A New Approach for Comparing Communication Infrastructures of Power Systems

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Abstract— **Power system communication infrastructures are responsible for data transmitting among different entities in power systems. System data and information (provided by sensors) are crucial for monitoring, operating and controlling reasons. On the one hand, real-time and near real-time processes of power systems utilize communication infrastructure for sharing their information. On the other hand, power system sensors and actuators are distributed in wide geographical area and they belong to communication system. Consequently, some network parameters e.g. communication delay and reliability; which may be not essential in other communication systems; have become a major concern in power system communication infrastructures. This study aims to propose a method for comparing any given power system communication infrastructures in terms of latency (delay) and reliability. The simulation results indicate that although two communication networks may be similar in the view of cost and service, our proposal method can recognize reliable communication network with better latency condition.**

Power System Communication Infrastructure; Communication Delay; Communication Reliability; Network Hops

I. INTRODUCTION

Online data and information are crucial for operating and controlling power systems. Generally, data and information of power systems are shared through a special type of communication networks, which are also known as power system control networks. A control network is responsible for exchanging data and information among different entities in the system for operating and controlling this system. According to the definition [1], a control network is any group of devices working in a peer-to-peer fashion to monitor sensors, control actuators, communicate reliably, manage network operation, and provide complete access to network data.

Due to the fact that power system control networks distribute in wide geographical area, these types of control networks can be considered as wide-area control networks (WAN) [1]. Such control WANs communicate system data among sensors, actuators, control center(s) and other data-enabled equipments in real-time or near real-time. As a result of real-time processing, some network parameters of power system control networks such as network delay (latency) and reliability are of major concerns [1], [2].

In a control WANs e.g. a power system control network, decision making location is known as control center; while the location where an action is performed by system actuators is known as controlled area [1]. A controlled area may be a single node or multiple networked nodes.

The aim of this study is to propose a new method for comparing two given power system communication networks with each other based on their reliabilities and latencies. The remainder of this paper organized as follows: two critical network parameters; latency and reliability; are investigated and formulated in section II. In the same section, two indices are defined and they are related to these two critical network parameters. In section III, the problem is defined and new algorithm is proposed to solve this problem. Two power system communication infrastructures are compared with each other by using proposal algorithm in section IV. This paper ends with concluding and remarks in section V.

II. RELIABILITY AND LATENCY CALCULATION

As discussed earlier, reliability and latency of power system communication infrastructures are two critical parameters for such systems. In this section, we review and calculate these parameters.

Historically, different kinds of transmission media are used in power system communications [2], [3]. Nowadays, due to specific communication requirements in power systems, the communication infrastructures of such systems are made by special type of fiber optic cables called optical power grand wire (OPGW) [2]. In transmission systems, OPGW combines shielding and communication operations, such that it is replaced with shield wire and it is suspended above the transmission lines [3]. Due to the high price of OPGW cables and their installation difficulties (especially live-line cases), the back-bones of power grid communication systems are designed by using minimum spanning tree (MST) configuration [2], [4]. MST problem is one of the well-known optimization issues used for designing back-bone networks [4].

It is perfectly clear that in a spanning tree graph; only one path exists between two considered nodes [2]. As a result, in a MST backbone network, only a unique path is found between a considered node and control center. Such a path includes some routers which are connected by media links.

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Considering above-mentioned facts into account, it can be observed that in a power system control network with MST configuration, "the number of routers" and "the length of transmission media" between a considered node and control center are two useful indices, which are uniquely assigned to this node. Therefore, we define these two indices for a considered node as follows:

- N_R: The number of routers between considered node and control center.
- L_M: The length of transmission media between considered node and control center.

In the next two subsections, we try to relate predefined indices to network latency and reliability.

A. Latency Calculation

The transmitted packets in a control network are different than packets of other networks. These packets are in low volume and they are periodically transmitted in specified times. In [5], the communication latency between a node and control center is investigated and formulated in following way:

$$T = T_s + T_b + T_p + T_r \tag{1}$$

where, T_s is the serial delay, T_b is the between packet delay, T_p is the propagation delay, and T_r is the routing delay.

In (1), the last two latency values; propagation delay and routing delay; can be considered as infrastructural latency [1].

According to [5], the propagation delay in a transmission link with L_M length can be calculated as follows:

$$T_p = \frac{L_M}{v} \tag{2}$$

where, L_M is the length of media, and v is the velocity at which the data are sent through it (e.g., 0.6c to c, where c is the speed of light).

In [5], the path from a node to the control center is traced, and all of the routing delays are added up, hence; total routing delay for a node can be represented as follows:

$$T_r = \sum_{i=1}^{N_R} T_{i^{th}\ Router} \tag{3}$$

where, $T_{i^{th}\ Router}$ is the latency of i^{th} router and N_R is the number of network routers in the path between a node and control center. N_R is also known as "network hops".

For illustration purposes, we assume that all routers have the same latency value (T_{Router}). Therefore, the infrastructural latency (T_{infra}) of a considered node with N_R and L_M indices can be written as follows:

$$T_{infra} = \frac{L_M}{v} + N_R \times T_{Router} \tag{4}$$

Inspection of (4) indicates that any increase in L_M and N_R indices of a node are responsible for increasing the infrastructural latency of this node.

B. Latency Calculation

Due to the special characteristics of a spanning tree network; calculation of its reliability is easier than reliabilities of other networks [6]. Since only one path exists between any considered node and the control center; a node will be in service if and only if all links and nodes of this path work properly. As a result, it can be assumed that all components are series; therefore:

$$R_{node} = \prod_{i=1}^{N_R} R_{i^{th}\ Router} \times \prod_{j=1}^{M} R_{j^{th}\ Link} \tag{5}$$

where, R_{node} is reliability of considered node; $R_{i^{th}\ Router}$ is reliability of i^{th} node in the path between the node and the control center; $R_{j^{th}\ Link}$ is reliability of j^{th} link in this path; N_R is number of path's routers, and M is the number of links in the path.

To simplify reliability calculation, it is assumed that all routers have the same reliability value. We also assume that the links between a node and control center are jointed and its length is L_M. Hence, (5) can be summarized as follows:

$$R_{node} = R_{Router}{}^{N_R} \times R_{L_M} \tag{6}$$

For the purposes of simplification, it is assumed that the failure of jointed link only depends on its length (L_M) [7]. By considering this simplification, the reliability of jointed link will reduce if its length increases. On the other hand, R_{Router} is less than one. Therefore, if R_{Router} is multiplied by itself N_R times, it will become smaller. Taking these facts into consideration, it is perfectly clear that any increase in N_R or L_M values of a node result in decreasing the reliability of the node.

III. Problem Definition and Proposal Method

The aim of this study is to compare two given power system communication infrastructures, which are made by same transmission media, with each other. The comparison criterions are communication latency and reliability, which are two critical network parameters in control networks.

As mentioned earlier, communication latency and reliability of a node are directly related to N_R and L_M indices of this node, and such that, the increase in these indices result in increasing node latency and decreasing node reliability. As a result, we use these indices for comparing two communication systems.

The next issue is finding an algorithm, which can obtain the predefined indices. Breadth-First Search (BFS) algorithm is an effective way to traverse a graph by visiting all the nodes connected directly to a starting node [8]. Assuming that the starting node will be control center of a given network, BFS can easily calculate N_R and L_M of all nodes by traversing whole network. Thus, the comparison method can be suggested as follows:

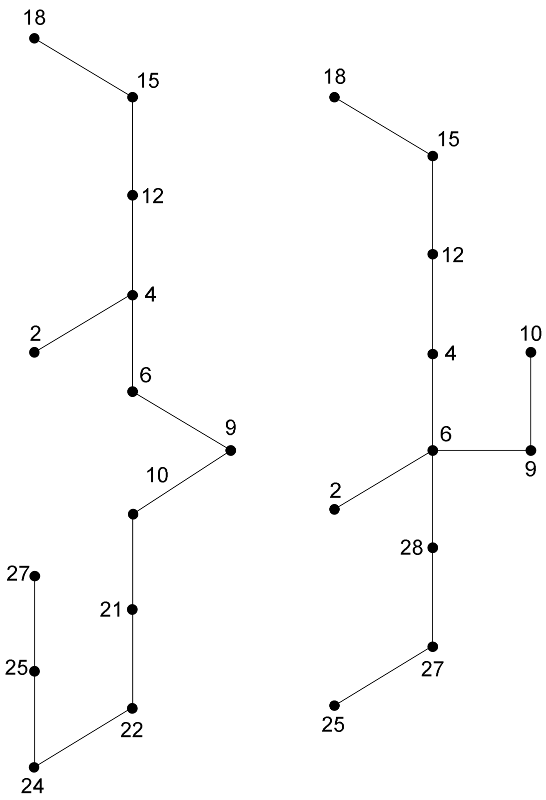
If we want to compare two given power system control networks based on their latency and reliability, the proposed comparison method act as follows: for each network, we assume that starting node is control center of this network.

Then, BFS traverses all nodes of each network and calculates predefined indices. In order to provide a general view of two network indices, a distribution function is fitted on histogram of each index. The mean and variance values of indices help us to find the better control network from reliability and latency points of view.

It is noted that if the number of network nodes is not enough that we cannot fit appropriate distribution functions on their indices' histograms, only mean values of indices can be used as comparison criteria.

IV. Case Studies and Simulation Results

In this section, in order to demonstrate our method, two given power system control networks are compared with each other. These networks are suggested for IEEE 30 bus test system (see appendix 1), which are designed for connecting phasor measurement units (PMUs) to control center in such test system. The installed PMUs are located at buses 2, 4, 6, 9, 10, 12, 15, 18, 25 and 27 [9]. The control center is *a priori* determined and it is located at bus 6. Assuming that all transmission lines have the same conductors with the same configurations, the distances between system buses can be extracted from system admittance matrix [10]. These control networks are shown in Fig. 1. Note that the node numbers point to bus numbers.



(a) (b)

Figure 1. Sample Control Networks.

We aim to find the better power system control network in terms of reliability and latency. To carry out this, BFS algorithm is run for each case in order to estimate N_R and L_M indices. In both cases, node 6 is assumed as starting node. The N_R and L_M indices of plan A are shown in (7).

$$N_{R1} = \begin{array}{r} 2 \\ 4 \\ 6 \\ 9 \\ 10 \\ 12 \\ 15 \\ 18 \\ 21 \\ 22 \\ 24 \\ 25 \\ 27 \end{array} \begin{bmatrix} 2 \\ 1 \\ 0 \\ 1 \\ 2 \\ 2 \\ 3 \\ 4 \\ 3 \\ 4 \\ 5 \\ 6 \\ 7 \end{bmatrix} \quad L_{M1} = \begin{array}{r} 2 \\ 4 \\ 6 \\ 9 \\ 10 \\ 12 \\ 15 \\ 18 \\ 21 \\ 22 \\ 24 \\ 25 \\ 27 \end{array} \begin{bmatrix} 122 \\ 23 \\ 0 \\ 122 \\ 186 \\ 174 \\ 250 \\ 378 \\ 226 \\ 238 \\ 343 \\ 535 \\ 657 \end{bmatrix} \tag{7}$$

The indices of plan B are estimated as follows:

$$N_{R2} = \begin{array}{r} 2 \\ 4 \\ 6 \\ 9 \\ 10 \\ 12 \\ 15 \\ 18 \\ 25 \\ 27 \\ 28 \end{array} \begin{bmatrix} 1 \\ 1 \\ 0 \\ 1 \\ 2 \\ 2 \\ 3 \\ 4 \\ 3 \\ 2 \\ 1 \end{bmatrix} \quad L_{M2} = \begin{array}{r} 2 \\ 4 \\ 6 \\ 9 \\ 10 \\ 12 \\ 15 \\ 18 \\ 25 \\ 27 \\ 28 \end{array} \begin{bmatrix} 105 \\ 23 \\ 0 \\ 122 \\ 186 \\ 174 \\ 250 \\ 378 \\ 390 \\ 268 \\ 35 \end{bmatrix} \tag{8}$$

The information of networks and their N_R and L_M indices are illustrated in table I. The first two columns; "No. of Nodes" and "No. of Links"; are the information of communication systems with spanning tree configuration. The column "Coverage Percentage" implies the coverage percentage of OPGW cables (relative media length to total length of transmission lines). The last two columns; N_R mean and L_M mean; illustrate the mean values of defined indices.

TABLE I
Information of Plans

Plan	No. of Nodes	No. of Links	Coverage Percentage	N_R Mean	L_M Mean
A	13	12	23.67	3.07692	250.308
B	11	10	22.09	1.81818	175.545

Examination of table 1 demonstrates that while the total length of OPGW cables in both plans are almost the same, the average network hops in plan A is approximately one time bigger than the average of network hops in plan B. Similarly, it can also be observed that, in average, the length of OPGW media from a considered node to control center are 175 km for plan B and 250 km for plan A.

As a consequence of pre-mentioned facts, it can be concluded that although both plans have used approximately the same amount of OPGW, the plan B is better than the other plan in terms of reliability and latency. This indicates that the proposed method can find the reliable power system communication infrastructure with minimum latency.

The fitted normal distribution functions on N_R and L_M indices are shown in fig. 2.

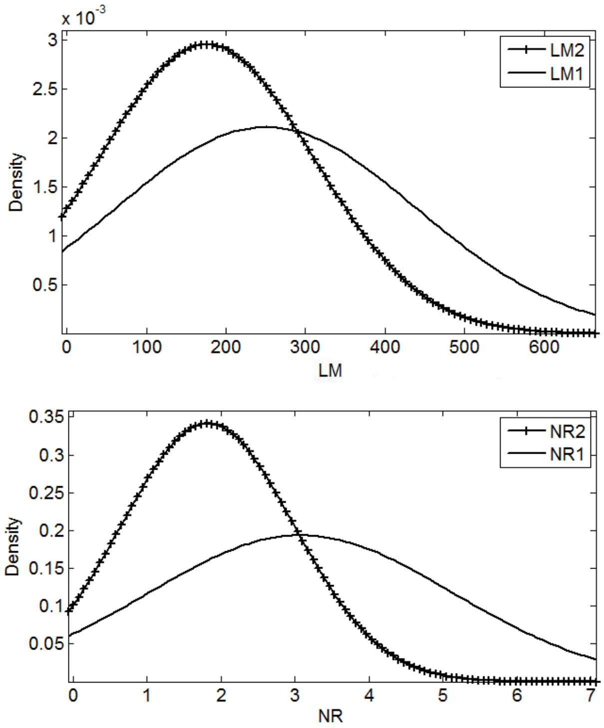


Figure 2. Distribution Functions of L_M and N_R.

V. CONCLUSION

Power systems data and information have been shared through power system control networks. A control network is a group of nodes that monitors sensors, controls actuators and manages system operations. Since power system control networks distribute in wide geographical area, it can be considered as control WANs. In a control WAN, decision making location is known as control center, while the location where an action should be performed is known as controlled area.

Due to the fact that real-time and near real-time processes are performed by power system communication networks, some communication parameters such as communication delay and reliability are of crucial importance for these types of networks. As a consequence of this importance, this paper proposes a method to compare two power system communication networks in terms of delay and reliability. To carry out this, two new indices; related to the distance between nodes to control center and the network hops of nodes; are defined and communication delay and reliability are calculated by using these indices.

By using BFS algorithm, these defined indices are estimated from control center to any nodes and therefore, any given power system communication networks can be compared with each other. The results confirm that, although two communication networks may be the same in terms of service and pricing, the proposed method can recognize reliable communication network with better latency condition.

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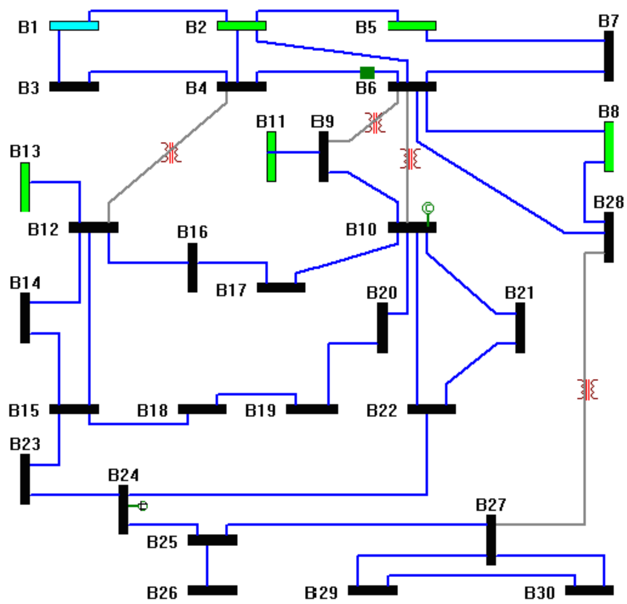
APPENDIX



Appendix 1. IEEE 30 bus Test Network [9].