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REVIEW ARTICLE

A Review of State-of-the-Art Techniques for Power Flow Analysis

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HIGHLIGHTS

- *Review of State-of-the-Art Techniques for Power Flow Analysis.*

GRAPHICAL ABSTRACT

A review of State-of-the-Art Techniques for Power Flow Analysis (PFA) that are newly proposed are presented in this paper. The State-of-the-Art Techniques such as Particle Swamp Optimization Algorithm for optimal Power Flow Incorporating Wind Farms, Hybrid Firefly and Particle Swamp Optimization Algorithm, etc., have generally shown superiority over and above the existing classical methods such as Newton-Raphson, Gaus-Siedel e.tc. The histogram of Figure A shows comparison of the average time of convergence between the classical and State-of-the-Art Techniques.

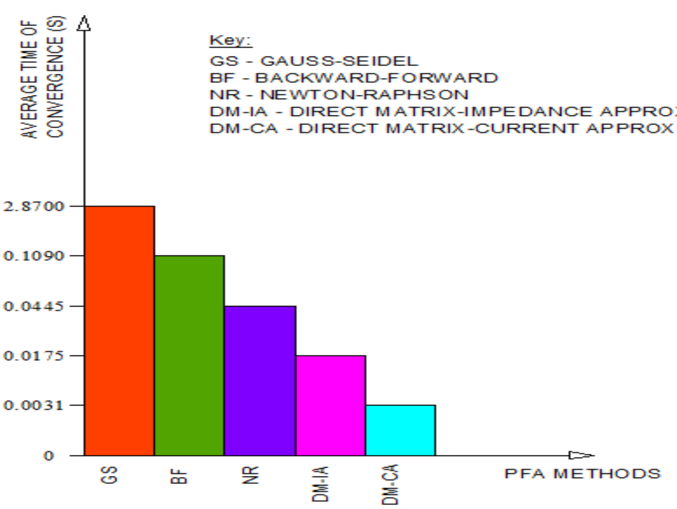

Figure A. Comparison of average time of convergence of the PFA methods

Keywords:

- Power FLow
- Newton-Raphson
- Gaus-Siedel
- Fast Decoupled

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Aim of Article: *The purpose of this research is to contribute in reviewing the State-of-the-Art techniques for power flow analysis thereby highlighting the most effective techniques for implementation.*

Theory and Methodology: *PFA plays a leading role in advanced energy management systems application which include contingency analysis, state estimation, reliability assessment and optimal power flow. Calculations of PFA are made by characteristic values of various components such as busbars, generators, power lines and transformers on power system*

Findings and Results: *The State-of-the-Art methods of PFA were reviewed and, from the results contained in the reviewed papers, the methods showed superior performance over the classical ones.*

Conclusion : *This paper presents a review of the State-of-the-Art Techniques for PFA in comparison with classical methods. The State-of-the-Art Techniques were found to be more effective and therefore more suitable for application.*

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ABSTRACT

A Review of State-of-the-Art Techniques for Power Flow Analysis (PFA) which are newly proposed is presented in this paper. However, some of the existing classical methods for the Power Flow Analysis such as Newton-Raphson method, Gauss-Seiadel method, and Fast Decoupled Power Flow Technique were also discussed so as to give a background and a wider view of the improvements recorded so far. From the findings, State-of-the-Art Techniques such as Particle Swamp Optimization Algorithm for optimal Power Flow Incorporating Wind Farms, Hybrid Firefly and Particle Swamp Optimization Algorithm, Mann Iteration Process Technique for III-Conditioned System, and Modified Gauss-Seidel (MGS) method have shown superiority over and above the existing classical methods when it comes to accuracy, convergence speed and overall efficiency. Particularly, there are two newly proposed methods for dc grids namely Direct Matrix–Current Application and Direct Matrix-Impedance Approximation methods that stand out as regards accuracy, convergence and computational speed which means they can be used in planning, optimization and analysis purposes. Furthermore, MGS was validated using a 6-bus system in 3 cases. Each case had less than 25 iterations and the maximum voltage magnitude, phase angle and system frequency error in all the cases studied were less than 0.01%, 0.1% and 0.001% respectively.

Keywords: *Power Flow, Neuton-Raphson, Gaus-Siedel, Fast Decoupled*

I. INTRODUCTION

The importance of Power Flow Analysis (PFA) in power system cannot be over emphasized. Its role is very fundamental in the various advanced energy management systems application that include; contingency analysis, state estimation, reliability assessment and optimal power flow especially that, in recent times, the growth of electric utilities is rampant hence, the need for cost effective, secure and reliable power supply generation for economic operations [1]. Power flow analysis entails reducing to a minimum level, the real ΔPi and reactive ΔQi power residuals mismatches in a power system, so that the voltage magnitude and phase angle solutions are accurate [2]. Calculations of PFA are made by characteristic values of various components such as busbars, generators, power lines and transformers on power system [3]. To reduce complexity and increase computational speed, digital computer has been used for nearly five decades in solving the power flow equations however, there is still problem of solving certain typical power system network – despite a recorded substantial progress. This is due to the adherence to nonlinearity and operating constraints of the system [4]. For a large-scale power system particularly, due to the nonlinearity, an analysis of AC power flow can be computationally intensive in multistage, or online applications [5]. Also, the inherent nonconvexity power flow could make the optimization intractable when involved in optimization-based applications [5]. As interconnected power systems are expanding in recent years, the complexity in handling AC PF has become one of the binding factors for power system analysis and optimization [5]. Some of the widely used classical methods of solving the nonlinear PF equations include Newton-Raphson method, Gauss-Seidel method, Fast Decoupled method, etc. However, more functional evaluations are required during each iteration which is a limitation. Another limitation associated with these methods is that they may converge to a root different from the expected one or even diverge if the starting value is not close enough to the root. Therefore, the new state of the art methods of PF analysis is discovered to generally give better results than the classical methods and give the power the room to flow perfectly, fitting the new grid changes like Decentralized Generation (DG) [6]. These State-of-the-Art methods include Direct Matrix-Current Application (DM-CA) and Direct Matrix-Impedance Approximation (DM-IA) [5], Particle Swamp Optimization (PSO) Algorithm for Optimal PF Incorporating Wind Farm [6], Hybrid Firefly and Particle Swarm Optimization (HFPSO) [7], Artificial Neural Networks (ANNs) [8], Quasi-Oppositional Heap-Based Optimization (QOHBO) Technique [9], Three Stage Semi-Implicit Approach (3S-SIA) [10], Mann Iteration Process (MIP) For Ill-Conditioned System [11], Hybrid of Current-balance and Power-balance formulation using Rectangular Coordinates (HCPB) [12], Modified Gauss-Seidel (MGS) [13], Batched Fast Decoupled Method [14], Newton-Raphson Load Flow Analysis in Power System Networks with STATCOM in New Approach [14] and so on. This paper will therefore, focus on these state-of-the-art techniques.

II. CLASSICAL METHODS OF POWER FLOW ANALYSIS

Finding the voltage magnitude and phase angle of each bus, when power is generated, and loads as pre-specified is the major consideration in power flow studies. And to that extent, the buses are classified as load bus (P-Q bus), generator bus (P-V bus) and slack bus (swing bus) [4]. Power flow system outputs are voltages at various buses, network line flows as well as losses in the system. The outputs are determined by resolving nodal power equations which are non-linear. This is where classical methods of power flow analysis, which are iterative, like Newton-Raphson, Gauss-Seidel and Fast-Decoupled techniques are employed to resolve these equations.

A. Slack Bus

This is a special generator bus serving as the reference bus. Its voltage is assumed to be fixed in both magnitude and phase, for instance $1 < 0° \, pu$.

B. Load (PQ) Bus

It is a bus at which the real and reactive power are specified, and for which the bus voltage will be calculated.

C. Generator (PV) Bus

This is a bus at which the magnitude of the voltage is defined and is kept constant by adjusting the field current of a synchronous generator.

D. Newton-Raphson

It is one of the classical methods of PFA. It is used to find solution to equations of $f(x) = 0$ forms by iteration. After determining an interval [a,b] that contains a single root, Newton Raphson is applied. The method is about substituting the curve $y = f(x)$ for the tangent to the curve itself, starting from any point. After a number of iterations, the recurrence relation of the method is given by the following expression [6].

$$x_{n+1} = x_n - f(x_n)/ f'(x_n)$$

However, when looking for a solution that is too far away from the considered interval, sometimes, Newton-Raphson may fail to converge [6].

E. Gauss-Seidel

This is another iterative method also used to solve the power flow equations. Recall that:

$$I_{bus} = Y_{bus} * V_{bus} \text{ (A)}$$

The current I_k of k-th of the I_{bus}, is written in a less compact form as;

$$I_k = \sum_{n=1}^{N} Y_{kn} \, . \, V_n \text{ (A)}$$

The complex power can be written as:

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$S_k = P_k + jQ_k = V_k \cdot I_k^*$ (A)

And when the current is expressed as a function of I_k, we have

$I_k = (P_k + jQ_k)/V_k^*$ (A)
And finally, we have:

$V_k = 1/Y_{kk}[(P_k + jQ_k)/V_k^* - (\sum_{n=1}^{k-1} Y_{kn} \cdot V_n + \sum_{n=k+1}^{N} Y_{kn} \cdot V_n)]$ (V)

With k = 1, 2, ..., N nodes. This expression links V_k ($V_{kt} + jV_{ki}$) with the active and reactive power of the individual bus and is the solving equation underlying the Gauss-Seidel method [6].

However, the Gauss-Seidel method has a slow convergence where the convergence speed has the same order of magnitude as the number of busbars.

F. Fast-Decoupled Power Flow Technique

This method includes two steps; (1) decoupling real and reactive power calculations; (2) obtaining of the Jacobian matrix elements directly from the Y-bus.

III. STATE-OF-THE-ART METHODS OF POWER FLOW ANALYSIS

In the previous section, we have seen how classical methods use iteration to solve power flow equations, which could be for AC or DC systems. Despite the fact that the methods are used on DC grids, they are originally used in power flow studies for AC networks. However, among the new methods developed for PFA, two new methods for dc grids were developed and compared with the classical methods, they perform better as regards convergence, accuracy and computational effort needed. These methods are Direct Matrix-Current Application (DM-CA) and Direct Matrix -Impedance Approximation (DM-IA) [7]. Other new PFA methods are also discussed in this section.

A. DM-CA And DM-IA

Table 1 shows comparison of various PF techniques as applied to IEEE test feeder. Accuracy is defined as a Root Mean Square Error (RMSE) with regard to the actual solution of the power flow problem and the desired convergence tolerance ϵ. The average number of iterations, RMSE, and computation time average are also contained in the Table.

Table 1. RMSE, average iterations and computation time needed for various PF techniques

Simulation Convergence Tolerance, $\epsilon = 10^{-6}$ [7]

Method	RMSE [p.u.]	Average Iterations	Average Time [s]
Gauss-Seidel	0.000189	367	2.87
Newton-Raphson	$1.1 * 10^{-9}$	2.74	0.0445
Backward-Forward	$3.0 * 10^{-9}$	2.88	0.109
DM-CA	$2.9 * 10^{-9}$	2.87	0.0031
DM-IA	$2.7 * 10^{-14}$	2.00	0.0175
Quadratic Solver	$5.3 * 10^{-15}$	N/A	240
Optimization Problem	$4.1 * 10^{-10}$	2.00	9.54

B. Particle Swarm Optimization (PSO) Algorithm for Optimal Power Flow Incorporating Wind Farms

One of the population-based optimization strategies is particle swarm optimization (PSO). In 1995, Dr. Eberhart and Dr. Kennedy created and developed this optimization approach. The social nature of fish schooling or bird flocking inspired this optimization strategy. The PSO was applied to a modified IEEE 30 bus system in which buses 11, 13, and 15 were replaced by a wind farm, and the results suggest that this technique may be used to solve any power flow problem. In comparison to Newton Raphson, it outperformed it [8].

C. Hybrid Firefly and Particle Swarm Optimization Algorithm (HFPSO)

This algorithm was created by Ibrahim Berkan Aydilek. The HFPSO method combines the Firefly Optimization (FFO) and Particle Swarm Optimization (PSO) [8] techniques to improve exploration and exploitation tactics to accelerate convergence[8]. To validate the

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algorithm's validity, a normal IEEE 30-bus test network was used, and it was discovered that the approach provides a good tool for dealing with OPF difficulties in power networks.

D. Artificial Neural Networks (ANNs)

Having the ability to learn complex non-linear input and output relationship is the main characteristic of neural networks where they use sequential training procedures and adapt themselves to the data application [10]. ANNs are generally a parallel computing system in massive form that consists of an extremely large number of many interconnections of simple processors [10]. Their models ideally try to use some organizational principles like learning, generalization and computation in a network of weighted graphs whereas the nodes are in the form of artificial neurons and directed edges are connections between neuron inputs and outputs [10]. See Figure 1.

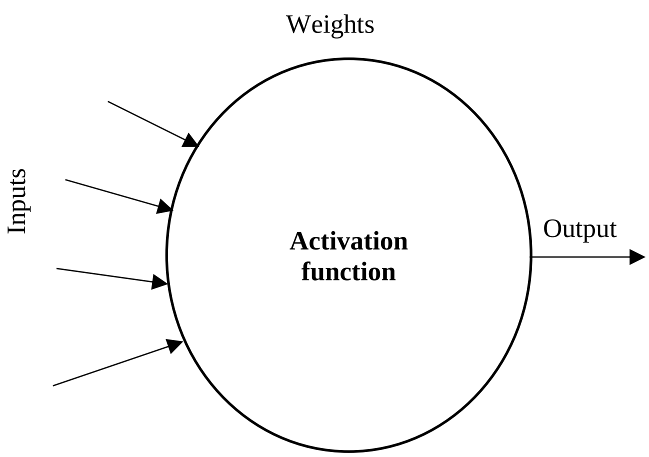

Fig. 1: An Artificial Neuron

E. Quasi-Oppositional Heap-Based Optimization (QOHBO) Technique

Modern power flow analysis techniques are designed to satisfy the increasing demand of power system by making analysis faster, detailed and more reliable, one new approach proposed utilizes the concept of quasi-oppositional learning to augment the speed of convergence by applying it to HBO (Heap-Based Optimization). Basetti in his research [11] proposed this method to ameliorate the convergence speed of PF iteration, as a derivative-free method. In this research, the QOHBO power flow technique is applied to a standard IEEE and ill-conditioned systems to test the effectiveness of the technique. The algorithm of this technique was validated when loaded to its maximum limit at high R/X ratio. The results obtained showed that the QOHBO power flow technique has less computation time, further enhanced reliability in the presence of photovoltaic generator (PVG) and could provide multiple PF solutions that can be utilized for voltage stability analysis. When compared to other well-known method, the robustness of the algorithm outperformed its counterparts.

F. Three (3) Stage Semi-Implicit Approach (3S-SIA)

Power-Flow (PF) problem has been customary solved using the classical Newton-Raphson technique (NR). These old methods are quite efficient for managing well-conditioned systems. Oppositely, NR finds multiple convergence issues in ill-conditioned systems. Power-Flow Analysis in a practical large-scale ill-conditioned system, is too complex and challenging for most available techniques. Marcos Tostado in his paper [12] tackles this issue by developing the Three Stage Semi-Implicit Approach (3S-SIA as) a novel efficient and robust PF method. This technique uses a Semi-Implicit approach but combines other numerical arrangements for improving its robustness and efficiency. The 3S-SIA is efficient in the sense that it requires just a matrix factorization in each iteration, resulting in similar computational burden when compared to NR. The result obtained proved that 3S-SIA is remarkably more robust than NR. Nevertheless, there are still some gaps in this method because the references in this paper do not provide comprehensive theoretical analysis about convergence properties of semi-implicit approaches.

G. Mann Iteration Process (MIP) Technique for Ill-Conditioned System

A wide-ranging theoretical analysis is provided, from which it has been demonstrated that the Mann Iteration Process with asymptotic stability may achieve a high convergence rate. It also constitutes highly robust methodology, improving the properties of the Newton-Raphson method. In all cases, the results obtained with the Mann Iteration Process are superior to that obtained using other classical methodologies, being able to efficiently solve various large-scale ill-conditioned systems [13].

H. Current - Balance Technique

The most widely used power flow analysis formulation is the power balance formulation [14]. In the power balance form, the summation of power injected and absorbed at each bus and by the network respectively, must be equal to zero [14]. However, evaluation of the Jacobian matrix is main computational drawback of the power balance form. Therefore, the current-balance is used at each bus, in place of the power-balance which is, essentially, Kirchoff's current law [14]. Thus, the proposed current-balance power-balance technique approach is the expression in rectangular form, the variables of the combination of current balance equations for PQ buses, power balance equations and voltage magnitude constraints equation for the PV buses [14].

I. The Modified Gauss Seidel (MGS)

For application in an islanded microgrid, the Gauss-Seidel method requires some modifications [15]. These include calculation of the system frequency and variables of all the buses [15]. Also, in the iteration procedure, the Ybus needs to be included since it's the function of the system frequency hence, changes after every iteration. More so, the system losses need to be distributed among the DGs [15]. A 6-bus system is used to validate the proposed technique with the parameters of the systems given. Within the three cases studied, there were less than 25 iterations for each case. Also, the maximum voltage magnitude, phase angle and system frequency error in all the cases studied were less than 0.01%, 0.1% and 0.001% respectively [15].

J. Batched Fast Decoupled Method

There is a significant increase in computing time of load flow problem due to its massive growth, and as a result, its application in many real time analyzing tools has been limited [16]. Therefore, to improve its performance, a parallel computing strategy must be utilized with state-of-the-art devices so as to accelerate the computations [16]. So, a massive load flow problem can be solved by processing severally or independently on CPU, hence, the design of the proposed GPU – accelerated batched decouple solver [16]. This technique concentrates on the calculation of the imbalanced load of the forward and backward substitutions (FS/BS) and their solution using fixed coefficient matrices [16]. Furthermore, the proposed solver, achieves a speed up of 24.17x for 13659-bus system by discovering the parallelism of massive load flows and a single load flow compared with implementation on CPU [16].

K. A New Approach Newton-Raphson Load Flow Analysis in Power System Networks with STATCOM

Newton Raphson is the most reliable classical method of power flow analysis because of its fast convergence speed, and accuracy [17]. However, as the power system is expanding, so is the dimension of load flow equations growing from several thousands, very fast, to tens of thousands. This, compelled the interested researchers to continue seeking for the methods that can efficiently tackle such problems. Therefore, STATCOM is one of the most useful devices for improving quality of the power in electrical power system due to its quick voltage regulation, transient stability improvement and variable reactive power compensation [17].
The equation for the i^{th} bus with STATCOM is rewritten as follows [17]:

$S_i = (P_{Li} + jQ_{Li}) + (P_{si} + jQ_{si})$ (1)

$P_i = P_{Li} + P_{si}\ ,\ Q_i = Q_{Li} + Q_{si}$ (2)

$I_{si} = (P_{si} - jQ_{si})/V_i^*$ (3)

$V_{si} = V_i - I_{si}Z_{si}$ (4)

L. Generalized Hopfield Neural Network

A fixed weight is used in formulating this proposed LFA method. The method can solve any order of a nonlinear algebraic set of load flow equations its cost of computation less than the usual [3]. An energy function used in designing the proposed method has the equations;

$$E = \sum_{j=1}^{n} \big(gj(.)\big)2 \dots \dots \dots (1)$$

And $gj(.) = fj(x_1, x_2, \dots, x_j x_n \dots \dots \dots (2)$

In this technique, the number of the neurons is selected based on the number of parameters to be determined [4]. Therefore, two approaches were deployed;
1st approach: Its formulation is using real and reactive power flow. It is tested on a 3-bus and 5-bus systems and, the form of energy function is found to be feasible for solving the load flow problem [4].
2nd approach: Real and reactive power mismatches were used to form the energy function (since its required to reduce the real and reactive power mismatches to zero in order to obtain the phasor forms of the voltage at all the buses in a load flow analysis of a power system), and the

energy function found is the minimizing function whose value is reduced to zero, or at least, the minimum value[4]. Therefore, this approach is found to be more appropriate in solving the PF problem.

Overall, the proposed GHNN method is found to have very less computing time, converges very fast, simple program formulation and less memory required when compared with Newton Raphson method [4].

IV. PERFORMANCE COMPARISON BETWEEN STATE-OF-THE-ART AND CLASSICAL METHODS OF POWER FLOW ANALYSIS

As evidently seen from the highlighted methods, there is a clear performance superiority by the State-of-the-art techniques when compared against the classical ones.

When performing iterations, a classical method like Newton Raphson will fail to converge when interval [a,b] of the f(x)=0 containing a single root is far away from the solution.

Furthermore, Gauss-Seidel method converges very slowly with an identical magnitude order between the convergence speed and the busbar number.

However, on the part of the State-of-the-art methods, for example, Particle Swarm Optimization (PSO) Algorithm for Optimal Power Flow Incorporating wind farms outperformed the Newton Raphson method as it can be used to solve any power flow problem.

Moreso, as contained in Table 1, the accuracy error (RMSE) of some of the techniques used on some IEEE test feeders showed that the RMSE value of the DM-CA technique compared to that of the Gauss-Seidel had an average of 2.87 iterations and an average time of 0.0032s while the Gauss-Seidel method had 367 and 2.87s average iterations and average time respectively. Therefore, State-of-the-Art PFA methods have no doubt come with significant improvements over and above the Classical PFA methods.

V. CONCLUSION

This paper focuses on review of some of State-of-the-Art techniques for PFA. However, some of the popular Classical methods namely GS, NR, BF, QS and OP were considered in comparison with two newly proposed State-of-the-Art PFA methods for dc grids as regards accuracy, convergence and computational effort needed. The two newly proposed state-of-the-art methods for dc, which are DM-CA and DM-IA, showed superior performance, which means they can be used for planning, optimization and analysis purposes [7].

Furthermore, the paper presented more State-of-the-Art techniques that were proposed, which show superiority over the existing classical methods in terms of accuracy, speed of convergence and overall efficiency. These methods/techniques include PSO, HFPSO, ANNs, QOHBO, 3S-SIA, MIP, HCPB, MGS and Batched Fast Decoupled Methods. Others include A New Approach New-Raphson Load Flow Analysis in Power System Networks with STATCOM and Load flow analysis using generalized Hopfield neural network. As demands increase, it is expected that more techniques will be developed as researches continue.

CONFLICTS OF INTEREST

There was no conflict of interest between the authors and their respective institutions.

RESEARCH AND PUBLICATION ETHICS

In the studies carried out within the scope of this article, the rules of research and publication ethics were followed.

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