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Effect of Distributed Wind Generation on the Voltage Sag of Distribution Networks

Mohamed Shaaban, Christy E. A. Benedict

Abstract**:** ***As the issue of global warming is worsening, the shift towards using renewable energy resources is becoming more of an obligation rather than an option. With the continual decline in the cost of distributed small and medium-scale renewables and government sponsored programs, the outlook of growth of these converter-based resources remain high. Renewable energy resources are connected at the end-user terminals, in close proximity to the load at the distribution network. Such connection in the locale brings perceived benefits of transmission loss reduction, increased energy efficiency and improved voltage regulation. Yet, distributed renewable generation have noticeable effects on system's power quality. This paper investigates the impacts of distributed wind generation on the voltage sag of distribution systems. A systematic approach is constructed to capture voltage sag occurrence incidents, due to wind generation connected at distribution nodes, and trigger the dynamic voltage restorer (DVR) into active operation mode to rectify the voltage sag problem. A test feeder system is represented using MATLAB/Simulink with wind turbines connected at several nodes of the system. A model for the DVR is developed in Simulink. It was then integrated with the test feeder system. Simulation results show that the incorporation of increased proportions of wind generation into the distribution network may give rise to negative operating conflicts as far as the voltage sag is concerned. Results manifest that the DVR is capable of effective correction of the voltage sag, caused by a three phase short-circuit fault, in presence of high penetration levels of variable wind generation connected at disparate locations in the distribution network.***

Keywords **:** ***Distributed generation (DG), Distribution network, Dynamic voltage restorer (DVR), Power quality, Voltage sag.***

I. INTRODUCTION

The introduction of renewable energy systems is largely attributed to global warming and the near depletion of conventional energy resources. The issue of global warming is associated with increasing levels of greenhouse gases ejected into the atmosphere, mainly due to the burning of fossil fuels in electricity generation. This could have long-term environmental impacts on Earth. It is also believed that fossil fuels have perhaps a few decades of supply left [1]. Since renewable energy comes from natural resources, they are always replenishable. In fact, the amount of renewable energy sources available to tap from at the Earth's surface is astounding.

Technological advances in distributed generation (DG) technologies allowed the integration of small-scale generators into the distribution network, directly close to the loads [2]. Various DG renewable energy based technologies have emerged. These include solar PV, wind, biomass, mini-hydro, and fuel cells [3]. Malaysia has a significant potential of renewable energy sources, and the government has enacted several policies to encourage the wider adoption of renewable energy in the country [4].

A renewable DG can be either dispatchable, such as biomass, or non-dispatchable (variable) such as solar PV and wind. Variable renewable DGs are highly dependent on the amount of energy harvested from its sources, which is unpredictable and has a time varying nature. Whereas the spurt of renewable DG connection to the distribution system has brought forward significant benefits to customers and utilities alike [5], it created new challenges due to the intermittency characteristics of variable renewable generation [6]. Since the integration of renewable DGs into the grid takes place with the aid of power electronic converters, power quality will become a major issue of concern.

Power quality is an umbrella concept that applies to a wide variety of electromagnetic phenomena that characterize the voltage and current at a given time and at a given location on the power system [7]. The increasing application of electronic equipment, due to the uptrend of DG connection at the distribution system level, can cause electromagnetic disturbances. The categories of low-frequency, short duration phenomena causing electromagnetic disturbances include harmonics, interharmonics, interruptions, flicker, voltage imbalances and voltage sag [8].

Voltage sag is a short duration event of a decrease in rms voltage to between 0.1 pu and 0.9 pu for durations from 0.5 cycles to 1 minute [8]. Despite being short, voltage sag propagates through the power system affecting loads and utility equipment. Voltage sags are usually associated with system faults. It can also be caused by switching heavy loads or starting large motors [7]. Voltage sag is the most common cause of equipment malfunction in modern automated industry costing significant financial losses [9]. It is therefore necessary to avoid the consequences of voltage sag and deal with such problem in a cost-effective manner.

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* Correspondence Author

Mohamed Shaaban*, Department of Electrical and Electronic Engineering, Faculty of Engineering Universiti Malaysia Sarawak, 94300 Kota Samarahan, Sarawak, Malaysia.

Christy E. A. Benedict, Department of Electrical and Electronic Engineering, Faculty of Engineering Universiti Malaysia Sarawak, 94300 Kota Samarahan, Sarawak, Malaysia.

Among the devices used effectively for voltage sag mitigation is the dynamic voltage restorer (DVR). DVR is one of the Flexible AC Transmission Systems (FACTS) devices which is used to preserve sensitive loads from disturbances [10]. In essence, DVR is a power-electronic converter-based,
custom power device that provides partial compensation during voltage sag to protect critical loads from supply-side voltage disturbances [11].
It is widely acknowledged that the chief power quality issue associated with wind generation is voltage regulation [6-7]. Therefore, most of the reported applications tend to optimize the size and location of the respective wind generation for voltage regulation enhancement [5]. In practice, nonetheless, size and location of wind generation are driven by economics, including wind resource availability, as well as the decision of individual customers, not utility companies.
In this paper, a model of a distribution network is constructed in MATLAB/Simulink, which has wind turbine generators connected disparately at various feeder locations. With the event of a voltage sag detected due to a three-phase fault occurring in the system, a DVR model is developed, in Simulink, and connected to the distribution feeder network. Simulation results are presented to illustrate voltage sag occurrence and highlight the adequacy of the proposed approach in mitigating the voltage sag.

The rest of the paper is organized as follows: in Section II the problem statement is spelled out. The structure and operation of the dynamic voltage restorer (DVR) are explained in Section III. The proposed approach is highlighted in Section IV. Simulation results are presented in Section V. Section VI provides the conclusions.

II. PROBLEM STATEMENT

Integration of distributed generation of the variable renewable type, such as solar PV and wind, continues to grow at astounding levels. In 2016 alone, an additional annual capacity of 75 GW of solar PV and 55 GW of wind energy were achieved globally [12]. Despite the advantages of connecting renewable DGs close to loads at the distribution system, there are major concerns as far as the power quality problem is concerned since the connection to the distribution grid is materialized via power electronic converters. The latter could cause power quality problems such as voltage sag. Whereas most of the previous investigations gravitate towards optimizing DG size and location to provide a better voltage sag performance [13], DG sizing and placement are not related, from the practical point of view, to the properties of the distribution grid. In fact, and in most cases, DG units are not owned by the electric utility operating the distribution grid.

The aim of this paper, therefore, is to study the impact of connecting distributed wind generators, to the distribution grid in a large proportion and at various locations, at customers' will and without being optimized. The objective is to identify voltage sag occurrence through dynamic system simulation. Furthermore, to develop a simulation model of the DVR, in MATLAB, to mitigate the voltage sag and apply the developed mitigation model to a test system.

III. DYNAMIC VOLTAGE RESTORER (DVR)

DVR, also known as active voltage conditioner (AVC), is a custom power device used to protect sensitive and critical feeder loads against voltage sags and swells caused by faults or disturbances in the supply voltage [7]. DVR is a series connected, converter-based compensation, device that injects a dynamically controlled voltage in the sag duration to control the load voltage. A typical structure of the DVR is shown in Fig. 1.

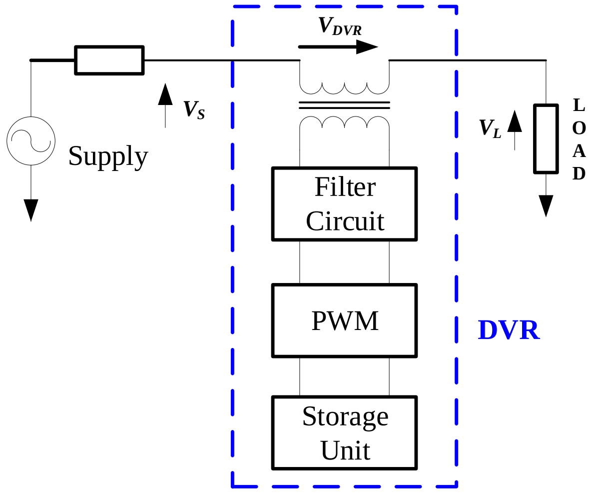

Fig. 1. Schematic circuit diagram of the DVR

A. Basic Elements

DVR is normally connected between the point of common coupling (PCC) and feeder load in the distribution network. DVR is composed of the following basic elements [14]:

- **Storage unit**

A DC energy storage is needed to supply active power during compensation. Energy storage devices can be capacitors or batteries. Since a system with a large disturbance would require high active power compensation, the capacity of the storage unit has a pronounced effect on the compensation capability of the DVR. Due to the high maintenance costs involved therein, modern DVR designs are emerging, which draw the additional energy required during voltage sag from the utility supply [11].

- **Converter**

It is a voltage source converter (VSC) that uses pulse-width modulation (PWM) to convert the DC voltage generated by the storage unit to a sinusoidal voltage with the required magnitude, phase, and frequency.

- **Injection transformer**

It connects the compensating voltage from the converter to the high voltage side connected to the distribution network. It not only steps up the AC voltage supplied by the VSC to the desired level, but also tends to limit the coupling of noise and transient energy from the primary side to the secondary side. The level of voltage sag compensation provided by the DVR depends on the rating of the injection transformer and the VSC. Furthermore, the injection transformer isolates the load from the DVR system.

- **Filter circuit**

As the PWM inverted waveform is converted into a sinusoidal waveform, a filter is required to reduce the undesired harmonic components of the waveform generated from the converter.

B. Modes of Operations

DVR has three modes of operation [11], [15].

- **Protection mode**

The DVR is isolated from the system during high load current, short circuit fault in downstream power lines, or large inrush current. Such incidents can damage the DVR components including the injection transformer.

- **Standby mode**

In the standby mode, DVR injects zero voltage if there are no errors. DVR do not absorb or deliver active power during standby mode. Actually, bypassing the DVR in this mode will prevent power losses in the DVR circuit. Nonetheless, DVR can operate in a self-charging mode if the energy storage is to be charged.

- **Injection mode**

In the injection mode, also called compensation mode or active mode, DVR injects the required voltage in a very short time, when the disturbance occurs, for voltage sag correction. DVR supplies reactive power to the load, while absorbing active power from the grid. When a voltage disturbance is detected, DVR is switched into the injection mode. This mode comes to an end when the voltage is restored to its nominal value.

With an increasing connection of renewable distribution generation, DVR can be a power means, if properly designed, to reduce the influence of voltage fluctuation.

IV. PROPOSED APPROACH

The main goal is to study the impact of wind generation on system's voltage sag, when connected in large proportions to the distribution network. Furthermore, to mitigate the resulting voltage sag via using the DVR. A flowchart summarizing the steps carried out by the proposed approach to achieve this end is illustrated in Fig. 2.
A simulation model of the test feeder system is first developed and wind generators, representing variable renewable energy sources, are connected at different sites in the test feeder. A fault is applied to the system and voltage sag is recorded. A DVR model is then extended and integrated at the test feeder system. Dynamic simulations are conducted to demonstrate the capability of the DVR to compensate the voltage sag. The DVR settings are retuned until the voltage sag is completely eliminated.

V. SIMULATION RESULTS

A. Test System

The testbed system used in this paper to showcase the implementation of the proposed approach is the IEEE 13 node test feeder network [16]. IEEE13 node test feeder provides a good test of the convergence of a developed algorithm for a very unbalanced system [17]. The standard test feeder system configuration is shown in Fig. 3. The modified 33kV/0.575kV 50 Hz IEEE 13 node distribution system has a combination of three phase and single-phase spot loads. The total system load amounts to 1.901 MW, 1.112 MVAr.

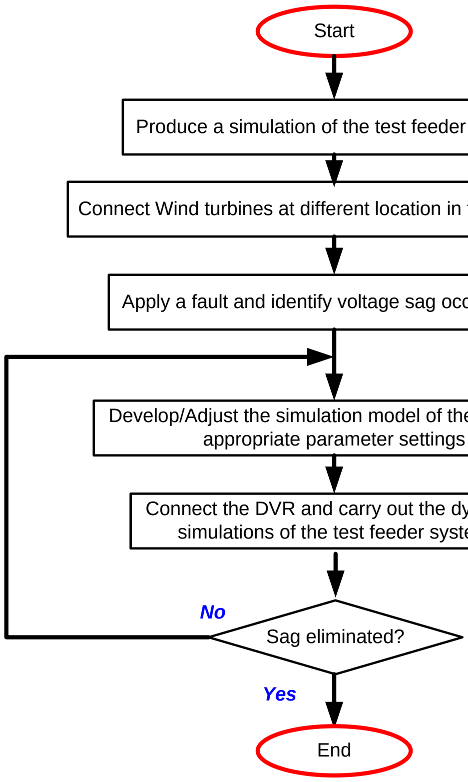

Fig. 2. Flowchart of the proposed approach.

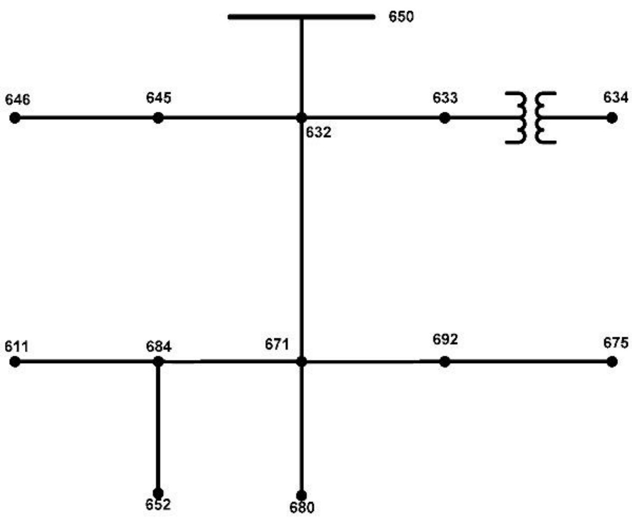

Fig. 3.IEEE 13 node test feeder.

MATLAB is a programming language used for solving technical problems. Simulink is a graphical programming language included in MATLAB for the simulation of dynamic systems. SimPowerSystems is a set of Simulink blocks that contains standard devices and units in electric power systems. In this paper, MATLAB/ Simulink with SimPower Systems is the simulation tool employed herein [18].

Simulink is also the platform used to develop models simulating the voltage sag, three-phase line fault model, wind turbine generators and the DVR. The IEEE 13 node test feeder model developed in Simulink is demonstrated in Fig 4.

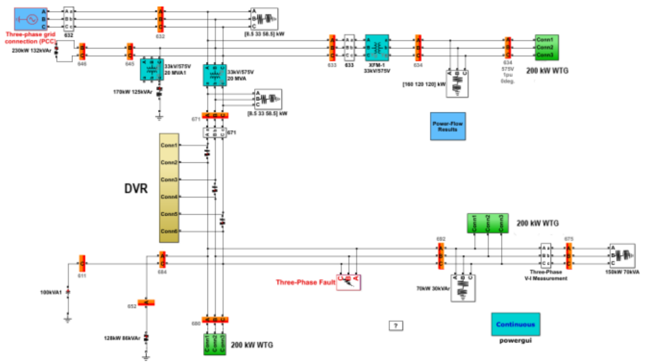

Fig. 4. Modified IEEE 13 node test feeder Simulink model.

The PCC or the connection to the grid (three phase source) is at node 632. Simulation of the power flow solution at steady state conditions showed that unbalanced system voltages are within acceptable range close to 1.0 pu. Voltage unbalance, due to normal factors in this case as a result of the uneven distribution of single phase loads among the three phases, may cause adverse effects on the system. However, distribution systems are inherently asymmetrical. With the current trend of connecting more single-phase DGs to low-voltage distribution networks, it is important to analyze the system under practical operating conditions in realistic distribution networks. Control of DGs can be used to mitigate voltage unbalance in distribution grids [19].

B. Wind Generation

Three identical wind turbine generators (WTGs) each of 200 kW, three-phase connected, are distributed across the system at nodes 634, 675 and 680 as shown in Fig. 4. Since the WTGs are symmetrically connected to the three phases, they will not contribute to the voltage unbalance experienced by the IEEE 13 node feeder network. In fact, WTGs may limit the voltage unbalance [7].

It is assumed that the WTG locations are selected based on adequate business case study, including proper wind resource assessment as well as economic feasibility analysis. The main issue here, is that the decision on WTGs size and location is solely based on economic factors, completely away from the hosting utility. Wind penetration level, in this case, amounts to 31.5% of the total supplied load. This penetration level is considered high and may have consequences on the distribution grid.

Each of the variable speed, pitch controlled WTG uses a synchronous generator. The WTG has two converters and a diode rectifier [18]. These two converters are: a DC/AC PWM grid-connected converter and generator-connected DC/DC PWM boost converter. This WTG model allows extracting maximum energy from the wind, even at low-speeds, by optimizing the turbine speed. Nonetheless, in such configuration, the rectifier input current contains higher levels of harmonics. The main parameters of the WTG are listed in Table I.

C. Voltage Sag Occurrence

Voltage sag can occur due to sudden disconnection of a large load or system faults. A three-phase line-line-line (LLL) fault model is created between node 671 and 692, closer to 692, to simulate balanced voltage sag caused by symmetrical line faults.

Table- I: WTG main parameters

Quantity	Value
Rated power	200 kW
Grid voltage	575 V
Nominal wind speed	11 m/s
WT inertia constant	4.32 s
Maximum pitch angle	27 degrees

The impact of the fault is simulated on three test case studies in this paper. These case studies are: network without WTGS, network with WTGs, and network with WTGs and DVR.

- **No WTGs**

In this case study, the network experiences the three-phase fault outlined before. The instantaneous waveforms of the voltages for a 0.15 second simulation time is shown in Fig. 5. The fault block is set to simulate the fault from 0.05 second for a duration of 2.5 cycles. It can be observed that nodes 680 and 692 experience voltage sags, whereas nodes 632 remains largely unaffected by the fault. This is because nodes 680 and 692 lie in the area of vulnerability of the given fault, while the other nodes are not. Area of vulnerability (AOV) for a given bus is defined as the network area where the fault at any location will result in a voltage sag of a specified magnitude at the bus of interest [7], [20].

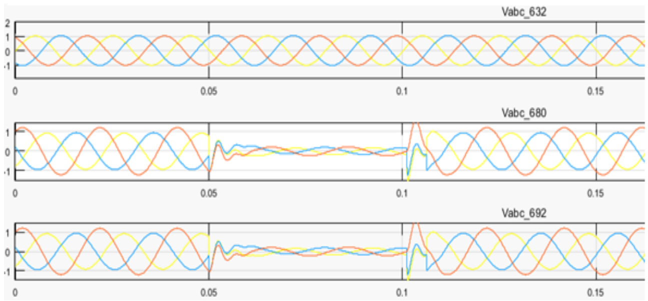

Fig. 5.Voltage waveform at different nodes, caused by the fault, with no WTGs.

- **With WTGs**

When the three WTGs are connected to the test feeder network as shown in Fig. 4., voltage sag instantaneous waveforms at the three respective nodes, due to the fault, are demonstrated in Fig. 6. Voltage sag, seemingly, becomes more sever with the integration of distributed WTGs to the distribution grid. In addition, notable harmonics exist following fault clearance. As the amount of WTG increases, leading to a higher penetration level, the fault current increases depending on fault type and its relative position. This, in turn, can trigger operating conflicts subject to the interaction of the WTGs with the distribution grid.

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While it is touted that the presence of WTGs in distribution grids can reduce voltage sags [13], WTGs have exhibited an adverse effect on voltage sag as it turned out in this case. Such effect was inadvertently masked, to an extent, with the tendency to optimize the size and location of DGs in distribution networks.

As explained before, such an optimization exercise is not tenable in current grid operation practices.

Notwithstanding, analysis of the impact of WTGs on the voltage sag should be carried out on a case-by-case basis. WTG size, location, technology, penetration level, host distribution network characteristics, and feeder loading could well influence the system behavior following a fault.

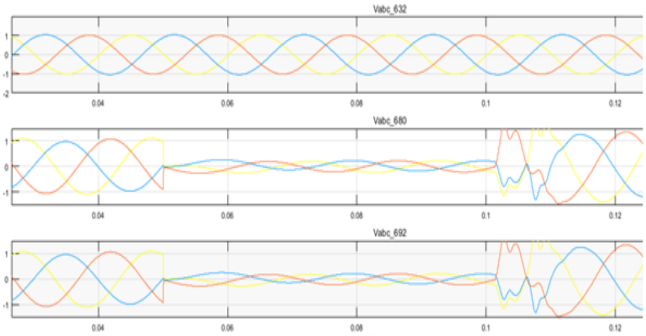

Fig. 6.Voltage sag at different nodes, caused by the fault, with WTGs connected.

D. Voltage Sag Mitigation Using DVR

DVR is developed in Simulink as shown in Fig. 7. DVR is now connected between nodes 671 and 692. The performance of the DVR is to be demonstrated as far as its capability to mitigate the voltage sag at sensitive load locations is concerned. DVR is simulated only to be operating during the fault, in the injection mode [14].

When the DVR is applied, as illustrated in Fig. 8, it injects voltage of proper magnitude to compensate for the voltage sag, rendering significant voltage recovery in the load voltage waveforms. The load voltage is the voltage at node 692, which appears to be compensated. The voltage at node 680 still retains voltage sag, albeit maintaining less harmonics once the fault is cleared. It appears while the DVR can mitigate the voltage sag with local effect only, it can also bring about wider improvement on evolving harmonics in the network, following fault clearance, in the area of vulnerability of the fault. The results clearly demonstrate that the DVR model, adopted in this paper, is adequate to correct the voltage sag at the load terminals.

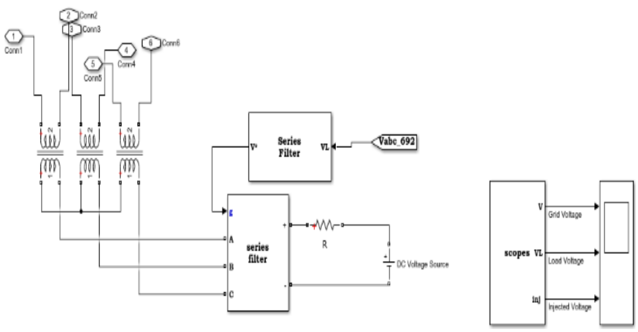

Fig. 7.DVR Simulink model.

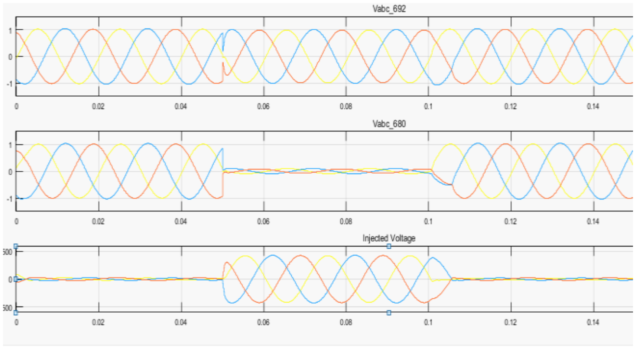

Fig. 8. Compensated voltage waveform after DVR application.

VI. CONCLUSIONS

The transition of modern power systems toward integrated grids with increased renewable energy resources connected at the distribution system level presents new challenges to system operation and planning. Voltage sag is a power quality problem that is always singled out as the main cause of equipment failure in industrial plants. The impact of integrating a large share of distributed wind generation on the voltage sag in a distribution network was presented in this paper. MATLAB/Simulink was employed to construct a dynamic model of the IEEE 13 bus test feeder system. Wind turbine generation were connected at disparate locations of the feeder system. As a three-phase short circuit at one lateral has created a voltage sag at the fault location, DVR has effectively managed to compensate the voltage sag at the load terminals.

Wind generation is customarily connected to distribution networks based on technical feasibility assessment, resource availability, and economic merits, rather than central utility optimization planning exercises. Therefore, incorporating wind generation to the distribution grid in a discretionary manner can prompt adverse operating conflicts. Simulation results suggest that the rapid fluctuations of energy output from the WTGs, a distinct characteristic of variable wind generation, may contribute to the voltage sag experienced by the system.

Further research is needed to better understand the influence of higher penetration levels of renewable DGs on the voltage sag of the distribution system under different fault types and system conditions.

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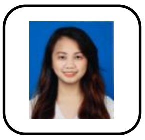
AUTHORS PROFILE

Mohamed Shaaban received his B.Sc. (honors) and M.Sc. degrees from Suez Canal University, Egypt and his Ph.D. degree (all in Electrical Engineering) from the University of Hong Kong in 1990, 1996, and 2002 respectively. He held previous appointments in Suez Canal University and Port Said University, Egypt, Qassim University, Saudi Arabia, University of Strathclyde, UK, and Universiti Teknologi Malaysia (UTM). He was a Visiting Professor at Washington State University, Pullman, WA, USA in 2007 and National Chung Cheng University, Taiwan in 2015. He is currently an Associate Professor in the Department of Electrical and Electronic Engineering, Universiti Malaysia Sarawak (UNIMAS). His current research interests include distributed generation scheduling, large-scale optimization, microgrid operation, smart distribution grids, renewable energy integration, and big data analytics. Dr. Shaaban is a Chartered Engineer, UK and a Senior Member, IEEE.



Christy Emylia A. Benedict Graduated from Universiti Malaysia Sarawak (UNIMAS) with a Bachelor in Electrical Engineering in 2018. Christy is currently a project engineer at a Korean company. She has contributed to the company in three projects related to her education background.