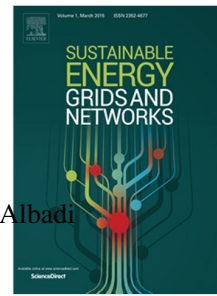


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Development of an Enterprise Geographic Information System (GIS) Integrated with Smart Grid

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ABSTRACT

This article uses a Geographical Information System (GIS) platform to create an on-line monitoring system in order to display real-time operational data measured at different points of an electricity network. The network with all its assets will be displayed on a geographical map. This provides the electricity utilities with a tool for monitoring, control, asset management, and demand side management in a smart grid. The system is tested as a pilot using the low-voltage network at Sultan Qaboos University (SQU), Oman. The article illustrates the pilot implementation of an enterprise GIS for application in smart grids, where the technical procedures of development phases of GIS data model and GIS web application have been described in details. The developed system produces spatial representation of the electricity network and its assets including renewable energy systems with their operational data on the map of existing electrical distribution network. It provides the utilities the ability to monitor the system components and their operation performance in real time with their location on a map.

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1. Introduction

Nowadays, power sector in many countries is undergoing critical transformation through the creation of smart grids (Hosseinzadeh, et al., 2016). Introduction of a smart grid leads to closer mutual interactions between electricity utilities and their customers, who are connected via distribution systems. Efficient functioning of these segments are essential for sustainable growth in power sector and the economy (Silva et al., 2014). One aim of developing a smart grid is to enable the coordination of Distributed Energy Resources (DER)s. Such coordination is possible through an architecture that empowers monitoring the status of the grid, and controlling the DERs and other resources (Angioni et al., 2017).

In the past, the evolution of the distribution network toward the smart grid model has been essentially focused on two areas: automation of the medium-voltage network and deployment of smart metering. In most cases a deep investigation of the low-voltage network has been left out. This network segment will probably be the most affected by regulatory actions promoting intermittent renewable generations and distributed storage (Barbato et al., 2017). There is a need to develop tools for monitoring this segment of the network. Practical approaches

using existing knowledge and commercially available technologies may be used to develop such tools. Geographic Information System (GIS) is a well-developed system that helps in abstracting physical features on the surface of the globe for the management, analysis, and display of geographic data. This data is represented by a series of information sets based on the specific project needs. Applications of GIS have demonstrated several new visions of decision making processes and information management and dissemination (Lin, 2017). Hence, GIS has been introduced to distribution companies for developing accurate database and improving power supply monitoring (Shin, Yi, Kim, Lee, & Ryu, 2011). Use of GIS enables distribution companies to easily access updatable databases which are required for monitoring and maintaining reliable quality power supply, efficient metering, billing and collection, and comprehensive energy audit (Environmental Systems Research Institute [ESRI], 2009).

In the last decade, several researchers investigated the application of GIS for electric utilities (Bock, 2006; Luan et al., 2015; Onyewuchi et al., 2015; Shin, et al., 2011; Short, 2013); GIS was used as a tool for demand side management in residential microgrid (Monika et al., 2015). Advanced application of GIS for wood pole asset management was reported in (Onyewuchi et al., 2015) where information on pole inspections and probabilistic pole loss estimates were integrated with

spatial data of poles in GIS to increase utilities' visibility into the vulnerability of their pole plants and improve emergency preparedness. In (Short, 2013), to help utilities to better plan and operate distribution circuits, a GIS data model for monitoring different phases of transformers and taps was developed by integrating Advanced Metering Infrastructure (AMI) measurements in GIS. In (Shin et al., 2011), a load analysis model using Internet GIS was developed to enable utilities observe the current situation in electric network for illustrative demand analysis, load management, monitoring the spatial load distribution, analyzing the relationship between customers load and possible outages. GIS has been used for wind characteristics and mapping (Palaiologou, 2011), too.

This paper explains the establishment of an enterprise GIS application, which can collect data from several sources, with reference to their location on a GIS map, in a control room. The developed platform will be very useful for different smart grid applications such as monitoring, control, asset management, and demand side management. The proposed platform, which is implemented at Sultan Qaboos University (SQU) in Oman, collects data from DERs that are installed in the University Campus, along with their accurate timing and location to a room remote from the two DERs. The server in the room can then make the data available on the web using a GIS Web Application that was developed and tested. This pilot implementation of enterprise GIS integration with smart grid provides spatial representation of the SQU renewable energy systems and their operational and asset specification data along with the existing grid distribution electrical networks feeding SQU. The system provides ability to control, search and analyze the historical information. In comparison to above references and conducted research, in this work a GIS monitoring system that provides on-line measurements of electric components on their actual geographic on a satellite map was developed and tested. This proposed solution can be used as an educational tool for teaching and professional training where the electrical configuration of a university campus has been illustrated on GIS and the real-time value of power flow of DERs production is trackable. This work offers a practical solution that does not rely on any simulation software, and stores real on-line measurement in a database. The simulation software can display real-time and historical data in various charts that can be further studied and analyzed for different research purposes.

In the rest of this paper, Section 2 provides an overview of the proposed methodology and Section 3 covers GIS technology and its application for smart grid. Section 4 describes the development of the enterprise GIS in two phases: I) development of the data model and II) the web application. Additionally, Section 4 presents the application of the developed system to the online monitoring of the DERs, and also, controlling, searching and analyzing the historical information. Section 5 discusses the project limitations and suggests future work. Finally, Section 6 summarizes the paper.

2. Overview of the Proposed GIS-based Monitoring and Control System

Fig. 1. shows where the web-based enterprise GIS fits in the general concept of transforming a conventional grid to smart grid. This transformation necessitates replacing the old electromagnetic meters with smart meters, automating the electric system by installing sensors

for tracking purposes and equipping it with advanced protection devices. Also, tools are required to study how demand can rely on intermittent resources and prosumers in the power network. To have a system setup for on-line monitoring and control, the spatial data of each electric component needs to be built and retrieved by enterprise GIS web application. The procedure of building Enterprise GIS Web based is described in detail in the following sections of the paper.

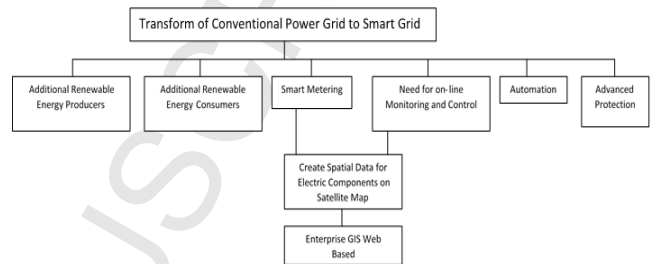


Fig. 1. GIS-Based Monitoring and Control System as a component of a smart grid

The proposed work offers several advantages to distribution utilities to monitor the grid in real time over the satellite maps where each electrical component has been drawn in its geographical location. Currently, distribution utilities use SCADA that provides the status of electric system over single line diagrams (SLDs). As Fig. 2(a) shows, SLDs provide information about the connection configuration of electrical components. However, having GIS in conjunction with system analysis tools, Fig. 2(b), will improve the visibility of the network; therefore, improves the performance and increases the system operation efficiency due to reduced maintenance frequency and duration that can be achieved as a result of rapid outage identification. The proposed application provides a user-friendly management system to the renewable DER. The user can see measurements of the electrical quantities such as voltage and current on several points of the system. In the developed system, the user can track energy production on-line and get real-time statistical and analytical reports on different parts of the network as well as production information of DERs.

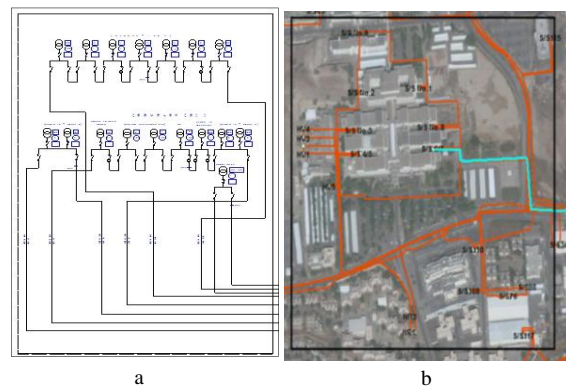


Fig. 2. SQU HV Network (a) SLDs, (b) GIS-Based Monitor

3. GIS Enabling Technology

GIS is a computer program that integrates three main parts of information, system software and system hardware to enable presenting, investigating, managing and capturing all types of geographical-referenced information obtained from navigation systems such as Global Positioning System (GPS). GIS integrates five main components needed to perform GIS task: system software which provides the functions and tools to store, analyze and display geographic information including a database management system, system hardware which is a key factor to the output type and processing speed, people who develop the procedures and define the tasks in GIS, procedures to produce correct and reproducible results and data to be mapped and analyzed (Meehan, 2007). During the past decade, huge amount of GIS data became available through the internet and much of it is free. However, it is critical to apply accurate data from right sources and design precise models and maps to enable good decision making (Luan et al., 2015; Short, 2013). Hardware technology infrastructure to support GIS implementation is determined based on system requirements. Using web services requires the minimal investment for GIS infrastructure, whereas an enterprise GIS application needs careful development and a significant investment on different phases such as computerization, networking and database connectivity (Meehan, 2007). GIS softwares can be classified based on their applications. For example, ESRI supplies GIS software based on user task from simple mapping tools, ArcGIS Desktop, to high-end technology software to manage complex systems such as ArcGIS Server, where IT and GIS professionals manage, secure, and share geographic content. These services can be consumed in desktop, web, and mobile apps ArcGIS for server connection with relational database management systems and supports on premise, cloud, virtual, and hybrid deployments (Elkadiri et al., 2014; Krouk, 2011).

3.1. Application of GIS in Distribution Utilities

To improve reliability and efficiency of a distribution system, establishing a well-set and firm communication network is essential. By increasing the size of electric network and its complexity, integration of geographical context with grid model becomes crucial. Having GIS in conjunction with system analysis tools simplifies project management for maintenance and fault occurrences in a distribution system. The identification of the geographical location of an electric network and equipment helps in network improvement and also monitoring commercial procedures; for instance, network planning, maintenance connection, repair operations and expansion in the electric network (ESRI, 2009). Integrating GIS with Supervisory Control and Data Acquisition (SCADA) can improve communication network performance in electrical grid. Enterprise GIS is a platform that supports an electric utility IT system by creating spatial information for utility resources and providing this information to the enterprise. The core system applications combine the data provided by SCADA, GIS and consumer billing/financial systems along with other outside sources such as weather systems and traffic image (Balakrishna et al., 2014).

3.2. The Importance of Enterprise GIS for a Smart Grid

Smart distribution grid is a concept of having an intelligent electric distribution system, which responds to specified requirements and communicates with electric customers directly. Some features of a smart grid are management of electric loads in a more efficient way, improvement in automation and in system restoration after an outage incident, and development of more mutual interactions between energy sectors and consumers (Platform, 2010). Also, smart grid facilitates monitoring, control, and energy management of renewable energy sources. GIS creates data foundation for utilities to improve their engineering analysis, outage management, and customer service (Datta and Mohanty, 2013). Enterprise GIS will help management of data by allowing utilities to gather condition data from desktop, server, and mobile components. By using GIS, the relation of electric system and the environment can easily be identified. Utilities use GIS tools for advanced tracing and network modeling and studying the association between electric networks. GIS presents complete state of the grid in a realistic model. Utilities can use GIS to define the best location for sensors, communication cabinets, poles, etc. Fig. 3 (Balakrishna et al., 2014) shows a configuration for an enterprise GIS-based dispatcher.

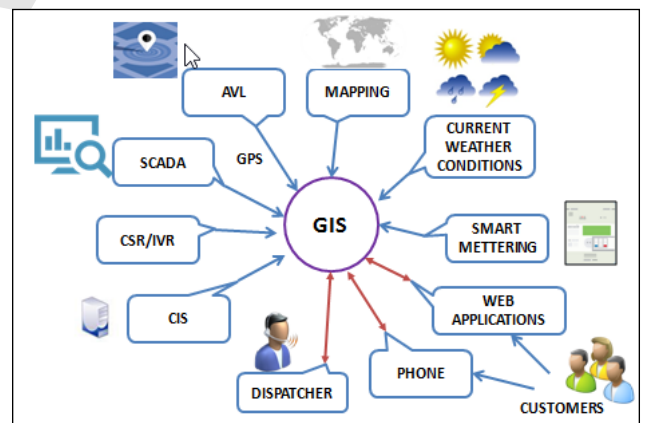


Fig. 3. Configuration for Enterprise GIS-based dispatcher (Balakrishna et al., 2014)

4. SQU Pilot Implementation of Enterprise GIS Integration with Smart Grid

Oman's power sector infrastructure is facing strain as a result of the country's industrial expansions and population growth. In the Main Interconnected System (MIS) of Oman, the supplied electricity grew from 8,402 GWh in 2005 to 25,513 GWh in 2015. During the same period, the peak demand increased from 2,395MW to 5,472MW (Albadi, 2017). The steep growth in demand requires continuous addition of capacities. The MIS peak demand is projected to grow at a rate of 8% each year to reach 9,529 MW in 2022 (OPWP_Oman, 2016). Based on expected demand in near future, shortage of gas resources and the availability of solar and wind energy resources in Oman, the contribution of renewable energy resources in the generation supply mix is expected to increase. In September 2017, the Council of Financial Affairs and Energy Resources mandated the target of having 10% renewable energy of total supplied electricity by 2025. Moreover,

Oman power utilities have set several expectations such as improvement of revenue, improvement of performance, reduction of customer complaints, good billing system and information collection, and reduction of outage time. Besides, it is essential to produce electricity from renewable energy sources to secure future electricity supply in Oman. To reach these objectives, it is suggested that Oman conventional electric network be converted to smart grid in carefully planned steps. In this conversion, the implementation of the enterprise system to boost the network performance is recommended. The implemented pilot Enterprise GIS integration with smart grid at SQU can be easily upscaled for implementation in electricity utilities. The developed GIS enterprise system in this paper, provides ability to control, search and analyze the historical information of the system under study. This pilot implementation of the GIS platform was carried out in two phases of development, GIS data model and GIS web application. In the first phase, the GIS data model of SQU renewable energy system with all its components, such as wind turbines and photovoltaic cells and also configuration of distribution and primary station components layout was built in the ArcGIS software. In the second phase, the developed GIS model in the ArcGIS software was presented as a web GIS solution.

4.1. GIS Data Model

The data model is a structured way of describing the data needed in a workflow. Unified Modeling language (UML) is the standard format for most data models. The purpose of the data model is to capture in one document three essential components of data used in the workflows and process models: the attributes, relationships, and behavior. An example of attribute is wind turbine specifications such as speed. An example of relationship is how a wire is connected to an electrical distribution panel. An example of behavior is whether a material type is valid for a power station. Some of the data needed in a workflow may come from outside the utility such as street data, buildings data, railways crossings and rivers (Meehan, 2007).

The GIS data model represents objects with defined boundaries on the surface of the earth as point line and polygon. GIS data sets of any undertaken study can be created, modified, displayed and explored in a GIS software where the user can allocate symbols and generate map layouts for publishing/printing. The Geodatabase and the GIS Data Model for SQU electric network has been developed in Arc Catalog where all data sets were identified and then edited in ArcMap. In ArcMap, various data sets have been added for the electrical network, land base and buildings with flexibility to add more data layers according to users need. The main data set included are the electrical and renewable energy data like transformers, substations, solar panels, wind turbines and other components. The Modeling procedure is described here to provide a clear view for the process.

4.1.1. Geodatabase

Geodatabase is a vector data storage format. It is a collection mechanism of datasets, feature classes, and related attribute tables. While the data model describes the structure of the data to be used in the enterprise GIS, the geodataset is the data itself. A data set is conceptually similar to a coverage, it encompasses a defined spatial

extent and holds feature classes that typically share some sort of topological or attribute relationship. A feature class contains both the spatial and attribute data for geographic features. Geodatabase may contain several feature datasets and related tables and has mainly two formats: a personal geodatabase which is actually a Microsoft Access Database file and enterprise geodatabase which is accessed by GIS through a spatial data base engine (ESRI, 2015; Meehan, 2007).

4.1.2. ArcMap Basemap

ArcMap provides the context and framework for working with geo data which is called basemap layer. Basemap layer is a collection of map layers which uses for locational reference and provides a continuous visual background on which users draw, edit and analyze their operational data (ESRI, 2016b). ArcMap provides different types of basemap that can be added as a layer in geographic information model such as: World Imagery, World Street Map, World Topographic Map, Light/Dark Gray Canvas Map, National Geographic Map, World Oceans Map, and Terrain with Label Map. This project uses Imagery Basemap where satellite image of SQU campus can be zoomed to visualize SQU buildings, roads and electric substations.

4.1.3. Conversion of CAD to Geodata

The SQU plots (buildings and roads) were stored in the form of CAD drawings and it was required to get use of this data in GIS. ArcMap plus Arc Toolbox supports Multi CAD to Geodatabase (GDB) conversion tools. Users can change the CAD data to shape file depending on the need. In the GDB, the data should be stored in different geometry formats, lines, polygons and points. The user should identify the layers properties, which are going to be transformed from CAD to GDB in ArcMap. For example, the cables are transformed and loaded as lines and the buildings as polygons (ESRI, 2010). Another essential step before adding the CAD data to ArcMap is the projection. Each geographic information should be projected to the same Zone where the geographic data resides. The SQU CAD data was projected and referenced to Oman Zone, thus the data was projected to UTM Zone 40N for Oman and similarly the GDB where the CAD data will be loaded. The projection systems are available in ArcMap in the form of '.prj' files which are predefined and easily identified. The SQU CAD files passed with a cleansing stage where the unnecessary layers and blocks that are not required in GIS were purged.

4.1.4. Conversion of Single-Line Diagrams to Electricity Network

Technical information about electric grid and energy systems in SQU were added to the ArcMap, having built the fundamental layers of buildings and roads. SQU electric network contains two primary stations; Primary Station A (33kV/11kV) and Primary Station B (33kV/11kV). The single line diagrams (SLD) is the blueprint for a three-phase power system analysis which clearly demonstrates how the main components are connected (Mulley, 2004). The SLDs of both primaries show their configurations, internal connectivity, and distribution of feeders. The SLDs of primary stations show how the main electrical elements such as circuit breakers, transformers,

capacitors, bus bars, and conductors are connected. They also give information about the transformer rating, number of transformers in each station, the number of rings and their names in each station, substation names which are fed by each ring and ring path from a primary station to different substations. In addition to the data retrieved from both SLDs, the geographic paths of electric cables were obtained from CAD drawings of the SQU HV network. These data were converted into spatial information and added as layers into ArcMap. Fig. 4 shows GIS data model of electric network in SQU where 11 kV electrical cable network throughout the university is in orange color, 33 kV network is in green color and also all of the connected substations in the network are blue color polygons. There are more than a hundred of distribution substations feeding different departments and laboratories in SQU. In each substation, there is a transformer and several protective devices such as switches, breakers, fuses, etc. In the ArcMap, all the electric elements are shown by standardized schematic symbols in their actual spatial location. Obtained map can be considered as a vital roadmap for all the testing, service and maintenance activities. In this model, each of three phases is represented only with one conductor. Fig. 5. highlights the trace of feeders between primary stations and substations. In this work, we made it possible to measure the power flow and show them in their actual locations in real time. This is one of the main features of the developed GIS for monitoring the electricity network.



Fig. 4. Entire SQU HV (11kV) Network in ArcGIS Software

4.1.5. Creation of Geodatabase and Configuration of Primary Stations

The geodatabase consists of several types of geographic datasets held in a common file system folder or multiuser relational database such as Microsoft SQL Server. The fundamental datasets in the geodatabase are feature classes, raster datasets, and tables. The developer usually starts designing and building a geodatabase by creating a collection of the stated fundamental dataset, and then may add some advanced capabilities to geodatabase such as topologies, networks and subtypes to model GIS behavior, work with spatial relationships and maintain

data integrity (ESRI, 2008). Each feature class consists of the geometric shapes and its descriptive attributes. The most common type of feature classes used in the geodatabase are points, lines, polygons, and annotations. In addition to a geometric shape, its properties also can be defined such as whether it is single part feature or multipart. The raster datasets store attribute value and location coordinates in the ordering of the matrix, which is the spatial representations of geodatabase.

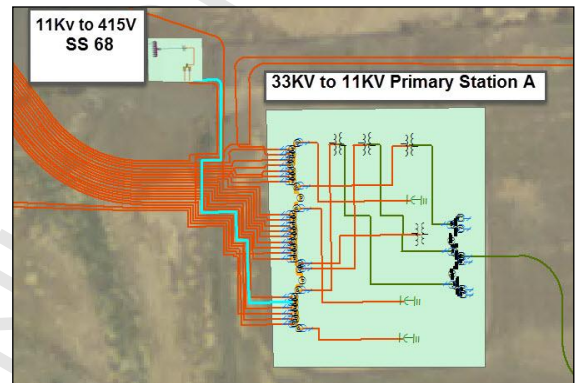


Fig. 5. Tracing Ring 8 from Transformer 3 in Primary Station A to Distribution Substation number 68 located in SQU

The attribute table is a tabular file which contains information about a set of geographic features in the database where each row represents a feature and each column represents an attribute. In SQU geodatabase, substation feature was represented as polygon, busbars and electric cables as lines, and circuit breakers, fuses, transformers, capacitor banks as points, and so on. Then, several attributes were created to indicate different characteristics of each electric feature, which are non-spatial information, and saved in a table and linked to the feature by a unique identifier. The information contained in the database needs to be accurate and up to date. Thus, ArcMap allows the user to edit the attributes of the features displayed on the map.



Fig. 6. Configuration of SQU Primary Station A

To configure the layouts of distribution and primary stations in SQU, part of the required information is obtained from SLDs such as number of transformers in each station, the number of rings in the primary stations, interconnection between different busbars, and number of circuit breakers and their connections. In addition, the electric utilities standards and connectivity rules are followed to model, create and convert the interconnection between electrical network features on different levels 33kV, 11kV and LV in ArcGIS software. The geographic data in ArcMap was actual and mapped on real coordinates. For example, the assets distribution within the boundary of a primary

station was mapped in a way that reflects the real assets distribution on site. Similarly, the transformer locations and switchgear rooms are shown in Fig. 6, where the locations of transformers and other assets are mapped on their actual locations as shown on the satellite image. The colors of layers and representation of some features were selected in line with utility standards which ensures the best visualization for the end user.

Fig. 7 shows that each primary station contained two main busbars, the 33KV and 11KV busbars and those are represented in black and yellow colors, respectively. The protection and control devices were symbolized in technically logical and an easy-to-use and easy-to-view way regardless of their physical dimensions. The sequence of the outgoing feeders and rings was configured based on actual configuration and remained in the same order. Similarly, the number of transformers and capacitor banks and other assets were determined.

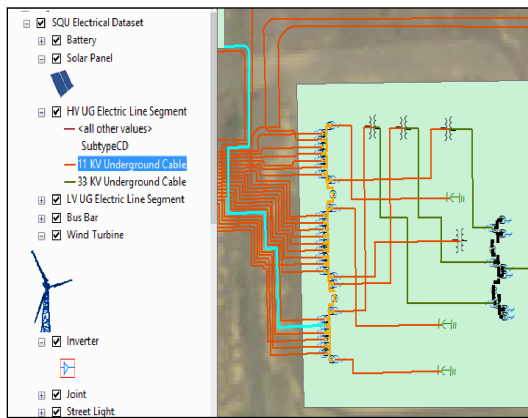


Fig. 7. ArcMap snapshot of Electric Data Set

4.1.6. Geodata for SQU Distributed Energy Systems

Two DERs were designed and built in SQU. One of them is located in the Electrical and Computer Engineering (ECE) Microgrid Lab and integrates the RE production of a set of rooftop PV panels, a wind turbine and a battery bank with the grid. The configuration of this system is shown in Fig. 8 where the output of PV panels is stored in a battery initially and then via hybrid grid inverter into a bidirectional meter. The power output from the wind turbine is directed to the meter through a separate inverter. If there is a load in the ECE Microgrid Lab, the total produced energy is firstly transferred to the load and then fed into the grid via a distribution panel (DP).

The second DER operates in a building which is named Eco Friendly House (the Eco-house) located in the SQU staff residential area. The Eco-house is a highly energy-efficient house that is designed to address the local climatic environment constraints in Oman and supports green architecture and sustainability (Engineering, 2014). Fig. 9 illustrates the configuration of the energy system in the Eco-house. In this system, main DP receives the solar energy output of the rooftop PV panels via three-phase 20 kW inverter concurrently with the electricity from the SQU grid. Thus, the load in the Eco-house firstly consumes the produced solar energy from PV panels and if extra power is needed, it is taken from the SQU network.

To create the GIS data model for the aforementioned smart energy systems in SQU network, a number of features were created to represent different RE electric components in ArcMap environment such as solar panel, wind turbine, battery bank, inverter, meter and a load (a motor). The online layout for GIS data model of ECE Microgrid Lab is shown and described in detail in the following section.

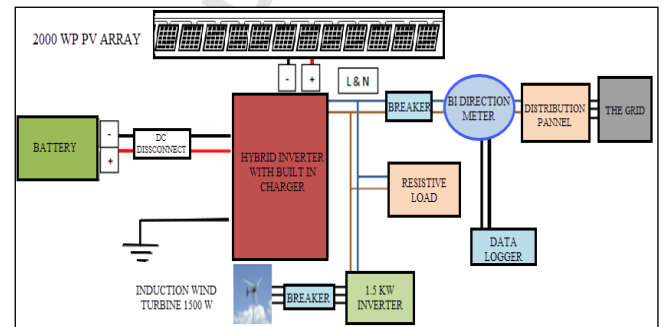


Fig. 8. Microgrid Energy System Layout

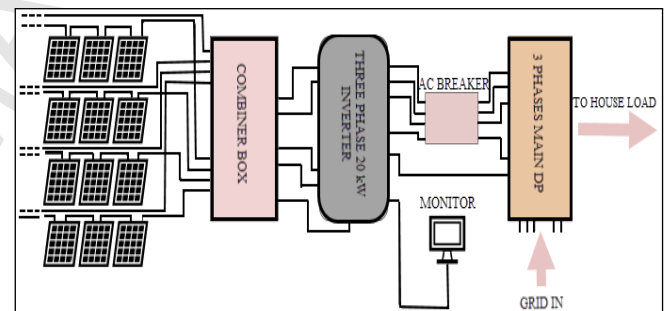


Fig. 9. The Eco-house Energy System Layout

4.2. GIS Web Application Development

Web GIS uses a wide variety of resources to design and create a type of distributed information system which is comprised of at least a server and a client which can be a web browser, desktop or mobile application. Through the internet, the information is accessible over the web, ignoring how far away the server and client are from each other. Therefore, GIS web introduces significant advantages over traditional desktop GIS, including a global reach, a large number of users, better cross-platform capability, low cost as averaged by the number of users, easy to use, unified updates, and diverse applications (ESRI, 2016a).

4.2.1. GIS Web Architecture

The GIS application presented in this paper is leveraging the power of ASP.NET MVC along with HTML 5 and also advanced Java Script Libraries like: JQuery and Dojo. This application uses SQL Server Database as the main repository containing user information and smart energy systems readings from the Eco-house and ECE Microgrid Lab. As Fig. 8 illustrates, using LabVIEW, the energy measurements of the smart energy systems are directly read from their sites and then

transformed to a specific folder on the main integration server inside SQU network via the Google Drive.

Time synchronization is a very important aspect in all distributed systems (Zhang et al., 2013). A distributed measuring system is proposed in (Rinaldi et al., 2016), which uses a communication infrastructure to interconnect meters and it has a cost-effective network-based time synchronization instead of costly GPS solutions. The proposed distributed system for monitoring of voltage dips has been deployed in a real distribution grid in Italy. The SQU web application as a real-time system has a computing system that guarantees a response for reading on-line data for strict time constraints. Real-time data acquisition system shown in Fig. 10 retrieves data from two energy systems, where the Eco-house is connected to external network and ECE Microgrid Lab is connected to SQU local network. To show live data in the web application, CSV processor as a data storing service can contain an algorithm to synchronize the on-line data which provides a common timescale for individual systems to accurately synchronize the internal clock offset and drift. CSV processor automatically and continuously checks the shared folders for any new readings (stored in CSV file) every two minutes, parses the readings and stores in the corresponding tables in SQU centralized database. In case the CSV processor does not receive new records after the specific time, a 'failure message' will be shown in the online layout instead of live message. Application server reads the data directly from SQU SQL server database and displays the real/historical readings to end users on the application web interface.

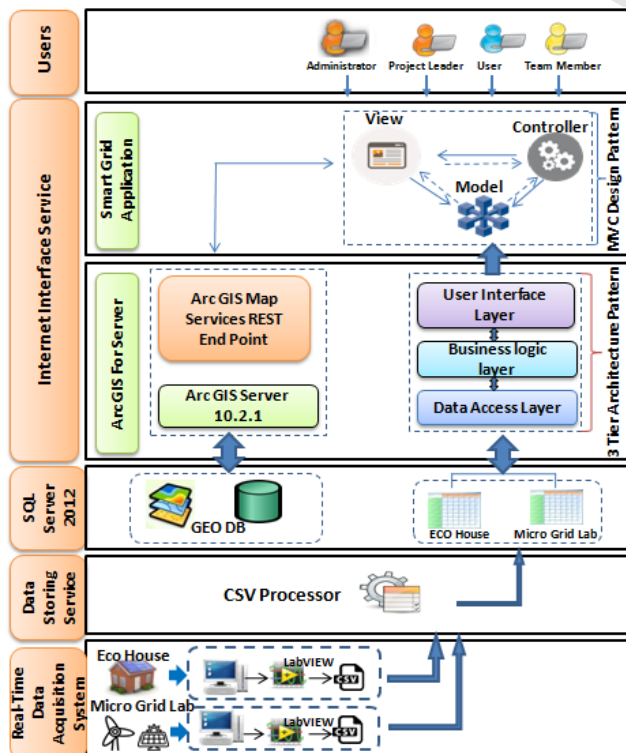


Fig. 10. System Architecture for SQU Web Application

SQU Geodata also resides in the same centralized database server. Geodata publishes to the web as a Map Service by leveraging the

power of ESRI ArcServer. The end users of the SQU web application use the map services which are consumed in the application. The ArcServer also manages the process of Map Printing through its Asynchronous Printing Service.

4.2.2. Solution Features

The web application shown in Fig. 11 provides a set of functionalities that serve the project needs in different ways. These features include users' registration, login, visualizing GIS layers from the web, features legend, bookmarks, asset labels, find tool, print tool, charts and statistics.

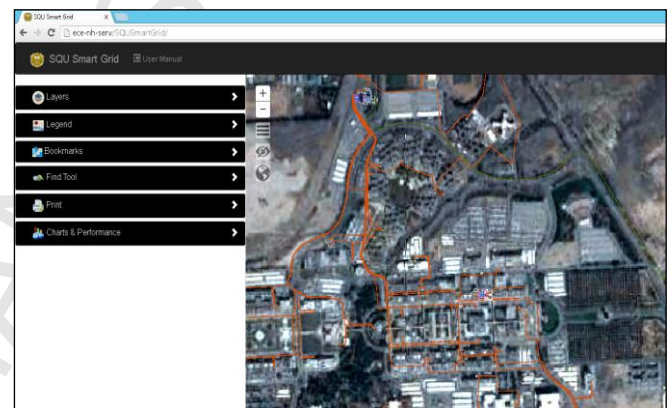


Fig. 11. SQU Web Application with all features enabled

End users can register to SQU web application at any time; thus, it was essential to specify some roles and add some credentials and restrictions for each user type. The project leader is the one who has the full privilege to access full solution and he assigns the roles for each of the other users. After each registration, a request will be forwarded to the team leader to reject or approve the request and assign the role. The Leader will evaluate the request and assign an administrator, team member, or a user role in which the privileges vary with each role.

As Fig. 12 illustrates, the layers were added to the web application to enable the user to identify each of the layers available on the map in addition to the legend. The web application was developed to be user friendly allowing to toggle off/on any of the layers available on the map, change the visibility range, pan, zoom in/out, the satellite image and full screen view. All the features are labeled and the name of each feature can be viewed by pointing to it which provides a better understanding for the available layers.

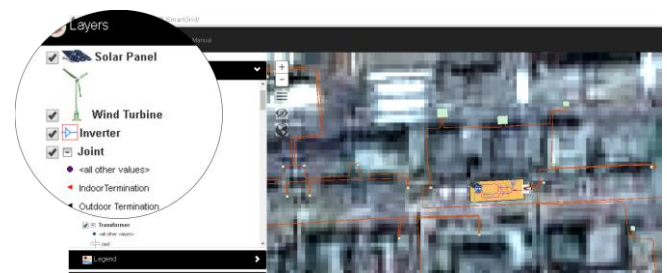


Fig. 12. Toggle layers' visibility

In SQU application, bookmarks allow users to easily navigate to predefined map extent. Two main bookmarks, one for the Eco-house and the other for the ECE Microgrid Lab online data were saved in the application. The DER system components inside the Eco-house and ECE Microgrid Lab were presenting the output power measurements via labels containing the online live data of output power and additional current and voltage measurements. Fig. 13 shows the online layout for smart energy system in the ECE Microgrid Lab integrated with live measurement data of the solar panels, the wind turbine, the battery, the load and power exchange between the grid and the Microgrid DP.

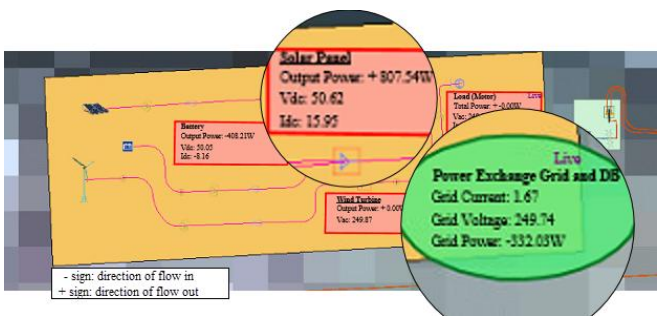


Fig. 13. ECE Microgrid Lab online layout

According to the utility standards, the designer usually configures some of the repetitive features in one feature and adds their number as a variable attribute. One example is the photovoltaic modules case in SQU where 12 PV modules, residing on ECE microgrid lab roof, were abstracted by one module and user could identify the actual number of modules in the attribute table of this feature. In this system, DC power produced from two sets of six PV modules charges the battery installed in the system and then a total DC power is inverted to AC power. The combination of production from the PV panels and the wind turbine is used by the load installed in the Microgrid Lab and the extra power is provided into the grid.

The records are updated every 2-minute time interval and stored in the data base, the application is set to update the online data automatically whenever changed to keep showing the most updated records. If no records were found within the set time interval, then the labels would generate a "Fail" message to indicate that the live data were not available.

The web application allows users to search the attribute data of modeled feature classes within SQU Geodata via find tool. The search results are displayed in a table at the bottom of the map, and users are able to investigate all features attributes being listed, and they are also able to zoom to any of the result and so navigate directly to the asset or feature containing that attributed information. SQU web application provides a printout facility in which the user can print any part of SQU map network at any given extent in the SQU predefined template.

One of the key features provided by the SQU web application is the charts and statistics tool. Through this tool, the power flow values of photovoltaic modules, wind turbine, load and grid power plus the voltage of the battery were presented on a graph demonstrating power over time and voltage over time in the case of Battery. Five charts represent RE power values and battery voltage in ECE Microgrid Lab

and three charts of the Eco-house. Fig.16 illustrates how graphs can be extracted from the saved data in the server. The figure shows how solar production in its peak time is added to the grid power entering to the ECE Microgrid Lab. It can also be seen from Fig. 14 that the wind power is not a promising resource in the place where SQU is located. However, the production of wind turbine in the energy system can be used to charge batteries over the night where it is more windy and there is no sun to charge batteries.

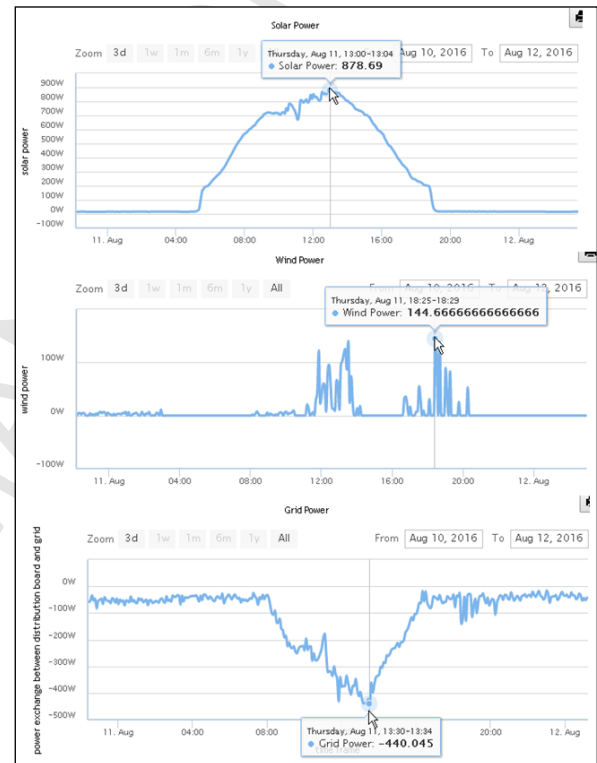


Fig. 14. ECE Microgrid RE Production in One day and its effect in the Grid input as taken remotely from the web-based GIS

The charts are updated automatically every 2 minutes to keep most updated information. The tool enables the user to represent historical data on charts for one week, or one month or simply choose a time interval and represent the related data over the graphs. In a similar manner to the map network, the charts could be printed on SQU template according to the type of use.

In the context of a smart grid, this system will be the main building block of a real-time monitoring system, which provides live operational data of each component of the system with their locations. It can be used in various applications. For example, it can be used for monitoring the power assets and adjusting the system controllers to keep all quantities within acceptable ranges. In addition, it can be used to manage the energy flow between the microgrids of renewable energy systems and the main grid. This can then enable the electricity network to integrate more renewable energy sources with the network, which will have a positive impact on preserving the environment.

5. Discussion and Future Works

In this project, we have faced a number of limitations that can be addressed in the future work. The cost of software and other components is one of the challenges encountered upon developing the solution. ESRI is the sole supplier of the ARC GIS products. ESRI provides support to educational institutions, but at the time of carrying out this project, this support was not spread to renewable energy solutions. The investment in hardware system and IT equipment will lead in expansion of memory space requirement. Improvement of the system speed to measure and store on-line data in smaller interval is needed. Having larger database enables us to introduce new functions to the developed web application such as forecasting the power grid load or prediction of DER production. To do so, meta-heuristic methods for manipulating the database may be used. Boosting the measured data with a smaller time interval will also result in better presentation of historical data charts in the web application with smoother trends. The work can be expanded by including an entire electrical power network in the GIS web application by modernizing some of the electrical components in the system and adding more sensors into the network.

In the future work, eliminating some sources of uncertainty in the database is suggested. Part of manipulated geodata in this work were formed by converting the existing single-line diagrams (AutoCAD or printed) into GIS database. Thus, the coordinate system is relied on previous sketches. To improve the accuracy of the geodata, advanced GPS technologies (like Trimble Geo7x) are to be used to detect the exact location of 11 and 0.415 kV cables as well as other components in the SQU network. Another source of uncertainty was the timing precision in recording on-line measurement. As proposed method conducts measurement from two locations, university campus (Microgrid Lab) and residential area (the Eco-house), the web application retrieves data from local telecom network and the university domain network in parallel. Decreasing the interval of data measurement, the timing mismatch might propagate error in the system. To eliminate/reduce the error, the measurement timing from different networks are to be synchronized. Alternatively, one domain for retrieving data is to be used.

The GIS data model for this project was created in ArcMap environment as a collection of layers and electric features. The National Geographical Department in each individual country owns the most accurate and updated maps for the country, but their database is not accessible and only the authorized people can purchase their maps. For this work, the geodatabase is assigned as the common data storage and management framework in ArcGIS. A geodatabase stores GIS data in a central location for easy access and management, where the database resides on server in which ARC GIS for server is installed. The user of ARC GIS for desktop can log to Arc Catalog to browse the database location through a functionality called database connection. In future work, we plan to share our database as open database to some entities such as EnergyMap.info. The complete GIS based map of SQU can be shared via Global Atlas of International Renewable Energy Agency (IRENA), which is freely available for global researchers.

Additionally, the concept of Cellular Automata (CA) may be used for further expansion of this work for a comprehensive planning of a smart city, which contains various sources of renewable energy in the

form of distributed generation. In the literature, an increasing application of CA is observed in the simulation of urban system developments. For example, (Batty and Xie, 1994) simulated land use dynamics in the city of Buffalo, USA, with CA and GIS; (Yang, et al., 2008) presented a study that tested the support vector machines (SVM), a data mining technique, as transition rules for CA. The proposed model was implemented, as a case study simulating the urban development in the Shenzhen city of China. (Cumò, et al., 2012) described the results of a Sustainable Urban Cells research project. The main objective of the project was to experience the sustainable reshaping of the city considering a minimum core of the larger city's model, i.e., the urban cell. The method attempted to provide a standard procedure to evaluate the performance and optimization of the urban cell energy balance through innovation technology either with the use of renewable resources or in the final consumptions.

These studies have demonstrated CA as a powerful tool for simulating complex urban dynamics. Therefore, it is suggested that this tool be added to the GIS platform of this paper for prediction of changes that will occur in the electrical distribution system of the future for planning the steps in developing a smart city.

6. Conclusions

This paper describes the development of a Geographic Information System (GIS) and demonstrates the integration of enterprise GIS with a pilot of smart grid at Sultan Qaboos University (SQU). The technical procedures of development phases, including the development of both the GIS data model and the GIS web application, were described in details. The paper demonstrates how the developed GIS web application enables users to visualize the existing distribution electrical networks along with smart energy systems in their actual geographical locations as layers on top of satellite images. It provides the users with a tool to monitor the renewable energy production of smart energy systems online. In addition, the solution provides the ability to control, search and analyze the power flow of renewable energy components to/from the main grid.

The proposed Enterprise GIS integration with smart grid can be easily up-scaled to enhance the operation of power distribution systems. With the proposed solution, energy consumers, producers and distributors will all have real-time information on demand and supply of power across the grid. The availability of such information in real time will enable an unprecedented level of control at every level of the system. The fact that users can see the grid information integrated with GIS is a key feature to making decisions. Combining real time measurements with their corresponding geographic references will enable full managerial control of the network and the energy assets. The functionality of the proposed solution can be customized based on the user need. For example, the most critical information of a certain asset on the grid can be prioritized and floated while less critical data may be simply filtered. In addition, the reporting system dashboard and automated analysis on the RES production and storage information enable the user to apply direct and immediate management actions on the system. The potential of different renewable resources as a promising source for electricity production in the specific zone can be determined by analyzing the corresponding production data.

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Highlights of the Paper:

Development of an Enterprise Geographic Information System (GIS) Integrated with Smart Grid

This paper has the following features.

- (1) Pilot implementation of an enterprise GIS, which makes a real-time monitor of electricity network;
- (2) Produces spatial representation of the electricity network and its assets with their real-time operational data on a geographical map;
- (3) The system provides ability to control, search and analyze the historical information.
- (4) The developed platform will be very useful for monitoring, control, asset management, and demand side management in a smart grid.