An Optimal PMU Placement Method for Disturbance Source Location of Forced Oscillation at Load Side

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ABSTRACT

This paper proposes a method for optimal placement of phasor measurement units (PMUs) to locate disturbance source of forced power oscillation at load side. Considering that the geographical wiring diagram is difficult to be digitally analyzed, the network topology of the geographical wiring diagram is established to get digital network information in the method. A network connectivity algorithm is used to generate incidence matrixes. Moreover, the process of topology identification and a dichotomous logic tree is used to determine whether the substation needs to be equipped with a PMU. All the impact loads in the system can be monitored after installing all the PMUs required. The effectiveness of the proposed method is verified via an example of a small-scale power system.

Keywords: phasor measurement units (PMUs), optimal placement, impact load, forced power oscillation, topology.

INTRODUCTION

With the development of the scale of power grid, forced power oscillation occurs more than once in the actual power system which seriously damages the safety and stability of power system. Periodical disturbance of impact load leads to forced power oscillation [1]. When the frequency of the periodical disturbance is the same with or close to it of the natural oscillation, the forced oscillation reaches its maximal amplitude characterized by dramatic swings of rotor angle among units and sharp fluctuations of transmission power in transmission lines. The control measures for routine low frequency oscillation with negative damping are not suitable for forced power oscillation with resonance mechanism any more. Locating disturbance source quickly and removing it accurately is now the best method for forced power oscillation suppression. Thus how to locate disturbance source is a problem that needs to be solved.

Monitoring and controlling the grid are more and more important for the increasing
stability problems [2]. Appearance of the PMU makes it possible to obtain real-time data of generator power angle and bus voltage in wide-area power system which provides necessary information for the monitoring and controlling of forced power oscillation [2-6]. Due to restrictions on the economic and technical conditions, PMUs are impossible to be installed on all nodes [7]. Besides, it’s not only economical but also necessary to do it. The problem of optimal PMU placement is using the least amount of PMUs to monitor all the nodes needed.

Existing studies mostly focus on the disturbance on prime mover [6-10]. There’s a blank in the area of optimal PMU placement for disturbance source location of forced power oscillation at load side. The remainder of this paper is organized as follows. First, in Section 2, the impact load to be monitored by PMU is introduced. Second, Section III presents the preparation for optimal PMU placement which includes the network connectivity algorithm to generate incidence matrixes and the process of topology identification. Third, in Section III, a dichotomous logic tree is built to determine whether the substation needs to be equipped with a PMU. Finally, analysis of the example is shown in Section V, and conclusions and future work are discussed in Section 4.

IMPACT LOAD TO BE MONITORED BY PMU

The impact load’s rate of power value change is fast, such as the load of electronic accelerators in nuclear physics research and steel rolling [11]. The loads of steel plants, cement plants, aluminum plants, ferroalloy plants are all impact loads. For example, the steel plants are generally large-scale and have huge power consumption. The large amount of production equipment, high load rate and special process like steel rolling and steelmaking make it easy to produce impact load.

In general, the impact load has the following characteristics [12] and a kind of impact load of tapping of ferrosilicon is shown in Figure 1.

- The impact load is initiative. It absorbs power from the system by its nature, which is the most important characteristic of impact load.
- The rate of power change is fast. It usually sharply rise or fall in a few second.
- It is continuous and cyclical. The cycle lasts a few seconds to a few minutes.
- The amplitude of the active power is up to 100MW or more. When the rectifier supplies power, the amplitude of the reactive power can also be up to 100MVar or more.
- The impact lasts up to several minutes.

![Figure 1. Impact Load of the Tapping of Ferrosilicon.](image)

Periodical disturbance caused by impact load leads to power system forced power oscillation. When the period of the periodical disturbance is the same with or close to it of the natural oscillation in the range of 0.4s to 10s, the forced oscillation is called resonance. Therefore, the impact load of steel plants, cement plants, aluminum plants, and ferroalloy plants whose period is in the range mentioned above is to be monitored by the PMU.
PREPARATION NETWORK TOPOLOGY OF THE GEOGRAPHICAL WIRING DIAGRAM

Network Connectivity Algorithm

Considering that the geographical wiring diagram is difficult to be digitally analyzed, the network topology of the geographical wiring diagram is established to get digital information in the method. The power plants and substations in the geographical wiring diagram are regarded as nodes of the network topology and transmission lines of various voltage levels are regarded as branches.

According to the topology theory, the node-branch incidence matrix can be used to describe the topology for any network [13]. The node-branch incidence matrix $A=[a_{ij}]$ is used to describe the relevance of nodes and branches. The meaning of each element of the node-branch incidence matrix $A=[a_{ij}]$ is explained as follows: $a_{ij}$ represents the relevance of the node $i$ and the branch $j$, and when the node $i$ and the branch $j$ is connected, $a_{ij}=1$, or when the node $i$ and the branch $j$ is not connected, $a_{ij}=0$. The branch-node incidence matrix is used to describe the relevance of branches and nodes. The branch-node incidence matrix is $B=[b_{jk}]$, in which $b_{jk}$ represents the relevance of the branch $j$ and the node $k$. When the branch $j$ and the node $k$ is connected, $b_{jk}=1$, or when the branch $j$ and the node $k$ is not connected, $b_{jk}=0$. The node-node incidence matrix is $C=[c_{ik}]$, in which represents the relevance of the node $i$ and the node $k$. When the node $i$ and the node $k$ is connected, $c_{ik}=1$, or when the node $i$ and the node $k$ is not connected, $c_{ik}=0$. The matrix $C$ is obviously a symmetric matrix.

According to the transfer property of the node-branch incidence matrix and the branch-node incidence matrix, if $a_{ij}=1$ and $b_{jk}=1$, $c_{ik}=a_{ij}\cap b_{jk}=1$. For the network topology of $m$ nodes and $n$ branches, the transfer property of the node-node incidence matrix is represented as follows:

$$C = A \cdot B$$

$$c_{ik} = \bigcup_{j=1}^{n} (a_{ij} \cap b_{jk})$$

Among them, the symbol $\cap$ means AND, and the symbol $\cup$ means OR. $A$ is the node-branch incidence matrix, $B$ is the branch-node incidence matrix, and $C$ is the node-node incidence matrix.

The information of how the nodes connect with each other through the branches can be obtained by the incidence matrix.

Multidimensional Arrays with Node Information

According to the incidence matrix, the connectivity of impact load with other substation is clear. Number every node and branch in the network. The information of substations under different voltage level is stored into different multidimensional arrays which includes the number of the substation, the amount of the impact loads connecting directly to the substation and the PMU installing situation (store 1 for that PMU has already been installed, and store 0 for not). The multidimensional array is shown in Figure 2.
Topology Identification

Every number of the substation node gets ergodic, and when it progresses to the kth impact load node, get its number i. Then analyze the ith row of the node-node incidence matrix. When the element of the row is $c_{ij}=1$, record the number j which is the number of the substation node connecting directly to the impact load.

According to the number of the substation node, the corresponding multidimensional array with the information of the number of impact loads connecting directly to the substation and the PMU installing situation can be found. The whole process is shown in Figure 3. Thus all the information needed to optimal PMU placement is obtained.

OPTIMAL PMU PLACEMENT

Assuming that all the 500kV and part of the 220kV substation are equipped with PMU, a dichotomous logic tree [14-15] was built shown in Figure 4 to solve the problem of optimal PMU placement. The process of the dichotomous logic tree is explained as follows:

- Determine whether the impact load is directly connected to the 500kV substation or the 220kV substation equipped with PMU. If it is yes, the impact load is already under monitoring which means it doesn’t need an extra PMU. If it is no, conduct the next step.
- Determine whether the impact load is the only impact load belonged to the superior 500kV substation. If it is yes, the impact load must be the disturbance source when the
PMU of the superior 500kV substation detects a forced power oscillation which means it doesn’t need an extra PMU. If it is no, conduct the next step.

- Determine whether the 220kV substation with the non-unique impact load connects with the other 220kV substation through the 220kV network. If it is yes, the disturbance will spread to the 500kV substation through the 220kV network. The PMU can’t locate the exact position of the disturbance source. So the 220kV substation needs to be equipped with a PMU. If there are N 220kV substations with impact loads connecting with each other in the network, at least N-1 220kV substations need a PMU and the 220kV substations with more than one impact load have to be equipped the PMU. If it is no, conduct the next step.

- Determine whether the impact load is the only impact load belonged to the superior 220kV substation. If it is yes, the disturbance spread to the 500kV substation through the only path, which can be monitored and located. So the 220kV substation doesn’t need to be equipped with a PMU. If it is no, there is no way to determine which one is the disturbance source and the 220kV substation needs a PMU.

![Figure 4. Analysis of the Example.](image)

**ANALYSIS OF THE EXAMPLE**

The effectiveness of the proposed method was verified via an example of a small-scale power system as shown in Figure 5. There are six 500kV substations, eight 220kV substations and six impact loads in the system. The optimal PMU placement at load side
focuses on the impact load and the relevant substation, so the power plant and the other kind of load is eliminated to reduce the amount of nodes and branches which accelerates the topology identification. The number of the branch and coterminous nodes is shown in Table I.

![Figure 5. An Example of a Small-Scale Power System.](image)

**TABLE I. NUMBER OF THE BRANCH AND COTERMINOUS NODES.**

<table>
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<tr>
<th>Branch number</th>
<th>Node number</th>
<th>Branch number</th>
<th>Node number</th>
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According to the method of the optimal PMU method, the NO.15 and NO.17 nodes need to be equipped with the PMU, which is the same result with the logical analysis.

**CONCLUSION AND DISCUSSION**

A method of the optimal PMU placement for disturbance source location of the forced power oscillation at load side has been presented in this paper. The impact load of steel plants, cement plants, aluminum plants, and ferroalloy plants to be monitored by the PMU was introduced whose period is in the range of 0.4s to 10s. Considering that the geographical wiring diagram is difficult to be digitally analyzed, the network topology of the geographical wiring diagram was established to get digital information in the method. The preparation for optimal PMU placement includes the network connectivity algorithm to generate incidence matrices and the process of topology identification. At the same time, a dichotomous logic tree was built to determine whether the substation needs to be equipped with a PMU.

The method fills the blank of optimal PMU placement for disturbance source location of forced power oscillation at load side which makes it possible to locate the disturbance source
more quickly and accurately. It makes monitoring and controlling the forced power oscillation at load side come true which bring a more secure, resilient and adaptable power system.

REFERENCES