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Complex Affine Arithmetic based Load Flow Analysis

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ABSTRACT: Even though real world analysis is non-linear and uncertain, most of the power system network analyses are the approximation rather than the worst case results. One of the power system network analysis mechanisms which is based on deterministic input is a load flow analysis. Due to the penetration of renewable energy sources and the environmental temperature change, power system network inputs are no longer constant rather varies between upper and lower extremes constantly. The main load flow analysis constants considered to vary with the variation of input are the active and reactive power at the generator and the buses. In order to get a load flow solution for the varying input power a probabilistic load flow analysis based on complex affine arithmetic (CAA) is proposed and tested on standard IEEE 57 bus systems. The result is validated by its mid way conservation of the deterministic load flow analysis result and a probabilistic Monte Carlo approach.

KEYWORDS: Affine Arithmetic, Load Flow Analysis, Monte Carlo, Renewable Energy, Uncertainty.

I.INTRODUCTION

Load flow analysis is the basics tools which helps a power engineer to get knowledge about the steady state operation of a power system network. Load flow analysis gives information about bus voltage and branch power flow without the consideration of the transient nature of the network. As a result its non consideration of transient state of the network, it contains a nonlinear mathematical equations without differentiation.

The application of digital computer in solving load flow analysis started in 1950s. So far a lot of mechanism has been developed. The developed mechanisms importance is measured by their convergence properties, memory usage, computing efficiency, convenience and ease of implementation. The solution process always has an iterative approach. Some algorithms converge with low iteration while the other takes several iterations to converge. The number of iterations for different algorithm does not show the memory consumption. Some with higher iteration may consume less memory than other which converges with a limited number of iterations. Similarly, the speed of convergence is not directly related to the number of iterations. For example a Gauss-Seidel algorithm which converges in three iterations is speedier than a Newton-Raphson based algorithm which converges with two iterations.

Probabilistic load flow analysis roots its base from deterministic power flow analysis. One of the probabilistic load flow analysis mechanism is called Monte Carlo simulation. Monte Carlo simulation is based on the statistical data of a given system containing a random number with in the desired bound. It handles both deterministic and probabilistic problems whether they are concerned or not concerned with the end results or the nature of the process. Monte Carlo simulation produces distributions of possible outcome values. When a probability distribution is used, variables can have different chances of occurrence with different outcomes. Probability distributions are a realistic way of describing uncertainty in different uncertain systems.

In solving probabilistic problem a random numbers are chosen or generated using digital machines within the boundary of the input variable and the original problem is simulated for each random variables. The simulation may range from few hundreds to thousands based the generated random variables. The number of the random variables depends on the convergence of the end results. If increasing the number of random variables has no effect on the

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overall maximum and minimum outputs, the simulation is said to be converged at the least number of the random variables [3]. Since its invention Monte Carlo simulation has been used for a system, with ordinary mathematics to calculus equipped with some sort of uncertainty. The simulation approach is used in a wide area of fields including Engineering, Finance, Medicine, Physics, Chemistry Biology and etc. In power system engineering it has been used to solve a problem containing internal or external uncertainty and provides a bounded output.

Probabilistic power flow analysis has been implemented using Monte Carlo simulation mechanism either to validate other methods or as an independent mechanism in since its invention. Some among many works done on the area of power system analysis in general and load flow analysis in particular will be discussed.
Several methods have been applied to deal with uncertainties in engineering in general and in probabilistic load flow analysis in particular since 17^{th} centuries by the time the presence of uncertainty and its effect in the end result is first noted [4].

Among different numerical and analytical methods which have been used to solve probabilistic load flow analysis Monte Carlo approach is the best known one in dealing with uncertainties. It become popular due to its flexibility, applicable both in linear and non linear system of equations, it can able to deal with large equations with high variance and etc. It is noted that it suffer from low speed convergence with incurs high computational burden specifically for a system which convergence with large number of random variables [3].

The mechanism of solving a probabilistic load flow analysis by Monte Carlo approach is by repeated simulation in order to get an accurate result. Monte Carlo approach is simply a mathematical technique which considers the presence of uncertainty by randomly assigning their value within a given bound to solve a probabilistic load flow analysis. It evaluates iteratively a deterministic load flow analysis using a set of random numbers. Monte Carlo approach is better used when the mathematical model is very complex, non linear or containing a number of uncertain variables. When it is coded in digital computer the simulation may take 10^{th} thousands or more of random variable depending on the mathematical model converge behaviour. Due to this problem its practical applicability is limited to some areas only [4]. Though Monte Carlo approach is slow for practical application, it is still used by researchers as the best mechanism for comparing the validity of new methods in the area of uncertain system. During comparing any method to Monte Carlo approach, all assumption made regarding uncertainty for the proposed method must be applied in simulating the Monte Carlo technique [5].

The second mechanism of probabilistic load flow analysis is based on interval mathematics. The application of Interval Arithmetic to solve probabilistic power flow analysis has been studied by many researchers. Since Monte Carlo approach is tedious, due to its high time and memory consumption to converge, researchers found Interval Arithmetic advantageous. The core point behind the application of any probabilistic and fuzzy system to analyse a power system network is the presence of uncertainty. Interval Arithmetic based power flow analysis not only considers the presence of uncertainty, but also provides a bounded interval inclusive of all possible solutions. A Newton operator is a key to solve a non-linear Interval Arithmetic based power flow equations, while a Gauss-Seidel approach is used to solve the linear equations. Using Newton operator and Gauss-Seidel approach in solving an interval based power flow problem gives reliable result [6].

To generalize that interval arithmetic based load flow analysis has a quality of low memory consumption and fast convergence in comparison to Monte Carlo simulation. It also effectively considers input uncertainties weather it is due to load or generation variation. Though it has the aforementioned advantages over Monte Carlo simulation, its dependency problem is a non ignorable drawback. As a result another mechanism based on CAA has the ability to solve the aforementioned drawbacks of both the Monte Carlo and interval arithmetic. The application of real affine arithmetic for load flow analysis based on Newtons power is dealt in detain in [1, 7]. This paper proposes a Gauss-Seidel load flow analysis based CAA for uncertain system network. The organization this paper is as follows: Section two discuses about CAA, section three deals about CAA based load flow analysis, Section four gives result and discussion and finally section five is dedicated to conclusion.

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II. BASICS OF COMPLEX AFFINE ARITHMETIC

Like any algebraic function AA functions has a set of rule governing them to give a desired result. Any number is an element of either a real number or a complex number. The general representation of CAA function is given by (1) [8-11].

$$\hat{a} = a_0 + \sum_{i=1}^{n} a_i \varepsilon_i \qquad (1)$$

From (1) $\hat{a}$ represents the affine function, a_0 represents the central value, a_i represents the partial deviation and ε_i represents the noise (symbolic) variable whose value is bounded by [-1, 1] interval. The affine to interval and the interval $[\underline{a}, \overline{a}]$ to affine is given by (2) respectively [9]. The common affine and non affine operation based on two affine functions in (3) for a constants'' is given by (4) and (5) respectively.

$$\left.\begin{aligned} A &= a_0 + a_i[-1,1] \\ \hat{a} &= \frac{[\underline{a} + \overline{a}]}{2} + \frac{[\overline{a} - \underline{a}]}{2}\varepsilon_i \end{aligned}\right\} \qquad (2)$$

Any other CAA function operation, for a single variable $\hat{k}$, is approximated by a Chebyshev formula given by (6). The detail of (6) can be found from [8-11].

$$\left.\begin{aligned} \hat{k} &= k_0 + \sum_{i=1}^{n} k_i \varepsilon_i \\ \hat{l} &= l_0 + \sum_{i=1}^{n} l_i \varepsilon_i \end{aligned}\right\} \qquad (3)$$

$$\left.\begin{aligned} \hat{k} \pm \hat{l} &= (k_0 \pm l_0) + \sum_{i=1}^{n} (k_i \pm l_i)\varepsilon_i && (a) \\ d\hat{l} &= (dl_0) + \sum_{i=1}^{n} (dl_i)\varepsilon_i && (b) \\ \hat{k} \pm d &= (k_0 \pm d) + \sum_{i=1}^{n} k_i \varepsilon_i && (c) \end{aligned}\right\} \qquad (4)$$

$$\left.\begin{aligned} \hat{k}^c \hat{l}^c &= k_0^c l_c^c + \sum_{i=1}^{n} (k_i^c l_0^c + l_i^c k_0^c)\varepsilon_i + (\sum_{i=1}^{n} l_i^c \sum_{i=1}^{n} k_i^c)\varepsilon_{n+1} \\ \frac{\hat{k}^c}{\hat{l}^c} &= \frac{(\hat{k}^c)(\hat{l}^c)^*}{(\hat{l}^c)(\hat{l}^c)^*} \end{aligned}\right\} \qquad (5)$$

$$\hat{p} = \alpha\hat{k} + \xi + \delta\varepsilon_{n+1} \qquad (6)$$

Since (4-5) are non affine operation they append with a new symbolic variable ε_{n+1} which is unique from the other and represents all non affine approximations [8-11].

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III. CAA BASED LOAD FLOW ANALYSIS

The CAA based load flow analysis initially formulated from the general Gauss-Seidel equation. The equation given by (7) represents the bus CAA voltage, the active and reactive power respectively [12]. Initially the central voltage and angle is found from deterministic analysis and made to be interval using percent of uncertainty which is considered in this paper to be 20%. The interval is converted to CAA using interval to affine conversion in (2b). In the same way the deterministic real and reactive power for each bus made to be interval using 20 % uncertainty and converted to CAA using (2). The converted CAA for voltage, real and reactive power for each bus is shown in 7 (a-c) respectively.

$$\left.\begin{aligned} \hat{V}_i &= V_{i,0} + \frac{V_i}{2}(\varepsilon_{p,i} + \varepsilon_{q,i}) && a \\ \hat{P}_i &= P_{i,0} + P_{i,i}\varepsilon_{p,i} && b \\ \hat{Q}_i &= Q_{i,0} + Q_{i,i}\varepsilon_{q,i} && c \end{aligned}\right\} \qquad (7)$$

where $\hat{V}_i$ $\hat{P}_i$ and $\hat{Q}_i$ are the CAA form of the voltage, the real and reactive power respectively. The terms $V_{i,0}$ and ($P_{i,0}$, $Q_{i,0)}$ are the central values found from deterministic load flow analysis without uncertainty and deterministic inputs respectively. The partial deviation, $V_{i,}$ $P_{i,0}$ and $Q_{i,0}$ are generated due to the presence of uncertainty according to interval to affine conversion in (2). The symbolic variables $\varepsilon_{p,i}$ and $\varepsilon_{q,i}$ denotes uncertainty due to active and reactive power variation respectively. The CAA voltage shares both the uncertainty due to real and reactive power equally as shown in (7a). Applying all affine and non affine operation from 1-6 and using the inputs in (7) the CAA Gauss-Seidel voltage equation in (8) results the complex equation in (9).

$$\hat{V}_{a,n} = \frac{1}{Y_{n,n}}\left[\frac{\hat{P}_n - j\hat{Q}_n}{\hat{V}_n^*} - \sum_{\substack{k=1 \\ k\neq n}}^{N} Y_{n,k}\hat{V}_k\right] \qquad (8)$$

The central term in (9) found from deterministic analysis and the partial deviations are directly from the analysis of (8). Equation (9) contains central value, partial deviation from active and reactive power uncertainty and additionally it contains approximation errors coefficients which come from the application of non affine operations.

$$V_{a,i} = V_{i,0} + \sum_{j=1}^{n} | V_{n,j}^{p} | \varepsilon_{p,j} + \sum_{j=1}^{n} | V_{n,j}^{q} | \varepsilon_{q,j} + \sum_{j=1}^{k} | V_{n,j} | \varepsilon_{h,j} \qquad (9)$$

In (9) the central term is found from base load flow analysis without uncertainty and is always constant. As a result it cannot be optimized rather taken as it is. The partial deviations angle $\delta_{e,n}$ found from the conversion of CAA partial deviation of (9) into angle. Both the partial deviations angle ($\delta_{e,n}$) and voltage ($V_{e,n}$) for optimization, omits the central term. Since Voltage has a maximum limit in a bus the partial deviations are optimized in a way not violate the bus voltage limits. Assuming '*p*' is the percent of uncertainty with $u_l=(p/2)*(V_{i,lim}-V_{i,0})$ and a_n= p/2. The maximum angle uncertainty limit is considered to be the percent of uncertainty initially taken [2, 12]. The final optimization equation based on the partial deviation results of (9) become as shown in (10-11).

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$$
\begin{aligned}
&\min/\max \quad V_{e,n} \\
&s.t \quad -u_n \le V_{e,n} \le u_n \\
&\qquad -1 \le \varepsilon_p \le 1 \\
&\qquad -1 \le \varepsilon_q \le 1 \\
&\qquad -1 \le \varepsilon_h \le 1
\end{aligned} \tag{10}
$$

$$
\begin{aligned}
&\min/\max \quad \delta_{e,n} \\
&s.t \quad a_{\mathrm{n}} \le \delta_{e,n} \le a_n \\
&\qquad -1 \le \varepsilon_p \le 1 \\
&\qquad -1 \le \varepsilon_q \le 1 \\
&\qquad -1 \le \varepsilon_h \le 1
\end{aligned} \tag{11}
$$

The procedure starting from (7) to (11) is repeated until a convergence is reached. In order to test the proposed result an IEEE bus system is used as shown in the next section.

IV. RESULT AND DISCUSSION

The IEEE-57 bus system is used to test the proposed method. A 20 % real and reactive power uncertainty is considered and the result of the bus voltage magnitude and angle including the deterministic output is shown in Fig 1 and 2 respectively.

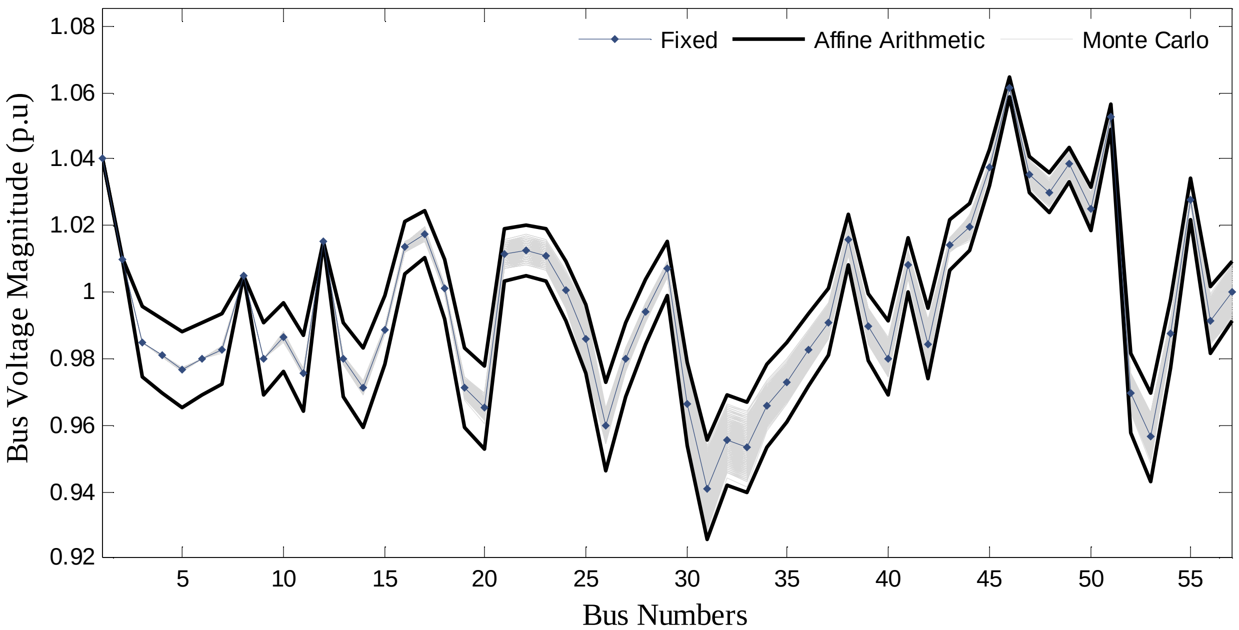

Fig 1 Bus Voltage Magnitude in per unit for the two uncertain and fixed system analyses

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In Fig 1 and 2 the gray plot contains the 3000 results of the Monte Carlo iteration. For Monte Carlo approach to converge higher number iterations are mandatory. As seen from the two figures the proposed affine arithmetic approach conserves the Monte Carlo and the fixed results.

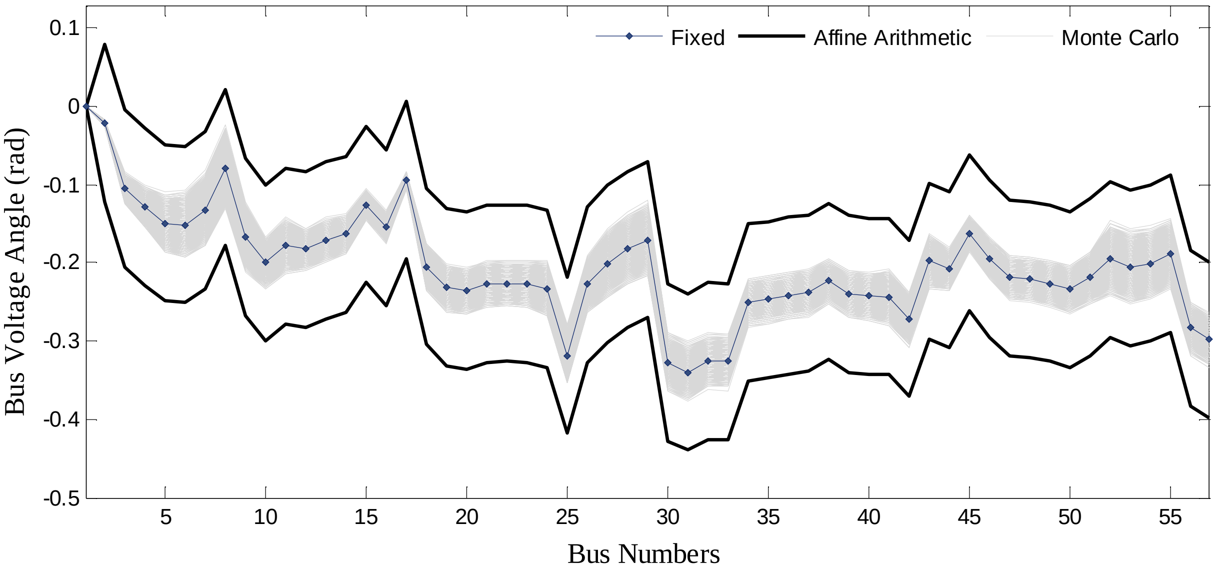

Fig 2 Bus Voltage Angle in rad for the two uncertain and fixed system analyses

Since uncertainty based analysis is to find the worst case response in this case CAA based result is more representative than the Monte Carlo approach. In terms of convergence the CAA based load flow analysis converges in two iterations while the Monte Carlo approach takes 3000 iteration to provide unchanging extreme boundary results.

VI.CONCLUSION

On this paper a CAA based load flow analysis for a system containing variable generation and load is proposed. The proposed method is tested on an IEEE bus system and satisfactory comparison methods, using Monte Carlo and fixed system analysis mechanism, are performed. The result of the proposed algorithm perfectly conserves the Monte Carlo approach based outputs. Additionally, the ordinary load flow analysis result, with no consideration of uncertainty, conserved in the mid of the uncertain system results. The inclusion of the both the fixed at the mid and the Monte Carlo output by the CAA result is due to the nature of affine arithmetic to consider round of and truncation error better then the two. The proposed method can be used in load flow analysis in planning stage for reliable power delivery during worst case scenario.

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