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Optimal Voltage Regulator Placement In a Radial Distribution System Using Fuzzy Logic

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Abstract

The operation and planning studies of a distribution system require a steady state condition of the system for various load demands. Voltage has always been considered as an integral part of the power system response. There are several factors which contribute to voltage collapse such as increased loading on transmission lines, reactive power constraints, on load tap changer dynamics and load characteristics. So, we proposed a computer algorithm for optimal voltage control, suitable for large radial distribution network.

Our aim is to obtain optimal voltage control with voltage regulators and then to decrease the total cost of voltage regulators and losses, to obtain net saving. This algorithm makes the initial selection, installations and tap setting of the voltage regulators which provide a smooth voltage profile along the network. It is also used to obtain the minimum number of the initially selected voltage regulators, by moving them in such way as to control the network voltage at the minimum possible cost. Software using MATLAB has been developed and also implemented using Fuzzy Logic and the results of both, conventional and using Fuzzy are compared.

Index Terms: Back tracking algorithm, fuzzy expert system, voltage regulators, Radial distribution system, Fuzzy system.

I. INTRODUCTION

General description of Distribution System

Distribution system is that part of the electric power system which connects the high voltage transmission network to the low voltage consumer service point. In any distribution system the power is distributed to various uses through feeders, distributors and service mains. Feeders are conductors of large current carrying capacity which carry the current in bulk to the feeding points. Distributors are conductors from which the current is tapped of for the supply to the consumer premises.

Basic Distribution Systems

There are two basic structures for distribution system namely

(i) Radial distribution system
(ii) Ring main distribution system

(i)Radial Distribution System:

If the distributor is connected to the supply system on one end only then is system is said to be a radial distribution system. In such a case the end of the distributor nearest to the generating station would be heavily loaded and the consumers at the distance end of the distributor would be subjected to large voltage variations as the load varies. The consumer is dependent upon a single feeder so that a fault on any feeder or distributor cuts off the supply to the consumers who are on the side of fault away from the station.

(ii)Ring Main Distribution System:

Ring main employs a feeder which covers the whole area of supply finally returns to the generating station. The feeder is closed on itself. This arrangement is similar to two feeders in parallel on different buses.

Distribution System Losses

It has been established that 70% of the total losses occur in the primary and secondary distribution system, while transmission and sub transmission lines account for only 30% of the total losses. Distribution losses are 15.5% of the generation capacity and target level is 7.5%. Therefore the primary and secondary distribution must be properly planned to ensure losses within the acceptability limits.

II.LOAD FLOWS

Load flow technique is an important and basic tool in the field of power system Engineering. The computational procedure required to determine the steady state operating conditions of a power system network is termed as load flow. It is used in the planning and operation of the power system in order to keep the voltage and powers with in limits. It is essential for the continuous monitoring of the current state of the system and also for analyzing the effectiveness of the system. For these, load flow analysis is solved as efficiently as possible.

Mathematical formulation:

Consider a branch connected between buses 1 and 2 as shown in fig 1.

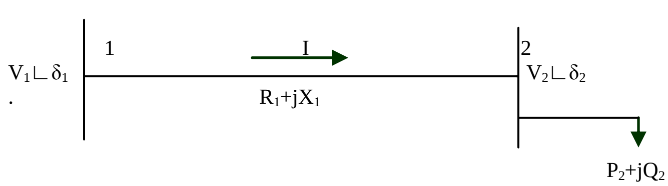

Fig. 2.1 Electrical equivalent of a typical branch 1

In figure (2.1) $V_1\angle\delta_1$ and $V_2\angle\delta_2$ are the voltage magnitudes and phase angles of two buses 1 and 2. Let the current flowing through branch is I. The substation voltage is assumed to be 1+j0 p.u. Let power factor angle of load P_2+Q_2 be θ_2.Let R_1 and X_1 be the resistance and reactance of the line 1 respectively. The phasor diagram of fig 2.1 is shown in fig.2.2.

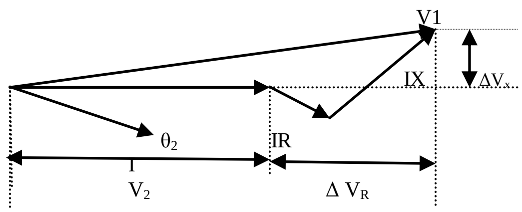

Fig. 2.2.Basic phasor diagram of a branch connected between twobuses

From fig. 2.2 the equations are

$$|V_1|^2=(|V_2|+\Delta V_R)^2+(\Delta V_X)^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots..(2.1)$$

$$|V_1|^2=(|V_2|+(IR_1\cos\theta_2+I\,X_1\sin\theta_2))^2+(IX_1\cos\theta_2-IR_1\sin\theta_2)^2 \quad \ldots.(2.2)$$

To eliminate 'I'in equation (2.2)

$$I\cos\theta_2=P_2/|V_2|$$

$$I\sin\theta_2=Q_2/|V_2|$$

where

P_2 = Total active power load including local load and active power losses beyond bus 2.

Q_2 = Total reactive power load including local load and reactive power losses beyond bus 2.

The equation (2.2) becomes

$$|V_1|^2=[|V_2|+(P_2R_1+Q_2X_1)/|V_2|]^2+[(P_2X_1-Q_2R_1)/|V_2|]^2$$

$$|V_1|^2=|V_2|^2+2|V_2|(P_2R_1+Q_2X_1)/|V_2|+(P_2R_1+Q_2X_1)^2/|V_2|^2+(P_2X_1-Q_2R_1)^2/|V_2|^2$$

$$|V_1|^2|V_2|^2=|V_2|^4+(P_2R_1+Q_2X_1)^2+2|V_2|^2(P_2R_1+Q_2X_1)+(P_2X_1-Q_2R_1)^2$$

$$|V_2|^4+2|V_2|^2(P_2R_1+Q_2X_1)+(P_2^2+Q_2^2)(R_1^2+X_1^2)-|V_1|^2|V_2|^2=0$$

$$|V_2|^4+2|V_2|^2(P_2R_1+Q_2X_1-|V_1|^2/2)+.(P_2^2+Q_2^2)(R_1^2+X_1^2)=0 \ldots\ldots \ldots.(2.3)$$

Equation (2.3) has a straightforward solution and does not depend on the phase angle, which simplifies the problem formulation. In a distribution system, the voltage angle is not so important because the variation of voltage angle from the substation to the tail end of the distribution feeder is only few degrees. Note that the two solutions of V_2, only considering the positive root of the quadratic equation give a realistic value.Therefore from equation (2.3) the solution of V_2 can be written as

$$|V_2|=\{|V_1|^2-(R_1^2+X_1^2)(P_2^2+Q_2^2)/|V_2|^2-2(P_2R_1+Q_2X_1)\}^{1/2} \ldots(2.4)$$

In general

$$|V_{i+1}|=\{|V_i|^2-(R_i^2+X_i^2)(P_{i+1}^2+Q_{i+1}^2)/|V_{i+1}|^2-2(P_{i+1}R_i+Q_{i+1}X_i)\}^{1/2} \quad \ldots(2.5)$$

Where

Bus no i=1, 2……nbus.

Branch no j=1, 2,3…..nbus-1.

nbus=total number of buses.

The real and reactive power loss of branch 'j' are given by

$$P_{loss}[j]=R_j*(P^2_{i+1}+Q^2_{i+1})/|V_{i+1}|^2 \quad \ldots(2.6)$$

$$Q_{loss}[j]=X_j*(P^2_{i+1}+Q^2_{i+1})/|V_{i+1}|^2 \ldots.(2.7)$$

The total active and reactive power losses are given by

$$TPL=\sum_{j=1}^{nbus-1}P_{loss}[j] \quad \ldots.(2.8)$$

$$TQL=\sum_{j=1}^{nbus-1}Q_{loss}[j] \quad \ldots.(2.9)$$

Usually the substation voltage V_i is known and is taken as V_1= 1.0 (p.u). Initially, $P_{loss}[j]$ and $Q_{loss}[j]$ are set to zero for all j. Then the initial estimate of P_{i+1} and Q_{i+1} will be the sum of the loads of all the buses beyond bus i plus the local load of bus i. Compute V_{i+1}, $P_{loss}[j]$, $Q_{loss}[j]$ using equations (2.5), (2.6) and (2.7). This will complete one iteration. Update the loads $P_{(i+1)}$ and $Q_{(i+1)}$ (by including losses) and repeat the same procedure until all the voltage magnitudes are computed to a tolerance level of 0.0001 p.u in successive iterations.

III. Voltage Regulators

The problem of determination of optimal number and location of voltage regulator can be formulated as an optimization problem. This algorithm is to obtain the optimal location for placing Voltage regulators that maintain the voltages within the limits of the RDS so as to maximize an objective function, which consists of capital investment and capitalized energy loss costs.

The objective function is formulated as maximizing the cost function,

$$\text{Max. } F = K_e\times P_{lr}\times 8760\times LLf-K_{VR}\times N\,(\alpha+\beta)$$

The VR problem consists of two sub problems, that of optimal placement and optimal choice of tap setting. The first sub problem determines the location and number of VRs to be placed and the second sub problem decides the tap positions of VR. The first step involves the selection of VRs at the buses where the voltage is violating the upper and lower limits. The optimal number and placement of voltage regulators required is obtained by applying the proposed back tracking algorithm.

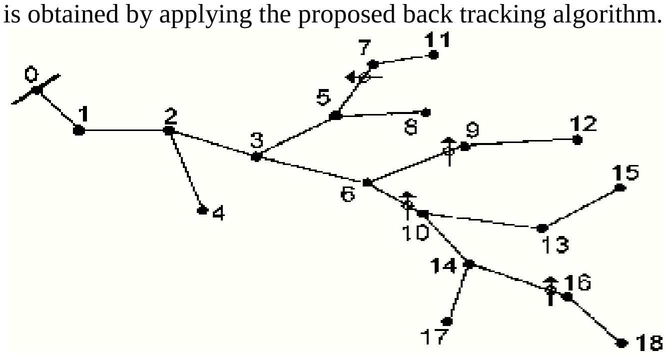

Fig. 3a The 19 bus RDS before installation of Voltage regulators

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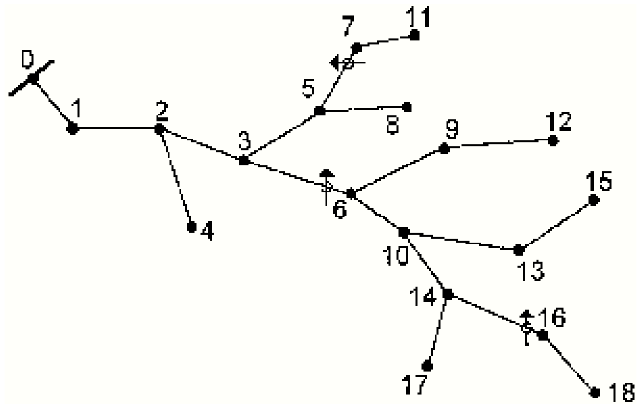

Fig.3b The19busRDSafterinstallationofVoltageregulators

Let the initial voltage regulators are located at buses 8, 11, 13 and 18 as shown in Fig. 3a.It is proposed to reduce the number of VRs in a practical system by shifting the VR's to the junction of laterals (such as from buses 11 and 13 to bus 10) and observe the voltage profile and the objective function by computing voltages at each bus. If it satisfies the above two constraints, then this will be taken as optimal position for the single VR at bus 10 instead of two VRs at buses 11 and 13 (shown in Fig 3b). This procedure is repeated starting from the tail end buses towards the source bus and find the optimal number and location of VRs.

Algorithm for optimum voltage regulator placement in RDS using proposed back tracking algorithm:

Step 1 . Read line and load data.
Step 2. Run load flows for the system and compute the voltages at each bus, real and reactive power losses of the system.
Step 3. Identify the buses, which have violation of voltage limits.
Step4. Obtain optimal number of VRs and location of VRs by using back tracking algorithm.
Step 5. Obtain the optimal tap position of VR using Eqn. (3), so that the voltage is within the specified limits.

Step 6. Again run the load flows with VR, then compute voltages at all buses, real and reactive power losses If voltages are not within the limits, go to step 3.
Step7. Determine the reduction in power loss and net saving by using objective function (Eqn (2)).
Step 8. Print results.
Step 9. Stop.

IV. FUZZY LOGIC

Fuzzy logic, invented by Professor LotfiZadeh of UC-Berkeley in the mid 1960s, provides a representation scheme and a calculus for dealing with vague or uncertain concepts. It provides a mathematical way to represent vagueness in humanistic systems. The crisp set is defined in such a way as to dichotomize the individuals in some given universe of discourse into two groups as below:

a) Members (those who certainly belong to the set.)
b) Non-members (those who certainly do not belong to the set.)

Fuzzy Logic in Power Systems

Analytical approaches have been used over the years for many power system operation, planning and control problems. However, the mathematical formulations of real world problems are derived under certain restrictive assumptions and even with these assumptions, the solutions of large – scale power systems problems are not trivial. On the other hand, there are many uncertainties in various power system problems because power systems are large, complex, geographically widely distributed systems and influenced by unexpected events.

More recently, the deregulation of power utilities has introduced new issues into the existing problems. These facts make it difficult to effectively deal with many power systems problems through strict mathematical formulations alone Although a large number of AI techniques have been employed in power systems, fuzzy logic is a powerful tool in meeting challenging problems in power systems. This is so because fuzzy logic is the only technique, which can handle in precise, vague or 'fuzzy' information.

FuzzySystems.

Fuzzy logic is based on the way the brain deals with inexact information

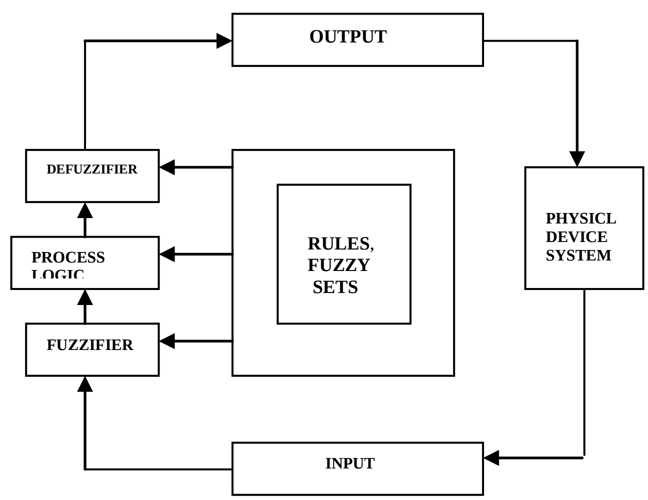

Fig. 4.5 FUZZY MODEL

Principal components in fuzzy logic model:

1. Fuzzifier / Fuzzification interface
2. Knowledge base / Knowledge repository
3. Defuzzifier
4. Process logic / Inference engine

WhenFuzzy?

Major feature of Fuzzy Logic is its ability to express the amount of ambiguity in human thinking and subjectivity in a comparatively undistorted manner. So, When the process is concerned with continuous phenomenon that are not easily broken down into discrete segments.

When a mathematical model of the process does not exist or exist but it is too difficult to encode, or is too complex to be evaluated fast enough for real time operation, or involves too much memory on the designated chip architecture.

When the process involves human interaction andAn expert is available who can specify the rules underlying the system behavior and fuzzy sets that represent the characteristics of each variable.With these properties, fuzzy logic techniques find their applications in such areas as Control most widely applied area,Pattern recognition.(e.g.: image, audio, signal processing),Quantitative Analysis(operations research, management),Inference(e.g. expert systems for diagnosis, prediction, planning, natural language processing, intelligent inference, intelligent robots, softmare engineering) andInformation retrieval. (e.g. data bases)

V. FUZZY IMPLEMENTATION

The entire frame work to solve the optimal voltage regulator placement problem includes the use of numerical procedures which are coupled to the fuzzy. First a vector based load flow calculates the power losses in each line and voltages at every bus. The voltage regulators are placed at every bus and total real power losses is obtained for each case. The per unit voltages at every bus and the power losses obtained are the inputs to the FES which determines the bus most suitable for placing voltage regulator without violating the limits. The FES(Fuzzy Expert System) contains a set of rules which are developed from qualitative descriptions. In a FES, rules may be fired with some degree using fuzzy interfacing for determining the suitability of voltage regulator placement at a particular bus, a set of multiple antecedent fuzzy rules have been established.

Table 5.1 Rules for Fuzzy Expert System

AND		VOLTAGE				
		Low	**Low-normal**	**Normal**	**High-normal**	**High**
POWERLOSSINDEX	**Low**	Low-medium	Low-medium	Low	Low	Low
	Low-medium	Medium	Low-Medium	Low-Medium	Low	Low
	Medium	High-Medium	Medium	Low-Medium	Low	Low
	High-medium	High-medium	High-medium	Medium	Low-medium	Low
	High	High	High-medium	Medium	Low-medium	Low-medium

inputs to the rules are the voltages and power loss indices and the output consequent is the suitability of The voltage regulator placement. The rules are summarized in the fuzzy decision matrix in table given above.Fuzzy variables of PLI (power loss index) are low, low-medium, medium, high-medium, high.

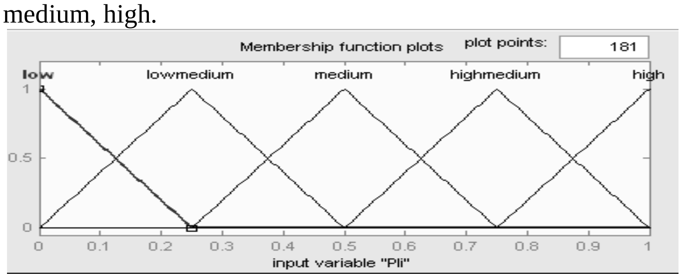

Fig 5.1 Member ship functions for power loss index

Fuzzy variables for Voltage are low, low-normal, normal, high-normal, high.

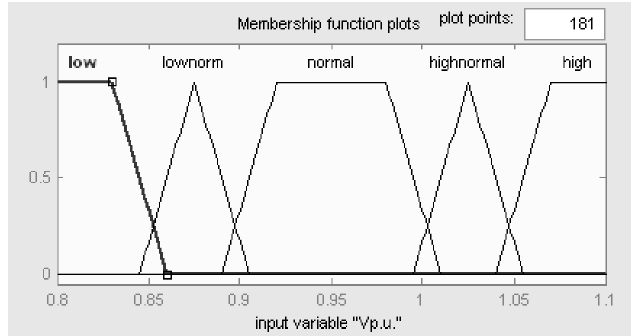

Fig 5.2 Membership Functions for voltage

Fuzzy variables for Voltage regulator suitability index are low, low-medium, medium, high-medium, high.

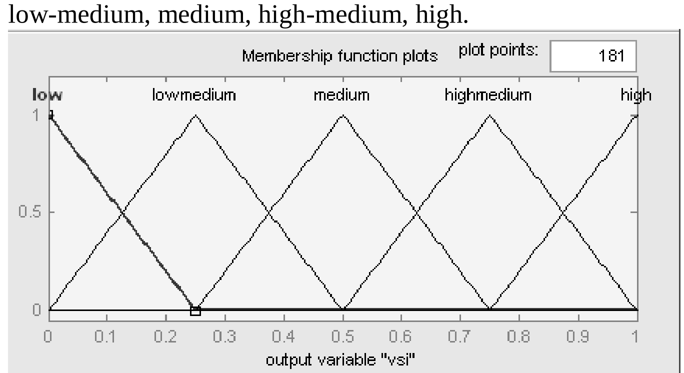

Fig 5.3 Membership functions for Voltage regulator suitability index

These fuzzy variables described by linguistic terms are represented by membership functions.

5.1 Fuzzy inference and defuzzification techniques.

After the FES receives inputs from the load flow program, several rules may fire with some degree of membership the fuzzy inferencing methods used by fuzzy clips are based on the max-min or max-prod methods.The MAX-MIN METHOD involves truncating the consequent membership function of each fired rule at the minimum membership value of all the antecedents. A final aggregated membership function is achieved by taking the union of all the truncated consequent membership functions of the fired rules. For the voltage regulator problem, resulting voltage regulator placement suitability membership function μ_s of bus i for k fired rules is

$$\mu_s(i) = \min_k[\min[\mu_p(i), \mu_v(i)]]$$

whereμ_p and $\mu_v$are the membership functions of the power loss index and voltage level respectively. Once the suitability membership function of a node is calculated, It must bedefuzzified in order to determine the buses suitability ranking. The centroid method of defuzzification is used, this finds the center of area of the membership function. Thus, the voltage regulator suitability index is determined by:

$$S = \int\mu_s(z).zdz/(\int\mu_s(z)dz)$$

5.2 Algorithm for optimum voltage regulator placement in RDS using FES:

Step 1. Read line and load data.

Step 2. Run load flows for the system and compute the voltages at each bus, real and reactive power losses of the system.

Step 3. Install the voltage regulator at every bus and compute

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the total real power loss of the system at each case and convert into normalized values.

Step4. Obtain optimal number of VRs and location of VRs by giving voltages and power loss indices as inputs to FES.

Step 5. Obtain the optimal tap position of VR using Eqn. (3) so that the voltage is within the specified limits.

Step 6. Again run the load flows with VR, then compute voltages at all buses, real and reactive power losses. If voltages are not within the limits, go to step 3.

Step 7. Determine the reduction in power loss and net saving by using objective function (Eqn (2)).

Step 8. Print results.

Step 9. Stop.

VI. RESULTS AND ANALYSIS

The proposed method is illustrated with a radial distribution systems of 47 bus. Consider 47 bus Radial Distribution System. The Line and Load data is given in Appendix and the single line diagram is shown in Fig.3. For the positioning of voltage regulators, the upper and lower bounds of voltage are taken as ±5% of base value. The voltage regulators are of 11kV, 200MVA with 32 steps of 0.00625 p.u.each.

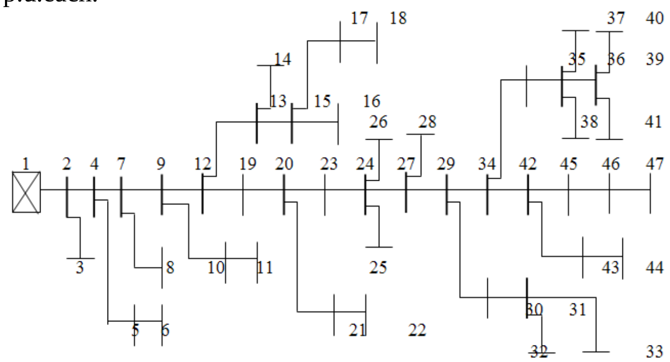

Fig. 6.1 Single line diagram of 47 bus RDS

The reduction in real power loss, net saving and %voltage regulation for the system is shown in Table 6.2.

Parameter	Before	With VRs: VRs at all buses (except at bus 1)	After (VR at buses 2, 36, 42)
P_{loss} (%)	16.6835	13.1796	13.0954
Net saving(in Rs.)	-----	(-) 1,14,850	2,79,380
Voltage regulation (%)	16.7039	6.7039	4.6964

I**Table 6.2 Summary of Results of 47 bus RDS**

It is observed that from Table 6.2, without voltage regulators in the system the percentage power loss is 16.6835 and percentage voltage regulation is 16.7039. With voltage regulators at all buses (except at bus1), the percentage power loss is 13.1796 and percentage voltage regulation is 6.7039 but the net saving is (-) Rs.1, 14,850 (cost of voltage regulators itself is more than cost of total energy losses), with voltage regulators at optimal locations (obtained with proposed method) of buses 2,36,and 42 the percentage power loss is reduced to 13.0954 and percentage voltage regulation is reduced to 4.6964. The optimal net saving is increased to Rs.2, 79,380.

Results of FES:

The proposed method is illustrated with a radial distribution systems of 47 bus.By applying the above FES algorithm for the 47 bus system, it is found that two voltage regulators at bus 2 are sufficient to maintain the voltage profile at all buses. One voltage regulator with 10% tapping and another voltage regulator with 0.625% tapping. The bus voltages without and with voltage regulators is shown in the Table 6.3.

Table 6.3Load Flow Results Without and With Voltage Regulators

Bus No.	Bus Voltages before VR placement	Bus Voltages with **two** Voltage regulators at bus 2
1	1.0000	1.0000
2	0.9378	1.0440
3	0.9376	1.0439
4	0.9132	1.0224
5	0.9128	1.0220
6	0.9126	1.0218
7	0.9090	1.0184
8	0.9087	1.0187
9	0.9004	1.0110
10	0.9001	1.0108
11	0.8997	1.0105
12	0.8911	1.0028
13	0.8863	0.9986
14	0.8861	0.9984
15	0.8852	0.9977
16	0.8848	0.9973
17	0.8846	0.9971
18	0.8842	0.9967
19	0.8839	0.9965
20	0.8760	0.9896
21	0.8754	0.9891
22	0.8751	0.9888
23	0.8555	0.9716
24	0.8536	0.9699
25	0.8533	0.9697
26	0.8531	0.9696
27	0.8508	0.9675
28	0.8507	0.9674
29	0.8480	0.9651
30	0.8469	0.9641
31	0.8455	0.9629
32	0.8452	0.9626
33	0.8452	0.9625
34	0.8438	0.9614
35	0.8420	0.9598
36	0.8375	0.9558

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37	0.8373	0.9557
38	0.8372	0.9556
39	0.8362	0.9547
40	0.8359	0.9545
41	0.8357	0.9543
42	0.8381	0.9564
43	0.8373	0.9557
44	0.8370	0.9554
45	0.8344	0.9532
46	0.8333	0.9522
47	0.8330	0.9519

Table 6.4 Summary of results:

Parameter	**Befo re**	**With VRs**	
		VRs at all buses (except at bus 1)	**After (two VRs at bus 2)**
P_{loss}(%)	16.68 35	13.1796	12.9647
Net saving	-----	- Rs.1,14,85 0	Rs.3,26,169
Voltage regulation (%)	16.70 39	6.7039	4.8106

It is observed that from Table6.4 , without voltage regulators in the system the percentage power loss is 16.6835 and percentage voltage regulation is 16.7039. With voltage regulators at all buses (except at bus1), the percentage power loss is 13.1796 and percentage voltage regulation is 6.7039 but the net saving is (-) Rs.1, 14,850 (cost of voltage regulators itself is more than cost of total energy losses), with two voltage regulators at optimal location (obtained with proposed method) of bus 2 the percentage power loss is reduced to 12.9647 and percentage voltage regulation is reduced to 4.8106. The optimal net saving is increased to Rs.3, 26,169.

Comparison of results

Consider a practical **47bus** RDS, **withoutvoltageregulators** the total real power loss percentage is **16**.**6835** and percentage voltage regulation is **16**.**7039**, by applying **backtrackingalgorithm** the optimal number and location of voltage regulators is **three** voltage regulators at **2**, **36** and **42** buses. With voltage regulators at these buses the total real power loss percentage is reduced to **13**.**0954** and percentage voltage regulation is improved to **4**.**6964** and the net saving is Rs. **2**, **79,380.** By applying the proposed **FES** (Fuzzy Expert System) the optimal number and location of Voltage regulators is**two** regulators at bus **2** only. With Voltage regulators at bus 2 the total real power loss percentage is still reduced to **12**.**9647** and percentage voltage regulation is **4**.**8106** and the net saving has still increased to Rs. **3**, **26**,**169.**

Parameter	**Before**	**With voltage regulators**	
		Using back tracking algorithm with voltage regulators at buses 2,36,42	**Using Fuzzy Expert System Two voltage regulators at bus 2 only**
P_{loss}(%)	16.6835	13.0954	12.9647
Net saving (in Rs.)	--------	2,79,380	3,26,169
Voltageregulation (%)	16.7039	4.6964	4.8106

Table 6.7: Summary of result for 47 bus system with and without fuzzy

VII.**CONCLUSION**

In radial distribution systems it is necessary to maintain voltage levels at various buses by using capacitors or conductor grading or placing VR at suitable locations. The proposed Back tracking algorithm determines the optimal number, location and tap positions of voltage regulators to maintain voltage profile with in the desired limits and reduces the losses in the system which in turn maximizes the net savings in the operation of the system. In addition to the back tracking algorithm a method using Fuzzy is also proposed and the results of FES are compared with the results of back tracking algorithm. It is concluded that the FES also gives the optimal location and number along with the tap setting of the voltage regulators. The proposed FES provides good voltage regulation, and reduces the power loss which in turn increases the net savings when compared to the back tracking algorithm. The algorithms are tested with two Radial distribution systems consisting of 47 bus and the results are provided.

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