Research Article

Reverse harmonic load flow analysis using an evolutionary technique

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Abstract

In the present paper, a new approach to estimate the harmonic distortions is proposed by considering the existence of harmonic sources in the power system. The algorithm employs a differential evolution technique by formulating the reverse harmonic load flow problem for each harmonic order and by considering a limited number of phasor measurement units (PMUs) deployed across the power system. The technique utilizes the measured voltage and current harmonics obtained using synchronized PMUs with known transmission network as input data. The proposed technique estimates the harmonic voltage phasors at the unmonitored buses of the power system with reasonable accuracy. The effectiveness and efficiency of the proposed method is validated by applying it to five bus and IEEE 14-bus test systems by considering uncertainty in measurement noise. It is shown that the proposed approach yields optimum solution and provides reliable and accurate harmonic state estimates.

Keywords Differential evolution · Reverse harmonic power flow · Harmonic state estimation · Harmonic voltage phasor

1 Introduction

With the significant growth of power electronic devices has led to an increase in the harmonic distortion of power supply waveform [1]. Harmonic distortion can be defined as the voltages and currents having frequencies that are integer multiples of the fundamental frequency and further any deviation from the perfect sinusoidal waveform [2]. The penetration of these harmonics into the system not only affects the quality of power supply but also causes a severe problem in various power system components [1]. In order to maintain high-quality power supply, these harmonic sources should be assessed, monitored, and mitigated [3]. Because of this reason, harmonic analysis has become a vital factor in power system analysis and design.

Harmonic state estimation (HSE) is a reverse procedure to harmonic load flow analysis. In harmonic power flow analysis, response (harmonic distortion) of the power system is determined by injecting harmonic sources at one or more locations of the power system network. Whereas in HSE, harmonic sources (harmonic injections) are evaluated for the power system network response given by a set of harmonic measurements [1]. Although the measurement meters are becoming less costly, it is neither efficient nor essential to deploy phasor measurement units (PMUs) at every bus of the power system to perform state estimation. Consequently, various PMU placement methods have been developed to deploy these PMUs optimally across the power system network. In such circumstances, the HSE process is suggested when limited locations are selected for the installation of PMUs [4]. The HSE process utilizes a set of measurements obtained from PMUs along with the system configuration supplied by the topological processor, network parameters, PMU meter location, and measurements to estimate the harmonic states of the power system [4].

In [5], HSE is performed by using the least-square based state estimation to compute the frequency spectra at various buses that are suspected as harmonic sources. The

authors in [6] have identified and tracked the harmonic sources present in the power system using the conventional Kalman filter technique. In [7], wavelet transform is described as more suitable for small frequency varying signals; however, this method suffers from a high computational burden. To overcome this drawback, the computational time taken by HSE algorithm is reduced by utilizing the parallel processing technique for harmonic monitoring in [8]. Further, at non-monitored buses, historical load data is used.

Similarly, the authors in [9] suggested a fast and accurate HSE based on the concept of matrix algebra and using a genetic algorithm (GA) optimization technique. In [10], L1-norm minimization method is utilized to solve HSE by formulating it as a constrained Sparsity maximization method. The concept of safety barrier interior point technique based on weighted least square (WLS) methodology is suggested in [11] by considering harmonic branch currents as state variables. However, the conventional WLS approach may not converge in the presence of uneven measurement weights. To overcome this drawback, various soft computing techniques such as artificial intelligence method based on back proportion neural network algorithm [12], genetic algorithm (GA) [13], evolutionary strategy [4], particle swarm optimizer (PSO) [14], and modified artificial bee colony [15] have been proposed by the researchers. However, AI, GA, and PSO techniques take long computational time to converge, and often these methods struck in local minima [16]. Further, the genetic algorithm technique suffers from high computational time and the performance of PSO is sensitive to change in control parameter settings [17, 18]. Therefore, to overcome these drawbacks, several hybrid optimization techniques have been proposed in the literature.

In [19], a hybrid optimization technique based on the firefly algorithm and recursive least square (RLS) is suggested to estimate the magnitude and phase angle of electrical harmonics. Subsequently, RLS and biogeography-based optimization (BBO) [20, 21], particle swarm optimization (PSO) and gradient decent (GD) method [22], weighted least squares (WLS) and SVD [23], genetic algorithm and least square method [24], genetic algorithm based on adaptive perceptron [25], gravity search algorithm (GSA) and RLS [26] have been suggested to estimate the harmonic voltage phasors at all the buses. It has been observed that this approach has improved the accuracy in estimating the harmonic states of the power system when compared to individual optimization techniques. However, the sensitivity of these techniques to various levels of measurement noises has not been tested while estimating the harmonic state estimates. Further, these techniques require tuning of a large number of control variables to obtain the desired accuracy. Therefore, the contribution of the present work is threefold: (1) to propose hybrid differential evolution and weighted least square technique to reverse harmonic load flow problem. (2) To investigate the efficiency of the proposed method by performing the sensitivity analysis under various measurement noise levels. (3) To provide accurate harmonic state estimates by considering a limited number of PMUs. Further, to validate the efficacy of the proposed scheme, it is applied to five bus and modified IEEE 14-bus systems.

The present paper is alienated into various sections. The outline of the harmonic state estimation problem is introduced in Sect. 2. Implementation of differential evolution to harmonic state estimation is explained in Sect. 3. Simulation study to perform HSE is described in Sect. 4. Section 5 provides the results and discussion. Finally, conclusions are drawn in Sect. 5.

2 Outline of the harmonic state estimation problem

HSE uses few coordinated measurements that provide harmonics voltage/current phasors, and voltage dips to determine the harmonic sources in the power system network. As the costs of the PMUs are high, it is uneconomical to install meters on every bus. Therefore, these PMUs are strategically installed at some of the buses to obtain a unique solution for a given problem and to make the entire power system network observable [27].

A general mathematical model for harmonic state estimation, which relates measurement vector Z to state variable vector X is given by

$$Z(h) = H(h).X(h) + e(h) \tag{1}$$

where $Z(h)$ represents the measurement vector, $H(h)$ denotes the measurement matrix, $X(h)$ is the state variable vector, $e(h)$ signifies the measurement error, and h represents the harmonic order. The HSE is formulated using the harmonic load model and harmonic measurements.

In the proposed method, the harmonic voltages are considered as state variables. Once these harmonic voltages are estimated, harmonic injection current and branch current flows are calculated according to (2) and (3), respectively.

$$I(h) = Y(h).V(h) \tag{2}$$

where $I(h)$ represents the nodal harmonic current injection measurement, $Y(h)$ is the nodal admittance matrix, $V(h)$ denotes the nodal harmonic voltages, and h is the harmonic order.

$$I_B(h) = Y_{BN}(h).V(h) \tag{3}$$

where $I_B(h)$ is the harmonic branch current, $Y_{BN}(h)$ is the harmonic node-line admittance matrix, $V(h)$ is the nodal harmonic voltages, and h is the harmonic order [27].

3 Implementation of differential evolution for harmonic state estimation

HSE problem is the process of evaluating the state of the power system for each harmonic order by making use of measurement data. The state of the system is defined as the voltage phasors at all the buses. The measurement data consists of voltage and current harmonics of the monitored buses that are obtained from PMUs. These PMUs are deployed optimally across the power system due to the high installation cost. The process of performing reverse harmonic load flow analysis using differential evolution is summarized in Fig. 1. Here, the DE algorithm [28] is utilized to minimize the difference between the measured and estimated values of voltage phasor, thus minimizing the error. The main steps involved in implementing the HSE are explained below.

Step 1 In the first stage, fundamental frequency state estimation is performed using DE by considering delta connected static VAR compensator (SVC) as a harmonic source. The voltage phasor obtained is used for calculating the current injection at the harmonic bus.

Step 2 In the second stage, harmonic penetration analysis is performed bestowing to CIGRE working group [29],

and passive elements are considered to behave linearly with frequency. Here, in this step due to the absence of actual field data, harmonic load flow analysis is performed using (2) and (3).

Step 3 Now select the harmonic order h. In the present work 5th, 7th, 11th, and 13th harmonics are considered.

Step 4 For each harmonic order, the population and control parameters of the DE are initialized.

Step 5 In the proposed method, a subset of nodal harmonic voltage phasors $V(h)$ and harmonic branch current phasors $I_B(h)$ obtained from the harmonic analysis is considered as a measurement set for harmonic order h. Now fitness of each chromosome is calculated according to the objective function shown in (4) for each corresponding harmonic order h.

$$\min J(X) = \sum_{i=1}^{n_{meas}} \frac{\left(V_{hM}^i - V_{hcalc}^i\right)^2}{\sigma^2} + \frac{\left(I_{B,hM}^i - I_{B,hcalc}^i\right)^2}{\sigma^2} \tag{4}$$

where n_{meas} denotes the number of measurements, V_{hM}^i represents the ith measured voltage of harmonic order h, $I_{B,hM}^i$ depicts the ith branch current 'B' measurement of harmonic order h, V_{hcalc}^i is the ith estimated voltage of harmonic order h, $I_{B,hcalc}^i$ represents the ith estimated branch current 'B' of harmonic order h.

Step 6 Now, initialize the iteration count of the DE algorithm by setting it as $i = 1$.

Step 7 In this step, the difference vector mutation is performed for each chromosome by selecting three other different chromosomes to obtain a target vector.

Step 8 In this step, a binomial crossover operation is performed to obtain a trial vector.

Step 9 After obtaining the trial vector, the selection is performed between the trial vector and the target vector. The best chromosome is selected for the next generation. Next increment the iteration count $i = i + 1$.

Step 10 If stopping criteria is not obtained, then go to step 6 else go to step 11.

Step 11 Now increment the harmonic order $h = h + 1$. If the states of the power system are obtained for each harmonic order, then go to the next step else go to step 3.
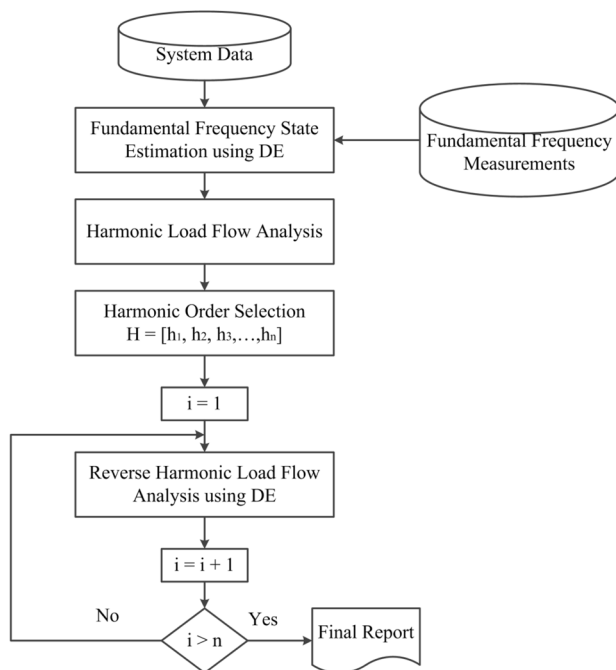
Step 12 Stop.

3.1 Overview of differential evolution algorithm

DE algorithm proposed by Price and Storn in the year 1995 is a numerical optimization technique that solves real-world problems using the principle of natural evolution. Alike, all other evolutionary techniques, DE produces an initial population P of size NP is randomly generated by sampling across the search space. Each individual in the population is termed as target vector [28].

Fig. 1 Flowchart of proposed power system HSE algorithm

$$P = \{y_i = (y_{i,1}, y_{i,2}, y_{i,3}, y_{i,4}, \ldots, y_{i,D}), \, i = 1, 2, 3, \ldots, NP\}$$
(5.1)

$$y_{i,j} = y_j^{\min} + rand.(y_j^{\max} - y_j^{\min}), \, j = 1, 2, 3, 4, \ldots, D$$
(5.2)

where $y_j^{\min}$ and $y_j^{\max}$ denote the lower and upper bounds of jth decision variable, NP represents the size of the population, D indicates the number of variables and *rand* is a uniformly distributed random number generated between 0 and 1.

After initialization, at each generation G, difference vector mutation is performed on each target vector y_i to obtain mutation vector v_i in the following way.

$$v_i = y_{r1} + F.(y_{r2} - y_{r3}), \, i = 1, 2, 3, 4, \ldots, NP$$
(6)

where r_1, r_2, and r_3 represent three distinct vectors (integers) that are selected randomly from [1, NP] and also different from ith vector, and F denotes the scaling factor.

Now, crossover operation is performed on the mutation and target vectors to obtain a trial vector u_i according to (7) [28]. This process enhances the diversity of the population by combining both the target vector and the mutation vector.

$$u_{i,j} = \begin{cases} v_{i,j}, & \text{if } rand_j \leq CR \text{ or } j = j_{rand} \\ y_{i,j}, & \text{otherwise} \end{cases}$$
(7)

where j_{rand} is a random number between 1 and D to make sure that the trial vector u_i is different from target vector y_i in at least one dimension, $rand_j$ represents a uniformly distributed random number generated between 0 and 1, and CR denotes the crossover rate.

Finally, the selection operation is performed between the target vector and the trail vector to select the better individual that survives for the next generation or iteration [28].

$$y_i = \begin{cases} u_i, & \text{if } f(u_i) \leq f(y_i) \\ y_i, & \text{otherwise} \end{cases}$$
(8)

This procedure is repeated for several iterations/generations till stopping criteria is achieved allowing the individuals in the population to enhance their fitness value as they explore the search space in obtaining the optimal solution.

A detailed explanation of the conventional DE algorithm can be found in [28]. The process of finding an optimum solution using differential evolution is summarized in Fig. 2.
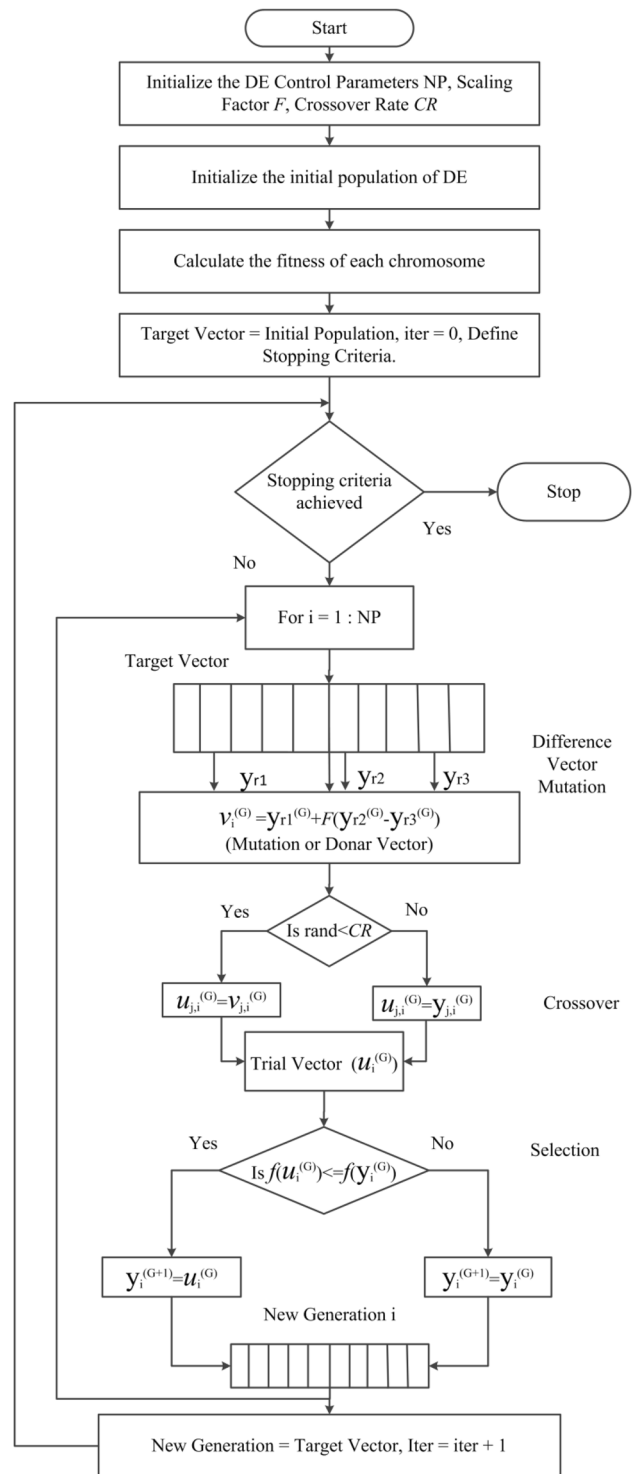

Fig. 2 Flow chart of DE for HSE

4 Simulation study

To verify the efficacy of the algorithm, the proposed HSE using DE method has been performed on five bus [29] and modified IEEE 14-bus system [30, 31]. For both the systems,

a delta connected SVC has been considered as a harmonic source whose current harmonic spectrum is given in [29] and [30], respectively. Further to verify the robustness of the proposed method, harmonic state estimation is performed on three different cases, namely, without measurement error, by introducing a 5% Gaussian measurement error, and by introducing a 10% Gaussian measurement error in each measurement. Moreover, in the present work for each harmonic frequency, harmonic voltage and current phasor measurements are taken as state variables. Hence, for an N bus system, the total number of state variables will be 2 N, i.e. N number of voltage magnitudes and N number of voltage angles. In the absence of actual field data, harmonic load flow is performed using (2) and (3) with a given admittance matrix and harmonic current injection to obtain the required measurement set [10]. For this purpose, the harmonic source is considered at buses 5 and 3 for five and IEEE 14 bus systems, respectively.

After obtaining the measured values, HSE using DE is performed at each harmonic frequency by considering both noiseless measurements and noisy measurements, and the harmonic voltage error is calculated using (9) and (10). Further, comparative results are not provided due to the data provided in other references is not the same as the data considered in the present work.

$$(\%) \, Harmonic \text{ voltage magnitude error} = \frac{|V_{base} - V_{estimated}|}{V_{base}} \times 100 \tag{9}$$

$$(\%) \, Harmonic \text{ voltage angle error} = \frac{|\theta_{base} - \theta_{estimated}|}{\theta_{base}} \times 100 \tag{10}$$

According to the author's experiments, the control parameter values provided in Table 1 are found to be appropriate for performing HSE for five and IEEE 14-bus systems. These control parameter values are obtained using the trial and error method by selecting various ranges of these values. For instance, for the selection of population size the population range of [25, 50, 75, 100, 125] has been considered. Similarly, for the selection of scaling constant F the range of [0.6, 0.8, 1, 1.2] and for the selection of crossover rate CR the range of [0.2, 0.4, 0.6] have been considered. Now, for each combination, the

algorithm is executed for 10 trials. It has been found that the number of trials has not affected the solution to a large extent. However, the different combinations of control parameters delivered a different solution. Among them, the better solution obtained by the combination of control parameters for all the trials is tabulated in Table 1.

5 Results and discussion

The effectiveness and efficiency of the proposed DE algorithm are verified by applying it to two test systems, namely five bus and IEEE 14 bus systems. The sensitivity of the proposed method to various measurement noises is analyzed under three different conditions, namely by considering noiseless measurements, with measurement noise of $\pm 5\%$, and with measurement noise of $\pm 10\%$, respectively.

5.1 Test case 1. Five bus system

5.1.1 Case A: without measurement noise

In this case study, HSE using DE has been performed in the absence of measurement error. Therefore, after performing harmonic power flow analysis, the requisite measurements are taken by the PMUs installed at different buses. It can be seen from Fig. 3 that the total number of PMUs required to make the power system observable is one that is placed on bus 2. Thus voltage phasor measurement at bus 2 and current phasor measurements flowing through transmission lines between buses {2-1, 2-3, 2-4, and 2-5} form the measurement set and considered for HSE. The results thus obtained from reverse harmonic load flow analysis are tabulated in Tables 2, 3, 4 and 5 for various harmonic frequencies 5, 7, 11, and 13, respectively. It can be observed that harmonic voltage error (the difference between estimated and actual value) that is calculated using (9) and (10) are small viz. less than 0.3%. Further, it is to be noted here

Table 1 Parameter selection for HSE using DE

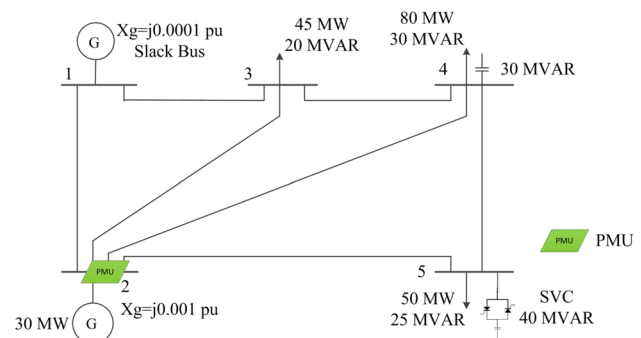| System\control parameters	Population size NP	Scaling constant F	Crossover rate CR
5-bus system	50	0.8	0.4
IEEE 14-bus system	100	0.8	0.4

Fig. 3 Five bus system with PMU placed at bus 2

Table 2 Estimated 5th harmonic voltage values for five bus system

Bus no.	Base voltage (p.u)	Estimated voltage (p.u)	Base angle (rad)	Estimated angle (rad)	% harmonic voltage error
1	0	0	1.8870	1.8869	0
2	0	0	2.4042	2.4042	0
3	0.0017	0.0017	1.7456	1.7455	0.1040
4	0.0021	0.0021	1.8157	1.8078	0.0136
5	0.0052	0.0052	2.5911	2.5968	0.0118

Table 3 Estimated 7th harmonic voltage values for five bus system

Bus no.	Base voltage (p.u)	Estimated voltage (p.u)	Base angle (rad)	Estimated angle (rad)	% harmonic voltage error
1	0	0	1.0218	1.0220	0
2	0	0	2.0754	2.0754	0
3	0.0012	0.0012	0.8440	0.8440	0.0122
4	0.0015	0.0012	0.9273	0.9269	0.0423
5	0.0033	0.0033	2.5536	2.5536	0.1224

Table 4 Estimated 11th harmonic voltage values for five bus system

Bus no.	Base voltage (p.u)	Estimated voltage (p.u)	Base angle (rad)	Estimated angle (rad)	% harmonic voltage error
1	0	0	−0.0825	−0.0825	0
2	0	0	2.5719	2.5719	0
3	0.0003	0.0003	−0.3217	−0.3218	0.0714
4	0.0004	0.0004	−0.1081	−0.1082	0.0657
5	0.0023	0.0023	2.6388	2.6388	0.1330

Table 5 Estimated 13th harmonic voltage values for five bus system

Bus no.	Base voltage (p.u)	Estimated voltage (p.u)	Base angle (rad)	Estimated angle (rad)	% harmonic voltage error
1	0	0	−0.2883	−0.2883	0
2	0	0	2.5850	2.5851	0
3	0.0002	0.0002	−0.3967	−0.3967	0.2560
4	0.0002	0.0002	−0.4636	−0.4633	0.0214
5	0.0022	0.0022	2.5783	2.5783	0.0635

that even though noiseless measurements are considered in the present case study small measurement errors are obtained using the proposed DE technique because the evolutionary techniques provide a near-optimum solution. However, this measurement error can be further decreased by increasing the number of iterations (stopping criteria).

5.1.2 Case B. With $\pm 5\%$ measurement error

In this case study, HSE using DE has been performed in the presence of measurement error. The measurements are simulated by adding Gaussian noise with zero mean and $\pm 5\%$ standard deviation. The results thus obtained by performing HSE are tabulated in Tables 6, 7, 8 and 9. Tables Tables 6, 7, 8 and 9 consist of six columns. The actual and estimated harmonic voltages magnitude and voltage phasor at each bus are shown in columns 2 to 5. The percentage of harmonic measurement error calculated using (9) and (10) is provided in column 6. This measurement error is calculated between the actual value and estimated value at each bus for harmonic frequencies 5, 7, 11, and 13. It can be observed that harmonic voltage error at all the buses is small viz. less than 1%.

Further, based on the estimated voltage magnitudes at all the buses, the location of the harmonic source can easily be identified. For example, consider fifth harmonic

Table 6 Estimated 5th harmonic voltage values for five bus system

Bus no.	Base voltage (p.u)	Estimated voltage (p.u)	Base angle (rad)	Estimated angle (rad)	% harmonic voltage error
1	0	0	1.8870	1.8869	0
2	0	0	2.4042	2.4042	0
3	0.0017	0.0017	1.7456	1.7439	0.2560
4	0.0021	0.0021	1.8157	1.8078	0.2237
5	0.0052	0.0052	2.5911	2.5968	0.1771

Table 7 Estimated 7th harmonic voltage values for five bus system

Bus no.	Base voltage (p.u)	Estimated voltage (p.u)	Base angle (rad)	Estimated angle (rad)	% harmonic voltage error
1	0	0	1.0218	1.0118	0
2	0	0	2.0754	2.0774	0
3	0.0012	0.0012	0.8440	0.8439	0.9166
4	0.0015	0.0015	0.9273	0.9273	0.7142
5	0.0033	0.0033	2.5536	2.5496	0.7908

Table 8 Estimated 11th harmonic voltage values for five bus system

Bus no.	Base voltage (p.u)	Estimated voltage (p.u)	Base angle (rad)	Estimated angle (rad)	% harmonic voltage error
1	0	0	-0.0825	-0.0825	0
2	0	0	2.5719	2.5666	0
3	0.0003	0.0003	-0.3217	-0.3192	0.9083
4	0.0004	0.0004	-0.1081	-0.1082	0.3826
5	0.0023	0.0023	2.6388	2.6311	0.8050

Table 9 Estimated 13th harmonic voltage values for five bus system

Bus no.	Base voltage (p.u)	Estimated voltage (p.u)	Base angle (rad)	Estimated angle (rad)	% harmonic voltage error
1	0	0	-0.2883	-0.2763	0
2	0	0	2.5850	2.5850	0
3	0.0002	0.0002	-0.3967	-0.3856	0.8497
4	0.0002	0.0002	-0.4636	-0.4631	0.7432
5	0.0022	0.0022	2.5783	2.5997	0.9375

estimated voltage values that are tabulated in Table 6 column 3. It is seen that the fifth harmonic estimated voltage magnitude at bus five is high when compared to the voltage magnitude at the remaining buses. Therefore, it can be said that the harmonic source is located on bus 5. Hence, the location of the harmonic source can be identified using this process.

5.1.3 Case C. With $\pm 10\%$ measurement error

In this experiment, HSE using DE has been performed in the presence of measurement error. The measurements are simulated by adding Gaussian noise with zero mean

and $\pm 10\%$ standard deviation. The results thus obtained using the proposed method are tabulated in Tables 10, 11, 12 and 13. These tables consist of six columns with column one denotes the bus number. The actual and estimated harmonic voltages magnitude and voltage phasor at each bus are shown in columns 2 to 5. The percentage of harmonic measurement error calculated using (9) and (10) is provided in column 6. This measurement error is calculated between the actual value and estimated value at each bus for harmonic frequencies 5, 7, 11, and 13. It can be observed that harmonic voltage error at all the buses is small, viz. less than 0.0076. Further, similar to cases A and B, based on the estimated voltage magnitudes at all the

Table 10 Estimated 5th harmonic voltage values for five bus system

Bus no.	Base voltage (p.u)	Estimated voltage (p.u)	Base angle (rad)	Estimated angle (rad)	% harmonic voltage error
1	0	0	1.8870	1.8972	0
2	0	0	2.4042	2.3842	0
3	0.0017	0.0016	1.7456	1.6839	1.1303
4	0.0021	0.0021	1.8157	1.8264	1.1221
5	0.0052	0.0052	2.5911	2.5913	0.2931

Table 11 Estimated 7th harmonic voltage values for five bus system

Bus no.	Base voltage (p.u)	Estimated voltage (p.u)	Base angle (rad)	Estimated angle (rad)	% harmonic voltage error
1	0	0	1.0218	1.0226	0
2	0	0	2.0754	2.0754	0
3	0.0012	0.0012	0.8440	0.8529	1.3442
4	0.0015	0.0014	0.9273	0.9273	3.2536
5	0.0033	0.0031	2.5536	2.5532	6.9375

Table 12 Estimated 11th harmonic voltage values for five bus system

Bus no.	Base voltage (p.u)	Estimated voltage (p.u)	Base angle (rad)	Estimated angle (rad)	% harmonic voltage error
1	0	0	−0.0825	−0.0825	0
2	0	0	2.5719	2.5719	0
3	0.0003	0.0003	−0.3217	−0.3221	0.6928
4	0.0004	0.0004	−0.1081	−0.1081	3.8497
5	0.0023	0.0023	2.6388	2.6153	0.9302

Table 13 Estimated 13th harmonic voltage values for five bus system

Bus no.	Base voltage (p.u)	Estimated voltage (p.u)	Base angle (rad)	Estimated angle (rad)	% harmonic voltage error
1	0	0	−0.2883	−0.2883	0
2	0	0	2.5850	2.5850	0
3	0.0002	0.0002	−0.3967	−0.3968	7.6430
4	0.0002	0.0002	−0.4636	−0.4761	5.5884
5	0.0022	0.0023	2.5783	2.5783	6.1951

buses, the location of the harmonic source can easily be identified. Furthermore, it can be perceived from column 6 of Tables 2, 3, 4, 5, 6, 7, 8, 9 and 10 that even though the measurement noise is increased from zero to ±10% the harmonic voltage measurement error remains very small. Therefore, it can be stated that the proposed method is less sensitive to measurement noise and can estimate accurate harmonic voltage phasor at all the buses.

5.2 Test case 2. IEEE 14-bus system

In the present case study, the robustness of the proposed method has been verified by applying it to the IEEE 14-bus system. Similar to five bus system, PMUs are optimally deployed across the power system by using the algorithm given in [27] such that the power system is completely observable. The PMUs are installed at buses 2, 6, 8, and 9, and these meter placement locations are shown in Fig. 4 with solid rhombus. Now, using this PMUs reverse harmonic load flow analysis is performed similarly to the procedure explained in Sect. 4. The results thus obtained are depicted in Figs. 5 and 6.

Figures 5 and 6 show the voltage magnitude and voltage angle error for all the case studies, namely without, with 5%, and with 10% Gaussian measurement error and for all the harmonic orders, namely 5th, 7th, 11th,
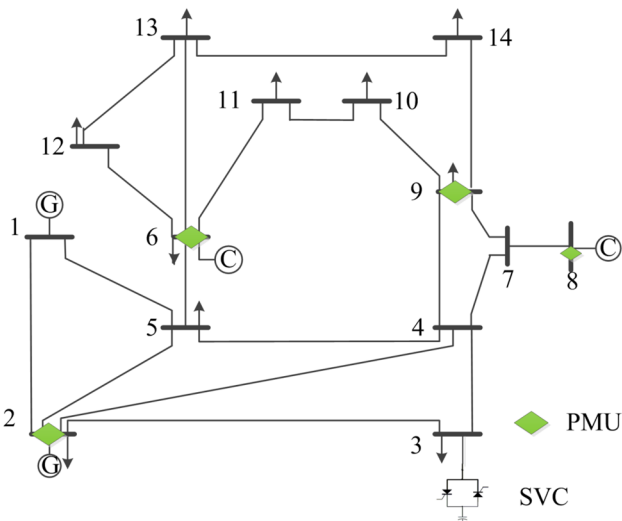
Fig. 4 Single line diagram of the modified IEEE 14-bus system

and 13th harmonics. From Fig. 5, it can be observed that the voltage magnitude error for without measurement noise case study is minimal, i.e. less than 1% for all harmonics orders. Hence, the proposed approach estimates the harmonic states accurately. Further, it can also be observed that the voltage magnitude error increases with an increase in measurement error. However, this error is small for all the harmonic orders. From Fig. 6 it can also be observed that similar to voltage magnitude error, the voltage angle error for without measurement error case study is approximately zero. However, the voltage angle error in the case of a 10% Gaussian measurement error gives very accurate results when compared

to a 5% Gaussian measurement error case study. However, for both the case studies, the voltage angle error is small which indicates the accurate harmonic state estimates. Hence, it can be concluded that the estimated error obtained for each harmonic frequency is negligibly small for voltage phasors at each bus. In comparison with five bus system, it can be seen that the IEEE 14 bus system also provides small harmonic measurement error. This shows the reliability and accuracy of the proposed method in obtaining the harmonic state estimates.

6 Conclusion

In the present work, a new method based on DE algorithm for reverse harmonic load flow analysis has been proposed to estimate the harmonic voltage phasors of the power system at different harmonic frequencies. The efficacy of the proposed approach has been verified by applying it to different measurement noise conditions. The robustness of the proposed method has been verified by applying it to five and IEEE 14 bus systems. Following are the major findings using the proposed method:

- The proposed method provides accurate harmonic state estimates for all the harmonic frequencies even with a limited number of measurement units.
- The proposed approach is less sensitive to measurement noise in providing accurate harmonic state estimates.
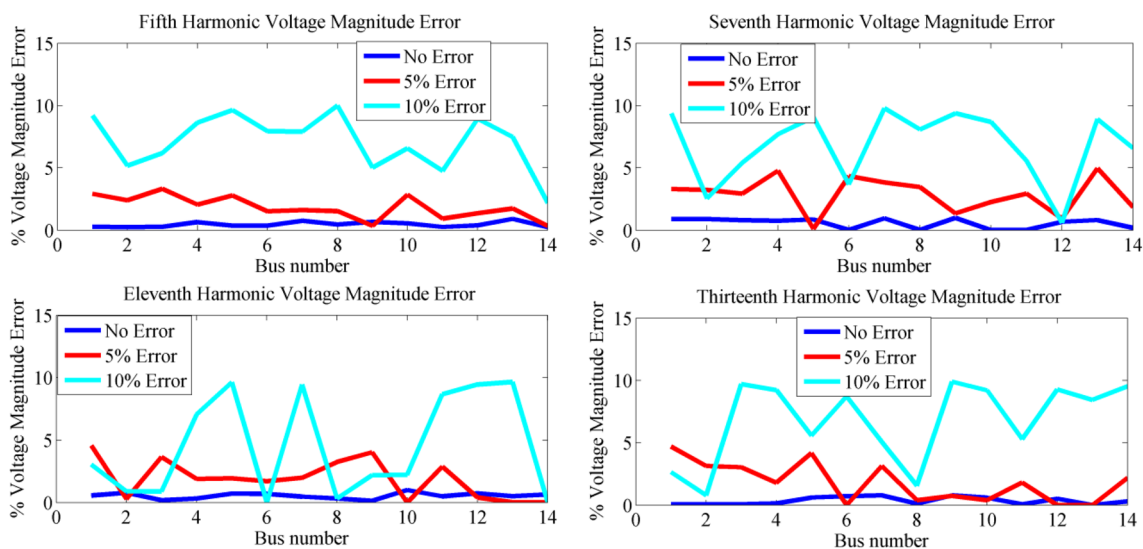

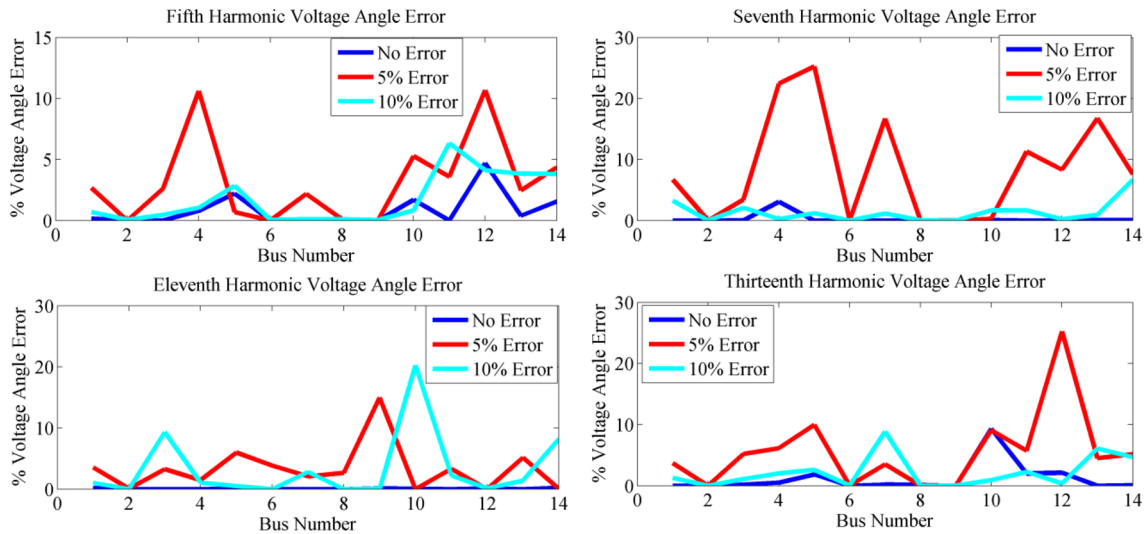**Fig. 5** Estimated voltage magnitude error obtained using HSE

Fig. 6 Estimated voltage angle error obtained using HSE

- The proposed method has the ability to identify the location of harmonic sources.

The main advantage of using differential evolution is that it searches the best solution in vast search space, and the fitness of the population either improves or remains constant but never declines. Even though the proposed methodology provides satisfactory results, the future work of the authors include the use of more number of harmonic sources, protection against various operating conditions that include loss of measurements, presence of outliers, and protection against cyber-attacks.

Compliance with ethical standards

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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