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A Parametric Test based Analysis of State Estimation Techniques under Data Uncertainties

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This work examines the statistical analysis of conventional and evolutionary strategies used to solve state estimation problems. All energy management systems use state estimation to determine the operational condition of the system. Moreover, with the rise of the electrical market and the notion of a smart grid, the assessment of system parameters has received considerable attention. Hence an assessment of the efficiency and robustness of various state estimation techniques used to compute the system parameters is very much required. This paper primarily focuses on the parametric tests used to access and compare the robustness of various state estimators. Case studies are conducted on IEEE 6 bus and 14 bus systems. In addition, this paper also provides a statistical evaluation of the performance of evolutionary algorithms with varying upper and lower optimal solution constraints. Furthermore, the algorithms' robustness under conditions of missing and infringed data is also determined. The findings derived from these estimators are compared with the base values, and the percentage error in estimated values is computed and analysed.

Keywords: Energy management system, Evolutionary strategies, Parametric tests, State estimation, Statistical analysis

Introduction

In an electrical power system, electricity is generated, transmitted, and distributed. Operating a power system is predicated on achieving economically efficient generation scheduling and ensuring the security of electric power components. To attain these objectives, power engineers must carefully monitor and forecast system operating states. Furthermore, with the reform of the power system and the entry of private companies into the energy market, the demand for real-time monitoring has become increasingly prominent in recent years. As a result, the system operator's primary concern is to find the best state estimate algorithm possible. In the literature, there are several algorithms for addressing the state estimation problem. State estimation is an essential tool for monitoring the power system.[1] The energy control centre estimates the power system state using real-time observations and a preset system model. This allows the centre to deliver the most accurate estimations possible regarding what is happening within the system. There are several pieces of research on state estimates, and those investigations have been reported in the literature. Iterative methods for estimating the state of a system, such as the Weighted Least Square approach and Gauss-Newton iterations[2,3], are some of the most common and widely used strategies for delivering information about the state of a system in practice. These methods worked well when applied to the state estimator application; however, they face difficulty with convergence if the initial estimate is too far from the actual system.

It is also possible to address the problem of state estimation non-iteratively by providing an appropriate collection of measurements[4–6]; but, to reach the same level of least-squares errors; the non-iterative method requires additional measurements and calculations. The authors created a decentralized state estimator taking into account the fact that border buses serve two regions simultaneously.[7] Analyzing the condition number of the Hessian matrix, the authors identifies the numerical behaviour of the techniques used to solve the estimation problem.[8] The only problem that exist is how to address the real and reactive power injections at the border of the two regions because the states for both the regions are independently assessed. The solution of this problem is addressed in the literature[9] where the authors have solved the linear

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state estimation model with PMU measurement and non linear ones with the RTU measurements. Authors proposed a new agent paradigm in literature[10] for electrical distribution network status estimation. Local agents in secondary substations are entrusted with state estimation responsibilities. These utilize historical data and probabilistic methods to evaluate the substation's performance and detect bad data. Using actual sensor measurement data as input, a case study evaluates the practicability of the concept. A fundamental method for the assessment of the state that is decentralized and uses several areas is discussed in the literature.[11] This technique examines the condition of a multi-region electric energy system while ensuring that the independence of each area is maintained throughout the process. The method has the drawback that convergence can only be guaranteed under certain conditions, specifically those in which the coupling between regions is weak. The calculation of the normalised residual is ambiguous, which is another significant difficulty with this method. Complex and nonlinear optimization problems are resolved using artificial intelligence (AI) methods.[12,13] The state estimation problem was solved using the modified version of genetic algorithm.[14] The sensitivity of the proposed modified genetic algorithm to genetic operators is also discussed in the paper. The method is first applied to IEEE 6 and 14 bus systems before being compared to the conventional weighted least squares formulation. The results indicate that modified GA will perform better on extremely small bus systems, whereas the standard technique will perform better on large systems. Several papers based on the concept of artificial neural networks (ANN) is presented in the literature.[15,16] The technique of particle swarm optimization has been used in many studies. Improved PSO and gravitational search algorithms were presented in Mallik *et al*.[17] for estimating the states of power system. Naka estimates the states of the distribution system[18] using a hybrid PSO approach. The PSO method for power system state estimation has been compared to several models.[19] The process of utilizing various techniques to estimate the static condition of a power system has also been studied.

Several conventional and non-conventional techniques are present in the literature for state estimation. However, the analysis of the techniques using various statistical methods is missing in the literature. Furthermore, the choice of a particular approach for determining power system states from a statistical perspective is still not reported in the literature as per the author's knowledge. In addition, the incorporation of the concept of change in the bounds is also lacking in all evolutionary algorithms. Changes made to the upper or lower bounds considerably affect the ability to forecast system states.

The following are some of the most important contributions made by this paper:

- The assessment of the effectiveness and robustness of the various state estimation techniques such as the WLS, Genetic algorithm and Particle Swarm using parametric tests like ANOVA and Z-test.
- The comparative analysis of the conventional and heuristics technique using various statistical attributes.
- The idea of change in the bounds is incorporated to investigate its impact on estimating power system states through heuristic methods.
- The impacts of data manipulation on state estimation are examined using IEEE 6 and 14 bus test systems.

The structure of the paper is as follows:

The paper starts with an introduction to the topic and the literature survey. Then we have discussed the theoretical consideration of the state estimation. Here we have also discussed the state estimation problem formulation. The numerous conventional, evolutionary strategies and the statistical methods are discussed under section methodologies. The later part of the paper presents results and discussion based on the case studies on IEEE 6 and 14 bus systems. Various parametric tests outcomes along with their analysis are also discussed in this section. Finally, the last section of the paper brings this paper to a close, drawing relevant conclusions drawn from the comparative analysis.

Theoretical Considerations

State estimators are a vital technical tool for contemporary Energy Management Systems. State estimation is an essential monitoring technique for power systems. In modern power systems, it also serves as a filter for bad data as it can easily identify and eliminate bad data from the system. It can easily cater to small random errors in the meter readings and detect and identify severe measurement inaccuracies along with the inaccuracies that arise due to communication failure. State estimators are utilised by the EMS for several purposes, including the improvement of algorithms for Locational Marginal Pricing (LMP). It contributes to a reduction in the amount of congestion inside the power grid. The state estimation heavily relies on the data, especially measurement data i.e. real and reactive power injections, real and reactive power flows, voltage magnitude and angles etc. and the technique used for the estimation of the power system. State estimation is therefore one method for overcoming and approximating the unknown values while filtering out errors.

The primary objective of power system state estimation is to estimate the state variables at any given time, such as the magnitude and angles of the voltage. There are numerous approaches to state estimation that are in the literature. These include both conventional and non-conventional ways of doing things. However, because there are so many methods, choosing one method over another for state estimation is a further important aspect to consider. It is necessary to conduct a comparative analysis of the various techniques. Although only a few articles have presented a comparative analysis of the different strategies, there is still no comparison of the methods from a statistical point of view found in the published literature. Therefore, statistical tests are the ideal approaches to use when trying to undertake a comparative analysis of different procedures using statistical means.

State Estimation Problem Formulation

State estimation is optimizing a given set of criteria to determine the actual values of a system's state variables. Finding a solution to the problem is possible by utilising deterministic, iterative, or bounded algorithms such as GA and PSO. The following equation describes the correlation between actual values, estimated values, and errors in the measurements.

$$z = h(x) + e \qquad \ldots (1)$$

where,

z – measurement vector – order (m × 1);
x – estimated state vector – (n × 1);
h – vector of nonlinear functions;
e – measurement error vector – (m × 1).

Methodologies

Many approaches to resolving state estimate problems may be found in the relevant research literature. These approaches include both traditional and nonconventional methodologies.

Conventional Weighted Least Square Method

The WLS method is one of the most widespread and well-known approaches to evaluating a state's value. The main aim of this technique is to reduce the sum of the squares of the difference between each measured value and the estimated value by dividing each square difference by the meter error variance. The estimation of the power system states, which includes voltage magnitudes and angles, using the weighted least square method is explained in Fig. 1 using a process flowchart.

Evolutionary Algorithms

Apart from conventional techniques, the problem of power system state estimation can also be solved using evolutionary algorithms, which provide a global optimum solution to an optimization problem, which sometimes a conventional technique lacks.

In this study, the Genetic Algorithm and the Particle Swarm Optimization methods are employed to solve the state estimation problem. Both techniques are heuristic in nature. The Genetic Algorithm derived its concept from Darwin's principle of natural selection, wherein the fittest individual represents the most optimum solution to any optimization issue. Similarly, the Particle Swarm Optimization approach replicates the behaviour of bird flocks or fish schools and how they migrate together in search of food. In 1995, Kennedy and Eberhart were the first to introduce this technique as a heuristic technique.[20] Various literature exhibits the summaries of recent advancements in PSO.[21] There are several different implementations of PSO available in the research literature; however, the version given by Shi and Eberhart[22] is by far the most popular and is the one that is utilized the most frequently. In this implementation, the entire population is regarded as a single neighbourhood for the duration of the optimization process. Particle swarm optimization has numerous uses in the power system.[23]

The heuristic techniques are powerful and efficient compared to the random search methods as they give a global optimum solution to an optimization problem that conventional methods cannot. The fitness function that needs to be optimized for determining the states of the power system is given by:

$$F(x) = \min \; J(x) \qquad \ldots (2)$$

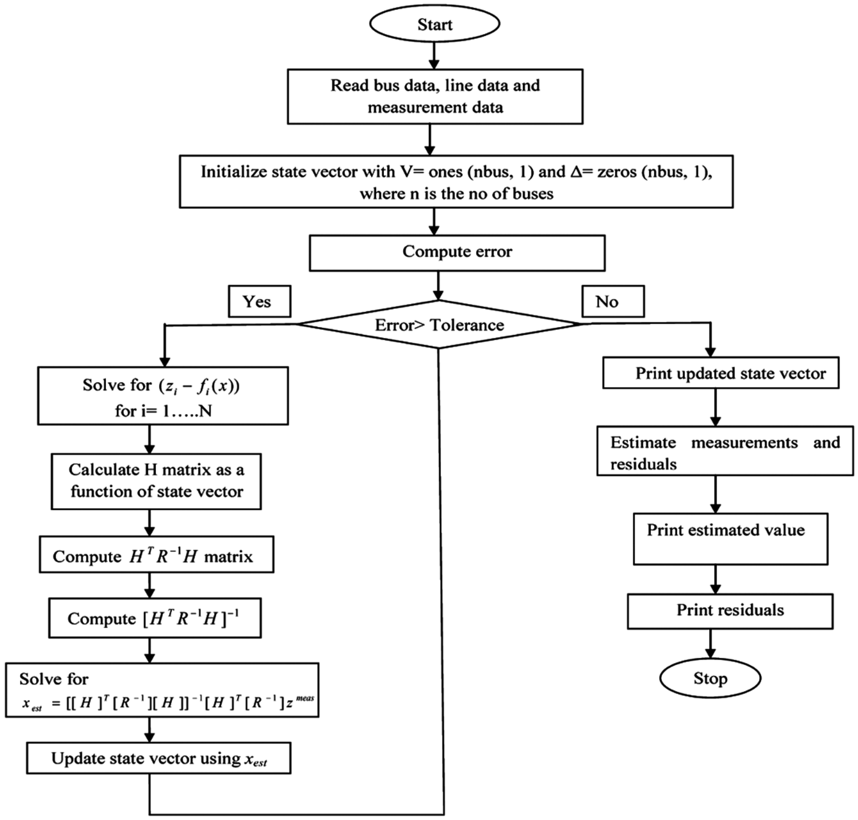

Fig. 1 — Process flow chart of implementation WLS for state estimation

Implementation of Evolutionary Algorithms

In present work the state estimation is also solved using evolutionary algorithms i.e. GA and PSO. The implementation of GA and PSO is presented through a flow diagram. The implementation of GA is presented thorough Fig. 2 and the implementation of PSO for state estimation is presented in Fig. 3 respectively.

Statistical Methods

There are two different statistical tests, namely parametric and non-parametric tests. Which test should one choose to take at this point? To accomplish this, we must analyze the data and determine the type of data we possess. If the information we are working with follows a normal distribution, we should select a parametric test; however, if the data do not follow a normal distribution, we should go with a non-parametric test. After analyzing the estimated data, we found that the data follows a characteristic curve of a normal distribution. As a result, we have decided to use parametric tests for the statistical analysis.

Parametric Tests

When the data follow a specific distribution, a statistician will apply a parametric test. In most contexts, parametric tests have more remarkable predictive ability than nonparametric tests. Comparatively, they call for a smaller number of samples than nonparametric tests. The analysis of variance, the z-test, the t-test and Pearson's Coefficient of Correlation are all examples of popular parametric tests. In this work, ANOVA and Z tests are chosen for statistical analysis to quickly compare the various statistical parameters of the techniques and come up with the most efficient and robust approach among all the selected methods.

- ***ANOVA (Analysis of Variance) -*** A test known as an ANOVA can determine whether or not the findings of a survey or experiment are statistically significant. Alternatively, we can say, they help decide whether one should reject the null hypothesis or accept the alternate hypothesis as an explanation for the data (Table 1). One-way and two-way are the two primary variations available. It is possible to do two-way tests with or without replication.

One- way ANOVA- We can apply a one-way analysis of variance (ANOVA) between groups to test for a difference between two groups.

Two- way ANOVA without replication- A two-way ANOVA without replication is performed when a single group is analyzed twice using the same criteria.

Two- way ANOVA with replication- In a two-way analysis of variance with replication there are two different groups, and members of each group are involved in more than one activity.

- ***Z test*** **-**A z-test is a statistical test used to determine if two population means differ when the variances are known and the sample size is large. In order to carry out an accurate z-test, it is necessary to assume that the test statistic follows a normal distribution. Moreover, an understanding of the standard deviation is necessary.

The formula for the z test involves comparing the z statistic and the z critical value to determine whether or not there is a substantial difference between the means of the two populations. The z critical value defines which fractions of the distribution graph are accepted and rejected while testing a hypothesis. If the test statistic falls within the region indicated for rejecting the null hypothesis, the null hypothesis can be rejected; if not, the null hypothesis cannot be rejected.

One sample z test: A one-sample test compares the sample mean to the population mean when the population's standard deviation is known.

Two sample z test: It checks whether the mean of two samples differs if a z test is performed on two samples.

Statistical analysis using a parametric test becomes essential when choosing the most appropriate technique among all the techniques used for state estimation. In this work, we have a set of base values obtained from NR load flow method. Then we have estimated the power system states using various state estimators, including conventional and non-conventional estimation techniques. The estimated states are the estimated values that include voltage magnitude and angle. For a technique chosen as the most robust and efficient state estimator, the estimated values of the voltage magnitude and angle should be very close to the base values; it can easily

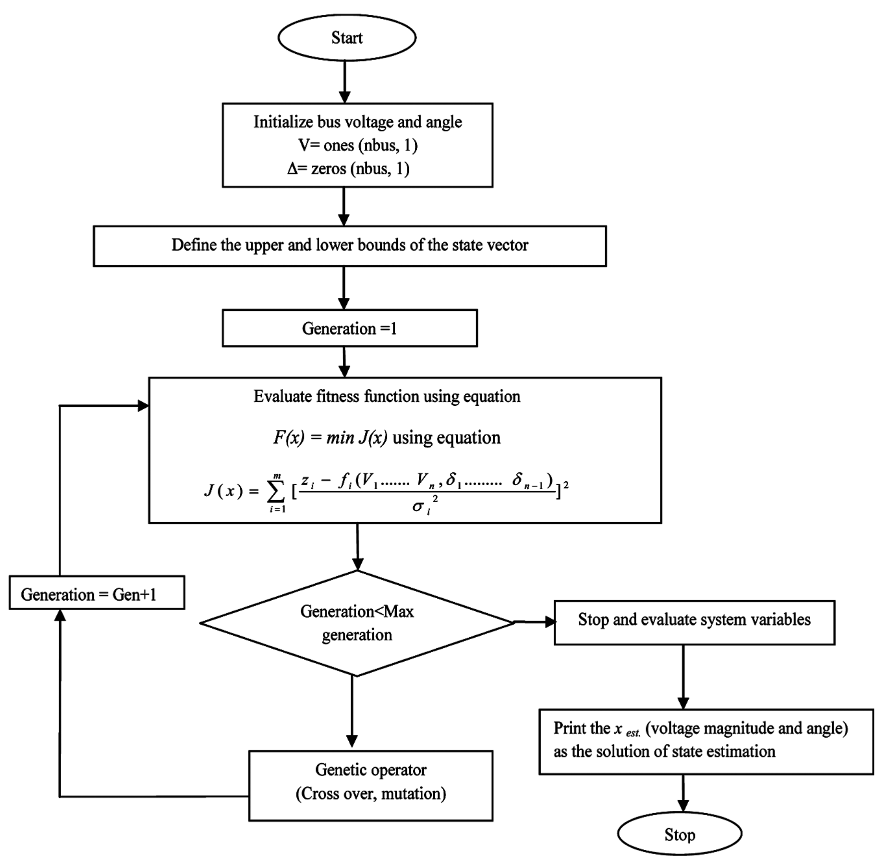

Fig. 2 — Process flow chart of implementation of GA for state estimation

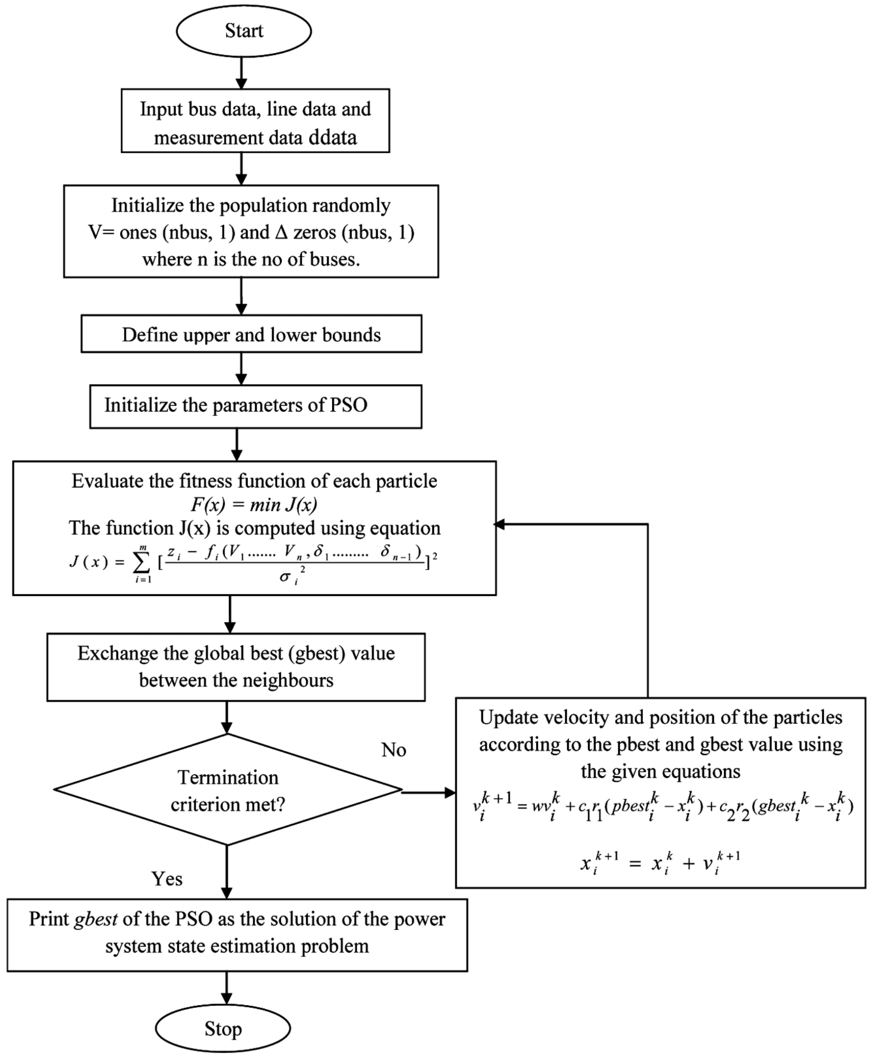

Fig. 3 — Process flow chart of implementation of PSO for state estimation

Table 1 — Matrix for a technique to be selected for state estimation

	Hypothesis Accepted for Voltage Magnitude	Hypothesis Rejected for Voltage Magnitude
Hypothesis Accepted for Voltage Angle	**Selected**	Not Selected
Hypothesis Rejected for Voltage Angle	Not Selected	Not Selected

be computed by comparing the base and estimated values. If the error is small, the estimated values are the actual replica of the base values.

Along with the percentage error check, some statistical tests are also essential to be performed so that we can choose the most suitable technique for performing state estimation in a power system. In order to carry out a parametric test, we need to start with the premise that there is no significant difference between the numbers we are using as our base and the values we have estimated. Then we will check the hypothesis after performing the tests and getting the p-values. If the base values and the estimated values are significantly different, the hypothesis will be rejected, and hence the state estimation technique will also be rejected. The techniques for which the hypothesis will be accepted will be chosen for state estimation.

In this paper parametric tests are performed on IEEE 14 bus system for the scenarios in which the data has been manipulated either by missing the data or by infringing the data. The tests are performed on the estimated data i.e. the voltage magnitudes and angles both. For a technique to be selected the following criterion needs to be full filled.

Results and Discussion

The present work deploys WLS, Genetic Algorithms, and Particle Swarm Optimization algorithms to experimentally evaluate their performance on standard IEEE 6 and 14 bus systems.[24] As evolutionary algorithms provide us with the global optimal solution to an optimization problem, it is essential to evaluate their performance when the bounds for the global optimal solution change. In addition, since estimates are based upon measured values, there is a substantial possibility that data will be overlooked or ignored during state estimation. Moreover, the deregulation of the power system has made the system more susceptible to FDI attacks. Players on the market can tamper with the measurement for monetary gain. Taking into account the likelihood of participant misconduct, a scenario is examined in which a state estimate is conducted under the situation of data infringement.

This paper analyses and compares the state estimation techniques using descriptive statistics and parametric tests. ANOVA and Z-tests are used to compare the different state estimators selected for this study. The parametric tests are performed on the IEEE 14 bus system for the missing and infringed data conditions to examine the robustness of the algorithms and select a specific technique to solve state estimation.

The parametric tests analyse the difference between the means of two independent populations and determine if the null hypothesis of no significant difference between the estimated and base values stays true. The tests are conducted in the present work between base values and estimated values obtained by various conventional and non conventional state estimators i.e. WLS, GA and PSO respectively.

The scenarios considered for the state estimation are:

i. When the bounds of the apparent optimal solution deviated by 2 per cent and 5 per cent, respectively, the states are estimated.
ii. When some measurement data is missing, the states are estimated. In this scenario, all bus systems have not considered the actual and reactive power flows between buses 2 and 5.
iii. When some measurement data is infringed, the states are estimated. In this instance, measurement data for the actual power flow between buses 1 and 2 are compromised.

A statistical analysis of the percentage error is conducted for each of the three scenarios outlined above. For evaluation purposes, the statistical attributes considered are: Mean, standard deviation, standard error, and parametric tests. The standard error is calculated as the sample, and population mean difference. The mean helps determine the data's central tendency, whereas the standard deviation determines the spread of the values from the mean value. The less standard error means the estimated values are a more accurate representation of base values. Finally, parametric tests are used to determine the validity of the hypothesis of a substantial difference between the estimated and base values.

IEEE 6 Bus Test System

Scenario 1 - Estimation of States considering variation in bounds

Descriptive Statistics Results

Results of the descriptive statistics for the scenario of variation in bounds are presented in Figs 4 and 5 for the IEEE 6 bus system. These statistics include the mean value of the percentage error computed from the

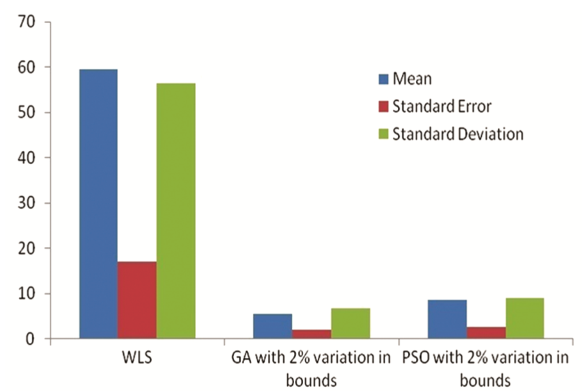

Fig. 4 — Results with 2% variation in bounds - IEEE 6 Bus

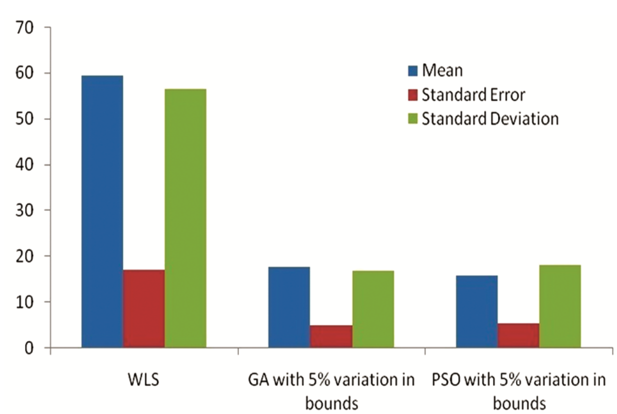

Fig. 5 — Results with 5% variation in bounds - IEEE 6 Bus

data sample of the percentage errors. It also includes the standard error and the standard deviation computed from the same data sample.

The comparison of the base states computed using the NR load flow method and states computed from state estimators (WLS, GA and PSO) with the variation of 2 per cent and 5 per cent in the bounds of the base states (magnitude of voltage and angle) gives the percentage error. The convergence graphs of genetic algorithm (GA) and particle swarm optimization (PSO) for variations of 2 per cent in the bounds of state variables obtained as the base states are illustrated in Fig. 6 and Fig. 7.

Result Analysis

For the case of variation in the bounds, it is seen in Figs 4 and 5 that the estimator utilizing a Genetic Algorithm as an optimization tool gives better results as compared to the other state estimation techniques. The percentage error, standard deviation, and standard error are considerably less compared to the conventional WLS technique. Furthermore, Figs 6 and 7 shows the convergence plots of GA and PSO, respectively, for 2 % variations in the bounds. It is found that the convergence of GA is faster as compared to PSO as GA is getting converged in 63 generations with the minimum value of fitness function, which is 4034.6, whereas the number of iterations in the case of PSO is 96. The minimum value of the fitness function is 4365.3, which is more compared to GA.

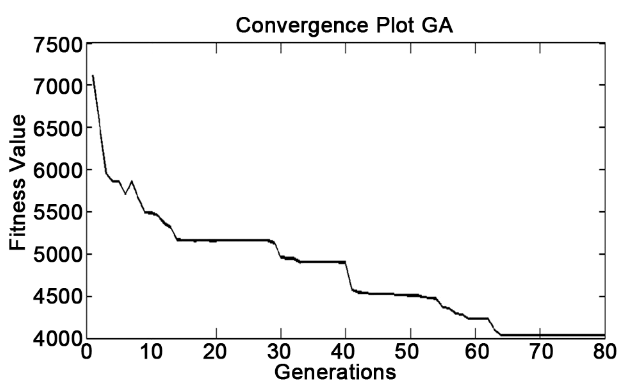

Fig. 6 — Convergence plot of GA with 2% variations in the bounds

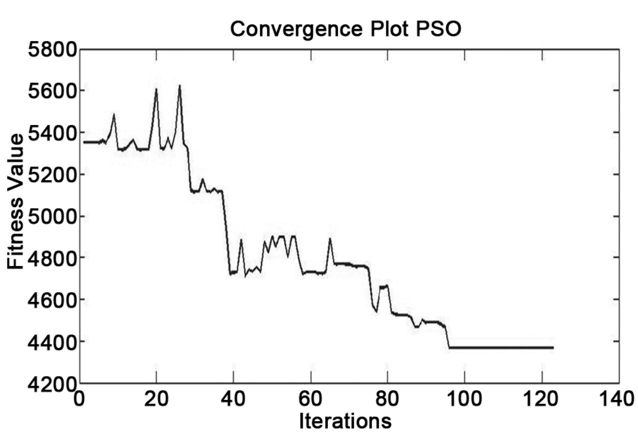

Fig. 7 — Convergence plot of PSO with 2% variations in the bounds

Scenario 2- Estimation of States with missing data

Descriptive Statistics Results

Considering the case when real and reactive power flow between bus no. 2 and bus no.5 is not taken into consideration, the descriptive statistical analysis findings are presented in Fig. 8. The figure (Fig. 8) shows the comparative analysis of the various state estimation techniques with statistical attributes like mean, standard deviation and standard error. The comparative analysis of the % error obtained from various state estimators is also shown in Fig. 9.

Result Analysis

The statistical summary results and the average percentage error results from WLS, GA and PSO are analysed in Fig. 8 and Fig. 9 with missing line measurement data. Observing the various statistical attributes, i.e. standard error, percentage error and standard deviation of all the state estimators, we

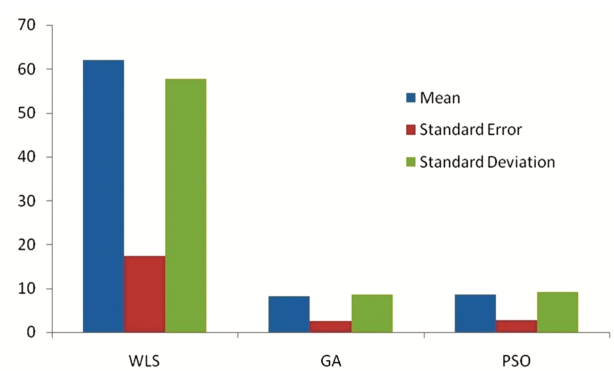

Fig. 8 — Descriptive statistical results with missing data –IEEE 6 Bus

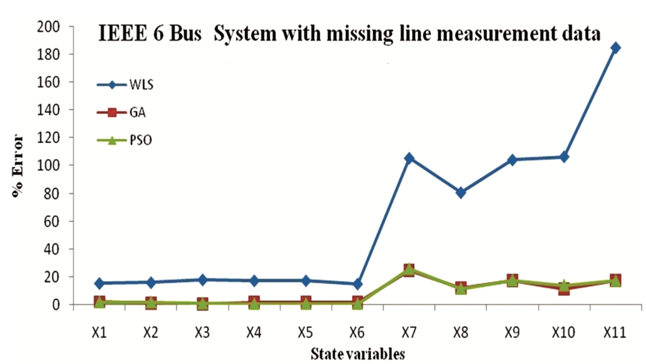

Fig. 9 — Variation in % error with missing data – IEEE 6 Bus

observed that they are the smallest in the GA state estimator. This was the case when real and reactive power flows between buses 2 and 5 were not taken into consideration.

Scenario 3- Estimation of States with infringed data

Descriptive Statistics Results

A descriptive statistical summary of the percentage error derived with all the state estimators when the measurement data for real power flow between bus no. 1 and bus no. 2 is infringed is shown in Fig. 10. The relative comparison of percentage errors for all state estimators is presented in Fig. 11.

Result Analysis

The outcomes of the statistical summary and average percentage error of estimated states utilising conventional Weighted Least Square technique and other evolutionary techniques, i.e. Genetic Algorithm and Particle Swarm Optimization technique considering manipulated measurement data, are examined in Fig. 10 and Fig. 11, respectively. Compared to alternative methods, it has been demonstrated that GA results in fewer errors overall, both in terms of the standard errors and the standard deviations. Despite this, the degree to which the data deviate from the central tendency is slightly more in the GA state estimator than in the PSO state estimator.

IEEE 14 Bus Test System

Scenario 1 - Estimation of States considering variation in bounds

Descriptive Statistics Results

For IEEE 14 bus system, the results of the descriptive statistics for the scenario of variation in bounds are provided in Figs 12 and 13. The statistical parameters presented in the figures (Figs 12, 13) include the data of the mean value of the percentage error. It also includes the computed standard error for the given data sample of the percentage error and the standard deviation computed from that data sample. The percentage error can be calculated by comparing the base states computed using the NR load flow method with the states computed from state estimators (WLS, GA, and PSO) with the variation of 2% and 5% in the bounds of the base states (voltage magnitude and angle).

Result Analysis

In IEEE 14 bus system also for the case of variation in the bounds, it is seen in Figs 12 and 13

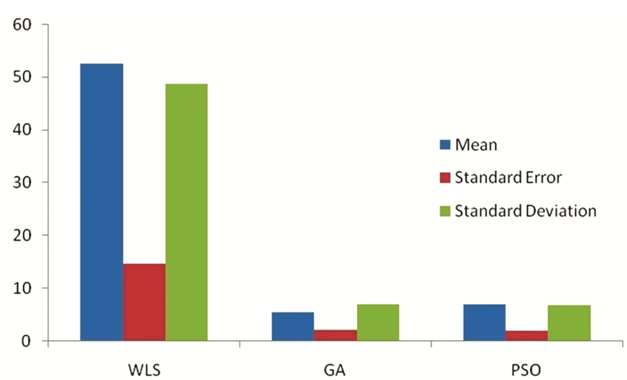

Fig. 10 — Descriptive statistical results with infringed data –IEEE 6 Bus

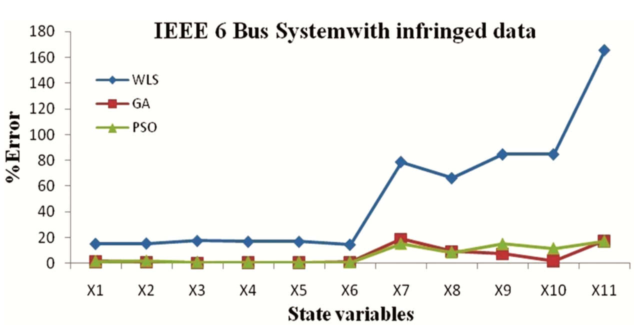

Fig. 11 — Variation in % error with infringed data – IEEE 6 Bus

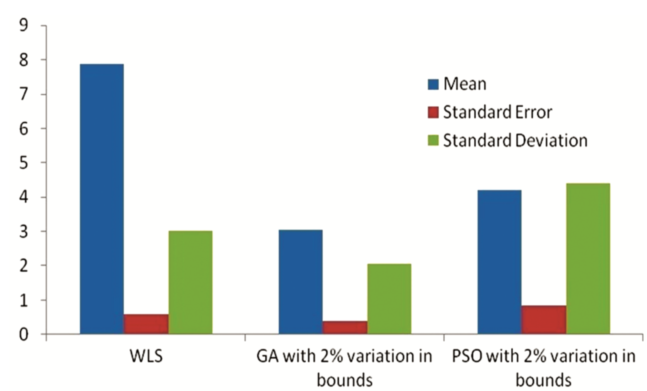

Fig. 12 — Results with 2% variation in bounds - IEEE 14 Bus

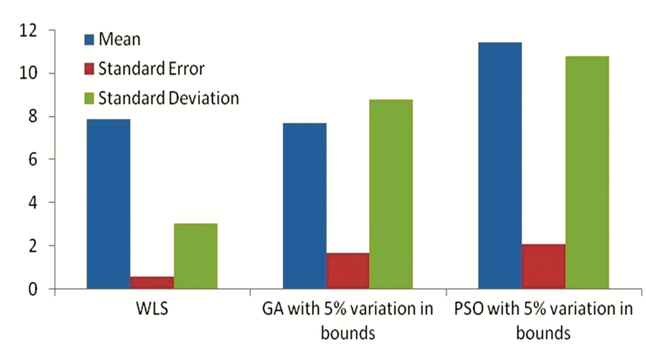

Fig. 13 — Results with 5 % variation in bounds - IEEE 14 Bus

that the estimator utilizing a Genetic Algorithm as an optimization tool gives better results as compared to the other state estimation techniques. The percentage error, standard deviation, and standard error are considerably less compared to the conventional WLS technique. We have also seen that with the increase in the percentage of variation in the bounds the percentage errors are also increasing for all the estimators, so it is always better to have minimum variation in the bounds.

Scenario 2- Estimation of States with missing data

Descriptive Statistics Results

A descriptive statistics of the percentage error obtained for the IEEE 14 bus without considering the reactive and real power flow between bus no.2 and bus no.5 is shown in Fig. 14. The comparative results of the various state estimators, showing the relative differences in percentage error across all methods when measurement data were missing are also presented in Fig. 15.

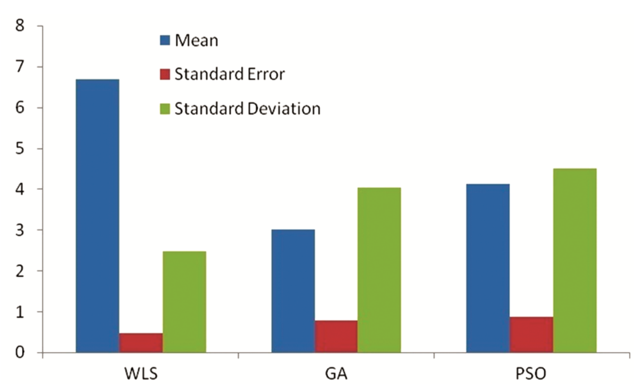

Fig. 14 — Descriptive statistical results with missing data –IEEE 14 Bus

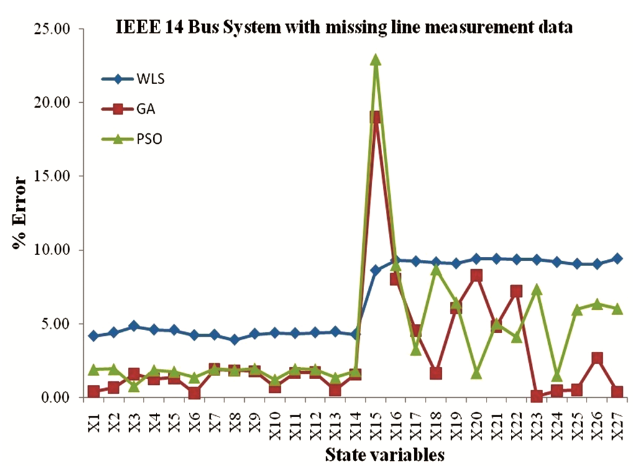

Fig. 15 — Variation in % error with missing data – IEEE 14 Bus

Result Analysis

Analyzing the statistical summary results of WLS, GA and PSO from Fig. 14, and average percentage error from Fig. 15 with missing line measurement data when real and reactive power flows between bus 2 and 5 are not taken into consideration, again it is found that the statistical attributes related with percentage error are lowest in GA based state estimator as compare to the other techniques.

Parametric Tests Results

The parametric test results with ANOVA for the estimated values of voltage magnitudes and angles are computed for the scenario where some missing measurement data between bus no. 2 and bus no. 5 are presented in Tables 2 and 3, respectively. These tables contain the parametric test results with ANOVA for the voltage magnitudes and angles. On the other hand, the outcomes of the Z test for the same are presented in Tables 4 and 5.

Result Analysis

- ***ANOVA (Analysis of Variance) Test Results***

- The ANOVA test results are provided in Tables 2

Table 2 — Test results with ANOVA for voltage magnitude in case of missing data

	WLS	GA	PSO
F- Value	29.74435	0.36965	1.10293
P- Value	1.02E-05	0.54847	0.30328
F Critical	4.225201	4.22520	4.225201

Table 3 — Test results with ANOVA for voltage angle in case of missing data

	WLS	GA	PSO
F- Value	0.367583	0.027776	0.018036
P- Value	0.549582	0.868925	0.8942
F Critical	4.225201	4.225201	4.225201

Table 4 — Test results with Z- test for voltage magnitude in case of missing data

	WLS	GA	PSO
Z value (one tail)	5.454829397	0.608198192	−1.05053237
P value	2.45099E-08	0.271528017	0.146736708
Z critical (one tail)	1.644853627	1.644853627	1.644853627

Table 5 — Test results with Z- test for voltage angle in case of missing data

	WLS	GA	PSO
Z value (one tail)	0.60629191	−0.16667	−0.1343
P value	0.272160465	0.433817	0.446582
Z critical (one tail)	1.644853627	1.644854	1.644854

and 3 for the case with missing data. For a hypothesis to be accepted, the p-value must be more than 0.05, and the F-value must be less than the F critical value. The p-value for WLS is less than 0.05, and the F- value is greater than the F critical value, indicating a substantial difference between the base value and the estimated value of voltage magnitude. Therefore, the hypothesis regarding the magnitude of the voltage is rejected. In contrast, the p- values for both GA and PSO are greater than 0.05 and the F- values are smaller than the F- critical values. Therefore, both the GA and PSO hypotheses are accepted.

Although, in the instance of voltage angels, the p-value is greater than 0.05 and the F-value is less than the F critical value, we can conclude that there is no significant difference between the base and the estimated value and accept the null hypothesis. The ANOVA test yields p-values more than 0.05 and F-values smaller than the F critical values for both GA and PSO. So again, the hypothesis is accepted by both.

Nonetheless, it is evident from Table 1 that both hypotheses must be accepted when choosing a technique. One hypothesis is accepted, and one is rejected for WLS, but both hypotheses are accepted for GA and PSO. When selecting a strategy for estimating the states of a power system, they will be given preference. Therefore, we can conclude that evolutionary procedures perform better than standard methodologies for state estimation.

- ***Z- Test Results -*** When actual and reactive power flows between bus no. 2 and bus no. 5 are omitted, the z-test results from Tables 4 and 5 are analysed to evaluate whether or not there is a statistically significant difference between the two sets of data. Regarding the magnitudes of voltage, the p-value for WLS is less than 0.05. The value of z is more than the z critical value, indicating a considerable difference between the base and the estimated magnitude of the voltage. Therefore, the hypothesis is rejected for WLS. However, the hypothesis is supported for GA and PSO because the p-value is more than 0.05, and the z value is less than the z critical value.

In the case of voltage angels, however, the hypothesis is accepted for all three procedures because the p-value is more than 0.05, the z-value is smaller than the z critical value, and there is no significant difference between the base and estimated value. Also, based on this test, we may conclude that GA-based estimators are preferable to WLS for state estimation.

Scenario 3- Estimation of States with infringed data

Descriptive Statistics Results

The statistical analysis of the % error that occurs when the measurement data for the real power flow between bus no. 1 and bus no. 2 is manipulated is presented in Fig. 16. As can be seen, Fig. 17 presents an analysis and comparison of the percentage error for each state estimator with infringed data.

Result Analysis

Using Fig. 16 and Fig. 17, respectively, are the statistical summary and the average percentage error of State Estimation when applying WLS, GA, and PSO with infringing data are analyzed. The dispersion of data from the central tendency is considerably greater in GA than in other state estimators; nevertheless, all of the other statistical features are lower in GA than in other state estimators.

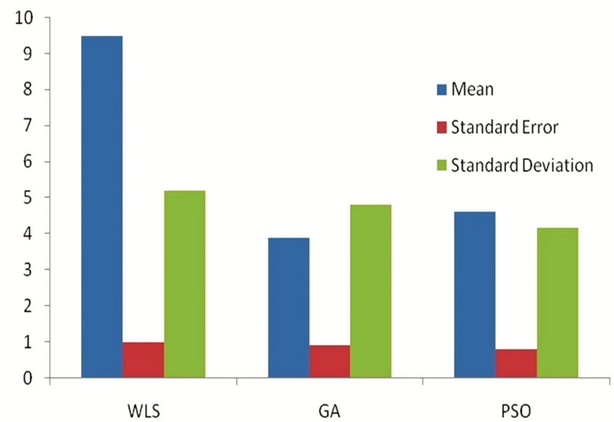

Fig. 16 — Descriptive statistical results with infringed data –IEEE 14 Bus

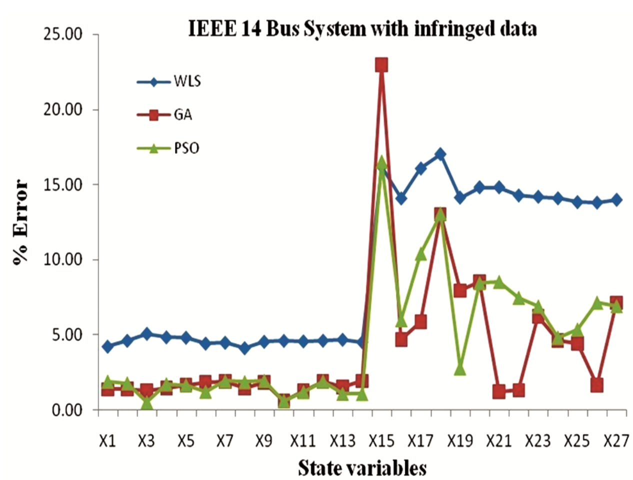

Fig. 17 — Variation in % error with infringed data – IEEE 14 Bus

Parametric Tests Results

The ANOVA test is applied for both the voltage magnitude and angles acquired from various state estimators. The parametric test ANOVA results are presented in Tables 6 and 7 for the case when some tampering with the measurement data is done. In contrast, the findings of the Z-test for the same are presented in Tables 8 and 9, respectively.

Result Analysis

- ***ANOVA (Analysis of Variance) Test Results* -** Results obtained from the ANOVA test are presented in Tables 6 and 7 for the scenario of infringed data. From the results, it is seen that, in the case of voltage magnitudes, the p-value for WLS is smaller than 0.05 and the F- value is more than the F critical value, which means there is a significant difference between the base and the estimated value of voltage magnitude. Hence the hypothesis is rejected for the case of voltage magnitude. In the case of GA and PSO, both the p- values are more than 0.05 and F- values are less than F- critical values. Hence the hypothesis for both GA and PSO is accepted.

Although in the case of voltage angels, in WLS, the p-value is more than 0.05 and the F- value is less than F critical value; hence, we can say that there is no significant difference between the base and the estimated value hypothesis is accepted. For GA and PSO, the p-values computed from the ANOVA test are more than 0.05 and the F- values are less than the F critical values. So the hypothesis is again accepted for both.

It is very much clear that both hypotheses must be accepted for selecting a technique. For WLS, one hypothesis is accepted, and one is rejected, while for GA and PSO, both are accepted. They will be given preference when selecting a strategy for estimating the states of a power system. Therefore, we can conclude that evolutionary processes perform better for state estimation than conventional techniques.

- ***Z- Test Results* -** The results of the z-test from Tables 8 and 9, when measurement data for real power flow between bus no.1 and bus no.2 are infringed, are analysed to determine whether or not there is a significant difference between the two sets of data. In the case of voltage magnitudes, the p-value for WLS is smaller than 0.05. The z value is more than the z critical value, which means there is a significant difference between the base and the estimated value of voltage magnitude. Hence the hypothesis is rejected for WLS, whereas, for GA and PSO, the hypothesis is accepted as the p-value is more than 0.05 and the z value is less than the z critical value.

Although in the case of voltage angels, the hypothesis is accepted for all three techniques as the p-value is more than 0.05, the z value is less than the z critical value, and there is no significant difference between the base and the estimated value. So from this test also, we can conclude that GA-based estimators are better to use for state estimation than WLS.

Table 6 — Test results with ANOVA for voltage magnitude in case of infringed data

	WLS	GA	PSO
F- Value	32.86955027	1.360909	0.61016
P- Value	4.91E-06	0.253969	0.441783
F Critical	4.225201	4.225201	4.225201

Table 7 — Test results with ANOVA for voltage angle in case of infringed data

	WLS	GA	PSO
F- Value	0.870885	0.023287	0.005892
P- Value	0.359296	0.879892	0.939405
F Critical	4.225201	4.225201	4.225201

Table 8 — Test results with Z test for voltage magnitude in case of infringed data

	WLS	GA	PSO
Z- Value (one tail)	5.734941	1.16681	−0.78134
P- Value	4.88E-09	0.12164	0.217301
Z Critical (one tail)	1.644854	1.64485	1.644853

Table 9 — Test results with Z test for voltage angle in case of infringed data

	WLS	GA	PSO
Z- Value (one tail)	0.93322	−0.1526	−0.07676
P- Value	0.17535	0.43935	0.46940
Z Critical (one tail)	1.64485	1.64485	1.64485

Conclusions

We have analysed all the results obtained from GA based state estimator and compared them to the WLS state estimator and the PSO based state estimation strategies. We concluded that the GA based state estimation strategy is the one that is best suited for investigating state estimation with a high level of accuracy. All test systems had relatively low mean values for their percentage errors, standard deviations, and overall standard errors when using GA. In addition, parametric tests such as ANOVA and Z-tests are also used to evaluate the estimators. The findings of the parametric tests point to the fact that evolutionary methods are superior to conventional approaches in terms of their accuracy as state estimators. Therefore, based on the research on error analysis and the parametric tests, we can determine that the GA-based state estimation technique is the most appropriate SE process out of the three processes involving statistical factors.

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