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Load Flow Studies Using Intelligent Techniques: Review

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Abstract: Load flow studies are a vital tool for investigating best-operating conditions and proper future planning of power system network. All power system analysis calculations include load flow studies, which are probably the most significant and common. The load flow analysis is used to determine the magnitude and phase angle of the voltage at each bus, as well as the amount of real and reactive power flowing through each transmission system line. In order to solve non-linear load flow problems considering different constraints, several conventional and intelligent techniques have been developed. While conventional methods usually find a solution in a decent amount of time, they frequently involve numerical robustness issues, such as a narrow convergence region and an ill-conditioned system. The load flow analysis methods based on intelligent techniques do not rely on the starting values of the variables and perform better than conventional methods when the power system becomes highly stressed. This paper provides a comprehensive review of various intelligent techniques, such as Particle Swarm Optimization (PSO), Genetic Algorithm (GA), Fuzzy Logic (FL), Ant Colony Optimization (ACO), Artificial Neural Network (ANN), Artificial Bee Colony (ABC), and others, that are used under various defined conditions for load flow studies of various power system networks.

Keywords: Particle Swarm Optimization (PSO), Genetic Algorithm (GA), Fuzzy Logic (FL), Ant Colony Optimization (ACO), Artificial Neural Network (ANN), Artificial Bee Colony (ABC)

1. Introduction

An important and crucial technique for evaluating the steady-state operation of the power system is load flow analysis. It offers a significant contribution in the analysis of the best operating conditions and planning of possible potential power system expansion. Parameters such as the magnitude of bus voltages, voltage angles, real and reactive power have been evaluated by the load flow analysis, which is useful to determine power flow in various parts of the power system [1].

Traditional approaches such as Gauss Siedel [2], Newton Raphson [3] and Fast Decoupled load flow [4] techniques have been used for solving power flow problems of various kinds of power systems networks. Gauss Siedel load flow method is easy to implement and requires small computer memory. Whereas Newton Raphson method, which is widely accepted, least sensitive to the selection of the slack bus, requires fewer iterations and reasonable computational time to reach convergence. Elements of Jacobian have to be calculated in every iteration that requires larger computer memory space and complex calculations. Choice of a particular method is a compromise between various attributes such as accuracy, reliability, number of iterations, convergence speed, computational time and choice of the slack bus, etc.

The intelligent techniques have the advantage of tuning only a few parameters to reach the near-optimal solution with minimum computational time and high accuracy. Moreover, the intelligent load flow techniques do not require any derivative information and are insensitive to an initial value of the solution variable. This paper offers a comprehensive overview of the various human and swarm intelligence techniques such as Particle Swarm Optimization (PSO), Genetic Algorithm (GA), Fuzzy Logic (FL), Ant Colony Optimization (ACO), Artificial Neural Network (ANN) techniques were applied during 1991-2021 to the load flow analysis of various power system networks.

In recent years, many researchers have proposed various solutions in the field approaches to research, simulation, and modeling of power systems. However, most of the previously reported approaches applied traditional load flow algorithms in their application, which are complex in design, required large controlling parameters and sometimes failed to converge despite the existence of a feasible operating point. Only a few articles have been published that used intelligent techniques for load flow analysis in their specific applications. The purpose of this review work is to stimulate a study on numerous optimization approaches used for load flow analysis of power system networks to have a better knowledge of all applied methodologies.

2. Problem Formulation

Each bus is associated with four variables, namely the magnitudes and angles of bus voltages, real and reactive power. Out of the four variables at each bus, two are known and two are not known. Buses are categorized into three different groups, based on the variables specified, as shown in the following table.

Table 1. *Bus Classification.*

Bus Types	Specified Variables	Unknown Variables
Slack Bus	Magnitude and phase angle of bus voltage	Real and reactive powers
Generator Bus (PV)	Bus voltages magnitudes and real powers (limit on reactive powers)	Bus voltage phase angles and reactive powers
Load Bus (PQ)	Real and reactive powers	Magnitudes and phase angles of bus voltages

The complex power injected to any bus is given by:

$$S_i = P_i + jQ_i = V_i I_i^* = V_i \sum_{j=1}^{n} V_j \, e^{j\delta_{ij}(G_{ij} - B_{ij})} \quad (1)$$

Breaking the real and imaginary part of the complex power are given by:

$$P_I = f_i(\delta, V) = V_i \sum_{j=1}^{n} V_j \left(G_{ij} Cos(\delta_i - \delta_j) + B_{ij} Sin(\delta_i - \delta_j) \right) \quad (2)$$

$$Q_i = g_i(\delta, V) = V_i \sum_{j=1}^{n} V_j \left(G_{ij} Cos(\delta_i - \delta_j) + B_{ij} Sin(\delta_i - \delta_j) \right) \quad (3)$$

Where $i = 1, 2, 3, 4 \ldots \ldots, n$

where G_{ij} is the conductance between i^{th} and j^{th}bus

and B_{ij} is the susceptance between i^{th} and j^{th}bus

The equations above require iterative methods, taking into account the following constraints, to reach a load flow solution.

(A) Subject to equality constraint:

$$\sum_{i=1}^{n} P_{G_i} - P_{demand} - P_{loss} = 0 \quad (4)$$

$$\sum_{i=1}^{n} Q_{G_i} - Q_{demand} - Q_{loss} = 0 \quad (5)$$

Where P_{G_i} and Q_{G_i} represent active and reactive power generation at i^{th} bus, P_{demand} and Q_{demand} represent system's total active and reactive power demand, P_{loss} and Q_{loss} represent total active and reactive power losses in the system respectively.

(B) Subject to inequality constraints:

$$V_{min} \leq V \leq V_{max} \quad (6)$$

$$\delta_{ij} \leq \delta_{ijmax} \quad (7)$$

$$P_{G_{imin}} \leq P_{G_i} \leq P_{G_{imax}} \quad (8)$$

$$Q_{G_{imin}} \leq Q_{G_i} \leq Q_{G_{imax}} \quad (9)$$

3. Intelligent Techniques for Load Flow Analysis

This section provides a detailed review of load flow analysis related research work using some of the intelligent techniques such as GA, PSO, AC, Fuzzy Logic, ANN and hybrid techniques done by various researchers.

3.1. Load Flow Using GA

GA [5] is an evolutionary search algorithm focused on Charles Darwin's theory of natural evolution and selection. There are five phases in optimization through GA i.e. Initial population, fitness function, selection, crossover and mutation. Many researchers have successfully used the GA in power flow studies of the power system.

X. Yin et al. [6] applied a simple GA based load flow method to solve load flow problems that do not require any auxiliary or derivative calculations. In the objective function, an additional term (penalty factor) was added for load flow analysis by the proposed methodology. Klos-Kerner three bus systems and Ward-Hale six bus systems were used as a test system for the load flow studies. An adaptive GA technique with a sharing function has also been used for investigating all possible solutions and found out to be more promising. However, the computational method was found to be more time-consuming.

K. P. Wong et al. [7] applied a Constrained GA based power flow technique. The IEEE 30, 57 and 118 bus systems were chosen for implementation and evaluation of the proposed technique. This technique has also been used to assess the transmission system's loading limits. A nodal voltage differential method and a gradient approach have been integrated into the proposed load flow method to accelerate the computational process.

H. A. Kubba et al. [8] implemented Real Coded GA (RCGA) load flow method on five bus system and a 362-bus Iraqi National Grid system and it was recommended by the authors that the proposed method can be used in small power system for online load flow problems and in large power system for planning studies. Reduced computational efforts and higher precision can be obtained by taking a suitable decision in the choice of number of bits required for the solution.

S. S. Shrawane et al. applied [9] an RCGA load flow method on five different topologies of the three bus system. Compared to the conventional Gauss Seidel load flow technique, the number of iterations needed was found to be lower in finding global minima.

H. Udatha et al. implemented [10] an RCGA with two crossover techniques, namely arithmetic and heuristic on three buses, five buses and six buses system. Two new offspring were produced with the help of two parent chromosomes using a random number before each crossover operation in the arithmetic crossover technique. In the heuristic crossover technique, the offspring chromosomes were generated from taking account of fitness ratio and distance between the parent chromosomes. The results were found similar as by NR load flow method.

3.2. Load Flow Using PSO

PSO [11] is a population-based swarm intelligence strategy that was introduced by Dr. Kennedy and Eberhart for the first time in 1995. PSO has been effectively implemented to various problems of real-world optimization inspired by bird flocking and fish schooling's social behavior.

P. Acharjee et al. [12] applied a Chaotic PSO (CPSO) based load flow technique for power flow studies. On standard and ill-conditioned IEEE 14, 30, 57 and 118 bus test systems. The performance and efficiency of the CPSO based load flow technique have been evaluated. The proposed technique was found to be reliable and more effective than NRLF in critical conditions like heavy loading of line high R/X ratio. The proposed technique required a fewer number of iterations when population size was increased. However, they found the performance of the proposed technique to be sluggish like other population based optimization methods.

S. Mehfuz et al. implemented [13] a PSO based two-dimensional search on IEEE 14 bus, which was simulated in ETAP. The PSO toolbox was used for the optimization of bus voltages magnitudes and angles. Total of 20 initial positions was taken at the start of the search and after each iteration, search area and inertia weight was reduced. Results calculated from proposed method were compared to traditional NRLF, GSLF and FDLF methods. The standard deviation for the magnitude of bus voltages and angles had been calculated, which showed the closeness in results obtained between the proposed and traditional methods.

D. Saini et al. used [14] PSO based power flow technique for optimal placement of STATCOM. The STATCOM was placed as a controllable voltage source in line to enhance the voltage profile in the test bus system. Various parameters in the PSO algorithm were adjusted to obtain the reduced real power loss by placing the STATCOM in the test system.

P. Ghosh et al. [15] implemented a PSO based load flow technique to reduce the power loss in the IEEE 14 and 30 bus test systems. The proposed technique's findings were compared to standard NRLF results. The line losses were found to be less by the proposed technique as compared to the traditional NRLF method.

3.3. Load Flow Using ACO

Initially introduced in his doctoral thesis by Marco Dorigo in 1992 and motivated by the actions of real ants, ACO [16] technique has been applied successfully to various combinatorial optimization problems.

J. G. Vlachogiannis et al. [17] used an ACO based load flow technique on IEEE 14 and 136 bus for constrained load flow analysis. The load flow problem was formulated as a combinatorial optimization problem. Total 41 operating conditions consisting different generation and load patterns were randomly created over whole planning period while satisfying all constraints for the power flow study. The authors found the proposed algorithm to be superior and flexible compared to probabilistic constrained load flow and Q-learning method. They also implemented the proposed technique on IEEE 14 bus for reactive power control under different operating constraints to reduce active power losses.

Y. Kumar et al. [18] proposed an ACO algorithm based load flow technique which was applied on IEEE 10, 13, 33 and 173 bus systems. The authors suggested that this proposed algorithm can also be used for power system networks containing FACTS devices. The computational time was found to be less than that of NRLF.

K. Upamanyu et al. [19] implemented an ACO based load flow algorithm on IEEE 30 bus. The proposed algorithm used a pheromone updating function to find the optimal transformer tap settings for minimizing power loss. In contrast to the traditional NRLF, the proposed algorithm yielded fewer iterations to reach the optimum solution. However, it was discovered that the constants of the pheromone updating function were highly dependent on the test system to which they were applied, which was a major flaw in the proposed algorithm. Hence applying them to any system directly is not feasible because it would result in an increase in the number of iterations and a decrease in accuracy.

3.4. Load Flow Using Fuzzy Logic

Lotfi A. Zadeh [20], in his research work “Fuzzy Sets” in 1965, proposed Fuzzy Logic, which is widely used in solving various optimization problems.

K. L. Lo et al. [21] adjusted various parameters like transformer tap position, line impedance and phase angle using fuzzy logic to meet the several constraints in load flow studies. FACTS devices like TCSC, TCPS, UPFC and OLTC were incorporated in the power system network for parameter adjustment. The proposed approach was implemented basically to assist convergence in power flow studies.

J. G. Viachogiannis [22] developed and implemented a new fuzzy based load flow (FLF) algorithm on 3 and 6 bus systems. Test systems were chosen for the load flow studies ranges from 3 bus systems to 1847 bus systems. The real and reactive power mismatches per voltages have been taken as crisp input values. CPU time for the power flow analysis of various test systems by the proposed algorithm was calculated and compared with the FDLF method. It showed that the proposed method was faster than the FDLF method by 10.2 times for the 1847 bus system and 2.8 times for the 3 bus systems.

P. R. Bijwe et al. [23] applied a fuzzy load flow method on six bus and modified IEEE 30 bus considering limits on reactive power at voltage controlled bus with multiple uncertainties. According to a given vary of uncertain variables and a range of dependent variables and functions could be defined by the proposed method rather than taking crisp data to solve the load flow problem.

P. Acharjee et al. [24] implemented a decoupled fuzzy power flow method on IEEE 14, 30, 57 and 118 bus system. The proposed algorithm utilizes the decoupling properties with the fuzzy approach to overcome the poor performance of traditional load flow methods in critical conditions like a line with higher R/X ratio and heavy loading.

H. A. Kubba et al. [25] applied the fuzzy based load flow method with Gaussian membership function on IEEE 14, 30 and Iraqi 362 bus system. Compared to the fuzzy load flow method with a triangular membership function and FDLF, this suggested method needed lesser iterations and computational time.

3.5. Load Flow Using ANN

ANN [26] inspired by biological neural networks has been successfully applied in various areas of power systems.

Leonardo Paucar et al. [27] applied an ANN based power flow technique on IEEE 30 bus systems. This proposed technique adopted Levenberg Marquardt second order algorithm to train multilayer perceptrons neural network. A total of 583 power flow cases were produced, 351 of which were selected for training and 232 of which were for testing the proposed load flow technique.

A. Jain et al. [28] used Back-propagation and Quickprop algorithms for training neural networks in ANN based stochastic load flow analysis. The sum of square error is minimized in the training of both the algorithm. A five bus system was chosen as a test system. Confidence limit in the outputs (voltage magnitudes, voltage angles and power flows) were calculated by both methods and compared to the traditional stochastic power flow method. The results obtained were found similar up to the second digit of the decimal.

J. Krishna et al. [29] used two Counter Propagation Neural Network (CPNN) to solve load flow problems. The two neural networks CPNN1 and CPNN2 were developed and trained to compute magnitudes and angles bus voltage, respectively. The IEEE 14 bus system was used as a test system, and the proposed load flow method's findings were compared to those of conventional NRLF. An absolute error of approx 1% was found in bus voltage magnitudes and bus voltage angles after computation by the proposed load flow method.

A. Karami et al. [30] used a Radial Basis Neural Network (RBFNN) with hybrid unsupervised and supervised training method for load flow analysis. The 39 bus New England test system has been chosen for load flow analysis and results were compared with the Multilayer Perceptrons (MLP) neural network load flow method. The mean squared error and the training time were found lesser in RBF NN as compared with MLP NN.

H. H. Müllera et al. [31] proposed an artificial neural network based load flow method that is comprised of MLP neural network trained with 2nd order Levenberg Marquardt algorithm. The standard IEEE 30 bus, 57 bus and an ill-conditioned 11 bus systems were chosen for the evaluation of the proposed load flow method. Several normal and contingency conditions, including various generation loading conditions, were considered. The maximum and mean error of bus voltages magnitude and angles were calculated for the different test systems.

S. Berat et al. [32] used a Back-propagation feed-forward ANN technique for power flow studies. To implement the proposed technique, a five bus test system was designed. Fifty active and reactive power values were taken for the training of the proposed neural network. The difference between the results achieved by the proposed technique and the GSLF technique for bus voltage magnitudes and angles was calculated. That showed the proposed technique worked properly while satisfying all the convergence limits.

M. Suresh et al. [33] proposed an RBFNN and Multilayer feed-forward ANN with Back Propagation algorithm to solve power flow problems of distribution network. For the implementation of the proposed load flow technique, the 15 bus and 33 bus distribution systems have been chosen as a test system. Mean squared error in bus voltage magnitude under different loading conditions was calculated for both the test systems. Results showed that the feed-forward network with the Back Propagation algorithm was more accurate and required less time for computation than the Radial Bias function network.

V V S Bhaskara Reddy et al. [34] proposed a Multilayer feed forward ANN based load flow method for the distribution system. The proposed method was applied on 10-node unbalanced and 33-node balanced test distribution system networks. Two training patterns were developed for distribution load flow studies, first by increasing the loads from 80% to 120% of the base load in small steps and second by randomly varying the load between ±20 percent to the base load at all the buses. Results calculated from the proposed load flow method were comparable with the forward/ backward sweep distribution load flow method.

Wael Abdullah Alsulami [35] proposed a Multilayer feed-forward ANN for a power flow analysis of the power system. Error Back-Propagation Learning method was applied to train the proposed ANN load flow method at various load levels. Four random sets of data consisting of 72 active power and 72 reactive power values were used to test and validate the proposed ANN methodology. Root Mean Squared Error of voltage magnitudes and angles were calculated for all four sets. For the same sets, the proposed method's findings were compared to the results of the traditional NRLF method. The biggest error in results acquired between the proposed and conventional method for voltage magnitude was 0.00787 and for angle was 0.008755.

3.6. Other Intelligent Techniques

Rick Rarick et al. [36] applied a Biogeography-Based Optimization (BBO) for power flow analysis to the IEEE 30 bus. The findings acquired by the BBO algorithm were compared with the GA power flow solution. A cost function based on a random voltage angle vector was assigned to each individual in the population from the weighted sum of the square of the mismatch at PV and PQ bus. Since both methods rely on stochastically generated quantities, the performance of both methods was assessed by Monte Carlo simulations. The Monte Carlo simulations showed that the cost and average cost calculated by the proposed method is less than GA power flow method.

M. Bezza et al. [37] applied a Firefly Algorithm (FA) based power flow method to the IEEE 14 bus test system. The results showed the active power losses were reduced and the grid was stable by controlling the voltage within limits. However, FA algorithm has the disadvantage that its parameters were invariable over time.

S. Mukherjee et al. [38] applied Moth-Flame Optimization Algorithm (MFOA) for power flow analysis to ill-conditioned IEEE 14, 30 and 57-bus test systems. The proposed algorithm's results were compared to load flow solutions created by the whale optimization algorithm (WOA) and the Biogeography-Based Optimization (BBO). The outcomes of the proposed algorithm showed that it required less computational time and number of iteration than the BBO and WOA load flow algorithm. The proposed method is highly flexible in tuning parameters and a better alternative for both normal and critical condition power flow analysis.

3.7. Load Flow Using Hybrid Method

V. Gopala Krishna Rao et al. [39] applied RBFNN based load flow algorithm with fuzzy set theory (FST) load modeling on IEEE 14 bus. The trapezoidal membership function was used to create load patterns for the test system's active and reactive power demands. Some load patterns were randomly selected and a 'newbre' function containing four arguments (input, goal, target and spread factor) is applied. The RBFNN was trained to verify the load features generated from FST. Results obtained showed that the mapping capability of the RBFN network was similar to the NRLF method.

T. O. Ting et al. [40] suggested a hybrid constrained GA and PSO based load flow method, which was tested on IEEE 30, 57 and 118 bus test systems under heavy load conditions. They compared the outcomes of the proposed method with the advanced constrained GA (ACGA) power flow technique. The proposed algorithm is derived from ACGA, where nodal voltage differential acceleration technique is replaced by PSO to analyze parameter sensitivity for mutation probability. The maximum loading point with 100% success rate obtained by the proposed method was found higher than the ACGA load flow algorithm. That allows the proposed method to work with better accuracy for larger systems under heavy loading than ACGA.

A. Singh et al. [41] implemented a hybrid PSO and ANN based power flow method at IEEE 14 bus for calculating magnitudes and angles of bus voltages under different conditions for loading and contingencies. Two PSO- ANN model was developed to calculate the angles and magnitudes of bus voltages. For testing and training of the proposed hybrid method, a total of 500 patterns corresponding to 25 load scenarios were produced. The NRLF method was used to generate 25 load scenarios for testing and training. The maximum percentage error in magnitude of bus voltage and voltage angle was found to 1% that showed the efficacy of the technique proposed.

K. Gnanambal et al. [42] applied a hybrid PSO-GA based technique to the sequence component frame of the 3-phase power flow analysis. The breeding approach of GA was used in order to generate child particles from randomly chosen worst parent particles in the proposed method. Two improvements that were varying the inertia weight between 0.1 to 0.9 and replacing worst position by taking an average of two best positions in the PSO technique was implemented for improving the performance of the proposed technique. Magnitudes of bus voltages and voltage angles were calculated for three phases balanced and unbalanced systems. The proposed method was also applied to a heavily loaded six bus system where the NRLF method failed to converge.

C. P. Salomon et al. [43] proposed a hybrid PSO with a biased mutation technique for the power flow analysis of six bus and nine bus systems. The mutation approach in the proposed method was used to change the position of the worst particle by a procedure consisting of adding random numbers ranging from 0 to 1 in each iteration that prevented the proposed method from converging in local minima. Unlike conventional techniques, the proposed technique did not require gradient information and able to solve non-convex problems. Compared with the NRLF method, the findings achieved by the proposed technique were found better and more efficient in reducing power mismatches.

Elnaz Davoodi et al. [44] proposed a hybrid method comprising of Simplex method and Improved Quantum-behaved PSO (IQPSO) technique for power flow studies. The proposed method was implemented for solving power flow problems in IEEE 14, 30, 57 bus standard and ill-conditioned test system. A new parameter based on global worst, personal best and global best was added in the QPSO to obtain greater local search ability and faster convergence than QPSO and PSO in the proposed method. A Deterministic Simplex method as local level and Stochastic IQPSO as a base level search was combined to obtain better global optimum value. The results achieved demonstrated the reliability and robustness of the load flow method proposed. Moreover, the proposed method was also tested under maximum loading considering reactive power limitations under the critical condition at PV buses in the load flow problem where the conventional NRLF method failed to converge.

Christopher O. Ahiakwo et al. [45] applied a Neuro-Swarm intelligence power flow analysis technique based on ANN and ABC algorithm at Diobu PHEDC 4-bus system for load flow problem studies. A feed-forward ANN trained by back-propagation algorithm studies memories and fine-tuned the parameters of the ABC algorithm in the proposed method. Bus voltage angles, voltage magnitudes and power flow in the system under normal and heavy loading were calculated by the proposed method. A load factor of 20 was used to analyze heavy loading conditions of the network for load flow study. The results showed that the proposed method needed lesser computational time and a lesser number of iterations than the PSO-based load flow method due to the neuro-swarm's self-adaptation property in the proposed load flow method.

4. Conclusions

This paper offers a detailed overview of the advancement of research in power system load flow analysis through various intelligent techniques. The research paper reviewed in this paper is organized according to different human and swarm intelligence techniques. From this review, we can conclude that the intelligent load flow methods outperform the conventional load flow methods in crucial scenarios like high R/X ratios and heavy loading. Furthermore, the intelligent load flow methods do not require any derivative information and are unaffected by the solution variable's initial value. However, in comparison to conventional load flow methods, the intelligent load flow methods are a little sluggish. Since load flow studies are a basic and fundamental tool for power system analysis and very few articles have been published on this particular topic, there is plenty of space that needs to be further investigated.

Other aspects which can be further investigated are summarized below:

1. Introducing new or improved intelligent load flow analysis techniques that are more accurate, have faster convergence, are less complex, take less time to compute, and require lesser iterations.
2. Investigating the impact of intelligent load flow techniques in power system operation, planning and extension in the presence of renewable generations and voltage control devices.

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