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Research Article

Influences of Wind Energy Integration into the Distribution Network

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Wind energy is one of the most promising renewable energy sources due to its availability and climate-friendly attributes. Large-scale integration of wind energy sources creates potential technical challenges due to the intermittent nature that needs to be investigated and mitigated as part of developing a sustainable power system for the future. Therefore, this study developed simulation models to investigate the potential challenges, in particular voltage fluctuations, zone substation, and distribution transformer loading, power flow characteristics, and harmonic emissions with the integration of wind energy into both the high voltage (HV) and low voltage (LV) distribution network (DN). From model analysis, it has been clearly indicated that influences of these problems increase with the increased integration of wind energy into both the high voltage and low voltage distribution network; however, the level of adverse impacts is higher in the LV DN compared to the HV DN.

1. Introduction

Renewable energy (RE), in particular wind energy, is the most promising of the RE sources which are free from GHG emissions, and it has potential to meet the energy demand due to its availability which encourages interest worldwide [1–3]. Over recent years there have been dramatic improvements in wind energy technologies, and wind is increasingly becoming an important energy source [4]. Integration of wind energy into the grid creates potential technical challenges that affect power quality (PQ) of the systems due to the intermittent nature of wind energy. Potential technical difficulties occur not only due to the intermittent nature of wind source but also due to the design of wind turbine types, electrical equipment, and the grid connection characteristics [5, 6]. With increased penetration of wind energy to the grid, the key potential technical challenges that affect quality of power observed include voltage fluctuation, reactive power compensation, switching actions, synchronisation, long transmission lines, low power factor, and harmonics [7–10]. Voltage fluctuation or instability as well as voltage sags/dips, noise, surges/spikes, and power outages are the common problems encountered during integration of large-scale wind energy into the grid. Variability of wind speed with time is not the only reason for these problems; grid connection issues, faults during operations, starting of large motors, and so forth are also responsible.

The energy conversion of the most modern wind turbines is done using fixed speed machines (often with the capability to operate at two different but constant speeds) and variable speed machines. Wound-rotor and permanent magnet synchronous generators are the most popular types of synchronous generators used in wind farms [11]. Induction generators are the most popular nowadays due to their simple, inexpensive, rugged, and low maintenance features. However, they require high starting currents and reactive power from the grid during operation [12]. Asynchronous or induction generators require power factor correction capacitors to start the generator and allow the wind farm to operate close to unity power factor. Reactive power will be injected if the capacitors are switched off after starting the wind farm that is use to maintain a uniform voltage profile on

Table 1: Allowable limit for distribution transformer (DT) loading, voltage regulation, and harmonics [18, 19].

Attributes	Recommended limit	Regulatory standard
DT loading	80% of the installed capacity, withstand up to 120%	
Inverter capacity	10 kVA for single phase 30 kVA for three phase	AS 4777 [18]
Voltage regulation	Allowable limit is ±6%, that is, 240 V ±6% for single phase and 415 V ±6% for three-phase systems Voltage rise due to PV at PCC is 1% at 240 V line to neutral voltage.	AS 4777 [18]
Harmonics	THD up to 50th harmonic should be less than 5% voltage harmonic limit to 8%.	AS 4777 [18]

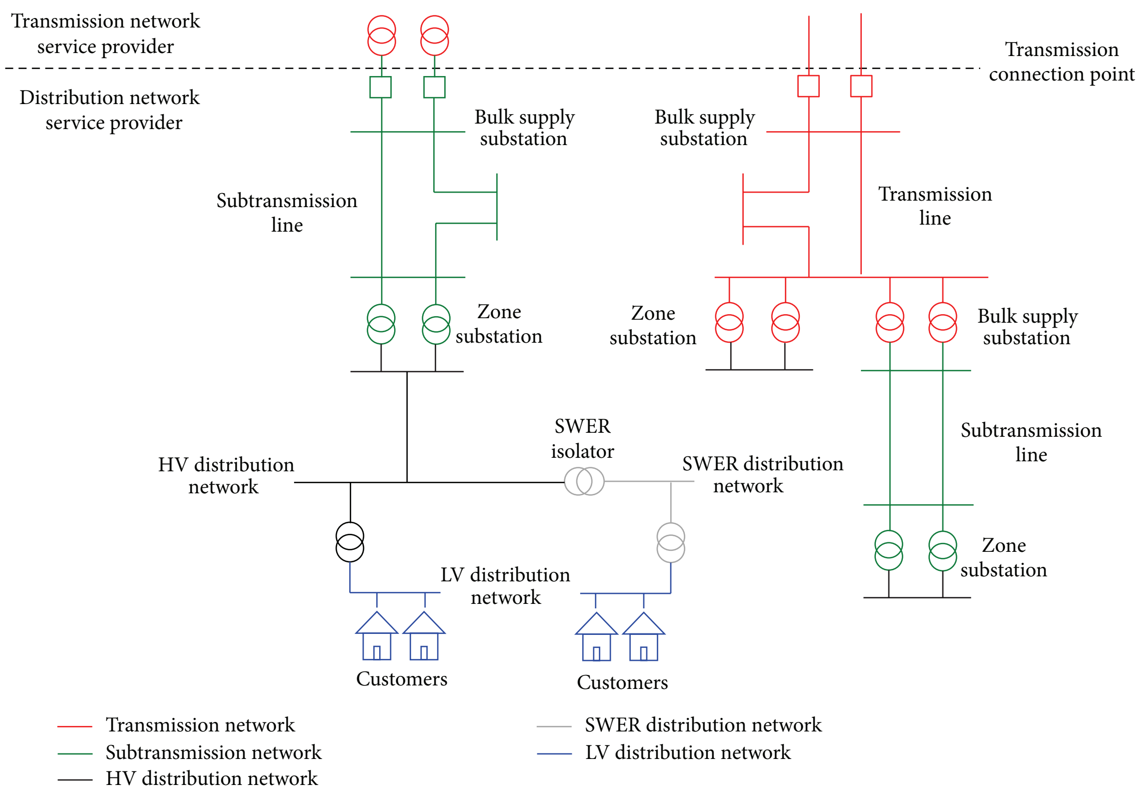


Figure 1: Ergon Power Distribution Network [20].

the network. In addition to reactive power, control of active power is a challenging task in squirrel-cage induction generators as they cannot provide active power and hence producing fluctuating electrical power due to wind speed variation [13]. On the other hand, doubly fed induction generators (DFIGs) are widely used in wind energy harvesting systems due to their reduced-size power converter, flexibility in autonomous control of the active and reactive power, and relatively simple and rugged structure. However, voltage unbalance and system harmonics can worsen the performance of DFIGs by introducing unwanted torque harmonics and inaccuracy in the generation of commanded active/reactive power [14].

Due to the fluctuations in the active and reactive power, the voltage at point of common connections (PCCs) fluctuates. Power electronic devices, together with operation of nonlinear appliances, inject harmonics into the grid which may potentially create voltage distortion problems [15]. Therefore, the major PQ problems encountered with the large-scale integration of wind energy into the grid are as follows [16, 17].

(i) Variations of wind speed cause power fluctuations on the grid.

(ii) In a weak grid, power fluctuations cause severe voltage fluctuations as well as significant line losses.

(iii) Uncontrollable reactive power consumption and low power factor.

(iv) Injection of harmonics into the grid which may potentially create voltage distortion problems.

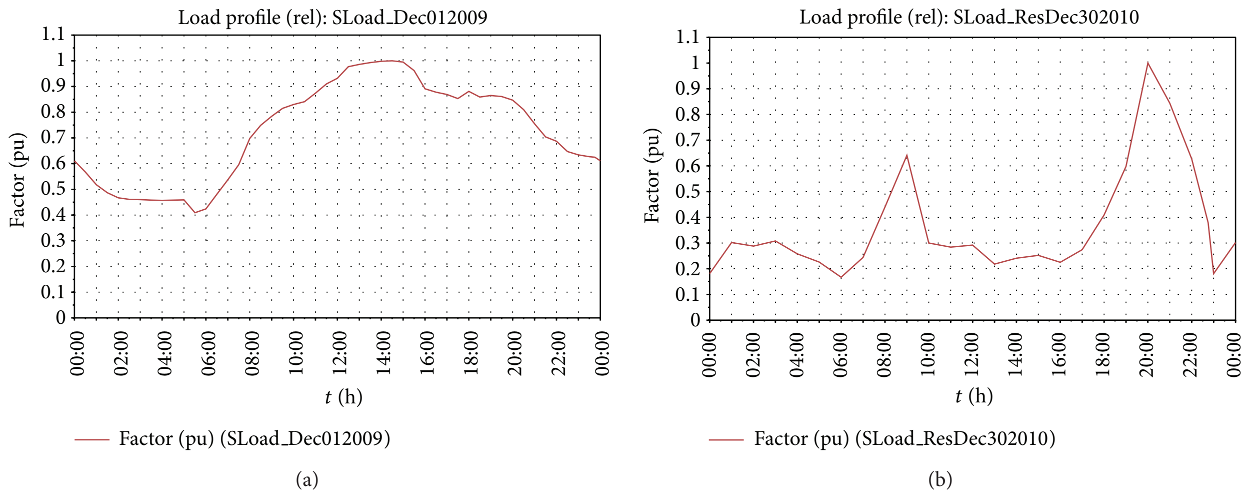


FIGURE 2: Rockhampton summer load profile (a) both commercial and residential and (b) only residential load.

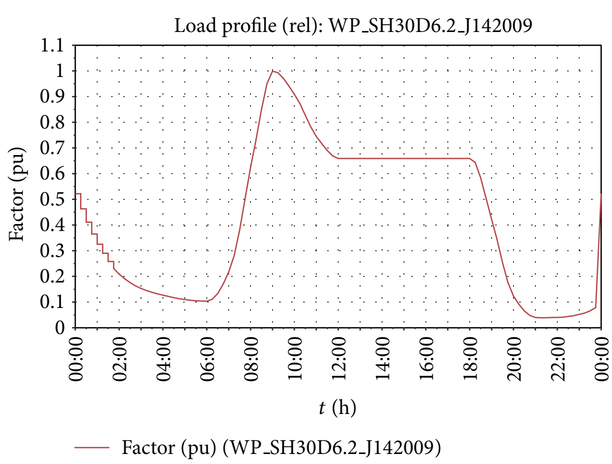


FIGURE 3: Rockhampton wind speed profile.

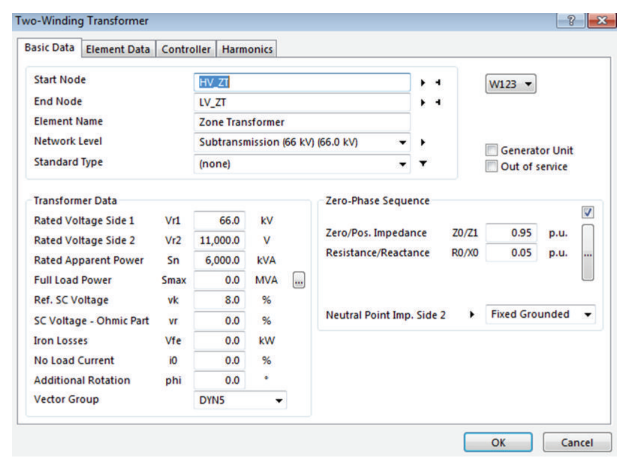


FIGURE 4: 66/11 kV Zone transformer.

Large-scale integration takes place under two main conditions: large wind farms connected to the transmission system and several small wind farms connected to the distribution system in one area of the power system [5]. There are several issues arising from large-scale wind power integration including voltage stability and dynamic power oscillations during normal operation of the power systems. In small-scale integration, the power system is assumed to have enough spinning reserve of active power that the frequency is able to be kept constant; therefore, only voltage problems are of concern. Lin et al. [21] investigated the current and future developments of power systems and wind energy integration into the systems in Taiwan. The major challenges focused on the study are wind turbine generators model, transmission planning criteria, renewable energy connection standards, wind variability, system reliability, and system operating costs.

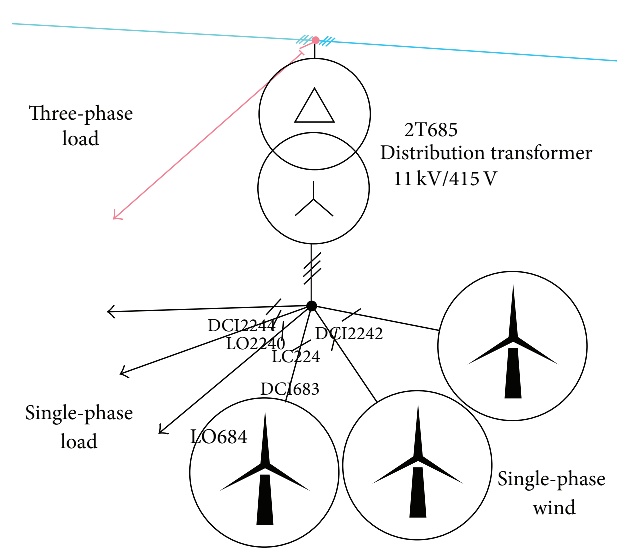


FIGURE 5: Single-phase load and wind turbine connection.

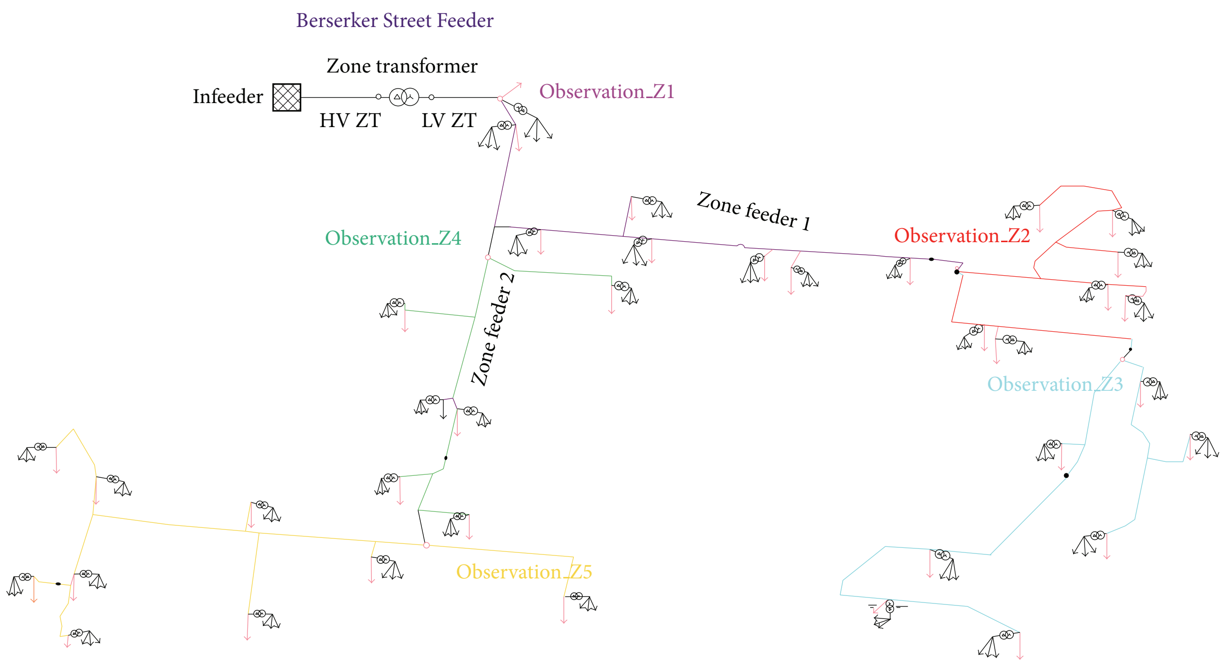


Figure 6: Only load connection.

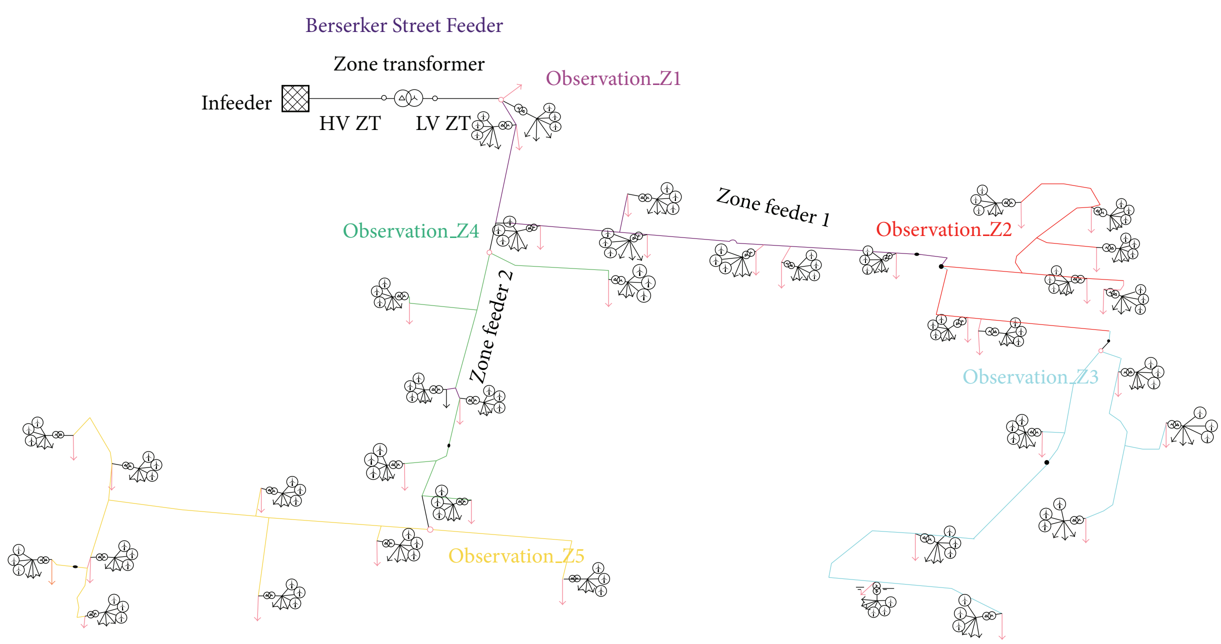
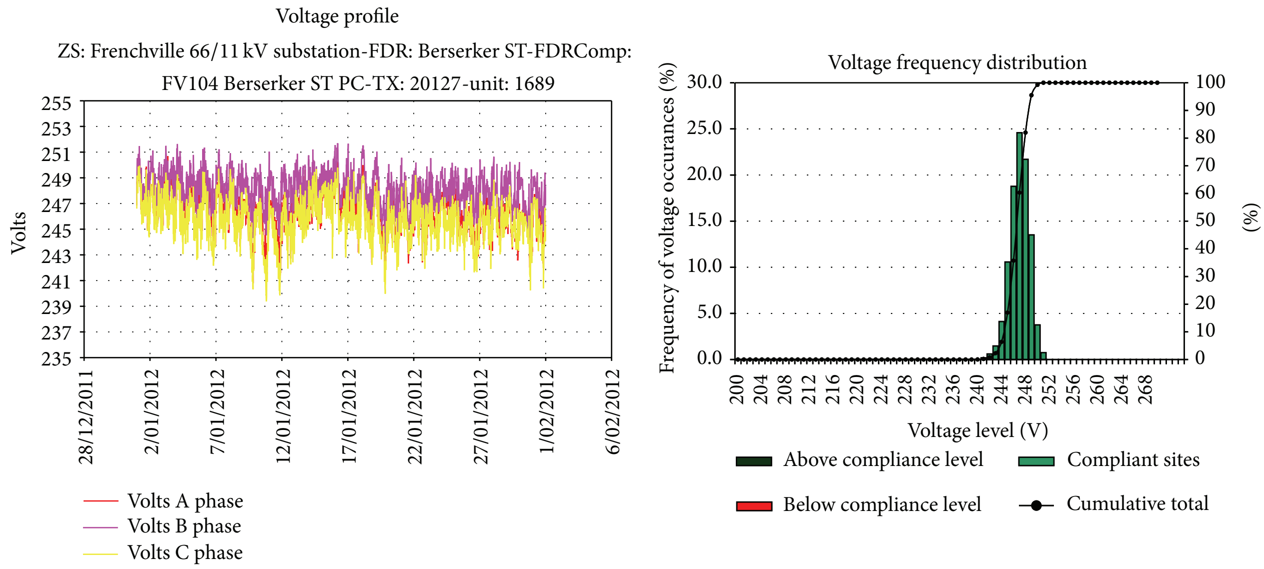


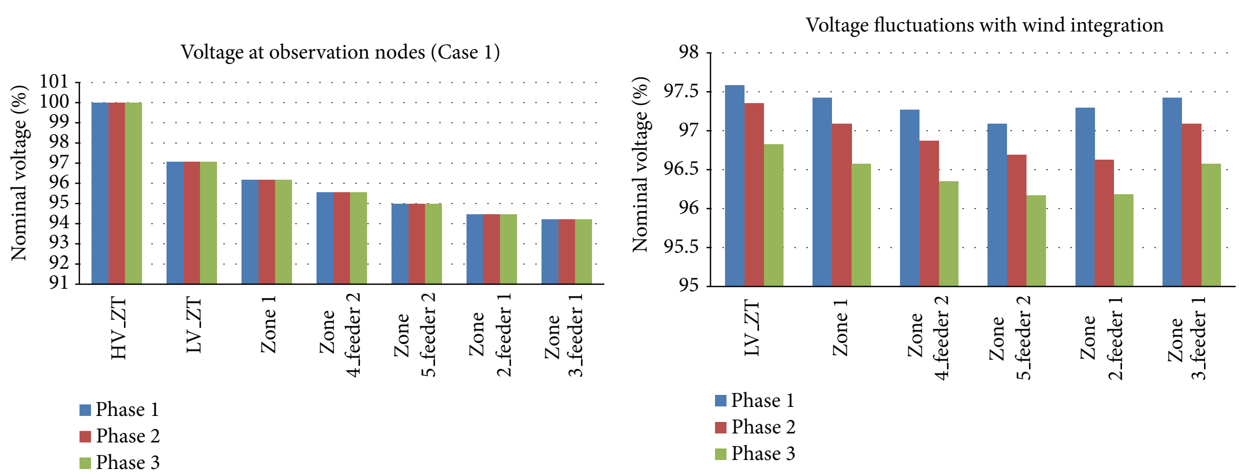
Figure 7: Wind integration with the feeder.

Ibrahim et al. [10] explore the potential technical challenges with possible solutions for wind power systems that include variability of wind, power system operating cost, and power quality. Authors concluded in [10] that the integration of the wind energy will be sustainable by using the power electronics equipment to connect the wind turbine at the electricity grid and development of hybrid systems with energy storage technologies. To evaluate voltage fluctuation and other PQ aspects, a comprehensive time-domain modelling of wind speed, wind turbine, and flickermeter was proposed by Ei-Tamaly et al. [22]. They investigated the influence of different factors on voltage fluctuation caused by wind turbines. In a study by El-Shimy et al. [23], it was observed that both the transient and voltage stability of the system are in a stable condition with a 24.55% wind penetration level and with SVC. However, the system became unstable in both transient and voltage stability at a 77.94% penetration level where it was found that SVC susceptance reached its



(a) (b)

Figure 8: (a) Voltage regulation and (b) frequency distribution from EDMI PQ meter.



(a) (b)

Figure 9: Voltage variation with (a) only load (Case 1) and (b) with 100% wind integration (Case 3).

upper limit. Characteristics of reactive power and voltage at the grid-connection point were evaluated through simulation analysis and it was observed that reactive power mostly depends on wind turbine power factor and active power output [24]. Results show that reactive power at the grid-connection point increases with the decrease of wind turbine PF. From the literature [12, 25], it was shown that DFIGs are the most efficient design for the regulation of reactive power and the adjustment of angular velocity to maximise the output power efficiency. These generators can also support the system during voltage sags, though this converter-based system injects harmonic distortion into the systems. Power quality behaviours, in particular voltage sags and harmonics injection into the network, were investigated in a study [26] on integrating wind energy into low voltage and medium voltage networks. Results showed low injection of voltage sags for all the three case study scenarios. Observed THD was within the safety limit as stated in the European standard EN 50160 [27]. However, THD increased with the increase of wind energy penetration into the system.

From the literature, it is observed that most of the available research was carried out primarily in the USA and Europe. However, the characteristics of Australian distribution networks are different compared to other developed countries in many forms. Therefore, research conducted by other countries could not simply be adopted without further research into the Australian context. Most of the research did not cover all of the potential technical impacts associated

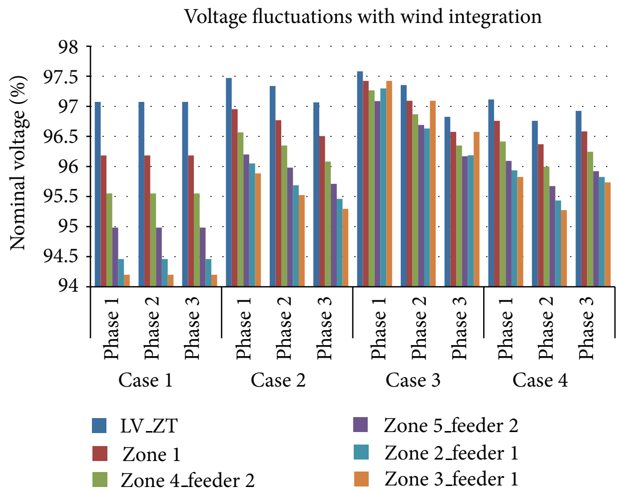


Figure 10: Voltage fluctuations with wind integration.

with integrating RE into the grid. Limited research has been conducted to explore adverse effects of the integration of large-scale RE into Australian power distribution networks. Therefore, to facilitate the integration of large-scale wind energy into the grid and to fulfil the Australian Government's 2020 emission target, this study developed models to investigate the influences of large-scale wind energy integration into the distribution network, in particular Rockhampton distribution network (DN). Initially, model was developed with integrating wind energy in the Berserker Street Feeder, Frenchville Substation under Rockhampton DN to explore the impacts in the observation nodes located in the high voltage (HV) DN, that is, 11 KV transmission line and zone transformer. Later, model was developed to investigate the impacts on the low voltage (LV) DN in particular integrating wind with a DT to supply electricity to the household customers.

2. Rockhampton Distribution Network

Generated electricity from Stanwell Power Station is transmitted over high voltage 132 kV transmission lines to Bulk Supply Substations (BSSs). BSSs supply power to the zone substations (ZSs) and large customers, and then ZSs feed the LV network or the residential customers. In Rockhampton city, seven zone substations link with forty-two feeders and each feeder is connected with a 66/11 kV step-down transformer to deliver 11 kV power supply to the high voltage DN. Basically, in Australia, the DN is a combination of HV (11 kV, 22 kV, and sometimes 33 kV), single wire earth return (SWER) (11 kV, 12.1 kV, and 19.1 kV), and LV (415 V L-L) lines. Step-down transformers (11 kV/415V) are used to supply electricity in the LV network, that is, to the customers' premises. A typical snapshot of the Rockhampton DN controlled by Ergon Energy is shown in Figure 1. Ergon Energy is the sole distribution network service provider (DNSP) in Rockhampton responsible for smooth power supply to the consumers [20, 28].

Electricity demand in Queensland, Australia, is increasing at a rate of 3.5% per year, and average customer peak demand is 4.3 kW [28] while average residential peak demand is 1.72 kW [29]. To meet energy demand, renewable energy, in particular wind turbine, is integrated into both the HV and the LV sides of the DN which introduce bidirectional power flow, in the network. In addition to uneven generation, integration of wind in various locations also increases loading on the DTs. Moreover, DTs are loaded maximally in peak demand time when wind cannot support load demand. Therefore, it is a future requirement to upgrade the capacity of existing DTs to accommodate increasing load demand. Moreover, as discussed earlier, the intermittent nature of output from wind turbine influences voltage regulation, power flow and harmonics at the PCC to the DN. Ergon Energy [30] as a DNSP provides allowable limits that facilitate RE integration into the LV DN to ensure uninterrupted and reliable power supply in the Rockhampton DN as shown in Table 1.

3. Impact Analysis Model

3.1. Introduction. This study developed an impact analysis model using PSS SINCAL [31] to investigate the impacts of large-scale wind energy integration into the Rockhampton DN. Considering flexibility and robustness of the model and to know the precise scenarios of the level of impacts on large-scale wind integration into the Rockhampton DN, this study explores the network from two different angles by dropping down the network from the HV DN to the LV DN. Initially, model was developed for Berserker Street Feeder under Frenchville Substation and explores the potential impacts of integrating large-scale wind energy into the feeder. Later, model was developed considering residential loading under a distribution transformer in the Berserker Street Feeder. In each of these case studies, several case scenarios were considered based on level of network loading and wind integration.

This study investigates voltage regulation, phase unbalance conditions, power flow characteristics, transformer utilisations, and total harmonic distortion of each busbar of a wind integrated system. Load flow analysis was carried out to investigate the voltage regulation with active and reactive power requirement of the HV and LV network. Load curve simulation was conducted to explore transformer loading, voltage, and power regulation of the system over time.

3.2. Model Evaluation

3.2.1. Load Allocation. From daily load profile (summer: January 01, 2009 and winter: July 01 2009) of Rockhampton, Capricornia region, Australia, it is shown that maximum load was measured at 2:00 PM in summer and at 6:00 PM in winter. Daily load profiles for summer used in this study are presented in Figure 2(a) in per unit (*p.u.*) values. However, load demand of the residential load depends mostly on the working nature and appliances used by residents which is different than the load profile shown in Figure 2(a). The

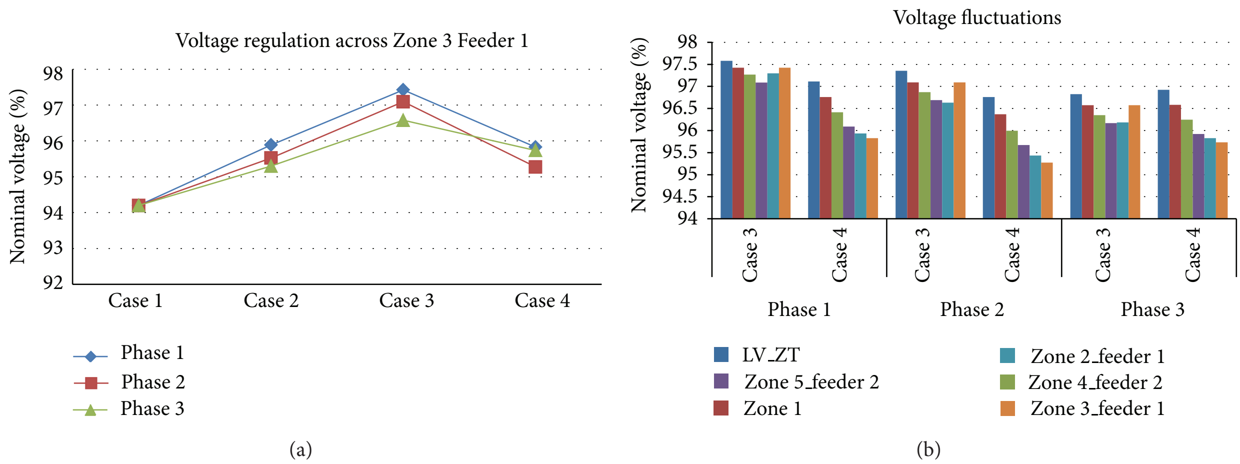


FIGURE 11: Voltage regulation (a) Zone 3 Feeder 1 and (b) with centralised and decentralised wind integration.

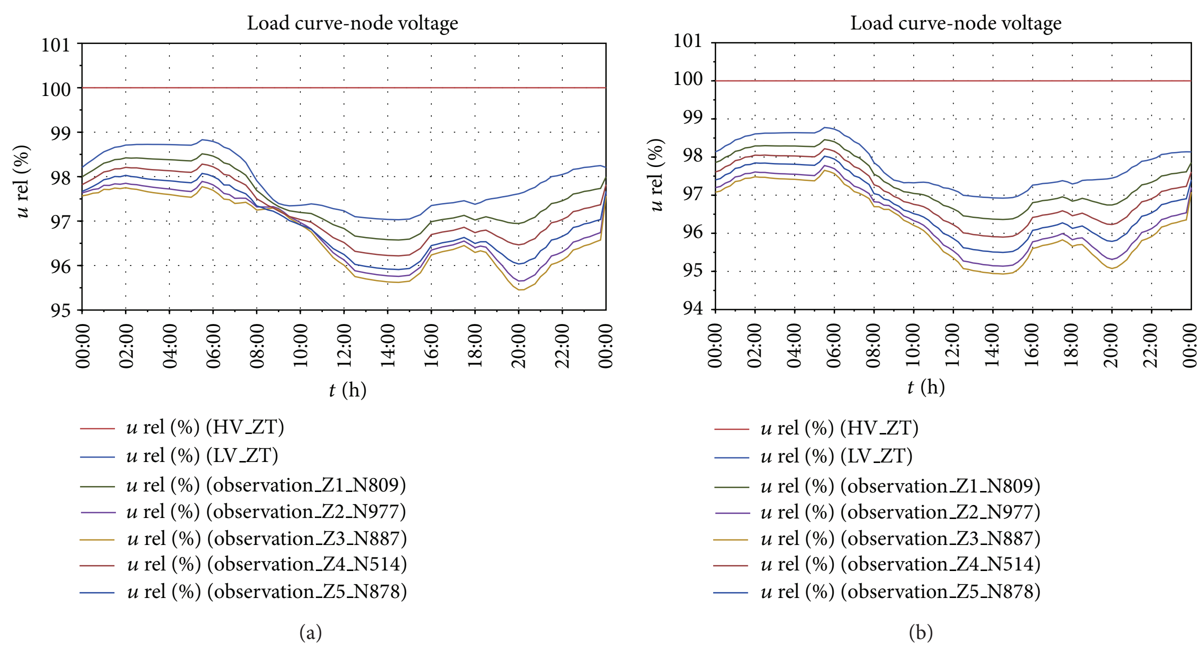


FIGURE 12: Voltage profile with 100% wind integration (a) decentralised and (b) centralised connection approach.

average load pattern in the residential areas is shown in Figure 2(b) in which it has been seen that electricity demand is very high in the evening and also in the morning when most households are at home.

Due to the nature of the dynamic power system, it is difficult to develop a harmonic distortion of generalized systems loads. Total harmonic current distortion of most typical daytime loads is 17.11% for the required input current of less than 16A [32]. Maximum THD observed in Berserker Street Feeder is 2.0% which is almost 12% of the stated THD as per AS/NZS 61000.3.2 [32]. However, considering flexibility of the models, this study considered current harmonic limits of 25% of the standard limits.

3.2.2. Wind Allocation. Hourly average summer wind speed of Rockhampton, Australia, collected from the BOM [33] is used for load flow analysis. Wind profiles are presented in *p.u.* value as shown in Figure 3 which was synthesised from the hourly wind speed collected from Rockhampton Aero Weather Station (REWS) from the year 2003 to 2010. From Figure 3, it has been observed that reasonable wind speed is available only from 7:30 AM to 7:30 PM and 11:30 PM to 1:00 AM. Peak wind speed is at 8:00 AM. The maximum current harmonics for interconnecting distributed resources such as wind with electric power systems are given in IEEE Std. 1547 [34]. This standard also accomplishes with the most common industry standard IEEE 519-92 for power quality

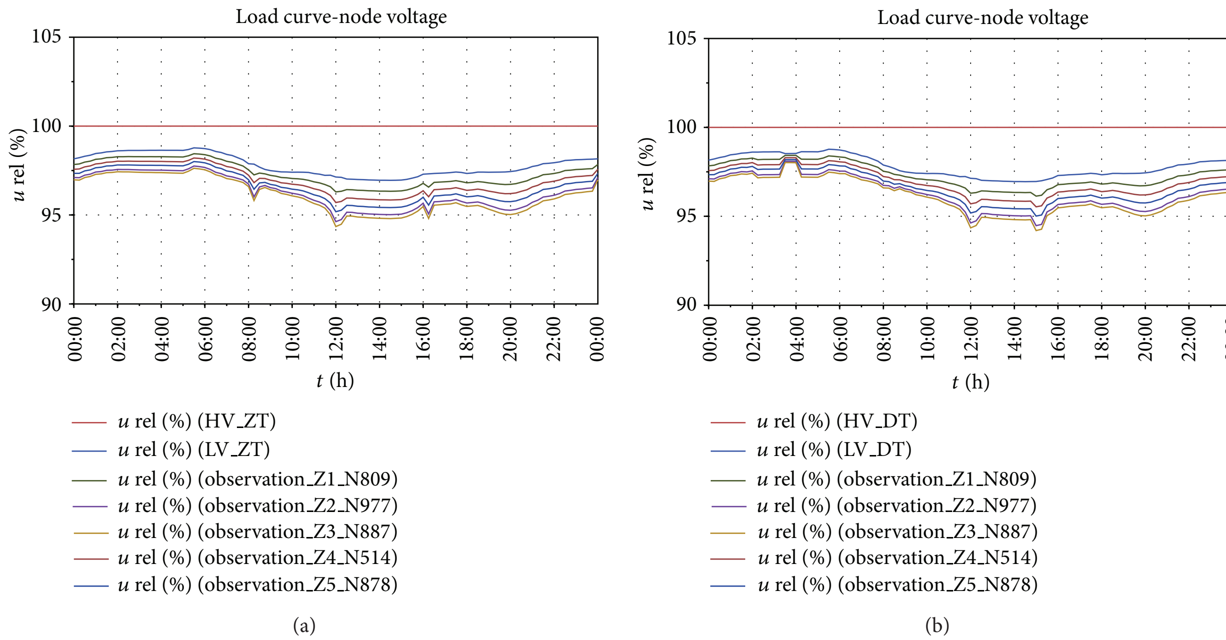


Figure 13: Voltage fluctuations due to storm (a) MFS and (b) FFS.

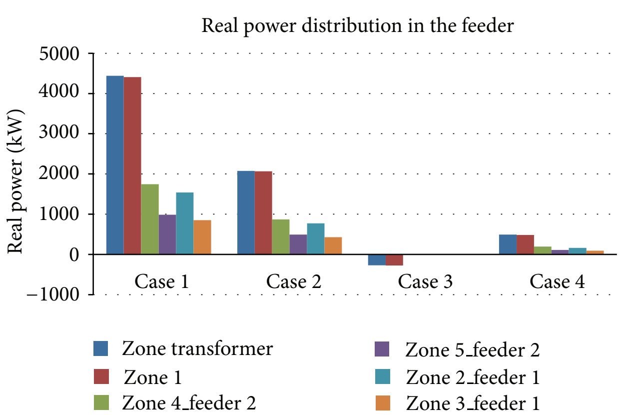


Figure 14: Active power distribution.

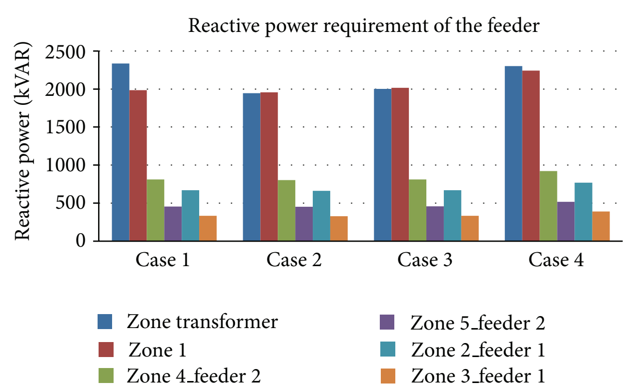


Figure 15: Reactive power requirement.

governing winds power plants. This study used 10 kW and 30 kW wind turbine in the LV DN and 30 kW and 100 kW in the HV DN with the current harmonic limits.

3.3. High Voltage (HV) Distribution Network

3.3.1. Berserker Street Feeder. Berserker Street Feeder, Frenchville Substation comprises of 1442 industrial and residential customers with a connected load of 4775 KVA. Ergon Energy as a local DNSP is fully responsible for smooth delivery of electricity to the customer in the Berserker Street Feeder. To monitor the PQ of the feeder, Ergon Energy installed an EDMI MK 10 PQ meter (PQ metering site 1689) in the transformer (TX: 20127) on Berserker Street Feeder, Frenchville Substation. This PQ meter measures phase voltages with angles, phase unbalance condition, and voltage harmonic distortion of the zone feeders. This study initially explores the data obtained from the PQ meter to analyse the potential PQ issues with their level of impacts on the feeder as well as in the DN. Currently, only 1% PV of total loading is integrated with the feeder and, hence, it can be stated that this results mostly based on the connected customer load along with line impedances. Therefore, simulation model was developed to further explore the impacts of large-scale RE integration into the Feeder.

A 66/11 kV step-down zone transformer (ZT) with a capacity of 6250KVA was considered in the Frenchville Substation to deliver power supply in the Berserker Street Feeder.

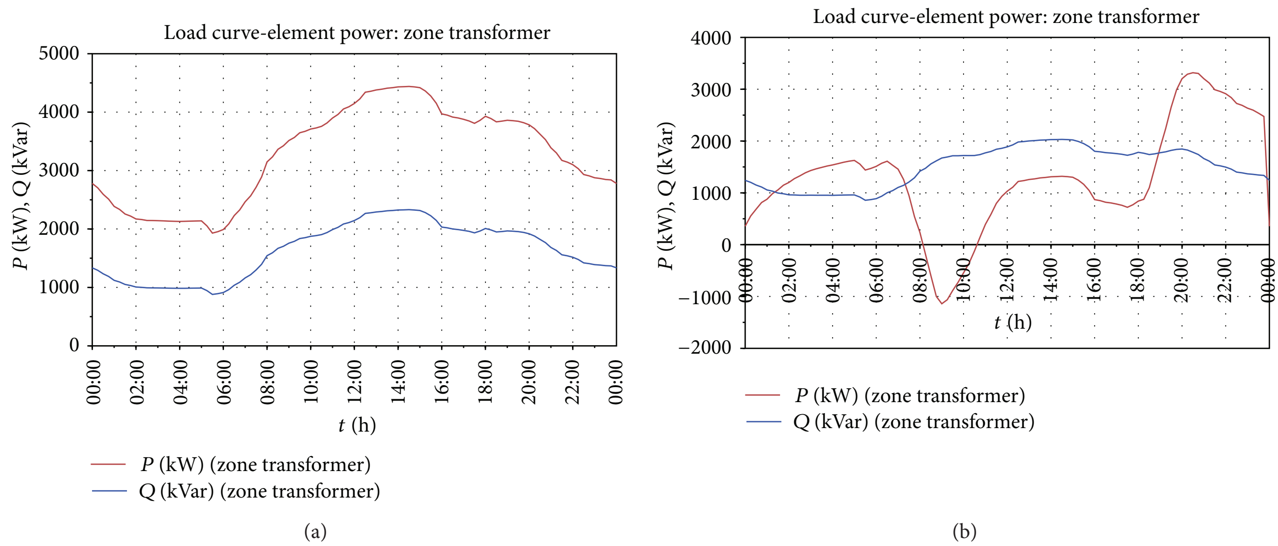


FIGURE 16: Power distribution across zone transformer (a) Case 1 and (b) Case 3.

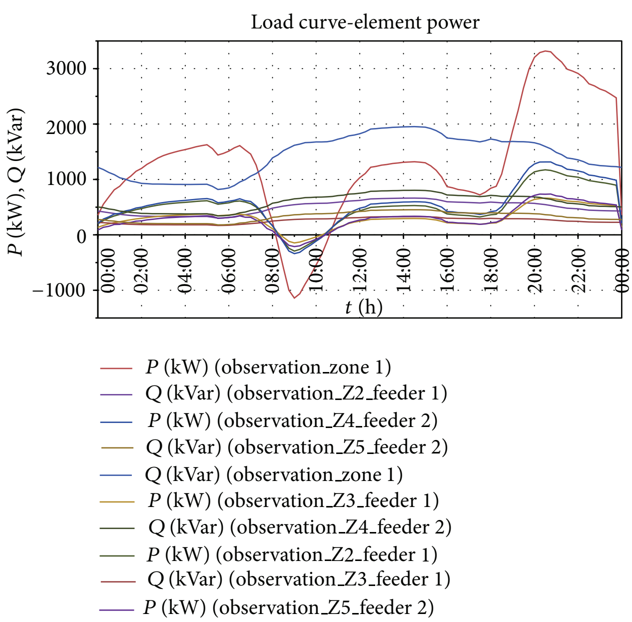


FIGURE 17: Power distribution across zone feeders for Case 3.

The zero sequence resistance and reactance of the step-down transformer is 1.2937 and 25.84414 with 8% short circuit voltage as shown in Figure 4. The feeder was subdivided into two zone feeders and several zone observation points to observe the transformer utilization, voltage regulation, power characteristics, and adverse harmonics effects of the feeder as well as in the HV DN. Observation node Zone 3 Feeder 1 was considered with the same transformer the PQ meter was connected with. Therefore, this zone has used to compare the model results with the real live data analysis information.

Each of the three phases HV load was transformed to three single-phase loads with equal amount through an 11 kV/415V DT, hence, zone wise load allocation remains the same. Single-phase wind turbine was connected in the LV side of the DT as shown in Figure 5 and amount of wind turbine utilisation depends on the percentage of load demand based on considered case scenarios. Wind turbine also connected in centralized connection approach and considered one centralized plant in each zone. Losses until inverter and inverter efficiency were considered as 5% and 97%, respectively, for wind.

3.3.2. Modelling Case Scenarios. Considering feeder load demand and future wind energy integration several case scenarios were considered and accordingly developed the model. Actual line length and impedances are considered for all of the studied case scenarios. The case scenarios considered in this case study are as follows.

Case 1 (*only grid*). This case study only considers connected loads without any RE integration, that is, only grid supplies electricity to the customers as shown in Figure 6.

Case 2 (*grid with 50% wind energy integration*). In this case, 50% energy from wind of total loading was connected in the feeder as shown in Figure 7.

Case 3 (*grid with 100% wind energy integration*). In this case, 100% energy from wind of total loading was connected in the feeder.

Case 4 (*grid with centralised 100% wind energy connection*). In this case, centralised wind generation was considered into the feeder and connected only one location in each zone. Each wind plant generates electricity that is expected to meet energy demand of the customers connected in each zone as the connected wind capacity is 100% of total loading.

In addition to the above-mentioned case scenarios, this study also further explores the impacts of integrating wind

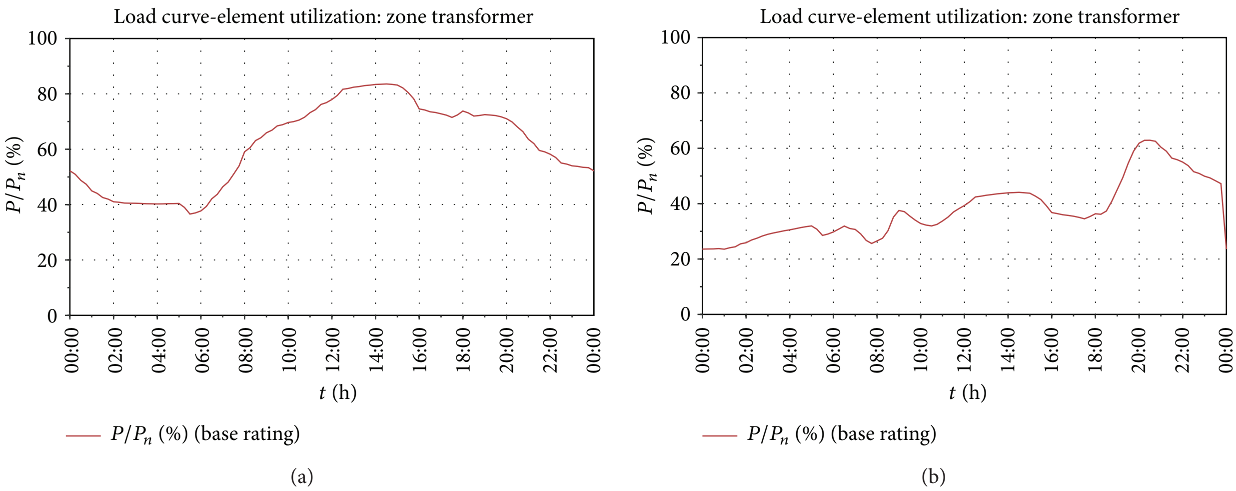


Figure 18: ZT utilisation (a) Case 1 and (b) Case 3.

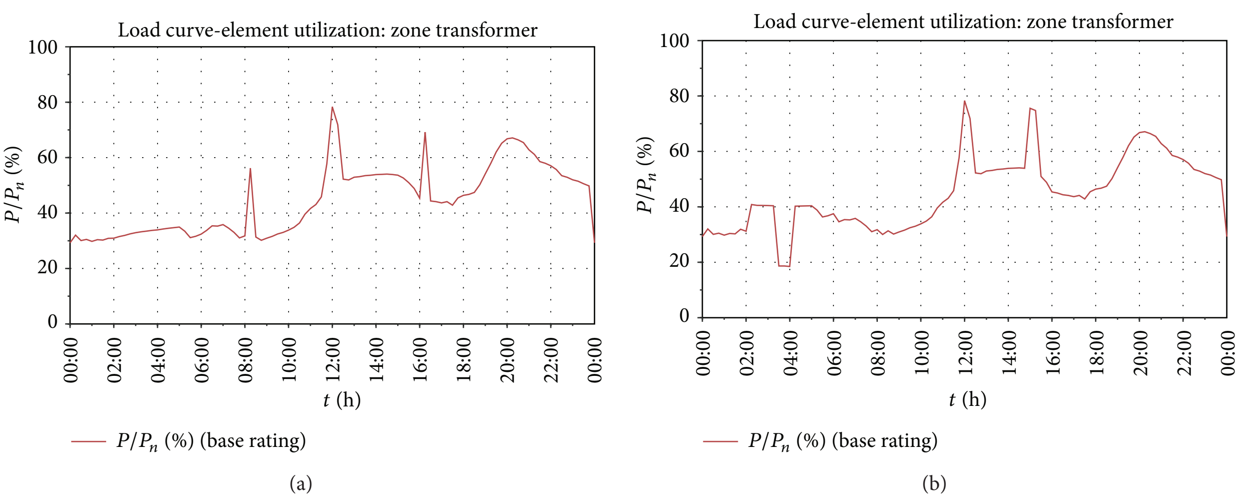


Figure 19: ZT utilisation (a) MFS and (b) FFS.

with fluctuating generation due to thunder or storm. Irregular winds speed, for example, during storm, causes uncertainties in the energy generation as well as malfunctioning of the DN. Therefore, this study considered the following cases to explore the effects of storm in energy generation.

(i) Base case: Grid with 100% wind energy integration.

(ii) Case MFS: Considered wind profiles with medium fluctuations during storm (MFS).

(iii) Case FFS: Considered wind profiles with frequent fluctuations during storm (FFS).

3.3.3. Results Analysis

(1) Voltage Regulation. From the load flow analyses, it was clearly evident that voltage of the Berserker Street Feeder fluctuates with the increased integration of wind turbine and causes uncertainties in the feeder as well as in the DN. From load flow analysis, it was observed that voltage gradually decreases from the source station, that is, zone substation to the load connection point. This study initially explores the voltage regulation scenarios of Berserker Street Feeder from the data collected by EDMI PQ meter at Ergon Energy. The EDMI meter measures phase voltages and phase angles of the zone feeders. Figures 8(a) and 8(b) show the voltage regulation and frequency distribution of voltages in the month of January. From Figures 8(a) and 8(b), it can be stated that observed minimum feeder phase voltage is 242 V and maximum phase voltage is 251 V while system voltage is only 250 V. Most of the time system voltage is lower than the nominal voltage and in few instances the voltage limit crosses the lower allowable limit of −6%.

Figure 9(a) shows the voltage variation of HV ZT, LV ZT, and zone observation points and from the figure it can be

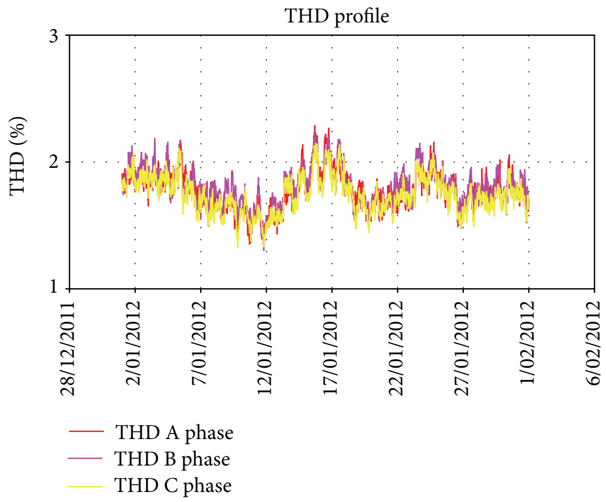


Figure 20: Voltage harmonic distortion measured by EDMI meter.

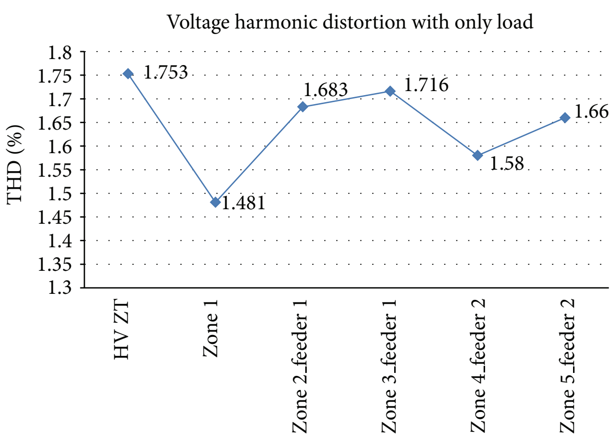


Figure 21: Voltage harmonic distortion for Case 1.

stated that voltage reduces from the HV ZT to rear end observation point Zone 3 Feeder 1 for Case 1. Transmission line impedances along with distribution transformer throughout the network are responsible for this voltage drop. From Figure 9(a), it was shown that voltages are the same for all phases as it is a balanced system. However, the phase voltages vary with integration of equal amount of wind turbine in each phase as voltage rises occur in both the phase and neutral conductors as shown in Figure 9(b). Moreover, wind turbine was connected near the load centre and causes bi-directional power flows in the system.

Voltage regulation from Case 1 to Case 4 is shown in Figure 10, in which it was shown that voltage level reduces from substation to the customer end for all of the case scenarios. However, phase voltages increase with the increase of wind energy integration in all of the observation points as shown from Case 2 to Case 3. This happened due to the bi-directional power flow at the point of wind turbine connection as the wind turbine was connected near the customer load. Load demand and electricity generation from wind turbine in a particular time are also responsible for uncertainties in the network.

Voltage regulation of Zone 3 Feeder 1 with the integration of wind energy is shown in Figure 11(a), in which it was clearly evident that voltage rises significantly with the increase of wind turbine integration into the network though the increased voltage levels are within the allowable safety limit. Case 2 and Case 3 have the same configurations except for the level of wind energy integration and from Figure 11(a) it was clearly indicated that feeder voltage rises with the increased integration of wind energy. Voltage in Zone 3 Feeder 1 in Case 1 was reduced to 94.2% of the nominal voltage. This result is almost identical to the voltage seen from the EDMI PQ meter.

This study also considered centralised and decentralised wind turbine connection approach to explore the suitability of wind integration into the Berserker Street Feeder. Figure 11(b) shows the voltage regulation of decentralised (Case 3) and centralised wind turbine connection (Case 4) and it was shown that phase voltages decreases in different observation points in the centralised connection approach. It is to be noted that load flow study only defines the maximum voltage levels in a particular time of the day. However, to know the exact voltage regulation scenarios over time this study carried out load curve analysis.

Figures 12(a) and 12(b) for Cases 3 and 4 show voltage regulation over time with wind energy generation through decentralised and centralised connection approach, respectively. From figures, it was shown that the amount of voltage reduction is higher in the centralised connection approach in comparison to decentralised connection. Feeder load demand is the lowest from 1:00 am to 6:00 am and the level of voltages across the zone transformer is 98.6% of the nominal voltage. Wind generation is maximum at 8:00 am while load demand is also high and hence, feeder voltage reduces to 97.5% as shown in Figure 12(a). Voltage further reduces with the increase of load demand in the middle of the day though there is sufficient generation from wind. Feeder voltage dropped to the lowest level at 8:00 pm while there was high load demand with minimum wind generation as shown in Figure 12(a).

Wind speed varies with thunder or storm and, hence, generation from wind turbine fluctuates with medium and frequent wind fluctuations which influence system voltage of the DN. Load curve analyses reveal the voltages in different observation point over time and from Figures 13(a) and 13(b) it was shown that the voltage varies over time with the medium and frequent wind fluctuations. From Figure 13(b), it was shown that the lowest voltage observed in Zone 3 Feeder 1 at 3:00 PM was 94.19% while in the base case (Case 3) the lowest observed voltage was 94.93% of the rated voltage.

(2) Power Distribution. This part of the study explores the power flow characteristics of Berserker Street Feeder for different studied system configurations and wind integration. Active power requirement in all of the observation zone point for different case scenarios were shown in Figure 14. From Figure 14, it was shown that power requirement from the grid was reduced with the increased integration of wind energy. Grid needs to supply 4440 kW active power to meet customer

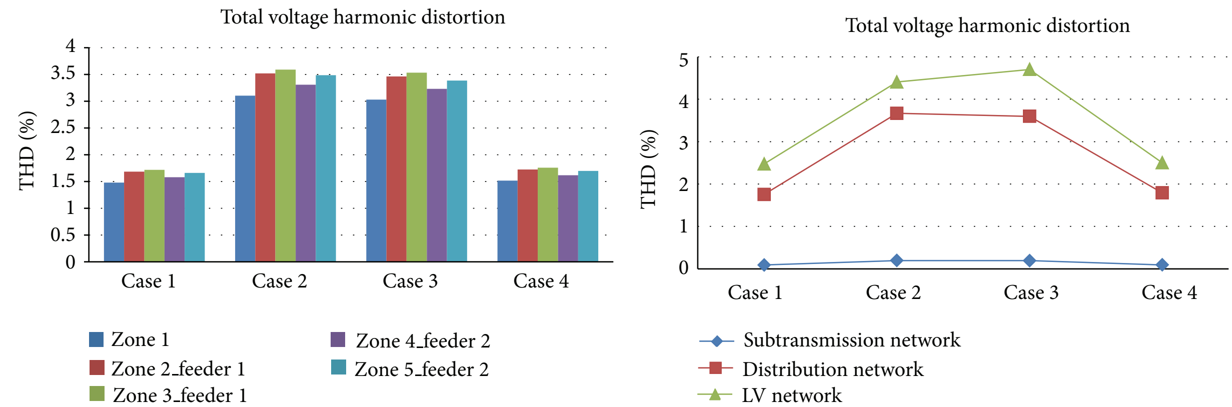


Figure 22: Voltage harmonic distortion (a) for all observation nodes and (b) only HV ZT and LV ZT.

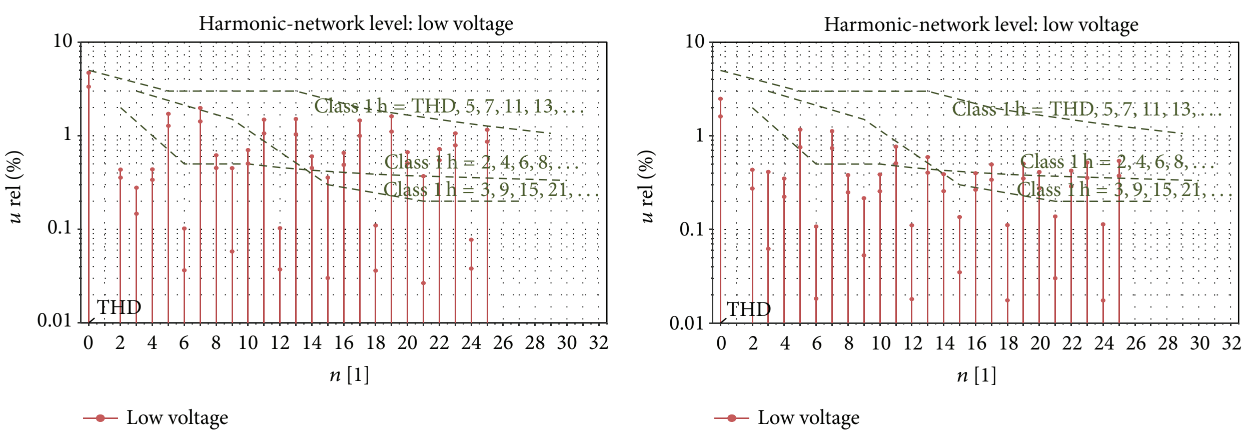


Figure 23: Voltage harmonic distortion with wind integration (a) Case 3 and (b) Case 4.

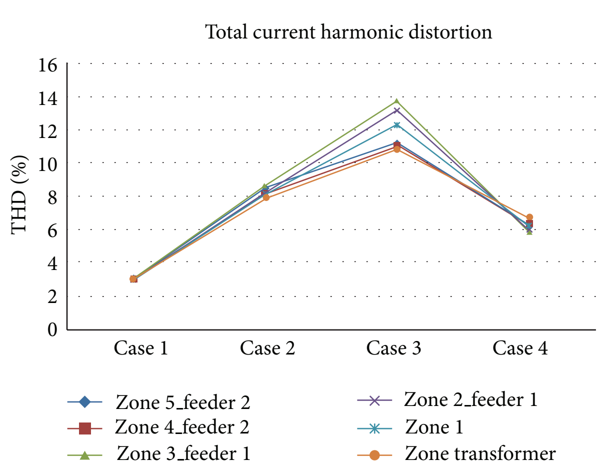


Figure 24: Total current harmonic distortion in balanced systems.

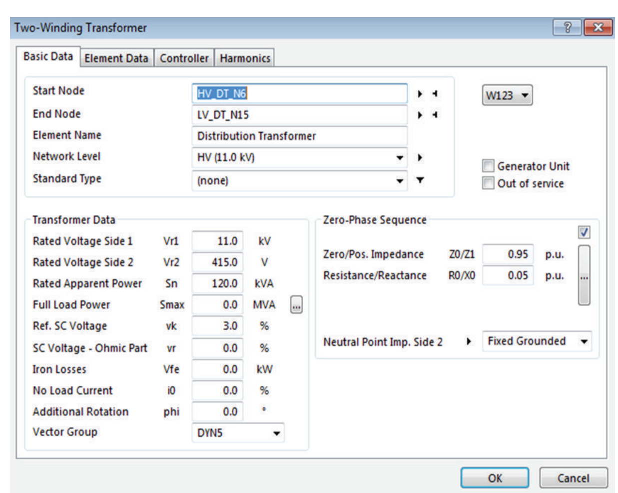


Figure 25: LV distribution transformer.

load demand in the Berserker Street Feeder without wind integration as shown in Case 1. However, power requirement from the grid is reduced with the increasing of energy generation from wind. In Case 3, with the integration of 100% wind of total loading, there was a surplus electricity

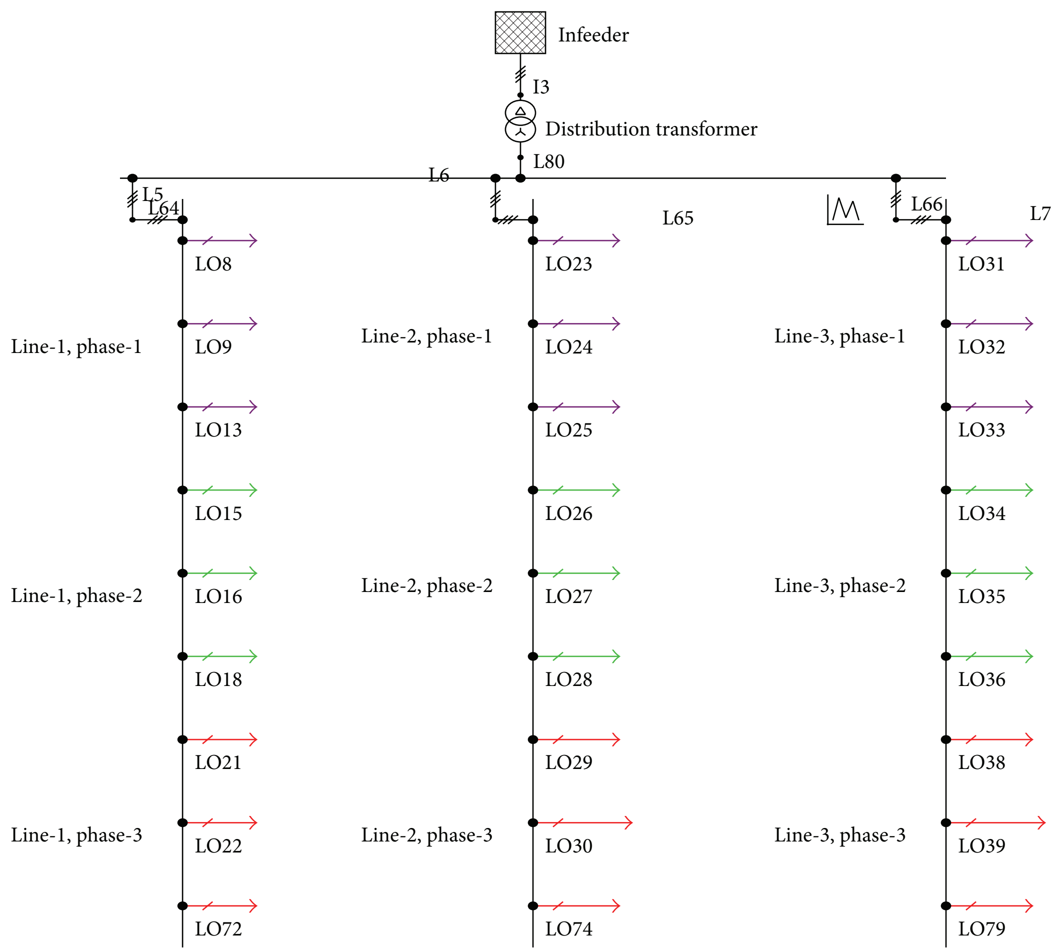


FIGURE 26: Only load connection.

of 268 kW that can be fed back to the grid in the Berserker Street Feeder. Basically, load flow analysis only provides the maximum energy generation. Actual generation from wind over time was explored from the load curve analysis.

Reactive power requirement in all of the observation points were shown in Figure 15. Reactive power requirement from the grid decreases significantly as the requirement of active power from grid decreases due to increased wind generation. However, overall reactive power requirement decreases slightly as wind power requires reactive power for its operation as shown in Figure 15. Reactive power requirement increases with the increase of wind integration as shown in Cases 2 and 3. In Case 4, it was shown that power generation is reduced in the centralised wind turbine connection compared to the decentralised connection (Case 3). However, reactive power requirement is increased from 2001 kVAR (Case 3) to 2302 kVAR (Case 4). From Figure 15, it was shown that customer connected nonlinear loads and wind turbine were responsible for the requirement of reactive power in the feeder. This also influences poor power factor regulation in the DN as well as affects the PQ of the network.

Power generation over time was observed in Figures 16(a) and 16(b) for Cases 1 and 3. From Figure 16(b), it has seen that wind energy has the capability to generate energy throughout the day and maximum generation from wind was at 8:00 am and can feedback surplus electricity to the grid. From Figures 16(a) and 16(b), it can be stated that at 12:00 am grid needs to supply approximately 2550 kW and 375 kW electricity, respectively, while at 8:00 am 3250 kW and 250 kW and at 8:00 pm 3750 kW and 3200 kW electricity. Power distribution across different zone observation points was shown in Figure 17.

(3) Zone Substation Transformer (ZT) Utilisation. Transformers connected in the DN have specific loading or utilisation capacity and for smooth power supply to customers, it is essential to operate each ZT within its safe operating limits designated by local DNSP. From Figure 18(a), it was shown that without any RE integration the maximum utilisation of the zone substation transformer is 86.3% at 2:00 pm while the load demand is maximum. ZT utilisation was reduced to 44% at 2:00 pm and 62% at 8:00 pm with the integration of wind turbine into the feeder as shown in Figure 18(b).

Variations in wind speed due to storm also influence ZT loading as well as network power generation. ZT loading was increased with the decrease of wind speed and raised to 78%

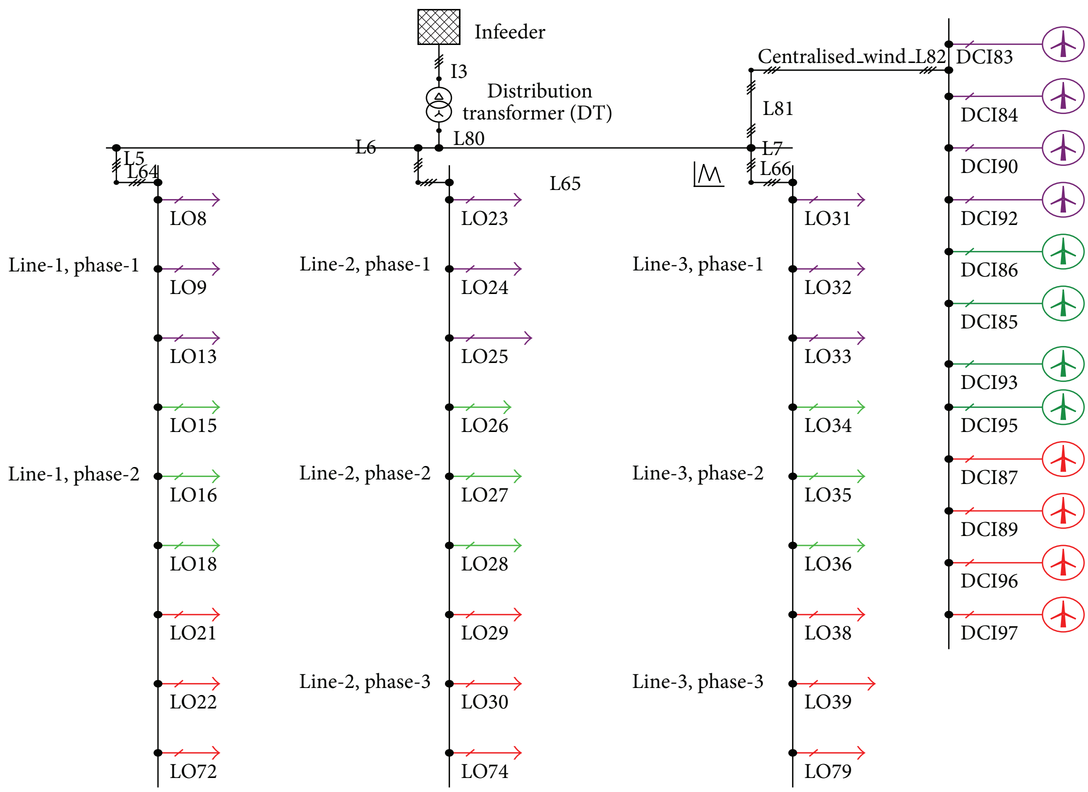


Figure 27: Centralised wind connection.

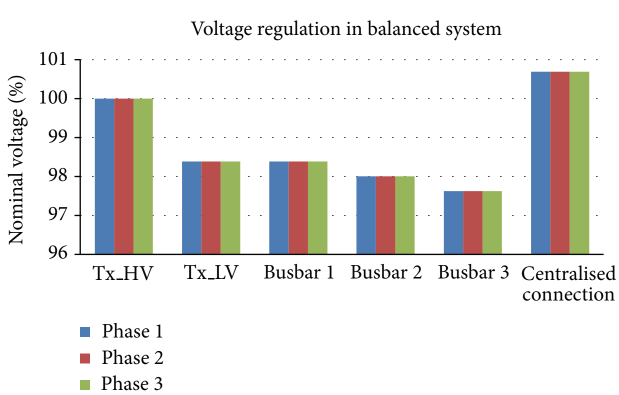


Figure 28: Voltage fluctuations in three phases.

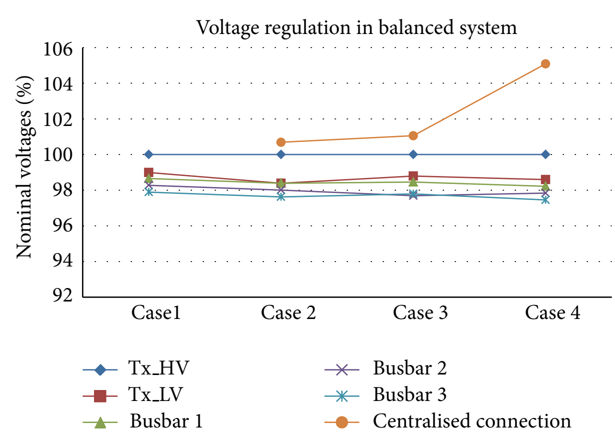


Figure 29: Voltage fluctuations with centralised wind integration.

at 12:00 pm while only 44% in the base case (Case 3) as shown in Figures 19(a) and 19(b). On the other hand, ZT loading was decreased to 18% at 4:00 pm with the increase wind speed while 34% in the base case (Case 3).

(4) Harmonic Distortion. From the collected EDMI data, this study further analyses the total harmonic distortion of Berserker Street Feeder in summer and winter. Figure 20 shows the frequency distribution of THD in the month of January 2012. It was shown that total voltage harmonic distortion in the month of January (summer) is 1.8% while in the month of July (winter) is 2.0%. This study initially developed model considering only customer load connection (Case 1) and explored total voltage harmonic distortion for summer in different observation nodes in the feeder as shown in Figure 21 in which it was shown that THD across ZT transformer is 1.75% and across Zone 3 Feeder 1 is 1.72%. It can be stated that observed THD is almost identical to the THD obtained from collected data and, hence, model results validated the real live EDMI PQ meter data with negligible error. This study further explores the THD of the

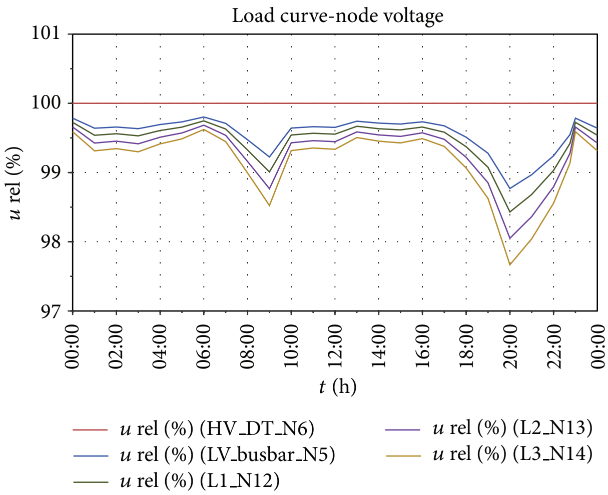


Figure 30: Voltage variations without wind integration.

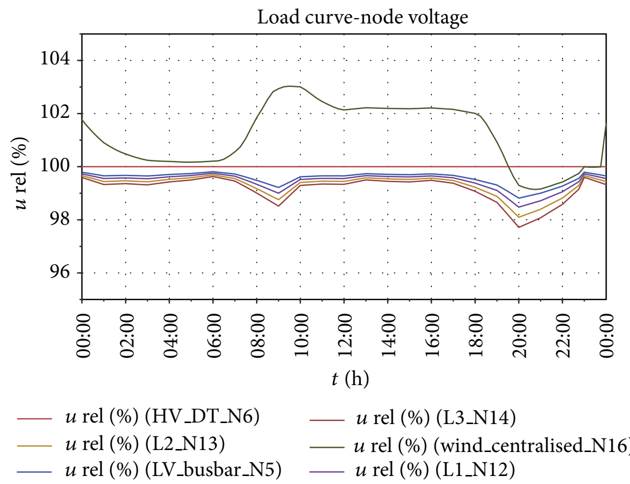


Figure 31: Voltage variations with 100% wind of total loading.

feeder considering different wind energy integration and load demand.

Voltage harmonic distortion of different studied case scenarios are shown in Figure 22(a) in which it is evident that voltage harmonics in different observation point increase with the increase of wind energy integration. Cases 2 and 3 were same systems configurations except for the fact that level of wind integration and total voltage harmonics distortion for Cases 2 and 3 are 4.4% and 4.69%. Therefore, it can be stated that use of power electronic devices in wind turbine along with intermittent generation causes harmonics in the system. Voltage harmonics distortion across the HV and LV sides of the zone transformer is shown in Figure 22(b) in which it has been seen that harmonic distortion exceeded the regulatory limits across the LV side of the ZT for Cases 2 and 3 while in the HV side all cases are within the safe limits. However, harmonics in the transmission line are almost negligible. From Figures 22(a) and 22(b), it was shown that voltage harmonics of the feeder were reduced in centralised connection approach compared to decentralised connection approach.

Individual harmonics level in addition to the THD is shown in Figures 23(a) and 23(b) for Cases 3 and 4 and in which it has been clearly indicated that total voltage harmonics are lower in centralized wind turbine connection (Case 4) compared to decentralized (Case 3) connection approach. From Figure 23(a), it was shown that THD just touches the threshold level, however, 8th, 10th, 14th, 16th, 19th, 20th, and 21st harmonics exceeded the allowable regulatory limits. Total voltage harmonics distortion for all of the studied cases except for Case 3 are within the Australian regulatory standard limit as stated in AS4777 [25].

Harmonic current is the most concern as most of the adverse effects in the distribution network causes are due to these currents. From the simulation results, it has been clearly indicated that current harmonics increase with the increase of wind integration into the Berserker Street Feeder as well as in the DN. Total current harmonic distortion in different observation zone point is shown in Figure 24 in which it is clearly indicated that harmonic distortion increase with the increase of wind turbine utlisation. THDs for Cases 1, 2, 3, and 4 are 3.02%, 7.91%, 10.81%, and 6.71% across the zone transformer in which Case 3 exceeded the regulatory standard limit as shown in Figure 24. Current harmonic distortion was reduced in the case of centralised connection (Case 4) compared to decentralised connection (Case 3) approach.

Therefore, it can be evident that integration of large-scale wind energy into the Berserker Street Feeder, Frenchville substation causes uncertainties in the HV DN and introduces voltage fluctuations, poor power factor regulation, and injected harmonics. Next section further explores the influences of wind energy integration into the LV DN.

3.4. Low Voltage (LV) Distribution Network

3.4.1. Waterloo Street. This part of the study investigates the potential barriers to integrating wind energy into the LV DN. This study considers a residential load of 94.5 KVA at Waterloo Street under Berserker Feeder and this HV load was transformed to LV load by connecting through 120 KVA 11 KV/415 V DT as shown in Figure 25. The zero to positive sequence ratio of the DT is 0.95 and resistance to reactance ratio of 0.05 with short circuit reference voltage of 3.0%. Customer loads are connected from a central busbar comprising three busbars 100 m, 200 m, and 300 m apart from the DT. Based on the average summer load demand, the system comprises all equal residential consumer loads of 3.5 KVA with 0.9 power factors, 9 loads in a line with 3 loads in each phase, a total of 27 customers connected in the system as shown in Figure 26. Wind energy was considered for centralised bulk generation and connected centrally which is 500 m from the DT and only 10 kW and 30 kW wind turbines were used considering 5% losses until inverted with an inverter efficiency of 97%.

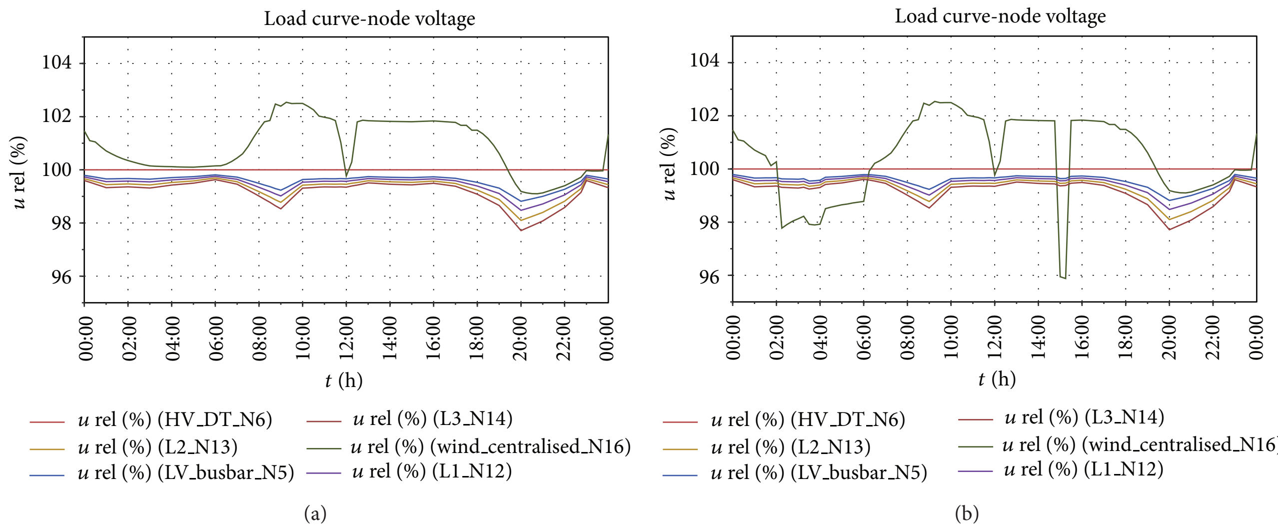


FIGURE 32: Voltage fluctuations due to (a) MFS and (b) FFS.

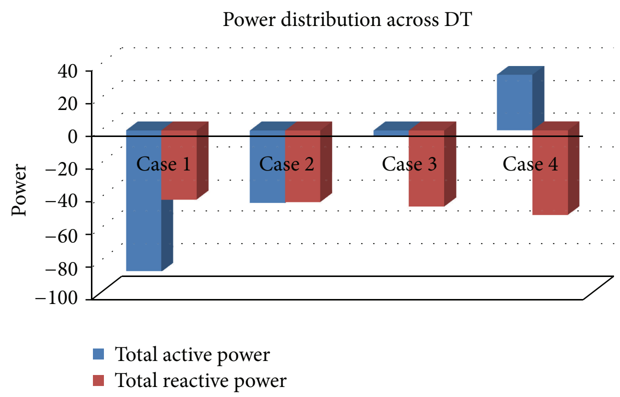


FIGURE 33: Active and reactive power of a wind integrated system.

3.4.2. Modelling Case Scenarios. Several case scenarios were considered based on load and wind integration limits.

Case 1 (only grid). Only grid supplies electricity to 27 residential customers.

Case 2 (grid with centralised 50% wind connection). In this case, centralised wind was integrated into the feeder as shown in Figure 27.

Case 3. Grid with centralised 100% wind connection.

Case 4. Grid with centralised 150% wind connection.

In addition to the above-mentioned case scenarios, this study also explores the impacts of wind integration considering fluctuating generation from wind due to thunder or storm. The considered cases are as follows.

(i) Base case: Grid with 100% wind integration.

(ii) Case MFS.

(iii) Case FFS.

3.4.3. Results and Analysis.

(1) Voltage Regulation. From load flow analysis, it was observed that voltage level gradually decreases from source to the receiving end. Figure 28 shows the voltage changes of a three-phase balanced system from LV side of the transformer to the end busbar (Busbar 3) for Case 2. It is to be noted that Case 2 comprises equal amount of wind turbine in each phases; hence, changes of voltages in different busbar or node points are the same for all of the phases.

Voltage regulation of studied case scenarios was shown in Figure 29. This figure presented the voltage changes with respect to nominal voltage in different observation points only for Phase 1 as it is a balanced system. From Figure 29, it has been seen that for all of the case studies voltage gradually drops from LV side of DT to Busbar 1, Busbar 2, and Busbar 3. From Figure, it was shown that system voltage reduces with 50% centralised wind turbine connection (Case 2) of total loading in compared to only load connected system (Case 1) though the voltage at the point of wind turbine connection is 100.68% of the nominal voltage. However, voltages in the busbar and the point of turbine connection rise with the increased integration of wind turbine as shown for Case 3. In Case 4, 150% wind energy of total loading was connected and, hence, reverse power flows occur due to increased generation which causes voltage reduction in the busbars though the voltage in the point of wind turbine connection increases. Voltages at the point of wind turbine connection are 101.05% and 105.08% of the nominal voltage for Cases 3 and 4, respectively, which exceeded the regulatory standard of 1% at the ponit of RE connection by DNSP.

Voltage variations over time in the LV DN and different busbars for Case 1 (without wind integration) and Case 3 (100% wind integration of total loading) are shown in Figures 30 and 31, respectively. These figures also indicate that the receiving end voltage of the system is lower than the sending end voltage. For the centralised wind connection in Case 3, voltage rises significantly across the wind turbine and

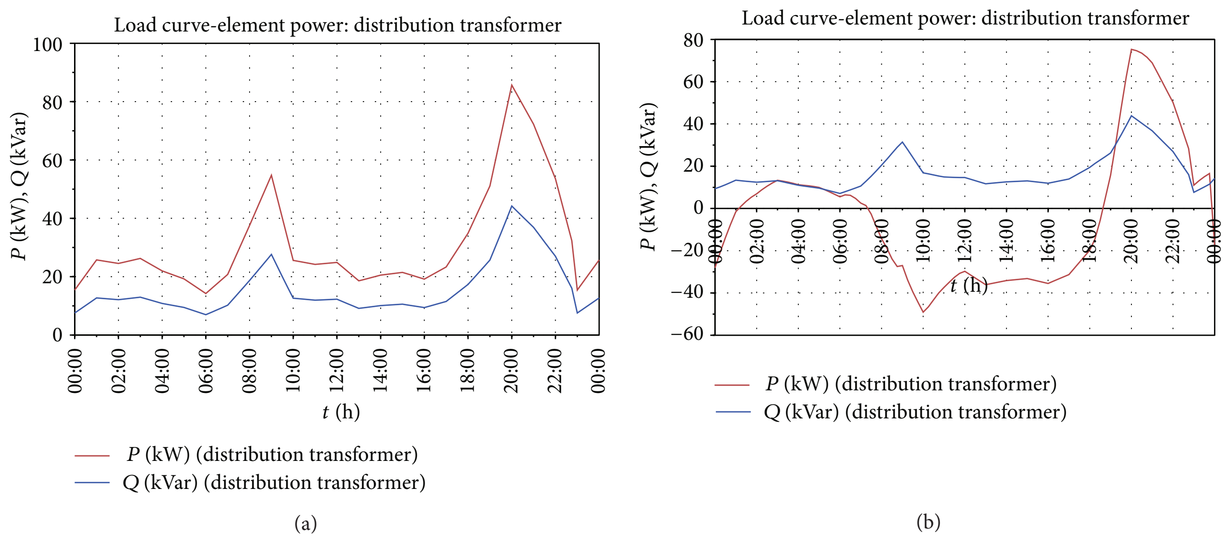


Figure 34: Power distribution in the network for (a) Case 1 and (b) Case 3.

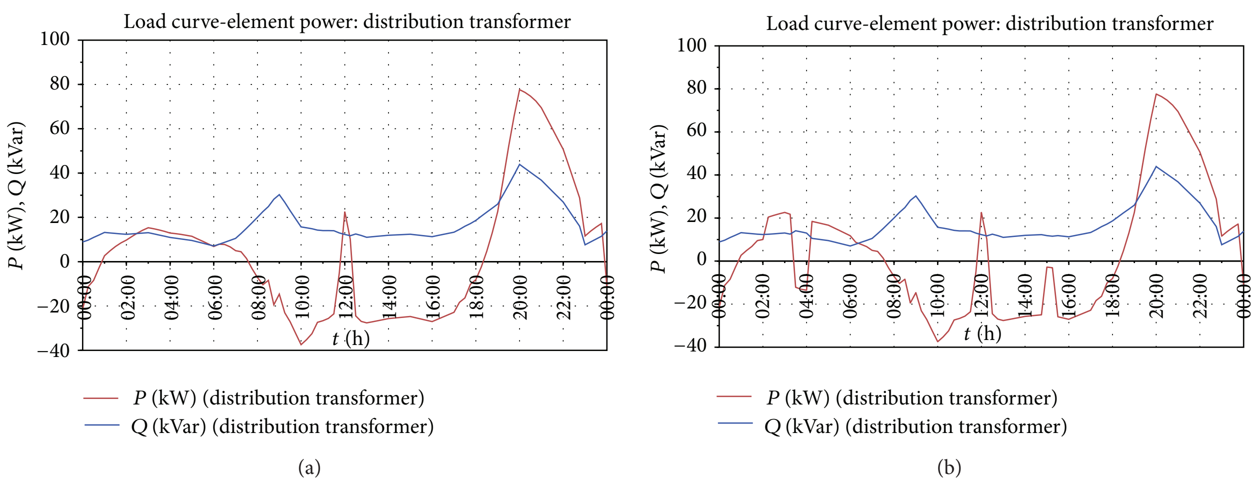


Figure 35: Comparison of power utilization for Cases (a) MFS and (b) FFS.

exceeded the nominal voltage during the day except from 7:30 pm to 10:30 pm while generation from wind is minimum as shown in Figure 31. The observed maximum voltage at the point of wind turbine connection was 103.03% which exceeded the allowable regulatory limit defined by DNSP. However, voltage across the LV side of the DT is within the regulatory limit and 98.79% of the nominal voltage.

Natural disaster affects the regular wind speed that causes voltage fluctuations and uncertain generation from wind sources. Load curve analysis determines the voltages on HV and LV sides of the DT and busbar of the network over time, with considerations given to different storm conditions such as continuous medium and frequent fluctuations. From Figures 32(a) and 32(b), it is shown that voltage reduced significantly in the point of wind turbine connection with the variations of winds speed due to storm or thunder. For Case FFS in Figure 32(b), the voltage at the point of wind turbine connection reduced to 95.8% at 3:00 pm while in the base case the voltage is 102.2% at 3:00 pm.

(2) Power Distribution. Power distribution across the DT was explored for different case studies. From power flow analysis in Figure 33, it has been seen that for Case 1, that is, without any wind energy integration grid need to supply 85.68 kW active power with 41.89 kVar reactive power to fullfil household load demand, while in Case 4 with the integration of 150% wind of total loading, system has surplus electricity of 33.73 kW after meeting household demand that can be fed back to the grid. Cases 2, 3, and 4 are same configurations except for the amount of wind turbine integration in which it was shown that electricity generation was increased with the increased integration of wind turbine and

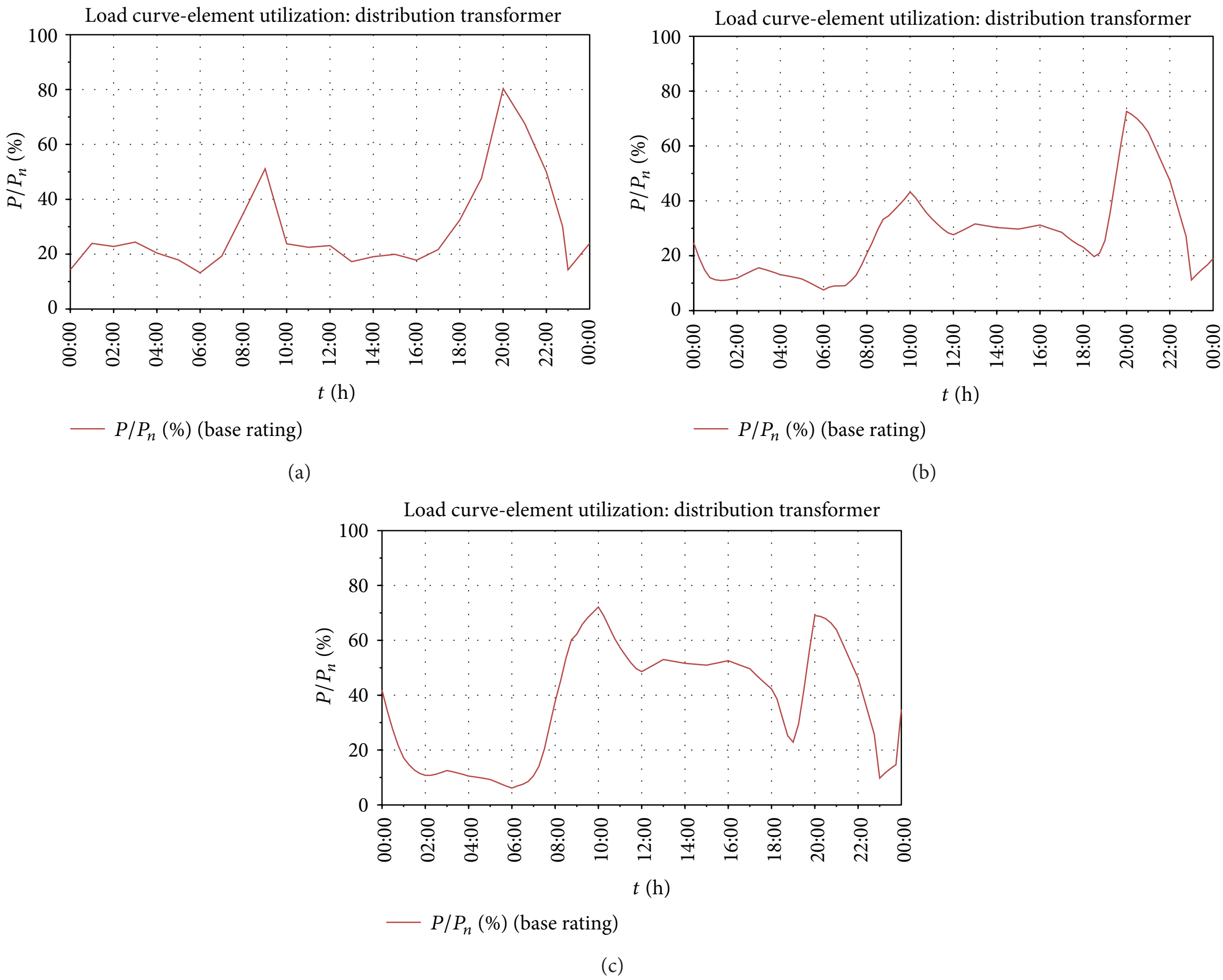


Figure 36: DT loading (a) Case 1, (b) Case 3, and (c) Case 4.

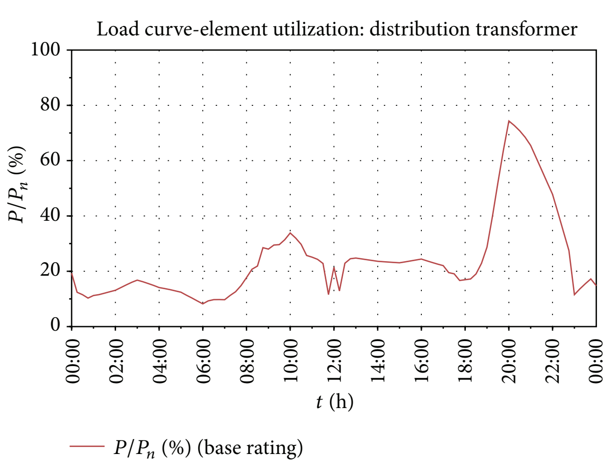


Figure 37: DT loading with wind fluctuating.

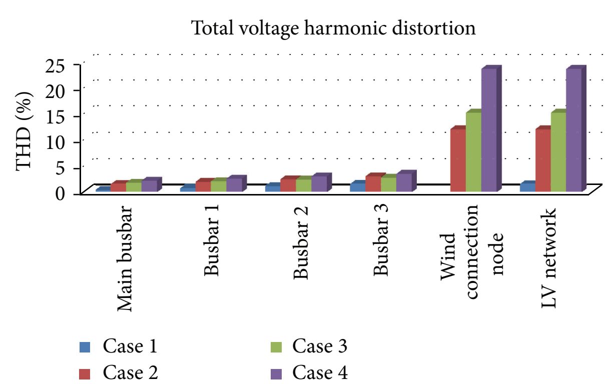


Figure 38: Voltage harmonics for different studied cases.

hence reduces the requirement of real power from the grid. However, increased integration of wind turbine increases reactive power requirement as wind turbine requires reactive for its operation. However, most of the reactive power is required for household load.

Power requirement from the grid over the time to meet customer load demand is shown in Figures 34(a) and 34(b) for Cases 1 and 3. Wind turbine produces electricity most of the time of the day and contributed to meet customer load

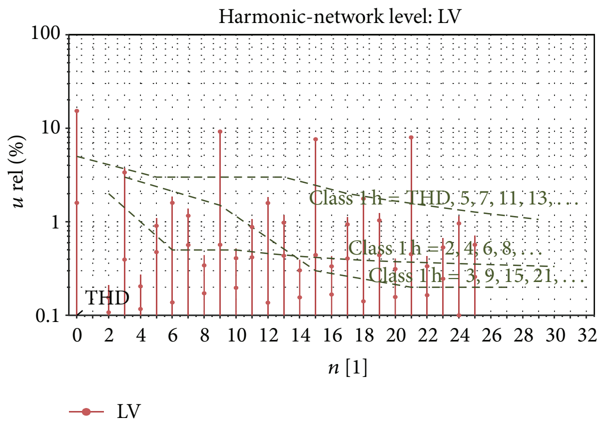


Figure 39: Total voltage harmonics in LV network for Case 3.

demand as shown in Figure 34(b). With the integration of wind energy, system can feed back surplus electricity after meeting customer load demand into the grid from 7:30 am to 6:30 pm as wind generates sufficient energy during this period. However, grid needs to supply electricity at night as enough generation is not possible from the wind turbine.

Cloud movement also causes power fluctuations in LV DN as shown in Figures 35(a) and 35(b). Figure 35(a) shows that with the random medium fluctuations of winds speed due to storm influences power generation and system required power from the grid from 11:50 am to 12:20 pm instead of feedback to the grid as shown in the base case (Case 3) in Figure 34(b). From Figure 35(b) it can be stated that systems can feed back surplus electricity to the grid from 3:25 am to 4:05 am instead of taking electricty from the grid as shown for the base case (Case 3) in Figure 34(b) while system needed power instead of feedback to the gird from 11:50 am to 12:20 pm. Therefore, it can be concluded that weather condition is responsible for electricity generation from wind turbine and causes uncertainties in the LV network such as voltage and power fluctuations.

(3) Distribution Transformer (DT) Utilization. From the load curve analysis, it can be seen that integration of wind turbine increases the DT loading when generation from the wind is maximum with minimum household load demand. Peak DT utilization without any wind connection is 80.33% at 8:00 pm as shown in Figure 36(a). Wind turbine can produce energy all over the day and hence from Figure 36(b) it is shown that wind energy can meet load demand partially at 8:00 pm and DT loading reduced to 70%. On the other hand, at 8:00 am while electricity generation from wind is maximum, DT loading reduced to 20% while 35% without wind integration as shown in Figure 36(a). With the increased integration of wind as shown in Figure 36(c), it has been seen that DT utilization increased to 105% at 8:00 pm and at 10:00 am DT loading in Cases 1, 3, and 4 is 24%, 44%, and 63%, respectively.

Thunder storm causes uncertainty in the LV DN which causes power fluctuations as well as influences DT loading. Figure 37 shows the DT loading with the fluctuating winds speed due to storm. However, for reliable power supply to the residential customer, it is essential to keep the DT within its allowable limit.

(4) Harmonic Analysis. From harmonic analysis, it has been seen that total voltage harmonic distortion increases with the increase of wind turbine integration into the DN. Figure 38 shows the voltage harmonics level in the main busbar, Busbar 1, Busbar 2, Busbar 3, centralized wind connection point, and LV network for the different studied case scenarios. Injected harmonics due to only customer's nonlinear loads are shown in Case 1, Figure 38. Wind turbine injected significant harmonics into the network as shown for Cases 2, 3, and 4 and level of harmonics increases with the increased integration of wind turbine. THD at the LV network was 12.12%, 15.28% and 23.65% for Cases 2, 3, and 4, respectively, in which it was shown that level of voltage harmonics exceeded the regulatory standard.

Figure 39 shows the detail of voltage harmonic distortion in the LV network with different harmonic orders for Case 3. From Figure 39 for Case 3, it has been seen that in addition to THD, 3rd, 6th, 9th, 15th, 18th, 21st, and 24th harmonics exceeded the threshold limits. Wind energy integration into the DN introduces significant harmonics and exceeded the Australian regulatory standard limit as stated in AS4777 [25].

Current harmonic distortion of different studied case scenarios are shown in Figure 40(a). Harmonics in the busbar are the same for all cases as wind turbine is connected centrally and the same amount of loads is connected in the systems. With the integration of 50% and 100%, wind turbine of total loading current harmonic increased to 9.05% and 19.12% as shown in Figure 40(b). Harmonic current for Case 4 is reduced to 17.23% as this system generates wind power more than the household load demand and causes reverse power flow in the system by feeding back surplus electricity to the grid.

4. Conclusions

Wind energy has enormous potentialities and encourages interest worldwide for the large-scale penetration into the energy mix as it is free from the GHG emissions that cause global warming. As a case study, this paper investigated the influences of integrating large-scale wind energy into the Rockhampton DN. Considering flexibility, robustness of the model both HV DN and LV DN were explored and analyses the influences in particular, ZT and DT utilization, voltage regulation, power flow, and harmonics in the network. Each case study comprises several case scenarios based on level of wind integration and connection approach.

From simulation analyses, it can be concluded that level of the observed impacts increases with the increased integration of wind energy into the grid. However, the impacts are lower in the HV DN compared to the LV DN. Level of system voltages and current harmonics increase with the increased integration of wind turbine into the HV DN. However, voltage and harmonic are lower in the case of centralised connection approach compared to decentralised confection approach. Current harmonic distortion exceeded

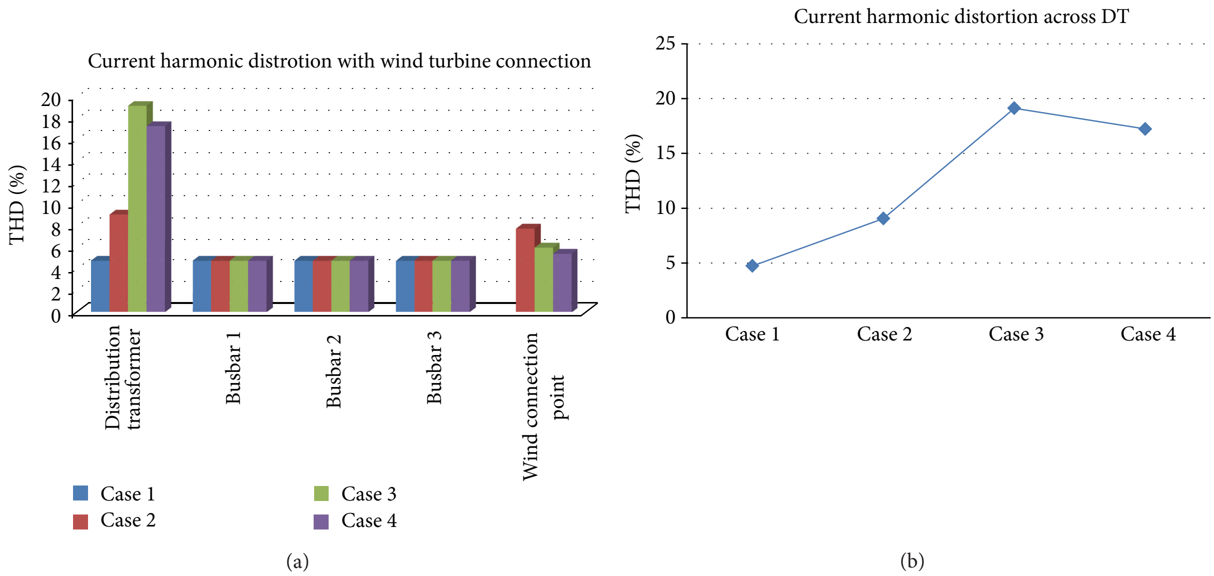


Figure 40: Current harmonic distortion (a) across all observation points and (b) across only DT.

the regulatory standard in both case studies for HV DN and LV DN. Voltage at the point of wind turbine connection exceeded the nominal voltage as well as regulatory standard in case of LV DN. Few of the case scenarios generate wind energy more than the load demand and hence feed back surplus electricity to the grid. In addition to load wind turbine is responsible for reactive power which also causes poor power factor in the DN. Findings of this study are expected to be used as guidelines by the policy makers and utilities for deployment of large-scale wind energy into the energy mix.

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