Dependent Communication Systems: A New Approach for Designing Communication Infrastructures of Smartgrid

Mohammad Shahraeini, Mohammad H. Javidi, and Mohammad S. Ghazizadeh

Abstract—The term "smartgrid" refers to the power system that integrates new digital measurements, new digital control devices, and communication technology. The first step toward this goal is to establish a two-way communication infrastructure for the purpose of data delivery among data resources, system actuators and control centers. Phasor measurement unit (PMU) is a kind of new data resources that are widely used in power systems, recently. On the other hand, state estimation (SE) is basis application in control centers and it is known as kernel of other smartgrid applications. This study aims to plan a communication infrastructure that creates communication routes from PMUs of a SE to the control center in a power network. To do this, a new concept is introduced to power system communication called dependent communication system (DCS). A DCS has been made by independent transmission media (e.g. optical power grand wire), which is typically attached to the power systems. In this paper, OPGW based DCS designing problem is formulated as an optimization problem. This optimization problem is solved by genetic algorithm. It will be shown that DCS planning is an effective and flexible approach for designing communication infrastructures of smart grids. The results confirm that almost 25 percent of lengths of transmission lines should be covered by OPGW in order to create communication routes from PMUs to the control center. Hence, it is proved that the price of high speed, reliable and secure communication infrastructure of a smartgrid is considerable in comparison with the price of data resources e.g. PMUs.

Index Terms—Genetic Algorithm, Optical Power Grand Wire, Power System Communication, Smartgrid.

1 Introduction

SMART GRID is a term which has been introduced in power system literatures, recently. This term implicitly implies the integration of all elements connected to a power grid (especially measurements and control devices) with a communication infrastructure [1]. In other word, the first major step toward establishing smartgrid in a power system is to plan and design a two-way communication infrastructure in the entire system. Such a communication infrastructure (CI) is responsible for data delivery among different entities (e.g. data resources, control center(s) and actuators) in an electrical infrastructure.

New communication systems are designed based on a layer model. The first layer of these systems, referred as the physical layer, is a kind of medium that establishes the physical connection between transmitter and receiver. The characteristics of the communication systems will become seriously influenced by the characteristics of its media.

The communication media which are established in power systems have been classified into dependent and independent media. Dependent media (e.g. optical power grand wire) are part of power network elements and they are normally owned by power system operators.

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In this study, we introduce a new concept in power system communication; namely "dependent communication systems". Dependent communication systems (DCS) of power systems are normally made by one of the dependent transmission media.

As DCS is part of a power system and usually owned by system operator, it can be optimally designed in conjunction with power system planning problems. Consequently, DCS can be regarded as a great opportunity for implementing power system communications in next generation power networks in order to deploy the functions of smartgrid.

The functions of smartgrid are normally performed by some computer aided tools, which are called smartgrid applications and they are typically located at control centers of power systems [2]. These applications are also known as ICT applications of power systems [1], since they deal with data and information of such systems.

ICT applications acquire system data, which are provided by data resources of system. Such resources are distributed in the entire system. In control center, acquired data is processed; and accordingly, useful information about the entire system is obtained. In the same location, some "control applications" may make decision about system operation, generation and planning; hence, some actions are commanded by these applications. The control command resulted from these control applications are transmitted to the system actuators. Communication infrastructure of smartgrid is responsible for transmitting raw data from data resources to the control center, and control commands from control center to the system actuators.

Indeed, communication infrastructure of a power system acts as neural network of a human body while the control center of this system acts as human brain. Alternatively, the data provided by data resources of a power system is similar to the human sense. As in case of failure or mal-functioning of human neural network paralyzed may happen, failure of power system communication infrastructure may cause huge problems in system operation, generation and control. Consequently, especial attention should be paid to communication infrastructure, which is as important as electrical infrastructure itself [2]. These two infrastructures (communication and electrical) have become increasingly interdependent so that in the case of failure in each one, the other one may also become out of service [3], [4].

One of the most important ICT applications which is performed in generation and transmission level of power systems is Wide Area Measurement System (WAMS) [1]. In general, WAMS well-combines data provided by new data resources (e.g. phasor measurement units) together with the ability of communication systems in order to operate, monitor, and control a power system in wide geographical area [2].

Typically, WAMS consists of different modules which perform different functions about generation and operation of power systems. Sate estimation (SE) is basis module of WAMS since it provides creditable data from raw data measured by data resources [2].

The aim of this study is to introduce a new method for designing DCS in power systems. Such a DCS creates communication routes from data resources of an application (e.g. state estimation) to the control center. Since the intended application i.e. SE is kernel of the other ICT applications [2], implementation of this DCS will guarantee the overall performance of other applications.

The remainder of this paper is organized as follows. In Section 2, three interconnected sub-functions of smartgrid are reviewed. In the same section, the recent studies; related to the communication systems of power grids; are summarized as well. The problem is defined and formulated as a genetic algorithm problem in Section 3. A case study is illustrated in Section 4 and it will be solved by proposed algorithm. This paper ends with some concluding remarks in Section 5.

2 Smartgrid Sub-Functions

Generally, a smartgrid function can be divided into the three different interconnected sub-functions; data acquisition, data transmitting and data processing [1]. Data resources of system, communication infrastructure, and ICT applications are performed these sub-functions, respectively. The block diagram of ICT in power systems is illustrated in Fig. 1.

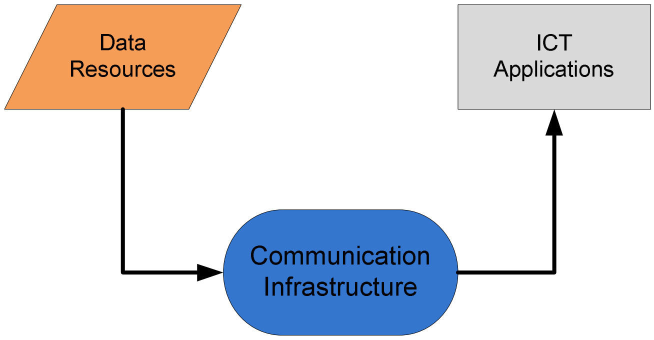

Fig. 1. ICT Block Diagram in Power Systems.

An inspection of Fig. 1 indicates that communication infrastructure provides efficient connectivity between data resources and ICT applications. It also provides connections between control applications and system actuators. It is noted that the latter connections are not shown in Fig. 1. This fact reveals that why a power grid that its elements communicate through a two-way communication system is defined as a smartgrid [1].

In this section, the sub-functions of smartgrid will be reviewed in the separate subsections.

2.2 Data Resources

Data Resources i.e. measurement devices are distributed in the whole system and are responsible for providing the inputs required for different ICT applications. Phasor measurement unit (PMU), supervisory control and data acquisition (SCADA), digital protective relay (DPR) and digital fault recorder (DFR) are some examples of measurement devices [1].

In recent years, one of the data resources, which has been commonly used in power systems, is PMU. In such units, to have a common time reference, times received from global position system (GPS) satellites are used for synchronization of measured phasor data [5]. The sample rate of PMUs may vary from 30 to 60 samples per second. Because of this high sampling rate, PMUs provide large amounts of data; and consequently, they need modern communication systems with medium to high bandwidth in order to deliver their data [6].

Phasor measurement units may cause simplification and changing of many smartgrid applications. On the other hand, installation of such measurements in all buses of a power system is a very expensive and money consuming approach. As a result, many researches related to the data resources are concerned with optimal placement of PMUs [7], [8], [9].

2.2 Smartgrid Applications

Smartgrid applications (i.e. ICT applications) are some computer aided tools which are normally performed in power system control centers. Such applications process data of power systems and obtain useful information of such systems. The raw data of a power system is provided by data resources of such a system, which are distributed in the entire system. Communication infrastructure of a smartgrid is responsible for data transmitting from data resources of power system (which are installed locally or at remote sites) to the control centers. Hence, one of the major tasks of smartgrid communication infrastructure is data delivery from local and remote sites to the ICT applications, which are normally located at central control center (CCC) or area control center (ACC) [2].

In control center, after obtaining information of a power system from raw data, some decisions about system operation, generation and planning are made. As a result of these decisions which are made by some "control applications", some actions should occasionally be performed by system actuators. Such actions are normally transmitted as control command through communication infrastructure. As a consequence of these facts, it can be deduced that another major task of smartgrid communication infrastructure is data delivery from control center(s) to the system actuators [2].

As previously mentioned, WAMS is most important ICT application which is performed at generation and transmission level of a power system. State estimation is kernel of WAMS applications by which the state of a system is estimated using a set of measurements and grid equations [3]. In a SE application, the observability of the system is of major concern. A system can be observable if the number of measured independent variables is equal with or more than the number of variables that should be estimated. However, this condition may not necessarily be adequate. The observability of a system is significantly related to the location of data measuring devices and the way they are distributed [10].

As described before, PMUs have been recently used as one of essential data resources for providing phasor data used for observability algorithms. When a PMU is installed at a system bus, such a bus is known as PMU enabled bus. In the case of installing a PMU at a system bus, bus voltage phasor and all current phasors of incidence branches are directly measured by this PMU. Hence, installation of a PMU at a bus makes that bus and all of its neighbors observable [7]. This has been considered as basic observability rule for PMU.

It is also previously mentioned that many studies which are performed in data resources field are concerned about the optimal placement of PMUs in the entire system. In such placement algorithms, the observability of the system is of major concern. As a result, many studies related to the PMU are placed such units in the way that the entire system is observable based on pre mentioned basic observability rule [7], [8], [9].

2.4 Communication Infrastructure

Communication infrastructure of a power system makes communication routes from data resources to the control center(s); and from the control center(s) to the system actuators.

As previously explained, new communication systems are designed based on open system interconnection (OSI) layer model. In this architecture, upper layers relay data, assuming that the lower layers work perfectly. In fact, this model is an effective architecture for explanation, design, implementation, standardization and use of communications networks. The OSI reference model consists of seven layers: physical, data link, network, transport, session, presentation, and application [1].

The first layer of these systems, referred as the physical layer, is a kind of medium that establishes the physical connection between transmitter and receiver. The characteristics of the communication systems will become seriously influenced by the characteristics of its media. As a result, the characteristics of the transmission media play an important role in communication infrastructure of a power system. Some main characteristics of a medium are as follows: cost, bandwidth, propagation delay, security and reliability [1].

While the communication system in a power system is crucial and mandatory, few researches have been performed in this field and most of them consider only the characteristics of such systems. In [11], various media used in WAMS including wireless links, telephone lines, optical fibers and power line communication (PLC) have been examined and their propagation delays have been calculated. In addition, the effects of temperature and sunlight on delay of optical power ground wire (OPGW) fibers have been studied in [12]. The communication infrastructure for strategic power infrastructure defense (SPID) project (which is done by EPRI) is designed in [13]. The communication network adopted in this research is an optical fiber meshed network in which the key nodes represent big utilities. In [14], Chenine *et al.* present the results of a survey on the communication systems and technical requirements for PMU based applications in a power system.

As explained above, the first layer of communication systems, referred to the transmission media, plays an important role in such systems. In our recent work [1], we have classified power grid transmission media into the two main group; dependent and independent ones. Dependent media are part of power network elements e.g. power line communication (PLC), broadband over power line (BPL), optical power ground wire (OPGW) and all-dielectric self supporting (ADSS). In contrast, independent media do not depend on the power systems and may be of the type available to all users as an open access media (e.g. wireless communication media) or those owned by data service providing companies (such as leased line or dark fiber provided by telecommunication companies).

In addition to the above facts, data resources of a power system are distributed in wide geographical area and many resources may be located at buses which are not covered by telecommunication companies. In these cases, independent transmission media (e.g. leased line) cannot be suggested for establishing communication infrastructure. Hence, due to the fact that power system buses are a part of electrical infrastructure and they are connected together by transmission lines; dependent guided media (e.g. OPGW) has become a more popular media in power systems, since they can connect buses to the control center in the case of lacking communications. OPGW, regardless of its high price, satisfies all of the communication requirements of smartgrid applications. Due to this fact, communication infrastructure of smartgrid, which is made by OPGW, may be very expensive. However, this is not only because of the expenses of its media but also because of the cost imposed by the necessity of live-line installation of OPGW links as a media [15], [16]. As a result of this high capital cost, the optimal plan of OPGW links should be planned in the way that all required communication routes are created.

To carry out above mentioned planning issue, first, we have introduced a new concept to the power system communication literatures; namely "Dependent Communication System". A Dependent Communication System (DCS) is made by one of the dependent transmission media; and consequently, such a DCS is a part of power system elements and usually is owned by system operator. As a result of this, DCS designing can be arranged as a planning issue in a power system. In the next section, we will define the DCS planning problem and the formulation for this problem will be addressed.

3 Problem Definition and Formulation

The aim of this study is to provide a new method for designing DCS in power systems. Such a DCS aims to create communication paths from data resources of system to the control center. In the current study, the locations of data resources of power systems are not of major concern; hence, we have used pre-determined measurements, which are previously located by one of the measurement placement algorithms. Consequently, in the first step of this investigation, we should choose the type of measurements and the locations of them. After that, suitable dependent transmission media should be opted such that all communication requirements of selected measurements are fulfilled by this media.

3.1 Determination of Measurements and Media

In the first step of designing DCS, the type and location of data resources should be determined. As previously mentioned, WAMS applications perform the tasks which are related to the generation and transmission. SE is kernel of WAMS since it provides creditable data from raw data measured by data resources. Hence, SE is a suitable choice for DCS implementation. On the other hand, it is also mentioned that in SE, observability of the entire system is of major concern and many investigations are placed PMUs based on system observability. As a result, a set of PMU, which are previously located for system observation, are considered as the location of the measurements.

On the other hand, it is previously mentioned that the sample rate of PMU is high and therefore, modern communication systems with medium to high bandwidth are needed to communicate data of PMUs. OPGW fulfills all communication requirements of PMUs. As a result, in this study, OPWG is used as dependent media for DCS implementation.

OPGW cables perform both the functions of grounding and communication. This kind of cable may be used in transmission or distribution lines. In transmission lines, OPGW is replaced with shield wire and is suspended above the lines [1].

3.2 Problem Formulation

Consider an n-bus; b-branch power system for which m measurements are taken. Such a system can be represented by non-oriented graph $G = (V, E)$, where V is a set of graph vertices (i.e. all system buses), and E is a set of graph edges (i.e. all transmission lines). The information of graph G can be represented by n-dimensional matrix (A), which is known as adjacency matrix described below:

$$a_{ij} = \begin{cases} 1\, if\ i_{th}\ bus\ conneted\ \ to\ j_{th}\ bus \\ 0\, otherwise \end{cases} \qquad (1)$$
$$a_{ii} = 0$$

In Addition to adjacency matrix, the lengths of transmission lines are needed and they can be represented by distance matrix (D). The distance matrix is similar to adjacency matrix in which any of its arrays represents the distance between two system buses.

The locations of measurements (i.e. PMUs) are predetermined by a placement algorithm and represented by an n-dimensional vector ($\hat{M}$) as follows:

$$M_i = \begin{cases} 1\ if\ \ a\ PMU\ \ is\ installed\ \ at\ i_{th}\ bus \\ 0 \qquad\qquad otherwise \end{cases} \qquad (2)$$

When the locations of system PMUs are determined, the system operator remains concerned about the planning of OPGW links that should be attached to the transmission lines in order to create communication routes to the control center. The control center may be geographically located anywhere in the system. Since all system data should be transmitted to the control center, it is obvious that the optimum design of the communication infrastructure in a power system also depends on the location of control center. In this paper, it is assumed that the location of control center is *a priori* determined as well.

Now, the locations of PMUs and control center (CC) have been determined. As previously explained, DCS is a part of power network. This indicates that in a power network, the vertices of a proposed DCS are some network buses; and alternatively, the edges of such a DCS are some transmission lines of such a power network. As a result, in an n-bus power network which has been represented by graph $G = (V, E)$, a proposed DCS composes a sub-graph $G_M = (V_M, E_M)$. G_M is also known as metrical sub-graph [17].

In above mentioned OPGW planning issue, the metrical sub-graphs that contain control center and all PMU enabled buses are accepted. It is perfectly clear that the minimum size of these metrical sub-graphs is optimal plan of OPGW. As a result, an optimization issue for prementioned OPGW planning can be defined as follows:

$$\begin{cases} Min\ \{E_M\} \\ s.t. \begin{cases} \{CC, \hat{M}\} \subset V_M \\ G_M(V_M, E_M)\, is\, a\, connected\ graph \end{cases} \end{cases} \qquad (3)$$

where, $G_M = (V_M, E_M)$ is a proposed metrical subgraph, V_M and E_M are sets of its vertices and edges, respectively, and $\{E_M\}$ stands for the total length of OPGW in the proposed metrical sub-graph. A graph is said to be connected if every pair of vertices in the graph are connected through some paths [18].

To be able to solve problem described in (3), one of the optimization methods should be applied. However, as designing of CI in a smartgrid is an offline problem, the speed of the solution algorithm is not important. On the other hand, because of the high price of OPGW, and its high installation cost, the accuracy of the solution will be of major concern. Therefore, genetic algorithm (GA) has been adopted as a solution algorithm. A brief summary of GA will be presented in the next sub-section.

3.3 Genetic Algorithm

The idea of GA is borrowed from genetics and natural selection. GA is a search method for traveling from one population to a new population. The populations consist of chromosomes i.e. strings of zeros and ones, and chromosomes are made by genes e.g. bits. In GA, particular type of objective function (called fitness function) has been used. A new population has been made by using selection operator together with two main GA operators; crossover and mutation. Basic concepts of GA and its main operators are described below [19]:

Initial population: In the first step of GA, many chromosomes are randomly generated. Occasionally, some initial chromosomes may be chosen in areas where optimal solutions are likely to be found.

Selection: The chromosomes of parents are chosen by selection process. The chromosomes with higher fitness have more chance to be selected. Roulette wheel and tournament methods are some selection operators which are commonly used.

Crossover: This operator interchanges subparts of two chromosomes of parents. The location of crossover is specified randomly. Typically, crossover operator is not used for all parents but is applied with probability P_C.

Mutation: This operator changes the value of a gene. The position of mutation is randomly selected by a probabilistic function. Similar to crossover, mutation is not applied for all parents. Small value of probability (P_M) is chosen for mutation of parents.

The stop condition: Generation of population and their evolutions are continued till this condition is met. The condition can be the number of generations, the value of the fitness function, the number of generations that the best individual is not change, and etc.

Heuristic Functions: Typically, some heuristic functions may be used in GA in order to increase the speed and efficiency of search process. For instance, choosing some initial chromosomes in initial population is a heuristic approach. Another heuristic function in GA is elitism. Such a function copies the best individual (or a few best individuals) to new population without any changes. Elitism can very rapidly increase GA performance, because it prevents losing the best found individuals.

The next subsection describes our proposed GA for designing dependent CIs of smartgrid.

3.4 Proposed GA

The proposed gene for an n-bus power network, represented by $G=(V,E)$, is an n dimensional matrix similar to adjacency matrix, which represents the locations of OPGW links in transmission lines. Thus, the arrays of this matrix can be defined as follows:

$$g_{ij} = \begin{cases} 1 & if\ OPGW \quad connet\ \ i_{th}\ bus\ to\ j_{th}\ bus \\ 0 & \qquad otherwise \end{cases} \qquad (4)$$
$$g_{ii} = 0$$

As described before, the price of OPGW cable and its live-line installation cost is very high. On the other hand, the total costs of OPGW and its installation are directly related to its length. As a consequence of these facts, the length of OPGW, represented by a gene, has been assumed as objective function in (3). The lengths of OPGW links represented by an individual are described by a matrix and it can be calculated by array multiplication of gene and distance matrices. The array multiplication (.*) is the array-by-array product of two matrices that have the same size. The distance matrix of a DCS, represented by a gene (g), can be calculated as follows:

$$D_g = g.*D \qquad (5)$$

where, g is a proposed gene, D is a distance matrix, and D_g stands for distance matrix of this gene.

Our proposed fitness function is total value of normalized OPGW length and penalty function which is described below:

$$fitness = \frac{\hat{1}^T.D_g.\hat{1}}{\hat{1}^T.D.\hat{1}} + Penalty \qquad (6)$$

where, $\hat{1}$ is a n-dimensional vector whose it's all arrays equal to one.

The penalty function results from constrain i.e. connected graph condition. Such a condition can be examined by breadth-first-search (BFS) algorithm. BFS traverse a graph by visiting all the nodes which are directly connected to a starting node [2]. The penalty function is calculated as follows:

- The control center of entire system is applied as starting node.
- For an individual represented by a gene, the paths between starting node and all PMU enabled buses are examined by BFS algorithm.
- For each PMU enabled bus, in which this path does not exist, the penalty function is increased by one.

An inspection of (6) reveals that if all PMUs can communicate to control center through a metrical sub-graph, the fitness function of this sub-graph equals or less than one.

4 Case Study and Simulation Results

In this section, a case study is described in order to demonstrate our approach. In power system studies, the IEEE test networks are well-known power networks which have been widely used for determining algorithms [20].

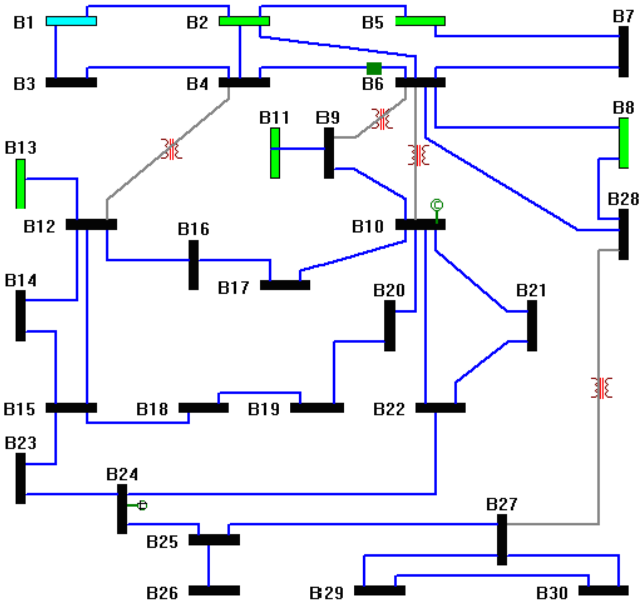

Fig. 2. IEEE 30 Bus Test Network.

4.1 Case Study Information

To carry out our investigation for designing DCS in a power network, the IEEE 30 bus test network is considered as a case study [20]. This network is depicted in Fig. 2.

The PMUs are predetermined and they are previously located at buses 2, 4, 6, 9, 10, 12, 15, 18, 25 and 27 by Xu *et al.* [7], and accordingly, the entire system has been observed by this set of PMU. Furthermore, we consider that the control center has been *a priori* determined and it has been 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 [20].

4.2 Implementation of Proposed Algorithm

The proposed GA optimization technique, describe in previous section, is applied in order to find the minimum metrical sub-graph in pre-mentioned case study. The population size is equal to 30 individuals. The tournament selection method is applied. Based on a trial conclusion, the probabilities of crossover and mutation are equaled to $P_C = 0.6$ and $P_M = 0.2$, respectively.

In our optimization method, two heuristic functions are applied as follows:

First, in the initial population, 29 individuals are generated randomly and one of the individual is assumed to be adjacency matrix of 30 bus test network. Such a matrix ensures that in the initial population, at least one feasible individual exists. This resulted from this fact that the individual represented by adjacency matrix is an OPGW plan which covers all transmission lines.

The second heuristic function is elitism. In each generation, five best individuals are transferred to the next generation without any changes. As a result, at the end of the optimization, in addition to the global minimum, we may have some local minimums that may be useful for system operators.

Since this optimization program is an offline issue and the speed of algorithm is not of major concern, we stop the optimization if the best individual is not change for 100 generations. The above search process stops in 267th generation since pre-mentioned "stop condition" has been satisfied. The evolution of best individual during generations is depicted in Fig. 3.

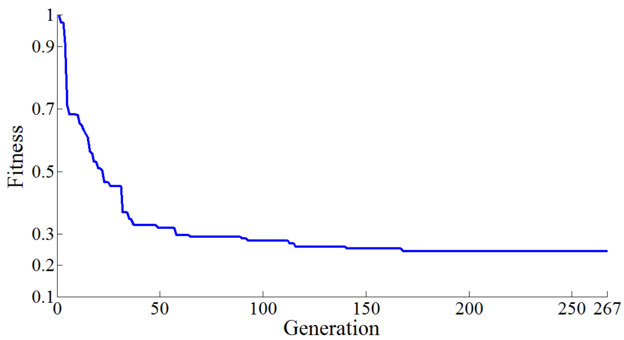

Fig. 3. GA Evolution for IEEE 30 Bus Test Network.

4.3 Simulation Results

As previously mentioned, the elitism is applied to proposed algorithm and five best individuals are transferred to the next generation without any changes.

The two of best individuals at the end of optimization are selected and depicted in Fig. 4. It is noted that the node numbers point to the bus numbers in IEEE 30 bus test system.

The fitness values of plan A and B equal to 0.2209 and 0.2367, respectively. If these values are multiplied by 100, the coverage percentage of OPGW for each DCS will be obtained.

As previously described, when elitism has been applied in a GA, in addition to the global minimum, the last generation may include some local minimums that may be of particular interest. The above information about the two proposed DCS indicates that although the plan A should be assumed as the best individual; and accordingly, it should be considered as the final answer, the total lengths of OPGW in these two plans are almost the same. Consequently, if some DCS characteristics (instead of or in addition to the OPGW length) are crucial and mandatory, the other local minimums can be suggested to the system operator. For instance, if bus 21 and bus 22 are next PMU candidates and they should be connected to the control center, the plan B (regardless of its higher installation cost) is assumed as final proposed DCS.

An examination of individuals during generation evolution indicates that many numbers of spanning trees have been formed by GA. Spanning tree is a loop free sub-graph in which every pair of its nodes are connected to each other by some paths of this tree [2]. Spanning tree formation is resulted from objective function and constraints described in (3) as follows:

Firstly, we know that objective function is minimiza-

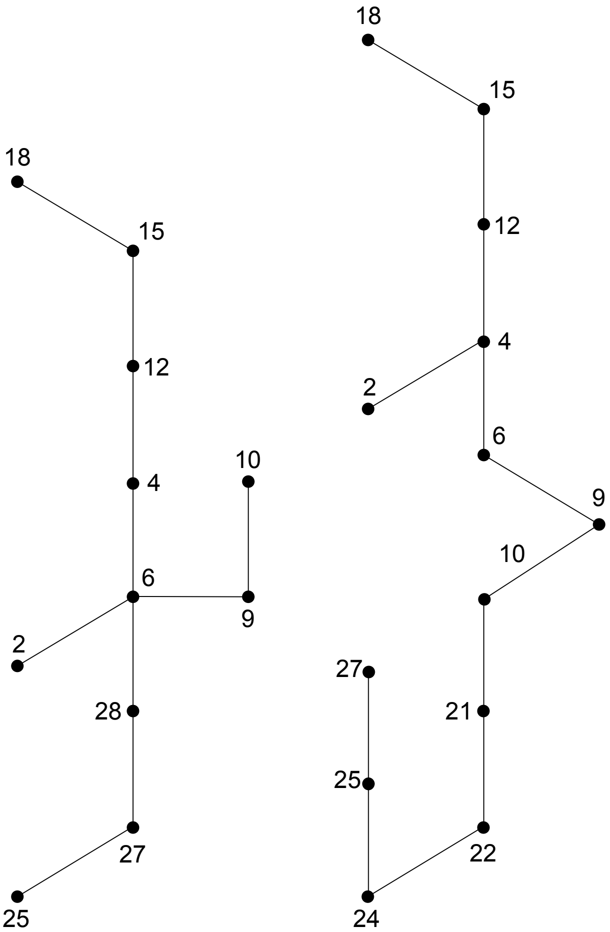

Fig. 4. Two Proposed DCS for IEEE 30 Bus Test Network.

tion of OPGW length. It is clear that the length of OPWG is directly related to the total length of metrical sub-graph; hence, GA tries to form loop free metrical sub-graphs by eliminating redundant and unneeded links.

Secondly, connected graph condition, which is derived from optimization constrain, creates a path between every pair of nodes in metrical sub-graph.

Considering two above properties, it can be observed that generation evolution of proposed GA forms spanning trees in which all PMUs and CC belong to their vertices. In general, if the initial population is large enough and GA is run for many generations, the proposed optimization problem finds a minimum spanning tree (MST) of OPGW. MST is one of the well-known approaches used for designing backbone communication networks [2].

To be able to provide an overall evaluation of proposed algorithm, three different IEEE test networks are considered and solved by our proposal algorithm. The information of IEEE 14, 57 and 118 bus test networks can be found in [20]. The locations of PMUs in each network are predetermined by Xu *et al.* in [7]. The control center location of each network is *a priori* determined as well and is assumed to be at bus 1 of each network. The information of proposed DCS for IEEE 14, 30, 57 and 118 bus test networks are shown in Table 1.

An inspection of above information in Table 1 reveals

TABLE 1
DCS INFORMATION FOR IEEE TEST NETWORKS

No. of Buses	No. of Links	No. of PMUs	No. of DCS Links	No. of DCS Nodes	OPGW Coverage Percentage
14	20	4	6	7	21.02
30	41	10	10	11	22.09
57	78	17	33	34	35.52
118	179	32	69	70	27.89

that in an interconnected power network, almost 25 percent of shield wires of transmission lines should be replaced with OPGW cables. As a result of this replacement, 55% of system buses and 35% of the number of system links are approximately covered by OPGW based DCS. As a result of this DCS establishing, the entire system has been observed by PMUs and all states of the system can be estimated by PMU based SE.

5 CONCLUSION

The term smartgrid refers to the next-generation, managed power system that integrates new measurement devices, digital control equipments, together with information and communication technology in the generation, delivery and consumption of electrical energy. The first and major challenge in smartgrid is establishing a two-way communication infrastructure for the purpose of data delivery among data resources, system actuators and control centers.

In this paper, a new concept has been introduced to the power system communication literatures; namely dependent communication system (DCS). A DCS has been made by independent transmission media (e.g. OPGW), which is typically attached to the power systems a part of those systems. As DCS is an attached part of power network and it usually owned by system operator, it can be optimally designed in conjunction of power system planning issues.

On the other hand, the functions of smartgrid are normally performed by some computer aided tools located at control center. Wide area measurement systems are some ICT applications which are performed in generation and transmission levels of power systems. State estimation has been known as kernel of WAMS applications since it provides creditable data from raw data measured by data resources of system. Phasor measurement units are new data resources that directly measure phasors of voltages and currents in power systems. They are widely used as data resources of SEs, recently.

This study aims to plan an OPGW based DCS in the way that all PMUs of system can communicate with control center. To do this, an optimization problem has been formulated in order to find minimum length OPGW plan on transmission lines. This problem is solved by GA, and consequently, the best plan and some other local minimums of problem are found by our proposed algorithm.

The simulation results obtained for a case study indicate that during the optimization process, the proposed algorithm form many spanning trees in which PMUs and control center belong to them. Although the minimum one of these trees can be assumed as the final OPGW plan, some other spanning trees (which satisfy the constraint) may be of interest.

The results also confirm that in an interconnected power network, almost 25 percent of shield wires of transmission lines should be replaced with OPGW cables. As a result of this replacement, 55% of system buses and 35% of the number of system links are approximately covered by OPGW based DCS for the purpose of full system observability. This confirms that the price of high speed, reliable and secure communication infrastructure of a smartgrid is considerable in comparison with the price of data resources.

Further investigations should be performed to consider co-optimizing of both PMUs placement together with placement of OPGW links in the network, simultaneously. Furthermore, the effects of independent media attachment (e.g. leased lines or dark fibers) across a DCS should be examined in terms of network cost, reliability and security.

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