Phase Load Balancing in the Secondary Distribution Network Using Fuzzy Logic

M.W. Siti, A.A. Jimoh and D.V. Nicolae

Abstract— **The electrical network system is to ensure that an adequate supply is available to meet the estimated load of the consumers in both the near and more distant future. This must of course, be done for minimum possible cost consistent with satisfactory reliability and quality of the supply. In order to avoid excessive voltage drop and minimize loss, it may be economical to install apparatus to balance or partially balance the loads. It is believed that the technology to achieve an automatic load balancing lends itself readily for the implementation of different types of algorithms for automatically rearranging the connection of consumers on the low voltage and of a feeder for optimal performance. In this paper the fuzzy logic is been implemented to balance the load in the secondary part of the transformer.**

Index Terms — **Load Balancing, Fuzzy Logic, Artificial Intelligence, Expert System, Distribution System.**

I. INTRODUCTION

THE distribution system technology has changed drastically, both qualitatively and quantitatively. This may be adduced to the fact that with increase in technological development, the dependence on electric power supply has increased considerably. Consequently, while demand has increased, the need for a steady power supply with minimum power interruptions and fast fault restoration has also increased. To meet these demands, automation of the power distribution system needs to be widely adopted. All switches and circuit-breakers involved in the controlled networks are equipped with facilities for remote operation. The control interface equipments must withstand extreme climatic conditions. Also, control equipments at each location must have a dependable power source. To cope with the complexity of the distribution, the latest computer, communication, and power electronics equipment in distribution technologies are needed to be employed. The distribution automation can be defined as an integrated system concept. It includes control, monitoring and some times, decision to alter any kind of loads. The automatic distribution system provides directions for automatic reclosing of the switches and remote monitoring of the loads contributing towards phase balancing.

The phase voltage and current unbalances are major factors leading to extra losses, communication interference, equipment overloading and malfunctioning of the protective relay which consequently results into service quality and operation efficiency being reduced [2]. Phase unbalance is also manifested in increased complex power unbalance, increased power loss, enhanced voltage drop, and increased neutral current.

Traditionally, to reduce the unbalance current in a feeder the connection phases of some feeders are changed manually after some field measurement and software analysis. Although in some cases this process can improve the phase current unbalance, this strategy is more time-consuming and erroneous. In this paper, it is proposed the use of support vector machine based load balancing as novel procedures to perform the feeder phase balancing.

In most of the cases, the phase voltage and current unbalances can be greatly improved by suitably arranging the connection phases between the distribution transformers and a primary feeder. It is also possible to advance the phase current unbalances in every feeder segment by means of changing the connection phases [1]. The phase voltage unbalances along a feeder can also be improved in common cases by system reconfiguration, which involves the rearrangement of loads or transfer of load from heavily loaded area to the less loaded.

In the modern power distribution systems, the sectionalizing switches and the tie switches for feeder reconfiguration are extensively used [2]. The authors in [3] presented the way to control the tie switches using heuristic combinatorial optimization-based method. The only disadvantage with the tie-switch control is that, in most of the cases, it makes the current and the voltage unbalances worse. The reference [5, 6, 7, 8, 9] presented the use of the neural networks to find the optimum switching option of the loads among the different phases. On the basis of these results, other networks identify the radial topology satisfying the optimal condition.

In all these the phase balancing problem is mathematically formulated and then solved. The results are therefore used to initiate certain actions to eliminate or minimize the problem. With the fuzzy logic it is wondered if there can not be simpler, more straightforward, better, and faster method. It is possible to use historical data with a more intelligent method to arrive at actions that minimize or eliminate the phase unbalance. This will not require solving a more complex problem as an intermediate step. In this paper, therefore, such a novel method is proposed by the use of support vector machine based phase balancing as procedure to perform the feeder load/phase balancing.

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II. Problem Description

A. *Representation of the Feeder*

The distribution feeder is usually a three-phase, four-wire system with a radial or open loop structure. To improve the system phase voltage and current unbalances the connection between the specific feeder and the distribution transformer should be suitably arranged. The domestic loads are connected, as in most cases, in a single-phase. For the problem in this paper, it is assumed that each feeder contains 50 domestic loads or connections to it, following average domestic load flow studies in South Africa [4]. So, the total load to the three phases can be 150 connections as shown in Fig. 1. In Fig. 1, each load can be through the switch selector connected only to the one of the three phases.

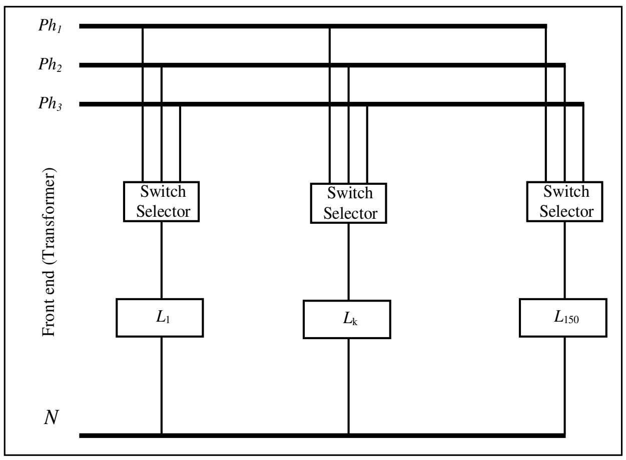

Fig. 1. Example distribution feeder.

B. Current Phase Balancing Technique

Most of the township houses in South Africa use the average of three kilowatt power. The major electricity usage is for lighting and domestic works in domestic environment. However, sudden power increase, like the use of heater etc, oftentimes introduces an unknown power in the distribution system, making the transformers to burst and the cables to burn, causing unbalance in the network. To balance the network, the engineers and the technicians must change the phases manually after some field measurement. The changes made to upgrade transformation in different area affect the size of the conductor, but in most of the cases, the size of the phase conductor for the entire line of the feeder is the same. However, the number of phase conductors may be different in different sections for economic reasons.

The power losses depend on the real and the reactive power flows, which are related to the real and reactive loads. Minimum power loss reconfiguration is aimed at by the means of controllable switch-breakers installed at each of the connection on the network feeders, since both the loads and the switch breaker status are physically distributed. In the general formulation of the phase balancing problem, the load values are the independent variables, whereas the switch-breaker statuses are the optimization variables. The objective can be fulfilled performing a control strategy in which the status of each switch breaker depends on the total loads from each feeder. In this way, the network can be optimally operated and it is not necessary to know the load in advance.

For the real implementation of a control system, the following elements are necessary:

- A measurement system for real loads.
- A transmission data system for the load data connecting each point.
- A transmission system for sending the input signals to the switch breaker.
- The control cannot start if the above described components and system are not properly installed and in correct condition.

C. *Proposed Technique*

For the above-mentioned system, in this paper, it is proposed a fuzzy logic-based load balancing technique along with combinatorial optimization oriented expert system for implementing the load change decision. The architecture of the proposed system is shown in Fig. 2.

In Fig. 2, the input is the total phase load (for each of the three phases). The average unbalance per phase, calculated according to (2), is checked against a threshold of 10 kW. If the average unbalance per phase is below 10 kW, it can be assumed that the system is more or less balanced and discard any further load balancing. Otherwise, it goes for the fuzzy logic-based load balancing. The output from the fuzzy-based load balancing step is the load change values for each phase. A *negative* value indicates that the specific phase has surplus load and should *release* that amount of load, while a *positive* value indicates that the specific phase is less loaded and should receive that amount of load.

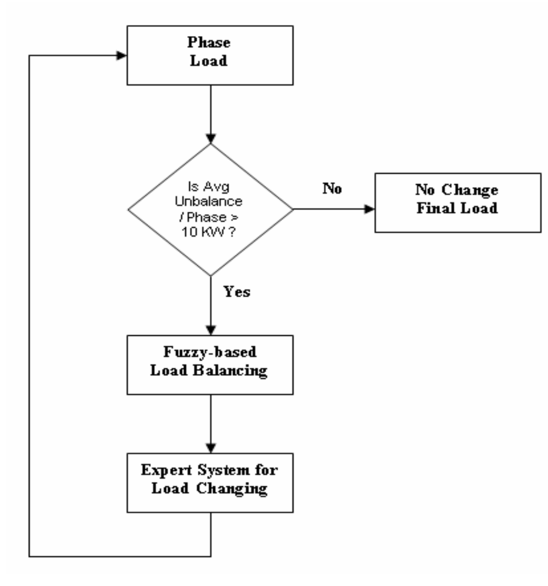

Fig. 2. Architecture for the proposed load balancing system.

This load change configuration is the input to the expert system which tries to optimally shift the specific number of load points. However, sometimes the expert system may not be able to execute the exact amount of load change as directed by the fuzzy step. This is because the actual load points for any phase might not result in an optimum combination which sums up to the exact change value indicated by the fuzzy step. So, it is implemented the best possible change from the expert system and iteratively check the system unbalance until the average unbalance (AU) below 10 kW is achieved, if ever.

$$AU/ph = \frac{|L_{ph1} - l_{ph2}| + |L_{ph2} - L_{ph3}| + |L_{ph3} - L_{ph1}|}{3} \qquad (1)$$

where L_{ph1}, L_{ph2} and L_{ph3} are the loads (power) drawn from the phase one, two and three respectively.

III. Fuzzy Logic-Based Load Balancing

In this section, the fuzzy logic-based load balancing technique is described in details. As described in section 3, it is assumed the average per phase capacity of the system to be 150 kW, with 50 load points connected to any specific phase. For designing the fuzzy controller, it is further assumed the maximum overload capacity of any phase to be 300 kW. Beyond 300 kW the fuzzy controller should not be used for load balancing. Because, in any case, when any phase reaches its 200% overload condition, it should be cut out from the service to prevent power breakdown and severe overloading of the transformer.

A. Fuzzy Controller: Input and Output

To design the fuzzy controller, there first are design the input and the output variables. For the load balancing purpose, as described in section 3.3, it is chosen the input as ‘Load’, i.e., the total phase load (kW) for each of the three

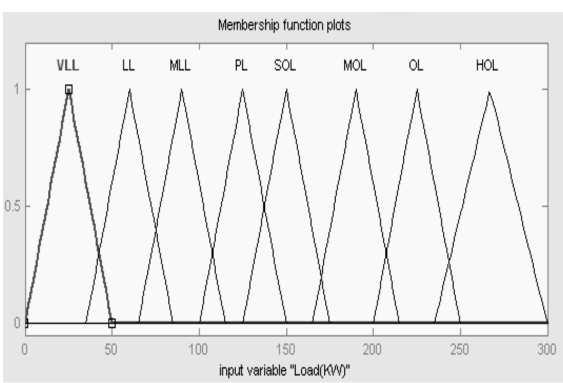

Fig. 4. Fuzzy membership functions for the input variable

TABLE I.
FUZZY NOMENCLATURE FOR THE INPUT VARIABLE

SL. No.	Input (load) Description	Fuzzy Nomenclature	kW Range
1	Very Less Loaded	VLL	0 to 50
2	Less Loaded	LL	35 to 85
3	Medium Less Loaded	MLL	65 to 115
4	Perfectly Loaded	PL	100 to 150
5	Slightly Overloaded	SOL	125 to 175
6	Medium Overloaded	MOL	165 to 215
7	Overloaded	OL	200 to 250
8	Heavily Overloaded	HOL	235 to 300

TABLE II
FUZZY NOMENCLATURE FOR THE OUTPUT VARIABLE

SL. No.	Output (change) Description	Fuzzy Nomenclature	kW Range
1	High Subtraction	HS	-150 to -85
2	Subtraction	S	-100 to -50
3	Medium Subtraction	MS	-65 to -15
4	Slight Subtraction	SS	-50 to 25
5	Perfect Addition	PA	0 to 50
6	Medium Addition	MA	35 to 85
7	Large Addition	LA	65 to 115
8	Very Large Addition	VLA	100 to 150

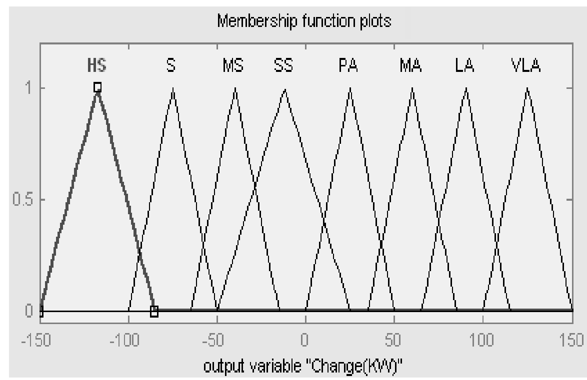

Fig. 4. Fuzzy membership functions for the output variable

B. Fuzzy Rules and Surface

Next, it is determined the IF-THEN fuzzy rule set [8] governing the input and output variable as described in Table III.

TABLE III
FUZZY RULES FOR THE INPUT AND OUTPUT VARIABLE

Rule No	Rule Description
1	If Load VLL then Change is VLA
2	If Load is LL then Change is LA
3	If Load is MLL then change is MA
4	If Load is PL then change is PA
5	If load is SOL then change is SS
6	If Load is MOL then change is MS
7	If Load is OL then change is S
8	If Load is HOL then change is HS

phases, and the output as ‘Change’, i.e., the change of load (kW, positive or negative) to be made for each phase. For the input variable, Fig. 3 and Table I show the fuzzy nomenclature and the respective triangular fuzzy membership functions [8]. And for the output variable, Table II shows the fuzzy nomenclature, and Fig. 4 the corresponding triangular fuzzy membership functions [8].

Corresponding to the fuzzy input, output variables and the associated rule set, the fuzzy surface [8] is shown in Fig. 5, depicting the nonlinear relationship between the input and the output variable.

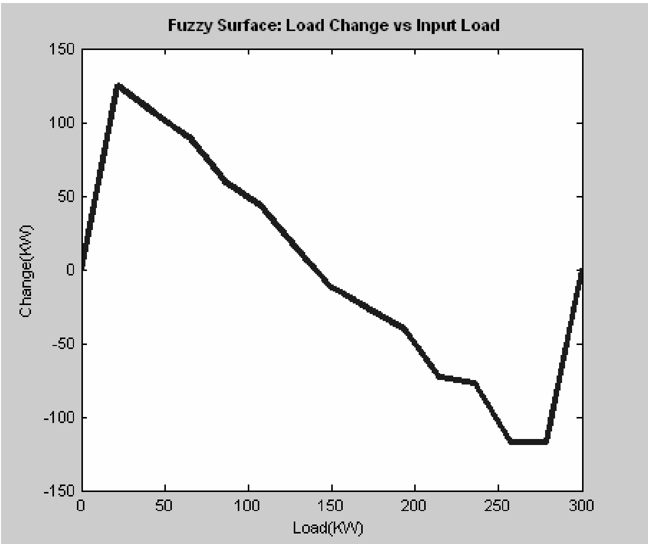

Fig. 5. Nonlinear relationship between the input and the output variable

C. Simulation Results

In this section, it is shown the application results using the fuzzy logic-based load balancing technique. Matlab® fuzzy toolbox [9] was used for the simulation. It has been utilized the Mamdani [10] fuzzy inferencing technique. Let us take an example input load configuration of [245 120 82] kW for the

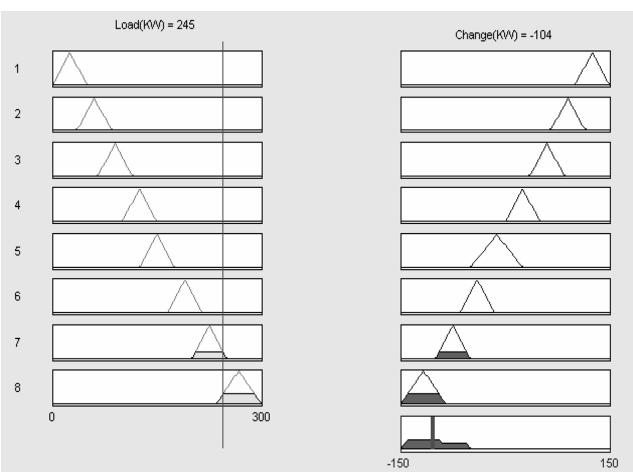

Fig. 6. Determination of the output load change for phase 1 of the input load.

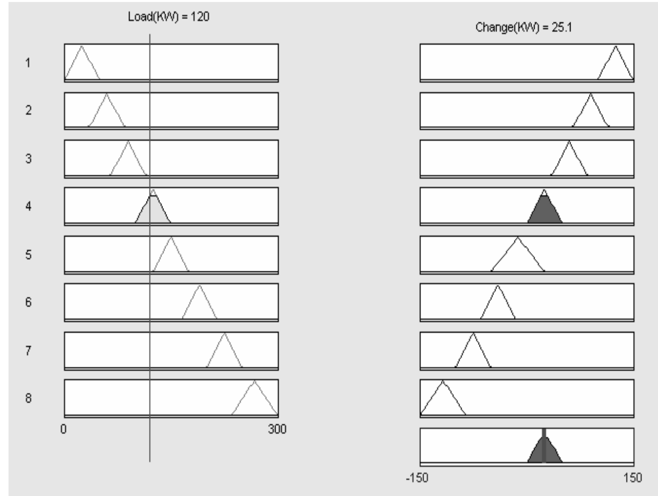

Fig. 8. Determination of the output load change for phase 3 of the input load.

three phases. The above described fuzzy controller is then used to do the balancing. The graphical determination of the output load change for the three phases corresponding to this input load and involving the eight fuzzy rules are shown in Fig. 6 to 8. The defuzzification operation is based on the Mamdani (centroid) technique [10].So, after rounding the output load change, for the input load

$$P_{in} = [245\ 120\ 82]^T \text{ (kW)} \tag{2}$$

the output load change configuration is:

$$\Delta P_{fuzzy} = [-104\ 25\ 65]^T \text{ (kW)} \tag{3}$$

However, with this load change configuration, it is going to have an error. Because the positive and the negative totals are not equal, i.e. $\Sigma\Delta P_{fuzzy} = -14 \neq 0$ kW. So, if this load change configuration is implemented, this will result in reduction of -14 kW of total load. This is not possible, because, with the load balancing it can only interchange the load points amongst the three phases, keeping the total load same, i.e., without increasing or decreasing the total load.

So, it has to be performed an error correction. The average error (AE) is given as:

$$AE = round\left(\frac{\sum \Delta P_{fuzzy}}{3}\right). \tag{4}$$

Then, this average error is used to construct the error matrix ΔP_{error}, by distributing the AE evenly among the three phases.

$$\Delta P_{error} = \begin{bmatrix} AE \\ AE \\ \sum \Delta P_{fuzzy} - 2 * AE \end{bmatrix} \tag{5}$$

Finally, the load change configuration ΔP, is obtained by subtracting the ΔP_{error} from the uncorrected fuzzy output ΔP_{fuzzy}.

$$\Delta P = \Delta P_{fuzzy} - \Delta P_{error} \tag{6}$$

and:

$$\sum \Delta P = 0 \tag{7}$$

Applying (4)-(7) in our example case, the following parameters are:

AE = -5 kW, $\Delta P_{error} = [-5\ -5\ -5]^T$ kW and:

$$\Delta P = \begin{bmatrix} -104 \\ 25 \\ 65 \end{bmatrix} - \begin{bmatrix} -5 \\ -5 \\ -4 \end{bmatrix} = \begin{bmatrix} -99 \\ 30 \\ 69 \end{bmatrix} \text{ (kW)} \tag{8}$$

The final output should be:

$$P_{final} = P_{in} + \Delta P = \begin{bmatrix} 245 \\ 120 \\ 82 \end{bmatrix} + \begin{bmatrix} -99 \\ 30 \\ 69 \end{bmatrix} = \begin{bmatrix} 146 \\ 150 \\ 151 \end{bmatrix} \text{ kW} \tag{9}$$

Applying (7) on P_{in} and P_{final} , the Initial Absolute Unbalance (IAUB)/Phase and Final Absolute Unbalance (FAUB)/Phase will be, respectively:

$$\text{(IAUB)/Phase} = 108.67 \text{ kW} \tag{10}$$

$$\text{(FAUB)/Phase} = 3.33 \text{ kW} \tag{11}$$

TABLE IV
APPLICATION RESULTS FOR DIFFERENT PHASE LOADING

Test Case	Initial Load (kW)	IAUB/Phase (kW)	Initial Fuzzy Change (kW)	Error (kW)	Final Fuzzy Change (kW)	Final Load (kW)	FAUB/Phase (kW)
1	$\begin{bmatrix} 157 \\ 134 \\ 120 \end{bmatrix}$	24.7	$\begin{bmatrix} -12 \\ 5 \\ 25 \end{bmatrix}$	$\begin{bmatrix} 6 \\ 6 \\ 6 \end{bmatrix}$	$\begin{bmatrix} -18 \\ -1 \\ 19 \end{bmatrix}$	$\begin{bmatrix} 139 \\ 133 \\ 139 \end{bmatrix}$	4
2	$\begin{bmatrix} 140 \\ 145 \\ 156 \end{bmatrix}$	10.7	$\begin{bmatrix} -1 \\ -12 \\ -5 \end{bmatrix}$	$\begin{bmatrix} -6 \\ -6 \\ -7 \end{bmatrix}$	$\begin{bmatrix} 5 \\ 0 \\ -5 \end{bmatrix}$	$\begin{bmatrix} 145 \\ 145 \\ 151 \end{bmatrix}$	4
3	$\begin{bmatrix} 205 \\ 170 \\ 162 \end{bmatrix}$	30	$\begin{bmatrix} -52 \\ -21 \\ -12 \end{bmatrix}$	$\begin{bmatrix} -28 \\ -28 \\ -29 \end{bmatrix}$	$\begin{bmatrix} -24 \\ 7 \\ 17 \end{bmatrix}$	$\begin{bmatrix} 181 \\ 177 \\ 179 \end{bmatrix}$	2.67
4	$\begin{bmatrix} 140 \\ 145 \\ 156 \end{bmatrix}$	58	$\begin{bmatrix} -21 \\ 60 \\ 64 \end{bmatrix}$	$\begin{bmatrix} 34 \\ 34 \\ 35 \end{bmatrix}$	$\begin{bmatrix} -55 \\ 26 \\ 29 \end{bmatrix}$	$\begin{bmatrix} 115 \\ 121 \\ 112 \end{bmatrix}$	6
5	$\begin{bmatrix} 140 \\ 145 \\ 156 \end{bmatrix}$	50.7	$\begin{bmatrix} 25 \\ 76 \\ 108 \end{bmatrix}$	$\begin{bmatrix} 70 \\ 70 \\ 69 \end{bmatrix}$	$\begin{bmatrix} -45 \\ 6 \\ 39 \end{bmatrix}$	$\begin{bmatrix} 72 \\ 80 \\ 81 \end{bmatrix}$	6

The reduction of unbalance indicates improvement of the phase balancing. Table IV shows more application results for different feeder load configurations.

The input loads for this study were acquired from a load data survey in a South African city [4]. The input superset consists of many load data for the three phases for any specific time-period of a day over a month. We selected the input loads randomly from the superset. The results presented in Table IV are chosen to represent different phase loading conditions. For each application, the final fuzzy output change configuration is passed onto the expert system for implementing the load change operation, described in the following section.

IV. CONCLUSIONS

In this paper, a fuzzy logic-based load balancing system has been presented. The input to the fuzzy step is the total load (kW) per phase of the feeders. Output of the fuzzy step is the load change values, negative value for load releasing and positive value for load receiving. Sum of the positive and negative values is zero, i.e., the total load remains unchanged for the entire phase balancing. The output of the fuzzy step is the input to the load. It also performs the optimal inter-changing of the load points between the releasing and the receiving phases. The load balancing system is tested at the three-phase, four-wire unbalanced feeders and the simulation results obtained on the Matlab platform show a substantial improvement of the unbalance conditions.

The proposed phase balancing system using the fuzzy logic is effective for reducing the feeder unbalance and can be generically extended further extended to other distribution systems and feeder load configurations.

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