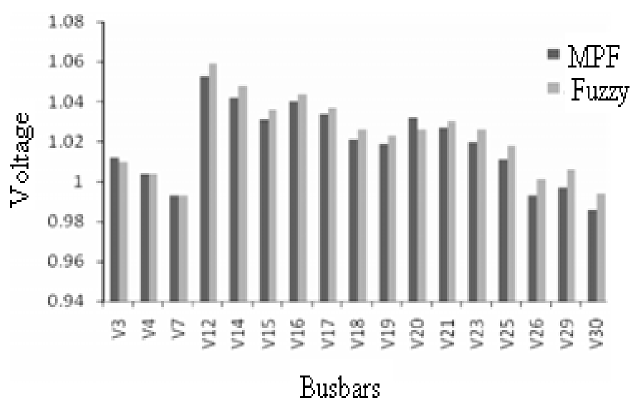


Figure 3: Voltages at load buses at full load

## V. RESULTS AND DISCUSSIONS

For verifying the effectiveness of the proposed method, a modified IEEE 30-bus test system shown in Fig 2 is tested Tables 1 and 2 list system parameters and initial buses data In this system, there are reactive power sources a1 buses 10, 11 19. 24 and terminal generator voltage regulators at buses *25,* 26. 27. 28, 29 In order to show the effectiveness and adaptability of the proposed technique, executing the control actions of Fuzzy give the results of load voltages as in Fig3. The same figure compares the resultant load voltages obtained by MPF and Fuzzy techniques. It is clear that error between load voltages obtained by the two techniques is acceptable. Then, the Fuzzy is capable of suggesting proper control action to keep voltages at load buses within limits.

Four cases are investigated the following

*Case 1*: Load of bus 2 increases, which causes bus 2 to violate the voltage constraint, but the violation, is not serious.
*Case 2*: Load of buses 2, 11 and 13 increases, it causes voltage violations at buses 2, 11 and 13.
*Case 3*: Buses 2, 11 and 13 are heavily loaded like case 2; a double-circuit breakdown at line 28 is occurred. Simultaneously, the upper limit of reactive power at bus 10 is reduced to 13.2 p.u.. It causes a larger range of voltage violation at buses 2, 11 and 13.
*Case 4*: In addition to the disturbances described in case 3, there are the upper limits of reactive power at buses 10, 11, 19, and 24 all reduced to 0.2 p.u..
Very interesting definition of benefit with capacitor application can be found in one of the main benefits of applying capacitors is that they can reduce distribution line losses. Losses come from current through the resistance of conductors. Some of that current transmits real power, but some flows to supply reactive power. Reactive power provides magnetizing for motors and other inductive loads. Reactive power does not spin kWh meters and performs no useful work, but it must be supplied. Using capacitors to supply reactive power reduces the amount of current in the line. Since line losses are a function of the current squared, *I2R*, reducing reactive power flow on lines significantly reduces losses.

# VI. METHOD APPLIED TO REGIONAL GRID

In this method, the candidate positions of reactive power sources will be first identified using an optimal power flow (OPF) framework with the minimum total cost objective including costs of new reactive power sources.

Table1. Variation of line voltage stability using fuzzy with load increments for IEEE 30 bus system

| Line Details | | | Load in Percent of Base Case Load | | | | | |
|---|---|---|---|---|---|---|---|---|
| No. | Starting Bus | Ending Bus | 100 % | 200 % | 300 % | 350 % | 380 % | 401 % |
| 1 | 1 | 2 | 0.0359 | 0.0359 | 0.0359 | 0.0359 | 0.0359 | 0.0359 |
| 2 | 2 | 3 | 0.0867 | 0.0867 | 0.0867 | 0.0867 | 0.0867 | 0.0867 |
| 3 | 2 | 6 | 0.0332 | 0.1373 | 0.3225 | 0.4875 | 0.6517 | 0.9157 |
| 4 | 1 | 8 | 0.0572 | 0.1558 | 0.3420 | 0.5144 | 0.6895 | 0.9722 |
| 5 | 2 | 8 | 0.0209 | 0.1184 | 0.3036 | 0.4764 | 0.6536 | 0.9455 |
| 6 | 3 | 6 | 0.0516 | 0.0494 | 0.2313 | 0.3964 | 0.5639 | 0.8427 |
| 7 | 6 | 8 | 0.0121 | 0.0180 | 0.0175 | 0.0104 | 0.0019 | 0.0361 |
| 8 | 8 | 4 | 0.0785 | 0.1682 | 0.3208 | 0.4467 | 0.5638 | 0.7430 |
| 9 | 6 | 7 | 0.0830 | 0.0947 | 0.1251 | 0.1587 | 0.1979 | 0.2793 |
| 10 | 7 | 5 | 0.0531 | 0.1382 | 0.2661 | 0.3639 | 0.4160 | 0.5821 |
| 11 | 6 | 9 | 0.0821 | 0.0529 | 0.0258 | 0.0162 | 0.0170 | 0.0449 |
| 12 | 7 | 9 | 0.0010 | 0.0435 | 0.1047 | 0.1524 | 0.1968 | 0.2652 |
| 13 | 9 | 10 | 0.0070 | 0.0039 | 0.0069 | 0.0199 | 0.0353 | 0.0672 |
| 14 | 4 | 11 | 0.0062 | 0.0808 | 0.1893 | 0.2719 | 0.3465 | 0.4578 |
| 15 | 4 | 12 | 0.0185 | 0.0642 | 0.1200 | 0.1553 | 0.1822 | 0.2133 |
| 16 | 4 | 13 | 0.0265 | 0.0928 | 0.1783 | 0.2357 | 0.2819 | 0.3399 |

After solving the basic OPF we choose the candidate locations for optimal allocations of reactive power to the system. Then the reactive power sources are applied to different candidate places one by one and at several candidate places at the same time iteratively. The cost-benefit analysis will then be worked out against the candidate locations, with different standard sizes of reactive power sources, so as to arrive at the optimal plan for reactive power support in an iterative manner. Fig.1. presents the flow chart for the proposed method. The selected positions and sizes of reactive power are those which generate the system benefits larger than the costs involved which make the investment economically justifiable. The simulations and results of this method will be given in below.Table1 implies the load variation of the system with uniform increment and clearly indicates that voltage collapse is to be occurred in the critical lines (3, 4 and 5) of the IEEE 30 bus system.

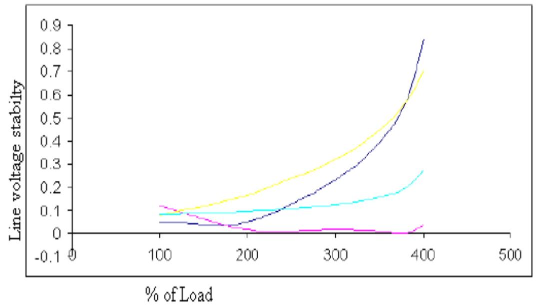


Fig4. Variation of bus voltage stability using fuzzy index with load increments of line on IEEE 30 bus system

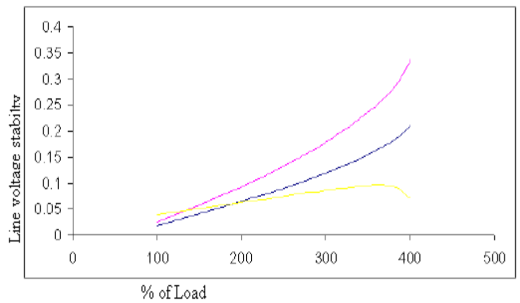


Fig5. Variation of bus voltage stability using fuzzy index with load increments of line of the IEEE 30 Bus system

Table2: y-bus Vs Bus Voltage Magnitudes in p.u

| Y | V |
|---|---|
| 4.2881 - 12.9014i | 0.9861 |
| 2.8588 - 8.6009i | 0.9545 |
| 0.7210 - 1.6759i | 1.0097 |
| 1.5443 - 5.0094i | 1.0112 |
| 1.4279 - 4.0956i | 0.9938 |
| 1.6077 - 4.8491i | 1.0110 |
| 5.2963 - 14.1159i | 0.9922 |
| 1.0310 - 4.1223i | 1.0096 |
| 3.2349 - 9.5033i | 1.0055 |
| 4.2644 - 14.0424i | 0.9979 |
| 2.1751 - 5.9006i | 0.9758 |
| 1.5164 - 5.1666i | 1.0074 |
| 2.7847 - 8.2039i | 0.9749 |
| 4.6436 - 16.2812i | 1.0076 |
| 4.1406 - 21.1681i | 0.9964 |
| 2.6050 - 17.9710i | 1.0002 |
| 2.6921 - 14.3083i | 0.9967 |
| 3.2926 - 13.0793i | 0.9899 |
| 5.8773 - 15.2118i | 0.9902 |
| 4.1459 - 20.8194i | 0.9917 |
| 1.8325 - 7.3300i | 0.9948 |
| 4.8804 - 19.4813i | 0.9958 |
| 2.1604 - 8.4658i | 0.9931 |
| 4.3854 - 18.1333i | 0.9891 |
| 1.8487 - 7.3604i | 1.0150 |
| 1.3556 - 5.1270i | 1.0250 |
| 4.6948 - 14.0845i | 1.0160 |
| 2.2695 - 2.6877i | |
| 1.0313 - 2.6339i | |
| 2.7922 - 10.0847i | |
| 1.1657 - 2.6998i | |
| 6.3532 - 19.0194i | |
| 2.2994 - 7.4099i | |

Table3. Bus Data

| Bus | Type | Vsp | theta | PGi | QGi | PLi | QLi |
|---|---|---|---|---|---|---|---|
| 1 | 3 | 0.984 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 2 | 3 | 0.9602 | 0.00 | 0.00 | 0.00 | 0.1032 | 0.0288 |
| 3 | 3 | 1.0086 | 0.00 | 0.00 | 0.00 | 0.1431 | 0.0563 |
| 4 | 3 | 1.0087 | 0.00 | 0.00 | 0.00 | 0.1834 | 0.0774 |
| 5 | 3 | 0.9921 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 6 | 3 | 1.0092 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 7 | 3 | 0.9917 | 0.00 | 0.00 | 0.00 | 0.2410 | 0.1163 |
| 8 | 3 | 1.0082 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 9 | 3 | 1.0033 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 10 | 3 | 0.9945 | 0.00 | 0.00 | 0.00 | 0.112 | 0.0518 |
| 11 | 3 | 0.9741 | 0.00 | 0.00 | 0.00 | 0.1024 | 0.0294 |
| 12 | 3 | 1.0009 | 0.00 | 0.00 | 0.00 | 0.1291 | 0.0367 |
| 13 | 3 | 0.9732 | 0.00 | 0.00 | 0.00 | 0.1041 | 0.0421 |
| 14 | 3 | 0.9917 | 0.00 | 0.00 | 0.00 | 0.1235 | 0.0467 |
| 15 | 3 | 0.9873 | 0.00 | 0.00 | 0.00 | 0.0812 | 0.0255 |
| 16 | 3 | 0.9944 | 0.00 | 0.00 | 0.00 | 0.0731 | 0.0475 |
| 17 | 3 | 0.9915 | 0.00 | 0.00 | 0.00 | 0.1122 | 0.0475 |
| 18 | 3 | 0.9831 | 0.00 | 0.00 | 0.00 | 0.1122 | 0.0475 |
| 19 | 3 | 0.9843 | 0.00 | 0.00 | 0.00 | 0.0612 | 0.0172 |
| 20 | 3 | 0.9871 | 0.00 | 0.00 | 0.00 | 0.1423 | 0.0573 |
| 21 | 3 | 0.9912 | 0.00 | 0.00 | 0.00 | 0.0552 | 0.0552 |
| 22 | 3 | 0.9922 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 23 | 3 | 0.9853 | 0.00 | 0.00 | 0.00 | 0.0923 | 0.0342 |
| 24 | 3 | 0.9848 | 0.00 | 0.00 | 0.00 | 0.0782 | 0.0232 |
| 25 | 2 | 1.0150 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 26 | 2 | 1.0250 | 0.00 | 0.1073 | 0.0342 | 0.00 | 0.00 |
| 27 | 2 | 1.0160 | 0.00 | 0.1192 | 0.0362 | 0.00 | 0.00 |
| 28 | 2 | 1.0212 | 0.00 | 0.0993 | 0.0483 | 0.00 | 0.00 |
| 29 | 2 | 1.0123 | 0.00 | 0.00 | 0 | 0.00 | 0.00 |
| 30 | 1 | 1.0500 | 0.00 | 0.00 | 0 | 0.00 | 0.00 |

# 7. CONCLUSIONS

This work presents the successful analysis on voltage stability using Fuzzy Based and performs satisfactorily on power systems under all possible conditions such as increased load and line compensation with series and shunt capacitances for both in off-line and on- line simulation applications. The shortcomings of previous methods are overcome and consistent results are obtained. Though the number of iterations is more in fuzzy logic load flow method, the proposed algorithm does not require the factorization, refactorization and computation of Jacobin matrix at each iteration which shows the validity of the proposed algorithm. In the proposed model, more than one controlling devices are likely to be selected for coordinated control. Therefore, robust voltage control can be easily accomplished by the proposed model. Simulation results of the application example show that the proposed voltage control will lead as closely as possible to the desired system conditions and flexible operation of the controlling devices is realized by employing the fuzzy model, the problem can be solved simply by applying the max and min-operations. By defining certain fuzzy variables, the operator's intuition in operating a power system is more pertinently reflected. This method enables the system engineers to have coordinated variable control for satisfactorily operating the system. Besides, owing to its much less computational requirements, the method can be applied on line in this paper, the method for successful capacitor placement with the objective function of active power losses reduction together with cost-benefit analysis was proposed. The method was implemented on the example of real power grid of one of the Georgian regions. As we could observe from our iterations, in case if we make investments for addition of reactive power in power system for loss reduction objective, reduced losses will easily recover investment costs caused due to the capacitors addition. However this was not true for all the cases in our iterations and some cases were not successful and effective. Our iterations, made on real power grid shows, that in some cases even though the losses are reduced, the investment cost could be so high, that economically it becomes not effective to implement such changes. Especially it is true when we maximally reduce losses and for this we need to apply many sources of reactive power in different locations of the grid. In such case it becomes even more difficult to operate the number of capacitors as with connection and disconnections of reactive power sources many factors of power system should be considered. However in our iterations we made assumptions regarding the time for the investment recovery, average peak-hours per day and number of peak-hour days per year as well as the investment cost for reactive power support addition. If we change these assumptions, then the results of cost-benefit comparisons will change and unsuccessful iterations could become successful or vice versa. Also our suggested method of reactive power addition for the loss reduction purpose becomes even more effective and economically worthwhile in power systems with higher loads and where peak-hour operations are longer. For being able to significantly improve the performance of power systems and to reduce losses, reactive power should be applied properly and controlled.

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