Smart management system for improving the reliability and availability of substations in smart grid with distributed generation

Shady S. Refaat, Amira Mohamed

Abstract: Electrical power control and management is key to improving the efficiency and security of energy supply. Proper management would help in safely diversifying energy supplies, reducing energy consumption during peak load, and improving grid integration condition and reliability. Therefore, this study presents a novel real-time and smart power management system for monitoring and controlling power flow between substations, distributed renewable energy sources, and loads towards optimising energy consumption and balancing electric power supply. The concept and architecture of the proposed system are discussed within the context of the smart grid principle. The proposed energy management system does not require any changes in the traditional substations. Simulation results and implementation are conducted to demonstrate the validity of the proposed system.

1 Introduction

The integration of renewable energy sources has increased substantially over the last decade. Substations play a significant role in the integration of renewable energy into the power grid. Electrical substations are the mediator between electric transmission systems and distribution systems [1]. The main task of the substation is to step down high voltage in suitable levels for the distribution system. They are also used to control the flow of electric current in various directions [2, 3]. Furthermore, they smooth and filter voltage fluctuations caused by, for example, an increased load. Electrical substations are divided into three main functions [4]: step-up substations, step-down substations, and distribution substations. The role of the step-up substations is to step-up voltage, while decreasing the current, in order to increase transmission efficiency. This substation exists in power-generating stations [5]. The step-down substations refer to step-down voltage from transmission lines. It usually exists in the sub-transmission networks, which are the suppliers of the distribution substations. The distribution substations refer to the step-down voltage of sub-transmission to suitable voltage levels for utilities to supply industrial, commercial, and residential sectors. They usually exist in the primary distribution system. In particular cases, in the distribution system, there are two more types of substations: collector substations and mobile substation. Collector substations are used in renewable energy power plants such as wind, solar, or hydroelectric to step up different output voltage to the transmission network system. Mobile substations are used in mobile usage applications for the continuity of services such as planned construction, maintenance, standby, or temporary service, and electrical power source in isolated areas [6]. Distribution systems serve as the link between the distribution substations to the customers. They mainly consist of medium-voltage-fused disconnect, current and potential transformers, low-voltage switchboard, load-break switches, air-break switches, drop-down lift-off switches, line and bus isolators, circuit breakers, auto-reclosers, capacitor banks, fuses, lightning arresters, distribution transformers, AC and DC auxiliary power supplies, and feeders [7]. The power flows through several substations: between electricity generation and the consumer sector. Therefore, the development of effective smart control and power flow management strategy among renewable energies, loads, and the grid, particularly at the substation level, is a well-known challenge. Electrical power control and management is the key towards improving the efficiency and security of energy supply. This would help in diversifying energy supplies, reducing energy consumption during peak load, and improving grid integration reliability. A lot of research work has been conducted for the energy management system (EMS) for distribution substations [8–12]. In [8], the authors proposed the use of Internet of things (IoTs) to monitor and control different system parameters for energy management in the smart grid. The solution could be used to control the network profile remotely depending on collecting the information of the power system right from the substation to the end user through sensors and actuators for real-time data decision-making. It continuously collects the information and transfers the data through communication protocol using the IoT platform. The drawbacks of using the IoT platform are the compatibility and security. In [9], an EMS was proposed for a battery substation to support the high-speed train. The proposed algorithm manages the stored energy to support train operation on traditional 3 kV DC rail networks. The proposed control algorithm succeeded to reduce the peak current of the substation. In [10–12], energy management optimisation schemes for power substations were presented to achieve renewable energy sources (RES) and storage units’ coordination in the railway power substation. The proposed system controls the power flow through balancing and optimising the power flow using fuzzy rules. Fig. 1.

Energy management plays a curial role in monitoring, controlling, and optimising the operation of distribution substations, while increasing the resilience and reliability of the power grid. This helps in reducing CO2 emission, reducing power peaks in the grid, minimising grid energy losses, and increasing power grid efficiency. The EMS should meet various objectives such as availability, economical, expandability, and maintainability in the design to optimise energy production/consumption and to provide the monitoring functions and tools. Therefore, this paper presents a novel real-time and smart power management system that can be used to monitor and control power flow between substations, renewable energy sources, and loads towards optimising energy consumption and balancing electric power supply. The proposed algorithm manages power consumption by assigning the load demand according to utilities power supply events, electric power production from renewable sources, demand patterns, and capacity of the system. The data are processed and fed to the presented algorithm, which accurately manages the demand power, give its decision of utilising switch generators, renewable sources, equipment, lines, and feeders in and out of any electric system at the substation level.
The main contribution of this paper is presenting the benefits of implementing energy management at the substation level to improve smart grid reliability and stability across the distribution system. The paper provides a brief overview of the recent approaches used to implement management and control decisions in the smart grid.

Therefore, our objective in this paper is to offer the following:

- Analyse the feasibility of implementing smart grid technologies.
- Presenting a comprehensive overview of distributed generation in the smart grid in terms of energy management.
- Presenting a clear concept of implementing energy management in the smart grid.
- Highlighting the challenges of the power management system for substations of distributed generation in the smart grid.

The paper is organised as follows. In Section 1, a comprehensive overview on substations is given, while the integration of distributed generation in the smart grid is given in Section 2. Section 3 describes the smart grid applications in the context of generation, network, and demand sides. A brief description of the proposed energy management in substations is given in Section 4. Challenges and expected potential benefits of substation EMSs in the smart grid are presented in Section 5. Finally, a conclusion is provided in Section 6.

2 Smart grid substation

A smart grid is composed of two organisational structures: power infrastructure and communication infrastructure [13, 14]. The power infrastructure is responsible for the electrical energy generation and distribution. The communication infrastructure is responsible for controlling and managing the information. The smart grid provides a platform to remotely monitor and manage energy usage for consumers securely, reliably, and cost-effectively. It converts the grid from a static infrastructure to a dynamic form. The dynamic control and management at every level in the complete energy chain – from generation to consumption – in the smart grid involves smart energy-efficient controllable equipment, smart distributed energy resources, advanced dynamic control architecture, and distributed optimisation architecture of substations. The distribution substation for a smart grid has to move beyond the classical concept in control, protection, automation, operation, and data collection. It is directed into using smart devices in order to achieve the smart distribution substation functions, which are as follows:

- Reduce the voltage to an acceptable level for distribution networks.
- Voltage regulation through changing the voltage level to another level to compensate the effect of voltage variation on electrical loads.
- Switch transmission and distribution networks into and out of the grid system.
- Regulate the connection of transmission and distribution networks and prevent loss of synchronism in the grid.
- Integrate renewable and non-renewable electricity generation plants to the power grid.
- Transfer power through the transmission networks to the distribution networks.
- Change the high-voltage direct current transmission system to the alternating current.
- Eliminate lightening and other electrical surges from the transmission and distribution networks.
- Protect transmission and distribution networks.
- Measure electric power qualities in the networks.
- Control and optimise the exchange of energy between the smart grid and traditional grid.
- Connect communication signals to the electric networks.
- Transmit data over the electric power distribution network for networks monitoring, control, and protection purposes.
- Make interconnections between the electric systems of more than one utility.
- Isolate faults in either the transmission or the distribution networks.
- Isolate faults in either the transmission or the distribution networks.
- Load shedding and prevention of loss of synchronism in the distribution system.

The modernised substation has a more flexible architecture. Intelligent electronic devices (IEDs) and digital relays streamline the flow of information within the substation to monitor and to remotely control grid and equipment. The emerging new digital substation is, in fact, a complex cyber–physical system in which diverse physical devices such as transformers and circuit breakers seamlessly operate with cyber devices such as digital protection relays, routers, and switches. The goal is to achieve high flexibility and responsiveness of transmission and distribution network using real-time data in order to control grid stability and manoeuvre to the changing grid conditions.

Smart substation will improve the network performance and rationalise existing grid resources. It will help in the integration of energy sources, reduction of catastrophic failure by improving the reliability of the networks, and improving power quality and load profile (Fig. 2).

3 Smart grid applications

Smart grid applications can be classified into three main categories of the electrical grid: generation, transmission, and distribution. On the generation side, it is associated with the integration of modern technologies such as microgrids, distributed energy resources, vehicle to grid (V2G), and virtual power plants (VPP). Microgrids are attracting a great attention since they integrate distributed generation with the main grid reliably and cleanly. In addition, microgrids can sell or buy power to or from the utility grid which

---

Fig. 1 Distribution generation electricity paradigm in smart grid

Fig. 2 Smart grid applications
ensures the continuity of power transfer. Microgrids can also be disconnected from the grid and work in the islanded mode in the case of any disturbances that may affect the network. Electric transportation applications involve the flow of electricity from vehicles to grid (V2G) and vice versa. These applications use the electric vehicles, hybrid and fuel cells based, which provide clean mobile distributed generation resources. Applications for the network side play a significant role in distributed intelligence and interoperability between generation and customer side. Areas for improvement include automated EMS, distribution management system (DMS), automation, supervisory control and data acquisition (SCADA) system, and smart substation. Those applications have been the subject of significant research in the past decade and have been identified as very promising components of the grid. The smart substation and its application have received little attention in research. This paper discusses real-world examples of smart grid applications at the network side. One of these applications is the DMS in the smart grid, which works to plan and optimise distribution system operations that is divided in distribution automation (DA) and distribution system monitoring and maintenance. DA provides real-time operation using all information of the grid structure, automation control, communication, and management data. Distribution system monitoring and maintenance depend on self-monitoring, fault detection, and diagnostics for equipment. It provides power and energy management, fast response time to the distribution network allowing an efficient integration of renewable sources. The EMS is also considered as one of the most important applications to the smart grid. It allows the utility to detect the fault or the power outage through measuring devices such as smart metres and outage detection units. These devices can also report over- and under-voltage situations. One of the most appropriate applications is DA and SCADA systems. Distributed automation works as real-time remote monitoring and control of distribution system assets such as distributed field sensors, feeder switches, reclosers, and capacitor switches. In addition, it provides decision support to improve system performance. The SCADA system is considered as the communication system for remote data acquisition in order to manage and control information and help in taking decisions, which in turn make the electric grid more reliable and self-healing while at the same time help reducing peak demand for electricity.

Smart grid technology changes the vision that we have on the configuration of the electrical grid to get more functionality and lower cost than the traditional ones by using the new intelligent electrical substation called the smart substation. The concept of smart substation is based on adopting digital technology such as the modern advanced system, control, and software. The built digital substation has advanced functionalities such as automatic operation, distributed coordination and control, and smart analysis and condition-based maintenance which helps in achieving reliable, secure, and economic distribution of power. Demand side application is one of the most important parts in the smart grid. It is associated with the interconnected and flexible programmes which allow utilities and customers to shift demand energy during peak periods and reduce their overall energy consumption. Demand side applications and programmes include smart metres, demand response (DR), home energy management systems, and electrical vehicle charging stations. For the conventional power grid, the utility works on collecting data from electric metres and transferring it to a central database to be analysed which is called the prepaid metre. However, the smart grid can perform the prepaid metre functions in a smart way with the ability to disconnect or reconnect loads to the system which is called the smart metering.

One of the most important applications of the smart grid in distribution is the DR. DR includes direct load control through smart thermostat, smart appliances, to provide load reduction during peak demand periods in the distribution grid taking into consideration the customer promises. The application of the smart grid and smart charging stations in support of plug-in electrical vehicles is now being rolled out to consumers to drastically reduce the dependence on oil. In addition, this helps emitting no air pollutants when running in all-electric modes and increasing flexibility in the generation process and scheduling. This technology reduces the dependence on the utility power grid which in turn lowers the maintenance cost. The smart grid, with its system of controls and smart metres, will help to effectively run through a home EMS which in turn saves energy. A smart grid can manage and control the power through the interactive relationship between the utilities, grid operators, and consumers.

4 Challenges expected and potential benefits

The smart grid provides through its applications great benefits to different parties. Utilities will gain low maintenance cost and lower distribution cost, grid operators will gain more data help in communication, monitoring, and control capabilities which leads to better reliability, and consumers will gain control over the consumed power, reduce electricity consumption with a more reliable grid. All these advantages will be beneficial to the environment where the ‘smart grid’ could reduce electrical energy consumption by 5–10%, carbon dioxide emissions by 13–25%, and the cost of power-related disturbances to business by 87% (Source: The Electric Power Research Institute). The Smart Grid vision presents a power system that is more intelligent, more decentralised, and more controllable than today's grid. Implementing intelligent technology of smart grid in power transmission and distribution is considered the development trend of substation technology nowadays.

The benefits obtained from the proposed smart management system for substations and integration of distributed generation in the smart grid are divided into two types: direct benefits and indirect benefits. The direct benefits are as follows:

- Enabling active participation of consumers which transform the centralised grid control to less centralised and more consumer interactive based.
- Improvement of energy system reliability, flexibility, and load management.
- Operating efficiently.
- Reducing distribution losses.
- Anticipating and responding to system disturbances (self-healing).
- Providing power quality for the digital economy.

Indirect benefits of the smart management system for substations and integration of distributed generation include the reduction of overall expenses through reducing both capital and operations expenses. As demand increases, utilities must provide the needed power to meet the peak loads which is extremely of high cost. Smart management to supply and demand of energy efficiently will help reducing the need to build more power plants, which in turn decreases the capital cost. In addition, it enables utility to reduce power outage, decrease the risk of premature failure, and increase the reliability of electric grid components, which provide an excellent opportunity for improving both energy efficiency and reducing operating cost. Indirect benefits can bring more overall advantages to the electricity company such as:

- Improve their monitoring and forecasts of energy consumption
- Manage energy procurement with greater precision.
- Pinpoint inefficiencies at macro (e.g. city-wide) and micro (e.g. household) levels.
- Predict potential power outages and equipment failures which leads to the optimisation of infrastructure replacement investment.
- Hone their customer segmentation and tailor their offerings based on customer behaviour.
- Drastically reduce their operational costs.
- Accommodate renewable energy sources across the network.

To gain all mentioned benefits, the smart substation must be able to (i) interact and share device information and real-time operation data, (ii) acquire optimised management for the substation assets based on the real-time condition, (iii) realise the maintenance and dispatch strategies, and (iv) support the power system continuity.
using smart regulation. Achieving these requirements in smart substations in turn leads to system reliability, security, interoperability, re-configurability, controllability, maintainability, flexibility, reduced cost, and environmental impact which are considered great but come with essential challenges. These challenges are described briefly as follows.

4.1 Privacy problems
One of the biggest challenges facing the smart grid applications is related to the cyber security of the systems. Due to the electricity usage of information stored in the smart metres, the high data rates of the process between utilities and customers and the requirement of very high availability of this data create big challenges. The challenge is related mainly to the privacy protection mechanisms needed to protect the information and to decrease the chance of anyone gaining control over the power supply of any customer. Cyber security issues may cause system failure or power cut, and/or create extra cost and effort for the user when running the system. The optimum solution is developing cyber security protocols working in parallel with all smart substations.

4.2 Grid volatility
Smart grid depends on control and management of all grid points especially at both generation and end user sides. However, the grid has insufficient intelligence in between, at transmission and distribution station, due to the lack-sophisticated instrumentation and the switching function to integrate substations. The weakest point in the grid is the integration of nodes. Developing intelligence software to control these nodes is a mandatory to gain a volatile smart grid.

4.3 Reliability
One of the important goals for any power network is reliability, which is inversely proportional to the number of used IEDs (when increasing their number in the system, the overall system's reliability decreases), therefore the effect of these devices has to be considered in the final architecture.

4.4 Testability and maintainability
The system needs to be provisioned to facilitate testing and maintenance. Testing is defined here as verification and re-verification of a complete Portfolio Creation and Maintenance (PC&M) after it has been deployed, repaired, or after a major work such as a substation expansion, firmware upgrade or component replacement. Maintainability is defined as the existence of simple, safe, and trusted means of performing firmware and setting changes and replacing of faulty elements of the system.

5 Modified IEEE30-bus system
Some potential SCADA and EMS applications for substation automation systems are being developed, such as automated execution of control and restoration sequences; on-line monitoring and failure analysis of circuit breakers (CBs); enhancement of the traditional state estimation with local substation data; automated analysis of faults. Some new technologies, such as Petri Nets, are also being used to improve substation automation functions. Many of these new functions need to be tested for their reliability and accuracy before they are physically implemented in real substations. In most cases, it is difficult to test these applications in a real substation environment because such experiments are expensive and time-consuming. Thus, a software substation model is needed, which can fully simulate the real-time monitoring, control, and operation planning as well as historical and post-mortem analysis.

In this paper, the IEEE 30-bus test system with L-S PV is simulated using a comprehensive analysis power system software ETAP platform for the design, simulation, operation, and automation of power network and PV system as shown in Fig. 3. The standard IEEE 30 bus system consists of 30 buses, 6 synchronous generating units, 4 transformers and 24 load points. Generator no.1 is in swing mode at slack bus. The other generators are in voltage control mode; in addition, a generator PV bus is added at bus no.12. Generators no. 1 and 2 are rated at 135 kV, speed 1800rpm and of 4 pole. All loads in service in the test system are 3-phase and voltage is rated at 135 kV. The system total real power is 283.4 MW, and total reactive power is 126.2 Mvar. The total real power losses are 17.563 MW and total reactive power is 33.045 Mvar. A 154 MW penetration L-S PV has been considered for the analysis in our cases studies.

6 Switching sequence management
DMS power application is used for both derivation and in field performing of a set of switching operations, which are necessary to transfer a network from current to target topology (e. g. to transfer a part of a feeder with renewable energies to an adjacent feeder, for execution of supply restoration process, etc). The most important parts of the switching operations are performed remotely using SCADA system. SCADA performs automatic monitoring, protecting and controlling of various equipment in distribution systems with the use of IEDs or remote terminal units. It restores the power service during fault condition and maintains the desired operating conditions. SCADA improves the reliability of supply by reducing duration of outages and it gives the cost-effective operation of distribution system. Therefore, distribution SCADA supervises the entire electrical distribution system. It is used in the substation to minimise the fault duration and extent, significantly improving performance metric for the customers on the feeders. In addition, it is the automatic check of equipment loading and thermal limits to determine whether load transfers can safely take place. A case study presents the switching sequence management to evaluate the impact of change switching sequence (C.B PV1 and C.B PV2 open) on the modified system, the sequences of the outage of large-scale PV plant (PV1, PV2) on the power system, the switching sequence design to initially open C.B PV2. Immediately after the switch C.B PV1 is open. When C.B PV1 is open, the buses 26, 29, 30 become under voltage; the voltage at these buses is decreased and generators 1 and 2 become overloaded trying to supply active and reactive power to the system, while generator 11 becomes overexcited. The lines (13–2), (13–7) remain stable until the C.B PV2 is open, then the lines become under over voltage, and the buses (28, 4) become under voltage as summarised in Table 1.

The prospective consequences of switching actions can be present in avoiding inadvertent outages of the generators in the modified model. The modified IEEE-30 bus has been optimised for losses with the optimal power flow (OPF) method, which optimises the active and reactive powers at the same time. The network losses have been reduced from 8.222 to 5.047 MW and the reactive power has reduced from 32.193 to 29.251 Mvar. After changing the switching sequence management of the model, the losses could again be reduced from 5.047 to 4.989 MW and the reactive power reduced from 29.251 to 28.951 Mvar as shown in Table 2. The minimum loss value achieved by optimal switching operations depends on the network configuration and loads connected before the optimal switching sequence.

7 Conclusion
This paper gives an overview of implementing energy management at the substation level to improve smart grid reliability and stability across the distribution system. The EMS is essential for getting a robust and reliable smart grid. DMS is a powerful tool utilised to change distribution network topology during normal and contingency conditions for improving the reliability and availability in the smart grid. Optimal switching operations can be determined through network losses. Network losses have been reduced due to switching sequence management. Future research should be conducted to investigate the analysis of voltage profiles during the network reconfiguration process by switching actions with different switching sequence.
Acknowledgment

This publication was made possible by NPRP grant [NPRP 7-106-2-053] from the Qatar National Research Fund (a member of Qatar Foundation). The statements made herein are solely the responsibility of the authors.

References

[1] Refaat, S.S., Abu-Rub, H., Sanfilippo, A.P., et al.: ‘Impact of grid-tied large-scale photovoltaic system on dynamic voltage stability of electric power grids’. IET Renew. Power Gener., 2017, 12, (2), pp. 157–164

[2] Knowlton, A.E., Shoop, R.M.: ‘Standard handbook for electrical engineers’ (McGraw-Hill, New York, NY, USA, 1957)

[3] Eremita, M., Liu, C.-C., Edriss, A.-A., (Eds.): ‘Advanced solutions in power systems: HVDC, FACTS, and artificial intelligence’ vol. 52. (John Wiley & Sons, New York, NY, USA 2016)

[4] Refaat, S.S., Abu-Rub, H.: ‘Smart grid condition assessment: concepts, benefits, and developments’, Power Electron. Drives, 2016, 1, (2), pp. 147–163

[5] Tsuboi, T., Takami, J., Otake, S.: ‘Design of insulation test with one-minute step-up method for substation equipment’, IEEE Trans. Dielectr. Insul., 2008, 15, (5), pp. 1271–1280

[6] Lopez-Roldan, J., Enns, J., Guillaume, P., et al.: ‘Mobile substations: application, engineering and structural dynamics’, IEEE/PES Transmission and Distribution Conference and Exhibition, Dallas, TX, USA, January 1 2006, pp. 1–6

[7] McDonald, J.D., Wojcieczky, B., Flynn, B., et al.: ‘Distribution systems, substations, and integration of distributed generation’. Electrical Transmission Systems and Smart Grids, Springer New York, 2013, pp. 7–68

[8] Ravikumar, V.J., Lokhande, S.S., Gohokar, V.N.: ‘Energy management system in smart grid using internet of things’. IEEE Int. Conf. on Power Electronics, Intelligent Control and Energy Systems (ICPEICES), India, 2016, pp. 1–4

[9] Calderaro, V., Galdi, V., Gruber, G., et al.: ‘Energy management of auxiliary battery substation supporting high-speed train on 3 kV DC systems’. Renewable Energy Research and Applications (ICRERA), Italy, 2015, pp. 1224–1229

[10] Pankovits, P., Pouget, J., Robyns, B., et al.: ‘Towards railway-smartgrid: energy management optimization for hybrid railway power substations’. Innovative Smart Grid Technologies Conf. Europe (ISGT-Europe), Istanbul, Turkey, 2014, pp. 1–6

[11] Kezunovic, M., Guan, Y., Guo, C., et al.: ‘The 21st century substation design: vision of the future’. Proc. IEEE Symp. Bulk Power Syst. Dynam. Control (BEP) o VIII (BREP), Brazil, 2010, pp. 1–8

[12] Zahiran, M.: ‘Smart grid technology, vision management and control’, WSEAS Trans. Syst., 2013, 12, (2), pp. 1–11

[13] Qiao, W., Li, F., Sunet, H., et al.: ‘Smart transmission grid: vision and framework’, IEEE trans. Smart Grid, 2010, 1, (2), pp. 168–177

[14] Refaat, S.S., Mohamed, A., Abu-Rub, H.; ‘Big data impact on stability and reliability improvement of smart grid’. to be published in IEEE Big Data 2017

Table 1 Impact of change switching sequence management

| Affected elements | Original IEEE-30 bus with PV system | C.B_PV1 | C.B_PV2 |
|-------------------|-------------------------------------|---------|---------|
| generator 1       | stable                              | overload| overload|
| generator 2       | stable                              | overload| overload|
| generator 11      | stable                              | over excited | over excited |
| bus no. (26, 29, 30, 28,4) | stable                              | under voltage | under voltage |
| line (13-2), (13-7) | stable                              | stable   | over voltage |

Table 2 System Performance reliability indices

| Losses          | Modified IEEE-30 bus without PV1&PV2 plant, OPF | Modified IEEE-30 bus With PV1&PV2 plant | Modified IEEE-30 bus Without PV1&PV2 plant, optimal |
|-----------------|-----------------------------------------------|------------------------------------------|------------------------------------------------------|
| MW              | 8.222                                         | 5.047                                    | 4.989                                                |
| MVAR            | 32.193                                         | 29.251                                   | 28.951                                               |

Fig. 3 Single-line diagram of the modified IEEE-30 model power system