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Power Quality Impacts of Grid-Tied PV Inverters on Low Voltage Distribution Networks a Smart OpenDSS Model to Find Power Quality Threshold Limits

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ABSTRACT

As a renewable initiative, risen attention can be seen in solar photovoltaic (PV) installations in the world. Since tropical countries and even many other countries during summer experience higher irradiance levels, there is great potential for PV generation in solar panels. However, power quality can be impacted when the number of PV modules is increased in a network due to the emergence of harmonics, unbalanced voltages, voltage flicker, neutral voltage variations, etc. Therefore, it is essential to empirically analyse power quality parameters, i.e., total harmonic distortion (THD), voltage unbalance, etc., and find threshold margins of PV capacities in a network.

Based on a case study conducted in Negombo, Sri Lanka, this work determines power quality impacts with reference to the number of PV interconnections in a distributed network. For the task, a low-voltage distribution network was chosen which was fed by a 250kVA, 11/0.4kV transformer with domestic loads and grid-tied PV inverters. A simulation model was developed in Open Distribution System Simulator (OpenDSS) with time-varying load patterns and PV generation. Consequently, a smart efficient method was introduced to model domestic loads with unique time-varying demand patterns. A determination criterion was established to derive snapshot load flow instants using time-varying load flow results to analyse voltage profiles along distribution feeders. Then, the model was enhanced to quantify the power quality parameters such as individual harmonic content, THD of voltage as well as current and neutral voltage variation. The results reveal that node voltage has improved with PV interception without violating the upper limit. The THD of voltage and current have slightly increased with the addition of PV inverters.

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Introduction

As a global initiative to address the energy crisis in the world, many countries are focusing on renewable energy resources, *i.e., solar, wind, hydropower, etc*. Since solar is considered a dominant candidate, the implementation of photovoltaic (PV) which is the phenomenon of conversion of sunlight into electricity, is growing at an exponential rate. Large-scale PV power plants are connected to high voltage networks, whereas medium and small-scale PV plants are penetrated to distribution networks. Hence, the latter categories fall under the dispersed generation candidates. Small-scale PVs are mainly installed on rooftops that are connected to low-voltage (LV) distribution feeders. Due to the accelerated implementation of small-scale PVs into distribution networks, the impact of high penetration has become a challenge to maintain grid codes while harvesting this free solar energy. Figure 1 shows the basic components of a grid-tied PV system connected to an LV distribution network. PVs in such networks greatly affect phase voltage profile, neutral voltage variation, power flow patterns and power quality parameters because of the control schemes and non-dispatchable characteristics of these grid-tied systems. Although the individual impact of a small-scale rooftop PV is considerably small, the aggregated effect would be significant in terms of the operational behaviour of network components, protection coordination, and safety as well as the lifetime of home appliances.

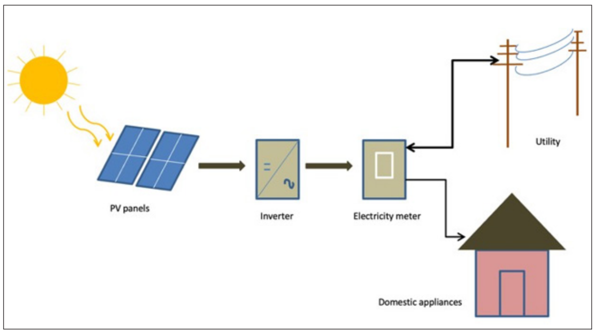

Figure 1: Basic Grid-Tied Rooftop PV System

Modelling a PV system is a complex task since several external parameters such as ambient temperature, irradiance level, inverter control algorithms, and specifications of the solar panel and inverters affect the power output. As a result, it impacts power quality. Power quality is the availability of reliable and continuous electric power without causing intolerable electromagnetic disturbances to network components and appliances. Voltage sags and swells, momentary interruptions, voltage transients, harmonic voltages, frequency and voltage fluctuations are several power quality indices. In literature, many studies regarding PV impacts focus on the fact that PV arrays are constant current sources. Therefore, those work tends to gain lower accuracy. In addition, the majority of work was conducted considering a single LV feeder with synthetic consumer loads, Institute of Electrical and Electronics Engineers (IEEE) standard test feeders, and single distribution transformer neglecting other medium-voltage (MV) loads connected to the MV feeder [1-4]. Thus, it is a necessity to develop a PV system with real-time characteristics including external conditions such as irradiance, ambient temperature, efficiency, etc., which govern the PV output and realistic consumer demand profiles [5,6]. In an effort in filling a research gap mentioned above, proposing a real-time residential realistic load modelling methodology to derive power quality aspects was recognised as a core objective of this research.

Our Contribution

This study empirically analyses power quality to find threshold margins of small-scale PV capacities in distribution networks. Furthermore, this work introduces a smart efficient method to model domestic loads with unique time-varying demand patterns based on daily consumption. The case study was performed using a low voltage network of a 250kVA distribution transformer in Negombo, Sri Lanka with rooftop PV inverters. For the tasks, power quality impacts such as harmonics, total harmonic distortion (THD) of voltage as well as current, voltage unbalance, neutral voltage and phase voltage profiles were investigated. Harmonic voltages and currents were computed at several feeder nodes including point of common coupling (PCC) of PV inverters and transformer LV terminals. The effects of other MV loads too were considered for better approximation. This work:

- proposes an end-user domestic load modelling methodology with real-time demand profiles
- addresses methodologies for accurate determination of loading instants for power flows and harmonic analysis
- includes methodologies for modelling LV and MV lines, PV systems, domestic loads, and impacts of other loads such as transformers
- uses Open Distribution System Simulator (OpenDSS) for the analysis

During the LV distribution planning stage, the impact and the amount of PV penetration levels are not considered in Sri Lanka at present. That causes to deviate the expected operating conditions from the actual. Therefore, the importance of assessing distributed generation sources during LV planning is also addressed.

Literature Review

Distributed PVs are popular among retail electric consumers due to feed-in-tariff schemes and subsidised financial support for PV deployment in their houses. Therefore, studying their impact on distribution systems is an important subject of interest.

Modelling of PV Inverters, Loads and Distribution Feeders

PV system simulation comprises the modelling of PV arrays, direct current to alternating current (DC-AC) inverters, loads and distribution feeders. PV resources can be simulated as fixed current injectors [7]. The main functions of inverters are maximum power point tracking (MPPT), grid synchronisation, energy storage and disconnection during grid anomalies [8]. Modern inverters use active power curtailment and reactive power absorption techniques to mitigate voltage problems in the network [9]. Volt/Var and Volt/Watt methods also contribute to overcoming voltage problems [10]. The most common practice of modelling loads is the ZIP1 method. Determination of proper ZIP values and accurate diversity factors is a complex task [11]. In harmonic studies, an aggregate load is represented as a series or parallel combination of resistance and inductance. These resistance and inductance values are considered as constants throughout the frequency range [12]. In loads were designated with their measured harmonic spectra [13]. The impedance of a four-wire low-voltage overhead power line is described by a 5x5 series impedance and shunt nodal capacitance matrix [14]. Both impedance and capacitance values have self and mutual components. Carson's equation can be used to simplify the impedance and capacitance matrices into 4x4 matrices such that the ground element had been removed, and taking the effect of ground to the phase and neutral conductors [15]. If the voltage difference of the neutral wire between two adjacent nodes is zero, the simplified 4x4 matrices can be further reduced to 3x3 matrices using the Kron reduction [14].

Load Flow Algorithms

Load flow methods such as Newton-Raphson (N-R), Gauss-Siedel and Fast decoupled methods are specifically formulated for load flow studies on transmission networks [16,17]. In the bus number matrix has been used to develop a power flow algorithm for an unbalanced radial distribution network with renewable energy sources and distribution static compensators [15]. Load flow methods in OpenDSS use bus admittance matrices. It consists of two algorithms known as normal algorithm and the Newton method. The normal algorithm is a fixed-point method as long as the initial voltage guess is closer to the final solution. For highly meshed networks, the Newton method is used with non-linear equations and complex voltage vectors [13].

Impact of PV Deployments

The potential impact of small-scale residential PV deployment on distribution networks depends on feeder-specific parameters, *i.e., feeder layout, voltage class, X/R ratio2, substation capacity, loading pattern., and PV-specific parameters, i.e., the capacity, location along the feeder, inverter control schemes, correlation of PV output with load, electrical proximity to other PV, variability of PV output depending on weather conditions* [8,18,19]. Voltage magnitude is a crucial parameter that can be affected by the PV system. Voltage imbalance effects can be minimised by accommodating more single- phase PV systems connected to heavily loaded phases. How the penetration level of distributed generators affects the power loss and voltage profile to the network have been analysed in [4]. A suitable location for distributed generators has been determined based on voltage profile index (VPI) which describes how close the actual voltage fits with the ideal value. Since the fault current contribution of PV inverters is negligible, the impact of PV deployment on power system faults can be neglected. In fact, large-scale PV penetration can cause unnecessary breaker tripping, protection under-reach and coordination conflicts [1,20]. Transient over-voltage due to the intermittent nature of PV inverters is also a power quality concern.

During grid failures, local PV inverters are shut down by the activation of anti-islanding protection. During this disconnection period, local loads may experience higher voltages due to an abnormal rise in phase voltages. Voltage sags and swells can also be stated as another power quality parameter. Those determine the fault-ride-through capability of rooftop solar systems in some countries [21]. Harmonic levels in distribution systems are growing due to harmonic-rich domestic loads such as the latest lighting accessories and electric vehicle chargers. PV inverter units are another source of harmonics to distribution networks due to pulse width modulation (PWM) techniques used in inverters. Subsequently, this may cause unacceptable voltage distortion [19]. THD in voltage (THDv) defines the distortion of voltage due to higher order harmonic voltages, and it is measured by using Equation 1. THD in current (THDi) is defined in a similar manner to Equation 1.

Equation 1: THD of voltage.

$$THD_v = \frac{\sqrt{\sum_{n=2}^{50} V_n^2}}{V_1}$$

1 Constant impedance (Z), constant current (I), constant power (P)
2 X (reactance), R (resistance)

Where:

- THDv = THD of voltage related to fundamental voltage (%)
- V1 = fundamental phase voltage (V)
- n = harmonic order

Power Quality Standards of Grid-Connected PV

International Electrotechnical Commission (IEC) 61727-2004 and IEEE 1547-2018 provide guidance on grid- connected PV [22]. IEEE 519-2022, IEEE 399-1997 define harmonic generation, recommended limits and concepts involved in harmonic analysis [23-24]. Apart from these, IEC 61000-4-7, IEC 61000-4-30, IEC 61000-4-15 and IEEE 1453 define power quality indices [25,26]. All these standards specify parameters such as voltage deviation, frequency deviation, harmonic levels, three-phase unbalance, voltage flicker and allowable DC components [27]. With reference to the IEEE 519-2022, voltage distortion limits with reference to different bus voltage ranges at PCC are tabulated in Table 1 whereas current distortion limits are in Table 2. ISC is the maximum three-phase short circuit current, IL is the maximum fundamental current at the PCC, and thus ISC/IL is the short circuit ratio at the PCC. TDD is the total demand distortion. IEEE 3002.8-2018 standard further describes power system modelling techniques for harmonic analysis with two proposed methods [22]. The first method is the harmonic power flow method which uses a nodal admittance matrix and fast Fourier transform (FFT). The second method is based on nonlinear device voltage-current characteristics which uses an iterative approach.

Table 1: Voltage Distortion Limits

Bus Voltage at PCC (kV)	Individual Harmonic Content	Total Harmonic Distortion
V < 1	5.0%	8%
1 ≤ V < 69	3.0%	5%
69 ≤ V ≤ 161	1.5%	2.5%
V > 161	1.0%	1.5%

Table 2: Current Distortion Limits

ISC/IL	3 ≤ h < 11	11 ≤ h < 17	17 ≤ h < 23	23 ≤ h < 35	35 ≤ h < 50	TDD
< 20	4.0	2.0	1.5	0.6	0.3	5.0
20 < 50	7.0	3.5	2.5	1.0	0.5	8.0
50 < 100	10.0	4.5	4.0	1.5	0.7	12.0
100 < 1000	12.0	5.5	5.0	2.0	1.0	15.0
1000 >	15.0	7.0	6.0	2.5	1.4	20.0

Methodology

The 250kVA ,11/0.4kV, Dyn11 distribution transformer chosen for the case study is named BZ520. It is located in Negombo, Sri Lanka where the area is progressively experiencing higher penetration levels of a large number of PV interconnections because of high irradiance levels. According to the consumer database of Lanka Electricity Company (LECO) in June, 2019, the BZ520 had the highest number of rooftop PV inverters and a variety of loads, such as single-phase and three-phase loads, with both residential and commercial consumers. This transformer has four LV aerial bundled conductor lines. Table 3 includes the connection details of the consumer loads and PV interconnections at that time. There are 371 load connections, and 13 roof-top PV inverters connected to it. PV inverter capacities and their feeder locations are presented in Figure 2.

Table 3: Connection Details of Consumer Loads and PV Inverters of BZ520 Transformer

Feeder	Distance with spurs (m)	Consumers (unit)	PV (unit)
F1	542	68	4
F2	681	68	1
F3	608	105	3
F4	1082	130	5

The next task was to determine network boundaries for the simulation of the distribution system. The BZ520 is connected to Periyamulla-Cemetry (PERCM) feeder, which is one of the four 11kV overhead feeders of the primary substation (PSS) in Periyamulla. This PSS converts 33kV to 11kV via two 10MVA transformers. The distribution of other transformers of the PERCM feeder is illustrated in Figure 3. The impact of other transformers was also considered in the load flow solution. The two transformers which are upstream to the BZ520 were represented using 15-minute averaged demand values from the installed energy meters. To determine the combined effect of the remaining transformers, snapshot load flow was conducted using Neplan power system analysis software [28]. The voltage variation of the 11kV bus at the PSS at 15-minute intervals was used as the voltage profile, which reflects the effect of the upstream electrical network and other MV feeders of the PSS.

Furthermore, the averaged active and reactive power profiles of the PERCM feeder were normalised and multiplied with the load flow results to quantify the demand profile of the lump load. For the acquisition of the network and operational parameters, the voltage profile and the demand profile were recorded at the PERCM feeder. A harmonic spectrum was also recorded at the same location using Sonel PQM711 power quality analyser and the measured harmonic spectrum was used as an input parameter to the simulation model [29]. Both single- phase and three-phase short circuit levels at the 11kV terminals of the BZ520 were determined using ETAP 12.6.0 power system analysis software and were found out to be 60.58MVA and 42.31MVA, respectively [30].

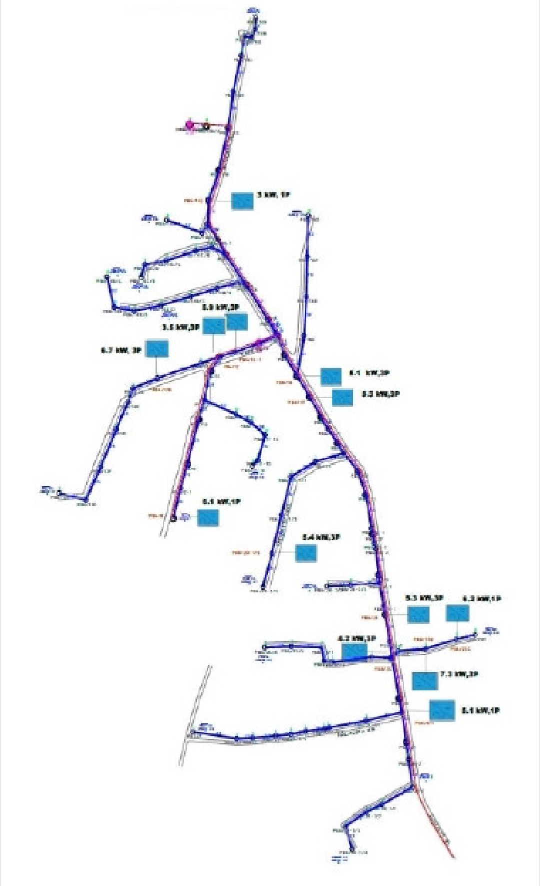

Figure 2: Dispersion of PV Inverters Connected to Distribution Network of BZ520

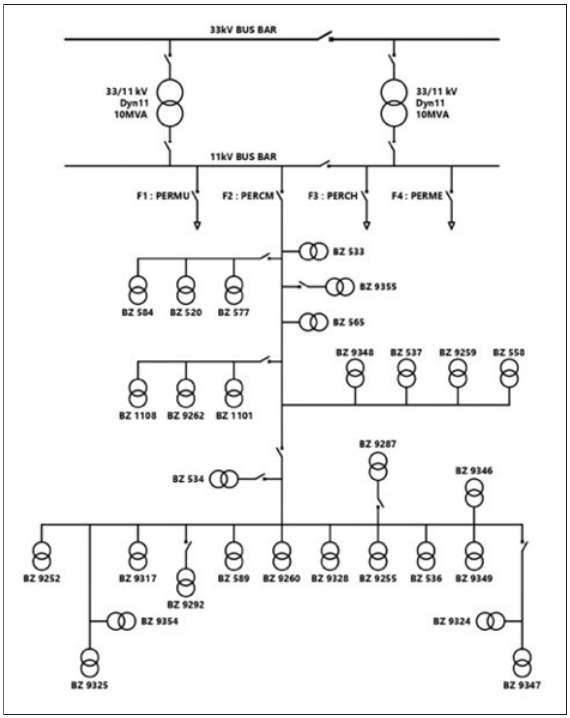

Figure 3: Transformer Dispersion of PERCM Feeder

Line Parameterisation

To model 11kV overhead conductors and 400V aerial bundled conductors, the OpenDSS generates line constants once their physical properties such as DC resistance, diameter, geometric mean radius, and x-y coordinates are given. The actual feeder topology was modelled by this method. This approach can be used where Carson's equations and Kron reduction methods cannot be used to model distribution circuits due to the fact that the neutral conductor is not grounded at every pole in Sri Lankan low-voltage distribution networks. LV feeders chosen for the study were equipped with 70mm2 and 50mm2 aerial bundled conductors. Line impedance and shunt nodal capacitance matrices were derived using Line Geometry and Line Constants libraries of the OpenDSS.

PV Modelling

The OpenDSS platform was used in this task due to extreme flexibility in PV modelling. It uses dedicated libraries for PV generators. The temperature coefficient factor of each PV array was obtained from manufacturer datasheets. Daily temperature variation at the 15-minute interval was obtained using a weather station located 5km away from the distribution network. Data logging was conducted for all PV inverters at the PCC using the power quality analyser. It was used to record the load flow and power quality parameters including the harmonic spectrum up to the 25th order. Inverter efficiency curves were obtained from inverter manufacturers’ datasheets. Figure 4 visualises the PV system developed in the OpenDSS.

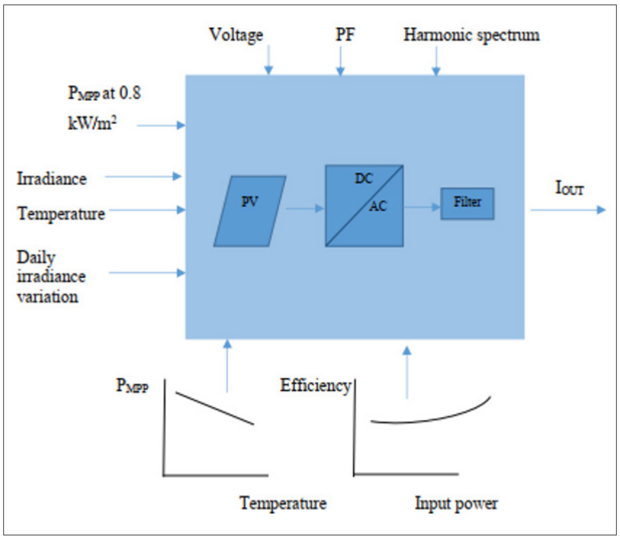

Figure 4: PV System Block Diagram used in OpenDSS

Load Categorisation

Three categories were defined based on monthly consumption. Hence, average monthly consumption was calculated by referring to 6-month records from January 2019 to June 2019 that are:

- Category I: Monthly consumption ≤ 100kWh
- Category II: 100kWh < Monthly consumption ≤ 200kWh
- Category III: Monthly consumption > 200kWh

All the consumers were put into one of the above categories based on the mentioned criteria. The average instantaneous demand per hour for each consumer was calculated using Equation 2. 720 is the number of hours for 30 days. Each consumer was represented by a unique average instantaneous value which was used as the multiplication factor. Field measurements were taken from three consumers of each category. Parametric values of terminal voltage, phase current, active power profile, reactive power profile, harmonic spectrum, THDv and THDi were recorded. Also, active and reactive power curves for the 24-hour duration were normalised by their corresponding highest value in the measurement matrices. These normalised active and reactive power curves were multiplied by previously determined average instantaneous demand for establishing a unique load profile for each consumer.

Equation 2: Average active power demand per hour.

$$AID = \frac{AMC}{720\ Hours}$$

Where:

- AID = average instantaneous demand per hour (kW)
- AMC = average monthly consumption (kWh)

Power Flow and Harmonic Analysis

A time series power flow solution was carried out for the developed OpenDSS model, including an 11kV busbar at the PSS, 11kV PERCM overhead feeder, MV lump load, PV inverters, domestic loads and low voltage lines. Using the solution derived at the LV terminals of the BZ520, three critical instants were identified called the maximum reverse power through the BZ520, the minimum active power demand instant and the maximum active power demand instant. Active and reactive power variation was extracted at important nodes in the network including the BZ520 transformer terminal, PV interconnection points, etc. Energy analysis was conducted to evaluate the transformer loss, the maximum demand, and energy flow with PV penetration. The voltage profile at each critical snapshot was determined for several nodes, such as PCC points, feeder starting points and feeder endpoints. Lastly, a harmonic analysis was conducted in the frequency domain with and without the presence of PV inverters to verify the power quality impact on the network. For that, PV inverters, domestic loads and an 11kV busbar were defined by their measured harmonic spectra during the harmonic simulation. During the harmonic simulation, the THDv, the THDi, individual harmonic voltages and the voltage unbalance factor (VUF) were calculated.

Results & Observations

Figure 5 illustrates the active and reactive power flow variation at the MV terminals of BZ520 during the PV injection status. An important observation could be noticed that the reverse power flow had appeared through the BZ520 to the MV side. The neutral link voltage derived at the BZ520 remains below 0.1V without PV injection while it rises to 0.2V with PV injection. Neutral current variation along Feeder 1 is illustrated in Figure 6 for both with PV and without PV injection concerns. The neutral current reaches a maximum of 17.8A during the maximum PV generation. The amount of neutral current increment occurs when the existence of single-phase PV inverters.

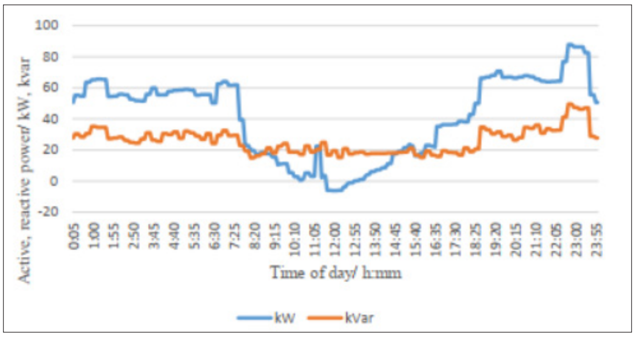

Figure 5: Power Flow Variation - 11kV Terminals of BZ520 with PV Injection

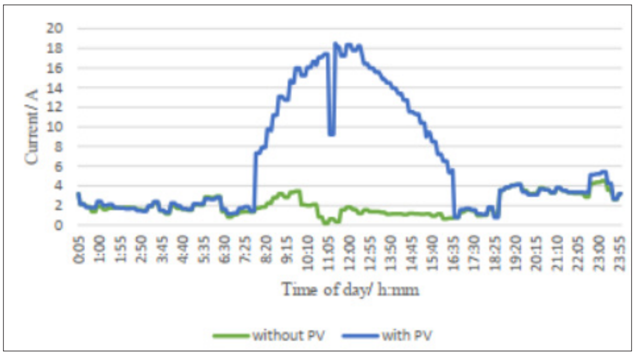

Figure 6: Neutral Current Variation at Feeder 1 with and without PV Injection

It was found that the transformer had delivered 990kWh of energy per day when PV penetration existed. Transformer energy loss was evaluated as 17.6 kWh per day. When PV penetration did not exist, the transformer had delivered 1272kWh of energy, and the loss was 18.7kWh. Therefore, 282kWh of energy saving was achieved. The transformer's maximum demand was recorded as 100.83kVA. During the reverse power flow instant, 9.6kW active power was transferred to the MV side through the BZ520. Observed node voltages in each snapshot is shown in Figure 7. The maximum PV generation was observed to occur at 12:00h. When the PV generation is its maximum, the node voltage is higher.

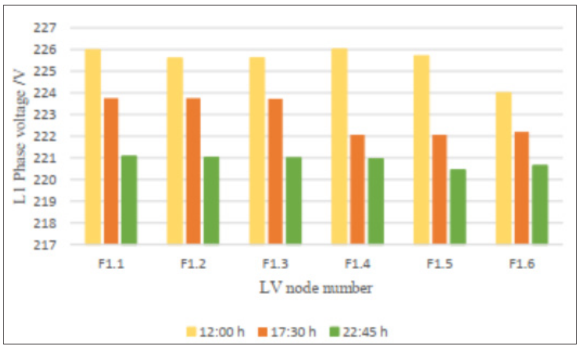

Figure 7: Phase Voltage Profiles of LV Nodes of F1 at Critical Snapshots

Regarding the THDv results, F4 has higher values compared to F1, F2 and F3. The highest value of the THDv is 1.1%. During the non-PV inclusion scenario, the maximum THDv has reduced to 0.8% in phase L3. Phase L3 exhibits the highest THDv values compared to the remaining L1 and L2 phases. Results of the THDi assessed for the F4 nodes during the maximum PV generation instant show that the maximum evaluated THDi is 12.9% in phase L3. The maximum THDi was approximately 8% for the same phase when PV generation was excluded.

Discussion

Modelling PV resources as fixed current injections reduces the accuracy due to the intermittent nature of solar irradiance, cloud transients, the power-temperature relationship of solar cells, inverter efficiency curves and ambient temperature variations. This study has considered all the above factors to increase the accuracy of PV modelling. Derivation of time-varying demand profile and power factor for domestic loads were achieved in this study using field measurements and an innovative load classification approach. Since it was realised that distribution system load modelling had not received the same level of attention as other power system components in general, this gap was appropriately filled by the methodology in this research, even though it is a combination of many variables, i.e, consumption pattern, living standards, type of equipment, etc. Load flow solutions such as N-R and Gauss-Siedel might encounter convergence problems and end up with anomalous nodal voltages because of radial feeder arrangement, low X/R ratio, unbalanced loading and single-phase distributed generation resources which are inherent characteristics in distribution networks. The OpenDSS platform uses a bus admittance matrix to solve load flow algorithms. Therefore, the nodal voltages are accurate.

Time series analysis was mainly conducted to analyse the voltage and power profile of the network with time. Since the domestic load consumption is higher than the PV generation, the reverse power flow could be observed from the LV side to the MV side through the BZ520 during 10:00h to 13:30h time period as shown in Figure 5. Reactive power is absorbed from the grid since PV inverters are operated at a unity power factor. When single-phase PV inverters are connected, the neutral link voltage increases significantly. LECO which is the distribution system operator in the Negombo area, practises to connect the neutral conductor to the ground at feeder ends in addition to the transformer neutral link. Due to the fact that, the neutral link voltage remains at a lower value even the neutral conductor breaks at a midpoint. Neutral conductor current depends on various factors such as loading patterns of phase conductors, phase balancing, earthing impedance, and balanced and unbalanced injection of PV which will ultimately define the power quality. An increase of neutral current occurs during the existence of single-phase PV resources. In conclusion, it can be stated that PV generation has a clear impact on the neutral current along LV feeders. Three-phase PV inverters do not adversely affect the neutral current because of the balanced current injection. Nonetheless, the Sri Lankan Grid Code does not define threshold levels for neutral voltages and currents that shall be maintained by the utility [31]. Single-phase PV and current harmonics (triplen harmonics) can be the reasons for having higher neutral currents.

According to the energy analysis of the network, PV modules have contributed to a total energy saving of 282kWh. The PV interconnections offer a total energy saving of 283kWh. However, the transformer loss has not improved by a considerable amount. This is mainly because the solar energy itself circulates among low-voltage feeders of the BZ520. Snapshot analysis helps to investigate voltage fluctuations, power flow along feeders, harmonic currents and voltages, capacity violations, etc., at specific time instants. As shown in Figure 7, the node voltage is higher at PV interconnection nodes during the maximum PV generation instants, whilst it is lower when PVs are not included. This reveals that higher voltages would exist in the vicinity of high PV penetrations. This phenomenon causes voltage regulation issues since distribution transformers are equipped with off-load tap changers. To mitigate voltage regulation issues, on-load tap changers or dedicated low-voltage feeders should be installed to absorb more PVs. The purpose of harmonic analysis is to examine the existing THD of PCC points of PV inverters. In THDv comparison between the statuses of with and without PV interconnections, the THDv remains below 8% of all nodes even with the maximum PV penetration instant. With reference to the simulation results, the THDv has increased with the presence of PV inverters. What is more, the THDi variations of the defined LV nodes of each feeder were determined with and without PV scenarios too. The THDi also surges with PV penetration compared to the non-PV application status. The allowable limit for the THDi depends on the short circuit ratio at each node. The short circuit level at the BZ520 low voltage terminals was calculated using the infinite bus method and the percentage impedance of the transformer which is 3.82% (nameplate data). Therefore, the short circuit level was found to be 9.45kA. The recommended THDi limits depend on the load currents at each PV inverter. The maximum load current among 13 PV inverters used for the study is 10.52A (7.29kW PV system). Consequently, the short circuit ratio became 898 for the worst-case scenario, and this ratio was compared with the recommended THDi values given in Table 2. According to the IEEE 519-2014, THDi should be lower than 15% for each node. The THDi has not increased beyond the recommended threshold of 15%.

Model validation was conducted to compare the simulated and the actual systems. A complete validation is impractical due to the complexity and large number of field measurements. Because of that reason, some locations were selected to validate the power profile of PV inverters and the power flow of the BZ520. Figure 8 represents the simulated and measured power flow of PV system 1. The actual power behaviour exhibits similar characteristics to the simulated power flow except for a few overshoots. The developed model can be adapted to any distribution network, which would be an added advantage to utilities to get insights about the real-time network behaviour. Before issuing the grid clearance certificate from the utility to PV developers, the operational performance and subsequent grid impacts of proposed PV systems can be analysed through flexible network conditions. If constraints exist, grid and feeder rehabilitations or augmentations can be identified in the early stage. This developed smart power quality analysis model can be utilised to evaluate PV penetration limits for a particular electricity network referring to the grid code.

Future Work

For a far better realisation of the simulation, the effect of other transformers in the 11kV PERCM feeder can be given as input functions. Even though the development of the entire 11kV feeder with all transformers in OpenDSS is a tedious coding process, more accurate results can be obtained. This model can be further improved to determine the optimum reactive power compensation and frequency support techniques. The benefits of integrating battery storage facilities with PV installations can be studied using the developed model. Such hybrid systems can be successfully promoted by introducing attractive feed-in tariff schemes.

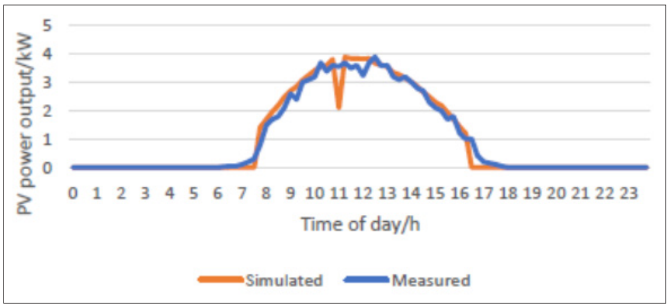

Figure 8: Simulated and Measured Power Difference of PV System 1

Conclusions

The maximum absorption of distributed generation resources into the electricity distribution networks without compromising the power quality is an emerging research area nowadays. This study was conducted to evaluate the power quality impacts and operational behaviour of a selected distribution network empirically with inclusion of highly penetrated PV systems. For the task, modelling of a high PV penetrated low voltage distribution network was executed in the OpenDSS platform. A smart and accurate methodology was proposed for each consumer in a network to derive unique active and reactive power profiles. According to the results, single-phase PV inverters cause higher voltage imbalances. Neutral current also increases with the addition of PV which causes a risk of higher neutral conductor loss. The simulated power flow pattern at the BZ520 transformer node matches the field measurements in a similar pattern. The developed model was enhanced to quantify the power quality parameters such as individual harmonic content, the THD of voltage and current, and neutral current variation. The results reveal that node voltage has improved with PV interception without violating the upper limit. The THDv and THDi have increased with the addition of PV inverters without violating the upper limits.

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