COMPARATIVE STUDY OF FUZZY LOGIC USING DIFFERENT FUZZY INFERENCE SYSTEMS AND CONVENTIONAL METHODS FOR CONSTRAINED POWER FLOW SOLUTIONS AND CONTINGENCY EVALUATION IN POWER SYSTEMS

[1]**Asst. Prof. Dr. Hassan A. Kubba**
[1]Electrical Engineering Department
[1]Engineering College
[1]Baghdad University

[2]**M.Sc. Safaa Alddin Ali Majeed**
[2]Electrical Engineering Department
[2]Engineering College
[2]Baghdad University

ABSTRACT: ***This research provides a comparison between the performances of Sugeno type versus Mamdani-type fuzzy load flow (FLF) inference systems, a fuzzy contingency evaluation (FCE) algorithm of electrical power systems using Triangular and Guassian membership functions based on fuzzy control theory. Fuzzy logic is used to deal with uncertainties such as bus injected active and reactive powers, and lines data in a simple manner thereby reducing the system complexity and the time required for calculations. In the fuzzy load flow methods, the real and reactive power mismatches per voltage magnitude at each bus of the power system are chosen as the crisp input values, which are fuzzified into the fuzzifier. The process logic uses a rule base to explode the fuzzy output signals which are defuzzified as crisp output values to be chosen as the corrections of voltage angle and magnitude at each bus of the system. A sparsity technique is implemented for the sparse matrices as input data in order to reduce the overall computation time and storage requirements. The performance of the proposed method have been tested on the IEEE 14-bus, and 30-busbar IEEE International test system. Results are compared to other powerful methods according to the following criteria namely, number of iterations, total computation time, storage requirements, and reliability of solving ill-conditioned power systems under normal operation and contingency conditions. The proposed method is faster (in overall computation time) than the fast decoupled load flow method by about 65% for the same power mismatch accuracy. Two characteristic features of the proposed fuzzy load flow are the real-time (on-line) applicability for small- as well as large-scale power systems. Also, the fuzzy system has many advantageous features such as optimized system complexity, control of power flow, control of nonlinear system, and its durability to include uncertainty in input data.***

KEY WORDS: Fast decoupled method, Fuzzy Load Flow, Fuzzy Logic, Newton-Raphson Method, Sugeno Fuzzy Inference System, Mamdani Fuzzy Inference systems, Load flow analysis, Contingency evaluation, Sparsity Technique.

I. NOMENCLATURE

ΔP : active power mismatch.
ΔQ : reactive power mismatch.
θ : voltage phase angle.
δ : branch admittance angle.
μA : membership function.
bkm : transmission line susceptance between buses k and m.
COA : Centroid of Area.
FDLF : Fast Decoupled Load Flow.
FLC : Fuzzy Logic Controller.
FLF : Fuzzy Load Flow.
FLFC: Fuzzy Load Flow Controller.
gkm : transmission line conductance between buses k and m.
I : bus current.
k : bus index.
mωk : excluding the case when m=k
Pk : injected active power at bus k.
Qk : injected reactive power at bus k.
|Vk| : bus voltage magnitude.
|Ykm| : magnitude of admittance between buses k and m.

II. INTRODUCTION

The load flow problem, which is to determine the power system static states (voltage magnitudes and voltage phase angles) at each busbar to find the steady state operating condition of a system, is very important and the most frequently carried out study by electrical power utilities for power system real-time operation, planning and control. The mathematical formulation of the electrical power flow problem results in a set of non-linear algebraic equations. The numerical methods such as Newton-Raphson method or the artificial intelligence methods such as Fuzzy logic applications are applied to solve the load flow problem. [1]. But the numerical methods may suffer from:

1- Size of the power systems.
2- Speed of the solution for on-line or real time applications.
3- Storage requirement.
4- Uncertainties in input data.
5- Ill-conditioned power systems.
6- Characteristics of the model of power systems

There are many criteria which should be taken into consideration to assess the performance of each method such as the number of iterations, speed of solution, storage requirement and reliability to solve ill-conditioned power systems and contingent operating conditions, and the degree of solution accuracy. Among these techniques is that of fuzzy logic applications. They have been used successfully to solve a wide range of optimization problems.

There are numerous assumptions in the load flow model that does not reflect the actual system and does not accurately represent the actual network flows and voltages. Conceptually, the standard load flow methodology provides a misleadingly precise answer arising from a static snapshot solution of a dynamic system assuming perfect knowledge of the network parameters, loading and generation set points. Solutions are then used to make a variety of decisions in planning and operations. Uncertainty is one of the most important issues in power system planning when decisions are made regarding the future system expansion and operation. Two types of uncertainty are:

1. Errors in the calculated or measured parameters of the various lines and transformers in the system.
2. Errors in the magnitude of the demand assumed for the system load buses.

In trying to include uncertainty into the solution process, analysts have tried different approaches. Most frequently, planners repeat the analysis under varying system conditions. A better solution would be to provide solutions over the range of uncertainties included, i.e., solutions that are sets of values instead of single points. Fuzzy systems have been increasingly used to develop more efficient schemes for the power system operation, planning, control, and management. Fuzzy systems rely on a set of rules. These rules allow the input to be fuzzy, i.e., more like the natural way that humans express knowledge. A fuzzy system is a growing area in research field of soft computing. Different logics and inference techniques of fuzzy systems are there in the historical data of soft computing. Fuzzy inference system is a computing framework based on the disciplines of fuzzy set theory, fuzzy if-then rules and fuzzy reasoning. The input required to Fuzzy inference system is in fuzzy form or in crisp form but the output it generates is always in fuzzy form. Fuzzy inference system is also called as fuzzy rule based system, fuzzy expert system, fuzzy associative memory, fuzzy controller, fuzzy model or simply fuzzy system on the basis of the target for which the system is designed. For example if the target of a system consist of temperature controlling tasks then the fuzzy system will be called as fuzzy controller [17]. In classical set theory an object can either a member of a given set or not while fuzzy set theory allows an object to belong to a set with a certain degree. Fuzzy system models fuzzy boundaries of linguistic terms by introducing gradual membership. Fuzzy set includes membership function. Membership function maps each element of a set to a membership degree [18].

III. FUZZY LOGIC THEORY

Most of our traditional tools for formal modeling, reasoning, and computing are crisp, deterministic, and precise in character. By crisp we mean dichotomous, that is yes-or-no-type rather than more-or-less type. In conventional dual logic, for instance, a statement can be true or false- and nothing in between. In set theory, an element can either belong to a set or not; and in optimization, a solution is either feasible or not [2]. The traditional way of representing elements u of a set A is through the characteristic function:

$$\mu_A(u) = 1 \text{ , if u is an element of the set A, and} \quad (1)$$

$$\mu_A(u) = 0 \text{ , if u is not an element of the set A} \quad (2)$$

In fuzzy sets, an object can belong to a set partially. The degree of membership is defined through a generalized characteristic function called the membership function:

$$\mu_A(u) : U \rightarrow [0,1] \quad (3)$$

Where, U is called the universe, and A is a fuzzy subset of U. The values of the membership function are real numbers in the interval [0,1], where 0 means that the object is not a member of the set and 1 means that it belongs entirely to the set. Each value of the function is called a membership degree [3]. As can be seen from fig. 1, the most widely used are the bell-shaped (Gaussian), triangular, trapezoidal and the singleton membership functions.

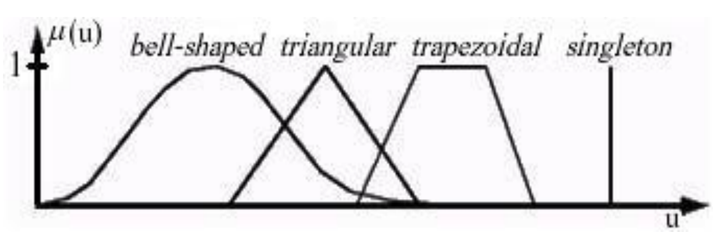


Fig. 1 Different shapes of membership functions

The main phases to solve any problem using the fuzzy logic approach are as follows:

1. Identifying the problem and choosing the type of fuzzy system which best suits the problem requirements.
2. Defining the input and output variables, their fuzzy values, and their membership functions.
3. Articulating the set of heuristic fuzzy rules.
4. Choosing the fuzzy inference system, fuzzification and defuzzification methods [4].

IV. FAST DECOUPLED LOAD FLOW (FDLF) METHOD

Fast decoupled load flow method, possibly the most popular method used by utilities, is well known for its speed of solution, reduced memory, and reliable convergence. The algorithm is simpler, faster and more reliable than Newton's method and has lower storage requirements. The fast decoupled load flow method is based on Newton's load flow method with the modifications of neglecting the Jacobian sub-matrices which relate the active power with voltage magnitude and the reactive power with voltage phase angle due to the weak coupling between ″P-V″ and ″Q-θ″ quantities in power transmission system. Together with other approximations and assumptions, the fast decoupled load flow equations become [5, 6]:

$$\left[\frac{\Delta P}{V}\right] = [B'][\Delta\theta] \tag{4}$$

$$\left[\frac{\Delta Q}{V}\right] = [B''][\Delta V] \tag{5}$$

Where $B'_{km} = -\frac{1}{x_{km}}$ for m≠k and $B'_{kk} = \sum_{m\omega k} \frac{1}{x_{km}}$ for m=k (6)

$B''_{km} = -B_{km}$ for m≠k and $B''_{kk} = \sum_{m\omega k} B_{km}$ for m=k (7)

(B′) and (B”) are highly sparse matrices.

V. PROPOSED FUZZY LOAD FLOW METHOD

The fuzzy load flow equations can be derived from fast decoupled load flow set of equations, being equations (4) and (5) respectively. In equation (4), the vector θ is updated but vector V is fixed. Equation (5) is used to update the vector V while vector θ is fixed.

The whole calculation will terminate if the errors of both these equations are within the desired error tolerance The above system of equations can be expressed as:

$$\Delta F = B \cdot \Delta X \tag{8}$$

This equation states that the correction of state vector ΔX at each bus of the system is directly proportional to the vector ΔF. The proposed fuzzy load flow method is based on the previous FDLF equation, but the repeated update of the state vector of the system are being performed using fuzzy logic control instead of using the conventional load flow approach. This can be expressed by:

$$\Delta X = fuz(\Delta F) \tag{9}$$

Where, fuz represents a fuzzy logic function.

The FLF algorithm is illustrated schematically in Fig. 2. In this figure, the power parameters ΔF_P and ΔF_Q are calculated and introduced to the $P-\theta$ fuzzy logic controller $FLC_{P\text{-}\theta}$ and the $Q-V$ fuzzy logic controller $FLC_{Q\text{-}V}$, respectively. The FLCs generate the correction of the state vectors ΔX, namely, the correction of the voltage angle $\Delta\theta$ for the $P-\theta$ cycle and the correction of voltage magnitude ΔV for the $Q-V$ cycle [7].

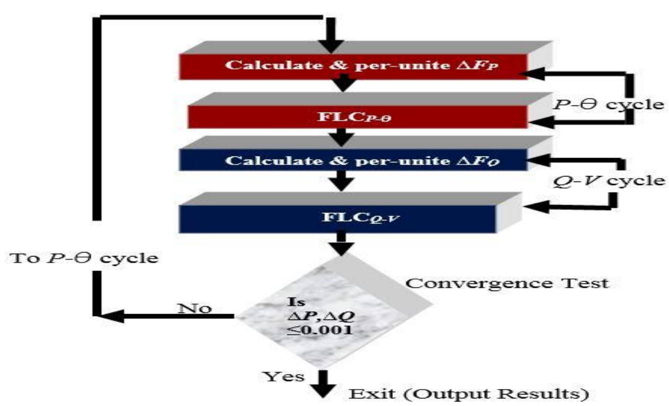


Fig. 2 Fuzzy Load Flow Algorithm

The proposed fuzzy load flow controller (FLFC) has a structure that may be shown in Fig. 3. It comprises four principal components: a fuzzification interface, a rule base, process logic and a defuzzification interface. The fuzzification interface involves the following functions during any iteration:

- Calculate and per unite the power parameters ΔF_P and ΔF_Q at each bus of the system.
- The above parameters are elected as crisp input signals.
  The maximum power parameter (ΔF_{Pmax} or ΔF_{Qmax})
  Determines the range of scale mapping that transfers the input signals into corresponding universe of discourse at every iteration.
- The input signals are fuzzified into corresponding fuzzy signals (ΔF_{Pfuz} or ΔF_{Qfuz}) with seven linguistic variables; large negative (LN), medium negative (MN), small negative (SN), zero (ZR), small positive (SP), medium positive (MP) and large positive (LP). It is being represented in Gaussian and triangular membership function form [8].

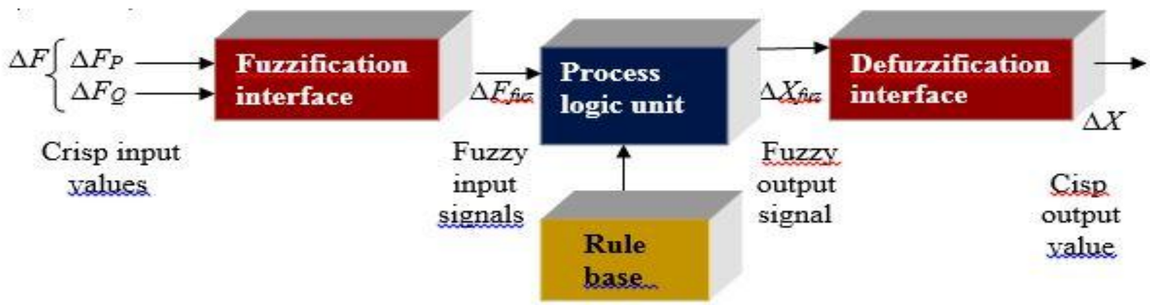


Figure 3 Structure of the Fuzzy Load Flow Controller

- Design of these fuzzy rules is based upon two observations. The first of them is that when the computed value obtained in any iteration is far away from the specified one, it will require more compensation from the fuzzy logic controller.
  The second is that these fuzzy rules are consistent with the observation that corrective action to state vector ΔX is directly proportional to power vector ΔF (eqn. 8) in any iteration [9].
- The fuzzy signals ΔF_{fuz} are sent to process logic, which generates the fuzzy output signals ΔX_{fuz} based on the previous rule base and are represented by seven linguistic variables similar to input fuzzy signals. The output fuzzy signals ΔX_{fuz} are then sent to the defuzzification interface, which performs the following function:

The maximum corrective action ΔX_{max} of state variables determines the range of scale mapping that transfers the output signals into the corresponding universe of discourse at every iteration. The maximum correction of these variables can be calculated by:

$$\Delta X_{\max} = \left(\frac{dF_k}{dX_k} \right)^{-1} \cdot \Delta F_{\max,k} \quad (10)$$

Where F_k expresses the real or reactive power balance equations at bus-k with maximum real or reactive power mismatches of the system, X_k represents the voltage angle or magnitude at bus-k.

VI. FUZZY INFERENCE SYSTEM

Fuzzy inference systems are widely applicable in economic, scientific and engineering application areas due to the intuitive nature of the system and ability to analyze human judgments. Fuzzy inference systems captures changing environment as an expert knowledge and easily integrated with fuzzy systems. Fuzzy inference systems have the output expressive power so one can easily understand the results and control the target. In decision making and control applications such as air conditioning system, use of fuzzy inference systems is attractive [19].

Fuzzy inference system is classified into three types on the basis of the consequent of the fuzzy rules that are required for the inference procedure: Mamdani fuzzy inference system, Sugeno and Tsukamoto fuzzy inference system. Mamdani fuzzy inference system was initially developed to control the steam engine and boiler combination by using a set of linguistic variables. Mamdani fuzzy inference system generates output in fuzzy form. So there is a need to convert this fuzzy output into crisp form by using different defuzzification techniques to defuzzify fuzzy output into crisp [20].

There are five methods of defuzzification. Centroid of area method of defuzzification is mostly used for estimating crisp output compressor speed because of the widespread acceptance in control application. Equation (11) represents formula for centroid of area. In this equation A is a fuzzy set, x is a universe of discourse and μA(x) is aggregated output membership function.

$$\frac{\int_i^n \mu_A(\mathrm{x})\mathrm{x}\mathrm{dx}}{\int_i^n \mu_A(\mathrm{x})\mathrm{dx}} \quad (11)$$

Takagi sugeno kang (TSK) fuzzy inference system is a systematic approach that can generate fuzzy rules from given input output data set. Antecedent of the rule in this system is in fuzzy form and consequent of rule is represented by a function in fuzzy input. it is similar to the Mamdani method in many respects. The first two parts of the fuzzy inference process, fuzzifing the inputs and applying the fuzzy operator, are exactly the same. The main difference between Mamdani and Sugeno is that the Sugeno output membership functions are either linear or constant. A typical rule in a Sugeno fuzzy model has the form:

If Input 1 = x and Input 2 = y, then Output is z = ax + by + c

For a zero-order Sugeno model, the output level z is a constant (a=b =0).

In fuzzy inference system with weighted average each rule has crisp output and overall output is calculated by weighted average. The mathematical equation for weighted average is shown by equation (12). Here W_i is the membership degree of the rule R_i and Z_i is a function in p, q and r [18].

Z = px + qy + r

$$\frac{\sum_i w_i z_i}{\sum_i w_i} \qquad (12)$$

VII. ILL-CONDITIONED POWER SYSTEMS

One of the measures of how much load flow solution methods are efficient is revealed by the success of the method in solving ill-conditioned power systems. Ill-conditioned systems can have many definitions. The one which we are concerned with is that system having small (or near zero) shunt admittance of a single (or multiple) bus(es) to the reference bus; the second which is happened most in reality is the presence of significant series capacitive reactances in branch admittances or shunt capacitances. These will deteriorate the diagonal dominance of the Nodal Admittance Matrix. Many conventional numerical methods such as Gauss-Seidel method, Newton-Raphson method, and some of the artificial intelligence methods such as conventional Genetic Algorithm failed to solve the load flow problem of ill-conditioned power systems. In this research, the ill-conditioned power systems load flow is solved by many methods and the proposed Fuzzy load flow method to test their reliability for solving such systems [12].

VIII. UNCERTAINTY AND FUZZY LOGIC

Uncertainty is known as the lack of certainty which is a condition having limited knowledge where the existing condition or future outcome with more than one possible outcome is impossible describing. It is fact that in a real world, there is various different type of uncertainty but in science the uncertainty are ignored and considered as lacking information. However, realizing the essential of considering uncertainty in science for a better outcome, the handling of uncertainty is being acknowledged. As a result, the different ways to model the uncertainty had been developed by using the concepts of fuzzy sets and possibility theories [21].

Uncertainty is a state when it is impossible to decide whether the claim in the model is true or false while imprecision is a state when the information in the model is not as specific as it should be. The uncertainty and imprecision resulted due to lack of knowledge about the database application. Vagueness or fuzziness concept corresponds to the inability to define precise boundary for some information and represent the inherent uncertainty. Ambiguity appears when there are different meanings of word or an expression. Events are not clearly specified in this concept and correspond to the lack of information. In common, the different between vagueness and ambiguity is that the vagueness follow different incompatible meanings nevertheless can be solving with further information. Inconsistency appears as a result when the model which contains two or more assertions cannot be true at the same time [21].

Different kind of uncertainty can be modeled through different way; one of the approaches is using fuzzy set theory to model the concept of fuzziness. The other way is using the possibility theory, since this theory offered appropriate formalism to model the imprecise knowledge and perception of human being into probability distribution.

Fuzzy logic is basically a multi-valued logic that allows intermediate values to be defined between conventional evaluations like yes and no, true and false, black and white, etc. Notions like very tall or too short or fairly good can be formulated mathematically and processed by computers. Fuzzy logic is a superset of conventional (Boolean) logic that has been extended to handle the concept of partial truth. A partially true statement may be indexed any value between completely true and completely false. There is a strong relationship between fuzzy logic and fuzzy subset theory as compared to the relationship between Boolean logic and the concept of a subset. A fuzzy subset A of a set U can be defined as a set of ordered pairs, each with the first element x from U and the second element from the interval {0,1} with exactly one ordered pair present for each element of U. This defines a mapping between elements of the set U and values in the interval {0, 1}. The zero value is used to represent complete non-membership, the value one is used to represent complete membership, and values in between are used to represent intermediate degrees of membership. The set U is referred to as the universe of discourse for the fuzzy subset A. Frequently, the mapping is described as function.

IX. SIMULATION AND IMPLEMENTATION RESULTS

Two test systems were used to demonstrate the performance of the two different fuzzy inference system using Triangular and Gaussian membership function under the same normal and different loading /contingency conditions (Fuzzy Contingency Evaluation, ″FCE″) with power mismatches of 0.001p.u. (0.1 MW/MVAr). Also, the compration between Sugeno fuzzy load flow and Mamdani fuzzy load flow and conventional method.

The power flow study has been carried out in all tests and practical systems using flat voltage condition and for power mismatch tolerance of 0.001p.u. Two fuzzy load flow controllers were used to achieve the convergent solutions. Also, the load flow problem was solved by two powerful numerical methods namely, Newton-Raphson (NR) and fast decoupled load flow method (FDLF) methods. The two test systems are:

1. 14-busbar IEEE International test system, the lines and buses data are presented in [1]. The ″14-bus″ test system consists of: 1 slack bus, 4 generator buses (PV) and 9 load buses (PQ) with 20 branches.
2. 30-busbar IEEE International test system consists of: 1 slack/swing bus, 5 generator (PV) buses, and 24 load (PQ) buses with 41 branches. The line and bus data are presented in [1].

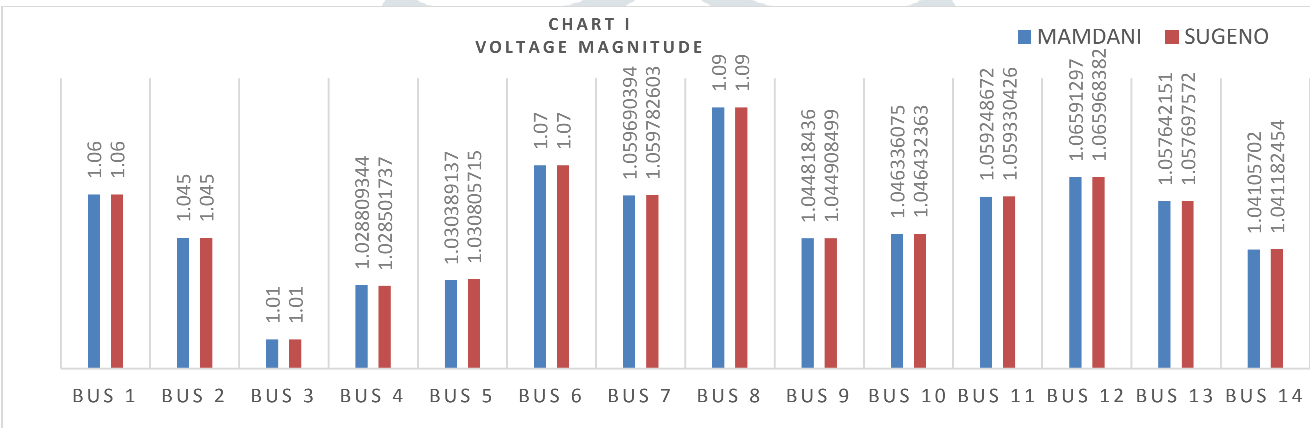
The FLF method was implemented on the IEEE 14-bus typical test system for the following cases of normal operation and contingent operation. The power mismatches (active and reactive) are given for each case of operation as shown below:

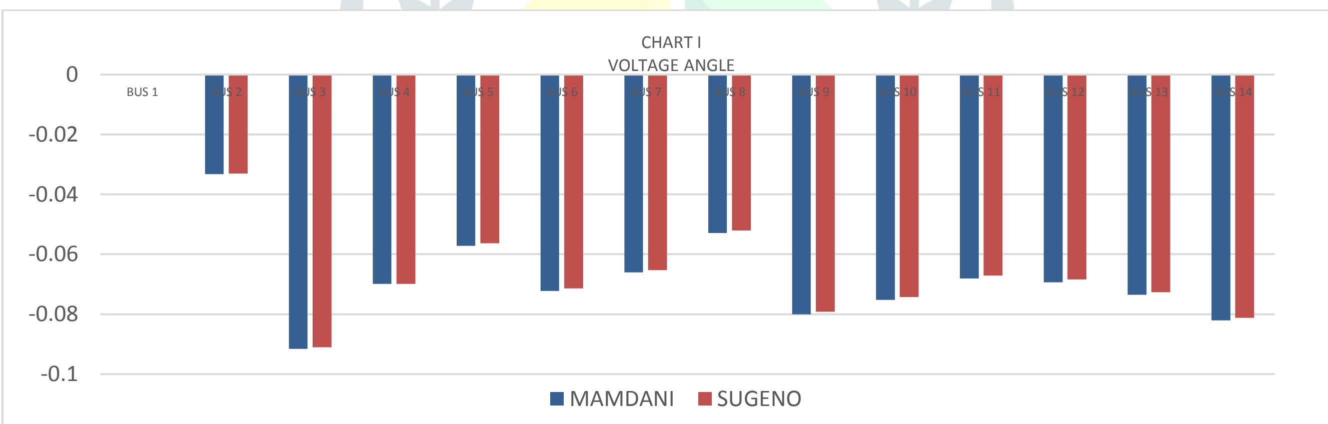
1. Normal operating conditions with power mismatches of 0.001 p.u. (0.1MW/MVAr).
2. Single-line outage with power mismatches of (0.001).
3. Single generator outage with power mismatches of 0.001.

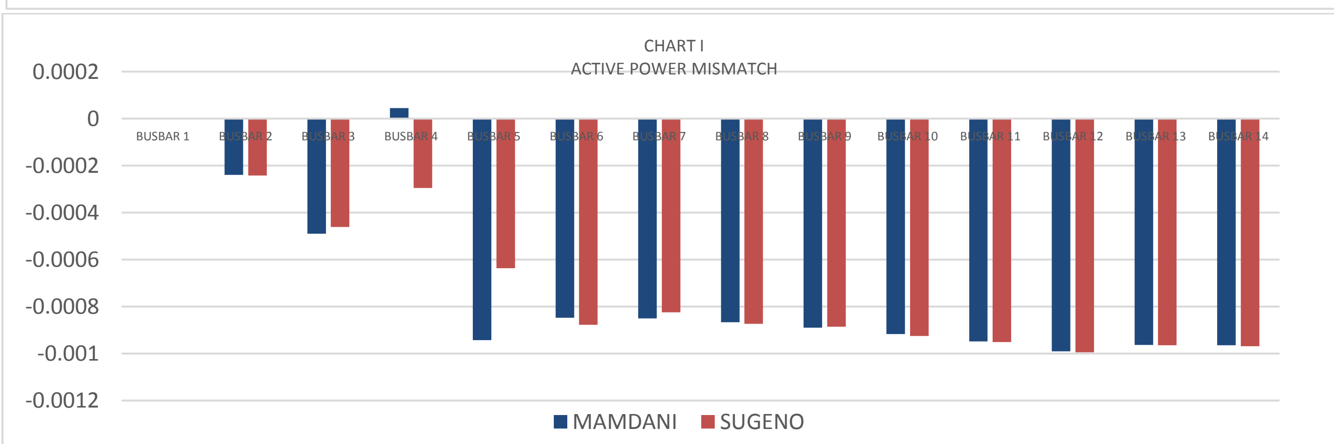
Robustness of the proposed method was studied in the latter step. Note that in the following curves, the per unit quantities are 100 MVA and 132 KV. The obtained results are exhibited in the following charts using fuzzy load flow using Triangular membership function.

CHART I

FUZZY LOAD FLOW SOLUTION FOR ″14-BUS″ TYPICAL TEST SYSTEM POWER MISMATCHES (ACTIVE / REACTIVE) = 0.001 p.u.







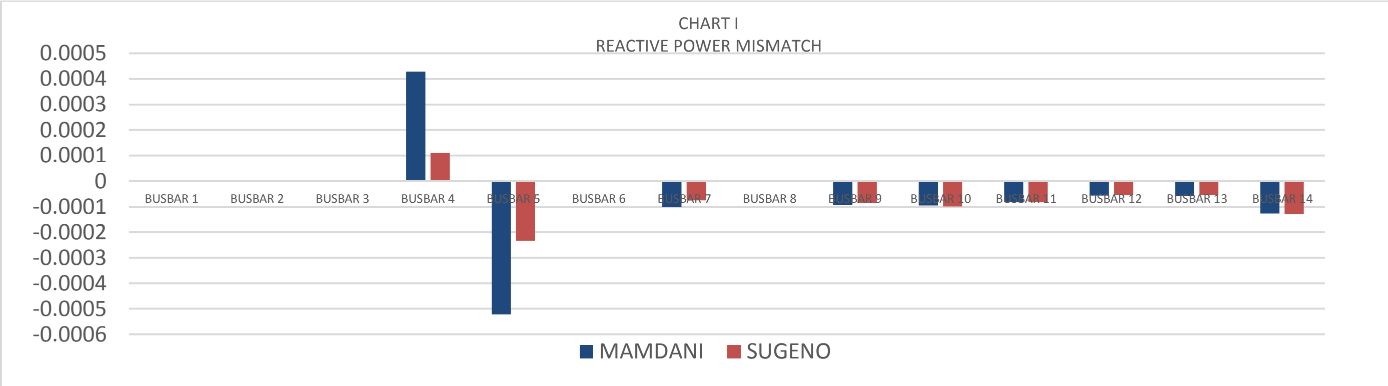
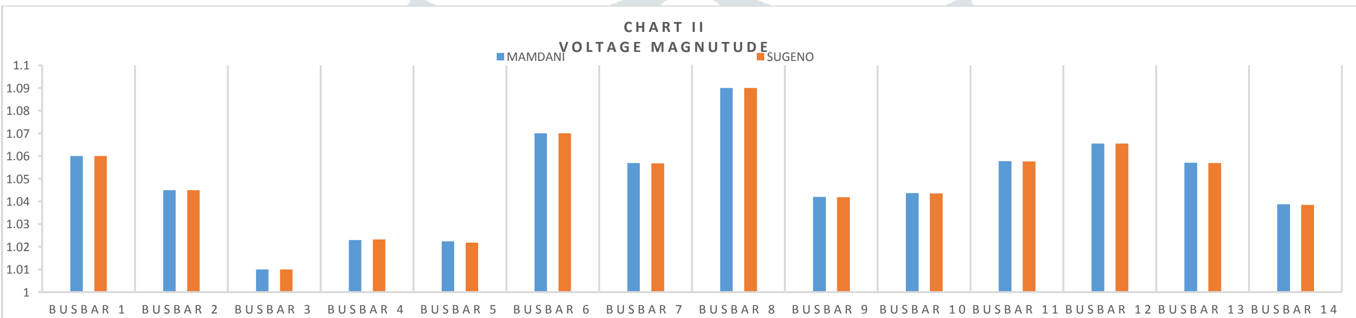
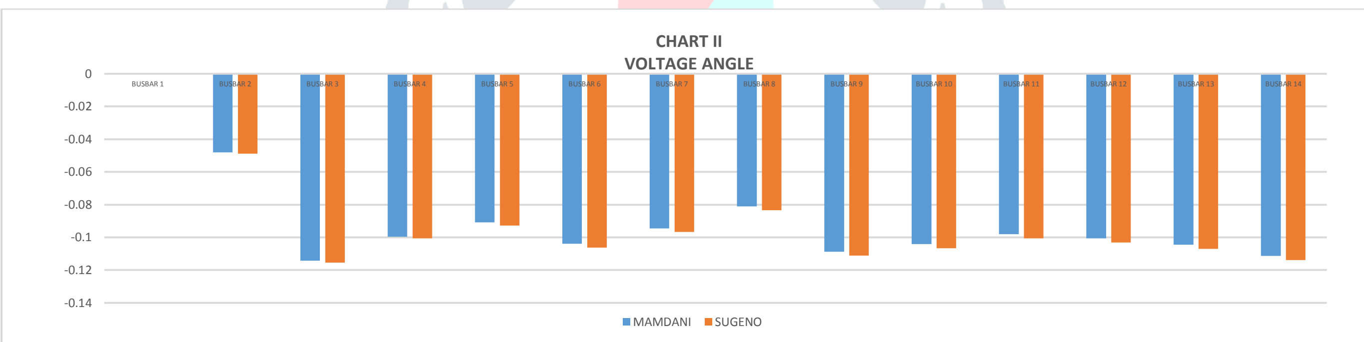
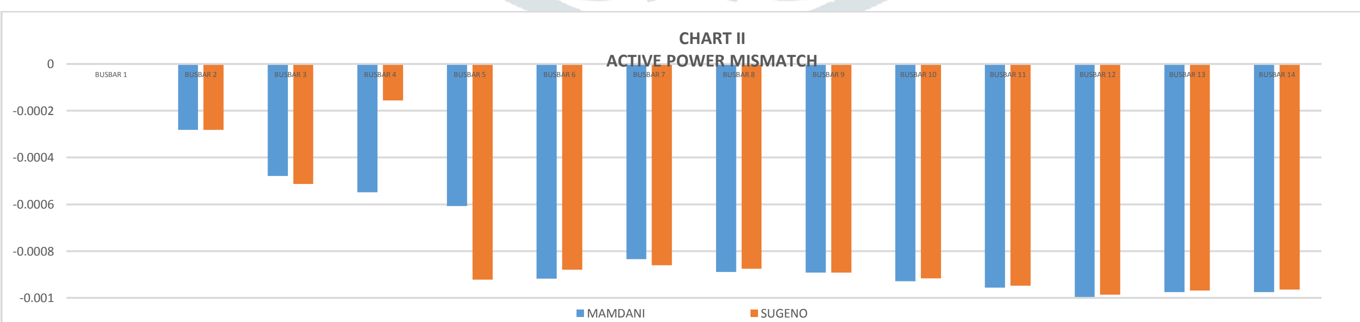


CHART II

FUZZY LOAD FLOW SOLUTION FOR ″14-BUS″ TYPICAL TEST SYSTEM SINGLE-LINE OUTAGE (FCE), POWER MISMATCHES (ACTIVE / REACTIVE) = 0.001p.u.







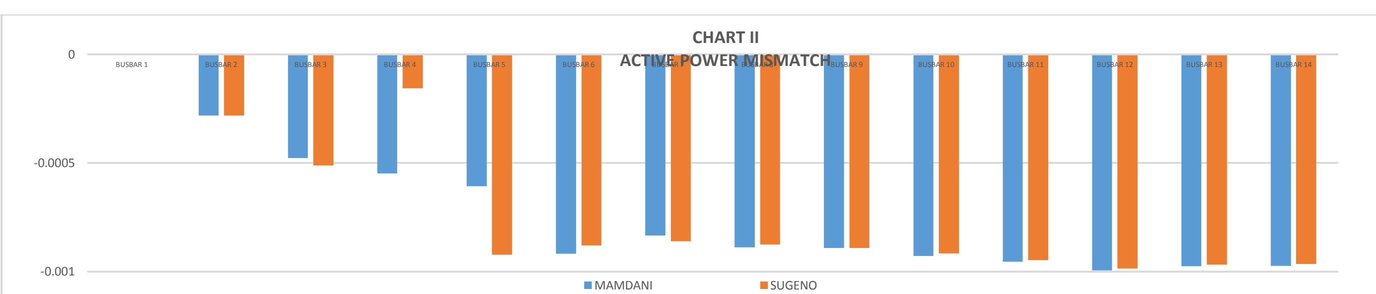
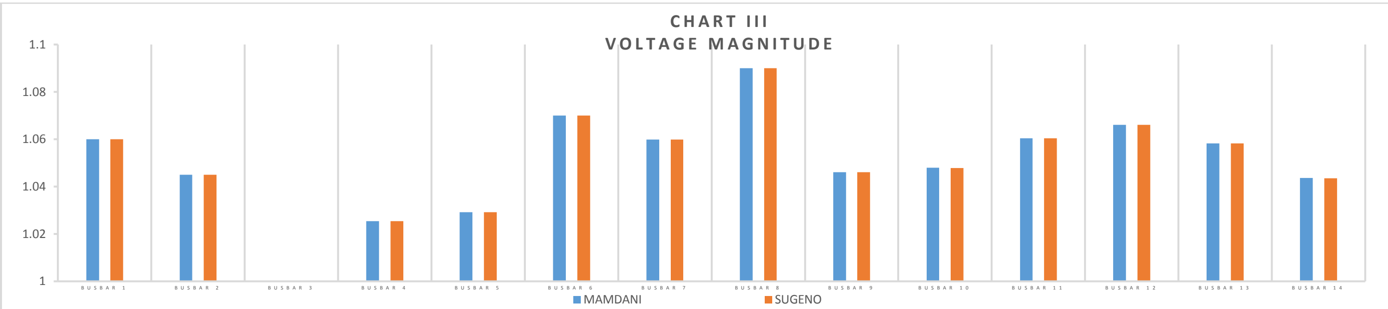
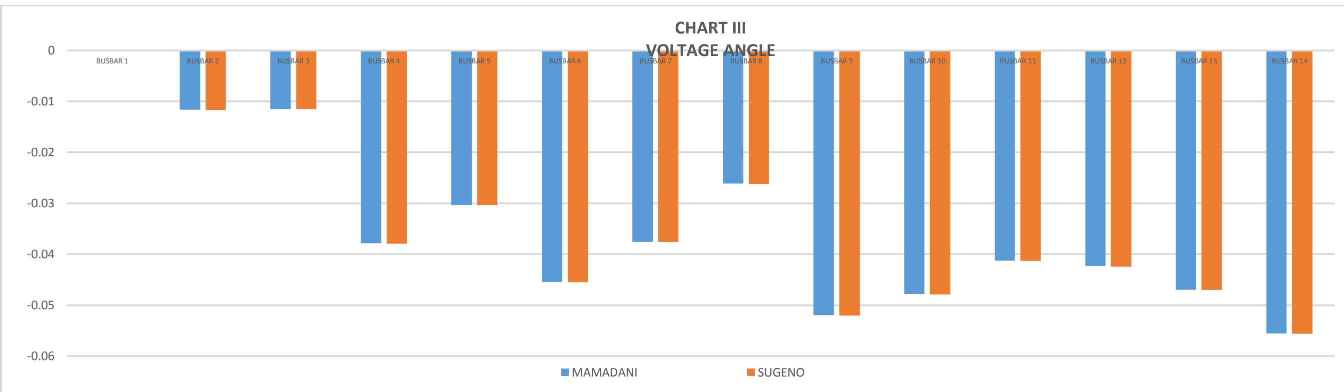
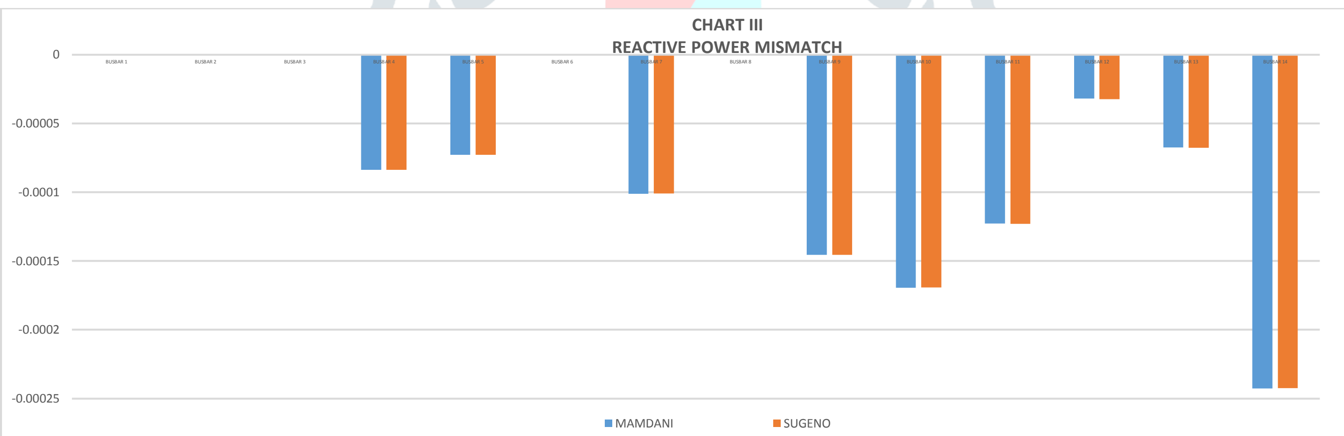


TABLE III
FUZZY LOAD FLOW SOLUTION FOR ″14-BUS″ TPYICAL TEST SYSTEM GENERATOR #3 OUTAGE (FCE), POWER MISMATCHES (ACTIVE / REACTIVE) = 0.001p.u.







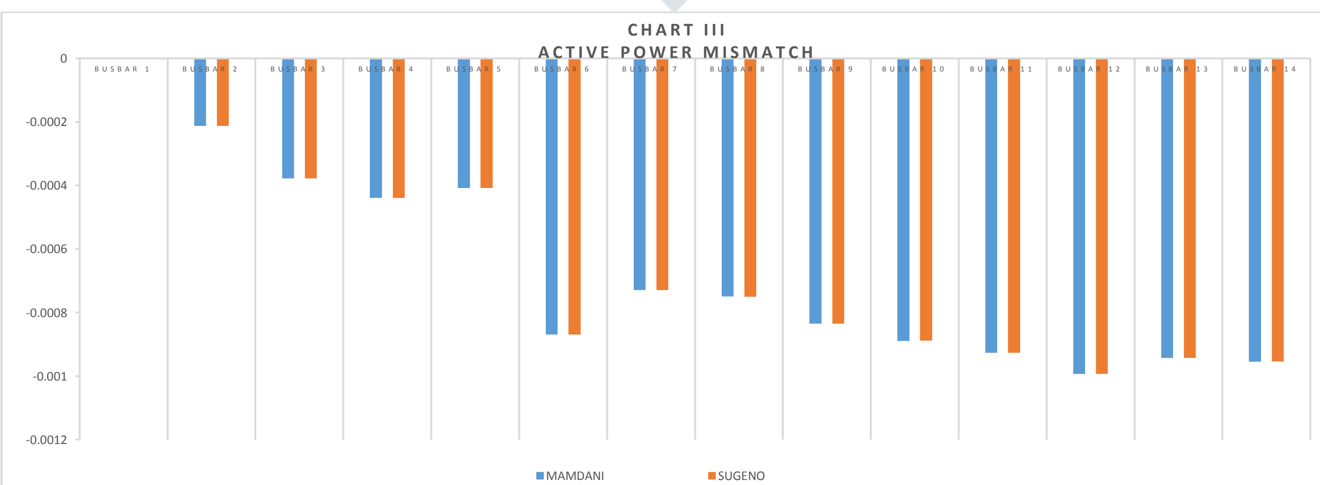


Table I shows both the time elapsed and the total number of iterations that are required to converge at a converged solution for the cases of normal and contingent operation represented by Charts (I) through (III) without sparsity technique.

TABLE I
TIMES AND NUMBER OF ITERATIONS FOR SOLUTION OF IEEE 14-BUS CASES

CHART Number	Total Time Required (sec)	Total Iterations Number (Iter.)	Total Time Required (sec)	Total Iterations Number (Iter.)
	MAMDANI		SUGENO	
I	0.211	9	0.167	9
II	0.215	11	0.171	10
III	0.214	11	0.172	10

The FLF solutions using Gaussian function efficiently converged for all tests and all systems for the same level of accuracy. The number of iterations required was less than that required in the FLF method using triangular membership functions and thus a faster computation time but it requires more iterations as compared to that required in fast decoupled load flow (FDLF) method. However the overall computation time (CPU time) requirement was less in FLF using Gaussian membership function compared to using triangular function and FDLF. Table II shows a comparison between Sugeno fuzzy load flow and Mamdani fuzzy load flow (Triangular and Gaussian membership functions), fast decoupled load flow ″FDLF″, and Newton-Raphson ″NR″ methods according to the following criteria: number of iterations and percentage computing time under the rated loadings.

TABLE II
COMPARISON OF FUZZY LOAD FLOW AND NUMERICAL METHODS ACCORDING TO NUMBER OF ITERATIONS REQUIRED & PERCENTAGE COMPUTING TIME

*TMF: Triangular membership function, *GMF: Gaussian membership function ,*MFLF: Mamdani fuzzy load flow,*SFLF: Sugeno fuzzy load flow

Type of test system	% Computing time						No. of iterations required					
	*MFLF *TMF	*SFlF TMF	MFLF *GMF	SFLF GMF	FDLF	N R	MFLF TMF	SFLF TMF	MFLF GMF	SFLF GMF	FDLF	NR
14-bus IEEE	11	9	10	7	32	100	9	9	8	8	3	4
30-bus IEEE	13	11	12	10	39	100	10	9	9	8	4	5

Table III illustrates the load flow solutions for 14-bus IEEE system under contingency conditions (Single line outage and one generator outage) using the six different methods.

TABLE III
COMPARISON OF FUZZY LOAD FLOW AND NUMERICAL METHODS FOR 14-BUS IEEE SYSTEM UNDER CONTINGENCY CONDITIONS

*DIV: Divergence

CONTINGENCY CONDITION	% Computing time						No. of iterations required					
	*MFLF *TMF	*SFlF TMF	MFLF *GMF	SFLF GMF	FDLF	N R	MFLF TMF	SFLF TMF	MFLF GMF	SFLF GMF	FDLF	NR
SingleLine Outage	70	40	30	15	100	*DIV	11	10	10	9	5	DIV
Generator 3 Outage	30	20	11	8	100	DIV	11	10	9	8	6	DIV

The FLF algorithms and numerical methods were implemented using MATLAB® Version 7.4.0.287 (R2007a) on a Pentium®IV Microprocessor personal computer with the following specifications: 2.0 GHz Intel® 2 Giga bytes cache memory, 2 Giga bytes RAM.

X. DISCUSSION

A novel method based on the fuzzy logic control to solve the load flow problem under normal and contingency conditions is presented and could be used as a base to incorporate all the modern power control strategies which are designed using fuzzy logic. All the obtained results in this research show that the computation time of the Fuzzy Load Flow (FLF) is less than the Fast Decoupled Load Flow (FDLF) according to the following analysis:

• The components of the fuzzy logic controller, the number of the fuzzy membership functions and their shapes are selected from computational experience to minimize the computing time and the number of iterations required for convergence of the solution. The repetitive solution of the FLF method requires only 2n calculations per iteration, where n is the number of buses of the system. In contrast, the Newton-Raphson (N-R) and Fast Decoupled Load Flow (FDLF) methods need a large number of calculations at any iteration on account of factorization, refactorization and computations on the Jacobian matrix also additional memory requirements.

• The mathematical formulation of the N-R and FDLF depends on the Taylor series expansion in which the third and higher terms of the series are omitted. So, all the nonlinearities of the problem are omitted and approximations are achieved while, no approximations are executed in FLF.

• Durability of the FLF method is to deal with and incorporate the uncertainties in the input data into the solution of the load flow problem.

• The digital computer is not operating with absolute accuracy so, the truncation (rounding-off) error may effect on the load flow solution by N-R and FDLF methods especially with ill-conditioned power systems.

The FLF method using Gaussian membership function requires less number of iterations and slightly less computing time than that required in the FLF method using triangular membership function, due to the smoothly varying curve of the Gaussian function. Thus, the Gaussian membership function can tackle fuzzy output signals more than the sharp triangular membership function.

The Sugeno FLF method requires less number of iterations and slightly less computing time than that required in the Mamdani FLF method. There are cases that the Sugeno FLF is more accurate than Mamdani FLF , but the results are almost same in Mamdani FLF and Sugeno FLF.

XI. CONCLUSIONS

In this paper, Fuzzy Logic was used efficiently to solve the load flow problem under different loading/contingency conditions used two systems due to its following merits:

1. The performance of 14-bus and 30-bus IEEE systems is efficient and stable in different contingency conditions, capable of sensing system overloads and rerouting power to prevent or minimize a potential outage; of working autonomously when conditions require resolution faster than humans can respond and cooperatively in aligning the goals of utilities, consumers and regulators, capable of meeting increased consumer demand without adding infrastructure.
2. The power loss are small and reasonable especially the active power loss consequently, the cost and environment pollution will be minimized.

Fuzzy Logic was used efficiently to solve the load flow problem due to its following merits:

1. FLF constitutes an alternative solution methodology which is simpler and faster.
2. It simplifies the complexity of obtaining a solution by incorporating the uncertainties in input data processed while the traditional methods imply repeated solution of the conventional load flow equations using for example the Newton-Raphson or the Fast Decoupled methods. However, as electric power systems grow in size and increase in complexity, the traditional approach of repeating the solutions becomes inefficient.
3. It is simple to implement.

The following points can be noted from the obtained results by implementing the Fuzzy Load Flow on the standard test systems in addition to the Enhanced Iraqi National Grid:

1. The proposed FLF can be used in the on-line operational stage in electric power control centers having either small- or large-scale power system configurations under varying normal and contingent operating conditions Also, it can be used in the off-line planning stage instead of the operational stage. Consequently, the FLF method can be treated as a worthwhile base, which is able to homogeneously incorporate all modern control strategies of load flow designed by means of fuzzy logic control.
2. Comparing the results of the FLF with the results′ sheet of the typical test systems reveals that the proposed FLF performs well and hence give reliable results.
3. Successful solution of different types of ill-conditioned power systems. Results are reliable in addition to low calculation time, whereas the Newton-Raphson and many numerical methods as well as some artificial intelligence methods for load flow solution diverged of many cases of ill-conditioned systems.
4. The FLF method for both membership functions (Triangular and Gaussian) required slightly more iteration as compared to that required in fast decoupled load flow (FDLF) method but, the overall computation time (CPU) requirement was less in the FLF method for the same level of accuracy.
5. The two membership functions (Triangular and Gaussian) used in the FLF are the most popular and suitable functions in fuzzy load flow solutions. The minimum number of fuzzy membership functions is seven with seven linguistic variables for reliable and accurate results (mismatch powers<0.0001p.u.). For more accuracy, we can use nine fuzzy membership functions and more, but it is time consuming and we do not need for such accuracy in load flow solution.
6. Accurate results in solving both the active and reactive power flows as compared with their values obtained when the typical test systems are solved using the Newton-Raphson load flow method.
7. Comparing the results of the Mamdani FLF with the result’s sheet of Sugeno FLF reveals that the Sugeno FLF is more faster than Mamdani FLF, also the Triangular MF is slower than Gaussian MF and the Gaussian MF is more accurate than Triangular MF.

8.The Sugeno FLF has more accurate results of different types of ill-conditioned power systems in addition to low calculation time, so it has the best performance in ill-conditioned power systems .

7. Using sparsity technique for the input sparse matrix data without complicating the algorithm’s programs gives reduction in overall computation time and storage requirements.

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APPENDIX A

Table (A.1) Load Flow Solution Results Using Newton-Raphson Method for IEEE 14 Bus for Power Mismatch =0.001

Bus Number	Bus Type	Voltage Mag.	Voltage Ang. (Deg.)
1	1	1.060	0
2	2	1.045	-4.98
3	2	1.010	-12.72
4	0	1.019	-10.33
5	0	1.020	-8.78
6	2	1.070	-14.22
7	0	1.062	-13.37
8	2	1.090	-13.36
9	0	1.056	-14.94
10	0	1.051	-15.1
11	0	1.057	-14.79
12	0	1.055	-15.07
13	0	1.050	-15.16
14	0	1.036	-16.04