**Ain Shams University**
**Faculty of Engineering**

# Enhancing Power System Observability with the Aid of Phasor Measurements Units

**By**

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B.Sc in Electrical Power Engineering

A thesis Submitted for the Requirement of Master Degree in Electrical Power Engineering

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**Cairo 2016**

# Approval Sheet

*For Thesis with Title*

# Enhancing Power System Observability with the Aid of Phasor Measurement Units

*Submitted in partial fulfillment for the requirement of degree in*

***Master of Science in Electric Engineering***

**Presented By**

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# Statement

This dissertation is submitted to Ain Shams University in partial fulfillment of the requirements of the degree in master of science in Electrical Engineering.

The work included in this thesis was carried out by the author in the department of Electrical Power and Machines, Ain Shams University.

No part of this thesis has been submitted for a degree or a qualification at any other university or institution.

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# Acknowledgement

My sincere gratitude is to **Dr. Said Fouad Mohamed Mekhamer** for his excellent supervision, encouragement, and the time he offered me during his period of supervision, support during the research period and helpful advices.

My special Thanks are to, **Dr. Walid Atef Omran** for his continuous guidance, encouragement, being a patience and a great supporter to me during research period.

Thanks are also extended to the members of my committee for their guidance and advice.

Last but not least, I am grateful to my wife and my son for their patience, support and encouragement during the research period.

# ABSTRACT

This thesis presents two methods for optimally allocating the phasor measurement units in the electrical power network. The two methods are Binary Integer Linear Programming (BILP) and the probabilistic failure method for minimizing the number of phasor measurement units needed which can achieve full system observability.

The full system observability is verified on both normal condition and N-1 contingency condition under either PMU failure or a transmission line failure using the Binary Integer Linear Programming (BILP). Moreover, the approach is used to locate the PMUs with considering the effect of limited number of measuring channels. The problem formulation also considered the effect of Zero Injection Buses (ZIB) by using a set of rules that improve the redundancy between PMUs by choosing better locations without increasing the required numbers of PMUs. The applied approach is tested on IEEE standard system i.e. 14 bus, 30 bus and 57 bus systems. The simulation results are compared with other studies to validate the efficiency and performance of the applied technique.

The implementation of the probabilistic failure method using state enumeration. Simulated systems show how this method is more efficient and reliable as it depends on evaluating two reliability indices which are the probability of unobservability of the bus and the probability of unobservability of the system. Adding the PMUs will be step by step till the probability of unobservability of the system is improved. The probabilistic failure method can deal with any PMU allocation method, as its ability to start at any existing system status regarding the number of PMUs or their locations. This method also is near to real systems where first PMUs have to be placed at the critical buses due to technical and economical issues, then more PMUs are placed till the system is fully observable and reliable. The probabilistic failure method is tested on the IEEE standard systems 14, 30 and 57 test systems. The simulations results are compared with other studies used in the literature to validate the performance of the applied technique.

Two papers (Journal and conference) are extracted and published from this thesis.

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**LIST OF ABBREVIATOINS**

| | |
|---|---|
| AGC | Automatic Generation Control |
| BILP | Binary Integer Linear Programming |
| ED | Economical Dispatch |
| EMS | Energy Management System |
| ES | Enumerated State (State Enumeration) |
| GPS | Global Positioning System |
| IED | Intelligent Electronic Device |
| KCL | Kirchhoff's Current Law |
| LAN | Local Area Network |
| NTC | Nominal Transfer Capacity |
| PE | Parameter Estimation |
| PMU | Phasor Measurement Unit |
| RTC | Real Time Transfer Capacity |
| RTU | Remote Terminal Unit |
| SCADA | Supervisory Control and Data Acquisition |
| SE | State Estimation |
| SPA | Standing Phase Angle |
| WAMPAC | Wide Area Monitoring, Protection And Control |
| WAMS | Wide Area Monitoring System |
| ZIB | Zero Injection Bus |

## LIST OF SYMBOLS

| | |
|---|---|
| $\boldsymbol{f_i}$ | Observability vector with i[th] entry representing the observability of bus *i* without considering limited number of measuring channels for PMU |
| $\boldsymbol{A}$ | The connectivity matrix without considering limited number of measuring channels for PMU |
| X | Is binary decision variable vector with its entries $x_i$ |
| $x_i$ | Indicates the location of the buses which are equipped by the PMUs |
| $L$ | Number of current measuring channels |
| $N_k$ | Number of neighboring buses at bus $k$ |
| $r_k$ | The possible series of channel assignments at bus $k$ with respect to neighboring buses |
| $^{N_k}C_l$ | the number of possible series of $L$ out of $N_k$ branches |
| $\boldsymbol{A^{new}}$ | The connectivity matrix with considering limited number of measuring channels for PMU |
| $\boldsymbol{F_i}$ | Observability vector with i[th] entry representing the observability of bus *i* with considering limited number of measuring channels for PMU |
| $\boldsymbol{Y}$ | Is binary decision variable vector with its entries $x_i$ |
| $y_i$ | Indicates the location of the buses which are equipped by the PMUs |
| $\boldsymbol{p_i}$ | The probability of success of a PMU or a line |
| $\boldsymbol{q_i}$ | The probability of failure of a PMU or a line |
| $r_s$ | The probability of a system state |
| $w_j$ | The probability of unobservability of bus $j$ |
| $w_T$ | The probability of incomplete observability for the whole system |
| $u_j$ | The bus observability |
| ε | The threshold value for the iteration process |

# CHAPTER ONE

# INTRODUCTION

## 1.1 Introduction

Since a long time, monitoring of power systems was depending on the measurements collected through remote terminal units (RTU). These measurements have the ability to measure the magnitude of bus voltage, the branch power flow and the power injections at buses. One of the most critical quantity to measure is the phase difference between each bus voltage phasors in the system. This phase difference was difficult to be measured. Direct measurement for voltage phase angle and current phasor is possible now by the availability of phasor measurement units (PMU) which use the Global Positioning Satellite System (GPS) signal to facilitate a time-synchronized measurements at any distant locations. However, if there is no phase angle measurements, the power system state estimation can estimate the phase angle of each bus with its magnitude based on the existing measurement of power flow, power injections,... etc.

Since the introduction of phasor measurements units for bus voltages and branch currents in the electrical power network, the application functions in control center have been affected. As the state estimation application in this case will be able to transform the problem formulation from nonlinear to linear, a large number of voltage and current phasors can be determined or measured. As all state estimator users are interested for such nonlinear to linear transformation that will be accomplished by setting up the right number of PMUs, this will strategically improve the state estimation process efficiently.

## 1.2 Motivation of the Study

Synchronized phasor measurement units (PMU) are widely populating in power systems due to their features and abilities to measure bus voltage and branch current phasors. Phasor measurement units are considered an essential part for various applications of energy management system (EMS). One of these applications is the state estimation. State estimation can provide a real time data for several application functions that can facilitate an efficient control on power system operation. So these devices are needed to be strategically placed to take the full advantages of their features and for cost minimization.

Optimal placement methods have been already addressed in previous publications considering the effect of contingencies either loss of a measurement or loss of a transmission line and the effect of the Zero Injection Buses (ZIB). All these studies considered same assumption that each PMU have a channel for measuring the voltage of the bus and indefinite number of current measuring channels that can measure indefinite neighboring branch currents, since these devices have the capability to measure the phasor voltage of the bus where the PMU is installed and the phasor voltage of its neighboring buses, as the branch parameters and the network connectivity are well known. In real power systems PMUs have a specified number of measurement channels that will be a factor of cost and will play a significant role in PMU placement formulation.

Power system reliability is the probability that a system has the ability to do its intended job within a certain time under a pre-determined operating conditions. Then for a highly reliable system, it is important that all the system components are able to carry out a given job within the specified requirements. So the power system reliability critically depends on the reliability of the PMUs monitoring the entire system, as PMUs are the data source for a failure happened in the power system either for a measurement or a transmission line. So PMUs allocation are determined considering the reliability of system observability.

## 1.3 Contribution of the Thesis

The main goal for this thesis is to present the effect of the limited number of current measuring channels for a PMU on their optimum allocation for power network observability including the cases of contingences. Contingencies include PMU failure or a transmission line failure.

Improving the reliability of power system observability is also presented. In actual installing PMUs for a power system; a few PMUs are placed at critical buses first then more PMUs are gradually set up at the remaining buses of the entire power system due to technical and economical limitations.

## 1.4 Thesis Outlines

This thesis comprises five chapters. It is organized as follows:

In chapter (1), the motivations for the research problem and the contributions to PMU placement problem are discussed.

In chapter (2), presents the general background information about synchronized phasor measurement units (PMUs) and review the relevant