Distribution Network Power Quality Modelling Requirements: Problems and Solutions

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Abstract

Beyond reliability of any power supply network, one of the most important utility needs in modern time is an actual quality of power being delivered to the consumers. Smart grid, which is the emerging future grid, requires not only reliable but also high power quality network. Power quality studies involve data gathering to model a distribution network under study. As efforts are made to improve the existing weak electric power network in Nigeria characterized by low reliability, the quality of power being delivered to the consumers requires adequate modelling as well. More often the sets of information required for this are not readily available and may pose problems for adequate design model. This paper examines the foregoing challenges involved in modelling the distribution network and proffers appropriate solutions. Characterizing power quality levels in distribution systems helps utility better respond to electric power consumers' needs for higher power quality as part of preparations for a smart grid.

1.0 Introduction

For sustainable infrastructure development in rural areas, the concept of the smart grid which is future grid should be adopted. This necessitates new modelling requirement. This is because there is a paradigm shift from existing conventional power analysis due to electronic non-linear loads (NLLs) that are increasing more and more in power distribution networks. Most electrical systems were originally designed for linear voltage and current and thus traditionally, loads are classified as constant impedance loads, constant kVA and constant current loads. Static load modelling including ZIP coefficients are established facet of power system models (Mclorn et al, 2017). However, the presence of NLLs in power networks has altered the characteristics and analysis of the network involved. In recent times, with the increasing electronics loads as a solution to energy problems, it is common to classify loads as linear loads and non-linear loads. Power quality (PQ) problems are due to the effects of NLLs or harmonic producing loads. It has been reported that between 15-20% of the utility distribution load consists of NLLs in the USA (Mayoral, et al, 2017). If non-linear loads increase in the power distribution system, voltage distortion increases in the direction from source to end-user, due to electrical circuit impedance. Loads cause current distortion in the majority of the cases (Stojkov and Nikolovski,2009). Excessive NLLs can cause serious problems such as overheating conductor, transformers, capacitor failure etc. (Davudi, Torabzad and Ojaghi, 2011; Palethorpe, (2002), Rojin, R. (2013). There is need therefore to establish if various PQ parameters such as voltage level, neutral current flow, harmonic level, unbalanced factors and frequency are within the specified limits. Modelling power supply appropriately is very important for successful harmonic study (El-Sadaary, 1998).

Engineering Recommendation G5/5 stated the roles and responsibility held by shareholders in ensuring compliance with the expected level of harmonic. Data such as harmonic impedance are needed for full assessment of the impact on the distribution network. The impact of existing levels of disturbances or distortion referred to as "background levels" is most significant when assessing the suitability of a proposed new load. A load causing voltage disturbances or harmonic level to be exceeded is an indication that such load cannot be accommodated (EDS, 2016). Also, the system impedance at a particular frequency is needed to calculate the resulting harmonic voltage distortion. Harmonic impedance is an important parameter for electric power system analysis (Monteiro, et al, 2018). Identifying problems in an electrical network before any extensive damage occurs is advisable for any power system. Not only does modelling of PQ necessary for the maintaining accurate operation of sensitive equipment, it also ensures that unnecessary energy losses in a power system are kept at a minimum which leads to more profits.

A harmonic analysis is required when there is a possibility of exceeding the harmonic limits at the PCC with the distribution network or due to malfunctioning of power electronic equipment (Khan, 2008.)

2.0 Requirements for PQ modelling in A Distribution Network

There is the need to identify PQ requirements in distribution networks as a result of high penetration of NLLs. Depending on the PQ in focus, the requirements vary slightly but with major requirement more or less the same. The requirements vary from country to country, utility to utility and even from substation to substation within a distribution company. Fig 1 shows modern power system with electronic solutions and standards for regulation as well. Obviously, in standards, the tendency in the setting up compatibility levels, e.g. for the voltage harmonics, shows a direct convergence to the increasing number of harmonic sources. Standards exist to regulate the impacts of electronics devices. The development of standards can help to keep the disturbances due to these non-linear devices within the limits. There are various standards and regulations across the globe on power quality.

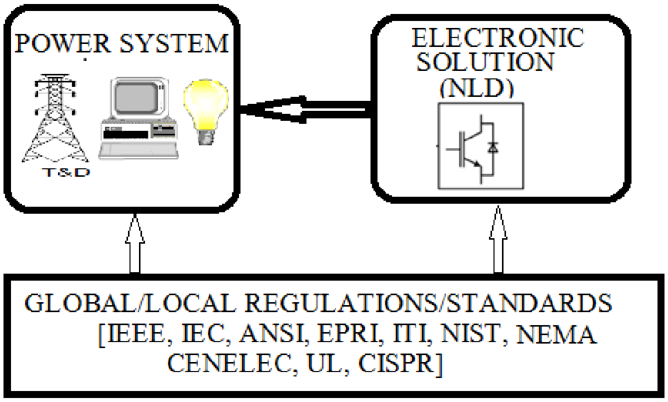


Fig.1: Modern Electrical Power System Components

Generally, the PQ modelling requirements can be divided into different components of power system such as source (utility) network model, transformer model, feeder model and loads model. Other major components include transmission line model, capacitor bank model etc. Load model includes induction motor, linear loads and harmonic producing loads. The network type, network width, load density and the quality of the grounding have influenced the choice. Generally, information on single-line diagram, Utility data, Customer data–linear and NLLs, PF, usage etc. are needed to properly address the PQ of any network. Single-line diagram often serves as the major substation reference drawing and require special emphasis (RUS, 2001). Table 1 shows a typical distribution feeder data.

Table 1: Typical Distribution Feeder Data (Source: EPRI, 2008)

Parameter	Typical Value
Conductor (19 stranded copper)	500MCM
GMR	4.69 ft
Earth resistivity	100 Ωm
Line-neutral spacing	4.00 ft
Section length	1.0 mile
Base	100 MVA
Voltage	13.2 kV
Z_1	0.0246+j0.1195Ω/1000
Z_0	0.0788+j0.5606Ω/1000
Positive sequence capacitance	50 nF/mi
Zero sequence capacitance	47.5 nF/mi

Prediction of harmonic propagation requires the knowledge of network structure and its impedance. If impedances are known, then it may be possible by simply redistributing sensitive loads or repositioning the NLL (Palethorpe, 2002). Harmonic analysis can then be performed for the base case to compute the impedances at the harmonic source buses. The nonlinear load current consists of a fundamental component and harmonics. Any other loads, even linear loads, connected at the point of common coupling (PCC) therefore have harmonic currents injected into them by the distorted PCC voltage. Such currents are referred to as contributions from the power system, or supply harmonics (Mazumdar, 2006). Voltage distortion is created by pulling distorted current through the impedance and the amount of distortion is directly proportional to the system impedance and amount of distorted current pulled through the impedance. Fig. 2 shows a measured current harmonic distortion of a NLL monitored in a distribution network with a power harmonic analyser.

Fig. 2: Harmonic Current Waveform Distortion due to harmonic-producing loads

Short circuit power is required to calculate the maximum harmonic voltage distortion. Detailed harmonic impedance model is thus required for certain assessment. The voltage distortion with certain current distortion depends on the short circuit ratio of the supply. The higher the ratio, the lower the voltage distortion. Short circuit ratio is a measure of the relative size of the customer load compared with the capacity of the distribution network (Palethorpe, 2000).

3.0 Solutions for Distribution Network Modelling

A model describes the mathematical relationship between inputs and output by obtaining a set of equations (mathematical model) that describes the behavior of the system. PQ modelling is a mathematical way of predicting PQ disturbance levels based on PQ indices data. Components such as transformers, capacitors, motors, and the utility system impedance are taken into account, and non-linear loads are represented by multiple frequency harmonic current sources. Such a modeling study will indicate if disturbance levels will fall within IEEE or utility limits. The analysis of PQ in rural distribution network is complex because multiple factors influence the emission of and propagation of harmonics through the network.

The conventional harmonic analysis methods used the Newton-Raphson power flow method, the admittance matrix, or the impedance matrix to obtain harmonic penetration in distribution systems.

It is almost important to understand the conventional power flow (CPF) to be able to effectively analyse harmonic power flow (HPF). Essentially, the difference between the CPF and HPF is that the equations derived for Newton-Raphson based CPF are written in Fourier series form for the Newton-Raphson based HPF. The additional equation required for Newton-Raphson based HPF results from the need to determine harmonic frequency voltages in addition to the fundamental frequency voltage in the power system. All equations are written as a function of the power system impedances and voltages throughout the system.

Examples of modelling solutions to some of the components of power system are discussed below.

Generator Modelling

The reactance used to model the synchronous generator in Fig. 3 for the hth harmonic frequency is given by:

$$\mathrm{X}_{\mathrm{gene}} = kX_2 \qquad (1)$$

Where X_2 is fundamental frequency negative sequence reactance of a synchronous machine.

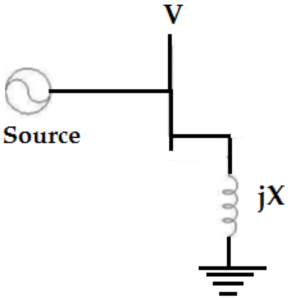


Fig. 3: Generator model

Induction Motor

The induction machine is one of the most commonly used motor loads. It is represented as in Fig. 4. Though similar to a synchronous machine, the harmonic impedance model can be obtained based on the per phase fundamental frequency model if the direct axis and quadrature axis subtransient reactance are unknown. The magnetizing inductance is ignored since it is very large compared to others. When harmonic current flow from the network into the stator windings of an induction machine, the resultant flux will rotate in the air gap at a speed of . Where the direction may be the same or opposite to the rotor's direction (Heidt, 1994).

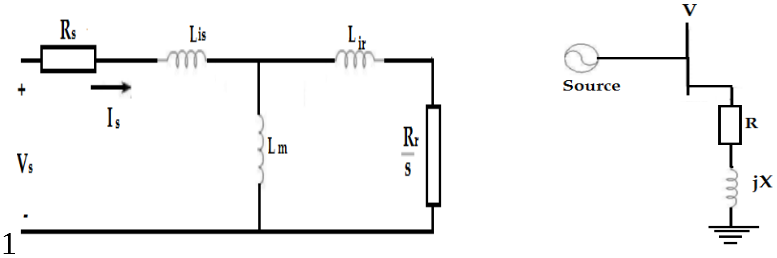


Fig. 4 Equivalent of Induction motor and HPF model of an induction motor

Where Vs is stator voltage at fundamental frequency (per phase), Isis stator current at fundamental frequency (per phase), Rs is stator winding resistance, Lis is the stator winding leakage inductance, Lm is the magnetizing inductance, Lir is the rotor winding leakage inductance and Rr is the rotor winding leakage resistance.

General Loads and Harmonic Producing Loads Model

The main purpose of a load model is to correctly represent the changes in active and reactive power demands of the modelled load as a function of variations of certain supply system parameters. Accordingly, the most frequently used load models can be described as a mathematical or analytical description of the changes in active and reactive power flows to a device, or group of devices connected to the power system, typically with respect to voltage and/or frequency (Gil, 2014). This is modelled with shunt resistor in parallel with an inductor as shown in Fig. 5. Their values can be obtained from fundamental frequency real and reactive power as shown in eqns. 2 and 3.

$$P_L = \frac{V_L^2}{R_L} \tag{2}$$

$$Q_L = \frac{V_L^2}{R_L} \tag{3}$$

In order to understand the injection of harmonic currents in the power distribution network, it is necessary to discuss the general characteristics of the NLLs. NLLs inject harmonic currents or harmonic voltages into the distribution network even when fed by a sinusoidal voltage or current waveform. NLLs can be broadly divided into two categories: harmonic current source type loads and harmonic voltage source type loads (Mollerstedt, 2000). Usually, nonlinear loads are modelled as harmonic current sources into a linear network. The impedance used to model an unknown conventional load at all harmonics frequencies is as given in eqns. (4) and (5).

$$R_L^h = R_L \tag{4}$$

$$X_L^h = kX_L \tag{5}$$

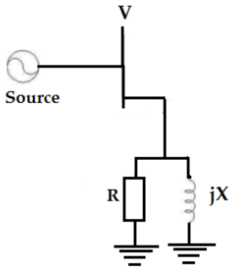


Fig. 5. General load represntation

Transformer Modelling

This is modelled with series impedance for the windings with a shunt magnetizing branch of the core. Since it involves harmonic study, transformer short circuit impedance, magnetizing characteristic and winding are considered very important as determinants of harmonic flow. Transformer saturation and skin effect are assumed negligible.

Case Study

A transformer supplying an area of distribution network under investigation is to be modelled for analysis. However, the information on the transformer nameplate was found to be grossly inadequate for modelling secondary distribution parameters. The available data from the manufacturer's specification as seen on the nameplate of the transformer are given in Table 2. The transformer feeds the multimedia section and administrative building of the Federal Polytechnic Ilaro. Relevant data from the areas are obtained to determine their load pattern. The operating capacity and installed capacity are used to estimate minimum and maximum system impedance as a function of frequency for different system conditions. This section presents only the aspect of transformer modelling and short circuit ratio used for further study for lack of space.

Table 2: Transformer Data for PQ Modelling

Parameter	Value
Transformer Ratings:- KVA	500
Up raiser cable: -	3
Volts: No load normal tap:{HV/ LV }	11000/433
Ampere Normal tap:{H.V/ L.V}	26.24/ 666.67
Phases:	3Φ
Frequency: Hz	50
Connection symbol:	DynII
Year of installation:	1997
Year of manufacturer: -	1981
Type of cooling:	ONAN
Tapping range	+-5% in 2.5% tapps

Impulse level (kV)	75
Losses at 75^0C (W)	5100
No load losses (W)	680
Impedance Z (%)	4.75

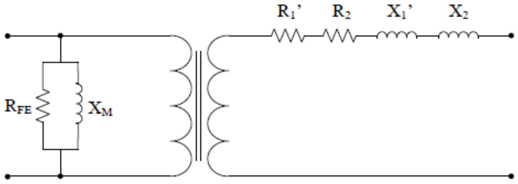


Fig. 6 Transformer equivalent circuit (Gil, 2014)

Figure 6 shows a model for the equivalent circuit of the transformer. Details steps to obtain the series and parallel resistance and reactance can be found in Gil (2014).

Determination of the short circuit ratio of the transformer for harmonic distortion evaluation

At any point within a power network, the equivalent impedance at fundamental frequency can be determined from short circuit current information. The size of customer loads compared with the capacity of the distribution network is called short-circuit ratio. This measure of short circuit ratio is made because the ultimate aim of imposing such a standard is to limit the voltage distortion on the network.

Short circuit ratio (SCR) is given as:

$$SCR = \frac{I_{sc}}{I_L}$$

Where I_{SC} is short circuit current and I_L is load demand for the average of twelve months. In this case, the operating load is taking as equivalent values.

$$I_{sc} = \frac{1000*0.5MVA}{\sqrt{3}\,x0.4}$$

$$I_{sc} = 2883.33\ A.$$

The average kW demand over the past 12 months is obtained by summing all the operating loads being served by the transformer as against all the installed loads as shown in Table 2. This serves as a good approximation.

Table 3: Loads classification of area under study

Loads	Values (kW)
Total non-linear load (Installed)	63.65
Total non-linear loads (operating)	63.246
Total linear Installed loads	153.335
Total linear loads (operating)	137.39

The total estimated value is 200.636 kW.

Therefore,

$$I_L = \frac{200.636}{\sqrt{3}\, x 0.4 X\ 0.85}$$

$$I_L = 340.7\ A.$$

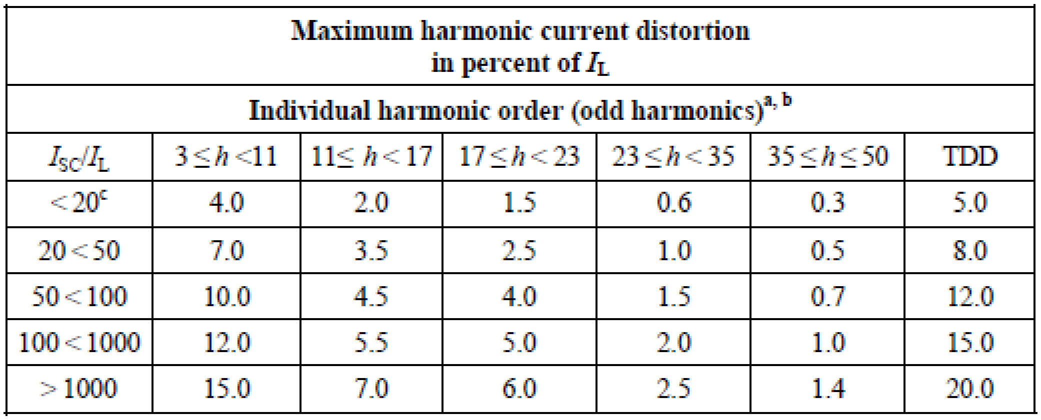
Hence, SCR is obtained as:

$$SCR = \frac{2883.33}{340.7}$$

$$SCR = 8.46.$$

Table 4 shows table 2 of IEEE 519-2014 standard on current distortion limit for systems less than 69kV.

Table 4: Current distortion limits for systems rated 120 V through 69 kV



Maximum harmonic current distortion in percent of I_L						
Individual harmonic order (odd harmonics)[a, b]						
I_{SC}/I_L	$3 \leq h < 11$	$11 \leq h < 17$	$17 \leq h < 23$	$23 \leq h < 35$	$35 \leq h \leq 50$	TDD
$< 20^c$	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

From this table, since the SCR is less than 20 then the maximum harmonic current distortion allowed for odd harmonic less than 11 is 4% while between 11 and less than 17 odd harmonic is 2% etc with maximum total demand distortion (TDD) 5%.

5.0 Conclusion

Distribution network operation demands technical solutions for necessary policy formulation and implementation in rural distribution network. Without the knowledge of a network structure and impedance, it will be difficult to adequately model a distribution network to predict harmonic propagation. This paper has discussed salient issues in PQ studies of a distribution network. The main requirements have been highlighted with case study. This knowledge will be useful to designers and consultant in power system analysis planning to accommodate increasing electronic NLLs. Adopting appropriate methods from the beginning is prerequisite for sustainable development in rural infrastructure. Such approach should be with smart grid in view. Also, Utilities need a monitoring system to help track and investigate harmonics and other various PQ problems such as voltage variations, unbalances etc. to maintain a high level of power quality and resolve issues before a problem develops.

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