# Real-Time Fuzzy Power Flow Solution, Contingency Evaluation, and Power Loss Calculations of Smart Power Grid

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***Abstract*— This paper presents a fuzzy load flow (FLF), a fuzzy contingency evaluation (FCE) algorithm and power loss calculations of electrical power systems using Gaussian 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, 30-bus test systems and 362-bus Enhanced Iraqi National Grid (EING) as a practical 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. The calculations of power loss in each branch of the systems, the successful solution of normal and contingent power systems especially the case of ill-conditioned power systems reveal the merits of the smart grid. 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.**

***Keywords*--- Fuzzy systems, Load flow analysis, Contingency evaluation, Sparse matrices**

## I. NOMENCLATURE

$\Delta P$ : active power mismatch.
$\Delta Q$ : reactive power mismatch.
$\Theta$ : voltage phase angle.
$\delta$ : branch admittance angle.
$\mu_A$ : membership function.
$b_{km}$ : 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.
$g_{km}$ : transmission line conductance between buses $k$ and $m$.
$I$ : bus current.
$k$ : bus index.
$m\omega k$ : excluding the case when $m=k$
$P_k$ : injected active power at bus $k$.
$Q_k$ : injected reactive power at bus $k$.
$|V_k|$ : bus voltage magnitude.
$|Y_{km}|$ : 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 optimization 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]. 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, 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.

The Smart Grid connects consumers to the grid in a way that is beneficial to both, because it turns out there’s a lot that average consumers can do to help the grid. Simply by connecting to consumers – by means of the right price signals and smart appliances, for example – a smarter grid can reduce the need for some of that infrastructure while keeping electricity reliable and affordable. As noted, during episodes of peak demand, stress on the grid threatens its reliability and raises the probability of widespread blackouts.

By enabling consumers to automatically reduce demand for brief periods through new technologies and motivating mechanisms like real-time pricing, the grid remains reliable – and consumers are compensated for their help.

Enabling consumer participation also provides tangible results for utilities which are experiencing difficulty in sitting new transmission lines and power plants. Ultimately, tapping the collaborative power of millions of consumers to shed load will put significant brakes on the need for new infrastructure at any cost. Instead, utilities will have time to build more cost-efficiencies into their sitting and building plans.

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.

## 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:

$\mu_A(u) = 1$, if *u* is an element of the set *A*, and (1)

$\mu_A(u) = 0$ □, if *u* is not an element of the set *A* (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:

$$\mu_A(u) : U \to [0,1] \tag{3}$$

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.

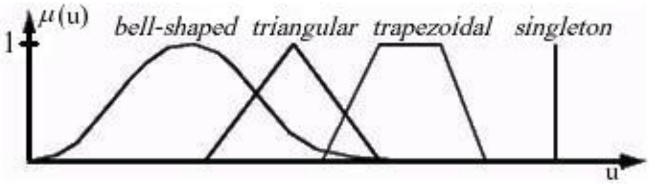

Fig. 1 Different shapes of membership functions

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.

Experimenting with the fuzzy system prototype; drawing the goal function and output fuzzy variables; changing membership functions and fuzzy rules if necessary; tuning the system and validation of results [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]:

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

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

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

$$\Delta F = B \cdot \Delta X \qquad (8)$$

This equation states that the correction of state vector $\Delta X$ at each bus of the system is directly proportional to the vector $\Delta F$. 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

$$\Delta X = fuz(\Delta F) \qquad (9)$$

Where, $fuz$ represents a fuzzy logic function.

The FLF algorithm is illustrated schematically in Fig. 2. In this figure, the power parameters $\Delta F_P$ and $\Delta F_Q$ 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 $\Delta X$, namely, the correction of the voltage angle $\Delta\theta$ for the $P-\theta$ cycle and the correction of voltage magnitude $\Delta V$ for the $Q-V$ cycle [7].

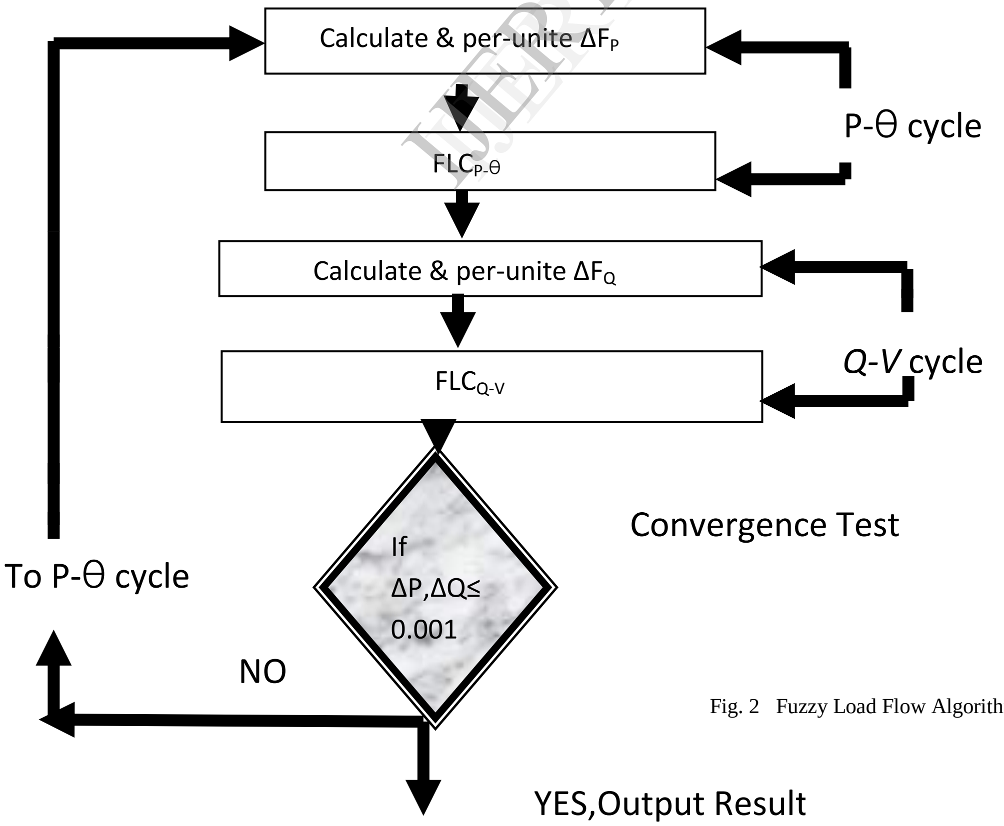

Fig. 2 Fuzzy Load Flow Algorithm

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 $\Delta F_P$ and $\Delta F_Q$ at each bus of the system.
- The above parameters are elected as crisp input signals.

The maximum power parameter ($\Delta F_{P\max}$ or $\Delta F_{Q\max}$) 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 ($\Delta F_{P\mathrm{fuz}}$ or $\Delta FQ_{\mathrm{fuz}}$) 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 membership function form [8].

The rule base involves seven rules tallying with seven linguistic variables:

Rule 1 : if $\Delta F_{\mathrm{fuz}}$ is LN then $\Delta X_{\mathrm{fuz}}$ is LN.
Rule 2 : if $\Delta F_{\mathrm{fuz}}$ is MN then $\Delta X_{\mathrm{fuz}}$ is MN.
Rule 3 : if $\Delta F_{\mathrm{fuz}}$ is SN then $\Delta X_{\mathrm{fuz}}$ is SN.
Rule 4 : if $\Delta F_{\mathrm{fuz}}$ is ZR then $\Delta X_{\mathrm{fuz}}$ is ZR.
Rule 5 : if $\Delta F_{\mathrm{fuz}}$ is SP then $\Delta X_{\mathrm{fuz}}$ is SP.
Rule 6 : if $\Delta F_{\mathrm{fuz}}$ is MP then $\Delta X_{\mathrm{fuz}}$ is MP.
Rule 7 : if $\Delta F_{\mathrm{fuz}}$ is LP then $\Delta X_{\mathrm{fuz}}$ is LP.

- 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 $\Delta X$ is directly proportional to power vector $\Delta F$ (eqn. 8) in any iteration [9].

- The fuzzy signals $\Delta F_{\mathrm{fuz}}$ are sent to process logic, which generates the fuzzy output signals $\Delta X_{\mathrm{fuz}}$ based on the previous rule base and are represented by seven linguistic variables similar to input fuzzy signals. The output fuzzy signals $\Delta X_{\mathrm{fuz}}$ are then sent to the defuzzification interface, which performs the following function:

The maximum corrective action $\Delta X_{\max}$ 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:

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

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*.

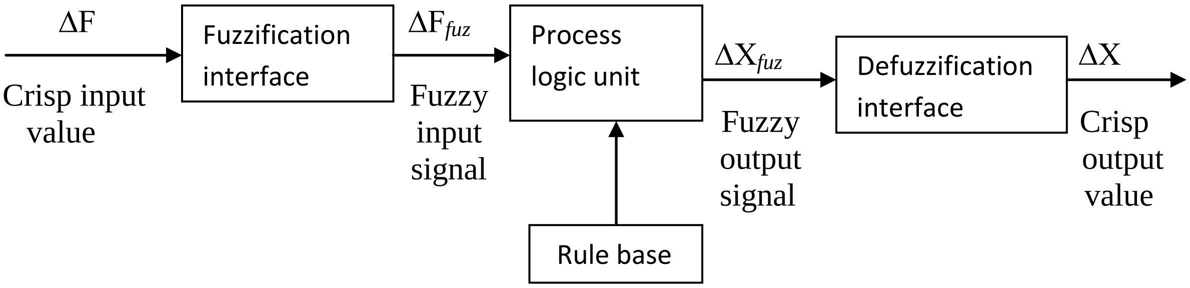

Figure 3 Structure of the Fuzzy Load Flow Controller

The Gaussian membership is built on the Gaussian distribution function, which is a smoothly varying curve. The Gaussian membership function has been used for fuzzification of the real and reactive power mismatches per voltage magnitude at each bus of the system and defuzzification of the fuzzy output signals for correction of voltage magnitudes and voltage phase angles. The input signals are fuzzified into corresponding fuzzy signals ($\Delta F_{Pfuz}$ or $\Delta F_{Qfuz}$) 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). They are represented in Gaussian functions as shown in fig. 4.

The two points (width and center) are designed as:

- LN : [$2\Delta F_m/3$, $-\Delta F_m$],
- MN : [$2\Delta F_m/3$, $-2\Delta F_m/3$],
- SN : [$2\Delta F_m/3$, $-\Delta F_m/3$],
- ZR : [$2\Delta F_m/3$, 0],
- SP : [$2\Delta F_m/3$, $\Delta F_m/3$],
- MP : [$2\Delta F_m/3$, $2\Delta F_m/3$],
- LP : [$2\Delta F_m/3$, $\Delta F_m$].

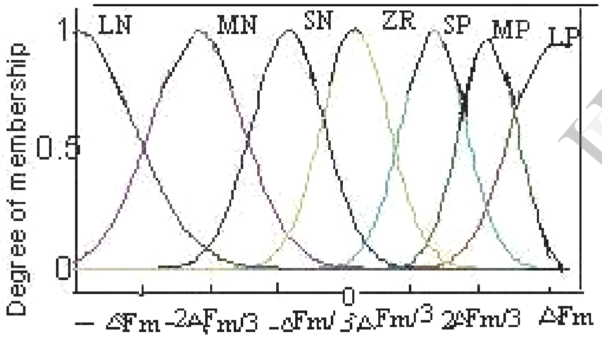

Fig. 4 Gaussian Membership Functions for Input Signals $\Delta F_{fuz}$

Finally, the defuzzifier will transform fuzzy output signals $\Delta X_{fuz}$ into crisp values $\Delta X$ for every bus of the network. The centroid-of-area (COA) defuzzification strategy is being adopted which is the most commonly used strategy. The COA defuzzification strategy is computationally efficient, works well with optimization, intuitive, has widespread acceptance, and is well suited to human input. This strategy finds the geometrical centre $y'$ which represents the crisp output value $\Delta X$ in the universe $V$ of an output variable $y$ (the fuzzy output signals $\Delta X_{fuz}$), which center "balances" the inferred membership function $B'$ as a fuzzy value for $y$ and $\mu_{B'}$ represents the degree of membership of the fuzzy output $y$. The following formula is used [10]:

$$y' = \frac{\sum \mu_{B'}(y) \cdot y}{\sum \mu_{B'}(y)} \tag{11}$$

and the state vector is being updated as

$$\Delta X^{i+1} = X^{i} + \Delta X \tag{12}$$

Where the index $i$ depicts the number of iterations.

The number of Gaussian fuzzy-membership functions used and fuzzy rules are selected heuristically to minimize the overall computing time required for convergence.

These fuzzy rules are consistent with the observation that corrective action to state vector ΔX is directly proportional to power vector ΔF at any iteration. The same Fuzzy Inference System is used in FLF, i.e., fuzzification, rule base, membership function, linguistic variable, and fuzzy output signals $\Delta X_{fuz}$ and defuzzification interface are implemented for a Gaussian function. Therefore, two points (width and center) of the Gaussian membership functions for output signals $\Delta X_{fuz}$ are redesigned in similar way to fig. 4, are listed as:

- LN : [$2\Delta X_m/3$, $-\Delta X_m$],
- MN : [$2\Delta X_m/3$, $-2\Delta X_m/3$],
- SN : [$2\Delta X_m/3$, $-\Delta X_m/3$],
- ZR : [$2\Delta X_m/3$, 0],
- SP : [$2\Delta X_m/3$, $\Delta X_m/3$],
- MP : [$2\Delta X_m/3$, $2\Delta X_m/3$],
- LP : [$2\Delta X_m/3$, $\Delta X_m$].

## VI. THE FEATURES OF AN ELECRICAL SMART GRID

The Smart Grid connects consumers to the grid in a way that is beneficial to both, because it turns out there's a lot that average consumers can do to help the grid.

Simply by connecting to consumers – by means of the right price signals and smart appliances, for example – a smarter grid can reduce the need for some of that infrastructure while keeping electricity reliable and affordable. As noted, during episodes of peak demand, stress on the grid threatens its reliability and raises the probability of widespread blackouts.

By enabling consumers to automatically reduce demand for brief periods through new technologies and motivating mechanisms like real-time pricing, the grid remains reliable – and consumers are compensated for their help.

Enabling consumer participation also provides tangible results for utilities which are experiencing difficulty in sitting new transmission lines and power plants. Ultimately, tapping the collaborative power of millions of consumers to shed load will put significant brakes on the need for new infrastructure at any cost. Instead, utilities will have time to build more cost-efficiencies into their sitting and building plans. The main features of the smart grid are [11]:

**Intelligent** – 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.

**Efficient** – capable of meeting increased consumer demand without adding infrastructure.

**Accommodating** – accepting energy from virtually any fuel source including solar and wind as easily and transparently as coal and natural gas; capable of integrating any and all better ideas and technologies – energy storage technologies, for example – as they are market-proven and ready to come online.

**Motivating** – enabling real-time communication between the consumer and utility so consumers can tailor their energy consumption based on individual preferences, like price and/or environmental concerns.

**Opportunistic** – creating new opportunities and markets by means of its ability to capitalize on plug-and-play innovation wherever and whenever appropriate.

**Quality-focused** – capable of delivering the power quality necessary – free of sags, spikes, disturbances and interruptions – to power our increasingly digital economy and the data centers, computers and electronics necessary to make it run.

**Resilient** – increasingly resistant to attack and natural disasters as it becomes more decentralized and reinforced with Smart Grid security protocols.

## 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. SPARSITY TECHNIQUES

Sparse matrices are a special class of matrices that contain a significant number of zero-valued elements. This property allows to:

- Store only the nonzero elements of the matrix, together with their indices, to reduce the storage requirements.
- Reduce the computation time for any arithmetic operation by eliminating operations on zero elements [13].

### *A. Sparse Matrix Storage*

For full matrices, any software package stores internally every matrix element. Zero-valued elements require the same amount of storage space as any other matrix element. For sparse matrices, however, the sparsity technique stores only the nonzero elements and their indices. For large matrices with a high percentage of zero-valued elements, this scheme significantly reduces the amount of memory required for data storage. The implementation of sparsity technique, for example in MATLAB uses three arrays internally to store sparse matrices with real elements. Consider an ($m$-by-$n$) sparse matrix with (NNZ) nonzero entries (NNZ is number of nonzero elements):

- The first array contains all the nonzero elements of the array in floating-point format. The length of this array is equal to (NNZ).
- The second array contains the corresponding integer row indices for the nonzero elements. This array also has length equal to (NNZ).
- The third array contains integer pointers to the start of each column. This array has length equal to (n).

This matrix requires storage for (NNZ) floating-point numbers and (NNZ+n) integers. At 8 bytes per floating-point number and 4 bytes per integer, the total number of bytes required to store a sparse matrix is:

$$\text{Grand total of bytes}=8*\text{NNZ}+4*(\text{NNZ}+n) \qquad (13)$$

Sparse matrices with complex elements are also possible. In this case, it uses a fourth array with (NNZ) elements to store the imaginary parts of the nonzero elements. An element is considered nonzero if either its real or imaginary part is nonzero.

### *B. Creating Sparse Matrices*

Every software package never creates sparse matrices automatically. Instead, we must determine if a matrix contains a large enough percentage of zeros to benefit from sparse techniques.

The ***density*** of a matrix is the number of nonzero elements divided by the total number of matrix elements. Matrices with very low density are often good candidates for use of the sparse format. In contrast, the *matrix sparsity* is the number of zero elements divided by the total number of matrix elements. Matrices with very high matrix sparsity are often good candidate for use of the sparse format [14].

### *C. Viewing sparse matrix*

We can provide a number of functions that let us get quantitative or graphical information about sparse matrices. The MATLAB's commands provide high-level information about matrix storage, including size and storage class. For example, the following list shows information about sparse and full versions of the same matrix:

Illustration example:

| Name | Size | Bytes | Class |
|---|---|---|---|
| M-full | (1100x1100) | 9680000 | double array |
| M-sparse | (1100x1100) | 4404 | sparse array |

Grand total is (1210000) elements using (9684404 bytes). Notice that the number of bytes used is much less in the sparse case, because zero-valued elements are not stored. In this case, the density of the sparse matrix is (4404/9680000), or approximately 0.00045 (0.045%) [15].

## IX. SIMULATION AND IMPLEMENTATION RESULTS

Three test systems were used to demonstrate the performance of the fuzzy load flow (FLF) using Gaussian membership function and Triangular 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 power loss in all branches of the systems was calculated. All these calculations can reveal many of the features of the smart grids.

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 three 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].
3. The Enhanced Iraqi National Grid (EING) which contains ″362- busbar″ consists of: 1 slack bus, 29 generator buses (PV) and 332 load buses (PQ) with 599 branches [16].

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, double-line, and triple-line outage with power mismatches of (0.001).
3. Single generator outage with power mismatches of 0.001.
4. To explore the performance of the FLF algorithm under conditions of overloaded load bus, the active power demand of load bus number (9) was increased twice. In the first case, the active power demand was increased from 29.5 MW to 35.4 MW, i.e., an increase by 20% above the rated load. In the second case, the increase was by 50% over the rated power demand with power mismatches of (0.001).
5. In addition to the cases mentioned above, the performance of the system was studied in the case of adding series capacitance to three branches of the system in order to deteriorate the diagonal dominance of the B′ and B″ matrices such that in ill-conditioned power systems.

Robustness of the proposed method was studied in the latter step. Note that in the following tables, 0, 1 and 2 under the Bus Type column stand for load, slack and generator buses respectively, and the per unit quantities are 100 MVA and 132 KV.

The obtained results are exhibited in the following tables using fuzzy load flow using Gaussian membership function. The obtained results by using Triangular membership function are very similar to the results using Gaussian membership function.

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

| Bus Number | Bus Type | Voltage Mag. | Voltage Angle(deg.) | $\Delta P$ (p.u) | $\Delta Q$ (p.u) |
|---|---|---|---|---|---|
| 1 | 1 | 1.060 | 0.000 | 0.0 | 0.0 |
| 2 | 2 | 1.045 | -9.648 | -0.000375 | 0.0 |
| 3 | 2 | 1.010 | -5.807 | -0.000293 | -0.0002897 |
| 4 | 0 | 1.035 | -4.538 | -0.000252 | -0.0005452 |
| 5 | 0 | 1.045 | -5.998 | -0.000372 | 0.0 |
| 6 | 2 | 1.070 | -5.808 | -0.000260 | 0.0000947 |
| 7 | 0 | 1.062 | -3.443 | -0.000252 | 0.0004596 |
| 8 | 2 | 1.090 | -3.794 | -0.000273 | 0.0002499 |
| 9 | 0 | 1.065 | -4.345 | -0.000275 | -0.0000522 |
| 10 | 0 | 1.069 | -3.191 | -0.000264 | 0.0005205 |
| 11 | 0 | 1.069 | -3.343 | -0.000252 | 0.0009391 |
| 12 | 0 | 1.070 | -3.633 | -0.000252 | 0.0 |
| 13 | 0 | 1.070 | -3.854 | -0.000280 | -0.0001060 |
| 14 | 0 | 1.080 | -2.384 | -0.000269 | 0.0 |

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

| Bus Number | Bus Type | Voltage Mag. | Voltage Angle (deg.) | $\Delta P$ (p.u) | $\Delta Q$ (p.u) |
|---|---|---|---|---|---|
| 1 | 1 | 1.060 | 0.000 | 0.0 | 0.0 |
| 2 | 2 | 1.045 | -2.882 | -0.000033 | 0.0 |
| 3 | 2 | 1.010 | -9.126 | -0.000059 | 0.0 |
| 4 | 0 | 1.028 | -5.861 | -0.000066 | -0.0009200 |
| 5 | 0 | 1.030 | -4.696 | -0.000065 | -0.0009934 |
| 6 | 2 | 1.070 | -5.669 | -0.000154 | 0.0 |
| 7 | 0 | 1.077 | -5.145 | -0.000185 | 0.0000294 |
| 8 | 2 | 1.090 | -4.331 | -0.000190 | 0.0 |
| 9 | 0 | 1.069 | -6.166 | -0.000177 | -0.0000824 |
| 10 | 0 | 1.066 | -5.902 | -0.000180 | -0.0002532 |
| 11 | 0 | 1.068 | -5.498 | -0.000174 | -0.0004217 |
| 12 | 0 | 1.066 | -5.600 | -0.000173 | -0.0009426 |
| 13 | 0 | 1.060 | -5.826 | -0.000171 | -0.0006446 |
| 14 | 0 | 1.055 | -6.288 | -0.000186 | -0.0006391 |

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

| Bus Number | Bus Type | Voltage Mag. | Voltage Angle (deg.) | $\Delta P$ (p.u) | $\Delta Q$ (p.u) |
|---|---|---|---|---|---|
| 1 | 1 | 1.060 | 0.000 | 0.0 | 0.0 |
| 2 | 2 | 1.045 | -3.840 | -0.00022 | 0.0 |
| 3 | 2 | 1.010 | -10.749 | -0.00039 | 0.0 |
| 4 | 0 | 1.025 | -7.945 | -0.00047 | -0.0007656 |
| 5 | 0 | 1.027 | -6.600 | -0.00043 | -0.0007453 |
| 6 | 2 | 1.070 | -9.709 | -0.00088 | 0.0 |
| 7 | 0 | 1.066 | -9.337 | -0.00079 | -0.000462 |
| 8 | 2 | 1.090 | -8.966 | -0.00087 | 0.0 |
| 9 | 0 | 1.061 | -10.516 | -0.00087 | -0.0005076 |
| 10 | 0 | 1.058 | -10.421 | -0.00092 | -0.0006499 |
| 11 | 0 | 1.063 | -9.973 | -0.00095 | -0.0005816 |
| 12 | 0 | 1.062 | -10.062 | -0.00098 | -0.0006884 |
| 13 | 0 | 1.056 | -10.245 | -0.00096 | -0.0005672 |
| 14 | 0 | 1.045 | -11.019 | -0.00099 | -0.0009994 |

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

| Bus Number | Bus Type | Voltage Mag. | Voltage Angle(deg.) | $\Delta P$ (p.u) | $\Delta Q$ (p.u) |
|---|---|---|---|---|---|
| 1 | 1 | 1.060 | 0.000 | 0.0 | 0.0 |
| 2 | 2 | 1.045 | 0.000 | 0.0 | 0.0 |
| 3 | 2 | 1.010 | -4.185 | -0.00038 | 0.0 |
| 4 | 0 | 1.025 | -1.990 | -0.00016 | -0.000937 |
| 5 | 0 | 1.026 | -1.292 | -0.00012 | -0.000984 |
| 6 | 2 | 1.070 | -0.948 | -0.00011 | 0.0 |
| 7 | 0 | 1.068 | -0.809 | -0.00013 | -0.000183 |
| 8 | 2 | 1.090 | -0.224 | -0.00007 | 0.0 |
| 9 | 0 | 1.063 | -1.301 | -0.00014 | -0.000091 |
| 10 | 0 | 1.060 | -0.845 | -0.00013 | 0.0000922 |
| 11 | 0 | 1.064 | -0.465 | -0.00010 | 0.0002734 |
| 12 | 0 | 1.063 | -0.522 | -0.00010 | 0.0002717 |
| 13 | 0 | 1.060 | -0.802 | -0.00012 | 0.0000094 |
| 14 | 0 | 1.057 | -1.023 | -0.00014 | -0.000181 |

TABLE V
FUZZY LOAD FLOW SOLUTION FOR ″14-BUS″ TPYICAL TEST SYSTEM GENERATOR #2 OUTAGE (FCE), POWER MISMATCHES (ACTIVE / REACTIVE) = 0.001p.u.

| Bus Number | Bus Type | Voltage Mag. | Voltage Angle(deg.) | $\Delta P$ (p.u) | $\Delta Q$ (p.u) |
|---|---|---|---|---|---|
| 1 | 1 | 1.060 | 0.000 | 0.0 | 0.0 |
| 2 | 2 | 1.045 | -23.417 | -0.000090 | 0.0 |
| 3 | 2 | 1.010 | -28.017 | -0.000093 | 0.0 |
| 4 | 0 | 1.013 | -22.965 | -0.000087 | -0.0008763 |
| 5 | 0 | 1.013 | -20.488 | -0.000080 | -0.0009993 |
| 6 | 2 | 1.070 | -24.722 | -0.000109 | 0.0 |
| 7 | 0 | 1.065 | -21.921 | -0.000095 | -0.0004067 |
| 8 | 2 | 1.090 | -21.496 | -0.000098 | 0.0 |
| 9 | 0 | 1.038 | -27.176 | -0.000115 | -0.0007151 |
| 10 | 0 | 1.038 | -26.711 | -0.000116 | -0.0007173 |
| 11 | 0 | 1.053 | -25.562 | -0.000115 | -0.0004984 |
| 12 | 0 | 1.061 | -25.102 | -0.000114 | -0.0003374 |
| 13 | 0 | 1.052 | -25.396 | -0.000114 | -0.0003383 |
| 14 | 0 | 1.031 | -26.943 | -0.000118 | -0.0007753 |

TABLE VI
FUZZY LOAD FLOW SOLUTION FOR ″14-BUS″ TYPICAL TEST SYSTEM 120% ACTIVE POWER OVERLOAD (FCE), POWER MISMATCHES (ACTIVE / REACTIVE) = 0.001p.u.

| Bus Number | Bus Type | Voltage Mag. | Voltage Angle(deg.) | $\Delta P$ (p.u) | $\Delta Q$ (p.u) |
|---|---|---|---|---|---|
| 1 | 1 | 1.060 | 0.000 | 0.0 | 0.0 |
| 2 | 2 | 1.045 | -4.009 | -0.00021 | 0.0 |
| 3 | 2 | 1.010 | -11.037 | -0.00037 | 0.0 |
| 4 | 0 | 1.024 | -8.312 | -0.00044 | -0.000776 |
| 5 | 0 | 1.026 | -6.920 | -0.00041 | -0.000754 |
| 6 | 2 | 1.070 | -10.302 | -0.00084 | 0.0 |
| 7 | 0 | 1.065 | -10.036 | -0.00076 | -0.000496 |
| 8 | 2 | 1.090 | -9.674 | -0.00083 | 0.0 |
| 9 | 0 | 1.060 | -11.378 | -0.00083 | -0.000547 |
| 10 | 0 | 1.056 | -11.241 | -0.00088 | -0.000673 |
| 11 | 0 | 1.062 | -10.687 | -0.00090 | -0.000584 |
| 12 | 0 | 1.061 | -10.688 | -0.00094 | -0.000663 |
| 13 | 0 | 1.055 | -10.887 | -0.00092 | -0.000552 |
| 14 | 0 | 1.044 | -11.796 | -0.00094 | -0.000996 |

TABLE VII
FUZZY LOAD FLOW SOLUTION FOR ″14-BUS″ TYPICAL TEST SYSTEM 150% ACTIVE POWER OVERLOAD (FCE), POWER MISMATCHES (ACTIVE / REACTIVE) = 0.001p.u.

| Bus Number | Bus Type | Voltage Mag. | Voltage Angle(deg.) | $\Delta P$ (p.u) | $\Delta Q$ (p.u) |
|---|---|---|---|---|---|
| 1 | 1 | 1.060 | 0.000 | 0.0 | 0.0 |
| 2 | 2 | 1.045 | 0.000 | 0.0 | 0.0 |
| 3 | 2 | 1.010 | -4.185 | -0.00038 | 0.0 |
| 4 | 0 | 1.025 | -19.990 | -0.00016 | - 0.000937 |
| 5 | 0 | 1.026 | -13.292 | -0.00012 | - 0.000984 |
| 6 | 2 | 1.070 | -5.948 | -0.00011 | 0.0 |
| 7 | 0 | 1.038 | -9.809 | -0.00013 | - 0.000183 |
| 8 | 2 | 1.090 | -8.224 | -0.00007 | 0.0 |
| 9 | 0 | 1.043 | -11.301 | -0.00014 | -0.000091 |
| 10 | 0 | 1.020 | -10.845 | -0.00013 | 0.0000922 |
| 11 | 0 | 1.034 | -10.465 | -0.00010 | 0.0002734 |
| 12 | 0 | 1.063 | -15.522 | -0.00010 | 0.0002717 |
| 13 | 0 | 1.040 | -12.802 | -0.00012 | 0.0000094 |
| 14 | 0 | 1.037 | -16.023 | -0.00014 | -0.000181 |

TABLE VIII
FUZZY LOAD FLOW SOLUTION FOR ″14-BUS″ TYPICAL TEST SYSTEM ADDITION OF SERIES CAPACITANCE (ill-conditioned system), POWER MISMATCHES (ACTIVE / REACTIVE) = 0.001p.u.

| Bus Number | Bus Type | Voltage Mag. | Voltage Angle (deg.) | $\Delta P$ (p.u) | $\Delta Q$ (p.u) |
|---|---|---|---|---|---|
| 1 | 1 | 1.060 | 0.000 | 0.0 | 0.0 |
| 2 | 2 | 1.045 | -2.204 | -0.00014 | 0.0 |
| 3 | 2 | 1.010 | -9.176 | -0.00032 | 0.0 |
| 4 | 0 | 1.025 | -6.887 | -0.00039 | -0.0007429 |
| 5 | 0 | 1.026 | -5.617 | -0.00036 | -0.0007187 |
| 6 | 2 | 1.070 | -8.892 | -0.00080 | 0.0 |
| 7 | 0 | 1.066 | -8.447 | -0.00072 | -0.0004551 |
| 8 | 2 | 1.090 | -8.109 | -0.00079 | 0.0 |
| 9 | 0 | 1.061 | -9.670 | -0.00079 | -0.0004971 |
| 10 | 0 | 1.058 | -9.599 | -0.00083 | -0.0006561 |
| 11 | 0 | 1.063 | -9.176 | -0.00086 | -0.0005804 |
| 12 | 0 | 1.061 | -9.286 | -0.00090 | -0.0006899 |
| 13 | 0 | 1.055 | -9.459 | -0.00088 | -0.0005684 |
| 14 | 0 | 1.045 | -10.231 | -0.00091 | -0.0009992 |

Table IX 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 Tables (I) through (VIII) without sparsity technique.

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

| Table Number | Total Time Required (sec) | Total Iterations Number (Iter.) |
|---|---|---|
| I | 0.2061 | 9 |
| II | 0.2060 | 4 |
| III | 0.1038 | 2 |
| IV | 0.5658 | 19 |
| V | 0.1013 | 5 |
| VI | 0.2066 | 10 |
| VII | 0.3921 | 9 |
| VIII | 0.55 | 15 |

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 X shows a comparison between fuzzy load flow ″FLF″ (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 X.
COMPARISON OF FUZZY LOAD FLOW AND NUMERICAL METHODS ACCORDING TO NUMBER OF ITERATIONS REQUIRED & PERCENTAGE COMPUTING TIME

| Type of test system | No. of iterations required | | | | % Computing time | | | |
|---|---|---|---|---|---|---|---|---|
| | FLF *TMF | FLF *GMF | FDLF | NR | FLF TMF | FLF GM-F | FDL-F | N R |
| 14-bus IEEE | 9 | 7 | 3 | 4 | 11 | 10 | 32 | 100 |
| 30-bus IEEE | 10 | 9 | 4 | 5 | 13 | 12 | 39 | 100 |
| 362-bus EING | 15 | 13 | 7 | 8 | 6 | 4 | 51 | 100 |

*TMF: Triangular membership function, GMF: Gaussian membership function

Table XI illustrates the load flow solutions for 14-bus IEEE system under contingency conditions (Triple lines outage and one generator outage) using the four different methods. In the case of triple-lines outage, lines connecting buses (1) and (2), (2) and (4), and (7) and (9) were the faulty lines in a respective order.

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

| CONTINGENCY CONDITION | NO. OF ITERATIONS | | | | % COMPUTING TIME | | | |
|---|---|---|---|---|---|---|---|---|
| | FLF TMF | FLF GMF | FDLF | N-R | FLF TMF | FLF GMF | FDLF | N-R |
| Triple Lines Outage | 19 | 12 | 5 | *Div | 70 | 30 | 100 | Div |
| Generator 2 Outage | 10 | 9 | 6 | Div | 30 | 11 | 100 | Div |

* Divergent solution

Table XII illustrates the reduction in computational time and storage requirements for different power systems by using the proposed fuzzy load flow (FLF) method using Gaussian function with sparsity technique. The reduction in computation time and storage requirements increase as the matrix density decreases or in other words matrix sparsity increases. Whereas the sparse matrix is the Nodal Admittance Matrix which is the main input data of any applied software for load flow solution.

TABLE XII
COMPARISON OF REDUCTION IN COMPUTATION TIME AND STORAGE REQUIREMENT FOR DIFFERENT POWER SYSTEMS USING THE FLF WITH SPARSITY TECHNIQUE METHOD.

| Type of power system | Matrix density of [Y] | %Reduction in Computational Time (FLF with sparsity technique) | %Reduction in Storage Requirement (FLF With sparsity technique) |
|---|---|---|---|
| 14-bus IEEE | 17.34% | 41% | 60% |
| 30-bus IEEE | 7.88% | 60% | 75% |
| 362-bus(EING) | 0.628% | 90% | 95% |

The durability of the proposed method (FLF with or without sparsity technique) for operation with ill-conditioned power systems was tested by adding series capacitances to certain branches of the system. The values of the inserted capacitance, which were used with the 30-bus IEEE system, are 0.03333 p.u. to 0.3333 p.u. on the same bases. The branches connecting buses (1) and (2), (3) and (4), and (9) and (10) were those branches where series capacitances were added. The system converged to solution easily without any difficulties with the same accuracy of 0.001 p.u.

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. Power Loss Calculations

Another important parameter for transmission planners should know is the line flows. After the bus voltage magnitudes and phase angles are obtained, one can calculate the line flows, both active and reactive power, to see the loading conditions of the transmission lines. The complex power flow is:

$$P_{km} - jQ_{km} = V_k^* I_{km} \tag{14}$$

And, $$P_{mk} - jQ_{mk} = V_m^* I_{mk} \tag{15}$$

The power loss in line (K-M) is the algebraic sum of the power flows determined from equations 14 and 15.

Tables XIII and XIV show the power flows in both directions and the power loss in each branch of the two IEEE test systems while, the results of EING are too huge to tabulate in this paper.

Table XIII
FUZZY LOAD FLOW SOLUTION FOR ″14-Bus″ IEEE SYSTEM ACTIVE AND REACTIVE POWER FLOWS POWER MISMATCHES = 0.001

| Line Number | Line Termi-nals | From Bus Power Inj. | | To Bus Power Inj. | | Loss P(MW) | Loss Q(MVAR) |
|---|---|---|---|---|---|---|---|
| | | P (MW) | Q (MVAR) | P (MW) | Q (MVAR) | | |
| 1 | 1-2 | 156.8 | -20 | -152.5 | 27.68 | 4.298 | 13.12 |
| 2 | 1-5 | 75.51 | 3.85 | -72.75 | 2.23 | 2.763 | 11.41 |
| 3 | 2-3 | 73.24 | 3.56 | -70.91 | 1.60 | 2.323 | 9.79 |
| 4 | 2-4 | 56.13 | -1.5 | -54.45 | 3.02 | 1.677 | 5.09 |
| 5 | 2-5 | 41.52 | 1.17 | -40.61 | -2.10 | 0.904 | 2.75 |
| 6 | 3-4 | -23.2 | 4.47 | 23.66 | -4.84 | 0.373 | 0.95 |
| 7 | 4-5 | -61.1 | 15.8 | 61.67 | -14.20 | 0.514 | 1.62 |
| 8 | 4-7 | 28.07 | -9.6 | -28.07 | 11.38 | 0.0 | 1.70 |
| 9 | 4-9 | 16.08 | -0.4 | -16.08 | 1.73 | 0.0 | 1.30 |
| 10 | 5-6 | 44.09 | 12.4 | -44.09 | -8.05 | 0.0 | 4.42 |
| 11 | 6-11 | 7.35 | 3.56 | -7.30 | -3.44 | 0.055 | 0.12 |
| 12 | 6-12 | 7.79 | 2.50 | -7.71 | -2.35 | 0.072 | 0.15 |
| 13 | 6-13 | 17.75 | 7.22 | -17.54 | -6.80 | 0.212 | 0.42 |
| 14 | 7-8 | 0.0 | -17 | 0.0 | 17.62 | 0.0 | 0.46 |
| 15 | 7-9 | 28.07 | 5.78 | -2807 | -4.98 | 0.0 | 0.80 |
| 16 | 9-10 | 5.23 | 4.22 | -5.21 | -4.18 | 0.013 | 0.03 |
| 17 | 9-14 | 9.43 | 3.61 | -9.31 | -3.36 | 0.116 | 0.25 |
| 18 | 10-11 | -3.79 | -1.6 | 3.80 | 1.64 | 0.013 | 0.03 |
| 19 | 12-13 | 1.61 | 0.75 | -1.61 | -0.75 | 0.006 | 0.01 |
| 20 | 13-14 | 5.64 | 1.75 | -5.59 | -1.64 | 0.054 | 0.11 |

TABLE XIV
FUZZY LOAD FLOW SOLUTION FOR ″30-Bus″ IEEE SYSTEM ACTIVE AND REACTIVE POWER FLOWS

| Line No. | Line Termi nals | From Bus Power Inj. | | To Bus Power Inj. | | Loss P(MW) | Loss Q(MVAR) |
|---|---|---|---|---|---|---|---|
| | | P (MW) | Q (MVAR) | P (MW) | Q (MVAR) | | |
| 1 | 1-2 | 173.84 | -3.279 | -168.67 | 12.961 | 5.164 | 9.682 |
| 2 | 1-3 | 88.013 | 9.421 | -84.842 | -2.216 | 3.171 | 7.206 |
| 3 | 2-4 | 43.511 | 3.618 | -42.483 | -4.297 | 1.028 | -0.679 |
| 4 | 3-4 | 82.442 | 1.016 | -81.567 | 0.644 | 0.876 | 1.659 |
| 5 | 2-5 | 82.533 | 6.827 | -79.484 | 1.705 | 3.049 | 8.532 |
| 6 | 2-6 | 60.932 | 4.754 | -58.885 | -2.382 | 2.046 | 2.372 |
| 7 | 4-6 | 70.455 | -13.554 | -69.455 | 6.685 | 1.000 | -6.869 |
| 8 | 5-7 | -14.71 | 10.716 | 14.882 | -12.283 | 0.166 | -1.567 |
| 9 | 6-7 | 38.075 | -1.834 | -37.682 | 1.383 | 0.393 | -0.451 |
| 10 | 6-8 | 29.568 | -3.308 | -29.478 | 2.800 | 0.108 | -0.507 |
| 11 | 6-9 | 26.713 | -4.818 | -26.713 | 6.307 | 0 | 1.489 |
| 12 | 6-10 | 15.181 | 3.434 | -15.181 | -2.149 | 0 | 1.284 |
| 13 | 9-11 | 0 | -22.717 | 0 | 23.737 | 0 | 1.020 |
| 14 | 9-10 | 26.713 | 16.410 | -26.713 | -15.383 | 0 | 1.027 |
| 15 | 4-12 | 45.996 | 15.608 | -45.996 | -10.383 | 0 | 5.225 |
| 16 | 12-13 | 0.000 | -20.302 | 0.000 | 20.831 | 0 | 0.530 |
| 17 | 12-14 | 8.286 | 3.543 | -8.194 | -3.353 | 0.092 | 0.191 |
| 18 | 12-15 | 18.716 | 11.447 | -18.424 | -10.871 | 0.292 | 0.576 |
| 19 | 12-16 | 7.793 | 8.194 | -7.682 | -7.961 | 0.111 | 0.233 |
| 20 | 14-15 | 1.994 | 1.753 | -1.980 | -1.739 | 0.015 | 0.013 |
| 21 | 16-17 | 4.182 | 6.161 | -4.154 | -6.058 | 0.028 | 0.102 |
| 22 | 15-18 | 6.628 | 4.052 | -6.566 | -3.925 | 0.063 | 0.127 |
| 23 | 18-19 | 3.366 | 3.025 | -3.353 | -2.999 | 0.013 | 0.026 |
| 24 | 19-20 | -6.147 | -0.401 | 6.160 | 0.427 | 0.013 | 0.026 |
| 25 | 10-20 | 8.427 | 1.277 | -8.360 | -1.127 | 0.067 | 0.149 |
| 26 | 10-17 | 4.853 | -0.239 | -4.846 | 0.258 | 0.008 | 0.020 |
| 27 | 10-21 | 15.430 | 9.940 | -15.315 | -9.692 | 0.115 | 0.248 |
| 28 | 10-22 | 7.384 | 4.554 | -7.330 | -4.443 | 0.054 | 0.111 |
| 29 | 21-22 | -2.185 | -1.508 | 2.186 | 1.510 | 0.001 | 0.002 |
| 30 | 15-23 | 5.575 | 6.058 | -5-510 | -5.926 | 0.065 | 0.132 |
| 31 | 22-24 | 5.144 | 2.934 | -5.103 | -2.871 | 0.041 | 0.063 |
| 32 | 23-24 | 2.310 | 4.326 | -2.278 | -4.261 | 0.032 | 0.065 |
| 33 | 24-25 | -1.319 | 0.432 | 1.322 | -0.425 | 0.004 | 0.007 |
| 34 | 25-26 | 3.548 | 2.371 | -3.500 | -2.300 | 0.048 | 0.071 |
| 35 | 25-27 | -4.870 | -1.946 | 4.901 | 2.005 | 0.031 | 0.059 |
| 36 | 28-27 | 18.200 | 6.805 | -18.200 | -5.368 | 0 | 1.437 |
| 37 | 27-29 | 6.197 | 1.683 | -6.106 | -1.51 | 0.091 | 0.173 |
| 38 | 27-30 | 7.101 | 1.68 | -6.930 | -1.357 | 0.172 | 0.323 |
| 39 | 29-30 | 3.706 | 0.61 | -3.67 | -0.543 | 0.036 | 0.067 |
| 40 | 8-28 | -0.522 | -0.651 | 0.523 | -3.528 | 0.002 | -4.179 |
| 41 | 6-28 | 18.785 | 2.222 | -18.723 | -3.276 | 0.062 | -1.054 |

## XI. 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 affect 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.

## XII. CONCLUSIONS

In this paper, Fuzzy Logic was used efficiently to solve the load flow problem under different loading/contingency conditions with power loss calculations in each branch of the used three systems due to its following merits:

1. The performance of 14-bus, 30-bus IEEE systems and the 362-bus EING 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
3. All these features and other conclusions reveal that these systems seem to be electrical smart grid in many issues.

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. 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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