Research article

Fuzzy logic based optimal placement of voltage regulators and capacitors for distribution systems efficiency improvement

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ABSTRACT

Electric power systems in most developing countries, especially Ethiopia, are fed by radial distribution systems (RDSs), which serve as the final link between the high voltage transmission system and the consumers. In this paper, a fuzzy logic optimization method was presented for the efficient location of voltage regulators (VR) and capacitors in distribution systems (DSs). An investigation of Gondar power distribution system was performed specifically at the Gondar feeder in Gondar, Ethiopia which has 60 nodes with a total capacity of 3.413 MW. The Gondar distribution system (DS) is classified into different zones for the purpose of proper operation and supply of electricity. The minimum bus voltage is 0.8515 p.u., while the active and reactive power losses of the feeder are 377.75kW and 222.51 KVAR respectively. Voltages and power loss (PL) indices of the DS nodes were modeled using fuzzy membership functions. A fuzzy expert system (FES) containing a set of heuristic rules was used to determine the voltage regulator (VR) and capacitor placement suitability index. The load flow analysis of the system was simulated using NEPLAN MATLAB software before and after recompense. The effectiveness of the results obtained from both the voltage regulator and capacitor placement optimality using the proposed method are presented and compared.

1. Introduction

Electric power systems are made up of three parts: generation system, transmission system, and distribution system (DS). The distribution substations in the DSs are normally fed by one or more transmission lines, and each distribution substation serves one or more principal feeders. The role of a DS is to deliver electrical energy from the distribution substation to the customers. As electricity demand increases daily, the demand on DSs also increases, therefore, they are being stretched beyond their capacity. As a result of this, the system losses increases and leads to poor voltage regulation. Therefore, it becomes imperative to make the DSs efficient and effective. It is important to note that voltage regulators (VRs) and capacitor banks are effective methods for power factor (PF) correction, power loss reduction, and voltage profile (VP) improvement, as they are the most preferred indicators of overall efficiency improvement in power systems [1]. The different methods used to maintain the voltage level of radial distribution systems (RDS) are by using Shunt capacitors, VRs, and by employing conductor grading in RDS [2]. A VR is used to keep the voltage within an acceptable tolerance limit for

distribution and to keep the control equipment in good working condition. Capacitors are often used in DSs to compensate for reactive power. Because capacitors reduce power and energy losses, increase the available capacity of the feeders, and improve the feeder VP, the amount of compensation supplied is very closely tied to the optimal placement of capacitors in the distribution system. Capacitors also reduce the lagging component current, increase the PF of the generators, improve regulation, increase savings, and more importantly reduce the cost of power to consumers. Loss minimization, VP, and PF improvement in DSs have recently assumed greater significance, since distributed generation improves the reliability, efficiency, and service quality of power systems. VRs and capacitors are commonly employed to provide reactive power compensation, improve PF, improve feeder VP, reduce power losses (PL), and increase the overall efficiency of the distribution system [3]. In this paper, a fuzzy-based VR optimal placement algorithm was proposed to give the best location, optimal number, and tap setting of VRs, with consideration that the bus voltage variation is within ±5% of the rated voltage with minimal losses. The proposed method is used to optimize the savings of the capital cost of the VR, the cost of energy loss in the RDS,

and also used to maintain the acceptable voltage limits at all buses. The proposed method is easy and simple to implement for any RDS since it is independent of the size of the system. The use of fuzzy logic (FL) has gotten a lot of attention in recent years because of its utility in eliminating the need for sophisticated mathematical models in problem-solving [4]. Also, FL is used for error minimization and for optimization. For this reason, FL technique is easier to use to solve problems [5, 6]. Authors in [5, 6] employed fuzzy based methods for efficiency improvement of a DS. In [5], Photo-Voltaic and Wind Turbine generations (PV and WT) were considered as Distributed Generators (DGs), while in our paper, a fuzzy logic optimization method was presented for the efficient location of voltage regulators (VR) and capacitor banks in distribution systems (DSs). In [5], an algorithm was presented using Fuzzy Logic Controller (FLC) technique and Ant-Lion Optimization Algorithm's (ALOA) for optimal DG placement, while in our paper, we have proposed two different algorithms (1st for optimal VR placement in the RDS using fuzzy logic, and 2nd for optimal capacitor placement and sizing using fuzzy expert system (FES) and index based method). In our approach, the ranking of the VR suitability index (VRSI) was used to determine the maximum value used to obtain the optimal placement of the VR.

The subsequent sections of this paper are organized as follows. Section 2 presents the related works and in section 3, we present how the data was collected and analyzed. Section 4 presents the results and discussion, and the paper is concluded in section 5.

2. Related works

Many algorithms have been developed to enhance DS efficiency by lowering power and energy losses, as well as optimizing voltage profile (VP). A few of these algorithms are based on the assumption that the load is variable, while most considered a fixed load. Some of these works applied reconfiguration for loss reduction or optimal placement of compensation devices in the system, while a few works applied both methods.

Authors in [7] proposed two algorithms, a fuzzy logic and Artificial Bee Colony (ABC) algorithm to increase the overall efficiency of a RDS by minimizing active power loss (APL) and improving VP. Firstly, fuzzy was used for the optimal placement of distributed generators (DG) in sensitive buses or nodes of the network. In the second stage, the ABC algorithm was used to identify the appropriate location, size, and number of DGs that are required in the RDS taking into account maximum power loss reduction. The methods are tested and simulated on a standard IEEE test bus system [8].

Authors in [9] presented a new algorithm for reduction of power losses (PLs) on distribution lines using a bionic random search plant growth simulation algorithm (PGSA). The algorithm was used to find the required number of shunt capacitors and their optimal locations to reduce APLs considering the system constraints. The method was tested and simulated on a standard IEEE 34 bus test system. Authors in [10] presented a fuzzy logic-based coordinated voltage control method for distribution networks (DN) with DG. The method uses three control methods which are PF control, on-load tap changer control, and generation curtailment control to provide a more controllable RDS.

In [11], the authors proposed a method to obtain optimal voltage control in a RDS with VRs. They also tried to reduce the total cost of VRs, PLs, and maximize net savings by using Back Tracking Algorithm (BTA) and Fuzzy Expert System (FES). Algorithms were implemented using MATLAB along with the Fuzzy logic toolbox. Finally, the results of both the BTA and FES were compared.

Authors in [12] used a fuzzy logic controller to reduce reactive power of a radial feeder. The authors examined the voltage level of the system to determine if it was within the limit in order to ensure that the PF was near unity. This in turn enhanced the dynamic performance of the capacitor banks with variable consumer loads. According to the authors of [13, 14], reducing total losses in DSs is critical for improving overall power

delivery efficiency. This can be accomplished by strategically putting automated voltage regulators (AVR) in a RDS. Two unique approaches for selecting the best number, placement, and tap set-ting of VRs in RDSs was proposed in [15]. The first method is an analytical method called the BTA and the second method is based on Fuzzy logic. The effectiveness of the proposed methods was tested with two test systems, a 47-bus practical RDS and a 69 bus RDS. Authors in [16, 17] used a Modified Cuckoo search algorithm for the optimal placement of AVR in DS. The proposed method has been tested on a standard 15-node, 33-node, and 69-node DS. The results obtained were better than those achieved with existing methods.

2.1. Power loss and voltage drop in an electric power distribution system

Reducing power losses is one of the major objectives of any electrical utility. This is because if the losses exceed a certain allowable level, it can endanger the company's financial status. Power losses affect the entire power systems, from generation to transmission and to distribution; but this paper is focused mainly on losses in DSs. Losses in electrical power DSs include technical and non-technical losses [18, 19, 20, 21]. The technical losses are related to the energy distribution process that occurs as a result of the physical nature of equipments and infrastructure of the power system, i.e., copper loss in conductor cables, transformer switches, and generators. The non-technical losses are related to the customer management process, improper operation of meters, and its illegal use in collaboration with utility personnel [22]. Power losses in DSs occur in both primary and secondary feeders. Line losses are proportional to the square of the current passing through the line's resistance (R). Eq. (1) can be used to compute the line loss.

$$Power\ loss = \frac{I^2 R}{1000}(KW) \tag{1}$$

where; I: Phase current through the line (A); R: Total resistance of the line

$$I = \sqrt{(I\cos\theta)^2 + (I\sin\theta)^2} \tag{2}$$

$$Power\ loss = \frac{I^2 R}{1000} = \frac{R}{1000}\left((I\cos\theta)^2 + (I\sin\theta)^2\right) \tag{3}$$

The average annual loss of the line can be calculated as:

$$L_{averrage} = L_{loss} * L_{SF} * 8760 \tag{4}$$

where; L$_{oss}$: Loss at peak load, L$_{sF}$: Loss factor
Loss factor (LF) can be calculated as:

$$L_{SF} = 0.2LF + 0.8(LF)^2 \tag{5}$$

LF: Annual factor of the line can be calculated using Eq. (6).

$$LF = \frac{Total\ annual\ energy}{Annual\ peak\ load * 8760} \tag{6}$$

It is possible to compute the annual losses in the primary feeder supply in relation to its transformers. The value of the load in this feeder
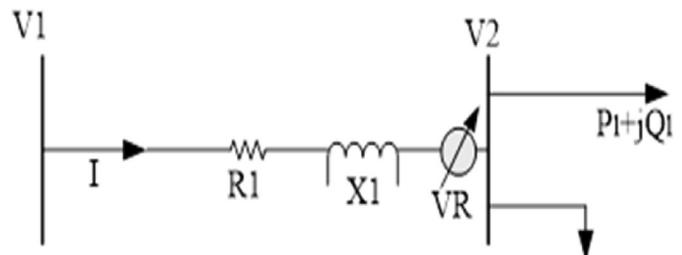

Figure 1. Typical distribution network after VR placement at the bus.
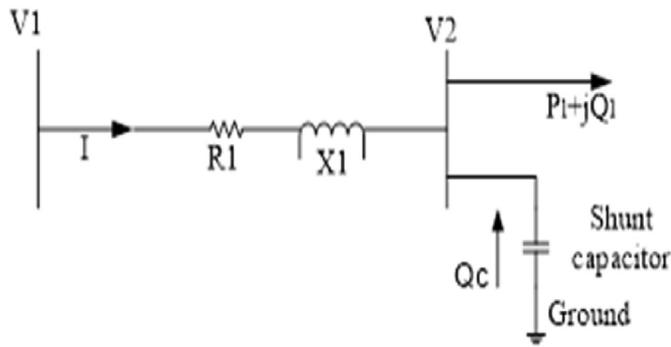
Figure 2. Reactive power balance for after capacitor placement at the bus.

can be considered a distributed load when it is relatively long and serves a few widely spaced transformers. Therefore, the power loss can be estimated using Eq. (7).

$$L_{loss} = \sum_{i=1}^{n} I_i^2 R_i / 1000 (KW) \tag{7}$$

where, I_i: Portion current (A); R_i: Portion resistance (Ohm); n: Portion of line

$$L_{Annual} = L_{Loss} * L_{SF} * 8760 \text{ (for one phase)} \tag{8}$$

$$L_{Annual} = 3 * L_{Loss} * L_{SF} * 8760 \text{ (for three phases)} \tag{9}$$

Therefore, the total percentage of losses per year can be calculated as Loss (%) = Loss*100/E;

E.c = energy cost KW/hour   (10)

From the generation system to the customer's meter, there exist a voltage drop in every element of the power system. All equipment connected to the utility system are designed to be used for a certain definite voltage. It is impractical to supply every customer on a power distribution line with the same voltage (constant voltage) that matches the nameplate voltage exactly. This is due to voltage drops in each part of the power system, from generation to the meter of the customer. Voltage drop in the DS can be calculated using Eq. (11) [23].

$$\Delta v = \sqrt{3} \sum_{i=1}^{n} I_i (R_i \cos\theta + X_i \sin\theta) L_i A \tag{11}$$

where; I_i: Portion current on line (A); θ: Angle between current and voltage; R_i: Resistance of the line (Ohm/km); X_i: Reactance of the line (Ohm/km); n: Number of portions; L_i: Portion length of the line (km).

The following methods are adopted for the reduction of distribution losses and improvement of VP: the use of HV distribution system, feeder reconfiguration, reinforcement of the feeder, grading of the conductor, DG placement, installing VRs, and installing of shunt capacitors [24, 25].

2.2. Optimal voltage regulator and capacitor placement in the distribution system

Automatic voltage boosters (AVBs) or voltage regulators (VR) are simply autotransformers with a primary or existing winding linked in parallel with the circuit and a second winding with taps connected in series with the circuit. The taps of the series windings are connected to an automatic tap changing mechanism. AVB is also considered as a tool for loss reduction and voltage control [25, 26, 27, 28]. Figure 1 shows a distribution network after VR has been placed at the bus.

2.2.1. Shunt capacitor bank in a power system

Shunt capacitors inject reactive power at the location they are placed in the distribution system. Shunt capacitor bank installation is used for reactive power compensation. Shunt capacitors help to regulate the distribution systems voltage and reduce the systems power losses. These capacitors also neutralize the effect created due to inductive loads. As shown in Figure 2, a bank of capacitors is connected at bus 2 of the system to deliver reactive power. The capacitor banks are installed at the receiving end node and in shunt with the load buses [29, 30, 31, 32, 33]. The voltage drop of the transmission line in a DS can be expressed with Eq. (12).

$$\text{Voltage drop} = jI_X X_L + I_R R \tag{12}$$

The capacitors impact on the line and its resultant voltage drop is given by Eq. (13).

$$jI_X X_L + I_R R - jI_C X_L \tag{13}$$

From Eqs. (12) and (13), it can be said that a capacitor is used to increase the voltage in a distribution line according to Eq. (14).
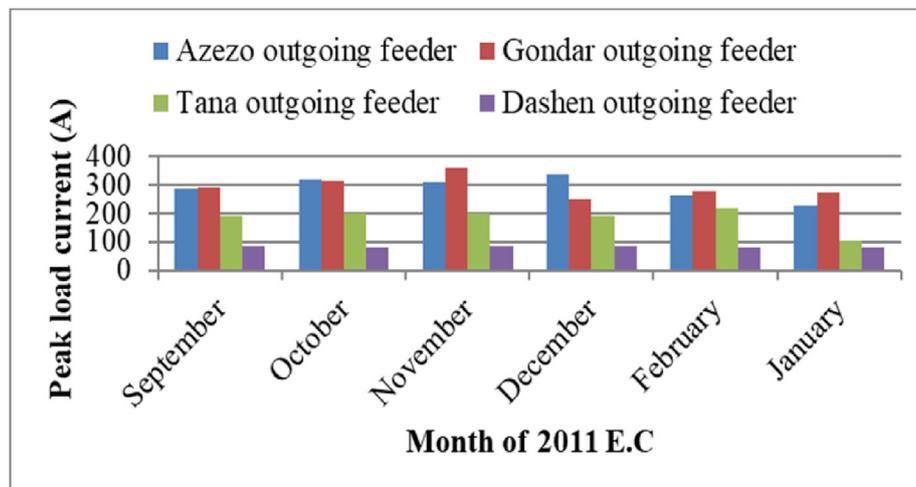
$$\text{Regulated voltage} = I_C X_L \tag{14}$$
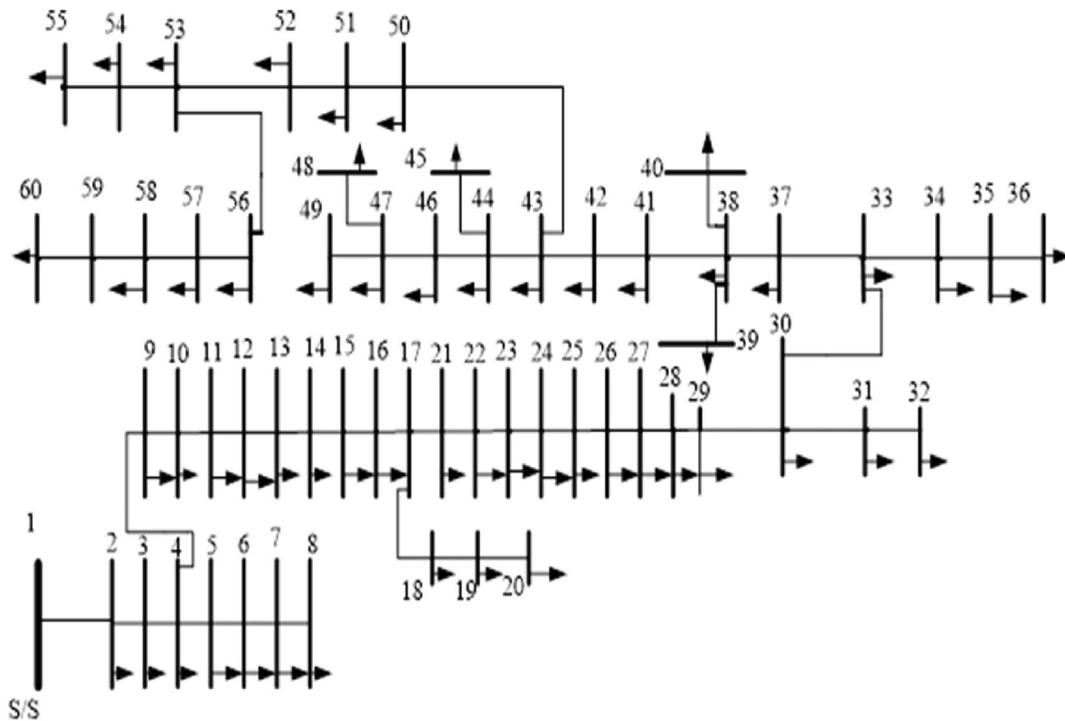

Figure 3. Peak load current data of six months.

Figure 4. Single line diagram of 60 buses Gondar feeder.

3. Data collection and analysis

Azezo substation consists of four outgoing radial feeders; these are Azezo, Gondar Tana, and Dashen feeders. In this paper, the selected feeder is Gondar 15KV outgoing feeder, because the Gondar feeder has larger demand at the substation, maximum loading capacity, and is a long distance radial distribution line.

3.1. Peak load current of feeders

The peak load current data for a period of six months was obtained. The location, duration, and amount of data collected is shown in Figure 3. The Gondar feeder is seen to have the highest value in the month of November followed by the Azezo in December of 2011.

3.2. 60-bus Gondar feeder

The Gondar feeder consists of a total number of 60–bus feeders, of which bus-1 is taken as the reference node or slack bus. The other 59 nodes are connected to loads through a step-down distribution transformer. The feeder is a stranded conductor of type AAC-95, AAC-50, ACSR-65, and ACSR-46 with a total length of 27 km. The overhead lines (feeder) are used to distribute medium voltage (15 kV) power from the Azezo substation I to the distribution transformers. The single line diagram of the Gondar feeder is shown in Figure 4.

3.3. Proposed fuzzy logic method

Fuzzy logic optimization method consists of four major components: fuzzification, rule base, inference mechanism, and a defuzzification interface. The inputs of the fuzzification in this work are PL indices and VP for each bus. The task of a fuzzification interface is to transform the numerical inputs into fuzzy variables. The defuzzification interface, on the other hand, does the opposite, converting fuzzy variables into numerical output. The conversions are aided by membership functions. If –then rules are created based on prior experience, historical facts, or the designer's desired outcome. The block diagram of the fuzzy inference system is shown in Figure 5.

3.3.1. Membership functions

The membership functions and a variety of fuzzy signals are used to fuzzify the signals. The output parameter is also fuzzified into linguistic variables and the input parameters are fuzzified into corresponding fuzzy signals with typical linguistic variables. Triangular and trapezoidal membership functions are two types of membership functions which are dependent on the variables' properties. The inputs and output membership functions are illustrated in the following consecutive figures. The input is shown in Figure 6. The decision matrix for determining suitable VR and capacitor locations, ranges for input P_{loss} variable and input bus voltage variable used are presented in Tables 1, 2, and 3. The ranges for output sensitivity index variables obtained are presented in Table 4, where: L = low, N = normal, LM = low medium, HN = high normal, M = medium, HM = high medium, H = high.

Buses with the highest Suitability-Degree are detected as suitable buses for compensation device replacement, such as those with large PL and small voltage profile. The input and output membership functions for the voltage profile and sensitivity index are shown in Figures 7 and 8.
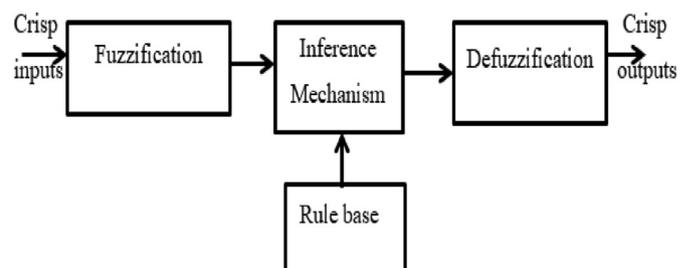

Figure 5. Block diagram of the fuzzy inference system.

Table 1. Decision matrix for determining suitable VR and capacitor locations.

AND		Voltage (p.u.)				
		L	LN	N	HN	H
Power loss index (p.u.)	L	LM	LM	L	L	L
	LM	M	LM	LM	L	L
	M	HM	M	LM	L	L
	HM	HM	HM	M	LM	L
	H	H	HM	M	LM	LM

Table 2. Ranges for input P$_{loss}$ variable.

P$_{loss}$ (p.u.) description	Linguistic term	Range
Low	L	0 to 0.125
Low medium	LM	0.16 to 0.385
Medium	M	0.38 to 0.66
High medium	HM	0.66 to 1
High	H	0.688 to 1

Table 3. Ranges for input bus voltage variable.

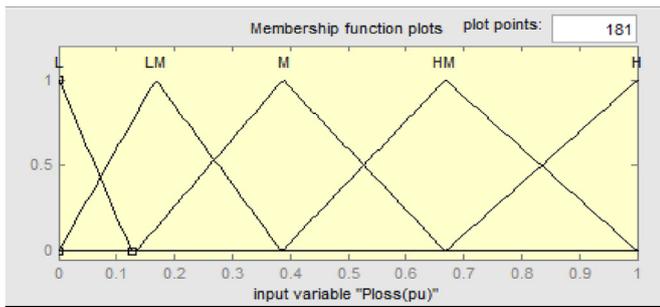| V (p.u.) description	Linguistic term	Range
Low	L	0.74 to 0.85
Low normal	LN	0.85 to 0.89
Normal	N	0.89 to 0.96
High normal	HN	0.96 to 0.98
High	H	0.98 to 1.05

Figure 6. Input 1 membership function of real power loss.

3.3.2. Optimal voltage regulator placement using fuzzy logic optimization

3.3.2.1. Mathematical formulation. The ideal number and location of Voltage Regulators (VR) can be determined as an optimization problem. The goal is to maximize the net savings function (S), which is written as:

$$MaxS = K_e * P_{lr} * 8760 - N_{VR}(K_{VR} + K_I) \tag{15}$$

Table 4. Ranges for output Sensitivity index variable.

SI (p.u.) description	Linguistic term	Range
Low	L	0 to 0.167
Low medium	LM	0.167 to 0.5
Medium	M	0.5 to 0.75
High medium	HM	0.75 to 0.88
High	H	0.88 to 1

where; P_{lr} = Reduction in power losses due to installation of VR = Power loss before installation of VR - Power loss after installation of VR; K_e = Cost of energy in Birr/kWh; V_{RN} = Number of voltage regulators; K_{VR} = Capital cost of each voltage regulator; and K_I = Installation cost of VR.

Assumption: The maintenance cost, interest, and balance of commercial banks are neglected.

Constraint: The objective function is subjected to the following constraint. The voltage at each bus should lie within the voltage limits. $V_{min} \leq V_i \leq V_{max}$, i = 1, 2 …number of buses.

3.3.3. Formulation of the optimum VR placement method in the RDS using fuzzy logic

Step 1: Read the line and load data.

Step 2: Calculate the voltage at each bus, as well as the total real and reactive PLs of the system by running load flows for the base system.

Step 3: The power loss indices and the p.u bus voltages are the inputs to the fuzzy expert system (FES).

Step 4: Use the centroid defuzzification method to defuzzy the FES outputs. This determines the VRs appropriateness index ranking (VRSI).
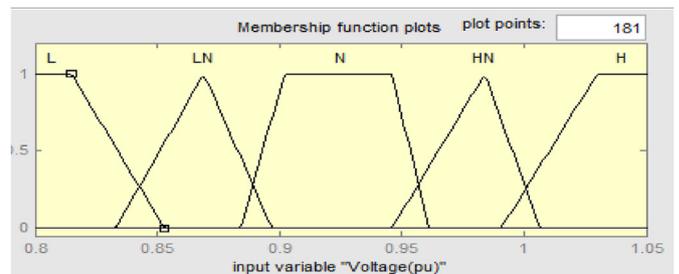

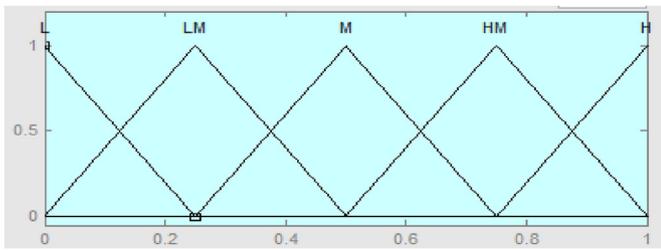**Figure 7.** Input 2 membership function of Voltage profile.

Figure 8. Output membership function of sensitivity index.

Step 5: Using the maximum value of VRSI, select the optimal location for the VR.

Step 6: Using Eq. (15), find the VR's ideal tap position so that the voltage stays within the stated limits.

Step 7: Run the load flows using VR once more, and then compute the voltages at all buses, as well as the total real and reactive PLs. If the voltages are not within the limits, go back to step 3 and try again.

Step 8: Calculate the overall real PL reduction and net savings.

Step 9: Print the outcome.

Step 10: Stop.

To achieve better regulation, we used the suitability index (SI) and tap setting of the voltage regulator as presented in Table 5.

3.3.4. Algorithm for capacitor placement and sizing using FES and index based method

In this section, the FES method is used for to solve the problem of optimal capacitor placement using MATLAB simulation to identify the best location in terms of maximum savings. The proposed algorithm for optimal capacitor placement is given as follows:

Read the feeder load data and line settings in **Step 1**.

Step 2: Calculate bus voltages and sectional losses using load flow analysis.

Step 3: Using FES, create membership functions for fuzzy PL and bus voltage inputs and calculate the sensitivity index.

Step 4: Using the sensitivity index values, choose the best bus for capacitor placement. The highest sensitivity index value is usually chosen.

Step 5: By knowing the sensitive buses, calculate the suitable capacitor size by using the index-based method.

Step 6: Evaluate the maximizum saving function after estimating the capacitor size.

Step 7: After capacitor installation, include the capacitor value in that relevant bus and complete the load flow.

Step 8: If there is no further voltage improvement, exit the process; otherwise, return to step 3.

Step 9: Assuming M buses have been selected for new capacitor placement, adjust the first capacitor I = 1) in integer steps, while leaving the others unchanged. Choose Qci as the first option with the lowest cost and no infractions. Repeat for a total of 2...M.

Step 10: If the savings function is not at its maximum, repeat step 9.

Step 11: Print the results.

Step 12: Stop.

3.3.4.1. Mathematical formulation. The objective function is to optimize the net savings function (S) by strategically installing the right size of capacitors in the right places. This is formulated as:

$$Max.S = K_e * P_{lr} * 8760 - N_c(K_I + K_c) \qquad (16)$$

where, S = net savings in Birr;

P_{lr} = Reduction of power losses due to installation of capacitor = Power loss before installation of capacitor - Power loss after installation of the capacitor;

K_e = Cost of energy in Birr/kWh; K_I = Installation cost in Birr; N_c = Total number of capacitor buses; and K_c = Capital cost of each capacitor.
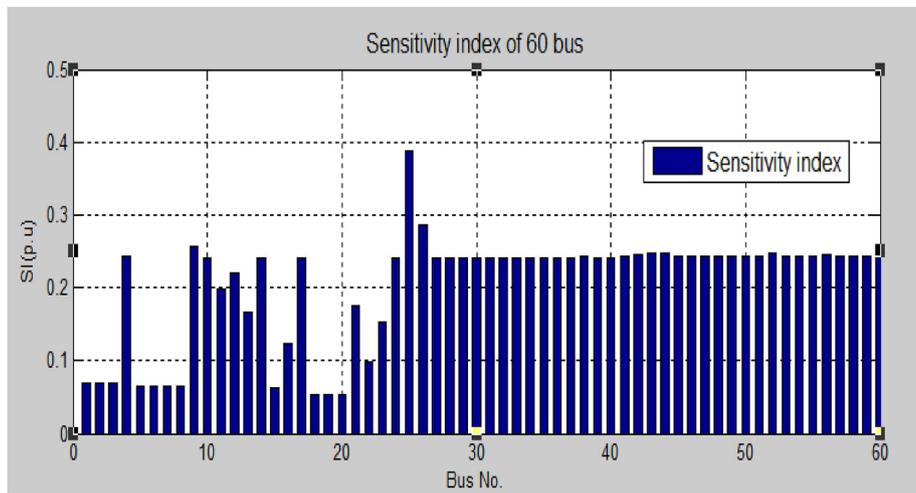

Figure 9. Candidate sensitivity index at each bus.

Table 5. SI and tap setting of the voltage regulator.

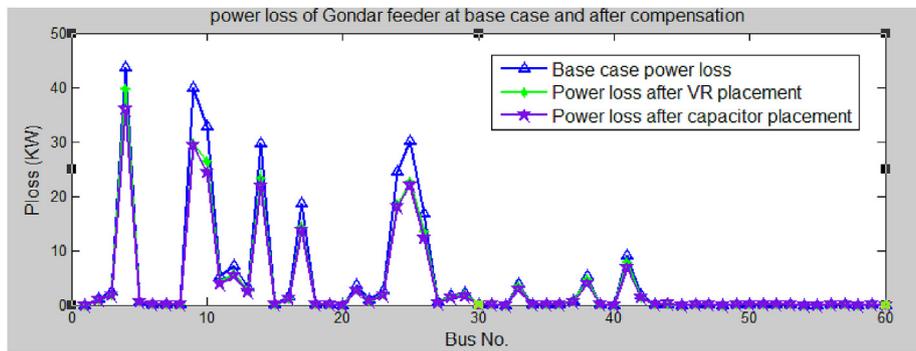| Bus No. to place VR	Voltage Regulator suitability index in FES	Tap setting of VR in p.u.	Type of tap position
25	0.387	0.09375 (15 steps)	Boost
26	0.286	0.0875 (14 steps)	Boost
9	0.258	0.075 (12 steps)	Boost
43	0.248	0.1 (16 steps)	Boost
44	0.248	0.1 (16 steps)	Boost

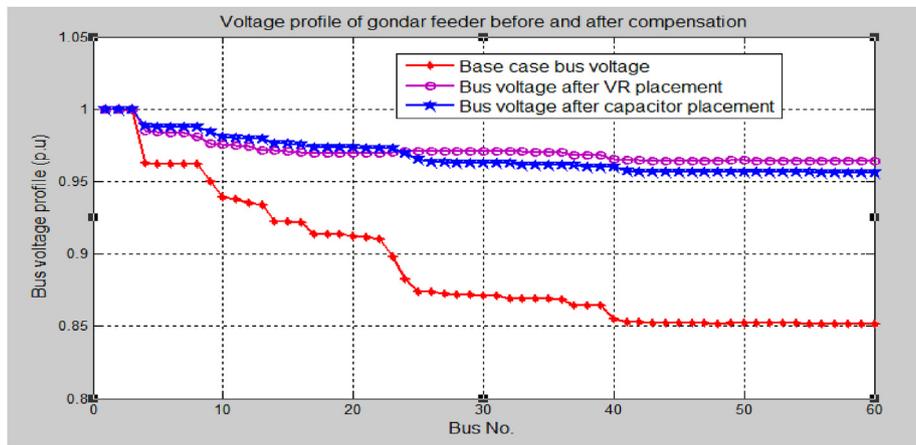**Figure 10.** Power loss before and after optimal placement of VR and capacitor.

Figure 11. The overall voltage profile before and after compensation.

Assumption: The maintenance cost, interest, and balance of commercial banks are neglected.

Constraints: The following constraints apply to the objective function. Each buses voltage should be within the voltage limit. $V_{\min} \leq V_i \leq V_{\max}$ i = 1, 2,… number of buses. The capacitor size that should be installed on an appropriate bus is less than the system's total reactive load. This is given by:

$$Q_c < \sum_{i=1}^{n} Q_i \tag{17}$$

where n = total number of buses.

4. Simulation results and discussion

4.1. Candidate sensitivity index at each bus

The simulation results of the sensitivity index of each candidate at each bus is shown in Figure 9. The results show that buses 27 to 60 have a sensitivity index of 0.25, while other buses have a varying sensitivity index (SI). This in turn causes the system to achieve a efficient reduction in power loss as shown in Figure 10. Its is also observed that from buses 27 to 60, there is a drastic reduction in power losses in the system. This leads to an improvement in voltage profile as shown in Figure 11. The results achieved before and after compensation using VR and capacitor are presented in Table 6. The results show that reactive power loss

Table 6. Results of the performance before and after the placement of VRs and capacitors.

| Description of system parameters	Without compensating	With Compensation	
	Base case	After VR placement	After capacitor placement
Max. voltage (p.u.)	1.00	1.00	1.00
Min. voltage (p.u.)	0.8515	0.9639	0.95628
Voltage regulation (%)	14.85	3.61	4.372
Real power loss (KW)	377.75	232.46	217.9
Real power loss reduction (Kw)	-	145.29	159.85
Real power loss reduction (%)	-	38.46	42.316
Reactive power loss (KVAr)	222.51	165.119	143.66
Reactive power loss reduction (KVAr)	-	57.391	78.85
Power factor of the system (PF)	0.879	0.98	0.993
Net saving (Birr/year)	-	**238,663.66**	**422,944.49**
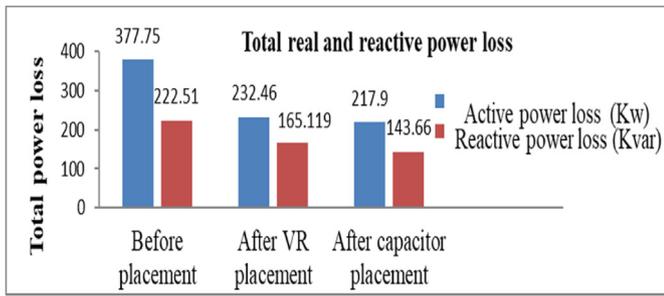
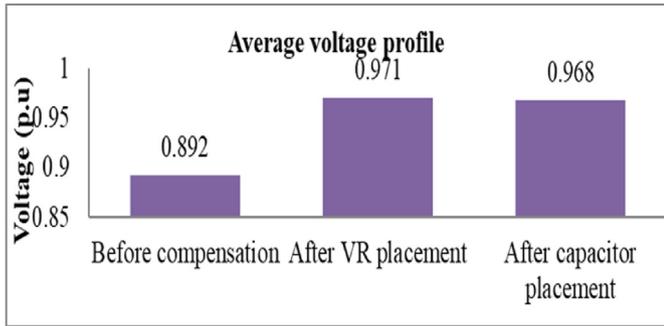**Figure 12.** Total real and reactive power loss analysis.

Figure 13. Average voltage profile analysis after placement of VRs and capacitors.
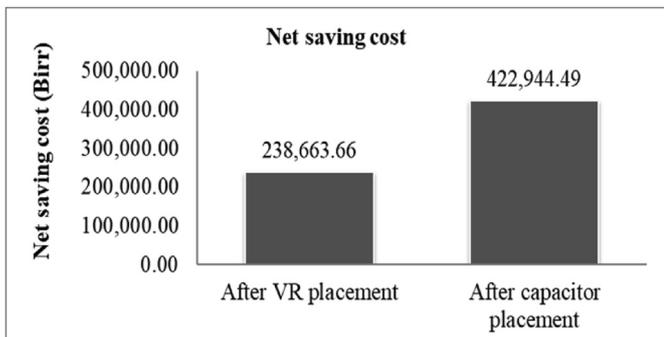

Figure 14. Cost savings analysis after the placement of voltage regulators and capacitors.

(KVAr) is greatly reduced from 222.51 KVAr without compensation to 165.119 KVAr after VR placement and 143.66 KVAr after capacitor placement. The proposed algorithm was tested using the 60 node RDS shown in Figure 4. From the results, several important observations were obtained. These are:

- The PLs of the distribution system can be effectively reduced by proper placement of VRs and capacitor banks.
- Also for PL reduction, the VP, PF, and net saving can be improved using the proposed method.

Table 7. Comparative analysis with related works.

Authors	Power factor	Reactive power loss (KVAr)
[5]	0.85	80.52
[22]	0.9	-
[26]	0.85	-
Proposed method	0.98	165.119

- The results from the comparative analysis show that the proposed method performs better than existing methods.

Figure 12 shows that the location of the capacitor is important for the reduction of both the total active and reactive PL of the RDS. Figure 13 shows that the location of VR is important for the improvement of the average VP than that of the capacitor. This means that the VRs can maintain the VP significantly regardless of economic feasibility as shown in Figure 14.

In this paper, net saving analysis is the objective function that has to be maximized by considering the system constraints for the location of VRs and capacitors. The results presented in Figure 14 indicates that the capacitor installation gives maximum cost savings than the installation of VRs in the RDS. Therefore, it is economical to use a capacitor for PL reduction, VP, and PF improvement in the Gondar distribution system. A comparative analysis of the proposed method with existing works was presented in Table 7. The results show that the proposed method obtained a better PF than other existing methods when the VRs and capacitors where placed optimally.

5. Conclusions

This paper presented a fuzzy based method to determine the optimal location for capacitor and voltage regulator (VR) placement in radial distribution systems (RDS). More precisely, a fuzzy expert system (FES) for solving VR and capacitor placement problems in RDS was presented in this paper. The method deals with an initial selection of nodes using the highest suitability index value. The proposed algorithm was tested on a 60 node RDS. The proposed loss minimization method using shunt capacitors reduces the current flowing in each section of the feeder and hence the voltage drop in the section. Therefore, the voltage profile (VP) is improved after the feeder line is compensated and the quality of the power is improved. The results indicate that by using capacitors, 159.85KW power is saved and also in the same way all the weak bus VPs are optimized to the standard ±5% voltage deviation level. The total real PL reduction is 38.46% using VRs and 42.316% using shunt capacitors. Whereas, the minimum bus voltage is improved to 0.9639 p.u and 0.9562 p.u, and the net saving is 238,663.66 birr/year and 422,944.49 birrs/year using VR and capacitors respectively. Generally, the capacitor placement significantly takes the higher percentage for the overall system improvement by satisfying the objective function and meeting the systems constraints. The relative efficiency of these components in terms of total system improvement is dependent on the system and its loading conditions.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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