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An Efficient Multi-objective Approach for Designing of Communication Interfaces in Smart Grids

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***Abstract* —The next generation of power systems require to use smart grid technologies due to their unique features like high speed, reliable and secure data communications to monitor, control and protect system effectively. Hence, one of the main requirements of achieving a smart grid is optimal designing of telecommunication systems. In this study, a novel dynamic Multi-Objective Shortest Path (MOSP) algorithm is presented to design a spanning graph of a communication infrastructure using high speed Optimal Power Ground Wire (OPGW) cables and Phasor Measurement Units (PMUs). Applicability of the proposed model is finally examined on a 17 bus and 118 bus standard test systems. The simulation results show better performance of the proposed algorithm compared to other shortest path algorithms.**

***Index Terms*—Communication interface, Phasor measurement unit, Multi-Objective shortest path algorithm, Smart grids.**

I. INTRODUCTION

There are convincing reasons which show that future power grids will be different compared to current power grids due to integration of intermittent energy generation resources which require new controlling, monitoring and protection models, and due to fast increasing rate of energy demand which necessitates using new generation technologies e.g. electrical vehicles rather than fossil fuel supplied resources and finally growing concerns regarding secure data and information exchange which highlight the need for using reliable and resilient communication structures. As a reasonable solution to these challenges, the smart grid technologies present a fast, reliable and flexible power distribution along with data communication through a bi-directional process between power generation companies and consumers using precise measurement devices to meet the new requirements of future electric power grids [1]. Hence, integration of a fast and reliable data exchange platform and an accurate measurement infrastructure is an inevitable part of an effective, automated and intelligent power grid.

In recent years, with the introduction of digital data measurement devices and new communication systems, considerable changes have been made around Energy Management Systems (EMSs). An EMS is a group of computer programs, technologies and agents, which working either solely or together to execute power system controlling and protection procedures [2]. New EMS systems offer new sets of unprecedented applications for the power system operators, such as wide dynamic analysis, synchronous fluctuations recording, state estimation, real time analysis of small fluctuations, and etc. Hence, it is necessary to design the measurement and communication infrastructures as physical layers of an EMS to ensure the full operability of smart grid.

There are varieties of advanced technologies introduced in recent years to use as a measurement and communication media to perform the main tasks of an EMS. Availability of each of these technologies can greatly affects the system design procedure. Remote Terminal Unit (RTU), Phasor Measurement Unit (PMU), Sequence Event Recorder (SER), Digital Protective Relay (DPR), and Digital Fault Recorder (DFR) can act as metering devices to acquire system data from the power grid's components. Among these items, PMUs are greatly used in recent years due to their easier synchronization process, higher precision, and better capability in dynamic real-time system monitoring [3]. Besides, the appropriate communication media which share data and information through smart grid can be divided into wire based methods such Optical Power Ground Wire (OPGW) cable, Power Line Carrier (PLC), coaxial cables, telephone twisted pairs and etc. and wireless technologies such as microwave, satellite, VHF, UHF and etc. Advantages and disadvantages for these communication technologies are discussed in [4]. Analyses in [4] have shown that using OPGW could lead to improving system technical indices like latency and reliability within the network. Moreover, there are many concerns regarding the use of current low-voltage communication facilities in the vicinity of high-voltage power lines due to both operational and safety issues. Optimal placing of OPGWs on the system connectivity graph along with using PMUs as metering devices not only could solve these safety and operational concerns, but also could assure the fully observable system.

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There are many studies conducted to optimally design the measurement infrastructure of an EMS and valuable results have been achieved. According to the related surveys [5], existing methods for finding the optimal PMU placement are categorized into two classes: evolutionary approaches and deterministic ones. Evolutionary search techniques, often known as population-based meta-heuristic algorithms, determine the PMU locations by stochastic exploration of a search space. On the other hand, deterministic approaches, which perform better in terms of computational time, have also been proposed for solving the aforementioned problem [6]-[7]. These techniques not only have linear formulations, but also result in globally optimal solutions. According to [5], Integer Linear Programming (ILP) is the most adaptable mathematical form to model a network. In this paper, an ILP approach is used to identify optimal locations of PMUs in a 17 bus test system as an input for designing of the physical structure of communication infrastructure through Multi-Objective Shortest Path (MOSP) algorithm.

A reliable communication infrastructure is responsible for distribution of data and controlling commands between different entities of the smart grid. There are few studies which propose an optimal physical design for the communication infrastructure of smart grids using new advanced technologies. Most of the conducted researches focus on requirements and challenges of future communication systems for smart grid. However, in [8], the measurement and communication infrastructures were designed optimally using evolutionary Genetic Algorithm (GA) using PMUs and OPGWs. The authors formulated and optimized this problem with a GA model in both simultaneous and independent approaches for measurement and communication infrastructures. However, they did not introduce any specific method to determine the location of the Central Control Bus (CCB). Also, their presented approach does not guarantee the global solution due to using an evolutionary algorithm. Similarly, in [9] power Communication Interface (CI) design has been presented for both centralized and decentralized approaches based on finding Minimum Spanning Tree (MST). The results have been examined through the IEEE 118-bus test system, including PMUs and conventional measurement devices.

In this paper, a graph-based MOSP algorithm is proposed for optimal designing of a smart grid communication interface. In this regard, ILP approach is used to estimate optimal locations of PMUs to obtain adequate level of system's observability. In the next step, PMUs location is considered as objectives in connectivity graph of the chosen test system to acquire the communication spanning tree using MOSP algorithm. To show superior performance of the presented method compared to existing Single-Objective Shortest Path Algorithms (SOSP) like Dijkstra algorithm, both solution methodologies is applied to the selected test systems and results gathered truthfully. Moreover, the best location for the central control bus is determined in terms of Optical fiber Power Ground Wire (OPGW) coverage. It should be stated that CCB is a bus in system which accommodates the EMS's computers and controlling devices and all measured data from measurement devices are sent to CCB.

This paper is organized as follows: section II provides a mathematical formulation of designing the communication infrastructure based on shortest path algorithms; section III presents the case study design architecture and compares them with SOSP algorithm's results. Finally, some conclusions are drawn from the outcomes of this paper in section IV.

II. Formulation for Communication Interface Design

There are two different ways to obtain the data transmission paths from PMU buses to the CCB using SOSP and MOSP algorithms. SOSP algorithms just track shortest paths from a single source to one determined node in the graph and find shortest paths independently. For example, Dijkstra, Bellman-Ford and kruksal's algorithms are kind of SOSP algorithms. However, according to the structure of the proposed design problem, it is necessary to find shortest paths from one centered bus to multiple PMU buses (objectives) simultaneously to check overlapped paths in the routing problem. This requires a MOSP algorithm to find the best solution routes for connecting PMU buses to CCB to guarantee the information transmission flow.

The presented MOSP method in this paper is a deterministic dynamic multi objective shortest path algorithm since it always checks the overlapped paths to find the best shortest path solution in the parent graph. It should be stated that this method is an extended form of Dijkstra's algorithm which find shortest paths from a single source to multi node objectives. Dijkstra's algorithm is a graph search algorithm that solves the single-source shortest paths problem on a weighted, directed graph for the case in which all edge weights are non-negative to produce a shortest path tree [10]. Thus, first of all, Dijkstra's algorithm is explained to be used in the routing problem for a graph with non-negative edges. Then, an extended form of Dijkstra's algorithm is addressed as MOSP algorithm since it always checks the overlapped paths to find the best possible architecture for the CI design problem.

A. Dijkstra's Algorithm

Power system's connectivity matrix addresses the connection status of system's buses. In fact, using a connectivity matrix, a parent graph of the chosen system can be determined. For calculating the best routing paths between measurement devices and the control center, SOSP and MOSP algorithms are taken into account to evaluate the best and shortest paths between these nodes.

Dijkstra's algorithm is a greedy graph search algorithm that solves the single-source shortest-paths problem [10]. In other words, this algorithm selects the best available option at each step without considering future consequences. The Dijkstra's algorithm as a SOSP algorithm calculates the shortest paths from a specific source node to any node in a parent graph such as $\mathrm{G} = (\mathrm{V}, \mathrm{E})$, where V is a set of vertices and E is a set of edges.

In the given parent graph which represents the connectivity status of chosen test system, if the edges weights are all considered non-negative, then the weighting factor ℓ for a given graph $\mathrm{G} = (\mathrm{V}, \mathrm{E})$ is defined as the sum of the edges weights from an initial node towards a destination vertex:

$$\forall u, v \in V \quad if\ (u, v) \subseteq E \rightarrow \ell(u, v) > 0$$

$$\ell(v_1, v_2, \dots, v_k) = \sum_{i=0}^{i=k-1} \ell(v_i, v_{i+1}) \tag{1}$$

where, $\ell(\mathrm{v_i}, \mathrm{v_{i+1}})$ is the geographical length between nodes $\mathrm{v_i}$ and $\mathrm{v_{i+1}}$. In this regard, the shortest path from a source node u to a destination node v, which is defined as $\mathrm{d(u, v)}$, is a path in graph G that contains minimum weight among all available paths between the mentioned nodes. If there is no edge between the source and destination nodes, then $\mathrm{d(u, v)} = \infty$.

$$S = \{u | u \in V\}$$

$$\forall u \in S, v \in V \rightarrow f(u, v)\ is\ defined \tag{2}$$

where, S is a subset of V made up gradually in an iterative process as follows: at first, a start point like s is selected from set V and inserted to set S. Then, the shortest path from the mentioned start point to all available nodes in set $\{\mathrm{V} - \mathrm{S}\}$ are determined according to (3).

$$d(s, v) = d(s, u) + min[\ell(u, v)]; \ \ \forall v \in V - S \tag{3}$$

where, node u could be any node between node s and node v. In the next step, the current node u, which is marked as the best solution node, enters into set S while the related edges to this node enter into set E. The mentioned process is done till all the system buses is investigated by the algorithm and all the nodes updated into set S.

B. MOSP algorithm

As mentioned before, an extended form of Dijkstra's algorithm as a MOSP algorithm is used to calculate the shortest paths from objective nodes to source node in the parent graph to optimally design CI in smart grid. The main aim of using MOSP algorithm is to consider overlapped paths in routing problem which reduces the employed percentage of communication medium in the design process. It is possible to use a SOSP algorithm to find shortest paths between control center and measurement devices; but this methodology is not necessarily best solution approach since there might be shortest paths between source and destination nodes by using overlapped paths in communication tree.

Figure.1 shows the step by step implementation process of the MOSP algorithm. First of all, optimal PMU locations should be obtained using ILP method proposed in [6]-[7]. In the second step, the shortest paths are calculated for PMU buses independently using Dijkstra's algorithm to create an auxiliary matrix N. Matrix N is sorted as descending values of PMU buses. This means that the first element of matrix N is farthest PMU bus from the CCB. In the next step, it is necessary to determine the exact distances between PMU buses to build the Distance Matrix (DM) to take into account existing overlapped routes. DM contains distances of PMU buses and CCB together. Afterward, the farthest PMU bus from the CCB which is the first element of matrix N is selected as a new start point in Dijkstra's algorithm. Then, the nearest PMU or CCB bus is found using Dijkstra's algorithm. If the solution is the same as the control center bus, obtained edges from previous results are added to set E and this step is implemented for the next PMU bus in matrix N. If not, the solution is considered as new start point and Dijkstra's algorithm is implemented for this node, and then this iterative process is continued until a complete path is created from the PMU bus to the control center bus. An illustrative example of MOSP algorithm has been presented in [6] for 14 bus test system.

III. NUMERICAL STUDIES AND RESULTS

A. 17 bus test system

As explained before, the aim of this paper is to propose a CI structure to allow system's controlling and measurement devices to send supervisory commends and information. In this regards, a 17 bus test system is considered as benchmark for a comparative study. It is noteworthy to state that in derivation of the distance matrix related to the aforementioned test network two assumptions have been made. First, it is assumed that all transmission lines have the same conductors with the same configurations to be able to calculate the length of transmission lines using admittance matrix. Besides, it should be noted that utilizing one communication medium for designing of the CI is just an assumption which is made and it is possible to propose approaches which work with multiple types of communication media in future studies. Second, the system's admittance matrix is used to calculate the system's connectivity matrix. In this regard, it is pivotal to have the total length of transmission lines for the selected test system which is assumed to be 1134 kilometers [8].

As it is mentioned before, the 17 bus test system's layout is considered for design problem. First, using ILP approach, two scenarios are defined for optimal placement of PMUs to obtain full observability of the system. The aim of defining two scenarios is to give a better insight of design process for both measurement and communication infrastructures since the locations of PMUs could greatly affect design of CI. Table I represents the best possible locations for PMUs in both scenarios without considering zero injection buses effect. It is noteworthy to state that considering zero injection buses may

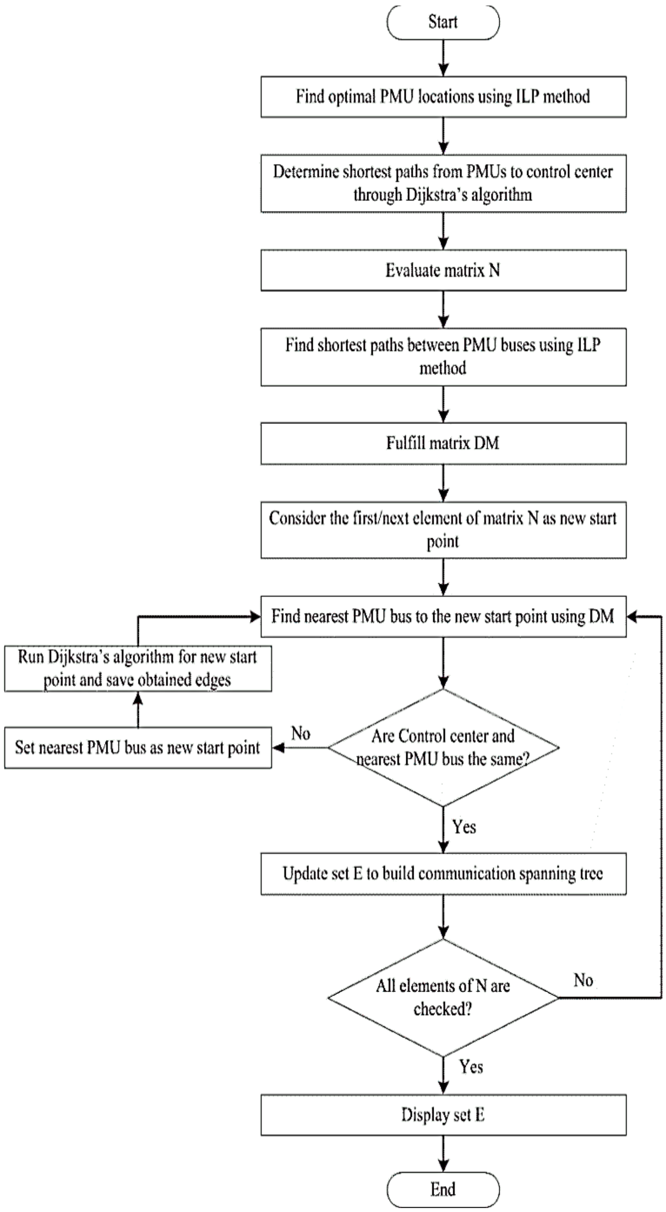

Figure 1. The flowchart of the proposed MOSP algorithm for communication system design

reduce number of PMUs in measurement infrastructure design [6]. In the next step, each bus is considered as control center bus (initial source node) and both independent (SOSP) and simultaneous (MOSP) algorithms are implemented to calculate the shortest paths between the selected control center and PMU buses. As shown in Table II, the best architectural design is introduced in terms of the OPGW coverage for suggested control center bus. It should be noted that OPGW coverage as an optimization parameter is firstly introduced in [8] and is equal to ratio of length of employed OPGW to total length of transmission lines in the selected test system. In the same table, CI Links shows the best selected routes for both methodologies to connect control center to PMU buses. Besides, the best control center bus signifies the most appropriate location for the central control bus based on the OPGW coverage. It is worth mentioning that to find best location of CCB, the proposed algorithm is applied to find OPGW coverage for each bus. The best location of CCB is a bus which proposes minimum percentage of OPGW coverage.

TABLE I
MEASUREMENT INFRASTRUCTURE PLACEMENT RESULTS FOR A 17 BUS TEST SYSTEMS FOR BOTH SCENARIOS

SCENARIO NO.	SCENARIO 1	SCENARIO 2
NO. OF BUS	5	5
BUS NO.	5,6,7,13,14	3,4,5,13,14

Figure.2 shows optimal architecture of communication infrastructure in both scenarios using MOSP and SOSP algorithms.

It should be noted that Dijkstra's algorithm is implemented as SOSP algorithm in this study. As it is indicated in Table II, OPGW coverage in scenario1 is 23.54% using MOSP algorithm, while the coverage percentage in SOSP approach is 26.90. This is due to the fact that line (5,6) is selected in MOSP approach instead of line (6,10) which is longer as it is shown in Figure.1(a). In other words, since PMU in bus 5 is already connected to control center by line (5,10), MOSP algorithm chooses line (5,6) because it connects PMU in bus 6 to communication tree with using less cable. This means that overlapped paths are taken into account in MOSP algorithm. However, SOSP algorithm finds shortest paths to PMU buses independently and does not consider the links through other PMU buses (Figure.1(b),(d)). Also, by comparing the results, it is determined that OPGW coverage in scenario 2 is 36.16% using MOSP algorithm which is suboptimal compared to similar coverage percentage in scenario1. Hence, it is more beneficial to consider scenario 1 as the best possible plan for placing PMUs in the selected test system since it is more cost effective from OPGW coverage and number of CI links points of view.

It is notable to state that the amount of used OPGW cable is significantly affects the investment cost of CI. The aim of this study is to reduce this cost by implementing a MOSP approach to minimize OPGW coverage. Besides, CI links for the selected plan are shown in Table II which shows the routes from control center to PMU buses. Number of CI links also determines the number of communication routers employed in the system to send and receive system's navigation data. Moreover, fewer number of CI links could result in better latency and reliability indices [11].

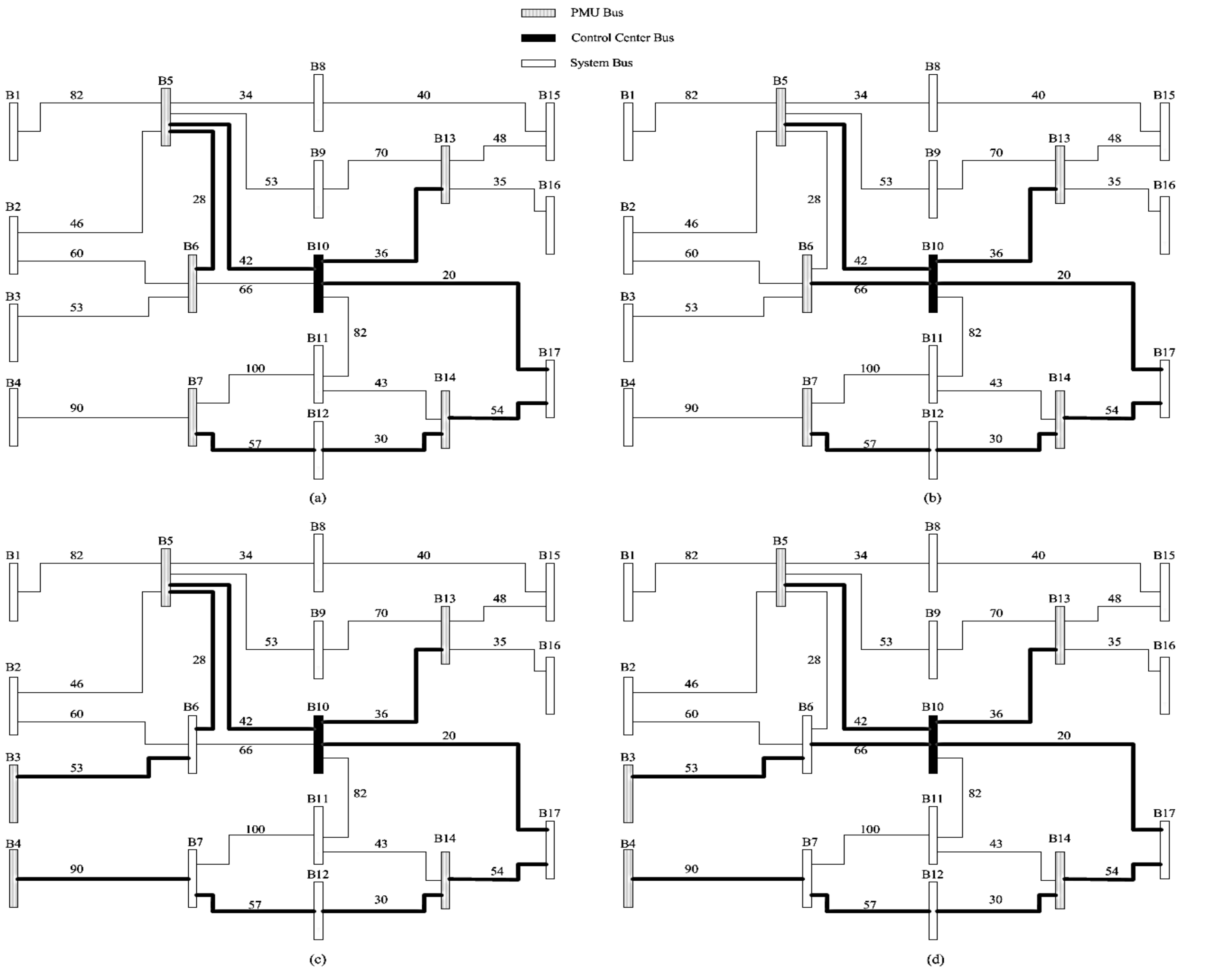

Figure 2. Communication infrastructure design for 17 bus test system, a) MOSP algorithm in scenario 1, b) SOSP algorithm in scenario 1, c) MOSP algorithm in scenario 2, and d) SOSP algorithm in scenario 2

TABLE II
COMMUNICATION INFRASTRUCTURE PLACEMENT COMPARATIVE RESULTS IN BOTH SCENARIOS

SCENARIO NO.	SCENARIO 1	SCENARIO 2
SUGGESTED CONTROL CENTER BUS (CCB)	10	10
OPGW COVERAGE USING MOSP ALGORITHM (%)	23.54	36.16
OPGW COVERAGE USING SOSP ALGORITHM (%)	26.90	39.51
CI LINKS FOR MOSP ALGORITHM	10 → **5** → **6** 10 → **13** 10 → 17 → **14** → 12 → **7**	10 → **5** → 6 → **3** 10 → **13** 10 → 17 → **14** → 12 → 7 → **4**
CI LINKS FOR SOSP ALGORITHM	10 → **5** 10 → **6** 10 → **13** 10 → 17 → **14** → 12 → **7**	10 → **5** 10 → 6 → **3** 10 → **13** 10 → 17 → **14** → 12 → 7 → **4**

B. *118 bus test system*

By considering results for 17 bus test system, it could be deduced that by enlarging test system, the effect of implementing proposed MOSP approach in reducing the communication medium will be significant. In this regard, IEEE 118 bus test system is considered as another benchmark for this study to investigate the effect of proposed algorithm in larger networks.

Similar to 17 bus test system, ILP approach firstly implemented to the selected test system to obtain locations of PMUs. Table III shows the locations of PMUs for IEEE 118 bus test system considering zero injection buses. Then, MOSP algorithm is employed to calculate the shortest routes from PMU buses to the assumed CCB. It should be noted that the total lengths of transmission lines in IEEE 118 test system is equal to 9884 kilometers. The same approach is also applied using SOSP algorithm for the selected test system to highlight the superior performance of MOSP algorithm in comparison with SOSP algorithm. As it is shown in Table IV, using MOSP algorithm in 118 bus test system could result in 23.65% OPGW coverage and 57 CI links. However, these indices in SOSP algorithm are 28.22% and 62 CI links respectively. In fact, using MOSP algorithm not only improves the OPGW coverage which leads to less investment costs, but also reduces the number of CI links which results in better reliability and latency indices.

TABLE III
PMU LOCATIONS RESULTS FOR IEEE 118 BUS TEST SYSTEM

Test System	Total # of PMUs	PMU Buses
118 Buses	28	3,9,11,12,15,17,21,25,28,34,40,45,49,53, 56,62,72,75,77,80,85,86,90,94,102,105,110,114

TABLE IV
COMPARISON OF THE PROPOSED DESIGN METHODOLOGIES IN IEEE 118 TEST SYSTEM

Simulation Type	CI Links	CCB	OPGW Coverage (%)
OPGW Coverage Using MOSP Algorithm (%)	57	65	23.65
OPGW Coverage Using SOSP Algorithm (%)	62	65	28.22

IV. CONCLUSION

In this paper, a novel MOSP algorithm proposed to design communication interface in smart grid to enable the system's components to share and transmit system's navigation commends and data. First, two scenarios were defined for optimal locations of PMUs based on integer linear programming method to obtain system's full observability. Second, a dynamic MOSP routing approach was implemented for optimal designing of the communication spanning tree. Then, the best architectural design was introduced in terms of OPGW coverage for the suggested central control bus. Finally, to investigate the superior performance of proposed method on the developed framework, a SOSP algorithm was also employed.

The results show that MOSP algorithm could take into account overlapped paths which in turn could decrease the investment cost of the system due to reduced percentage of OPGW coverage. Also, reduction in OPGW coverage and number of CI links could lead system to improving its latency and reliability indices.

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