Implementing Phasor Measurement Units Optimization for Power System Observability

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***Abstract*— The Phasor measurement units (PMUs) are widely acknowledged as one of the most promising developments in the field of real-time monitoring of power system. By aligning the time stamps of voltage and current phasor measurements that are consistent with Coordinated Universal Time (UTC), a coherent picture of the power system state can be achieved through either direct measurements or simple linear calculations. With the growing number of phasor measurement units (PMUs) planned for installation in the near future, both utilities and research institutions are looking for the best solutions to the placement of units as well as to the applications that make the most of phasor measurements A linear algorithm is used to determine the minimum number of phasor measurement units (PMUs) needed to make the system observable**.

***Keywords*— UTC, PMU, GPS.**

I. INTRODUCTION

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. 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. 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 . 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. Phasor measurement units (PMUs) are power system devices that provide synchronized measurements of real-time phasors of voltages and currents. Synchronization is achieved by same-time sampling of voltage and current waveforms using timing signals from the global positioning satellite (GPS). A number of phasor measurement units (PMUs) are already installed in several utilities around the world for various applications such as post-mortem analysis, adaptive protection, system protection schemes, and state estimation. Phasor measurement unit (PMU) technology can track the network dynamics in micro-second rate. This is a great advancement to the SCADA/EMS measurements, where the refreshment rate is seconds to minutes. Collected data from different phasor measurement units (PMUs) in the system will be sent to the phasor data concentrator (PDC) to align data from different phasor measurement units (PMUs) in the network. This is done based on the time tag. Next, the phasor measurement unit (PMU) data from phasor data concentrator (PDC) of each center is sent to the central facility where all collected data from different phasor measurement units (PMUs) in different utility systems will be synchronized.

1.1 Power System Observability

The Power system observability is a mathematical procedure that is use to estimates the states (bus voltages and angles) from the network data and sensor information. It can also be used to calculate system quantities and states where sensors are not available. Power system observability generally acquires the measurements in real time and processes them to obtain a snapshot of the power system. The data to the state estimator may get updated every few seconds to minutes or whenever there is a change in status of the network. A static state estimator is a steady state estimator that calculates the unknown values based on the most recent measurements. A dynamic state estimator predicts the future states of power system based on the present variations and forecasted loads Synchronized phasor measurements are becoming an important element of wide area measurement systems used in advanced power system monitoring, protection and control applications.

Phasor measurement units (PMUs) are power system devices that provide synchronized measurements of real-time phasors of voltages and currents. Synchronization is achieved by same-time sampling of voltage and current waveforms using timing signals from the global positioning satellite (GPS). A number of phasor measurement units (PMUs) are already installed in several utilities around the world for various applications such as post-mortem analysis, adaptive protection, system protection schemes, and state estimation. One of the most important issues that need to be addressed in the emerging technology of phasor measurement units (PMUs) is site selection. The intended system application influences the required number of installations. The cost of phasor measurement units (PMUs) limits the number that will be installed although an increased demand in the future is expected to bring down the cost. The placement sites are also limited by the available communication facilities, the cost of which may be higher than that of the phasor measurement units (PMUs).

A judicious choice of phasor measurement unit (PMU) locations is necessary to meet the criteria of cost and the intended phasor measurement unit (PMU) applications. Phasor measurement units (PMUs) become more and more attractive to power engineers because they can provide synchronized measurements of real-time phasors of voltage and currents. As the sole system monitor, state estimator plays an important role in the security of power system operations. Optimal placement of phasor measurement units (PMUs) in power systems to enhance state estimation is a problem that needs to be solved. PMUs are the most sophisticated device used in power systems which utilizes the high accuracy computation and the availability of global positioning satellite (GPS) signal. Although advanced techniques in measuring and synchronizing measurements are basics for phasor measurement units (PMUs) operation, advances in other areas are also required to achieve the benefits of phasor measurement units (PMUs). One such area is data communication where faster and more reliable communication channels have created the chance of streaming from remote phasor measurement units (PMUs) site to the power system center. Phasor measurement unit (PMU) technology can track the network dynamics in micro-second rate.

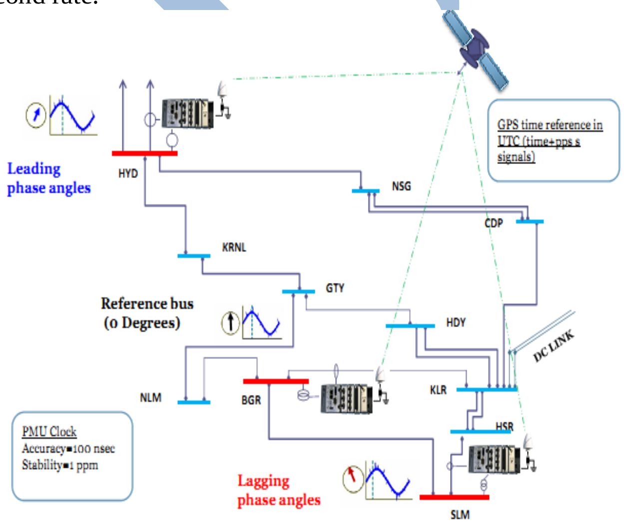

Fig.1.1 Power System Observability by PMUs

This is a great advancement to the SCADA/EMS measurements, where the refreshment rate is seconds to minutes. Collected data from different phasor measurement units (PMUs) in the system will be sent to the phasor data concentrator (PDC) to align data from different phasor measurement units (PMUs) in the network. This is done based on the time tag. Next, the phasor measurement unit (PMU) data from phasor data concentrator (PDC) of each center is sent to the central facility where all collected data from different phasor measurement units (PMUs) in different utility systems will be synchronized.

Researches and development of phasor measurements andtheir applications in power systems during the past two decades, show that a system designed based on utilizing these devices are very effective to meet the above three objectives and can satisfy the new wide area operational constraints in the following three major areas .

- Real-time wide area monitoring
- Real-time wide area control
- Real-time wide area adaptive protection

Generic architecture for a wide area monitoring, protection and control contains four different layers are given below:

Layer 1: Phasor Data Acquisition - Synchronized phasor devices such as phasor measurement units (PMUs) and digital fault recorders are installed at the bus and are capable of measuring the phasor voltage and current phasor and frequency at the bus. Basic phasor measurement process derives positive sequence, fundamental frequency phasors from voltage and current of the bus.

Layer 2*:* Phasor Data Management - Phasor data concentrator (PDC) collects data from different phasor measurement units (PMUs) as well as other phasor data concentrator (PDCs) and correlates them into a single data set. It can also stream the data set to the appropriate application, using the data buffer.

Layer 3*:* Data Service - This layer contains a set of necessary services to provide data to different applications. The major role of this layer is to provide data in proper format for different applications. Both appropriate format and fast execution are important in this layer as providing data in appropriate format in a desired time frame can leave enough time for running the application within the sampling time.

Layer 4*:* Applications - This layer contains the following three sections: real-time wide area control, real-time wide area monitoring and real-time wide area protection.

Four layers mentioned above forms one possible architecture which enables monitoring, control and protection of the system based on utilization of phasor measurement units (PMUs).

II. RELATED WORK

Many researchers have dedicated their attention to application of phasor measurement units (PMUs) in power systems observability. When placed at the bus, a phasor measurement unit can measure the phasor voltage of the bus and different number of phasor currents of branches incident to that bus, depending on the type of phasor measurement units. However, the cost of phasor measurement units and their installation does not allow utility companies to install phasor measurement units at every bus. Recent events have shown that the electric utility power system may have major blackouts and faults. It is possible to lose data from the network due to failure of communication systems during these incidents. It is necessary to receive information from the system so that decisions can be made by the operator to prevent any kind of collapse or to perform restoration. Phasor measurement units (PMUs) are the equipments used to take the real time snapshot of the power system .They measure out the magnitude and phase angle of each bus in power system in real time. But it is not possible to install the phasor measurement units (PMUs) on each bus due to high cost of phasor measurement units (PMUs) and communication complexity to each phasor measurement units (PMUs).

III. PROPOSED WORK

Power phasor measurement unit (PMU) placement technique, the basic phasor measurement unit (PMU) placement rules should be mentioned. A phasor measurement unit (PMU) installed on a certain bus is able to measure the voltage magnitude and phase angle of the local bus and the branch current phasor of all branches emerging from this bus. The voltage magnitude and phase angle of the neighbouring bus can be computed using voltage drop equations. Thus the buses monitored by a phasor measurement unit (PMU) are directly observable, the neighbouring buses connected to the phasor measurement unit (PMU) buses are indirectly observable and the other buses which are not associated with the phasor measurement unit (PMU) buses are unobservable. The following graph explains the bus observability in a system:

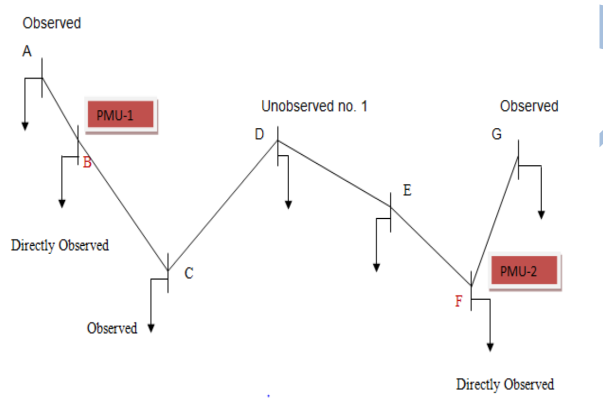

Fig.3.1 PMU Observability Analysis

In figure 3.1, the network has 7 buses from bus A to bus G. Assume two phasor measurement units(PMUs) are located on bus B and bus F, so bus B and F are directly observable. Bus A, C; E and G are all connected to bus B and F so they are indirectly observable. Bus D is not associated with any phasor measurement unit (PMU) bus, so bus D is unobservable. So in this 7-bus system example, 6 buses are observable and 1 bus is not observable. Thus, this system is not a completely observed system. A completely observed system means all the buses in this system should be directly observed or indirectly observed with a proper phasor measurement unit (PMU) placement scheme.

3.1 Influence of Zero-Injection Bus in PMU Placement

Zero-injection bus is a bus such that no current or power is injected into the system through this bus, which means no active or reactive load is associated with this bus. Figure 3.3 shows a zero-injection bus in a network. In the network below, bus A is a phasor measurement unit (PMU) bus, bus B is a zero-injection bus and bus C is a PQ bus in power system. Bus A is directly measured by the phasor measurement unit (PMU) installed at bus A, so bus A is directly observable; bus B which is connected to the phasor measurement unit (PMU) bus (bus A) is as well an observable bus by computing the voltage information with the voltage drop equations. Because bus B is a zero-injection bus, the current flowing through line A-B equals the current flowing through line B-C. Knowing the voltage information on bus B and the current phasor on line B-C, the voltage data on bus C can be calculated using Ohm's law. So in conclusion, bus A, B and C are all observable when bus B happens to be a zero injection bus. In contrast, if bus B is not a zero-injection bus, the assumption that the current phasor on line A-B equals that on line B-C will be invalid and thus the voltage information on bus C cannot be calculated without the current information on line B-C.

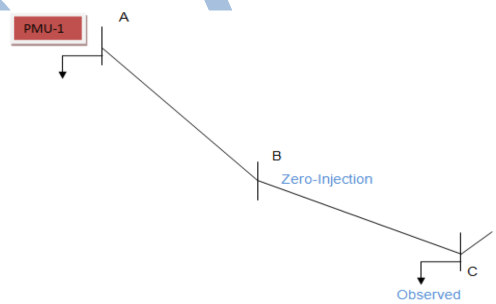

Fig.3.2 Zero-Injection Case

In this case, only bus A and B are observable when bus B is not a zero-injection bus. In short, considering the influence of zero-injection buses in a power system, the number of observed buses is expected to be increased and the optimal number of phasor measurement units (PMUs) required will be further minimized.

The observability conditions that have to be met for selecting the placement of phasor measurement unit (PMU) sets are:

Condition 1: For phasor measurement unit (PMU) installed at a bus, the bus voltage phasor and the current phasors of all incident branches are known.

Condition 2: If one end voltage phasor and the current phasor of a branch are known, then the voltage phasor at the other end of the branch can be calculated.

Condition 3: If voltage phasor of both ends of a branch are known, then the current phasor of this branch can be directly obtained.

Condition 4: If there is a zero-injection bus without PMU and the current phasor of the incident branches are all known but one, then the current phasor of the unknown branch can be calculated using Kirchhoff's current law (KCL).

Condition 5: If the voltage phasor of a zero-injection bus is unknown and the voltage phasor of all adjacent buses are known, then the voltage phasor of the zero-injection bus can be obtained through node voltage equations.

Condition 6: If the voltage phasor of a set of adjacent zero-injection buses are unknown, but the voltage phasor of all the adjacent buses to that set are known, then the voltage phasor of zero-injection buses can be computed by node voltage equations.The measurements obtained from

Condition 1 are called direct measurements. The measurements obtained from Conditions 2-3 are also called pseudo-measurement. The measurements obtained from Conditions 4-6 are called extension-measurements.

3.2 Observability Rules for PMUs

Placing a phasor measurement unit (PMU) at every bus would certainly provide all the necessary real-time Voltage magnitudes and angles for system observability; however this is redundant due to an important attribute of phasor measurement units (PMUs). Provided that you know a bus's voltage magnitude and angle, all current phasor and the connecting line parameters, then all connecting bus voltages and angles can be calculated. By ohm's law, if you know the voltage magnitude and phase at Bus A, the voltage at Bus B would be the voltage at bus A minus the voltage drop caused by the current travelling through the connecting line. This setup the first observability rule, that all buses connected to a directly observable bus are observable themselves, as illustrated in Figure 3.4.This significantly reduces the number of phasor measurement units (PMUs) needed for complete observability.

In this estimated that for a real system, phasor measurement units (PMUs) are required to be on a minimum of 20-30% of buses to achieve full system observability. Because of the ability of a phasor measurement unit (PMU) to observe neighbouring busses, phasor measurement unit placement for full observability is very similar to the graph theory topic of domination. There are also many special situations in which a bus can be calculated even if it is not connected to a directly observable bus. The following general rules cover many of these situations in which a bus does not have injection. If a bus without injection is observed and all but one of its connecting buses is observed, then the unobserved bus becomes observed.

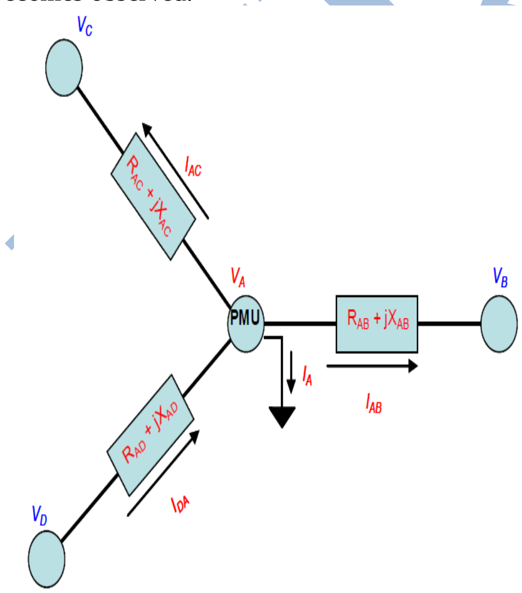

Figure 3.3 Example of the First Observability Rule

$$V_B = V_A - I_{AB}(R_{AB} + JX_{AB}) \quad (3.1)$$

$$V_c = V_A - I_{AC}(R_{AC} + JX_{AC}) \quad (3.2)$$

$$V_D = V_A + I_{DA}(R_{AD} + JX_{AD}) \quad (3.3)$$

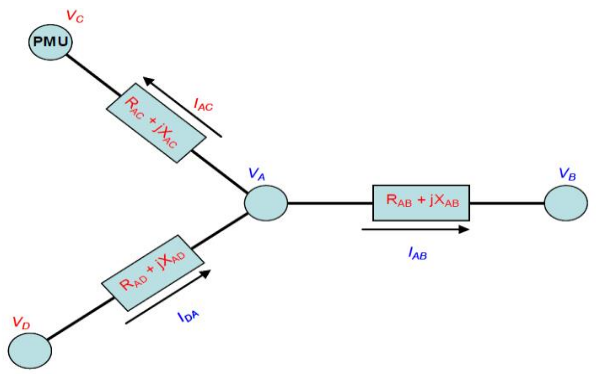

Figure 3.4 Example of the Second Observability Rule

$$V_A = V_C - I_{AC}(R_{AC} + JX_{AC} \quad (3.4)$$

$$I_{DA} = \frac{V_D - V_A}{R_{AC} + JX_{AC}} \quad (3.5)$$

$$I_{AB} = I_{DA} - I_{AC} \quad (3.6)$$

$$V_B = V_A - I_{AB}(R_{AB} + JX_{AB}) \quad (3.7)$$

An unobserved bus without injection connected only to observed buses is itself observable. Below the 3rd observability rule is given.

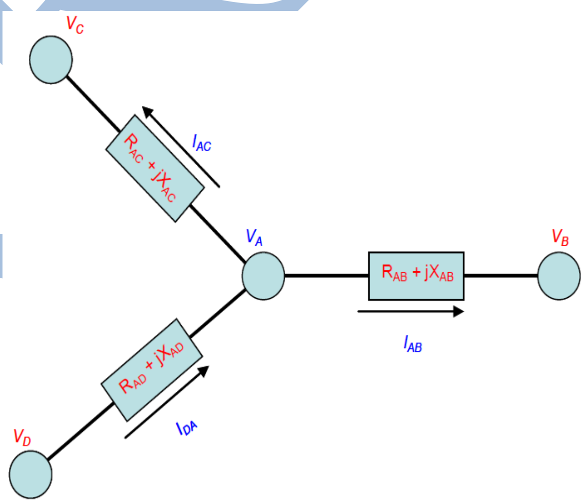

Figure 3.5 Example of the Third Observability Rule

$$V_A = V_B - I_{AB}(R_{AB} + JX_{AB}) \quad (3.8)$$

$$V_A = V_C - I_{AC}(R_{AC} + JX_{AC}) \quad (3.9)$$

$$V_A = V_C - I_{DA}(R_{AD} + JX_{AD}) \quad (3.10)$$

$$0 = I_{DA} - I_{AC} - I_{AB} \quad (3.11)$$

There could be other specific observability rules, but the three stated rules cover the vast majority of situations and are adequately comprehensive and easy to implement in placement algorithms. These rules states that if we have values of parameters, but others are unknown. By using these rules we can easily calculate the other parameters very easily. To recap:

1. All buses neighbouring a bus with a phasor measurement unit (PMU) are observable them- selves.

2. If all but one bus neighbouring an observable buses without injection are themselves observable, then all the

neighbouring buses are observable.
3. If all the buses neighbouring a bus without injection are observable, then that bus is also observable.

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. Matlab has its own programming language, also known by the name matlab, which is structured very much like most programming languages. Because its origin involved interfacing with many of the original linear algebra subroutines written in FORTRAN, matlab has roots there. But there is also much similarity with C due to later development of graphics functionality and the desktop GUI. The matlab programming language is thus not particularly difficult or obscure, and the primary task in becoming adept at using it involves learning the various notations and syntax rules.

4.1 Using the Editor

Matlab has the functionality of incorporating user-created files external to the command window. These files need to be placed in a folder or directory defined in the pathway and should consist of a series of valid matlab commands. These are thus equivalent to macros or subroutines in other programming languages, and are called m-files. They should have an extension of a period and a lower case m so that they can be recognized as matlab text files. The matlab7 GUI has a text editor interface that allows users to create m-files within the matlab application. It is launched from the navigation toolbar with file -> new ->m-file which opens up a new floating window ready for code text input. This editing window has its own toolbar with conventional Windows type pull down menus and button icons. Lines are numbered outside the text area for convenient referencing when debugging or inserting break, pause or flagging points. This editor tool is very convenient, with colour coding and indenting features that aid in construction, but m-files can also be created as plain ascii text in other text editors such as ms-word or note pad.

4.2 Types and Structures of M-files

There are two main types of m-files which are very similar to each other: script files that act as command sequence macros with no parameter passing and function files that also act as command sequence macros but which accept parameters by value and return a computed number, vector, or matrix assigned by the calling program. M-file scripts have no formal structure other than consisting of a sequence of valid matlab command line input. After saving an m-file, which can be done from the File pull down menu of the editor window, any subsequent command line reference to it will result in the execution of its contents. This applies both to input from a command window prompt and to any call from within another m-file.

A function m-file is similar except that the first command line should have the form function [var1 var2 {…}] = function name (arg1, arg2, {…}) and the returned information should assign the computed functional values to var1, var2, etc., obtained with the function computational algorithm. A trivial example:

Function f = double Val(x)

f = 2*x;

Which creates a function that doubles the value of the input as the return value? If you save this code with a name such as doubleval.m, any subsequent call to doubleval from the command window prompt or from another script will return a value twice as large.

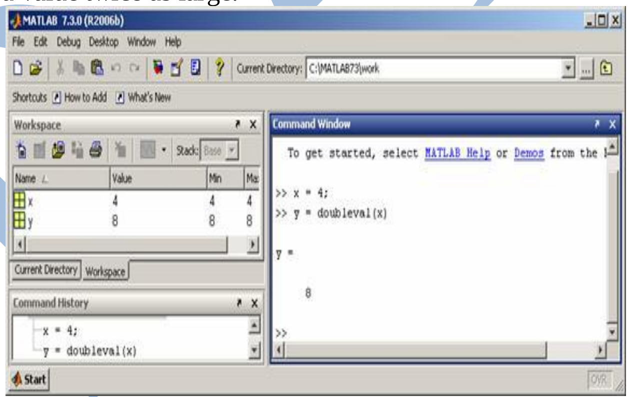

Fig. 4.5 Command Window

4.3 The Shortcut Utility

A matlab shortcut is an easy way to run a group of matlab commands that are used regularly, similar to a macro, but without the formality of having them incorporated as a script within the matlab path. Shortcuts can be created, run, and organized from the *start* >shortcuts menu or from the desktop shortcuts toolbar. From the Start button, select shortcuts >new shortcut. The shortcut editor dialog box appears. Create the shortcut by completing the dialog box using these steps:

1. Provide a shortcut name in the Label field to identify it.
2. Put the group of command statements in the call-back field. They can be entered directly from keyboard typing, copied and pasted, or dragged via a desktop tool. If imported, edit the statements as needed. The field uses the editor/debugger preferences for key bindings, colours and fonts, so the Call-back field will have an appearance similar to an m-file. Note that if you copy the statements from the command window, the prompts at the beginning of a line appear in the shortcut, but matlab removes these when the shortcut is saved.
3. Assign a category, which is like a directory, to be used for organizing shortcuts. To add the shortcut to the shortcuts toolbar, select the Toolbar Shortcuts category.
4. The default shortcuts icon is, but you may also select your own.
5. Click Save

Suppose that the following group of commands is desired for a shortcut

Clear;

Format long e;

Disp ('memory has been cleared');

The shortcut window would then be constructed something like the following

Fig. 4.6 Shortcut Editor

The new shortcut will be added to the Shortcuts entry in the matlab start button and to the shortcuts toolbar, if that category has been selected. Once created, a shortcut can then be run by selecting it from its category in the matlab start button. An alternative to creating and running shortcuts via the Start button is to use the Shortcuts toolbar. To show or hide the shortcuts toolbar, toggle the desktop>shortcuts toolbar menu item. To create and run shortcuts via the desktop Shortcuts toolbar, go through a similar procedure:

1. Select statements from the command history window, the command window, or an m- file.

2. Drag the selected group of commands to the desktop shortcuts toolbar and the shortcut editor dialog box will appear. Here the category field needs to be retained as toolbar shortcuts so that the shortcut will appear on the toolbar.

3. Choose a label, select an Icon, and click the save button. The shortcut icon and label will then appear on the toolbar.

VI. CONCLUSIONS

The 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). 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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