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Optimal Design of a Wide Area Measurement System for Improvement of Power Network Monitoring Using a Dynamic Multiobjective Shortest Path Algorithm

Amir Ghasemkhani, Hassan Monsef, Ashkan Rahimi-Kian, *Senior Member, IEEE*, and Amjad Anvari-Moghaddam, *Student Member, IEEE*

Abstract—Wide area measurement system (WAMS) usually contains three dependent infrastructures called management, measurement, and communication. For optimal operation of a power system, it is necessary to design these infrastructures suitably. In this paper, measurement and communication infrastructures in a wide area network are designed independently from a management viewpoint, considering an adequate level of system observability. In the first step, optimal placement of measurement devices is determined using an integer linear programming (ILP) solution methodology while taking into account zero-injection bus effects. In the next step, new dynamic multiobjective shortest path (MOSP) programming is presented for the optimal design of communication infrastructure. The best architecture design is introduced in terms of optical fiber power ground wire (OPGW) coverage for the suggested central control bus and the number of phasor measurement units (PMUs). The applicability of the proposed model is finally examined on several IEEE standard test systems. The simulation results show better performance of the proposed method compared with other conventional methods. The numerical results reveal that applying the proposed method could not only reduce the OPGW coverage cost, the number of PMUs, and the number of communication links but could also improve the system technical indexes such as latency as subsidiary results of the optimization process.

Index Terms—Communication infrastructure, dynamic multi-objective shortest path (MOSP) programming, measurement system, power system monitoring, wide area measurement system (WAMS) structural design.

I. INTRODUCTION

WIDE AREA MEASUREMENT SYSTEM (WAMS) is an intelligent and automatic network that applies modern and digital measurement devices, control systems, and communication tools to operate a reliable and efficient electric transmission network. It is a system that monitors the grid

parameters and expedites network calculations. Through WAMS, the performance of a typical power system is continuously monitored, and high-quality real-time data are provided for operators to discover impending events or outages. Generally, WAMS consists of three dependent subsystems called management, measurement, and communication. Although these subsystems are different from the functional viewpoint, their structures are partly similar.

In recent years, with the introduction of digital data recorders such as phasor measurement units (PMUs) and new communication systems, a revolution has been formed around energy management systems (EMSs) as key components of the WAMS. An EMS is defined as a collection of computer programs, which performs power system navigation algorithms and procedures [1], [2]. New EMSs provide new applications for power system operators, which were not previously possible. Some of these applications are monitoring, wide dynamic analysis, synchronous fluctuation recording, state estimation, and real-time analysis of small fluctuations [3]. Moreover, the development of WAMS based on synchronized PMUs greatly improves power grid observability and reduces the reporting time of the global system states, which, in turn, mitigates dynamic state estimation [4].

In this regard, numerous studies have been done, and valuable results have been achieved. According to the related literature, methods for finding the optimal PMU placement are classified into two categories: stochastic approaches and deterministic approaches. Stochastic search techniques, which are often known as population-based metaheuristic algorithms, identify the PMU locations by stochastic exploration of search space. The immune genetic algorithm, particle swarm optimization, binary search, the nondominated sorting genetic algorithm, iterated local search, tabu search, and artificial bee colony are some of these optimization methods that have been recently applied to the optimal PMU placement problem [5]–[12]. On the other hand, deterministic approaches, which require lower computational time and cost, have been also developed for solving the aforementioned problem [13], [14]. These techniques not only have linear formulations but also result in globally optimal solutions. For example, in [13], a contingency-constrained PMU placement problem has been solved using a linear integer programming method, considering the zero-injection

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The authors are with the School of Electrical and Computer Engineering, College of Engineering, University of Tehran, Tehran, Iran (e-mail: a.ghasemkhani@ut.ac.ir; hmonsef@ut.ac.ir; arkian@ut.ac.ir; a.anvari@ut.ac.ir).

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buses effect. Similarly, a linear formulation with an exhaustive search approach has been introduced in [14] for an optimal PMU placement problem. The proposed model in this reference seems to be time consuming. In [15]–[17], the PMU placement problem is solved using integer linear programming (ILP) techniques with and without conventional measurements and maximum measurement redundancy of all buses. In [18], Abiri *et al.* have solved an optimal PMU placement problem with the new rules on observability constraints that could reduce the number of PMUs. In addition, some contingency analyses were included in the modeling process to maximize the level of system redundancy. In [19] and [20], a novel concept has been introduced as incomplete observability for the PMU placement problem, where the number and locations of PMUs are not enough to calculate the states of system. Nuqui in [20] also presented an approach to estimate the voltages of unobservable buses using the observed and calculated buses.

As previously mentioned, the WAMS uses communication infrastructures to share data and information through the whole grid. Since the state estimation process is highly dependent on creditable data, designing a robust and efficient communication infrastructure is also inevitable. For example, in [21]–[23], the communication infrastructure requirements and architecture for a typical power grid have been described. Likewise, in [24], the optimal design of a power communication network has been proposed based on the genetic algorithm (GA) optimization model. Moreover, Jahromi and Rad have developed their model by taking into account the specific quality of service, which is necessary in various applications such as protection and SCADA. Again, in [25], the measurement and communication infrastructures were optimally designed using the GA. They formulated and optimized this problem with a GA model in both simultaneous and independent approaches. However, they did not introduce any specific method to evaluate the location of the central control bus (CCB). It should be noted that in this study, meter placement has been carried out only for PMUs as measurement devices. Similarly, in [26], a power communication structure has been designed for both centralized and decentralized approaches based on finding a minimum spanning tree (MST). The results have been investigated through the IEEE 118-bus test system, including PMUs and conventional power flow and injection measurement devices.

In this paper, a graph-based deterministic solution technique is proposed for the optimal design of the WAMS communication interface. In this regard, a linear integer programming approach is used for the optimal design of a measurement infrastructure, considering the zero-injection buses effect as presented in [13] and [14]. As an optimal output, the minimum number of PMUs is determined to make a system completely observable. In the second step, a new dynamic multiobjective shortest path (MOSP) algorithm is proposed to optimally design the physical structure of communication infrastructure through a comprehensive search space exploration. In other words, the proposed approach first optimizes PMU placement and then optimizes communication paths that connect all PMUs. It is possible to set up a coordination mechanism between these two optimization procedures, similar to a unified cooptimization formulation or an iterative process as proposed in [25].

However, it should be noticed that the proposed methodology in this study is a deterministic solution, which makes it hard to unify the optimization process as presented in metaheuristic approaches. Furthermore, the simulation results show better performance of the proposed method compared with other conventional methods with simultaneous and independent approaches. In addition, the best location for the central bus is determined based on optical fiber power ground wire (OPGW) coverage. Finally, based on the obtained results in previous steps, a sensitivity analysis is also performed over several test systems as supplementary analysis to determine the degree of importance for various elements of a monitoring/communication system. It is very pivotal to evaluate the effects of the communication and measurement unit's malfunctioning on the observability of system for subsequent analysis in the control center (CC). Furthermore, based on the concept of incomplete observability [19], three scenarios are defined to evaluate the economic effects of reduced observability on the implementation cost of WAMS. Likewise, new definitions are introduced for communication tree edges based on graph topology. Sensitivity analysis results distinguish the importance of defined connections.

This paper is organized as follows: Section II provides a general definition of WAMS. In Section III, the mathematical formulation of the WAMS domains is presented. Section IV presents the case study results and compares them with other methods in the literature; security and sensitivity analysis is also presented to bring up the necessity of backup plans in practical test systems. Finally, some conclusions are drawn from the outcomes of this paper in Section V.

II. COMPONENTS OF WAMS

As previously mentioned, the processes of data acquisition, data transmission, and data processing are performed within a WAMS via the measurement, communication, and EMSs, respectively. While measurement and communication infrastructures are expanded through the whole power grid, the EMSs are placed in the CC. For efficient, secure, and reliable system operation, it is necessary to design WAMS infrastructures properly. In the next three sections, the WAMS infrastructures are reviewed.

A. Measurement System

The main task of a measurement device is to acquire system data from all metering devices. The remote terminal unit, the PMU, the sequence event recorder, digital protective relay, and the digital fault recorder are some of these devices. Among these items, PMUs are widely used as measurement options, mainly due to their easier synchronization process, higher precision, and better capability in dynamic real-time system monitoring [27]. For efficient and economical design of a measurement system, the number of PMUs, their suitable placement, and the effects of zero-injection buses must be considered as the key design points. Regarding system observability, two main rules can be deduced according to Kirchhoff's circuit laws

(KCL) equations for zero-injection buses to be monitored by PMUs [13].

- i. If all buses, except one, connected to a zero-injection bus are being monitored, then the nonmonitored bus is observable.
- ii. If all buses connected to a nonmonitored zero-injection bus are being monitored, then the zero-injection bus is observable.

It is noteworthy that based on KCL equations, the sum of entering currents into a node is equal to the sum of the currents leaving that node.

B. Communication System

A typical WAMS is built upon a reliable communication system, which is responsible for data and information exchange among different entities of a power system. In other words, through a communication medium, measured data and controlling commands are transmitted. Due to the introduction of reliable and fast communication devices with significantly lower cost, modern communication systems are widely involved in the WAMS design procedure. On the other hand, the availability of a proper transmission medium can greatly affect the communication system design. As described in [28], OPGW, which is used in the construction of electric power transmission and distribution lines, can be optimally placed in a power system to combine the functions of measurement and communications. This plan of action not only reduces investment costs but also improves latency and reliability indexes within the network. Moreover, there are many concerns regarding the usage of current low-voltage communication facilities in the vicinity of high-voltage power lines. The concerns relate to both operational and safety issues. OPGW with their remarkable technical advantages can be integrated with other communication instruments in a power system. A parent graph can be defined for each power system based on existing nodes and connections. Then, using graph-based methods, a communication tree for transmission of data streams to the CC is developed. Replacing OPGW with low-voltage communication facilities on the communication tree along with using PMUs as metering devices assures the fully observable system.

In a typical communication system design problem, there are some important constraints that must be met correctly. At the extreme level, all the buses containing PMUs should be connected to the CCB through the shortest path considering a connected tree configuration. A communication infrastructure can be designed and developed optimally based on the dynamic MOSP programming concept as follows:

$$\text{Minimize } \sum \text{OPGW Links Length} \quad (1)$$

$$\text{s.t. } G = (V, E) \text{ is a connected tree} \quad (2)$$

where V is a set of vertices, and E is a set of edges.

C. EMS

The EMS consists of computer-aided tools and a group of applications used by operators in CCs to monitor, control, and optimize the performance of the electric network. Generally, various kinds of operations are performed by an EMS such as state monitoring, tie-line bias control, and economic dispatch; however, the most important function is the real-time or wide-area state estimation [29]. State estimation gives an approximation of power system real states by analyzing available raw data. In other words, it both estimates the system state and performs additional tasks such as power system structure analysis and observability analysis. From a functionality point of view, observability analysis is the most important part of a state estimator [30].

On the whole, since the existing SCADA-based EMS suffers from issues such as a relatively low data transmission rate, asynchronous data acquisition, and quasi-steady-state calculation, it would be necessary to design expert EMSs for better operation of future smart grids.

III. FORMULATION FOR MEASUREMENT AND COMMUNICATION SYSTEMS DESIGN

There are two types of control strategies in a power system, namely, centralized and decentralized strategies. In a centralized approach, all metering devices transmit their measured data to the CC, which is concentrated in a single location. By analyzing received data, essential commands are sent back to controllable devices. On the other hand, the decentralized strategy refers to a collection of divided areas, where, in each area, data aggregators send data to the area CC (ACC), and data acquisition and decision-making processes are executed in the ACC locally. In the next step, it is necessary for ACCs to share their local analyzed data among each other to stabilize the performance of the entire power system. Although it is more practical to divide the system to smaller parts and locate ACCs and phasor data concentrators (time synchronizer devices that actually consolidate the PMU data and pass it on to the CC or ACCs) for the whole system, the aim of this study is to propose a general methodology for designing a WAMS structure in a centralized approach. The implementation of an optimal design for a distributed and hierarchal system such as SCADA will be proposed in future studies.

Here, deterministic approaches for the optimal placement of measurement devices and their related communication infrastructures for the centralized control strategy are introduced with regard to technical and economic issues.

A. Measurement System Design

Based on the observability rules, the measurement infrastructure can be linearly formulated as follows:

$$\text{Minimize } \sum P_j \quad (3)$$

$$\text{s.t. } O_i \geq 1 \quad (4)$$

$$O_i = \sum \alpha_{ij} P_j + \sum \alpha_{ij} Z_j X_{ij} \quad \forall i \in B \quad (5)$$

$$\sum \alpha_{ij} X_{ij} = Z_j \quad \forall j \in B \quad (6)$$

where P_j is a binary decision variable (which is equal to 1 if a PMU is installed at bus j and 0 otherwise). Moreover, O_i is the observability function of bus- i , which should be equal to or greater than 1. B is also defined as a set of buses.

The adjacency matrix in (5) could be defined as follows:

$$\alpha_{ij} = \begin{cases} 1, & \text{if } i = j \\ 1, & \text{if buses } i \text{ and } j \text{ are connected} \\ 0, & \text{otherwise.} \end{cases} \quad (7)$$

Inclusion of zero-injection buses is considered in (5) with auxiliary variables, i.e., X_{ij} , appended to zero-injection buses and those adjacent to zero-injection buses. In fact, the second term of (5) applies observability rules for zero-injection buses in the proposed formulation. Likewise, parameter Z_j is a binary parameter to define the zero-injection buses, which is equal to 1 if bus j is a zero-injection bus and to 0 otherwise. The number of auxiliary variable for each nonzero-injection bus is defined based on the number of zero-injection buses that are connected to the bus. However, for zero-injection buses, 1 is added to this number. Whenever Z_j is equal to 1, there is one auxiliary variable that is connected to bus j . Hence, (5) and (6) guarantee the observability of zero-injection buses along with other nonzero-injection buses. In other words, $\sum \alpha_{ij} P_j$ ensures the observability of nonzero-injection buses, and $\sum \alpha_{ij} Z_j X_{ij}$ ensures the observability of zero-injection buses in the observability function.

B. Communication System Design

One of the challenging problems in communication design calculations is to find the shortest path in a given network regarding connected tree graphs. To address this issue, it is necessary to utilize dynamic shortest path programming to create a data transmission path from measurement instruments to the CCB. Shortest path programming is an old-aged problem, on which many research works have been conducted. For example, Dijkstra's algorithm is graph search algorithm that solves the single-source shortest-path problem on a weighted directed graph for the case in which all edge weights are nonnegative to produce a shortest path tree. This algorithm is often used in routing and as a subroutine in other graph algorithms [31], [32]. However, this algorithm just tracks shortest paths from a single source to one determined vertex in the graph and does not find shortest paths for more than one node simultaneously. Furthermore, the Bellman-Ford algorithm solves the single-source shortest-path problem in the general case in which edges can have negative weight and computes shortest paths from a single-source vertex to all of the other vertices in a weighted graph. Although the Bellman-Ford algorithm is remarkable in its simplicity and it has the further benefit of detecting whether a negative-weight cycle is reachable from the source, to create a spanning tree for a determined number of vertices, this algorithm does not take into account overlapped paths that may exist in the graph between a source node and specific vertices [32]–[34]. Moreover, the algorithms such as Kruskal's algorithm are a good example of greedy algorithms that compute an MST in a weighted graph. This algorithm finds

a subset of edges to form a tree that contains all vertices in the graph [32]–[35]. However, these kinds of algorithms fail to figure an MST with one centered node and form a tree that includes every specific vertex. Hence, it is necessary to develop a dynamic algorithm to create a minimum tree with a centered node that connects a central vertex to all specific nodes that have been determined before. To solve this problem, an MOSP algorithm is developed to design communication interface.

In this paper, a shortest path exploration algorithm (SPEA) is addressed to be used in the MOSP problem for a graph with nonnegative edges. The proposed routing algorithm calculates the shortest paths from a specific source node to any node in a given graph such as $G = (V, E)$, where V is a set of vertices, and E is a set of edges with two main conditions.

1. $E \subseteq V \times V$
2. E does not include any loop like (V, V) .

In a given graph $G = (V, E)$, if all the edges of a walk and all the vertices are different, then the walk is called a path. Similarly, if the edge weights are all considered positive, then the weighting factor ℓ for a given graph $G = (V, E)$ is defined as the sum of the edge weights from a source toward a destination bus, i.e.,

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

$$\ell(v_1, v_2, \dots, v_k) = \sum_{i=0}^{i=k-1} \ell(v_i, v_{i+1}) \quad (8)$$

where $\ell(v_i, v_{i+1})$ is the geographical distance between nodes v_i and v_{i+1} . In this regard, the shortest path from a source node u to a destination node v , which is defined as $d(u, v)$, 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 the destination, then $d(u, v)$ is considered infinite, i.e.,

$$S = \{u | u \in V\} \forall u \in S, v \in V \rightarrow d(u, v) \text{ is defined} \quad (9)$$

where S is a subset of V made up gradually in an iterative process as follows: At first, a start point such as 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 $\{V - S\}$ are determined according to

$$d(s, v) = d(s, u) + \min[\ell(u, v)]; \forall v \in V - S \quad (10)$$

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 a visited node, enters into set S while the related edges to this node enter into set E . The mentioned process is done until all the system buses are explored by the algorithm and all the nodes enter into set S . The SPEA is used to determine the shortest paths from PMU buses to the CCB in the MOSP routing algorithm, which is used for optimal communication interface placement; therefore, all the visited PMU nodes, which have moved into set S , could be considered as initial nodes (see Fig. 1). It could also be deduced that the nearest PMU bus has always the shortest path to the CCB among all the possible paths. There are two

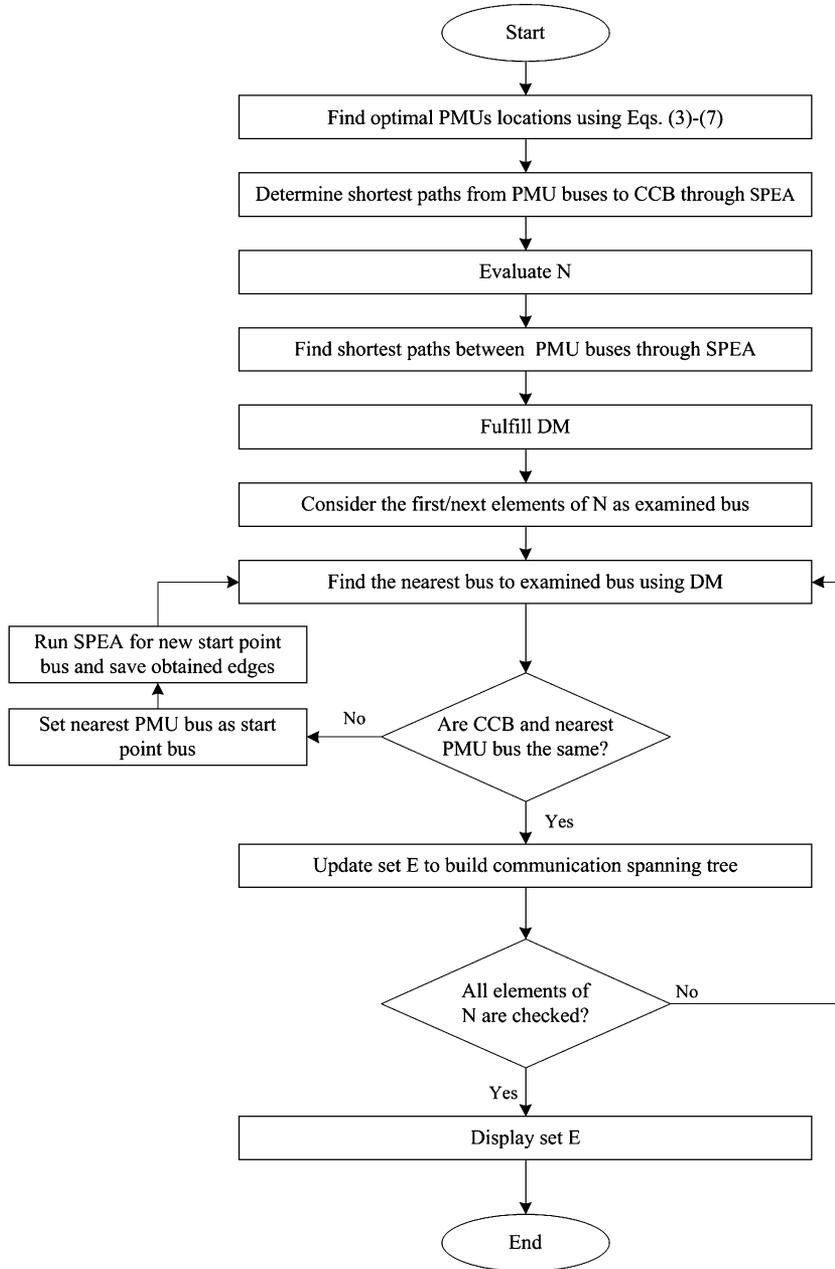


Fig. 1. Flowchart of the proposed approach for communication system design.

different ways to obtain the data transmission path from PMU buses to the CCB as follows:

- i. single-objective shortest path (SOSP);
- ii. MOSP.

In the case of an SOSP, the shortest path from each PMU bus to the CCB can be obtained independently using shortest path algorithms such as Dijkstra, whereas in a MOSP routing algorithm, which is presented in this paper, overlapped paths are used to create data transmission paths for all PMU buses. In other words, in the case of an MOSP algorithm, all the PMU buses, except the nearest one to the CCB, do not necessarily have shortest paths to the CCB, mainly due to the overlapped paths that could be used as means of data transmission with reduced OPGW coverage.

To get better insight into the MOSP routing algorithm and its application to optimal design procedures, an illustrative example based on the IEEE 14-bus test system is presented here. As shown in Fig. 2, the implementation of the ILP-based algorithm on this system results in the installation of three PMUs in buses 2, 6, and 9, regarding the optimal PMU placement problem. In this case, bus 7 is a zero-injection bus, and bus 8 has been made observable due to zero-injection bus effects. Likewise, the optimal design of a communication infrastructure can be determined using the MOSP algorithm considering previously mentioned instructions. First, bus 5 is selected as CCB considering the lowest value for OPGW coverage. Then, the SPEA is applied to obtain minimum distances from the CCB to other buses, which are necessary to build matrix N . Matrix N for an illustrative network in Fig. 2 is organized as descending

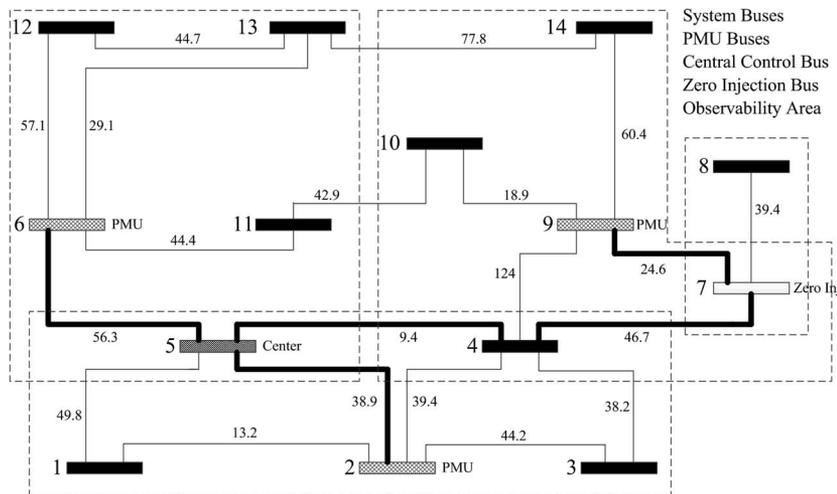


Fig. 2. Optimal design of a WAMS for the IEEE 14-bus test system based on the proposed method.

TABLE I
SHORTEST PATH VALUES FOR THE MAIN CENTRAL BUS
IN IEEE 14-BUS TEST SYSTEM

Bus #	1	2	3	4	5	6	7
Distance	49.8	38.9	47.6	9.4	0	56.3	56.1
Bus #	8	9	10	11	12	13	14
Distance	95.5	80.7	99.6	100.7	113.4	85.4	141.1

shortest path values for PMU buses from Table I, as shown in the following equation:

$$N = \begin{bmatrix} 9 & 6 & 2 \\ 80.7 & 56.3 & 38.9 \end{bmatrix}. \quad (11)$$

In the next step, the SPEA is implemented once more to determine the shortest path values between PMU buses. Then, a new distance matrix (DM) is defined for PMU buses and the CCB according to

$$DM = \begin{matrix} & 5 & 2 & 6 & 9 \\ \begin{matrix} 5 \\ 2 \\ 6 \\ 9 \end{matrix} & \begin{bmatrix} 0 & 38.9 & 56.3 & 80.7 \\ 38.9 & 0 & 95.2 & 110.7 \\ 56.3 & 95.2 & 0 & 106.2 \\ 80.7 & 110.7 & 106.2 & 0 \end{bmatrix} \end{matrix}. \quad (12)$$

Afterward, the farthest PMU bus to the main central bus is selected based on matrix N and considered as the evaluating PMU bus. Next, the nearest bus to the evaluating PMU bus is selected from the DM and considered as a new start point in the SPEA. If the selected start point (i.e., new candidate bus) is the same as the CCB, obtained edges from previous results are added to set E in (8), and this step is implemented for the next PMU bus. If not, the SPEA is implemented for the new start point, and then, this bus is set as a new evaluated PMU bus until a complete path is created from the PMU bus to the CCB. In this case, bus 9 is the most remote bus to the CCB and is set as a new start point bus. After implementing the shortest path algorithm for bus 9, edges (9, 7), (7, 4), and (4, 5) are obtained, and set E is updated. These steps are performed until all the PMU buses are considered and the communication spanning tree is created. The optimal design configuration of the IEEE 14-bus test system is shown in Fig. 2.

TABLE II
MEASUREMENT INFRASTRUCTURE PLACEMENT
RESULTS FOR IEEE TEST SYSTEMS

Test System	Total # of PMUs	PMU Buses
30 Buses	7	1,5,10,12,15,18,27
57 Buses	11	1,4,13,20,25,29,32,38,51,54,56
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

IV. NUMERICAL STUDIES AND SIMULATION RESULTS

As previously mentioned, the aim of this paper is to design measurement and communication infrastructures in a wide area network considering an adequate level of system observability, latency, and reliability. Therefore, an ILP solution methodology and a dynamic MOSP routing algorithm have been presented for the optimal design of related infrastructures, taking into account the central bus and zero-injection bus effects. Here, four test systems, including the IEEE 14-, 30-, 57-, and 118-bus networks, are introduced and used as benchmarks for doing a comparative study. Detailed information on these test systems can be found in [21] and [31]. It is also notable that in the derivation of distance matrices related to the aforementioned IEEE test networks, two assumptions have been made. First, it is assumed that all transmission lines have the same conductors with the same configurations. It should be noted that this study is proposing a general methodology for designing WAMS; therefore, utilizing one communication medium for designing a communication infrastructure is just an assumption that is made, and it is possible to propose approaches that work with multiple types of communication media (e.g., OPGW, power line carrier, all-dielectric self-supporting, or even wireless solutions) in future studies. Second, it is assumed that the total lengths of transmission lines in the IEEE 14, 30, 57, and 118 test networks are equal to 900, 3000, 5712, and 9884 km, respectively. Hence, we can obtain the relative distances between system buses from the system admittance matrix [25], [36].

Model optimization is done using the CPLEX solver in GAMS software package, and the communication system

TABLE III
COMMUNICATION INFRASTRUCTURE PLACEMENT RESULTS FOR IEEE TEST SYSTEMS

TEST SYSTEM	CI LINKS	CI NODES	BEST CCB	OPGW COVERAGE	OPGW LOCATIONS	SIMULATION TIME (MIN)
30 BUSES	12	13	4	22.57	(2,4)-(2,1)-(4,6)-(6,7)-(5,7)-(6,9)-(9,10)-(4,12)-(12,15)-(15,18)-(6,28)-(28,27)	0.032
57 BUSES	33	34	11	30.15	(4,3)-(3,2)-(2,1)-(13,15)-(15,3)-(9,13)-(38,22)-(22,21)-(21,20)-(32,31)-(31,30)-(30,25)-(9,8)-(8,7)-(7,29)-(38,37)-(37,36)-(36,35)-(35,34)-(34,32)-(13,14)-(14,46)-(46,47)-(47,48)-(48,38)-(9,10)-(10,51)-(9,55)-(55,54)-(13,11)-(11,43)-(43,41)-(41,56)	0.412
118 BUSES	57	58	65	23.65	(12,3)-(17,30)-(30,8)-(8,9)-(8,5)-(5,11)-(11,12)-(17,15)-(34,37)-(37,38)-(38,30)-(15,19)-(19,20)-(20,21)-(30,26)-(26,25)-(25,27)-(27,28)-(65,38)-(37,39)-(39,40)-(49,45)-(65,66)-(66,49)-(54,53)-(49,54)-(54,56)-(65,64)-(64,61)-(61,62)-(25,23)-(23,24)-(24,72)-(65,68)-(68,69)-(69,75)-(80,77)-(68,81)-(81,80)-(82,83)-(83,85)-(85,86)-(92,91)-(91,90)-(77,82)-(82,96)-(96,94)-(94,92)-(92,102)-(94,100)-(100,103)-(103,105)-(105,108)-(108,109)-(109,110)-(27,115)-(115,114)	22.40

TABLE IV
COMPARISON OF THE PROPOSED DESIGN METHODOLOGY WITH OTHER METHODS

Test System	Simulation Type	Total # of PMUs	CI Links	CI Nodes	CCB	OPGW Coverage (%)	Total Cost (in US million \$)
30 Buses	Proposed Method	7	12	13	4	22.57	7.051
	GA (Simultaneous) [25]	10	14	15	-	26.82	8.446
	GA (Independent) [25]	10	15	16	-	30.70	9.610
	Proposed Method for the same PMUs in Simultaneous approach	10	14	15	24,25,26	26.82	8.446
	Proposed Method for the same PMUs in Independent approach	10	16	17	25,26	29.97	9.391
57 Buses	Proposed Method	11	33	34	11	30.15	17.662
	GA (Simultaneous) [25]	19	39	40	-	33.1	19.667
	GA (Independent) [25]	17	37	38	-	38.13	22.460
	Proposed Method for the same PMUs in Simultaneous approach	19	35	36	14	30.38	18.113
	Proposed Method for the same PMUs in Independent approach	17	36	37	3,4	36.08	21.289
118 Buses	Proposed Method	28	57	58	65	23.65	24.496
	GA (Simultaneous) [25]	39	75	76	-	30.48	31.686
	GA (Independent) [25]	36	71	72	-	32.15	33.217
	Proposed Method for the same PMUs in Simultaneous approach	39	72	73	38,65,68	26.19	27.447
	Proposed Method for the same PMUs in Independent approach	36	70	71	65,81	24.99	26.140

design computations are done using MATLAB software package. The computer used for simulations had an Intel Core 2 Duo CPU P8700 running at 2.53 GHz with 3.0 GB of RAM.

A. Optimal Design of Measurement and Communication Systems

In the first step, by applying the ILP solution methodology to the IEEE 30-, 57-, and 118-bus test systems and taking into account the zero-injection bus effects, optimal placement of measurement devices is defined as shown in Table II. Based on the first-step results, the proposed dynamic MOSP programming is applied to the test systems for the optimal design of communication infrastructure. As shown in Table III, the best architectural design is introduced in terms of the OPGW coverage for the suggested CCB. In the same table, the CI links (which represent the number of communication links between the central bus and PMU buses), the CI nodes (which represent

the number of buses that exist in the communication cabling path), and the number of PMUs are shown. Moreover, the best CCB represents the most appropriate location for the CCB based on the OPGW coverage, whereas the OPGW locations represent the existing communication links. It is also notable that the evaluation of these indexes is necessary for the accurate determination of the router numbers between the CCB and the PMU buses. The simulation times for the MOSP algorithm are also presented in the same table.

To show the superior performance of the MOSP method in comparison with the methods presented in [25] for communication infrastructure, the solution methodologies are applied to the suggested test systems, and the simulation results are truthfully gathered. It should be noted that the aim of this paper is not to compare PMU placement methods. As shown in Table IV, the best solution of the proposed method not only demonstrates a lower number of PMUs in each case but also has lower OPGW coverage, CI link, and CI node indexes. Based on the results

TABLE V
CC PLACEMENT IN IEEE 30-BUS TEST SYSTEM BASED ON OPGW COVERAGE

Bus #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
OPGW Coverage	26.33	26.1	23.3	22.57	26.33	22.7	22.94	23.42	25	27.55	27.55	25.61	27.31	28.03	25.61
Bus #	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
OPGW Coverage	26.33	24.76	25.61	24.03	24.03	24.88	25.12	26.1	29	29.25	32.16	26.33	22.94	31.43	33.62

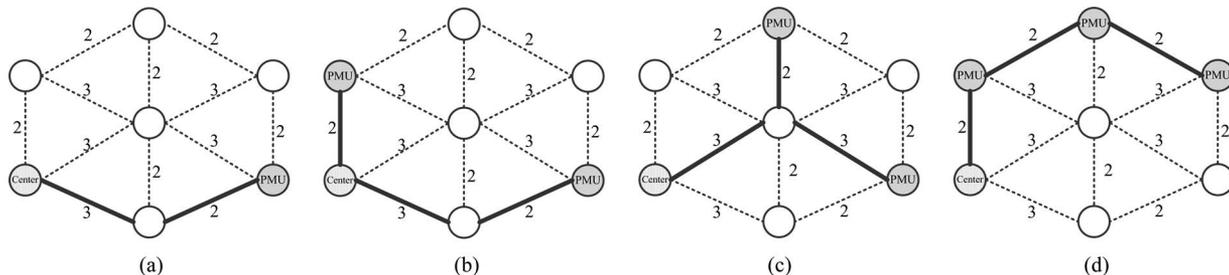


Fig. 3. Different types of shortest path dynamic programming. (a) Single-source shortest path routing. (b) Multisource shortest path routing with three DCTs. (c) Multisource shortest path routing with CCT-2 and two ICTs. (d) Multisource shortest path routing with CCT-3, CCT-2, and an ICT.

reported in [36] and [37], it is inferred from their numerical results that any increase in the communication media length, number of routers, and communication links would result in an increase in latency and a decrease in reliability indexes, which, in turn, would increase the investment costs. Moreover, the total costs shown in the last column of Table IV explain that each WAMS installation cost depends on the total number of PMUs and the related OPGW coverage. To have a fair comparison, each PMU's installation cost and the OPGW coverage cost per kilometer are used in [25]. Moreover, this approach is also implemented to the same number of PMUs presented in [25] for both strategies. The results show that, in most cases, better solutions can be found by this approach, comparing with those presented in [25]. For example, as shown in Table IV, using the same number of PMUs applied in the independent approach to the IEEE 118-bus test system, OPGW coverage is improved from 32.15% to 24.99%.

Once again, by implementing the mentioned MOSP algorithm for all nodes in a given graph, the OPGW coverage can be determined in each case. Subsequently, the placement of the central bus can be determined based on the lowest value for the OPGW coverage. Table V denotes the OPGW coverage for the 30-bus IEEE test system. As shown in Table V, bus 4 with the lowest coverage percentage (22.57%) is the best candidate for CCB.

Security Analysis: One of the most important issues in the communication system design procedure is to find the shortest path in a given network regarding a spanning tree as to provide reliable data transmission. However, the security analysis has to be an integral part of the system design. For further explanation of the mentioned point, let us consider a sample graph with a center bus and PMU nodes. As shown in Fig. 3(a), if the single-source shortest-path problem is solved based on the proposed method, the spanning tree will be obtained. On the contrary, regarding a large-scale power system, it will be necessary to solve an MOSP problem for the optimal placement of communication links. It is noteworthy that for different PMU locations, different types of connections for communication links will

TABLE VI
SECURITY ANALYSIS OF COMMUNICATION SPANNING TREES FOR DIFFERENT IEEE TEST SYSTEMS

Test System	CCT	ICT	DCT
14 Buses	-	-	5
30 Buses	3	7	2
57 Buses	14	16	3
118 Buses	28	26	3

be obtained. Although these configurations may be acceptable from a structural point of view, they will be surely different from a security viewpoint. Therefore, a security analysis should be done over candidate configurations. Generally, based on different locations of PMUs in a given network, three types of configurations can be introduced.

- i. Direct Connection Type (DCT): Compared with other connection types, DCT is the best in terms of communication security. As shown in Fig. 3(b), since all PMU buses are directly connected to the CCB, data transmission is performed independently for each PMU bus.
- ii. Common Connection Type (CCT- n): In this configuration, one link is placed in common with n PMU buses, as shown in Fig. 3(c) and (d) ($n \geq 2$). Since the common buses have a vital role in data transmission to CCB, this type suffers from low security communication.
- iii. Indirect Connection Type (ICT): As shown in Fig. 3(c) and (d), other links that are separated from the common link or put sequentially between consecutive PMU buses are called ICT. Moreover, data transmission for these connections highly depends on the previous CCTs performances. Since each ICT link transmits just one PMU data, its connection has a lower security importance.

As shown in Table VI, by locating a spanning tree for different IEEE test systems, the number of mentioned connections for each system is obtained. For example, a 30-bus system's communication spanning tree consists of 12 lines, which include three CCTs, seven ICTs, and two DCTs. This table

TABLE VII
SENSITIVITY ANALYSIS OF PMU BUSES FOR IEEE 30-BUS TEST SYSTEM

PMU Buses	1	5	10	12	15	18	27
Total # of unobservable Buses	2	2	7	3	1	1	3
Network unobservability (%)	6.67%	6.67%	23.33%	10%	3.33%	3.33%	10%
Total Cost (in US thousand \$)	80	80	280	120	40	40	120

TABLE VIII
SENSITIVITY ANALYSIS OF COMMUNICATION LINKS FOR IEEE 30-BUS TEST SYSTEM

Communication Links	(4,6)	(4,12)	(12,15)	(1,2)-(2,4)	(15,18)	(6,7)-(7,5)	(6,28)- (27,28)	(6,9)- (9,10)
Connection Type	CCT-3	CCT-3	CCT-2	DCT	ICT	ICT	ICT	ICT
Total # of Unobservable Buses	12	9	3	2	1	2	3	7
Network Unobservability (%)	40%	30%	10%	6.67%	3.33%	6.67%	10%	23.33%
Total Cost (in US thousand \$)	146	947	473	218-619	801	291-437	218-1456	765-400

illustrates that although DCTs are the most secure connections, cost consideration in locating the communication tree prevents the acquisition of full DCTs for the evaluated system.

Sensitivity Analysis: Complete system observability is one of the main objectives of an EMS, which should be met in most operating conditions. Generally, some of the system monitoring malfunctions or disturbances such as loss of PMUs or link outages can interrupt system observability or have negative effects on the whole system observability. To handle this issue more wisely, many researchers have tried to include contingency analysis into their PMU placement problems considering $N - 1$ or $N - 2$ criterion to provide full system redundancy [13], [14], [18]. Although these calculations can be helpful in evaluating reliability indexes and in understanding the level of system observability, they may be suboptimal from an economical point of view due to the excessive number of PMUs or links obtained in contingency analysis. In most practical cases, implementing such systems due to the mentioned reason is a challenging issue; thus, the backup plans are only provided for the elements that have vital roles on the system performances. Moreover, the degree of importance for various elements of a monitoring/communication system is not the same, and it would be better to evaluate failure consequences of different elements on the whole system performance and derive the most reliable backup plan thereafter. For instance, Salehizadeh *et al.* in [38] and [39] have proposed an index named degree of severity to evaluate the effects of transmission component failures in a power system. Likewise, in this paper, the consequences of PMUs and link outages are assessed based on the observability of the system. In other words, the importance degree for each element is calculated based on the network unobservability (NU) using (5) as follows:

$$NU = \frac{\text{Total number of unobservable buses}}{\text{Total number of buses}}. \quad (13)$$

Furthermore, it is possible to solve the PMU placement problem with incomplete observability [19]. Thus, it is important to determine the economic effects of reduced observability on the implementation cost of WAMS. In this regard, NU caused by loss of PMUs or communication link outages is determined. Malfunctioning in WAMS component performance can lead

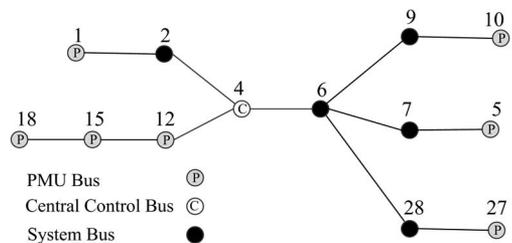


Fig. 4. IEEE 30-bus test system spanning tree.

to incomplete observability, which highlights the necessity of backup plans.

To investigate the contingency situations in the proposed model, sensitivity analysis of the PMU buses and communication links for an IEEE 30-bus test system is also performed. The obtained results are presented in Tables VII and VIII. In the same tables, the level of NU and the total number of unobservable buses are shown in the case of each contingency situation. In this regard, if NU is allowed to be equal to and less than 10% for an IEEE 30-bus test system, then it can be seen from Table VII that the level of unobservability for the loss of PMU at bus 10 reaches 23.33%, which is highly above the range. Therefore, it is necessary to set up a backup PMU in bus 10. Accordingly, sensitivity analysis for link outages is shown in Table VIII for an IEEE 30-bus test system. It is observed from the simulation results that the degree of importance for links varies by their positions in the tree. For example, ICT and DCT outages have a less negative effect on system observability compared with the outages of CCT- n . For further explanation, let us consider the spanning tree of an IEEE 30-bus test system, as depicted in Fig. 4. It is clearly observed that in the case of outage of links (4, 6) and (4, 12), three PMU buses and, in the case of outage of link (12, 15), two PMU buses are lost, whereas other link outages almost result in loss of one PMU. Regarding this point and a permissible NU value (which is assumed to be equal to and less than 10% for the examined network), it becomes necessary to provide means of backup for links (4, 6), (4, 12), (6, 9), and (9, 10). Likewise, there are some vital links in an IEEE 118-bus test system, which play important roles in data transmission and greatly affect system observability. As can be seen in Table IX, such link outages bring about loss

TABLE IX
SENSITIVITY ANALYSIS OF SOME CRITICAL COMMUNICATION LINKS FOR IEEE 118-BUS TEST SYSTEM

Communication Links	(38,65)	(65,68)	(30,38)	(68,81)- (80,81)	(77,80)	(77,82)	(82,96)- (94,96)	(15,17)	(64,65)- (61,64)	(91,92)- (90,91)
Connection Type	CCT-17	CCT-11	CCT-11	CCT-9	CCT-8	CCT-7	CCT-5	CCT-2	DCT	ICT
Total # of Unobservable Buses	44	41	36	36	29	20	19	4	4	2
Network Unobservability (%)	37.29%	34.75%	30.51%	30.51%	24.58%	22.03%	16.1%	3.39%	3.39%	1.69%
Total Cost (in US thousand \$)	524	85	287	107-196	558	453	281-461	232	160-142	675-444

TABLE X
SENSITIVITY ANALYSIS FOR LINKS IN IEEE 118-BUS TEST SYSTEM

Links	Total # of Unobservable Buses	Unobservability [%]
(38,65)	44	37.29
(65,68)	41	34.75
(68,81)-(80,81)-(30,38)	36	30.51
(77,80)	29	24.58
(77,82)	26	22.03
(82,96)-(94,96)	19	16.1
(65,66)-(66,49)	16	13.56
(26,30)-(25,26)	12	10.17
(8,30)	11	9.32
(17,30)-(94,100)-(100,103)-(103,105)	10	8.47
(5,8)-(5,11)	9	7.63
(49,54)-(37,38)	7	5.93
(82,83)-(83,85)	6	5.08
(11,12)-(54,56)-(25,27)	5	4.24
(65,64)-(64,61)-(61,62)-(92,94)-(15,17)-(105,108)-(108,109)-(109,110)	4	3.39
(68,69)-(69,75)-(34,37)-(37,39)-(39,40)-(15,19)-(19,20)-(20,21)-(23,25)-(23,24)-(24,72)-(27,115)-(114,115)	3	2.54
(92-102)-(8,9)-(27,28)-(92,91)-(91,90)-(45,49)-(53,54)	2	1.69
(3,12)-(85,86)	1	0.85

TABLE XI
SENSITIVITY ANALYSIS FOR PMUs IN IEEE 118-BUS TEST SYSTEM

PMU Buses	Total # Unobservable Buses	Unobservability [%]
56-80-105	5	4.24
17-49-62-94-110	4	3.39
12-21-25-34-40-72-75-77-85-114	3	2.54
9-28-45-53-90-103	2	1.69
3-11-15-86	1	0.85

of observability up to unacceptable levels, and it becomes a necessity to provide backup plans.

Moreover, to get better insights into the economic effects of incomplete observability for planning of backup plans, the analysis is carried out by comparing three destined scenarios in the IEEE 118-bus test system:

Scenario 1) NU is assumed to be equal to or less than 4%

Scenario 2) NU is assumed to be equal to or less than 12%

Scenario 3) NU is assumed to be equal to or less than 20%

As can be seen from Table X, the sensitivity analysis was performed for all PMU buses in case of failure. It is obvious that in the worst case, with failure of PMUs at buses 56, 80, and 105, nearly 4% of the system will become unobservable. It shows that the malfunction of PMUs in large test systems has slight effects on the system observability. Therefore, regarding the predefined scenarios, only in the first scenario will it be necessary to set up the backup PMUs.

The same analysis was performed to evaluate the importance of the links on the system's observability. As it is shown in

Table XI, the percentage of unobservability for all links in case of failure has been calculated. Based on the obtained results, there are some vital links, which have key roles in a large part of the system's data transmission. For example, if link (38, 65) is lost, about 37% of the system will become unobservable. Because with going out the mentioned link, all the PMUs that transmit their own and adjacent buses through the link will malfunction. Hence, setting up a backup link for such link is indispensable. In addition, the required backup plans for each of the aforementioned scenarios are presented in Table XII. The results show that as the NU's rate goes down, the cost of setting up backup plans would increase, which could be considered as a tradeoff between the level of observability in case of failure and the cost of backup plans.

V. CONCLUSION

In this paper, two novel measurement and communication infrastructures for a WAMS have been designed independently

TABLE XII
SENSITIVITY ANALYSIS OF PMUs AND LINKS FOR THREE SCENARIOS FOR IEEE 118-BUS TEST SYSTEM

Scenarios	# of critical PMUs	# of critical Links	Minimum Percent of Observability for System in case of Failure	Implementation cost of back-up plans (in US million \$)
Scenario 1	2	27	96%	10.46
Scenario 2	0	11	88%	3.63
Scenario 3	0	7	80%	2.20

with respect to the adequate level of system observability. First, the optimal locations of the measurement devices were determined using a linear programming method considering zero-injection bus effects. Second, a dynamic MOSP routing approach was presented for the optimal design of the communication infrastructure. Then, the best architectural design was introduced in terms of OPGW coverage for the suggested CCB and the number of PMUs. Furthermore, through different case studies, it was shown that the proposed method could perform better in terms of security and reliability indexes compared with the existing methods in the literature. Finally, to investigate the effects of contingency situations on the developed framework, several sensitivity and security analyses of the PMU buses and communication links for two different IEEE test systems were presented, and the necessity of a backup plan in each case was evaluated.

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Amir Ghasemkhani received the B.Sc. degree from the University of Tabriz, Tabriz, Iran, in 2011 and the M.Sc. degree from the University of Tehran, Tehran, Iran, in 2014.

His research interests include smart grids, modeling and optimization of power systems, power system economics and market, integrating distributed generation resources in power systems, and artificial intelligence techniques.



Hassan Monsef received the B.Sc. degree from Sharif University of Technology, Tehran, Iran, in 1986; the M.Sc. degree (with honors) from the University of Tehran, Tehran, in 1989; and the Ph.D. degree from Sharif University of Technology in 1996, all in power engineering.

Since 1996, he has been with the University College of Engineering, School of Electrical and Computer Engineering, University of Tehran, where he is currently an Associate Professor. His research interests include power system operation under

deregulation, reliability of power systems, power systems economics, renewable energy systems, and its integration in smart grids.



Ashkan Rahimi-Kian (SM'08) received the B.Sc. degree from the University of Tehran (UT), Tehran, Iran, in 1992 and the M.S. and Ph.D. degrees from The Ohio State University, Columbus, OH, USA, in 1998 and 2001, respectively, all in electrical engineering.

He was the Vice President of Engineering and Development with Genscape, Inc., Louisville, KY, USA, from September 2001 to October 2002 and a Research Associate with the School of Electrical and Computer Engineering (ECE), Cornell University, Ithaca, NY, USA, from November 2002 to December 2003. He is currently an Associate Professor of electrical engineering (Control and Intelligent Processing Center of Excellence) with the School of ECE, College of Engineering, UT. He is also the Founder and Director of the Smart Networks Research Laboratory (SNL), School of ECE, UT. His research interests include bidding strategies in dynamic energy markets, game theory and learning, intelligent transportation systems, decision-making in multiagent stochastic systems, stochastic optimal control, dynamic stock market modeling and decision-making using game theory, smart grid design, operation and control, estimation theory and applications in energy and financial systems, risk modeling, and management in energy and financial systems.



Amjad Anvari-Moghaddam (S'08) received the B.S. degree (Hon.) from Ferdowsi University of Mashhad, Mashhad, Iran, in 2008 and the M.Sc. degree (Hon.) from Shiraz University, Shiraz, Iran, in 2010. He is currently working toward the Ph.D. degree with the University of Tehran, Tehran, Iran, all in electrical engineering.

He is currently a Research Assistant with the University of Tehran. His research interests include smart microgrids, renewable energy sources, and multiagent systems design, operation, and control.