Mansoura Engineering Journal, (MEJ), Vol. 36, No. 3, September 2011.

# Optimal Placement of PMU Using Improved Tabu Search for Complete Observability of Power System and Out of Step Prediction

# تحديد المواقع المثلى لوحدات القياس الاتجاهى باستخدام البحث الممنوع المحسن لتحقيق الرؤية الكاملة لمنظومة القوى و توقع عدم اتزانها

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**ملخص**

تقدم الورقة البحثية طريقة لتحديد الموقع الأمثل لوحدات القياس الاتجاهى لتحقيق الرؤية الكاملة لمنظومة القوى. و تعتمد الطريقة المقترحة على الرؤية العددية و الذكاء الاصطناعى. و قد تم استخدام خوارزم ذكاء اصطناعى من نوع البحث الممنوع المحسن لتحديد الموقع الأمثل لوحدات القياس الاتجاهى للحفاظ على الرؤية الكاملة للمنظومة. كما تصف الورقة البحثية خوارزم لتوقع عدم اتزان المولدات مبنى على رؤية فارق جهد الوجه بين المحطات. و قد تم اختبار الخوارزمين على منظومتى **IEEE** ذات ستة قضبان و اربعة عشر قضيب و كذلك على شبكة ٥٠٠ ك ف المصرية. كما تم محاكاة نظم الاختبار و الخوارزمات المستخدمة باستخدام برامج **PSCAD** و **MATLAB**.

**Abstract**

This paper proposes an optimization method for optimal placement of phasor measurement units (PMUs) for complete observability of power system. The proposed method is based on numerical observability and artificial intelligence. The artificial intelligence algorithm used is the Improved Tabu Search (ITS) algorithm. The ITS is used to find the optimal placement for the PMU to keep the system complete observable. Also, the paper describes a predictive Out-Of-Step (OOS) algorithm based on the observation of the voltage phase difference between substations. The proposed optimal placement of PMUs and the OOS algorithms are tested using the IEEE 6 bus, IEEE 14 bus systems and the Egyptian 500 kV network. The test systems are simulated using the PSCAD software program. The placement algorithm and the OOS prediction algorithm are carried out using MATLAB script programs.

**Keywords**
Optimal placement of Phasor measurement units, Observability, Improved Tabu Search (ITS), Predictive Out-of-step Protection

## 1. Introduction

The phasor measurement units (PMUs) are measuring devices synchronized via signals from global positioning system (GPS) satellite transmission [1]. They are employed to measure the positive sequence of voltage and current phasors. By synchronized sampling of microprocessor-based systems, phasor calculations can be placed on a common reference. The magnitudes and angles of these phasors comprise the state of the power system and they are used in complete observability and transient stability analysis. The observability of a system can be assessed by considering the topology of the network and the types and locations of the measurements. Transient instability becomes more and more complicated as the power systems grow in more scale and complexity. OOS studies become more essential to prevent large scale black-out in power systems.

In recent years, there has been a significant research activity on the problem of finding the minimum number of PMUs and their optimal locations. In [2], a bisecting search method was implemented to find the minimum number of PMUs to make the system observable. In [3], the authors used a simulated annealing technique to find the optimal PMU locations. In [4], a genetic algorithm was used to find the optimal PMU locations. The

Accepted August 23, 2011.

minimum number of PMUs needed to make the system observable was found by using a bus-ranking methodology. In [5] and [6] the authors used integer programming to determine the minimum number of PMUs. The authors in [7] used the condition number of the normalized measurement matrix as a criterion for selecting candidate solutions, along with binary integer programming to select the PMU locations.

Various methods for the OOS detection have been developed and were in use in protection systems, such as tracking trajectory of the impedance vector measured at the generator terminals [8], rate of change of apparent resistance augmentation [9] or Liapunov theory [10].

The present paper first proposes an optimal search approach based on an improved tabu search (ITS) to determine the optimal locations of PMUs for complete system observability. Then the paper introduces a predictive OOS algorithm based on measuring the phase difference between several generators from voltage data collected at substation buses.

## 2. System Observability Analysis

The observability of a system can be assessed by considering the topology of the network and the types and locations of the measurements. The meter placement algorithm presented in this paper is based on the observability analysis method introduced earlier in [11] & [12]. This method will be briefly reviewed first.

### 2.1 Linear Size and Page Layout

Consider an N-bus system provided with m-measurements of voltage and current phasors contained in vector z. The vector z is linearly related to the N-dimensional state vector x containing N-nodal voltage phasors, resulting in n=2N - 1 state variables [11]. This yields the linear model

$$\mathbf{z} = \mathbf{H}\,\mathbf{x} + \mathbf{e} \tag{1}$$

Where $H$ is the $(m * N)$ design matrix and $e$ is an $(m * 1)$ additive measurement error vector.

By splitting the vector z into the $(m_V * 1)$ voltage and $(m_I * 1)$ current subvectors, $z_V$ and $z_I$, respectively. Also by splitting the vector x into the $(N_M * 1)$ measured and $(N_C * 1)$ nonmeasured sub-vectors, $V_M$ and $V_C$, respectively, relationship (1) becomes

$$\begin{bmatrix} Z_V \\ Z_I \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ Y_{IM} & Y_{IC} \end{bmatrix} \begin{bmatrix} V_M \\ V_C \end{bmatrix} + \begin{bmatrix} e_V \\ e_I \end{bmatrix} \tag{2}$$

Where **1** is the identity matrix and $Y_{IM}$ and $Y_{IC}$ are sub-matrices whose entries are series and shunt admittances of the network branches.

When the shunt elements are neglected, then the design matrix $H$ reduces to

$$H = \begin{bmatrix} 1 & 0 \\ M_{IB} Y_{BB} A_{MB}^T & M_{IB} Y_{BB} A_{CB}^T \end{bmatrix} \tag{3}$$

where $M_{IB}$ is the $(m_I$ x b) measurement-to-branch incidence matrix associated with the current phasor measurements. $Y_{BB}$ is the $(b$ x $b)$ diagonal matrix of the branch admittances. $A_{MB}$ and $A_{CB}$ are the $(N_M$ x $b)$ measured and $(N_C$ x $b)$ calculated node-to-branch incidence sub-matrices, respectively.

### 2.2 The Observability Check

The decoupled gain matrix for the real power measurements can be formed as [12]:

$$\mathbf{G} = \mathbf{H}^T\mathbf{H} \tag{4}$$

Note that, since the slack bus is also included in the formulation, the rank of $H$ (and $G$) will be at most (N-1), even for a fully observable system. This leads to the triangular factorization of a singular and symmetric gain matrix.

The symmetric matrix $G$ can be decomposed into its factors $LDL^T$ where the diagonal factor $D$, may have one or more zeros on its diagonal. If it have more than one zero on its diagonal then the system is unobservable.

## 3. Tabu Search Algorithm

Tabu search (TS) algorithm is a powerful optimization procedure that has been successfully applied to a number of combinatorial optimization problems. It is an optimization method developed by F.Glover [13]-[14] specifically for combinational optimization problem. It guides the search for the optimal solution making the use of memory systems which exploit its past history and leads to the best solution. Fundamental concept of simple TS involves individual, population and generation. If $v_k$ is the trial vector up to iteration $k$, $\Delta v_k$ is a move, then $v_{k+1}=v_k+\Delta v_k$ is the trial vector at iteration k+1. The set of all possible moves out of a current solution is called the set of candidate moves. One could operate with a subset of it.

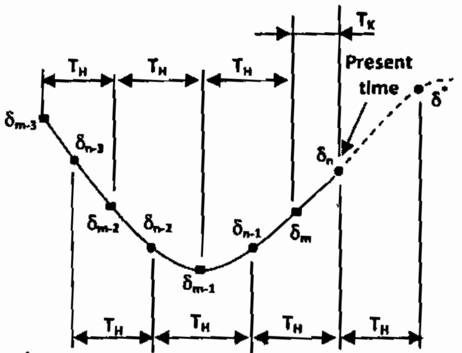
### 3.1 Tabu Restrictions

There are certain conditions imposed on moves, which make some of them forbidden. These forbidden moves are known as tabu. A tabu list will be formed to record these

The OOS prediction algorithm is carried out using M-files MATLAB programs.

### 6.1 Calculations of Predicted Value for Phase Difference

In [16], authors used the phase difference values for the present time and previous time to predict the future phase difference value. This method will be described using Fig.2.



$\delta^*$ : predicted relative phase angle $T_H$=200 μsec
$\delta_m$, $\delta_n$ : phase angles $T_K$=100 μsec

Fig.2 Method of Predicting Phase Difference

The predicted phase difference $\delta^*$ for time $T_H$ in the future is derived from the eight pieces of data indicated in Fig.2. These are the phase differences at time $T_K$ before the present time and in addition three values for this time minus increments of time $T_H$ ($\delta_m$, $\delta_{m-1}$, $\delta_{m-2}$, $\delta_{m-3}$) and the phase differences at the current time n and in addition three values for this time minus increments of $T_H$ ($\delta_n$, $\delta_{n-1}$, $\delta_{n-2}$, $\delta_{n-3}$). Equations (7) through (11) are used to perform the calculation.

$$\delta^* = \delta_n + \lambda\, d_n + \mu\, d_{n-1} \tag{7}$$

where,

$$d_n=\delta_n - \delta_{n-1}\ ,\ d_{n-1}=\delta_{n-1} - \delta_{n-2}\ ,\ d_{n-2} = \delta_{n-2} - \delta_{n-3} \tag{8}$$

$$d_m=\delta_m-\delta_{m-1}\ ,\ d_{m-1}=\delta_{m-1}-\delta_{m-2}\ ,\ d_{m-2} = \delta_{m-2} - \delta_{m-3} \tag{9}$$

$$\lambda = (d_n d_{m-2} - d_m d_{n-2})/(d_{n-1} d_{m-2} - d_{m-1} d_{n-2}) \tag{10}$$

$$\mu = (d_{n-1} d_m - d_{m-1} d_n)/(d_{n-1} d_{m-2} - d_{m-1} d_{n-2}) \tag{11}$$

Values of 200 μs and 100 μs were selected for $T_H$ and $T_K$, respectively, in order to predict accurately.

### 6.2 Threshold Value ($\delta$critical)

When the predicted phase difference value $\delta^*$ obtained by eq.(7) exceeds the setting value ($\delta_{critical}$), it is judged that the generator is unstable. $\delta_{critical}$ is the threshold value used to judge stability. The value for $\delta_{critical}$ is determined by testing the system under varying conditions. The selected value must guarantee operation when the system is unstable and must prevent operation when the system is stable [16].

## 7. Out-Of-Step Prediction Test Results

The previously explained prediction algorithm was applied to the phase difference between different generator buses of the test systems and the slack bus as recorded by simulating the systems on the PSCAD software. The sampling time was 100 μsec. The following are some results of the proposed algorithm.

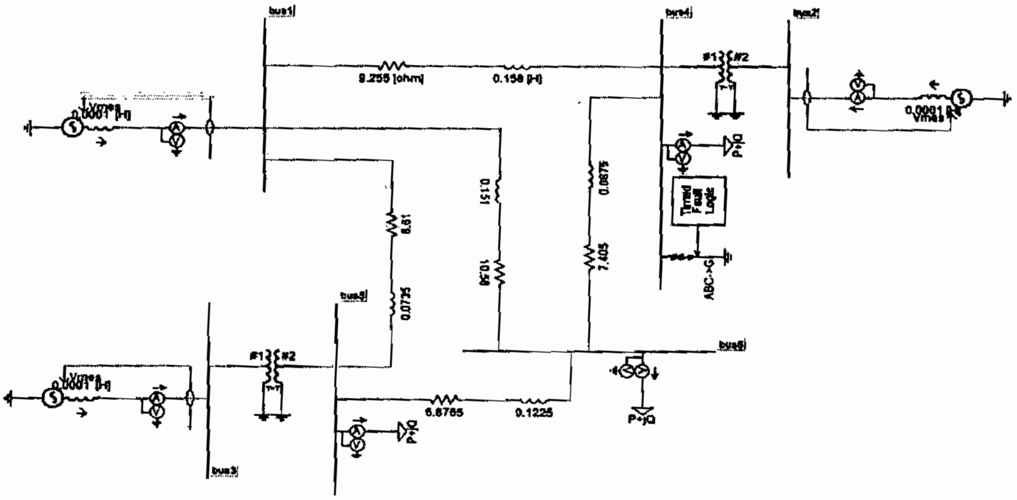


Fig.3 The PSCAD model of the IEEE 6-bus system

### 7.1 IEEE 6-Bus System

The PSCAD model of the IEEE 6-bus system is shown in Fig.3.

For a three-line-to-ground (3LG) fault at bus 4 the recorded phase difference between Gen.2 and Gen.1 (slack bus generator) is shown in Fig.4.

For a three-line-to-ground (3LG) fault at bus 4 the recorded phase difference between Gen.2 and Gen.1 (slack bus generator) is shown in Fig.4. The predicted phase difference and both recorded and predicted phase difference together are shown in Fig.5 and Fig.6, respectively.

As shown in Fig.6, the predicted and recorded phase difference angles are almost the same, which prove the accuracy of the prediction algorithm used.

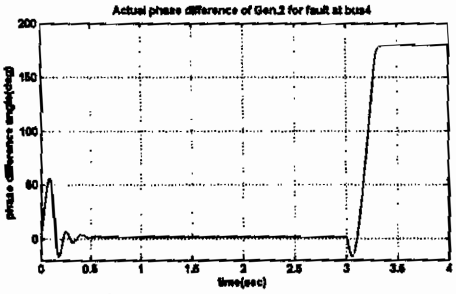


Fig.4 The recorded phase difference between Gen.2 and Gen.1 for a 3LG fault at bus 4

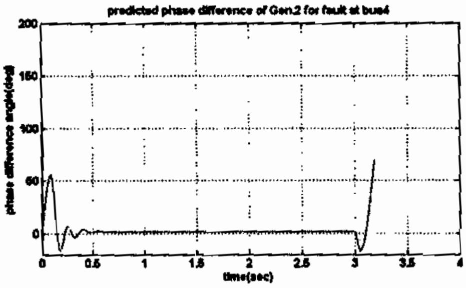


Fig.5 The predicted phase difference between Gen.2 and Gen.1 for a 3LG fault at bus 4

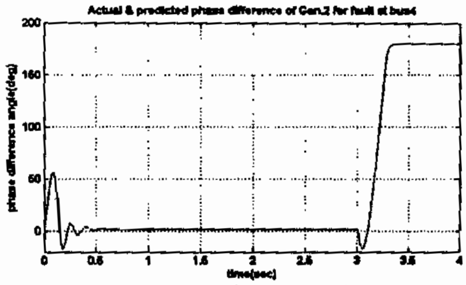


Fig.6 The recorded and predicted phase difference between Gen.2 and Gen.1 for a 3LG fault at bus 4

For the same fault at bus 4 the recorded phase difference between Gen.3 and Gen.1 (slack bus generator) is shown in Fig.7. The predicted phase difference and both recorded and predicted phase difference together are shown in Fig.8 and Fig.9, respectively.

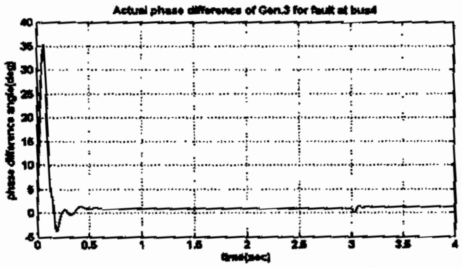


Fig.7 The recorded phase difference between Gen.3 and Gen.1 for a 3LG fault at bus 4

As shown in Fig.9, the predicted and recorded phase difference angles are almost the same, which further prove the accuracy of the prediction algorithm used. Through several tests of the system during faults of different types and different locations, the minimum threshold value ($\delta_{critical}$) of both generators was found to be 75 deg.

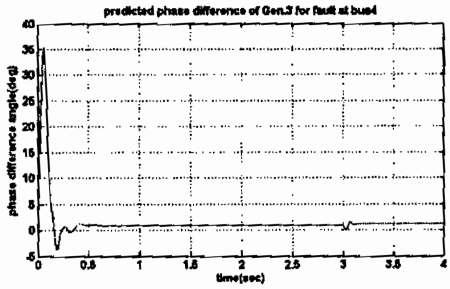


Fig.8 The predicted phase difference between Gen.3 and Gen.1 for a 3LG fault at bus 4

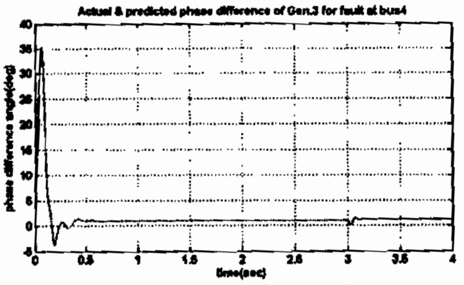


Fig.9 The recorded and predicted phase difference between Gen.3 and Gen.1 for a 3LG fault at bus 4

Referring to Fig.4 and Fig.7, under the same fault condition, Gen.2 will be out of step and Gen.3 will remain stable, where the phase difference angle of Gen.2 exceeded its critical value while that of Gen.3 did not exceed that value.

## 7.2 IEEE 14-Bus System

The PSCAD model of the IEEE 14-bus system is shown in Fig.10. For a three-line-to-ground (3LG) fault at bus 2 the recorded phase difference between Gen.2 and Gen.1 (slack bus generator) is shown in Fig.11. As shown in Fig.11, Gen.2 will be out of step where its phase difference angle exceeded its critical value.

The predicted phase difference and both recorded and predicted phase difference together are shown in Fig.12 and Fig.13, respectively. As shown in Fig.13, the predicted and recorded phase difference angles are almost the same.

Through several tests of the system during faults of different types and different locations, the minimum threshold value ($\delta_{critical}$) of generator 2 was found to be 60 deg.

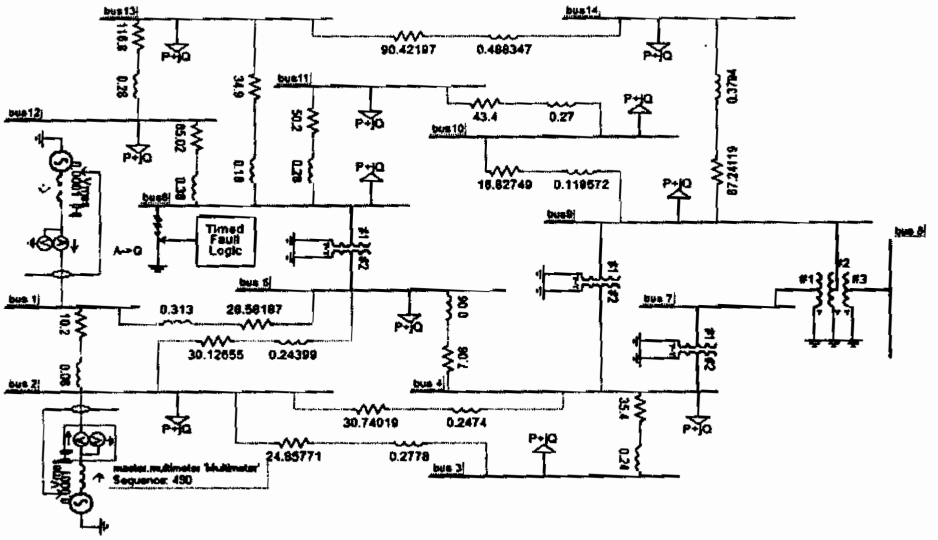


Fig.10 The PSCAD model of the IEEE 14-bus system

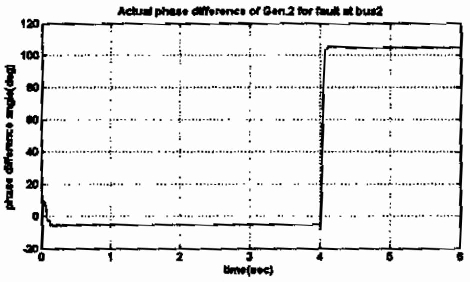


Fig.11 The recorded phase difference between Gen.2 and Gen.1 for a 3LG fault at bus 2

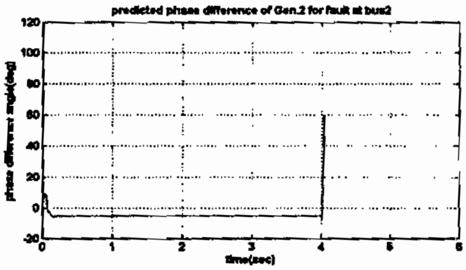


Fig.12 The predicted phase difference between Gen.2 and Gen.1 for a 3LG fault at bus 2

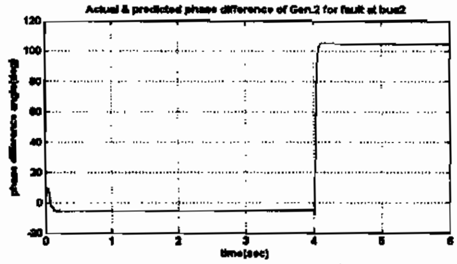


Fig.13 The recorded and predicted phase difference between Gen.2 and Gen.1 for a 3LG fault at bus 2

### 7.3 Egyptian 500 kV Network

The PSCAD model of the Egyptian 500 kV network is shown in Fig.14. As a sample of test results, the phase difference angles at Gen.3 during 3LG fault at bus 7 will be presented.

For a three-line-to-ground (3LG) fault at bus 7 the recorded phase differencc between Gen.3 and Gen.1 (slack bus generator) is shown in Fig.15.

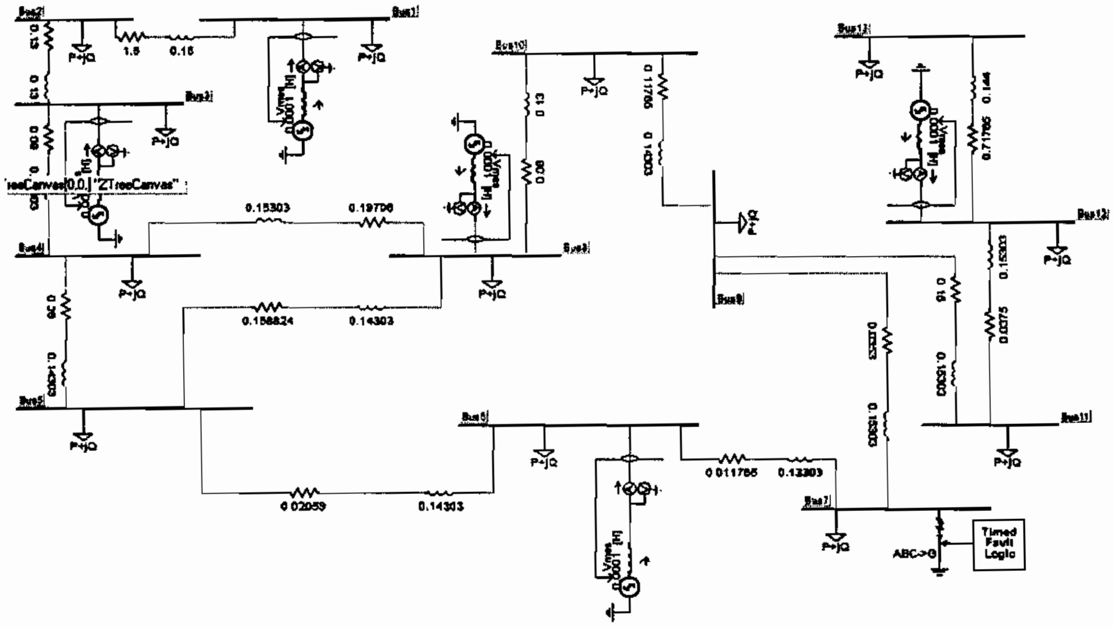


Fig.14 The PSCAD model of the Egyptian 500 kV network

The predicted phase difference and both recorded and predicted phase difference together are shown in Fig.16 and Fig.17, respectively.

Through several tests of the system during faults of different types and different locations, the minimum threshold value ($\delta_{critical}$) of all generators was found to be 50 deg.

As shown in Fig.15, for a 3LG fault at bus 7, Gen.3 will be out of step where its phase difference angle exceeded the critical value.

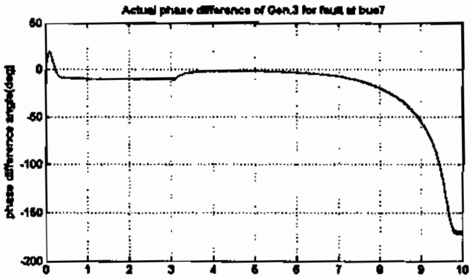


Fig.15 The recorded phase difference between Gen.3 and Gen.1 for a 3LG fault at bus 7

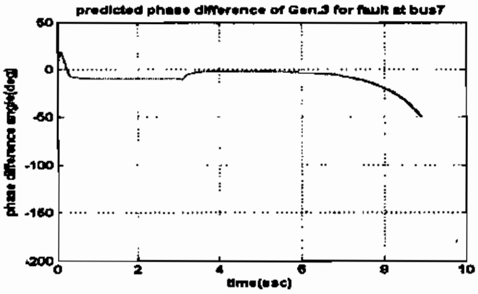


Fig.16 The predicted phase difference between Gen.3 and Gen.1 for a 3LG fault at bus 7

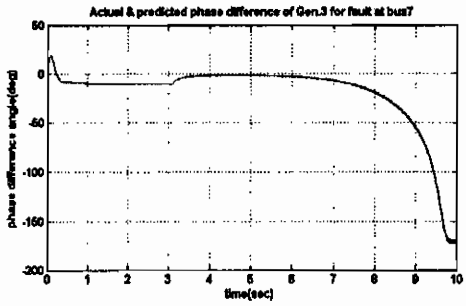


Fig.17 The recorded and predicted phase differcnce between Gen.3 and Gen.1 for a 3LG fault at bus 7

## 8. Conclusion

This paper proposed an optimization method for optimal placement of PMUs for complete observability of power system. The proposed method is based on numerical observation and artificial intelligence. The artificial intelligence algorithm used is the ITS algorithm, which is used to find the optimal placement for the PMU to keep the system complete observable. In addition, the paper described a predictive OOS algorithm based on the observation of the voltage phase difference between substations. The proposed optimal placement of PMUs and the OOS algorithms were tested using the IEEE 6 bus, IEEE 14 bus systems and the Egyptian 500 kV network. The test systems were simulated using the PSCAD software program. The placement algorithm and the OOS prediction algorithm were carried out using MATLAB script programs. It was shown by test results the effectiveness of both the PMUs placement and the prediction algorithms introduced.

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