Power Quality in High Density Residential Distribution Grids

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Abstract— Research in the field of power quality challenges in distribution grids is gaining a strong foothold. Historically, the urban distribution network only served to feed domestic loads that were mostly passive constant impedance loads with near ideal power factor. With increasing penetration levels of non-linear loads and inverter connected embedded generation the load profile is set to change drastically. As accountability for the resulting impact on power quality is difficult to assign in residential distribution grids it is in the interest of the municipalities, utilities and power distributers to design the networks to be robust. The design and planning guidelines of distribution grids have to be reviewed and amended to take an evolving load profile in conjunction with embedded generation into consideration to prevent equipment failures and to ensure that the expected equipment life cycles are met

***Index Terms*— Distribution Grid, Embedded Generation, Harmonic Emissions, Small Scale PV Generation;**

1 INTRODUCTION

As the cost of Photo Voltaic (PV) systems decreases and energy prices increase, it is expected that more residential customers will decide to install their own generation plants instead of purchasing electricity from utilities. With increasing penetration levels of embedded generation, the load profile of distribution grids is set to evolve [1]. Load flow is no longer unidirectional from grid to load as increasing embedded generation capacities allow the consumer to become the independent power producer. When installing grid connected PV systems in low voltage distribution grids there are numerous criteria that need to be considered. The South African utility Eskom and the National Energy Regulator of South Africa (NERSA) have developed small scale embedded generation integration guidelines and distribution grid planning criteria to address some of these [2 – 5]. The wide spread adoption of non-linear loads employing switch-mode power supplies including electronic appliances and CFL and LED lighting solutions also contribute to the evolution of the load profile.

The simulation model is required to be versatile so that different aspects pertaining to power quality can be investigated. A qualitative analysis method was implemented to filter the standards that are unambiguous and applicable to power quality in distribution grids. The selection process of the criteria deemed applicable is based on practical experience. To this end, voltage regulation, three-phase unbalance and harmonic emissions are the power quality aspects evaluated in the simulation.

The power quality standards are divided into two categories: Planning levels and compatibility levels. The planning levels are used during the network development stage and have to be complied with when new devices are integrated into the grid. The compatibility levels are related to the equipment design standards. Equipment manufacturers complying with the South African National Standards design their equipment to withstand the compatibility levels, adding some margin to achieve required equipment life cycles. When planning levels are exceeded, due to the integration of new devices, equipment immunity levels are more likely to be exceeded in the future resulting in equipment loss of life [6].

The compatibility level is defined as the 5% probability of equipment immunity levels being exceeded for 95% of system disturbances. Limits pertaining to current unbalance are not defined in the South African power quality standards. The planning and compatibility limits considered in this paper are summarized in Table I.

Table I. Power quality planning and compatibility levels [7].

	Planning Level	*Compatibility Level*
Voltage Variation	±3% step	±18% steady state
Voltage Unbalance	1.5%	3%
Voltage THD	5%	8% (11% Temporary)

The current THD limit is suggested to be 5% of the equipment rating being integrated. The voltage planning limits of the individual harmonics are less than 2% and decrease as the harmonic number increases. The voltage harmonics are percentages of the voltage rating where the measurement is performed. The current harmonics are more difficult to define as equipment ratings vary. The IEEE suggests that the measured harmonic currents should be compared to the System Short Circuit Level. As the short circuit level is also not fixed, this approach is also difficult to implement.

2 POWER QUALITY

The power quality aspects investigated in this paper do not include the protection, earthing and control requirements of distribution grids as these aspects are project and circumstance dependant. Voltage variation, unbalance and harmonic emissions are the power quality challenges most common to electric grids [8].

2.1 Voltage Variation

The voltage drop in a distribution grid between the point of supply or the point of connection and the load is due to the load current through the line - or cable impedance. An increase in load current increases the voltage drop [9].

Conversely, the voltage at the load increases when the current reduces. Distribution grid planning guidelines [2] also address the subject of voltage regulation in grids with embedded generation. Small scale devices with generation capacities less than 13.8 kVA are not required to regulate the voltage at the point of connection [3]. The tap changers of utility substation distribution transformers are the only devices that can regulate the downstream grid voltage in a residential distribution grid. A changing embedded generation output alters the load flow in the distribution grid, resulting in voltage variations in LV grids that cannot be controlled by the network operator [9]. In the case of small scale PV systems distributed throughout a residential grid, the voltage variation is small compared to the abrupt changes due to loads switching on or off. The solar irradiation changes slowly [10] compared to the instantaneous voltage jumps due to residential circuit breakers tripping. The resulting slow change in system voltage at the point of supply can therefore be regulated by the tap changer of substation distribution transformer similar to the regulation performed during the daily grid loading profile. PV inverters are designed to remain grid connected and operational when the power quality of the grid remains within the compliance limits. If the frequency was to exceed the required limit, all grid connected PV inverters would trip simultaneously resulting in an abrupt voltage change due to the change in load current in the distribution grid. The voltage regulation is one of the study themes investigated in the simulation network.

2.2 Unbalance

Current and voltage unbalance is another steady state measure that is impacted by the integration of single phase embedded generation. The unbalance associated with multiple single phase embedded generators can be approximated with the algorithm developed in [11]. The planning guidelines stipulate that single phase embedded generation should be balanced across all three phases to minimize the unbalance at the common distribution transformer. The limit for unbalance on distribution level is 3% [4]. Unbalance causes circulating currents in delta transformer windings increasing losses and operating temperature and reducing the expected life cycle [12]. The voltage unbalance measured on the LV transformer terminal is a function of the load current unbalance and the short circuit level. The measured voltage unbalance is therefore not always a sufficient measure of the detrimental effect of current unbalance in a transformer. The distribution transformers usually have a delta connected MV winding with a high zero-phase sequence reactance preventing the unbalance on the LV grid to mitigate to the MV network. Voltage unbalance on the MV terminals is therefore around 5 times smaller than the unbalance measured on the LV terminals.

In the case of high density residential clusters, it is not possible to ensure that the single phase embedded PV generation is perfectly balanced across the three phases. For the unbalance simulation, it is assumed that all generation is connected the same phase, for different penetration levels of embedded generation.

2.3 Harmonic Voltage and Current Emissions

Harmonic voltages and currents result from non-linear loads such as switch-mode devices or static power converters connected to a power system. Any given voltage or current waveform can be dissected into its constituent harmonics by means of the Fourier transform. Although magnitudes and angles can be calculated for all frequency sinusoids, for regulation purposes, the sinusoidal constituents are calculated as integral multiples of the fundamental frequency by means of discreet Fourier Transform [13] and the angles are usually omitted. Different types of loads and switch-mode power supplies and inverters add or subtract from the harmonic spectrum prevalent in a power system.

Odd harmonics are most prevalent in power systems as they are produced by full-wave inverters, rectifiers and other non-linear loads. The odd harmonics that are multiples of three are classified as zero-sequence harmonics or triplen harmonics that cancel in transformer delta windings in balanced three-phase systems [13]. The even harmonics are DC harmonics produced by half wave rectifiers, which are not implemented in typical electronic domestic loads.

When new devices, such as PV inverters, are connected to a power system the authority responsible for the power quality in the network assesses how the existing network is impacted. The network development guidelines state planning levels that are to be used in an apportionment of the available margin to ensure that the limits remain within the power quality criteria. The margins and apportionment levels of harmonic voltages and currents contained in the various standards were compiled before the widespread integration of inverter based embedded generation, especially on distribution level. [7] uses the principle employed on transmission level to place constraints on harmonic emission levels injected by equipment [4]. Harmonic voltage and current phase angles are not addressed in any of the power quality standards. It is therefore not possible to assess compliance with the harmonic current emission criteria of several devices operating in parallel. If the phase angle of an emitted harmonic is shifted 180° from the same harmonic in the background spectrum, the current at the respective harmonic is absorbed by the device. The magnitude of the resulting current vector may exceed the apportionment limit even when the direction of the current is from the grid into the device [14].

The harmonic voltage limits pertaining to the integration of small scale embedded generation fall into the category where harmonic emissions are deemed insignificant. From a regulatory point of view it becomes very difficult to hold individuals accountable for the harmonic emissions when several embedded generators connect to the same point of coupling. The maximum penetration level of embedded generation connecting to a common feeder inadvertently limits the combined harmonic emissions of several grid connected PV systems. In addition, multiple independent grid connected inverters partially cancel harmonic voltages and currents of each other due to changing phase angles of the respective harmonics. The apportioning method in the IEC 61000 standard applies a diversification factor of 0.5 to the apportionment limits where more than 4 independent inverters are connected [7].

The integration of switch-mode devices on transmission level requires a study of the harmonic impedance of the network. Line and shunt capacitance resonates with line reactance resulting in parallel and series resonance points on the impedance curve at various frequencies [15]. If a non-linear load or switch-mode device emits a certain harmonic current at the frequency where a parallel resonance occurs, it can be expected that the harmonic voltage at that frequency would be magnified, depending on magnitudes and harmonic phase angles. If a voltage harmonic emitted by a device occurs at a frequency of a series resonance in the impedance, the respective harmonic current would be magnified. On distribution level, the cable and line capacitance is very low as capacitance is a function of the voltage squared. The resulting harmonic impedance is therefore predominantly inductive, increasing linearly as a function of frequency. Without any series and parallel resonance points in the harmonic impedance voltage or current magnification due to resonances is not expected.

The PV inverters considered in this research employ L-C type filters to attenuate the switching harmonics and reduce the harmonic emissions below the apportionment limits. The L-C filter introduces a parallel and series resonance on the harmonic impedance at the natural frequency of the filter. When calculating the harmonic impedance of the grid at the point of connection the resonance points due to the L-C filter shift to lower frequencies, depending on the cable impedance between the filter and the calculation point. When harmonic currents resonate with the parallel resonance of the impedance, the resulting voltage may exceed the limit, while the source of the emissions remains within the limits [15].

All equipment is designed to accommodate adverse power quality in terms of harmonics, unbalance and over-voltages and overloading according to the power quality criteria. When harmonic limits used in the equipment design are exceeded, equipment losses and operating temperatures increase resulting in shorter life cycles [6].

3 SIMULATION MODEL

PSCAD EMTDC is used to investigate the three power quality aspects that are most common in residential distribution grids: Voltage variation, unbalance and harmonic emissions. The LV distribution grid in a residential complex or high density estate connects three single phase customers via 4-core LV cables to a central collection point which connects to the municipal MV grid via a pad mounted distribution transformer as in Figure 1.

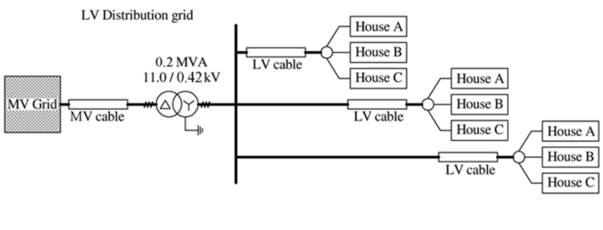

Fig. 1. High density residential distribution grid model.

The rating of the distribution cables and transformers is calculated according to various planning guidelines. The South African guidelines employ a statistical approach based on historical measurement data to calculate the equipment ratings based on Diversified Maximum Demand of N customers sharing a feeder with (1).

$$L = 0.23 \times N \times \frac{c}{a+b}\left[a + 1.28\sqrt{\frac{a \times b}{N(a+b+1)}}\right] \tag{1}$$

The demand curve depicted in Figure 2 assumes that the Notified Maximum Demand c of all the consumers is 60 A. The parameters a = 1.42 and b = 4.13 describe the beta probability density function applicable to the 15 year planning criteria of high density residential complexes.

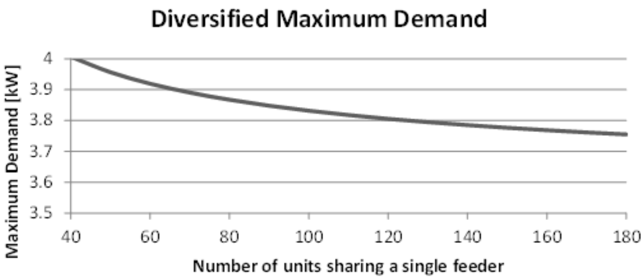

Fig. 2. Diversified Maximum Demand of customers sharing a feeder.

The function (1) approaches a demand of 3.5 kW per consumer, but due to physical constraints including complex area, technical losses and voltage drop, the number of units sharing a single feeder rarely exceeds 160.

3.1 Domestic load

The shaded areas in Figure 3 are the time windows that the respective appliances are in use, as stated by residents living in a complex.

<table>
<tr><th></th><th colspan="24">Time of Use</th></tr>
<tr><td>Geyser</td><td></td><td></td><td colspan="3">0.5</td><td></td><td colspan="3">1</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td colspan="3">1.5</td><td></td><td></td><td></td></tr>
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<tr><td>Base</td><td colspan="24">24</td></tr>
<tr><td>Time</td><td>0</td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td><td>6</td><td>7</td><td>8</td><td>9</td><td>10</td><td>11</td><td>12</td><td>13</td><td>14</td><td>15</td><td>16</td><td>17</td><td>18</td><td>19</td><td>20</td><td>21</td><td>22</td><td>23</td></tr>
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Fig. 3. Daily time-of-use of appliances.

Electronic appliances such as televisions, lighting, security measures and computers make up the Base load. The Base load is on average between 10% and 20% of the instantaneous demand. During off-peak times, the base load constitutes 20% of the total load.

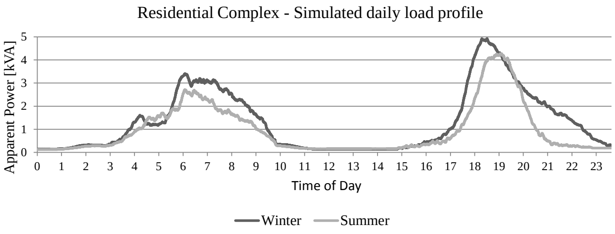

Fig. 4. Daily load profile of consumers in a 45 Unit residential complex.

The simulated daily load profile in Figure 4 compares the winter and summer load profiles during normal work weeks, representing the most onerous peak and off-peak loading times. The calculated peak demand of a 45 Unit complex is 4 kVA, while simulations and measurements suggest that a diversified winter peak demand of 4.9 kVA is possible. For the simulation in this paper, the peak load is based on the calculated value of 4.0 kVA and a minimum load is defined as 2.0 kVA.

3.2 Inverter connected PV system

The PV system is modelled in PSCAD as a PV panel with Maximum Power Point Tracker (MPPT) and DC-DC converter as depicted in Figure 5.

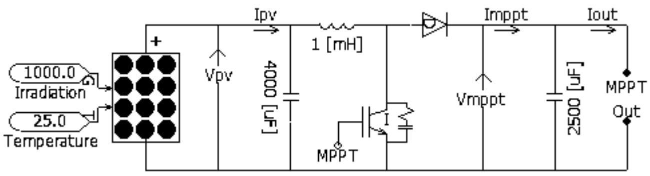

Fig. 5. PV system – PV panels and DC-DC converter

The MPPT DC-DC converter output is the input to the grid connected inverter in Figure 6.

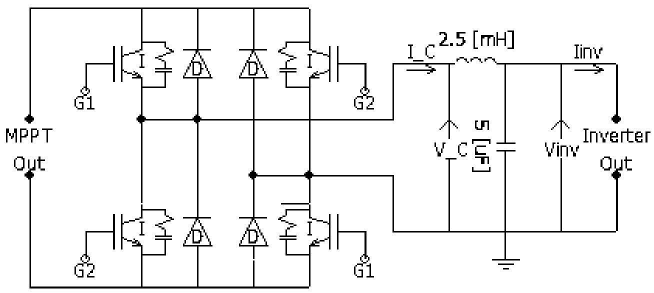

Fig. 6. PV system – Full bridge inverter.

The filter and converter inductors and capacitors are chosen to imitate the harmonic emissions of a practical 4 kW inverter while supplying rated output to a lab test setup. When the inverter output is adjusted, by slowly ramping the irradiation on the PV panels from 400 W/m2 to 1000 W/m2, the harmonic emission changes as a function of the duty cycles of the DC-DC converter and the inverter as indicated by the 3rd, 5th and 7th harmonic current in Figure.

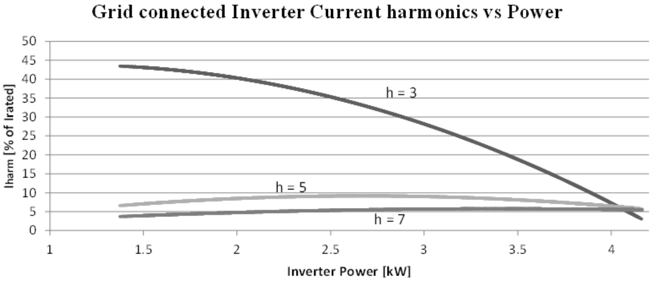

Fig. 7. PV system harmonic current emission under changing output.

For the harmonic emission simulation of the entire distribution grid with embedded generation, the peak harmonic currents emitted by the inverters are injected at the points where the inverters connect to the LV grid. The planning guidelines of the South African utility suggest that the maximum capacity of embedded generation be less than 25% of the transformer rating of a shared LV feeder [4]. In the example of the 45 unit complex, 25% of the 200 kVA transformer rating translates to the integration of 12 × 4 kVA PV generators.

The diversification of the angles of the individual harmonic current component injected at the 12 random locations in the distribution grid is achieved by rotating the angles at random rotational velocities while measuring the voltage and current spectrum at the common LV feeder. The velocities of the angle rotation is slow enough not to affect the harmonic currents and voltage magnitudes

3.3 Distribution Grid

The MV distribution grid is estimated by an ideal source with short circuit impedance typical to MV distribution substations. For the simulation a maximum short circuit current of 12.7 kA is chosen and a minimum short circuit current of 1.27 kA. These currents translate to a source impedance of 0.5Ω and 5.0 Ω respectively. Both have X/R ratios of 5, which is typical for distribution grids. The planning guideline stipulates that the MV feeder voltage should not vary by more than ±1.5%.

The LV cable distribution networks in high density clusters in South Africa are designed for three units closest to one another sharing an LV three-phase supply. The voltage drop over the cable length has to be less than 10% or 18.47V when the Notified Maximum Demand (NMD) is absorbed by the load. The residential distribution grid considered in this research is designed to allow each residential unit to have an NMD of 13.8 kVA with a circuit breaker rating of 60 A. The LV cable grid has to be rated to facilitate this 60 A current while limiting the voltage drop to 10%.

The size of the simulation distribution grid is chosen that the voltage drop over the longest LV cable remains within the 10% voltage drop criteria. The cables are selected from the list of Eskom standard cables [16].

Table II. Eskom Standard XLPE copper cable ratings [16].

Cable	*Area cu*	*R [pu/m]*	*X [pu/m]*	*B [pu/m]*	*length*
11 kV	25mm^2	$6.0\text{x}10^{-4}$	$7.7\text{x}10^{-4}$	$7.8\text{x}10^{-3}$	5km
400 V	25mm^2	0.327	0.687	$2.9\text{x}10^{-9}$	400m

3.4 Distribution Transformer

The transformer used in the example case is a standard Eskom 11/0.42 kV, 200kVA distribution transformer with 4.5% impedance and 1.35% copper losses [17]. The transformers in the South African distribution grids are selected from a list of standard transformers according to the number of customers sharing a feeder.

Table III. Eskom Standard Distribution transformer ratings [17].

TRF Rating [kVA]	***Impedance [%]***	***Customers sharing [#]***
100	4.5	24
200	4.5	50
315	4.5	81
400	4.5	104
500	5	131
630	5	167

These transformers usually do not have On Line Tap Changer (OLTC) and the voltage rating of the secondary is used to compensate for the voltage drop due to the transformer impedance.

4 RESULTS

The simulations are performed on 4 different operational scenarios, investigating the effect of different short circuit levels and loading profiles. The load is termed as a percentage of the transformer rating and the Short Circuit Level (SCL) is calculated on a base of 400 V at the transformer LV terminals.

4.1 Voltage Variation

The simulation network is initialised with the PV generators in service, each injecting 4 kW into the distribution grid. The voltage regulation is measured by disconnecting all the embedded PV generation, while recording the transformer LV winding positive sequence voltage.

Case 1: 10% embedded generation penetration level
Case 2: 25% embedded generation penetration level
Case 3: 40% embedded generation penetration level

Table IV. Voltage variation calculated on transformer LV winding.

	Scenario 1	***Scenario 2***	***Scenario 3***	***Scenario 4***
Load	90%	45%	90%	45%
SCL [MVA]	3.7	3.7	3.2	3.2
Case 1	0.26%	0.17%	0.56%	0.17%
Case 2	0.87%	0.56%	0.95%	0.76%
Case 3	1.04%	0.97%	1.96%	1.38%

The voltage variation results from the reduction in load current through the cable sections. Reducing the current results a smaller voltage drop, resulting in a higher PCC voltage. The change in total active power due to the disconnection of the PV generators is 20 kW, 48 kW and 80 kW for Case 1, Case and Case 3 respectively. The largest change in voltage calculated on the transformer LV windings is 0.95% for the maximum stipulated penetration level of 25%. When the penetration is increased to 40%, the transformer LV voltage can change by almost 2% when all embedded generation is disconnected simultaneously. The short circuit level has a significant impact on the voltage variation, especially under peak load conditions.

4.2 Unbalance

The unbalance is calculated from the simulation model with increasing penetration level of PV systems, connected to the same phase. For this calculation the residential appliance load is balanced across the three phases. The unbalance is calculated under different loading levels and short circuit scenarios. The cases considered are:

Case 1: 10% embedded generation penetration level
Case 2: 25% embedded generation penetration level
Case 3: 33% embedded generation penetration level

The unbalance is calculated on the transformer LV winding using (2).

$$\%V_{unbalance} = 100 \times \frac{V_{positive\ \ sequence}}{V_{negative\ \ sequence}} \tag{2}$$

Table V. Voltage unbalance calculated on transformer LV winding.

	Scenario 1	***Scenario 2***	***Scenario 3***	***Scenario 4***
Load	90%	45%	90%	45%
SCL [MVA]	3.7	3.7	3.2	3.2
Case 1	0.5%	0.6%	1.1%	0.7%
Case 2	2.0%	2.0%	2.0%	1.8%
Case 3	2.3%	2.4%	3.1%	3.1%

The simulation results indicate that the voltage unbalance planning limit of 1.5% is exceeded when the EG penetration level exceeds 25%. The voltage unbalance compatibility limit of 3% is only exceeded if the penetration level reaches 33% and the short circuit level is 3.2 MVA.

4.3 Harmonic emissions

For the assessment of the harmonics due to the PV systems distributed throughout the grid, the harmonic emissions of the loads have been omitted. The background harmonics in the rest of the MV grid have also not been accounted for. The three penetration levels investigated in the study are:

Case 1: 10% embedded generation penetration level
Case 2: 25% embedded generation penetration level
Case 3: 40% embedded generation penetration level

For each of the cases the magnitudes of harmonic current and voltage are calculated. The cases are calculated under peak and minimum load scenario and for a short circuit level of 3.7 MVA and 3.2 MVA.

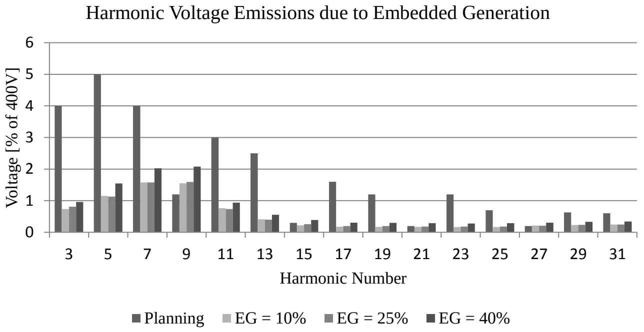

Fig. 8. Transformer LV winding simulated harmonic voltages.

The harmonic voltage planning and compatibility limits are only exceeded for the odd harmonics that are multiples of three. Due to the unbalance in the distribution grid, there is a zero-sequence path for the triplen harmonics to enter the transformer delta winding resulting in larger harmonic voltages than the standards anticipate in a balanced network. The calculated Total Harmonic Distortion is 3.4% for a penetration level of 25% and 4.2% when the penetration level reaches 40%.

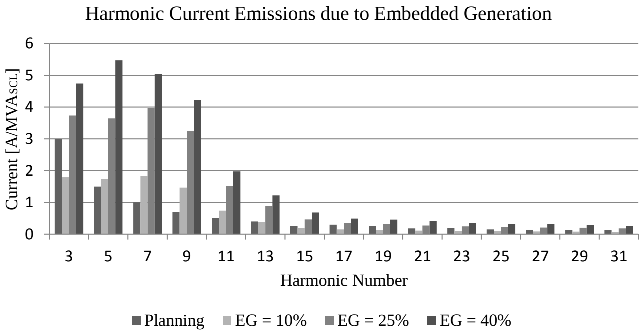

Fig. 8. Transformer LV winding simulated harmonic voltages.

The harmonic current limits contained in the planning guide [4] are exceeded for penetration levels of 25%. It should be noted that the simulated magnitudes correspond to the maximum harmonics that are generated during low irradiation levels.

5 CONCLUSION

The simulation model that was used to calculate the expected voltage variation, unbalance and harmonic emissions due to grid connected PV inverters is based on the planning criteria stating maximum penetration level, maximum generation capacity of individual generators, short circuit levels, cable lengths and loading. The load model suggested in the guidelines was found to be 20% larger than what field measurements showed. The load model used in the simulation is based on the measurement data and scaled to give a peak load of 4.0 kVA with a power factor of 0.9 as well as a minimum load of 2.0 kVA with a power factor of 0.9. The planning guideline [4] suggests that the penetration level of embedded generation connected to a shared feeder should not exceed 25%. For a penetration level of 25% of embedded generation in a high density residential complex, the voltage quality limits stated in the power quality standards listed in Table VI are not exceeded.

Table VI. Summary of power quality simulation results

	Planning	*Compatibility*	*Simulation*
Voltage Variation	±3% step	±18%	0.95%
Voltage Unbalance	1.5%	3%	2.0%
Voltage THD	5%	8%	3.4%
Current Unbalance	No Data	No Data	82%
Current THD	5%	No Data	7.5%

The current limits are not well defined. The South African standard stipulates a maximum current THD of 5% of the rated fundamental current of a new device connecting to the grid. The current THD is exceeded for an embedded generation penetration level of 25%. The standards and guidelines remain silent on current unbalance limits. The unbalance simulation considered all PV generators connected to the same phase, which is very unlikely. The maximum simulated current unbalance is then 82%. Without the PV generation embedded in the distribution grid, the unbalance in the LV network may reach levels of 35% for short periods during any given day. In conclusion:

- Switching embedded generation in or out of service does not cause voltage variations that exceed the planning limit of 3%.
- Voltage unbalance due to embedded generation connected to the same phase does not cause the compatibility limit of 3% to be exceeded.
- Current unbalance should be monitored as it is very likely that equipment ratings may be exceeded when the integration of embedded generation is not coordinated and balanced.
- Only voltage limits of the odd harmonics which are multiples of 3 are exceeded.
- Current harmonic planning limits of several harmonics are exceeded, even for penetration levels less than 25%.

There are four approaches that can be followed to mitigate the challenges associated with the power quality aspects:

1. Restrict the penetration levels of embedded generation even further
2. Assign authority to ensure that load and generation is balanced across the phases.
3. Install active filters to attenuate harmonic currents and voltages
4. Add more margin to the current and voltage ratings of distribution equipment

Power quality aspects relating to current unbalance and harmonic currents have to be addressed in the standards to avoid scenarios where future distribution grids and equipment are not rated to withstand the currents that are due to increasing penetration levels of embedded generation.

It will be beneficial to the distribution network planning departments of utilities and municipalities, the equipment manufacturers and consumers if the theory contained in this work can be validated against power quality recordings of a high density residential cluster once the penetration level of grid connected PV systems reaches the 25% level proposed in the planning guidelines.

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