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Optimal PMU Placement for Voltage Security Assessment using Decision Tree

F. Mahmoodianfard, M. Mohammadi, G. B. Gharehpetian, H. Askarian. Abyaneh

Abstract-- In this paper a Decision Tree method has been proposed for optimal PMU placement for voltage security assessment. In the proposed method the voltage security index for every operating point is calculated off-line. As a result, the system security status is determined for every operating point. Then the decision tree is trained using the database obtained from the previous stage. Simulation results show the efficiency of the proposed method comparing to other available methods such as artificial neural networks.

Index Terms-- Decision Tree, Machine Learning, Phase Measurement Unit, Security Assessment, Voltage Security

I. Introduction

REGULATORY and economic pressures have caused new transmission construction to lag the growth in demand. These forces have increased pressures on electricity markets and caused operators to maximize the utilization of the system. The result is an operating environment where operators are faced with quick changing and previously unseen power flow patterns and unforeseeable operational conditions with limited information available for real-time operation and decision-making. Besides, because of the ongoing development in power systems restructure the concept of system operation has turned into an important challenge. The main goal of restructuring is to increase the competition for reducing costs and improving the quality of energy delivered to consumers. In restructured networks, the economical issues can guide the power system toward operation near the thermal and dynamic margins and thus lead to poor power quality.

Wide area measurements using synchronized phasor measurement units are being extensively adopted to monitor power systems. PMU-based measurements are extensively used for a wide range of applications including situational awareness for operational decision making. A number of novel applications that utilize measurements from PMUs to determine small signal oscillatory modes, model parameter identification, and post scenario system analysis have also been developed [1]-[5]. With the initiation of the Eastern Interconnection Phasor Project (EIPP) [6] new opportunities have arisen to incorporate measurements from PMUs in real time analysis to evaluate system dynamic performance. Recent efforts involving the use of PMU measurements for voltage security analysis and monitoring power system dynamic behaviors have been developed [7]-[10].

The decision tree may be divided into the classification and regression trees. As the output variable, the former deals with qualitative one while the latter handles quantitative one. Most of the studies on applications of the decision tree to power systems are based on the classification tree. The reason why they focus on the classification tree is that the classification application is easier to handle than the regression one. Indeed, the regression tree itself does not work so well and need some techniques that supplement the function.

In this paper a decision tree approach is proposed for optimal PMU placement for on-line voltage security assessment. In the proposed method only one decision tree is trained to assess voltage security. This merit results the total training time to decline. It also reduces the required time for on-line operation of the trained tree.

In the following sections first we will have a short literature survey for decision tree and voltage security. Then the voltage security index index will be detailed. Finally the proposed method and the simulation results are presented.

II. Decision Tree

Decision Trees (DTs) developed in the proposed scheme are all classification trees of the classification and regression trees (CART) methodology introduced by Breiman et al. [11]. As shown in Fig. 1, a DT can predict the classification (e.g., “secure” or “insecure”) of an object. The object is represented by a vector comprising of the values of a group of critical attributes (CAs, e.g., A and B in Fig. 1). The classification process consists of dropping the vector of CAs down the DT starting at the root node until a terminal node is reached along a path, the class assigned to which is the classification result. At each inner (nonterminal) node, a question (i.e., a splitting rule) concerning a CA is asked to decide which child node the vector should drop into. For numerical variable A, the question compares it with a threshold; for categorical variable B, the question checks whether it belongs to a specified set.

A DT is built from a learning set and a test set. Each of their elements (i.e., cases) consists of a classification and a

F. Mahmoodianfard is with Amirkabir University of technology, Tehran Iran (email: fmahmoodian@aut.ac.ir)

M. Mohammadi is with Amirkabir University of technology, Tehran Iran (email: m.mohammadi@aut.ac.ir)

G. B. Gharehpetian is with Amirkabir University of technology, Tehran Iran (email: grptian@aut.ac.ir)

H. Askarian. Abyaneh is with Amirkabir University of technology, Tehran Iran (email: askarian@aut.ac.ir)

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vector comprising of the values of a group of CA candidates (called "predictors"). The building process initially grows a maximal (i.e., large enough) tree by recursively splitting a set of learning cases (i.e., a parent node) into two purer subsets (i.e., two new child nodes). To achieve each split, all possible splitting rules related to predictors are scored by how well different classes of cases in the parent node are separated [7].

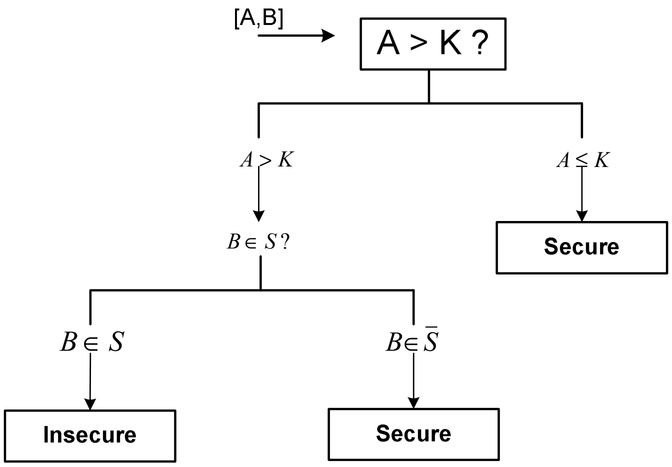

Fig 1. A DT example

A. Potential and problems with decision tree

Decision trees are attractive for the following reasons:

1) The decision tree is a nonparametric method.
2) Global complex decision regions (especially in high-dimensional spaces) can be approximated by the union of simpler local decision regions at various levels of the tree.
3) In contrast to conventional single-stage classifiers where each data sample is tested against all classes, thereby reducing efficiency, in a tree classifier a sample is tested against only certain subsets of classes, thus eliminating unnecessary computations.

The possible drawbacks of DT are:

1) Overlap especially when the number of classes is large, can cause the number of terminals to be much larger than the number of actual classes and thus increase the search time and memory space requirements.
2) The decision tree output is 0 or 1 (for binary classification); i.e. it only determines if the system is secure or not.
3) The decision tree operation completely depends on its design.

B. Feature selection using DT

One of the remarkable traits of DTs is that they inherently estimate the suitability of features for the separation of objects representing different classes. The occurrence of a feature in a tree provides the information about the importance of the associated feature. This facility can be directly exploited for the purpose of the feature selection. In decision tree problems we have two sets. One is the testing set and the other is the training set. First of all the test set is used for training decision tree. Then the trained decision tree is tested using the test set.

III. Voltage Security

Security refers to the degree of risk in a power system's ability to survive imminent disturbances (contingencies) without interruption to customer service. It relates to robustness of the system to imminent disturbances and, hence, depends on the system operating condition as well as the contingent probability of disturbances. Historically, ensuring secure operation has always been of paramount importance in the safe and economic operation of power systems. When a system has an insufficient degree of security, it becomes exposed to severe and, in some cases, catastrophic, system failures of the types observed recently in various power grids around the world, events that have enormous economic costs and may even lead to loss of life. However, the evolution of the electric power industry toward open markets over the last decade has introduced a number of factors that have increased the possible sources for system disturbances, reduced the robustness of systems, and reduced the predictability of operation. To ensure that a power system is sufficiently reliable, that there is an acceptable probability of it operating satisfactorily over the long run, the system must be 1) properly designed with security as a primary consideration and 2) monitored during operation to ensure sufficient security margin exists at all times (as actual operating conditions or contingencies may be different from those planned for) [12]. Voltage security (VS) is the ability of power system to maintain voltage security following one of the lists of "credible events." A credible event could be a linear or generator outage, load ramp, or any other event stressing the power system. Voltage security analysis associates the current system conditions to its voltage security status. The system condition is characterized by its state (complex bus voltage) or parameters calculated from it such as real and reactive flows, active injections, etc. VS status could be secure or insecure. If a system is insecure, preventive action must be initiated to reinstate voltage security. Preventive action includes capacitor switching, generator re-dispatching, locking of tap-changer, etc. if the system is secure, useful information is its distance from voltage insecurity. "Distance" here could be in terms of quantities such as total system load, or tie load flows. For example, a MW margin to voltage collapse is the distance in MW of load from the current to maximum loadability point for an assumed direction of load increase [9].

A. Review of conventional voltage security indices

This section reviews voltage security indices. Voltage security is related to the feasibility of the power flow solution. Many voltage security indices were proposed to measure a margin to the limitation of power flow solution. Venikov, et al. presented a criterion that made use of the sensitivity of reactive power with respect to voltage [13]. Afterwards, they developed an index with the determinant of the Jacobian matrix of the power flow equation [14]. In particular, they focused on the sign of the determinant to judge if a power flow solution is stable or not. Tamura, et al. proposed an index that employed an angle between a pair of multiple power flow solutions [15]. This is based on the fact that a pair of multiple power flow solutions becomes closer and merges at the saddle bifurcation point as power system conditions get heavy-loaded gradually. Carpentier, et al. presented an index with the optimal power flow calculation. The index shows that a power system lacks a large amount of reactive power if it approaches voltage insecurity. Kessel and Glavitsch developed an index called L eith the power calculation [16]. The index evaluates the power system conditions with the hybrid matrix. The advantage of the index is to require only one power flow calculation. Thomas and Tiranuchit presented a method that used the minimum singular value of the singular value decomposition technique [17]. Afterwards, Lof, et al. speeded up the method of Thomas and Tiranuchit with the sparse matrix technique [18]. In this paper, index L is used due to the computational efficiency.

B. Voltage security index L

In this paper, an L-index criterion has been used for the classification of operating points into ‘secure’ and ‘insecure’ states. Simulation has been done on IEEE 39-bus network. First, load flow operation is conducted on original network and on the network with contingency (outage of network’s line.) therefore, for each operating point L-index has been calculated according to equation (1). Then, a set of states are used for training the decision tree and another set for testing it.

For any one load bus $j \in \alpha_L$, voltage security index L_j can be defined as below [19]:

$$L_j = \left| l_j \right| = \left| 1 - \frac{\sum_{i \in \alpha_G} F_{ji} V_i}{V_j} \right| = \left| \frac{S_j^+}{Y_{jj}^{+*} V_j^2} \right| \quad (1)$$

Where

$$S_j^+ = \left(\sum_{k \in \alpha_L} \frac{Z_{jk}^*}{Z_{jj}^*} \cdot \frac{S_k}{V_k} \right) V_j$$

$$L = \underset{j \in \alpha_L}{Max}(L_j)$$

S_k : complex power of node k

V_k : complex voltage of node k

Z_{jk} : element of $Z^{LL}.Z^{LL}$

$$Y_{jj}^{+} = (Z_{jj}^{-1})$$

The range of L’s value is [0, 1]. When L approaches to 1 power system will approach to voltage collapse. Distance between L and 1 is the system security margin.

IV. Proposed Method

In this paper the following method has been proposed for voltage security assessment.

Step 1: At the first step, the required knowledge base has been prepared from off-line simulations.

Step 2: The voltage security index (L index) has been calculated for each network’s state and according to the defined threshold for VS the system status has been determined.

Step 3: The prepared knowledge base in step 1 has been divided into two sets. One set has been used for training the DT and the other one for testing it.

Step 4: The DT has been trained using the training set.

Step 5: The trained DT has been tested using the test set.

Step 6: The operation of DT has been assessed by three indices that are defined in equations (2), (3), (4).

Step 7: According to the conducted simulations, those PMUs that appear on the decision tree nodes show the optimal choice for PMU placement.

$$\text{Sensitivity} = \frac{TP}{TP + FN} \times 100 \quad (2)$$

$$\text{Specificity} = \frac{TN}{TN + FP} \times 100 \quad (3)$$

$$\text{Accuracy} = \frac{TP + TN}{TP + TN + FP + FN} \times 100 \quad (4)$$

The equations (2), (3), (4) are based on the consideration that a test point always falls into one of the following four categories: False Positive (FP) if the system labels it as “insecure” while it is “secure”; False Negative (FN) if the system labels it as “secure” while it is “insecure”; True Positive (TP) and True Negative (TN) if the system correctly predicts the label. Note that with this notification the number of “secure” points in the test set can be written as TP+FN, the number of “insecure” points as TN+FP, and the test set size as TP+FP+TN+FN.

V. Simulation Results

According to the proposed algorithm in section 5, simulations have been conducted on IEEE 39-bus network. The network schematic is represented in Fig. 3. For the simulation purpose the power flow operation has been conducted using DIgSILENT software. In this paper the threshold for voltage security assessment has been considered equal to 0.3. Those states corresponding to L index lower than 0.3 are categorized as “secure” and otherwise as “insecure”. The simulation procedure is operated for single contingency situations. In this paper, line outage is considered as contingency. After testing the trained decision tree, the results have been used for evaluating decision tree performance. According to the simulation results the performance indices (sensitivity, specificity and accuracy) has been calculated. The best PMU places have been determined based on the trained decision trees. The PMUs that appear on the higher stages of the decision tree show the optimal PMU places.

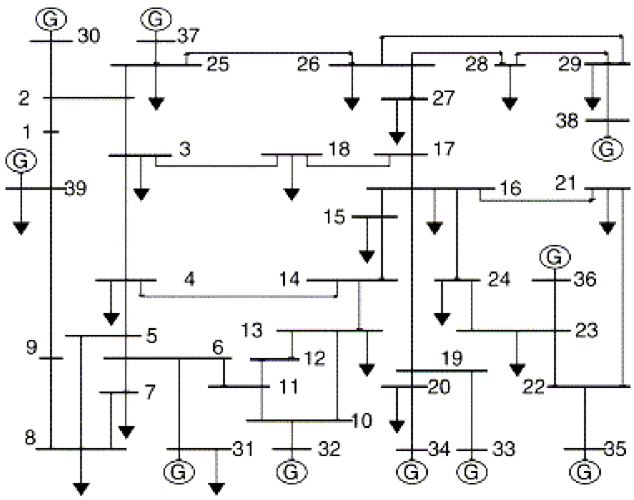

Fig. 3. IEEE 39-bus network

A part of simulation results is shown in table (1).

TABLE I
SIMULATION RESULTS FOR THE IEEE 39-BUS NETWORK

Network Lines		Sensitivity (%)	Specificity (%)	Accuracy (%)
From	To			
1	2	98.31	93.55	97.23
1	39	98.87	95.54	98.11
15	16	97.67	94.67	96.36
16	17	97.64	91.62	96.07
16	19	98.42	98.38	98.40
16	21	97.69	94.12	96.36
2	25	97.47	91.95	96.07
2	3	98.89	93.10	97.67
21	22	94.51	97.10	96.07
23	24	97.73	95.55	96.94
26	27	96.05	93.51	95.20
28	29	94.41	95.68	95.05
4	14	97.89	97.44	97.82
5	6	99.08	95.80	98.40
5	8	98.71	91.67	97.23
6	11	96.89	93.58	96.36
6	7	98.95	95.31	97.82
8	9	96.78	90.91	96.22

As it can be seen from table (1) the simulation results show a high efficiency in decision making. Table (2) shows the number of appropriate bus for PMU placement for each line outage. In the stated table the first column indicates the line that is not in the network.

TABLE II
OPTIMAL PMU PLACES FOR IEEE 39-BUS NETWORK

Network Lines		Optimal PMU Places (Bus Number)
From	To	
1	2	13
1	39	33
10	11	3
13	14	37
14	15	37
15	16	30
16	17	30
16	19	6
16	21	30,32
16	24	30
17	18	30
17	27	25
2	25	20,32
2	3	32
21	22	12
22	23	7
23	24	29
25	26	25
26	27	32
26	28	32
26	29	32,19
28	29	32
3	18	18
3	4	12
4	14	10
4	5	14
5	6	7
5	8	37
6	11	30

A sample decision tree, obtained form the simulation results, is presented in Fig. 4.

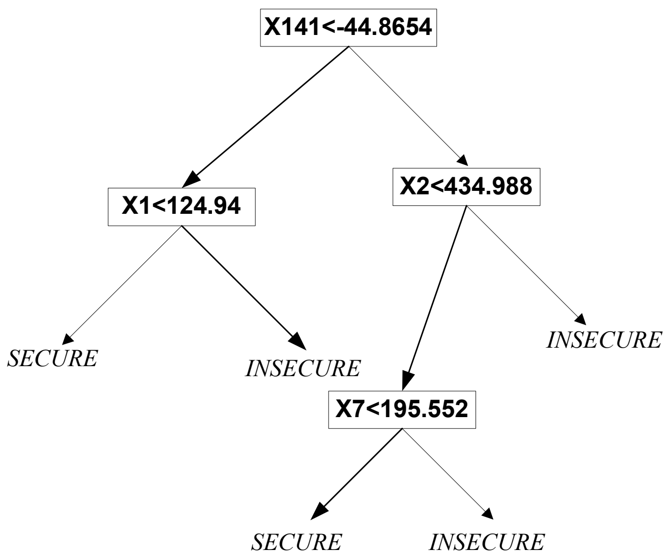

Fig. 4. A sample decision tree obtained from simulations

VI. CONCLUSION

In this paper a new decision tree based method has been used for voltage security assessment and optimum PMU placement. Simulations results show the high efficiency of this method. According to the simulation results the proposed method has acceptable performance indices and a great capability for voltage security assessment. Also, regarding the results for PMU placement, the buses 37, 30 and 32 are the best buses for PMU placement. It should be noted that decision making for security assessment is independent of input variables. So the size of the input data can be reduced and subsequently the decision making process will be less time consuming.

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