Real Time Data Monitoring in Smart Transmission Grid Using Wireless Sensors

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Abstract: In this paper, the design of three stage hybrid architecture for controlling and preventing certain disturbances caused in transmission lines is studied. The transmission lines of modern power systems are equipped with WSN (Wireless Sensor Network). Since WSNs are capable of cost efficient monitoring over a wide range of geographical areas. Consequently monitoring of mechanical parameters of transmission line in smart grid is achieved. The hybrid architecture composed of three stages wired, wireless and cellular technologies. The main intention of this paper is to study the cost efficient monitoring of various mechanical parameters which affecting the transmission line in smart grid. The placement problem for the optimal placement of cellular towers is solved to minimize the installation and operational costs.

Key words: Hybrid architecture, placement problem, wireless sensor networks, transmission lines, operational costs.

1. Introduction

Power system operators need to operate the transmission systems under complex situations and atmosphere. So the current monitoring, analysis and control strategy for transmission networks may not be able to meet increasingly diverse challenges. Most of the transmission lines currently used is highly vulnerable to many forms of natural and manmade disaster, which can affect the efficiency and stability of the grid. Hence by replacing the age old transmission lines with good communication network, the transmission process can be improved. Wireless sensor based communication networks solves the following concerns.

Concerns like real time structural framework, accurate fault diagnosis by identification and differentiation of electrical faults from the mechanical faults, cost reduction, maintenance. The use of sensor network dealt with several other applications like mechanical state processing and dynamic transmission line ratings. By using wireless networks we can achieve faster delivery of enormous amount of highly reliable information. The proposed network is able to transport sensitive data such as current state of the transmission line and its control to and from smart grid. The main objective in this paper is to design a communication framework to transport enormous data in low costs.

By using SCADA (Supervisory Control and Data Acquisition) System in substations, the enormous amount of sensitive data can be communicated easily with faster response. In transmission lines, if any disturbance occurs it is difficult to repair other than substations and distribution stations. Due to its large geographical coverage area the task of locating the faulted area is very much difficult. The recent blackouts in U.S. and Northern India have shown that the failure to access and understand the condition of the power system. And delay in taking appropriate corrective actions after an outage can lead to widespread blackout of large areas of power system. Hence smart grids are equipped with extra communication networks to solve the above concerns.
Thus the features of the smart grid are discussed in order to provide better results.

The smart grid represents the full suite of current and proposed responses to the challenges of power supply. Because of the miscellaneous range of factors there are numerous competing taxonomies and no accord on a universal description. The features of the smart power grid are listed below:

- Reliability;
- Flexibility;
- Efficiency;
- Load adjustment;
- Peak curtailment;
- Sustainability;
- Bidirectional energy flow.

This paper proposes the use of wireless sensor network technology for detection of mechanical disturbances in transmission lines such as: conductor failure, tower collapses, hot spots, wind conditions, etc. The proposed design involves the installation of sensors for mechanical monitoring in predetermined towers of a transmission lines and communicate via wireless networks. The main goal is to obtain a complete physical and electrical model of the power system in real time, diagnose permanent as well as temporary faults and to make security for extreme mechanical conditions. And also placement of cellular towers in the optimal location is done so as to enhance low extreme installation and operational costs.

2. Related Work

Several works and proposals have been made to improve the state of art in deployment of multiple wireless sensors to monitor the various mechanical parameters. In this work the goal is to install the reliable wireless sensors in particular vulnerable location of the transmission lines. So the sensed data should be transmitted to the control centre via proper communication wireless networks [1]. Due to the vast geographical expanse of transmission line infrastructure, wireless networking provides a feasible and cost effective for monitoring of long distance transmission line.

In the previous papers studied, authors develop a quadratic equation based solution for finding the optimal locations of cellular transceivers the objective is to minimize the delay in information delivery [2]. We distinct this work on the following grounds:

(1) The framework formulated and presented by the authors in reference paper relies strongly on proportion [3]. The core network infrastructure and the cellular infrastructure are implicit to be symmetric and accessible at all periods. As well, it is implicit that all transmission towers are identical and transfer same quantity of data. However certain parameters bring in irregularity as enumerated below:

- Bare Cellular Coverage (due to unavailability of cellular towers in the region) or cellular outage;
- Variation in the content of data transmitted by the towers in space of its location or environment;
- Serrated terrain in certain regions of the transmission line limits the usage of wireless devices and forcing the use of cellular networks;

(2) The evaluation done before uses minimizing delay as a goal. While cost concerns are mentioned, deployment and protection costs are not used as factors restraining the number of cellular transceivers;

(3) The method used already is quadratic equation for optimal placement of cellular transceivers. Roots of quadratic equations are rounded off to depict the number of cellular enabled towers. This leads to erroneous outcome. Also factors such as latency and bandwidth affect the placement of cellular transceivers.

In this paper, we propose an optimal solution which minimizes installation and operational costs while satisfying all the constraints such as latency and bandwidth. We provide a generic presentation for enhancing challenges such as asymmetric flow bandwidth, irregular cellular coverage, etc. Further our proposed method also provides a cost optimal deployment of cellular towers.

3. Design of Wireless Network

For designing a robust wireless sensor networks many
factors such as latency, resiliency, security and bandwidth constraints are taken into account [4]. While low cost of these wireless sensors gains large scale installation and less safeguarding cost. Transmission towers are deployed in a linear arrangement sharing hundreds of miles. In order to provide smart communication bandwidth is required to provide intended data to reach its destination in a given time.

While performing literature survey for our studies, we came to notice that the two level models are, given for supporting the overhead transmission line monitoring applications [5]. But including the topological factors of the transmission lines, the less bandwidth, less data wireless nodes would fail to transfer huge amount of data in a multi hop manner. The hierarchical model suggested offers a very costly solution with the ideas of deploying cellular transceivers on every tower. And this network can bring extremely low data transmission, the model is cost ineffective and it gets huge installation and subscription costs. The main work is to suggest the problem of finding optimal allocation of cellular transceivers.

Fig. 1 shows the proposed framework of wireless sensors. While studying, large consequences in enumerating the array of challenges associated with monitoring the wide area network like transmission grid was faced. Necessary control and preventive measures have to be made while the sensors provide the faulted data and the physical structure has to be cleared immediately in short duration of time. The linear system topology proves to be a major challenge for wireless network design with respect to latency constraints and bandwidth constraints. Performance evaluation of the linear network model shows that successful delivery ratio of the packets from the nodes far away from the substation is found to be much less than that of nodes near the substation because packets from a farther node have to travel a longer distance and the rate of collision is higher [6]. The effective monitoring of a large transmission line network requires a hybrid communication infrastructure. This hybrid communications can be a combination of wired (copper cable) and wireless (cellular/IEEE802.15.4) standards to enhance the capability of the overall network to meet newer requirements based on emerging smart grid applications [7].

This paper formulates a hybrid hierarchical network design problem that can provide cost effective data transmission while at the same time respecting the bandwidth, delay, and connectivity constraints. We formulate a placement problem to optimize the number and location of the cellular enabled towers to significantly reduce the operational and installation costs while respecting all the constraints. The hybrid structure composed of three
levels of technologies. Thus the architecture is explained briefly in the following sections for future classifications.

4. Three Level Hierarchical Network

This paper proposes a hierarchical three level wireless network model for time critical applications. Each level is equipped with an array of sensors and transceivers with varied capabilities such that together they achieve the necessary behavior. The plan involves the setting up of a private WSN of low cost, low data rate links, utilization of the existing SCADA network, and a wide area network such as cellular network comprised of expensive but high data rate links. The proposed network makes use of the existing SCADA links (Optical fiber) for communication between substations and control center and strategically utilizes the existing cellular network for data transmission from certain transmission towers directly to the control center. A set of wireless sensors on each tower is installed as part of the private WSN.

Fig.2 depicts a power transmission corridor with large number of transmission towers, and two substations, one at each end of the transmission line, and a control centre. Each level of the network forms a cluster supporting many to one communication from all the nodes in the cluster to the cluster head.

The first level of the network is responsible for collecting information regarding the tower. It is composed of sensor nodes installed in each transmission structure forming a sensor array in tower (SAT). This SAT consists of an array of sensor modules such as tension sensors, accelerometers, temperature sensors, tilt sensors, motion sensors, vision-based sensors, and infrared sensors, etc.

Each tower is equipped with a more sophisticated relay node with improved computation and communication capabilities. Data from each sensor in the SAT is transmitted to the relay node. The relay node is accountable for compressing the data received from the SAT and transmitting it to the advanced level. The second level of the network is accountable for transmission of data from towers that are far away from the substations. Consider a segment composed of a few towers in the middle of the transmission line network. Data from these towers cannot reach either of the substations due to limited bandwidth of the intermediate wireless links. In such cases, enabling one of these towers with Cellular capability can provide a feasible solution as exposed in Fig. 2. It is to be renowned that it is not required to enable all towers with cellular technology. The second level is thus composed of segments of such towers transmitting their aggregated information to the cellular enabled transmission tower which acts as the head of their segment. The cellular enabled tower is a transmission tower equipped with an additional cellular transceiver along with the relay node. This cellular transceiver offers an alternative way to deliver the tower’s data directly to the control center through a high bandwidth, low latency cellular network. The third level of the hierarchical network is composed of a single cluster consisting of two substations and the cellular towers. The control center acts as the cluster head. Thus, level 1 operates at each tower; level 2 operates at the granularity of a group of transmission towers. The dimension of the group will be dictated by the wireless link bandwidth and the required end to end latency. Level 3 operates at the level of the whole network where substations and cellular towers transmit to the control center. Table 1 summarizes the characteristics of various communication standards used in this paper.
Table 1  Technologies Used and Characteristics.

<table>
<thead>
<tr>
<th>Properties</th>
<th>Optical Fiber</th>
<th>Cellular</th>
<th>Wireless</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type of link in the network</td>
<td>Substation to Control Centre</td>
<td>Transmission towers to Cellular towers</td>
<td>Between towers or Between tower and substation</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>10 Gbps</td>
<td>Uplink 75 Mbps, Downlink 100 Mbps</td>
<td>250 kbps</td>
</tr>
<tr>
<td>Delay</td>
<td>≈ 1µsec</td>
<td>≈ 50 ms</td>
<td>≈ 16 ms</td>
</tr>
<tr>
<td>Transmission Range</td>
<td>0 since they are already exist</td>
<td>100m-10km+</td>
<td>10m-1.5km</td>
</tr>
<tr>
<td>Installation Cost</td>
<td>≈ 1x</td>
<td>≈ 5x-20x</td>
<td>≈ 2x</td>
</tr>
<tr>
<td>Channel Contention</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Subscription fee</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
</tr>
</tbody>
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5. Placement Problem Formulation

In order symbols for placement problem formulation to provide cost optimized operation in delay constrained and bandwidth constraints linear networks, the Strategic placement of cellular transceivers becomes very crucial. While the cellular transceivers provide low latency, high bandwidth links, they are costly to install and the subscription charges can direct the operational cost of the system. On the other hand, the wireless Zigbee devices are relatively inexpensive but provide very low data rates. Thus, there is a tradeoff between cost and delay. In this section, we first explain our network model and state the placement problem. Next, we formulate a mathematical program to find the optimal location of the cellular enabled towers. Placement graph is shown in the Fig. 3. To make optimal placement of cellular towers it is necessary to study the following concepts:

1. Network representation: The transmission line is represented as a graph, $G = (V, E)$. $V$ gives the set of vertices and $E$ gives the set of edges in $G$. the total vertices in the graph is equal to $N + 3$. The set of communication links which can be wired ($SS$, $CC$), cellular ($k$, $CC$) or wireless ($k$, $l$), where $k$, $l \in N$. Each link is given by $(cij, Bijd)$. Where $cij$ is the operational cost and $Bijd$ is the total bandwidth of the network representation.

2. Placement problem account: $G = (V, E)$ and a set of $N$ flows find a feasible path for each flow hence the sum of the cost of all the paths is minimized. If the minimum path chosen by a tower node is $k \in N$ includes the edge of $(k, CC)$, then the cellular tower is placed on the $kth$ tower.

3. Placement problem declaration: The algorithms input is the transmission line of $N$ transmission towers and latency constraints, $D$. Table 2 shows different symbols for problem formulation. The placement problem can thus formulated as

Minimize:

$$f(Si, j, Yi) = \tau \sum_{(i,j) \in E} cijSi, j + \sum_{i=1}^{N} IC.Yi$$ (1)

Subject to:

$$\sum_{(i,j) \in E} li, j, kXi, j, k \leq D \quad \forall k \in N$$ (2)

$$- \sum_{(i,j) \in E} Xi, j, i = -1 \quad \forall i \in N$$ (3)

$$\sum_{k=1}^{N} \sum_{i=j}^{CC} Xi, CC, k = N$$ (4)

$$\sum_{(j,k) \in E} Xj, i, k - \sum_{(i,j) \in E} Xi, j, k = 0 \quad \forall k, i \in N, i \neq k$$ (5)

$$Xi, j, k - Xi, CC, k = 0 \quad \forall j \in SS, \forall k \in N$$ (6)

$$\sum_{k \in N} bkXi, j, k \leq Bi, j \quad \forall(i, j) \in E$$ (7)

$$Xi, CC, k - Yi \leq 0 \quad \forall i, k \in N$$ (8)

$$Xi, j, k - Si, j \leq 0 \quad \forall(i, j) \in E, \forall k \in N$$ (9)

$$Xi, j, k, Yi, Si, j \in \{0,1\} \quad \forall i, j$$ (10)

The main objective is to minimize the cost function given in the Eq. (1). The model consists of two types: installation cost and operation cost. In Eq. (1) the cost is the sum of operational cost at $\tau$ and onetime cost of installing cellular towers. End to end latency is restricted in Eq. (2). And Eqs. (3)-(6) gives the flow conservation constraints. In Eq. (7) the total flow on each link must not exceed the bandwidth. Eq. (8) shows the link of type $(k, CC)$. Eq. (9) Gives cost of link $(i, j)$. 

The problem formulated above can be solved by using Integer Linear Programming solver. To verify the correctness of the solution, the model is solved using CPLEX solver.
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Fig. 3 Placement graph.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Representation</th>
</tr>
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<tbody>
<tr>
<td>Bij</td>
<td>Bandwidth</td>
</tr>
<tr>
<td>D</td>
<td>Deadline</td>
</tr>
<tr>
<td>lijk</td>
<td>Latency kth flow on link (i,j)</td>
</tr>
<tr>
<td>bk</td>
<td>Flow bandwidth for node k</td>
</tr>
<tr>
<td>cij</td>
<td>Operational cost</td>
</tr>
<tr>
<td>IC</td>
<td>Installation cost per cellular tower</td>
</tr>
<tr>
<td>Yi</td>
<td>Binary variable. Is 1 if tower i is cellular enabled.</td>
</tr>
<tr>
<td>X i,j,k</td>
<td>Binary variable. Is 1 if k selects (i,j).</td>
</tr>
<tr>
<td>Sij</td>
<td>Binary variable. Is 1 if (i,j) used by any flow.</td>
</tr>
</tbody>
</table>

Eq. (10) provides decision variables are binary variables.

6. Simulation Results

To simulate the studies, use of the network simulator 2 is enhanced. This is a discrete event simulator. The results and discussions are made as follows. The network animator output in NS2, as shown in Fig. 4, gives the entire three level hierarchical network of the smart transmission grid. It shows the Control Centre, two sub stations, cellular towers and transmission line towers. The results are analyzed using the graphs shown below, which are obtained in the simulation.

Fig. 5 shows the effect of variation in end to end flow latency with respect to cost. Here consider the time scale of one SCADA cycle which is 4-8 s. The results show that in cases of very stringent deadline requirement ($\approx 0.1$ s), a cellular transceiver should be installed on each tower. At the time scale (40 s) the cost becomes constant because now the system is more bandwidth limited than latency limited. Fig. 6 shows the effect of variation in the number of transmission towers with respect to the cost. Given the linear structure of the transmission line, the cost decreases for certain number of towers when towers increases cost also increases approximately linearly with respect to the number of towers in the network.

Fig. 7 shows the effect of variation in cellular coverage and its effect on the installation and operational cost of the network. The Variation in the number of nodes can be devoid of any cellular coverage from 100 to 300 of the network size. The analysis of this nature helps in finding the feasibility of the wireless option in the cellular constrained areas. Fig. 8 shows the effect of operational period on the total
costs (initial installation costs and operational costs over the operational period). In case of fixed operational costs, total costs increase rapidly with increasing operational period. In case of adaptive costs depending upon link utilization the total costs reduce dramatically. This graph illustrates how different factors such as available link bandwidth, operational period and cost ratios affect minimum cost network design.

Fig. 9 shows the impact of link unreliability on network design cost. At lower link reliabilities, a path should consist of lesser number of links to maintain path reliability constraint. This leads to more cellular towers being deployed resulting in higher costs.

Fig. 7  Number of towers outside cellular coverage Vs Cost.

Fig. 8  Operational period Vs Cost.

Fig. 9  Path reliability constraints (Max links) Vs Cost.

7. Conclusions

The smart grid of the future is generally characterized by more sensors, more communication, more computation, more control, but a comprehensive conceptual architecture is seldom presented. The assumption of a certain generic configuration of more sensors, more communication, more computers, more control, from which try to lay out the total information picture. From that the objective of how the present applications can be enhanced and new applications be developed that will make the operation of the grid more secure and reliable is viewed. Finally, the layout of a systematic plan of transition from the present grid to the smart grid is studied. In this work, the transmission of time sensitive sensor data through the transmission line network in the presence of delay and bandwidth constraints are studied. The analysis shows that a transmission line monitoring framework using WSN is indeed feasible using accessible technologies. The anticipated formulation is broad and encompasses variation in several factors such as asymmetric data creation at towers, wireless connection reliabilities.

References