A new Method to Distinction of Harmonic Producing loads in Electric Power System

F. Gharedaghi, M. Deysi, H. Jamali, A khalili

Dashtestan Branch, Islamic Azad University, Borazjan, Iran
Fariba.gharedaghi@yahoo.com

Abstract: This paper introduces a new approach at giving distribution network operators information about the possible presence of harmonic producing loads, along with an indication about the reliability of such information. Because of limitation the number of harmonic measurements that must be installed in the network, harmonic state estimation has been considered as one of the famous methods for measuring voltage and injection current busbar, lines current and placement these measurements with algorithm based on sequential elimination method. In other hands, Given that too many measurement instruments are needed for a complete observation of the electric quantities, a model based state estimation technique is proposed here. Also, after that algorithm could find location of measurements in various busbars at harmonics, technique minimization number of sites that they collect harmonic data from measurement devices, optimal placement of these measurements will be done. By use this technique, it can find optimal place of measurement for identification location and intensity of harmonic sources. This investigation have been performed on IEEE 14-bus with 69 possible location to install these measurement in Matlab software.

[F. Gharedaghi, M. Deysi, H. Jamali, A khalili. **A new Method to Distinction of Harmonic Producing loads in Electric Power System.** *Rep Opinion* 2017;9(2):99-105]. ISSN 1553-9873 (print); ISSN 2375-7205 (online). http://www.sciencepub.net/report. 8. doi:10.7537/marsroj090217.08.

Keywords: Harmonic measurement, modeling, optimal placement, condition number

1. Introduction

To response this challenge that how may we assessment harmonic pollution of power system due to harmonic sources, more electrical provider companies valuate power quality of consumers by measuring programs to detection that harmonic pollution is allowable standard or no. Clearly, area measurement indicate harmonic voltage and current will be produced due to continous variations in system structure or load. To measure harmonic disturbances, generally is required a device that is not installed in most of busbars because of cost problems. Therefore, because of electrical industry need to measure busbar voltage and current and lines current, ought be able to deliver data of harmonic devices by a method for Center Control to investigate that what’s harmonic pollution in network. There is a growing concern to limit the amount of harmonics in the system and out of this concern, harmonic standards have been formulated [1]. To effectively evaluate and diminish the harmonic distortion in power systems, the locations and magnitudes of harmonic sources have to be identified. This problem of determination of locations and magnitudes of the harmonic sources is generally termed as “reverse harmonic power flow problem [2] and to solve it, appropriate locations of the harmonic meters are very important [3].

Harmonic state estimation (HSE) is a reverse process of harmonic simulation, which analyzes the response of a power system to the given injection current sources. In addition, HSE is capable of providing information on harmonic at locations not monitored [4]. The number of harmonic instruments available for performing HSE is always limited due to cost and the quality of the estimates is a function of the number and location of the measurement points [3]. Therefore, a systematic procedure is needed to design the optimal measurement placement. A measurement placement algorithm for harmonic component identification is presented in [5], based on minimum variance criteria. The optimal procedure in [5] needs load and generation data at each harmonic order for all busbars, which is usually not available. In [6] a symbolic method for observability analysis is presented. This method identifies redundant measurements thus giving the minimum number of measurements that are needed to perform HSE. It should be noted that this method cannot detect cases when there are two dependent measurement equations because the actual values are lost.

Therefore, this paper considers a robust technique for optimal measurement placement for HSE in terms of the optimal number of measurement to identify the location and intensity of harmonic sources.

First of all, this paper investigates the use of harmonic state estimation in a power system in section I. Then, effect of harmonic sources is evaluated in an application example in section II. The algorithm based on sequential elimination is presented in section III. Finally, concluding remarks are made in section IV.

2. Harmonic State Estimation

The complete harmonic information throughout the power system can be estimated from a relatively small number of synchronized, partial and asymmetric measurements of phasor voltage and current harmonics at selected busbars and lines, which are distanat from the harmonic sources [6], [2]. A system-wide or partially observable HSE requiring synchronized measurement of phasor voltage and current harmonics made at diffrent measurement point is described in [7]. Like recent HSE algorithms, the present work uses voltage and current rather than real and reactive power as the observed quantities, for reasons outlined in [8].

A general mathematical model relating the measurement vector Z to the state variable vector X, to be estimated, can be indicated as follows:

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

Where $Z(h)$ is a measurement vector, $H(h)$ is a measurement matrix, $X(h)$ is a state vector to be estimated, $E(h)$ is the measurement noise at h th harmonic order. If the state variable to be estimated is the nodal voltage, then, for current injection measurement, the relation to the nodal voltage and nodal admittance matrix is (2) and for nodal voltage measurement, the relation to the nodal voltage is in (3), where I is identify matrix, and for line current measurement, the relation to the nodal voltage and line-node admittance matrix is in (4):

$$I_N(h) = Y_{NN}(h)V_N(h) \tag{2}$$

$$V_N(h) = I * V_N(h) \tag{3}$$

$$I_L(h) = Y_{LN}(h)V_N(h) \tag{4}$$

To be notice that the measurement noise in (1) do not affect the solvability of HSE, they may be ignored [9]. As a result, HSE considers only one harmonic order at a time. The system with N busbar (node) is partitioned into two submatrix of nonsource busbars and suspicious busbars, that is in (5) with $I_{No} = 0$. Then equation (2) can be splited as (6). As a result, by combination $I_{No} = 0$ and (6), equation (7) will earn:

$$V_N = \begin{bmatrix} V_{No} \\ V_{Ns} \end{bmatrix} \quad , I_N = \begin{bmatrix} I_{No} \\ I_{Ns} \end{bmatrix} \tag{5}$$

$$\begin{bmatrix} I_{No} \\ I_{Ns} \end{bmatrix} = \begin{bmatrix} Y_{NoNo} & Y_{NoNs} \\ Y_{NsNo} & Y_{NsNs} \end{bmatrix} \begin{bmatrix} V_{No} \\ V_{Ns} \end{bmatrix} \tag{6}$$

$$V_{No} = -Y_{NoNo}^{-1} Y_{NoNs} V_{Ns} \tag{7}$$

From $Z(h) = H(h)X(h)$, while $Z(h)$, $H(h)$ an $X(h)$ are related to (2)-(4). When $X(h)$ is V_N as in (5) and $H(h)$ is partitioned into two subsets of suspicious and no source busbars (H_{Ns}, H_{No}) in (8), and substitute V_{No} from (7) into (8), it yields (9), that when V_{Ns} are known, V_{No} can be calculated from (7) and then all state variable can be solved.

$$Z = \begin{bmatrix} H_{Ns} & H_{No} \end{bmatrix} \begin{bmatrix} V_{Ns} \\ V_{No} \end{bmatrix} \tag{8}$$

$$Z = \left[H_{Ns} + H_{No} \left(-Y_{NoNo}^{-1} Y_{NoNs} \right) \right] V_{Ns} \tag{9}$$

Equation (1) is usually under-determined system because of limitation of harmonic instruments and different ownership of different parts of the system. This results in H being singular and a result cannot be obtained with normal equation approach. Furthermore, even in completely or ever-determined system, the normal equations may be very singular or ill-conditioned. Although several methods have been suggested to solve such ill-conditioned problem, e.g.,[7,8], observability analysis is still needed prior to estimation.

3. Effect of Harmonic Sources

In this section, modeling of example network considers that it is IEEE 14-bus. This investigation will be performed so that the network has two harmonic sources. Harmonic studies have become an important aspect of power system analysis and design in recent years. Harmonic simulations are used to quantify the distortion in voltage and current waveforms in a power system and to determine the existence and mitigation of resonant conditions [10]. Figure (1) indicates single line diagram IEEE 14-bus. Data of system has been expressed in [11].

3.1. Harmonic Sources Modeling

This test system contains two harmonic sources. One is a twelve-pulse HVDC terminal at bus 3 and the other is a SVC at bus 8. The loads are modeled as constant power loads for load flow solutions and as impedances for harmonic solutions. The harmonic impedances are determined according to the 3rd model recommended in reference [12].

The harmonic cancellation effects due to Y-Y and Y-Delta transformer connections (at the HVDC terminal) and the impact of other harmonic sources (the SVC). For this purpose, the HVDC terminal is modeled as two six-pulse harmonic sources [10]. Harmonic filters are modeled as shunt harmonic impedances. All filters are the single-tuned type. The

HVDC terminal is modeled as two six-pulse bridge rectifiers according to the model of figure (2). Because voltage distortion at the HVDC terminal is small, sensitivity studies showed that the terminal can be modeled as two harmonic current sources. The source spectra is provided in Table 1. It must be noted that the magnitudes and phase angles should be scaled and shifted according to the load flow results [13], [14]. The HVDC terminal is modeled as a constant power load in the load flow solution. The SVC consists of harmonic filters and a delta-connected TCR. The TCR was modeled using the model of figure (3). The firing angle is about 120 degrees.

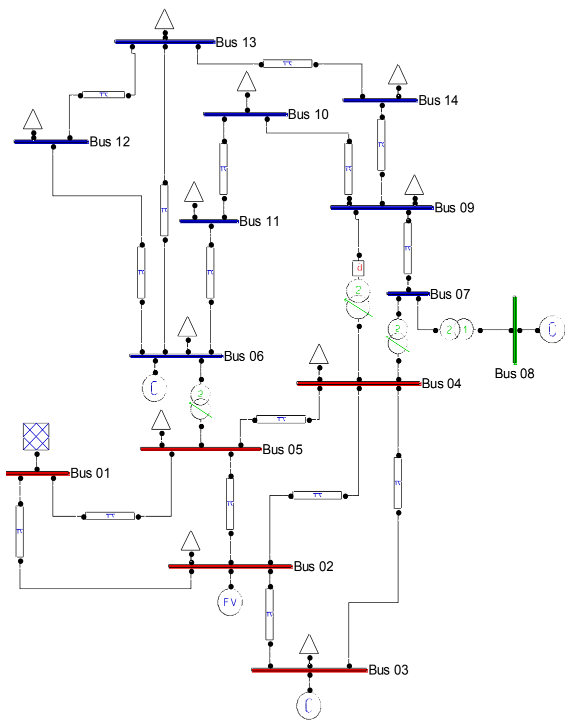

Figure 1. Single line diagram of IEEE 14-bus

Table 1. Harmonic source data

Six-Pulse HVDC		Delta-Connected TCR		Harmonic Order
Angle (deg)	Mag (pu)	Angle (deg)	Mag (pu)	
-49.56	1.0000	46.92	1.0000	1
-67.77	0.1941	-124.40	0.0702	5
11.90	0.1309	-29.87	0.0250	7
-7.13	0.0758	-23.75	0.0136	11
68.57	0.0586	71.50	0.0075	13
46.53	0.0379	77.12	0.0062	17
116.46	0.0329	173.43	0.0032	19
87.47	0.0226	178.02	0.0043	23
159.32	0.0241	-83.45	0.0013	25
126.79	0.0193	-80.45	0.0040	29

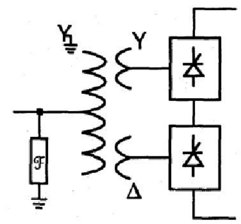

Fig 2. The model of HVDC terminal as two six-pulse bridge rectifiers

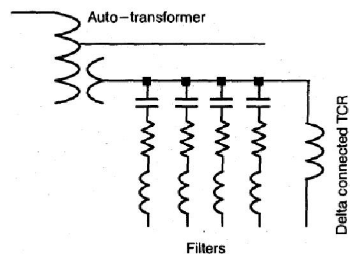

Fig 3. TCR model for load flow solution

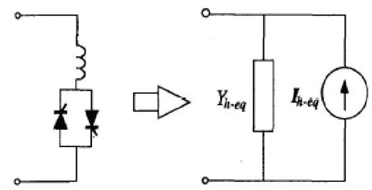

Fig 4. TCR model for harmonic load flow

To facilitate the solution of the case using programs without a TCR model, the equivalent load and harmonic spectra of the TCR are listed in Table 1.

With this information, the TCR can be represented as a constant reactive power load in load flow solution and a harmonic current source in harmonic analysis so that it can be indicated in figure 4. In this figure, we have as follow:

$$Y_{eq} = \left(jh\omega L_{eq} \right)^{-1} \;, L_{eq} = \pi L \left(\sigma - \sin \sigma \right)^{-1} \tag{10}$$

In (10) σ is conduction angle and it can be colculated by (11) so that α is firing angle:

$$\sigma = 2\left(180^{\circ} - \alpha\right) \tag{11}$$

Because the SVC is relatively small as compared to the HVDC, its impact on overall system harmonic distortion is not significant.

3.2. Load Flow Solution in Fundamental Frequency

Table 2. TCR and HVDC loads data

Reactive power (MVar)	Active power (MW)	Type of Source
12.9	0	TCR branch
3.363	59.505	HVDC link

To evaluate the distortion in voltage and current waveforms in this network, it must be analyzed harmonic simulations with load flow solution in fundamental frequency at presence SVC at 8 busbar and HVDC at 3 busbar. TCR and HVDC loads data for this type load flow are listed in table 2.

Table 3. Results of load flow in fundamental frequency

Bus Number	With Harmonic Sources		Without Harmonic Sources	
	Phase (deg)	Mag. of V (pu)	Phase (deg)	Mag. of V (pu)
Bus 01	0	1.06	0	
Bus 02	-4.8462	1.045	-4.9858	1.06 1.045 1.01
Bus 03	-14.5141	1.0423	-12.7257	1.0187
Bus 04	-10.2879	1.0167	-10.3353	1.0203
Bus 05	-8.6668	1.0195	-8.793	1.07
Bus 06	-13.5699	1.07	-14.2481	1.0621
Bus 07	-12.9842	1.0225	-13.3848	1.09
Bus 08	-12.9842	1.022	-13.3848	1.0567
Bus 09	-14.437	1.0148	-14.9655	1.0516
Bus 10	-14.5618	1.0167	-15.1244	1.0572
Bus 11	-14.1749	1.0392	-14.8182	1.0553
Bus 12	-14.4653	1.0522	-15.1021	1.0505 1.036
Bus 13	-14.5204	1.0442	-15.1835	
Bus 14	-15.5184	1.0091	-16.0599	

The results load flow IEEE 14-bus with and without presence harmonic sources have been in presented table 3 that this simulation have been performed with PSAT [15].

3.3. Harmonic Load Flow

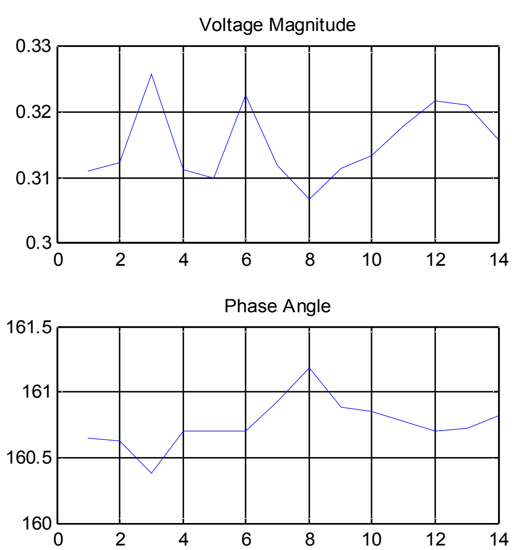

Fig 5. Diagrams of voltage and phase angle by placement harmonic sources in 3 and 8 busbars at 5^{th} harmonic

In this type of load flow all properties IEEE 14-bus will be runned only at one harmonic order so that it can be depended on generated frequency by harmonic source. We uses Injection Current method for this work. The results of harmonic load flow a 5^{th} harmonic with placement sources in 3 and 8 busbars have been showed in figure (5) and the results in the other harmonics have been provided in appendix A.

In figure (5), because of placing HVDC in 3 busbar, voltage magnitude of it has raised and phase angle in this busbar has fell down. But because of placing SVC in 8 busbar, voltage magnitude has decreased and phase angle has been raised.

4. Optimal Harmonic Meter Placement

However, the number of measuring devices available is limited due to cost and the quality of estimates is a function of the number and locations of the measurements. A proper methodology is needed for selecting optimal sites for the measuring devices. In this section a new criteria is proposed for optimal harmonic meter placement. Since the proposed algorithm is based on the sequential elimination and minimum condition number of the measurement matrix. The condition number of a matrix is the ratio of the largest (in magnitude) to the smallest singular value. A matrix is singular if its condition number is infinite, and it would be considered ill-conditioned if its condition number is too large.

As compared to complete enumeration, the benefits gained from using the sequential procedure are exciting because of the reduction in the number of possible combinations. In general, for N-bus system, M possible locations with P measuring devices are to be placed. The sequential method needs only to calculate *P(2M+1-P)/2* combinations to determine, whereas it is $\begin{bmatrix} M & P \end{bmatrix}^T$ for complete enumeration method.

After make measurement matrix (*H*), size of it must be calculated. Because of to obtain a unique solution, the minimum required number of harmonic meters (*P*) has to be equal to the number of state variables. As a result, algorithm needs to iterate until M possible locations equal to N-bus for to ensure a completely observable system. after that the size of measurement matrix is not equal, algorithm is be entered *For* loop and in this loop, each row of matrix *H* (each possible location) is temporarily eliminated one at a time and then in the next step the condition number of the new measurement matrix with M-1 row is calculated. In the out of *For* loop, vector of condition number from various matrixes that is called *MCN=min(CN),* is constituted and element of vector (the location) has a minimum condition number will be eliminated sequentially to reduce the number of M for the next iteration. In the second *For* loop by use from elements of *MCN* vector, the matrix that has minimum condition number is selected as the new measurement matrix, and then the new matrix is entered in the first *For* loop. In the next step of algorithm with the new matrix, the number of iterations would be reduced from *M* to *M-1*. The iterative procedure is performed until *M=N*. the number of possible locations will be reduced, from *M* to *M-1, M-2,…, M-(M-P).* The remaining locations after sequential elimination, base on minimum condition number, should be optimal for measurements.

5. Numerical Results

In this section IEEE 14-bus test system is used to test the proposed measurement placement algorithm. A schematic of this test system is shown in Fig. 6 and its total data are provided from [10]. There are 14 busbars, 35 branches and 41 lines. The equivalent π model is used to represent each transmission line.

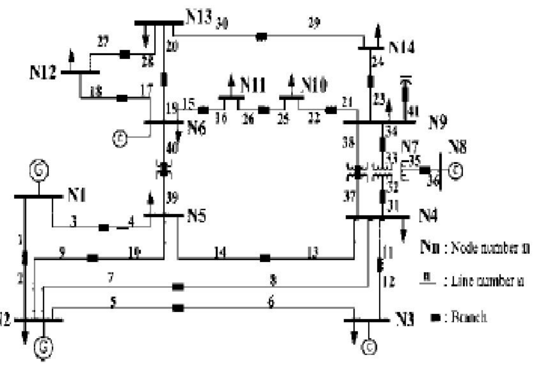

Figure 6. IEEE 14-bus test system to perform algorithm

The system consists of 10 loads connected at busbars 3-5 and 8-14 that contains two harmonic sources. One is a twelve pulse HVDC terminal at bus 3 and the other is a SVC at bus 8. There are 69 possible measurement locations (M), given that there are 14 injections current measurements, 14 busbars voltage measurements and 41 lines current measurements (both sending and receiving ends). In order to obtain a unique solution for harmonic state estimation, the minimum required numbers of harmonic instruments has to be equal to the number of state variables. As a result, the optimal number of harmonic instruments is equal to the number of state variables. Actually the state variable of the test system is 14, which using HSE algorithm can be reduced to the number of suspicious nodes (i.e. 10). The measurement placements obtained by using this proposed algorithm, which make application example full observable is shown in Table 4.

Table 4. Measurement placement in application example

Harmonic Order	Injection Current	Busbars Voltage	Line Current
5	-	11-14	4,8,11,25,34,36
13	-	3,8,11-14	14,15,22,34
17	-	3,4,8,11-14	10,22,34
25	-	3-5,8,10-14	20

Furthermore the measurement placements are different among harmonic orders, but all of the measurement placements from all harmonic orders are sufficient to uniquely calculate all state variables for all harmonic orders of the system correctly. The procedure of optimal measurement placement is defined as follow:

- Minimize the number of harmonic meter so that it be equal to the number of state variable.
- State estimators provide optimal estimates of bus voltage phasors based on the available measurements and knowledge about the network topology. These measurements are commonly provided by the remote terminal units (RTU) or sites at the substations and include real/reactive power flows, power injections, and magnitudes of bus voltages and branch currents. Then, minimize the number of sites is the next step for optimal measurement placement.

To reduce the monitoring costs attached to HSE, the number of units that collect measurement data should be minimized. To minimize the number of sites, from the network configuration, the process to find the best site should start from busbars 4,7-9. This site indicates that the measurement matrix is singular so that it may be not sufficient to solve all state variables correctly. Hence more sites have to be added. Then the new site is 4-9 that it is combination from 4,7-9 site and 5 and 6 site with 34 possible location. The measurement matrix of this site is not singular and it is sufficient to solve all state variables. Then algorithm is used. The results of use from algorithm in this site at 5th and 17th harmonics are showed in Table 5. After find optimal location to install harmonic meters by this new technique, HSE of these measurement devices is used to identify location of harmonic sources.

Figure (7) shows spectrum of harmonic injection currents in all busbars that it has been obtained by performing HSE with measurement devices that these have been founded. Therefore, we will be able to find location and intensity of harmonic sources in the application example.

Table 5. Measurement placement in 4-9 site

Harmonic Order	Injection Current	Busbars Voltage	Line Current
5	-	4,5,6,8,9	4,8,17,19,23
17	-	8	4,8,11,15,17,19,21,23

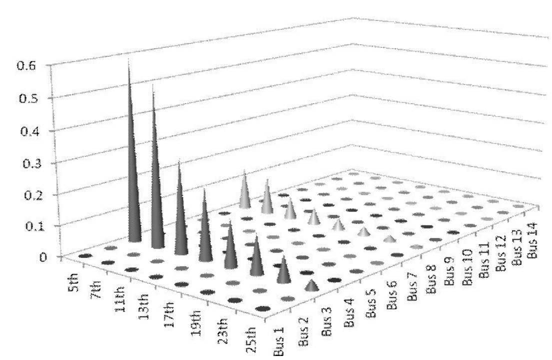

Figure 7. IEEE 14-bus test system to perform algorithm

6. Conclusion

In this research a new technique base on minimizing the number of sites that gather data of harmonic meters up to control center. Also, in this paper we indicated the effect of harmonic sources on voltage profile and phase angle of busbars. Finally, algorithm base on sequential elimination and minimum condition number has been demonstrated for placement of harmonic meters. By using this work, we will be able to identify location and intensity of harmonic sources in a case study example.

Corresponding Author:
Fariba Gheradaghi
Dashtestan Branch, Islamic Azad University, Borazjan, Iran
E-mail: Fariba.gharedaghi@yahoo.com

References

1. Ketabi A., Hosseini S.A., A New Method for Optimal Harmonic Meter Placement, American Journal of Applied Sciences, 2008: 5(11): 1499-1505.
2. Heydt G.T., Identification of Harmonic Sources by a State Estimation Technique, IEEE Trans. Power Delivery, 1989: 4: 569-576.
3. Ashwani K., Biswarup D., Genetic Algorithm-Based Meter Placement for Static Estimation of Harmonic Sources, IEEE Trans. Power Delivery, 2005: 20(2): 1088-1096.
4. Chakphed M., Watson N.R., An Optimal Measurement Placement Method for Power System Harmonic State Estimation, IEEE Trans. Power Delivery, 2005: 20(2): 1514-1521.

5. Farach J.E., Grady W.M., Arapostathis A., An Optimal Procedure for Placing Sensors and Estimating the Locations of Harmonic Sources in Power System, IEEE Trans. Power Delivery, 1993: 8(3): 1303-1310.
6. Watson N.R., Arrillaga J., Du Z.P., Modified Symbolic Observability for Harmonic State Estimation, IEE Proc. Generation, Transmission and Distribution, 147(2), 105-111.
7. Arrillaga J., Watson N.R., Chen S., Power System Quality Assessment, John Wiley and Sons, New York, 2000.
8. Meliopoulos A.P.S., Zhang F. and Zelingher S., Power system harmonic state estimation, IEEE Trans. Power Delivery, 1994: 9: 1701-1709.
9. Du Z.P., Arrillaga J., Watson N.R., Continuous harmonic state estimation of power systems, Proc. Inst. Elec. Eng., Gen., Transm. Distrib., 1996: 329-336.
10. IEEE Task Force on Harmonics Modeling and Simulation, Modeling and Simulation of the Propagation of Harmonics in Electric Power Networks, Part 1 & 2, IEEE Trans. On Power Delivery, 1996: 11(1): 452-474.
11. www.ee.washington.edu/research/pstca.
12. CIGRE Working Group 36-05, Harmonics, Characteristic Parameters, Methods of Study, Estimates of Existing Values in the Network, Electra, 1981: 77: 35-54.
13. Attia H. A., El-Metwally M., Fahmy O. M., Harmonic Distortion Effects and Mitigation in Distribution Systems, Journal of American Science, 2010: 6(10): 173-183.
14. N. Magaji, M. W. Mustafa, Determination of Best Location of FACTS Devices for Damping Oscillations, International Review of Electrical Engineering (IREE), Vol. 5, no. 3, pp. 1119-1126.
15. Power System Analysis Toolbox, Documentation for PSAT version 1.3.4, 2005.

2/25/2017