A Real-Time Fuzzy Load Flow and Contingency Analysis Based on Gaussian Distribution System

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ABSTRACT

Fuzzy logic is used to solve the load flow and contingency analysis problems, so decreasing computing time and its the best selection instead of the traditional methods. The proposed method is very accurate with outstanding computation time, which made the fuzzy load flow (FLF) suitable for real time application for small- as well as large-scale power systems. In addition that, the FLF efficiently able to solve load flow problem of ill-conditioned power systems and contingency analysis. The FLF method using Gaussian membership function requires less number of iterations and less computing time than that required in the FLF method using triangular membership function. Using sparsity technique for the input Ybus sparse matrix data gives reduction in overall computation time and storage requirements. The performance of the used methods had been tested on two typical test systems being the IEEE 14-bus and 30-bus systems in addition to the 362-bus Iraqi National Grid. All the obtained results under normal operating conditions show that the computation time of the fuzzy Load Flow (FLF) is less than the fast decoupled load flow (FDLF).

Keywords: Fast decoupled method, Fuzzy Load Flow, Fuzzy Contingency Analysis, Fuzzy Logic.

الحل اللحظي لمسألة سريان الحمل وتحليل الاضطرابات على اسس المنطق المضبب باستخدام دالة الكاوسين

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الخلاصة

تم في هذا البحث اقتراح طريقة لحساب مسألة سريان الاحمال و تحليل الاضطرابات أنيا في منظومات القدرة الكهربائية باستخدام نظرية المنطق المضبب. الطرق العددية غير كفوؤة لحل مسألة سريان الاحمال و تحليل الاضطرابات وذلك لان شبكات القدرة الكهربائية اصبحت اكثر تعقيد. لذا, فأن استخدام نظرية المنطق المضبب للحل هي البديل الافضل وذألك لعدم اعتمادها على خصائص المسألة. تم اختبار الطريقة المقترحة على منظومة قدرة قياسية و تمت مقارنة النتائج المتحصلة مع نتائج الحل باستخدام الطرق العددية لحل مسألة سريان الاحمال بهدف التحقق من صحة وثوقيه الطريقة المقترحة للعمل على الشبكة الوطنية العراقية. اوضحت النتائج باستخدام الطريقة المقترحة خاصية الحل اللحظي بما يوصى باستخدامها في انظمة القدرة صغيرة و كبيرة الحجم بالإضافة الى الامكانية التطبيقية لظروف عمل اعتيادية و طارئة.

الكلمات المفتاحية: المنطق المضبب, حل مسألة سريان الاحمال و تحليل الاضطرابات باستخدام المنطق المضبب.

1. INTRODUCTION

The load flow problem is one of the basic problems in the field of power system engineering. The development of numerical methods to solve the load flow problem has been continuing for many years. One of the most common computational procedures used in power system analysis is the load flow calculations **Grisby, 2012**.

The mathematical model of load flow problem is a set of non-linear simultaneous equations. The solution for these equations can be implemented using iterative methods, the traditional methods of repeating the solutions became inefficient as need a lot of calculations at any iteration so that the computational time will be large **Kubba, 1987**.

Contingency Analysis behaves like a fictitious test performs on a list of postulated contingency cases (single or multiple outages). The most important simulation of contingency analysis is to give the operators an indication of what might happen to the power system if an event occurs. The contingency analysis is time consuming as it involves the computation of complete AC load flow calculations following every possible outage events like outages occurring at various generators and transmission lines **Mishra and Khardenvis, 2012**.

Uncertainty is one of the most important issues in power system planning when decisions are made regarding the future system expansion and operation. The uncertainties in the power system come from the errors in input data of the power systems due to error in measurements and errors in the load demand for the system load buses **Grisby, 2012**.

In trying to include uncertainty into the solution process, analysis have tried different approaches. 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 **Tomsovic, et al., 1995**.

A brief survey of solving the load flow problem and contingency analysis by the fuzzy logic theory,

J.G. Vlachogiannis, made a new FLF method based on fuzzy logic controller (FLC) to solve the load flow problem using triangular membership functions to represent the fuzzy input and fuzzy output signal of the FLC **Vlachogiannis, 2001**. P. K. Satpathy, et al., proposed the fuzzy set theory that has been implemented for performing the power flow analysis in a fuzzy environment. A trapezoidal fuzzy membership function has been selected for this purpose **Satpathy, 2004**. P.Gajalakshmi and S.Rajesh, proposed fuzzy logic based power flow method. The input signals are fuzzified into corresponding fuzzy signals and output fuzzy signals represented in triangular membership function **Gajalakshmi and Rajesh, 2007**. P. Acharjee and Kawsar Ali, proposed the decoupled fuzzy load Flow, the fuzzy load flow algorithm (FLF) has been built up considering the decoupling properties of the power flow variables. Both power mismatche and summation of power mismatche are taken as two inputs for fuzzy logic controller **Acharjee and Ali, 2011**. K. L Lo and A. K. I. Abdewlall, applied fuzzy logic on contingency selection for voltage ranking **Lo and Abdewlall, 2000**. A.Y.Abdelaziz, et al., presented Fuzzy logic based algorithm for contingencies ranking **Abdelaziz, et al., 2013**. A load flow solution and contingency analysis methods based on the fuzzy control theory is developed in this paper. The proposed method is demonstrated on the IEEE 14 buses and 30 buses typical test systems and Iraqi National Grid for different normal and contingent operating conditions.

2. FUZZY LOGIC

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. The traditional way of representing elements u of a set A is through the characteristic function. **Zimmermann, 1996** :

$$\mu_A(u) = 1 \qquad \text{if } u \text{ is an element of the set } A \tag{1}$$

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

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:

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

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 **Lee, 2005**.

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 method, fuzzification and defuzzification methods if necessary.

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 **Zimmermann, 1996**.

3. SOLUTION OF THE LOAD FLOW PROBLEM

3.1 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 **Stott and Alsac, 1974**. 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 J_2 and J_3 Jacobian sub matrices due to the weak coupling between ″P-V″ and ″Q-δ″ quantities in power transmission system. Together with other approximations, the fast decoupled load flow equations become **Vlachogiannis, 1994**:

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

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

4. PROPOSED FUZZY LOAD FLOW METHOD

The fuzzy power flow equations are derived from fast decoupled load flow set of equations, being Eq. (4) and (5) respectively. In Eq. (4), the state vector δ is updated but state vector V is fixed. Eq. (5) is used to update the state vector V while state vector δ 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

$$\Delta F = B * \Delta X \tag{6}$$

The last 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 is being performed using fuzzy logic control instead of using the classical load flow approach. This can be expressed by

$$\Delta X = fuz(\Delta F) \tag{7}$$

Where fuz represents a fuzzy logic function.

The FLF algorithm is illustrated schematically in **Fig. 1** that the power parameters ΔF_P and ΔF_Q are calculated and introduced to the $P - \delta$ fuzzy logic controller FLC$_{P\text{-}\delta}$ 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 $\Delta\delta$ for the $P - \delta$ cycle and the correction of voltage magnitude ΔV for the $Q - V$ cycle.

The proposed fuzzy load flow controller (FLFC) has a structure that may be traced easily in **Fig.2** that comprises four principal components: a fuzzification interface, a rule base, process logic and a defuzzification interface. The fuzzification interface involves the following functions during iteration:

1. Calculate and per unit the power parameters ΔF_P and ΔF_Q at each bus of the system.
2. 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.
3. The input signals are fuzzified into corresponding fuzzy signals ($\Delta F_{P\text{fuz}}$ or ΔFQ_{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) **Vlachogiannis, 2001.** They are being represented in Gaussian membership function forms. **Fig.3** gives sketches of these membership functions. Each two points (width and center) are designed. These seven linguistic variables are designed by two points (width and center): 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 : [$2\Delta F_m/3$, ΔF_m].

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

Rule 1: if ΔF_{fuz} is LN then ΔX_{fuz} is LN, Rule 2: if ΔF_{fuz} is MN then ΔX_{fuz} is MN

Rule 3: if ΔF_{fuz} is SN then ΔX_{fuz} is SN, Rule 4: if ΔF_{fuz} is ZR then ΔX_{fuz} is ZR

Rule 5: if ΔF_{fuz} is SP then ΔX_{fuz} is SP, Rule 6: if ΔF_{fuz} is MP then ΔX_{fuz} is MP

Rule 7: if ΔF_{fuz} is LP then ΔX_{fuz} is LP

4. Design of these fuzzy rules is based upon two observations. The first of them is that when the computed value obtained in each 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 Eq. (7) at every iteration **Lo K., et al., 1999**.

5. 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:

$$\Delta X_{max} = \left(\frac{df_I}{dx_I}\right)^{-1} * \ \Delta F_{\text{max}\,I} \tag{8}$$

Where F_I expresses the real or reactive power balance equations at bus-I with maximum real or reactive power mismatches of the system, X_I represents the voltage angle or magnitude at bus-I **Vlachogiannis, 2001**. Therefore, each two points (width and center) of the Gaussian membership functions of ΔX_{fuz} is designated in a similar way to **Fig.3** as may be shown in **Fig.4**. Hence, the output fuzzy membership classes are redesigned in similar way to **Fig.2** and 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 : [$2\Delta X_m/3$, ΔX_m].

Finally, the defuzzifier will transform fuzzy output signals ΔX_{fuz} into crisp values ΔX for every bus of the network. The centroid-of-area (COA) defuzzification strategy is being adopted. This strategy finds the geometrical center *Zo* in the universe *C* of an output variable *Z*, which center ″balances″ the inferred membership function μ_C (z) as a fuzzy value for *Z*. The following formula is used **Ross, 2010**.

$$Zo = \frac{\sum_{i=1}^{n} \mu_c(Zi) * Zi}{\sum_{i=1}^{n} \mu_c(Zi)} \tag{9}$$

The second method is the Mean-of-Maxima (MOM), Sugeno method; this method finds the value *Zo* which has μ_C $(z)_{\text{max}}$ is the maximum membership degree according to the fuzzy output variable Z. The following formula is used

$$Zo = \sum_{i=1}^{n} \frac{\mu_c(Zi) max}{k} \tag{10}$$

and the state vector is being updated as

$$X^{i+1} = X^i + \Delta X \tag{11}$$

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.

5. IMPLEMENTATION RESULTS

The FLF method was implemented on the IEEE 14 buses shown in **Fig.5** and 30 buses typical test systems in 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 condition with power mismatch of (0.001 p.u, equivalent to 0.1 MW/MVAr).
2. Single-line, double-line, and triple-line outage with power mismatches of 0.001 p.u.
3. Single generator outage with power mismatches of (0.001 p.u.).
4. Overload of the active power demand of a load (PQ) bus in percentage of 125% of rated bus load demand with power mismatches of 0.001 p.u.
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. Robustness of the proposed method is studied in the later step.

The obtained results are exhibited in the **Table.1** for 14 Buses IEEE Typical Test System, Power Mismatches (Active / Reactive) = 0.001per unit (0.1 MW/MVAr), Normal Condition.

For contingent conditions (Single, Double and Triple-lines out of the service) the required number of iterations and the total computation time increases by a considerable amount. The FLF solution using GMF at these types of contingent conditions is remained sufficient for on-line operation. In a single-line outage, the line connecting buses (1) and (5) was brought out-of-service. In double-lines outage case, the lines connecting buses (1) and (5), and buses (4) and (9) were brought-of-service. The last case of line outages is the triple-lines outage. In this case, lines connecting buses (2) and (4), (7) and (8), and (10) and (11) were the faulty lines in respective order.

Tables.2 through **4** shows the results of the FLF solutions with (single, double and triple) lines outage using GMF. The required number of iterations and the total computation time increases by a considerable amount for contingent conditions (Single, Double and triple-lines out of the service). The importance of these studies is to know whether the system voltage magnitudes and voltages phase angles cross their limits (±5%) or not, causing unstable operation of the system or not.

Table.5 shows the system′s performance when the FLF algorithm using GMF is implemented under contingent operation of single generator outage. In this step, generator at bus number 3 was brought out-of-service. A generator outage is meant that its voltage magnitude, voltage angle, generated active/ reactive powers are all set to zero. It is noted that even with the voltage magnitude and voltage angle set initially to zero for the faulty generator bus, the final values of the voltage magnitude and angle of the faulty bus after the load flow calculations are implemented include non-zero values in the both cases.

This may be explained by assuming that the system tries to compensate for the lost generator voltage to keep the normal operating point unchanged as possible. For a contingent operation of two generators outage, the solution diverged. It means that the system could not compensate for the lost of two generators voltage to keep the system in a stable condition. It can be seen that FLF algorithm using GMF is faster from the other.

To explore the performance of the FLF algorithm using GMF under conditions of over-loading bus, the active power demand of load bus number (13) was increased. In the first case, the active power demand was increased from 13.5 MW to 16.875 MW, i.e. an increment by 25% above the rated load. The test results of these studies are presented in **Table.6** for 14-bus IEEE system for the FLF algorithm.

The FLF success to solve ill-conditioned power systems by adding a series capacitor of capacitive reactance 0.04 p.u on the same bases to branches connecting buses (2) and (3), (4) and (7), as well as

(7) and (9).The results are show in the **Table.7**. The FLF based on GMF was converged without facing any problems.

From **Tables.1 to 7**, it is concluded that the total computing time for load flow solution is the least in case of normal operating condition. As well as the number of iterations for most contingent conditions is larger than the normal condition. But, the time per iteration for the latter cases is too much such that the overall computing time is more than the normal operating condition. These depend on the configuration of the network and the type and location of faulted elements. These were demonstrated from the tables.

Implementing the fuzzy load flow method on the 362 buses Iraqi National Grid(two main connection grids: 132 and 400 KV connection grids) gave satisfactory results for both voltage magnitudes and angles. For a power mismatch of 0.001, the total time required to obtain a solution was about 1.0628 seconds with an iteration number of 25. Due to huge tabulations of the Iraqi National Grid results, they are omitted and not shown in this paper.

The FLF method based on GMF is faster and more accurate than TMF for on-line applications, planning as well as control of electrical power systems. The total computing time and number of iterations of the FLF algorithm based on GMF are less than FLF algorithm based on TMF for load flow solutions under normal and contingent conditions.

Table.8 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 normal conditions. From the table, it can be observed that FLF requires more iteration as compared to FDLF and NR methods for the tested systems. However, the total computation time is much less than FDLF and NR method. In the table, the % computation time is taken relative to NR method.

Table.9 illustrates the reduction in computational time and storage requirements for different power systems by using the proposed fuzzy load flow method using Gaussian function with sparsity technique. The reduction in computation time and storage requirements increases as the matrix density decreases. While the nodal admittance matrix is the main input data which is a sparse matrix.

Defuzzification interface is very important part of the FPF controller structure as it will transform fuzzy output signals ΔX_{fuz} into crisp values ΔX for all buses of the network. There are many defuzzification techniques but primarily only two of them are in common use, first the centroid-of-area (COA) defuzzification technique, secondly the Mean-of-Maxima Method (MOM) defuzzification techniques. These two defuzzification techniques are implemented. The comparison between them for major two criteria which are computational time and accuracy, are shown in **Table.10** shows that the defuzzification technique Mamdani-type (COA) is more accurate than the Mean-of-Maxima Method (MOM), Sugeno-type. The computing time required for both methods are comparably the same to providing the crisp output values.

6. CONCLUSION

A robust method based on the fuzzy logic controller to solving the load flow problem under normal and contingent conditions is presented and could be used as a base to incorporate all the modern power control strategies designed using fuzzy logic. All the obtained results 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.

Fuzzy Logic was used efficiently to solve the load flow problem due to its solution speed are simple and very fast, respectively. It simplifies the complexity of obtaining a solution by incorporating the uncertainties in input data processed. The proposed method provides faster solution; it can be implemented at real-time operation in electric power control centers having either small- or large-scale power system configurations on the IEEE 14 buses and 30 buses test system. In addition to the test system, the proposed method is tested on the 362 buses Iraqi National Grid to test its on-line characteristic.

The most important feature to mark is the capability of solving ill-conditioned cases of inserting series capacitors to certain lines of the transmission network. 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. The defuzzification strategy of the FLF method for both membership functions (Triangular and Gaussian) was implemented by using Center of Gravity (Centroid of Area) and the Mean-of-Maxima method, it is found that the first method is more accurate but the computing time is very slightly more. The reduction in overall computational time and storage requirements by using sparsity technique for the input sparse matrix data. All the points mentioned above recommend the use of the proposed method in power control centers.

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LIST OF SYMBOLS AND ABBREVIATIONS

ΔP: active power mismatch.
ΔQ: reactive power mismatch.
V : voltage magnitude
δ : voltage phase angle.
μ_A : membership function.
$\Delta\delta$: The correction of the voltage angle.
ΔV: The correction of voltage magnitude.
MOM: mean of maxima

FLFC: Fuzzy Load Flow Controller.
FLC : Fuzzy Logic Controller.
FLF : Fuzzy Load Flow
FDLF: Fast Decoupled Load Flow.
COA: Centroid of Area.

ΔF: real or reactive power mismatches per voltage magnitude vector
ΔX: correction of state vector (voltage angle or magnitude vector)
B': sparse-constant matrix of P- θ cycle
B'': sparse-constant matrix of Q- V cycle
B : represents either B' or B'' matrix

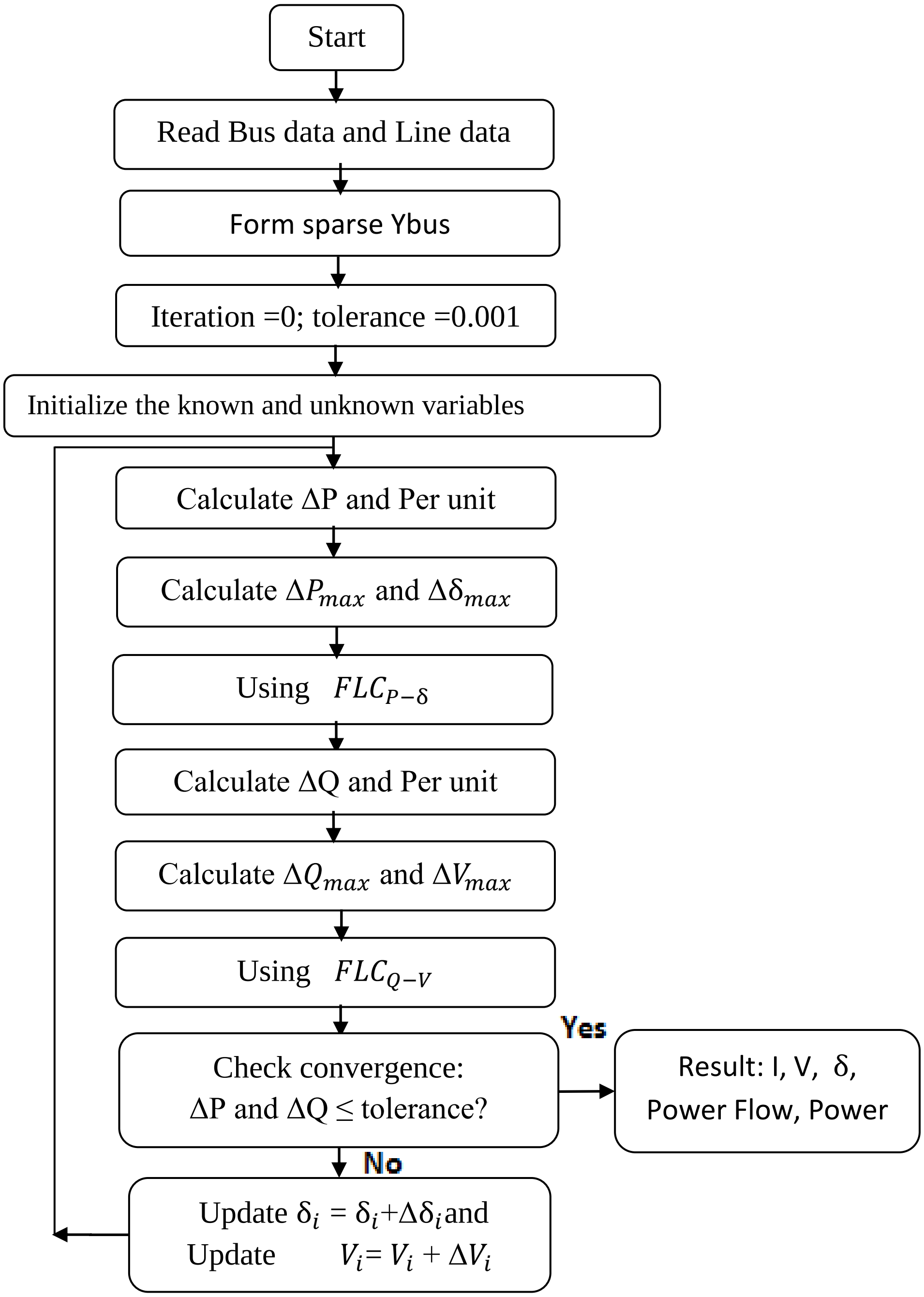

Figure1. Fuzzy Power flow algorithm.

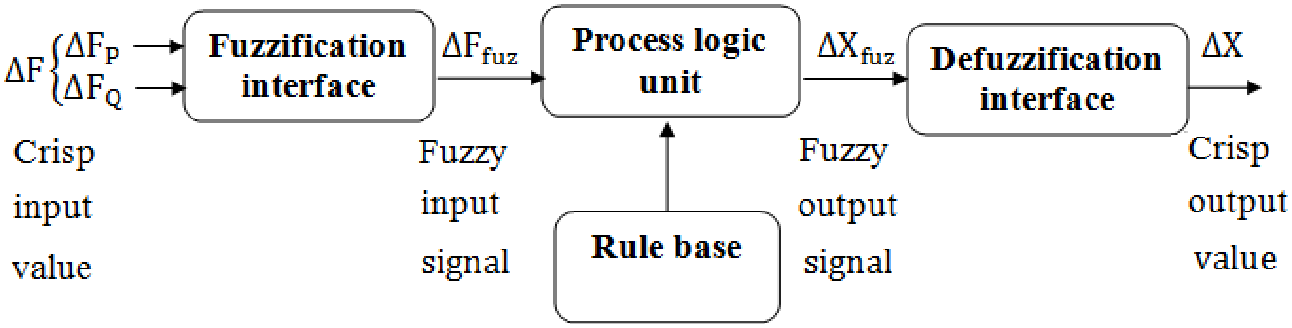

Figure2. Structure of the fuzzy load flow controller.

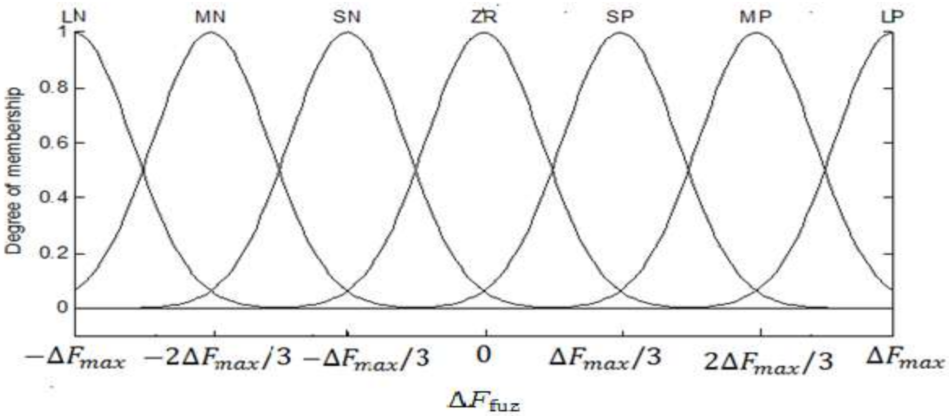

Figure3. Membership functions for input signals $\Delta F_{\text{fuz.}}$

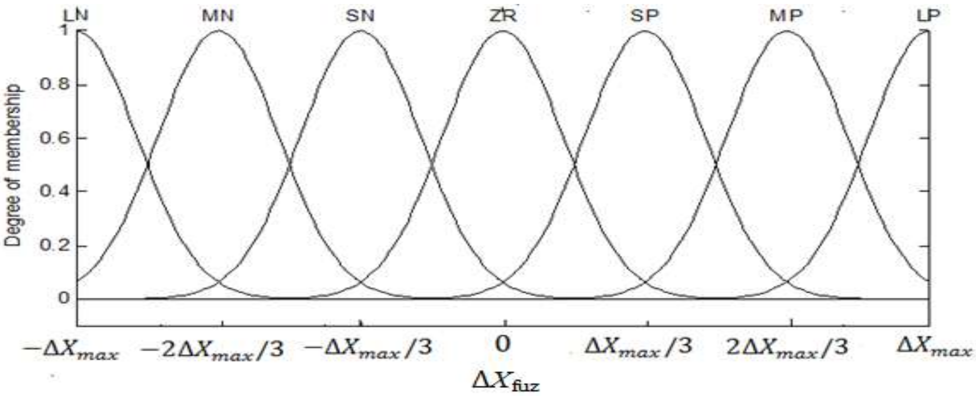

Figure4. Membership functions for output signals $\Delta X_{\text{fuz.}}$

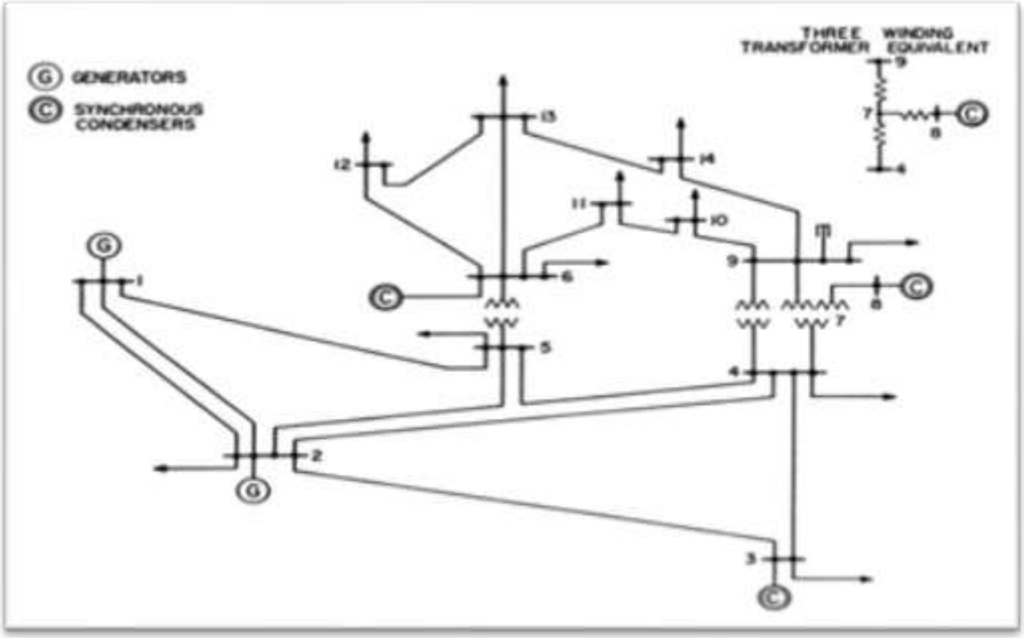

Figure5. Single-line Diagram of 14-Bus IEEE Test System.

Table1. Fuzzy load flow solution for 14 buses IEEE typical test system, power mismatches (Active / Reactive) = 0.001per unit (0.1 MW/MVAr), normal condition. Bus Type:(1: Stands for Slack bus; 2: Defines PV bus; 0: Defines PQ buses).

Bus Num.	Bus Type	Voltage Mag. (p.u.)	Voltage Angle (deg.)	ΔP (p.u)	ΔQ (p.u)
1	1	1.060	0.000	0.0	0.0
2	2	1.045	-3.734	0.000022	0.0
3	2	1.010	-9.929	0.000333	0.0
4	0	1.41	-8.341	0.000250	0.0009689
5	0	1.043	-6.156	0.000227	0.0009599
6	2	1.070	-5.836	0.000216	0.0
7	0	1.071	-6.691	0.000081	0.0004656
8	2	1.090	-6.424	0.000003	0.0
9	0	1.066	-8.390	0.000260	0.0000190
10	0	1.063	-6.823	0.000110	0.0001055
11	0	1.063	-7.406	0.000004	0.0000149
12	0	1.062	-7.543	0.000038	0.0000031
13	0	1.059	-6.994	0.000085	0.0000059
14	0	1.056	-6.433	0.000142	0.0000270
Number of iterations					9
Computation time					0.093410 sec

Table2. Fuzzy load flow solution for 14 buses IEEE typical test system, single-line outage.

Bus Num.	Bus Type	Voltage Mag.(p.u.)	Voltage Angle(deg.)	ΔP (p.u)	ΔQ (p.u)
1	1	1.060	0.000	0.0	0.0
2	2	1.045	-3.519	0.000003	0.0
3	2	1.010	-8.464	0.00025	0.0
4	0	1.037	-10.033	0.000219	0.000317
5	0	1.037	-9.761	0.000238	0.000950
6	2	1.070	-7.655	0.000236	0.0
7	0	1.073	-8.544	0.000110	0.000011
8	2	1.090	-8.456	0.000062	0.0
9	0	1.069	-10.661	0.000231	0.0000018
10	0	1.065	-8.745	0.000123	0.0000722
11	0	1.065	-8.634	0.000018	0.0000091
12	0	1.061	-9.888	0.000024	0.0000072
13	0	1.059	-9.149	0.000074	0.0000095
14	0	1.058	-8.204	0.000156	0.0000230
Number of iterations					10
Computation time					0.109894sec

Table3. Fuzzy load flow solution for 14 buses IEEE typical test system, double-lines outage.

Bus Num.	Bus Type	Voltage Mag. (p.u.)	Voltage Angle (deg.)	ΔP (p.u)	ΔQ (p.u)
1	1	1.060	0.000	0.0	0.0
2	2	1.045	-5.905	0.000021	0.0
3	2	1.010	-14.181	0.000187	0.0
4	0	1.035	-10.393	0.000188	0.000953
5	0	1.037	-10.390	0.000180	0.000974
6	2	1.070	-8.085	0.000184	0.0
7	0	1.072	-9.016	0.000133	0.000093
8	2	1.090	-8.587	0.000007	0.0
9	0	1.062	-10.807	0.000177	0.000015
10	0	1.063	-9.439	0.000153	0.000094
11	0	1.064	-9.773	0.000013	0.000060
12	0	1.061	-10.508	0.000048	0.000014
13	0	1.059	-9.742	0.000108	0.000064
14	0	1.056	-8.758	0.000155	0.000061
Number of iterations					11
Computation time					0.114429sec

Table4. Fuzzy load flow solution for 14 buses IEEE typical test system, triple-lines outage.

Bus Num.	Bus Type	Voltage Mag. (p.u.)	Voltage Angle (deg.)	ΔP (p.u)	ΔQ (p.u)
1	1	1.060	0.000	0.0	0.0
2	2	1.045	-6.685	0.000027	0.0
3	2	1.010	-14.327	0.000239	0.0
4	0	1.015	-12.175	0.000253	0.0009994
5	0	1.018	-14.287	0.000221	0.0001395
6	2	1.070	-12.706	0.000239	0.0
7	0	1.058	-13.951	0.000114	0.000032
8	2	1.090	-11.256	0.0	0.0
9	0	1.048	-11.152	0.000234	0.000023
10	0	1.054	-14.585	0.000118	0.000098
11	0	1.063	-15.410	0.000007	0.000008
12	0	1.050	-16.425	0.000031	0.000032
13	0	1.038	-15.174	0.000077	0.000031
14	0	1.041	-13.619	0.000152	0.000051
Number of iterations					12
Computation time					0.121348 sec

Table5. Fuzzy load flow solution for 14 buses IEEE typical test system, generator (3) outage.

Bus Number	Bus Type	Voltage Mag. (p.u.)	Voltage Angle (deg.)	ΔP (p.u)	ΔQ (p.u)
1	1	1.060	0.000	0.0	0.0
2	2	1.045	-4.425	0.000026	0.0
3	2	1.000	-0.000	0.000001	0.0
4	0	1.038	-10.844	0.000042	0.000285
5	0	1.040	-10.523	0.000009	0.000910
6	2	1.070	-9.436	0.000203	0.0
7	0	1.070	-9.797	0.000082	0.000068
8	2	1.090	-9.386	0.000005	0.0
9	0	1.065	-12.356	0.000189	0.000028
10	0	1.063	-9.124	0.000157	0.000085
11	0	1.062	-10.319	0.000055	0.000023
12	0	1.060	-11.118	0.000033	0.000015
13	0	1.058	-10.005	0.000097	0.000012
14	0	1.054	-9.747	0.000157	0.000006
Number of iterations					12
Computation time					0.128729 sec

Table6. FLF solution for 14 buses IEEE typical test system, 125% active power overloading.

Bus Num.	Bus Type	Voltage Mag. (p.u.)	Voltage Angle (deg.)	ΔP (p.u)	ΔQ (p.u)
1	1	1.060	0.000	0.0	0.0
2	2	1.045	-9.327	0.000008	0.0
3	2	1.010	-13.610	0.000426	0.0
4	0	1.030	-11.868	0.000264	0.000273
5	0	1.032	-13.216	0.000241	0.000847
6	2	1.070	-12.141	0.000213	0.0
7	0	1.064	-14.644	0.000083	0.000006
8	2	1.090	-13.855	0.000006	0.0
9	0	1.059	-16.505	0.000246	0.000016
10	0	1.055	-14.218	0.000120	0.000020
11	0	1.054	-14.653	0.000009	0.000016
12	0	1.061	-15.892	0.000025	0.000023
13	0	1.040	-13.651	0.000135	0.000024
14	0	1.049	-13.439	0.000144	0.000008
Number of iterations					9
Computation time					0.100163sec

Table7. FLF solution for 14 buses IEEE typical test system, Addition of Series Capacitance.

Bus Num.	Bus Type	Voltage Mag.(p.u)	Voltage Angle (deg.)	ΔP (p.u)	ΔQ (p.u)
1	1	1.060	0.000	0.0	0.0
2	2	1.045	-3.266	0.000038	0.0
3	2	1.010	-7.608	0.000213	0.0
4	0	1.039	-7.811	0.000210	0.000180
5	0	1.042	-6.683	0.000194	0.000992
6	2	1.070	-5.755	0.000216	0.0
7	0	1.072	-6.136	0.000133	0.000115
8	2	1.090	-5.928	0.000035	0.0
9	0	1.068	-7.945	0.000227	0.000047
10	0	1.065	-6.237	0.000135	0.000038
11	0	1.064	-7.030	0.000032	0.000411
12	0	1.061	-7.184	0.000037	0.000012
13	0	1.060	-6.580	0.000086	0.000031
14	0	1.058	-5.890	0.000156	0.000013
Number of iterations					16
Computation time					0.146616 sec

Table8. 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 GMF	FLF TMF	FDLF	N-R	FLF GMF	FLF TMF	FDLF	N-R
14-bus IEEE	9	16	3	4	8	19	32	100
30-bus IEEE	11	17	4	5	10	21	39	100
362-bus ING	28	34	7	8	12	22	51	100

Table9. 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	%Reduction in Storage Requirement (FLF With sparsity technique)
14-bus IEEE	17.34%	38%	55%
30-bus IEEE	78.8%	56%	69%
362-bus ING	0.628%	84%	88%

Table10. Comparison of reduction in computational time and accuracy requirement for different defuzzification technique methods.

Type of power system at normal condition	Fuzzy Load Flow Controller Structure using Defuzzification technique COA		Fuzzy Load Flow Controller Structure Using Defuzzification technique MOM	
	Computational Time	% Accuracy	Computational Time	% Accuracy
14-bus IEEE	0.093410 sec	80%	0.087745 sec	76%
30-bus IEEE	0.108791sec	74%	0.101423sec	68%
362-bus ING	1.062819 sec	65%	1.017269 sec	59%