Reviewing issue of Phasor Measurement Units Optimization for Power System Observability

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Abstract— **The electric power grid is a complex interconnected system that may be subjected to blackouts and faults. It is necessary for utilities to repair and restore their power system as quickly as possible during extreme conditions. The exact state of the electric grid is needed to perform any corrective or preventive actions during such conditions. To overcome this problem we find a method to find minimum number of phasor measurement units (PMUs) for complete observability of power system network for normal operating conditions. Phasor measurement unit (PMU), which is based on the global positioning system (GPS) technique, is able to provide power engineers with immediate and precise measurements**.

Keywords— **PMU, GPS.**

I. Introduction

The Economic growth and a global impetus to integrate intermittent renewable energy sources into the electric grid are causing the electrical network to undergo a fundamental paradigm shift. In order to cope with higher power flows and incorporate renewable, the modern grid requires widespread installation of new technologies to underpin grid stability. Utilities are working towards the concept of a smart grid: A grid where generation no longer blindly follows consumption, but rather where a dynamic, two-way relationship exists between the utility and consumer to enhance the efficiency of generation and transmission infrastructure. Phasor measurement units (PMUs) observe key power system metrics such as voltage magnitudes and phase angles and incorporate these with global positioning satellite (GPS) time stamps to synchronize measurements at geographically distant locations. These properties enable a phasor measurement unit (PMU) to generate a real time snapshot of a wide area monitoring system (WAMS) rendering the system fully observable [1]. The term full observability implies that each bus of the network has at least one phasor voltage measurement and one current measurement or a phasor voltage/current pseudo-measurement. Placing a phasor measurement unit (PMU) on each bus of a system would not be economic. The cost of phasor measurement unit (PMU) implementation must be minimized. Therefore the phasor measurement unit (PMU) optimal placement problem is formulated as a constrained optimization problem where the objective function is to achieve complete system observability with a minimum number of phasor measurement units (PMUs) placed at strategic bus locations. The electric power grid is a complex interconnected system that may be subjected to blackouts and faults. The exact state of the electric grid is needed to perform any corrective or preventive actions during such conditions. It is possible to get a reduced set of data or corrupted data during extreme contingencies for further analysis. A major loss of sensor data during extreme contingencies may prevent the determination of the exact state of the power system. Power system observability techniques helps to get a better picture of the power system with an available set of measurements [2]. Sensors like phasor measurement units (PMUs) are used to observe out the states of the power system in real time. Phasor measurement unit (PMU) is a device with capability of measuring the positive sequence of phasor voltage and phasor current measurements on each bus in electrical network. These measurements are synchronized through global positioning system (GPS) within a micro second. The main purpose is to optimize the number of phasor measurement units (PMUs) for full observability of the power system and compare the performance of each optimization technique algorithms.

1.1 States of the Power System

The operating condition of a power system at any given point of time is known as the state of the power system. The operating condition of a power system at a given point can be determined if the topology of the system and complex voltage phasor of the system is known [3].

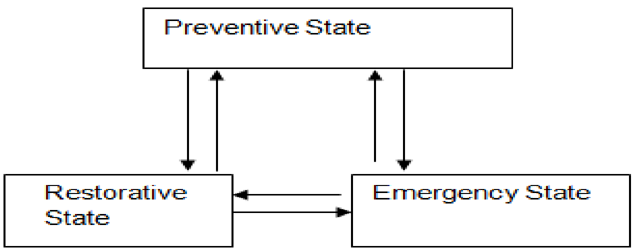

Fig. 1.1 Power System Operating States

Since the system can be specified just using the complex phasor voltages corresponding to that system, the complex phasor voltage is called “static state” of the system. Fig.1(a) shows power system operating states, where the solid arrow indicate the change in state by planned control action and dashed arrow indicate the change in state resulting from unavoidable circumstances (i.e. disturbances) or from incorrect control action. The overall control objective is to try to keep the power system operating in the preventive state [4].

A given power system can move into one of the following three states [3], [4].These states are given below:

1. Normal
2. Emergency
3. Restorative

Normal state: A system is said to work under normal condition if using the existing generation of the system, all loads can be fed with no violations in any operating constraints. Operating constrains includes the active and reactive powers which can be transferred through a transmission line and lower limits of the bus voltage magnitudes. Topology of the system is always changing due to contingency which are transmission line or generator outage. Line outages may happen due to expected causes such as switching, maintenance or unexpected reasons such as lightning. If the system remains in normal condition following the occurrence of a contingency, the system is called “secure-normal”. Otherwise the system is classified as “unsecure-normal” condition where the system is operating under the normal condition without violating any operating condition, but the system is vulnerable with respect to some of the contingencies.

Emergency State: Unexpected events can have a significant impact on system operating condition; it may also cause violation of some of the operating constraints while the system is operating. In such case the system is said to be working under emergency condition. Emergency state needs immediate recovery action to bring the system back to the normal state and avoid the system collapse.

Restorative State: One way to overcome the emergency state is to discontinue the various loads, transmission lines, transformers and other equipments. Removing loads and transformers might be able to confine the operating condition into the constraints limits. This may lead to re-gaining the stability with reduced load and reconfigured topology. As a result, the load versus generation balance may have to be restored in order to start supplying power to all the loads including the one removed from the system. This operating state is known as restorative state. In this state the various loads are restores in their previous states by some immediate actions. The objective of power system operator is to maintain the system in the normal secure state as the operating condition of power system changes during the day. To be able to achieve this goal, power system dispatcher should continuously monitor the system condition and operating state of the system. Necessary remedial actions should be taken in case the system found to be operating under insecure-normal condition. The sequence of actions which should be taken by power system operator is known as security analysis.

II.RELATED WORK

It is well known that the active power flow in a given line in power system is proportional to the difference between the phase angles of terminals of that line [16]. Therefore, measuring the phase angles difference across the power system transmission lines is important to power system engineers. The history of PMUs goes back to 1977 when a new symmetrical based algorithm was proposed in a paper to protect the transmission line in power systems. Symmetrical components of three phase voltage and current are described in that paper. Calculation of the positive sequence voltages and currents in a power system was the first step in the procedure employed by the phasor measurement units The power injection and flow measurement pairs are placed to observe the raw data of boundary bus and tie line for data exchange in wide-area state estimator [19]. Gou B. (2008) presented a simple optimal placement algorithm of phasor measurement unit (PMUs) by using integer linear programming. Cases with and without conventional power flow and injection measurements are considered.

III. PROPOSED WORK

Power system observability analysis is a fundamental component of real time state estimation. There are two mostly used algorithms for power network observability analysis: topology based algorithms and numerical methods. Topology methods are developed from graph theories, compared to numerical methods that are mainly based on numerical factorization of measurement Jacobi matrices. Numerical methods are less suitable for large system because they are involved with large dimension matrices that increase the computational complexity. If we model buses in a power system by vertices and model the transmission and distribution line connecting buses by edge, this problem is converted to be a domination problem and requires the extension of the topological observation theory.

3.1Phasor Measurement Units Placement Algorithm

Once a placement model is developed, a phasor measurement unit planner is ready to place phasor measurement units (PMUs) for full system observability. This chapter introduces a new placement algorithm developed by using Matlab [58]. Using several IEEE test systems, this algorithm’s results are compared with other algorithms. The main emphasis will be to examine how practical the new algorithm is with real transmission systems.

3.2 The Linear Algorithm

The goal of placement algorithms is to achieve full system observability with a minimum number of phasor measurement units, thereby reducing cost. The phasor measurement unit (PMU) placement problem is the important area that needs to be solved. There are simply too many possibilities to try random placements and check for full observability.

3.3 Creating a Node –Incidence Matrix for Power System:

By the topological information of a power system the interconnection of the various buses can be grouped in an array called bus connectivity matrix. To produce the bus

connectivity matrix the rule is simple:
If node i is connected to node j, then A_{ij}=1, where i≠ j andA_{ii}=0

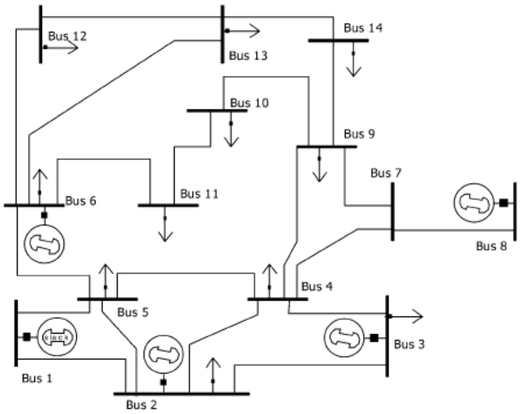

Fig.2.1 IEEE-14 bus system

Normally A is a large sparse matrix. For example, for the IEEE 14-bus system,

A= [0 1 0 0 1 0 0 0 0 0 0 0 0 0
1 0 1 1 1 0 0 0 0 0 0 0 0 0
0 1 0 1 0 0 0 0 0 0 0 0 0 0
0 1 1 0 1 0 1 0 1 0 0 0 0 0
1 1 0 1 0 1 0 0 0 0 0 0 0 0
0 0 0 0 1 0 0 0 0 0 1 1 1 0
0 0 0 1 0 0 0 1 1 0 0 0 0 0
0 0 0 0 0 0 1 0 0 0 0 0 0 0
0 0 0 1 0 0 1 0 0 1 0 0 0 1
0 0 0 0 0 0 0 0 1 0 1 0 0 0
0 0 0 0 0 1 0 0 0 1 0 0 0 0
0 0 0 0 0 1 0 0 0 0 0 0 1 0
0 0 0 0 0 1 0 0 0 0 0 1 0 1
0 0 0 0 0 0 0 0 1 0 0 0 1 0]

It is easy to find out that there are 8 nodes with degree 3 or more. Here K=8 and n=14. Where k is the nodes with degree 3 or more and n is the number of buses. So, the number of phasor measurement units (PMUs) needed that is, the only possible values for S between 3 and 4 using equation (4.1) and (4.2). S is the combination of buses where phasor measurement units will installed. Now we want to find out the minimum number of phasor measurement units (PMUs) and the dominating set S. The basic idea of this algorithm is to test all possible node combinations by the observation rules, until one combination is found to be able to “observe” all the system. We call a test for a combination as a measurement. For the IEEE 14-bus system, the maximum number of measurements is number of combinations produce by selecting numbers of a group in between 3-4, who will converge, will give the required number of phasor measurement units (PMUs) in the system. That is 70 for IEEE 14-bus system. We need to keep in mind that, in the implementation of the algorithm, we may not have to run all the 70 measurements to find out the S-set .The number of measurement before we get an S-set (which is usually not unique) can be any number between 1 and 70.

To get the fast solution, a good initial guess of phasor measurement units (PMUs) placement, this algorithm was tested for a list of distribution system and proven very good efficient. In [27] mathematically proved that for a tree having k vertices of degree at least 3, the “power dominating number”.

y_p(T)≥ (k+2)/3 (4.1)

y_p(T)≤ n/3 (4.2)

Where n is the total no. of vertices.

Equation (4.1) and (4.2) give the upper and lower bounds for the power dominating number. Although a power system does not have to a tree topology, these theorems corresponded to the computation result from [13] very well. Haynes at al. in this paper also gave an algorithm to find out the dominating set S and a partition of the whole set G into S so that each subset induces a “spider”. In, summarized most available topological based formulated algorithms including genetic algorithm (2009), Tabu search (2006), Integer linear programming (2008).However complexity of each algorithm is still left to be discussed. In engineering practice, we are most interested in the dominating set, i.e., where to mount the phasor measurement units (PMUs). The partition is not the primary concern. Taking advan-tage of the upper and lower bounds [13], a linear algorithm is proposed in this work. This algorithm is proven especially effective for small system.

IV SIMULATION SOFTWARE

The name MATLAB stands for Matrix Laboratory. Matlab was written originally to provide easy access to matrix software developed by the LINPAC (linear system package) and Eispack (Eigen system package) projects. Matlab is a high-performance language for technical computing. It integrates computation, visualization and programming environment. Furthermore, Matlab is a modern programming language environment: it has sophisticated data structures, contains built-in editing and debugging tools, and supports object-oriented programming. These factors make matlab an excellent tool for teaching and research. Matlab has many advantages compared to conventional computer languages (e.g., C, FORTRAN) for solving technical problems. Matlab is an interactive system whose basic data element is an array that does not require dimensioning. The software package has been commercially available since 1984 and is now considered as a standard tool at most universities and industries worldwide.

It has powerful built-in routines that enable a very wide variety of computations. It also has easy to use graphics commands that make the visualization of results immediately available. Specific applications are collected in packages referred to as toolbox. There are toolboxes for signal processing, symbolic computation, control theory, simulation, optimization and several other fields of applied science and engineering.

Matlab is a high-level technical computing language and interactive environment for algorithm development, data visualization, data analysis, and numeric computation. Using the matlab product, you can solve technical computing problems faster than with traditional programming languages, such as C, C++, and FORTRAN.

You can use matlab in a wide range of applications, including signal and image processing, communications, control design, test and measurement, financial modelling and analysis, and computational biology. Add-on toolboxes (collections of special-purpose matlab functions, available separately) extend the matlab environment to solve particular classes of problems in these application areas. Matlab provides a number of features for documenting and sharing your work. You can integrate your matlab code with other languages and applications, and distribute your matlab algorithms and applications. Features include:

- High-level language for technical computing
- Development environment for managing code, files, and data
- Interactive tools for iterative exploration, design, and problem solving
- Mathematical functions for linear algebra, statistics, Fourier analysis, filtering, optimization, and numerical integration
- 2-D and 3-D graphics functions for visualizing data
- Tools for building custom graphical user interfaces
- Functions for integrating matlab based algorithms with external applications and languages, such as C, C++, FORTRAN and Java.

The matlab system consists of these main parts:

4.1 Desktop Tools and Development Environment

This part of matlab is the set of tools and facilities that help you use and become more productive with matlab functions and files. Many of these tools are graphical user interfaces. It includes: the matlab desktop and command window, an editor and debugger, a code analyzer, and browsers for viewing help, the workspace, and folders.

4.2 Mathematical Function Library

This library is a vast collection of computational algorithms ranging from elementary functions, like sum, sine, cosine, and complex arithmetic to more sophisticated functions like matrix inverse, matrix eigenvalues, Bessel functions, and fast fourier transforms.

4.3 The Language

The matlab language is a high-level matrix/array language with control flow statements, functions, data structures, input/output, and object-oriented programming features. It allows both "programming in the small" to rapidly create quick programs you do not intend to reuse. You can also do "programming in the large" to create complex application programs intended for reuse.

4.4 Graphics

Matlab has extensive facilities for displaying vectors and matrices as graphs, as well as annotating and printing these graphs. It includes high-level functions for two-dimensional and three-dimensional data visualization, image processing, animation and presentation graphics. It also includes low-level functions that allow you to fully customize the appearance of graphics as well as to build complete graphical user interfaces on your matlab applications.

4.5 External Interfaces

The external interfaces library allows you to write C/C++ and fortran programs that interact with matlab. It includes facilities for calling routines from matlab (dynamic linking), for calling matlab as a computational engine, and for reading and writing mat-files.

V. STARTING MATLAB

After logging into your account, you can enter matlab double-clicking on the matlab shortcut icon (matlab 7.0.4) on your Windows desktop. When you start matlab, a special window called the matlab desktop appears. The desktop is a window that contains other windows. The major tools within or accessible from the desktop are:

- The Command Window
- The Command History
- The Workspace
- The Current Directory
- The Help Browser
- The Start button

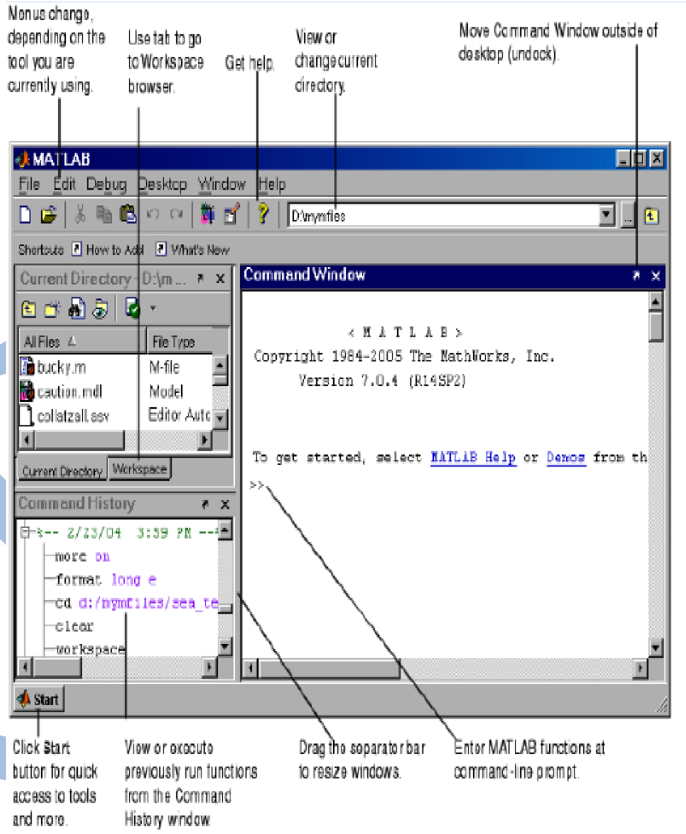

Figure 5.1 Graphical Interfaces to Matlab Workspace

When matlab is started for the first time, the screen looks like the one that shown in the Figure 5.1. This illustration also shows the default configuration of the matlab desktop. You can customize the arrangement of tools and documents to suit your needs. Now, we are interested in doing some simple calculations. We will assume that you have sufficient understanding of your computer under which matlab is being run. You are now faced with the matlab desktop on your computer, which contains the prompt (>>) in the Command Window. Usually, there are 2 types of prompt:

>>For full version

EDU> for educational version

Note: To simplify the notation, we will use this prompt, >>, as a standard prompt sign, though our matlab version is for educational purpose.

5.1 The Help Window

Separate from the main desktop layout is a Help desktop with its own layout. This utility can be launched by selecting Help ->matlab help from the help pull down menu. This help desktop has a right side which contains links to help with functions, help with graphics, and tutorial type documentation. The left side has various tabs that can be brought to the foreground for navigating by table of contents, by indexed keywords, or by a search on a particular string.

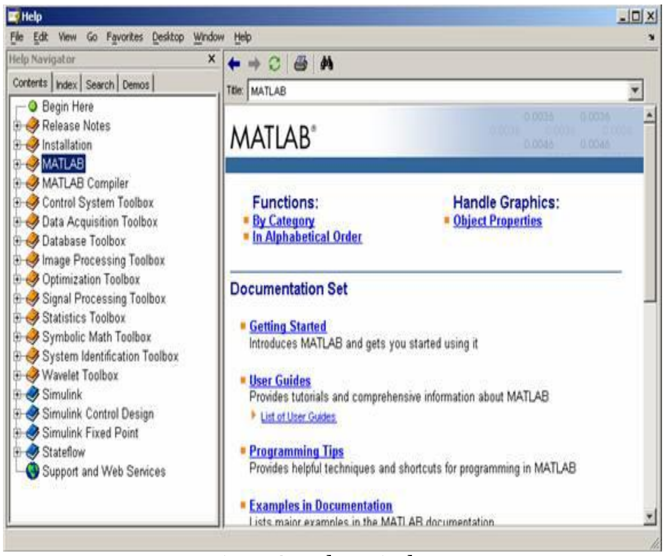

Fig. 5.2 Help Window

VI. CONCLUSIONS

The proposed linear algorithm takes advantage of the upper and lower bounds and the graph theorems that were mathematically proven, which greatly reduced the computation in seeking a dominating set in a power system. Compared to the algorithm in [19] and [20], the proposed algorithm can theoretically guarantee the minimum number of phasor measurement units (PMUs). Compared to the algorithms in [16], it is simpler and easier to be implemented. However, the computation complexity reflected by measurement study indicates that the linear algorithm should be very competitive to other topology based algorithm and other numerical methods and provides complete observability for the power system .

In this dissertation work, the main focus is on the optimization of phasor measurement units and therefore the objective is to make the entire system observable by optimal placement of phasor measurement units (PMUs). This work considered various scenarios where the system is first assumed to be observed by phasor measurement units (PMUs) only. While this appears impractical today, it may very well be the case in a few years when these devices become standard equipment at substations. Next, the placement problem is considered for a system with existing measurements, some of which may be phasor measurement units (PMUs). Case studies which are carried out on IEEE-14, IEEE-18, IEEE-24, IEEE-30 and IEEE-57 bus system can be made observable with only phasor measurement units (PMUs). Furthermore, zero injections, which can be considered free measurements, can significantly reduce the required number of phasor measurement units (PMUs) for a given system.

Phasor measurement units (PMUs) placement problem does not have a unique solution. Depending upon the starting point, the developed optimization scheme may yield different sets of optimal solutions, each one providing the same minimum number of phasor measurement units (PMUs) but at different locations. On the other hand, it is not unusual to have additional considerations apart from strict observability criterion, when deciding on the location of phasor measurement units (PMUs). These considerations can be taken into account by appropriately modifying the optimization problem which is formulated in this work. This can be done as an extension to this work in the future. One of the important functions of state estimators is to detect and eliminate bad measurements in the system. Bad data processing is strongly dependent upon the measurement redundancy as well as accuracy of the measurements used. Even for fully observable systems, strategic placement of few phasor measurement units (PMUs) can significantly improve bad data detection and identification capability. This aspect of phasor measurement units (PMU) placement can also be investigated in the future so that the operation of the existing state estimators can be improved via phasor measurement unit (PMU) placement.

6.1 Future Work

For further work we can try to find such solutions which give lesser capital investment for the phasor measurement units (PMUs) placement as the number of communication port, environmental concerns, technological issues and life cycle also contribute to the cost/unit of a phasor measurement unit (PMU) in the system. The work done in this report indicates that phasor measurement units (PMUs) have many benefits in the state estimation process. If the phasor measurement units (PMUs) are installed through the entire system, the linear formulation of the state estimation can be used which has fast execution time and improved accuracy. While the information about the interconnected different areas is becoming more important, a multi-area state estimation for a huge size of system is needed nowadays. Furthermore, each area should install phasor measurement unit (PMU) for the synchronization, and communicate between the different areas and central coordinator, while the concerned network areas are becoming larger. By doing so, the multi-area state estimation for a large network system can be done. In order to efficiently install phasor measurement units (PMUs) to the existing system, a research for the optimal phasor measurement units (PMUs) placement is needed. The way of deploying the phasor measurement units (PMUs) would determine improvement level of the accuracy and the cost. Also, an analysis for the cost effects of adding more phasor measurement unit (PMU) is required.

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