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Harmonic Analysis of Residential Microgrid Operating ON/OFF Grid with Non-linear Loads

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SUMMARY

In planning for Distributed Energy Resources (DER) connected to a smart home operating as a microgrid, careful consideration must be taken to ensure the microgrid is resilient during both grid-connected and islanded operation. Many define a reliable and resilient system to that of a power system that has high availability and can bounce back or recover quickly after a defined outage event. While this is true, a key component of a reliable power system applied in the low voltage residential space that is often overlooked is power quality. If the microgrid power system quality is not within pre-defined limits, system loads can and will prematurely fail. There are many factors to considered when designing a microgrid, including the size of a new DER, the preferred DER/microgrid control technology and load types, like non-linear loads. Non-linear loads, such as switch mode power supplies, LED lighting and rotary converters, are not only common in a typical smart home, but can make up most of the load profile. This paper discusses power system quality topics that need to be considered when implementing a DER as a key source of a microgrid on residential system that has a high volume of non-linear loads, often included in a smart home. Areas examined are total harmonic distortion (THD) levels with synchronous generators and inverter based DERs such as batteries. Actual smart home power quality field measurements and a case study simulated on a RTDS real time power system simulator is presented in this paper. Mitigation methods and solutions are also discussed.

KEYWORDS

DER, RTDS, TDD, THD, Harmonics

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INTRODUCTION

Power system harmonics are primarily generated from non-linear (non-sinusoidal) power sources such as grid inverters, loads such as switch mode power supplies, variable frequency drives (VFDs), and rotary converters. Grid inverters are required to meet voltage and current harmonic governed by industry standards such as UL and IEEE. However, when many non-linear loads are connected in a power distribution system, high harmonic levels can cause performance or failure issues on the devices connected. For instance, many devices such as audio-video equipment, require the power system to have a 5% or less harmonic distortion factor. Depending on the strength of the source (Grid, Distributed Generation (DG), etc.) having high levels of current THD can cause bad voltage distortion levels downstream in the power system. The “weaker” the source or the higher the system impedance, the higher the voltage distortion will be further down the power distribution system.

IEEE519 is a standard that is used often by utilities and consultants as a reference or guide for harmonic practices and requirements in power systems. In many cases, the required THD levels are applied incorrectly or misunderstood. The results on harmonic testing devices display the THD levels which are based on the measured load, which in many cases can be 30-50% of the system full load. The TDD limits that are called out in IEEE519 are based on the load limit (full load) of the system. The TDD reading will typically remain the same or reduce when a harmonics test is performed again at higher loads. The TDD is defined as the ratio of the root-sum-square value of the harmonic current to the maximum demand load current. So, at rated load current THD and TDD are the same. When the load drops, the value of TDD relative to THD will decrease proportionately with the load [2]. As an example, if the THD is 40% at 50% service loading, the TDD will be 20%.

$$I\,TDD = \frac{\sqrt{I_2^2+I_3^2+I_4^2+I_5^2\dots}}{I_L} \times 100\% \quad \text{Eq.1}$$

$$I\,THD = \frac{\sqrt{I_2^2+I_3^2+I_4^2+I_5^2\dots}}{I_1} \times 100\% \quad \text{Eq. 2}$$

Given the low short circuit contribution (high impedance voltage source) of a residential DER, low TDD harmonic levels are required at residential installations.

SMART HOME POWER QUALITY MEASUREMENTS

Total Harmonic Distortion (THD) current and voltage measurements were measured in a lab setting with an inverter based DER system OFF, inverter based DER running in parallel with Grid, and inverter based DER in Grid Forming (operating off grid with a low power PV based system in operation).

IEEE519 recommends harmonic measurements at the Point of Common Coupling (PCC). For our lab tests, we determined the best location for the measurement was at the Load Panel since this could be the closest point to residential loads of concern. See block diagram below.

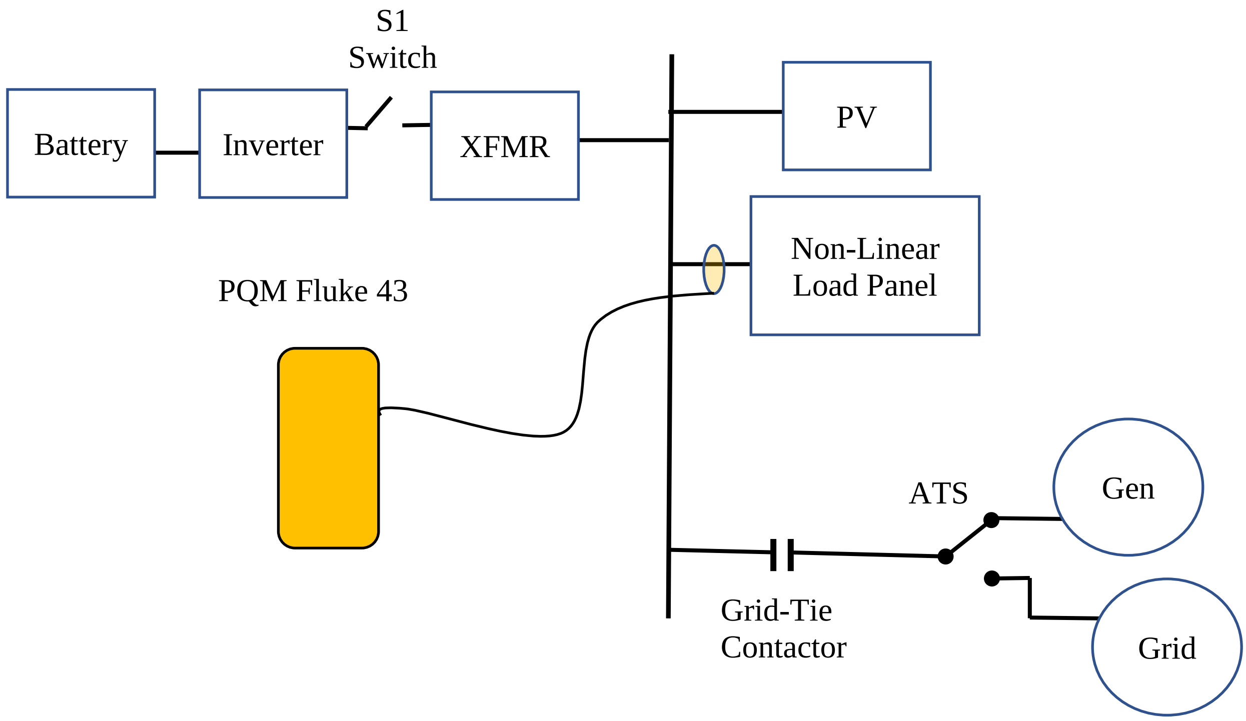

Figure 1 – 240VAC, 600A SERVICE Lab Test Topology

LAB TEST PROCEDURE

1. **<u>Grid Only:</u>** Take Current THD measurements with DER unit off (S1 OPEN, Grid-Tie Contactor CLOSED)
2. **<u>Grid + DER:</u>** Take Current THD measurements with DER unit running (S1 CLOSED, Grid-Tie Contactor CLOSED)
3. **<u>DER Only:</u>** Take Current THD measurements with DER Grid Forming (S1 CLOSED, Grid-Tie Contactor OPEN)

LAB TEST RESULTS

System Configuration	**Line Current**	**THD (Current)**	**3rd (Current)**	**5th (Current)**	**7th (Current)**
Grid Only	(L1) 50 A (L2) 59 A	(L1) 10.2% (L2) 11.0%	(L1) 8.5% (L2) 9.4%	(L1) 2.3% (L2) 1.5%	(L1) 4.3% (L2) 3.2%
Grid + DER	(L1) 50 A (L2) 59 A	(L1) 8.4% (L2) 10.4%	(L1) 7.1% (L2) 8.7%	(L1) 2.4% (L2) 3.4%	(L1) 3.8% (L2) 3.6%
DER Only	(L1) 42A (L2) 51A	(L1) 15.0% (L2) 15.7%	(L1) 13.0% (L2) 15.4%	(L1) 5.1% (L2) 3.2%	(L1) 2.6% (L2) 1.1%

Table 1 – Current THD Results

CALCULATE TDD PROCEDURE

a) *Lab Grid Short Circuit Current*

$$Isc = \frac{100KVA}{240V} \times \frac{1}{5\%} = 8.33kA$$

Transformer %Z = 5% and infinite bus from utility.

b) *DER Short Circuit Current*

$$Isc = \frac{100KW}{240V} \times 1.4\, p.u = 0.583kA$$

DER inverter short circuit output is 1.4p.u.

c) *Short Circuit Ratios (SCR)*

Grid = $\frac{8333}{400} = 21$

DER = $\frac{583}{400} = 1.5$

Note: Maximum Load current was set to 400A. If the maximum demand current at each residence is lower or higher, this SCR could force the TDD requirement into another category.

d) *Apply Short Circuit Ratios to IEEE 519 Table 2 and compare to test results*

Table 2—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	$3 \le h < 11$	$11 \le h < 17$	$17 \le h < 23$	$23 \le h < 35$	$35 \le h \le 50$	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

[a]Even harmonics are limited to 25% of the odd harmonic limits above.

[b]Current distortions that result in a dc offset, e.g., half-wave converters, are not allowed.

[c]All power generation equipment is limited to these values of current distortion, regardless of actual I_{sc}/I_L.

where

I_{sc} = maximum short-circuit current at PCC

I_L = maximum demand load current (fundamental frequency component) at the PCC under normal load operating conditions

Figure 2 – IEEE519 Table 2 Current Distortion Limits [1]

LAB RESULTS SUMMARY

The results reflect what the THD levels are based on the measured load, which in this case was approximately 120A. The TDD limits that are called out in IEEE519 are based on the load limit (full load) of the system. The TDD reading will remain the same or reduce when a harmonics test is performed again at higher loads. The measured results show the recommended individual %THD thresholds are violated in certain cases. As mentioned earlier in the report the measurements taken are THD readings and not TDD.

RTDS CASE STUDIES

This paper performed three case studies to examine a residential microgrids' harmonic profile during both grid-connected and island modes. The cases included synchronous and inverter-based DERs. The microgrid case study had a 208V 3-phase distribution system with a single connection to a 208VAC grid via a 100 KVA transformer. See Fig. 3. The DER portfolio consisted of (1) 30kW 208VAC synchronous generators and one (1) 100KVA inverter-based generator with a constant DC source emulating a 100 KW battery energy storage system (BESS). The distribution loads included non-linear and linear lumped loads. The following DER/DG configurations were modelled in an RTDS real time digital simulator.

- Parallel operation, 1 DGs and 1 inverter based DER with non-linear loads.
- Islanded operation, 1 DGs with non-linear loads.
- Islanded operation, 1 inverter based DER with non-linear loads.

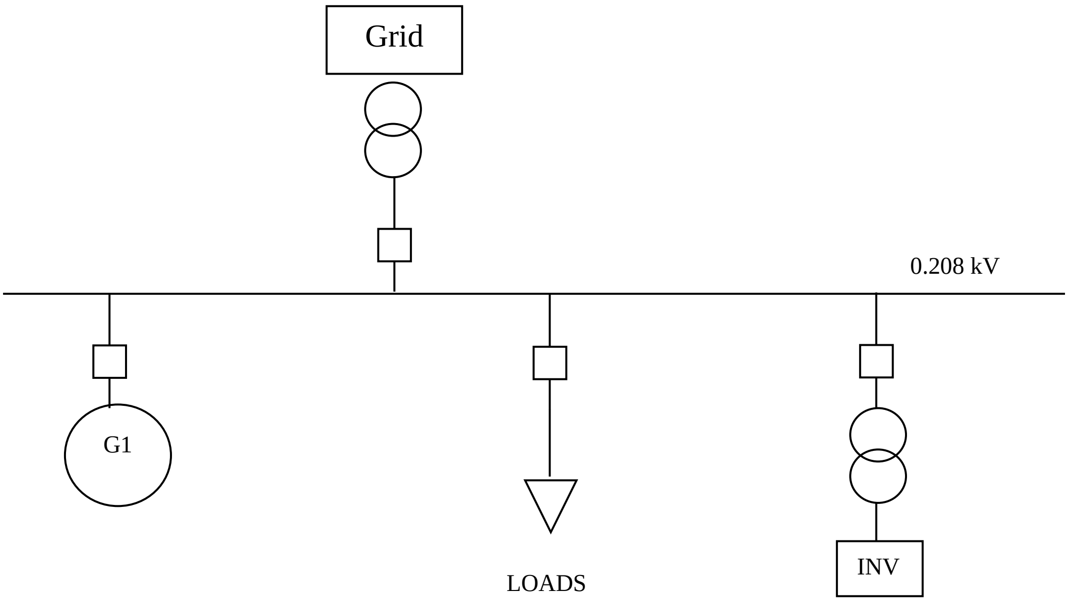

Fig. 3: Microgrid Case Study 1-line Diagram

Fourier analysis was performed and plotted using the line to neutral voltage measurements on the simulated residential 208V bus. In the first two cases, some harmonic frequencies are present with peak frequencies around 180Hz. See Fig. 4. In addition to the non-linear loads, the frequencies outside the fundamental can be attributed to inverter model characteristics. The short circuit contribution from the 100KVA transformer and the generator's transient reactance provide the microgrid system adequate I_{sc}/I_{load} ratio. This mitigates high voltage distortion levels throughout the residential power distribution system.

In the third case the inverter is operating the microgrid in isochronous mode controlling the non-linear loads to the nominal voltage and frequency. In Figure 5 there are additional frequencies off the fundamental. This additional distortion can be damaging to equipment within the residence.

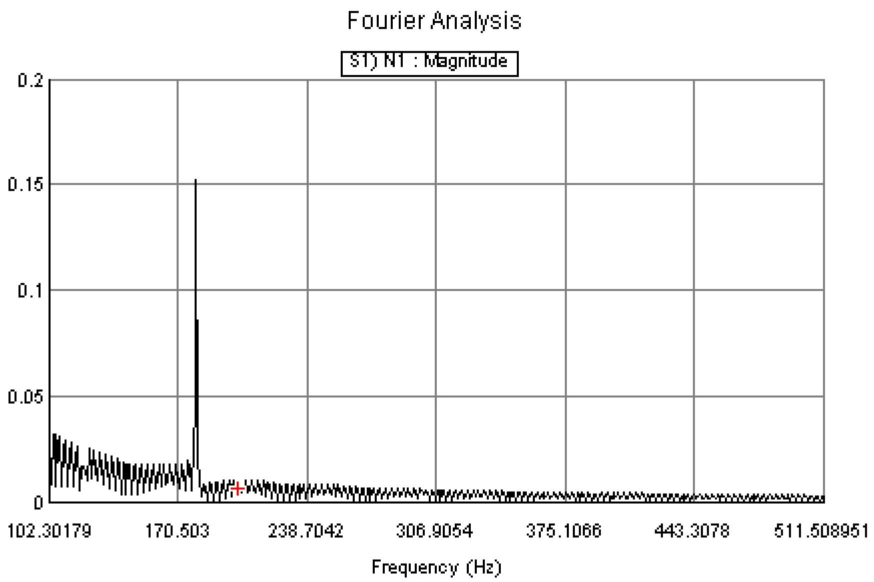

Fig. 4: Microgrid Case Study: Fourier Analysis Grid + DG + Inverter with Non-Linear Load

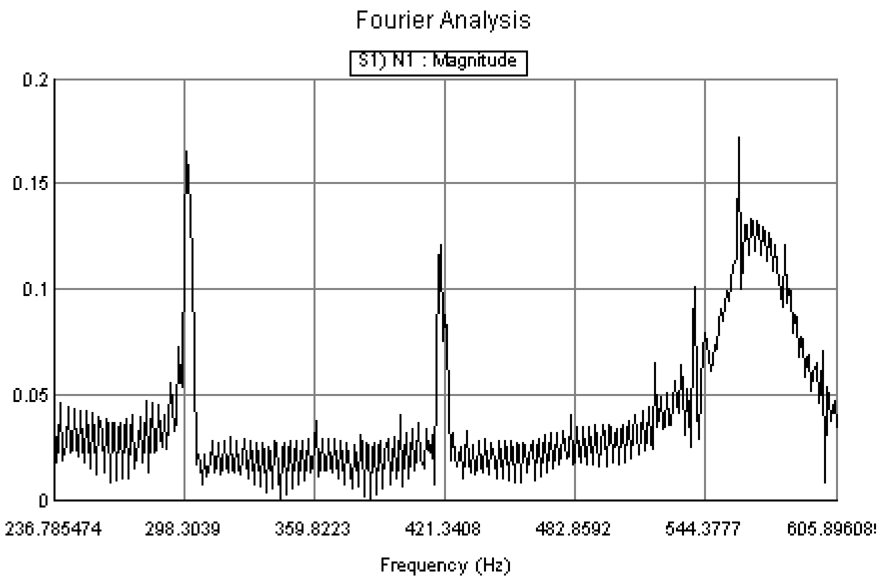

Fig. 5: Microgrid Case Study: Fourier Analysis Inverter Only with Non-Linear Load

CONCLUSION

Designing a resilient microgrid requires careful planning and detailed design. One of the major technical challenges when designing a microgrid in a residential application, that will operate in grid-connected and island modes, is understanding and benchmarking the power quality for each installation. Due to the changes in the nominal load/short circuit current ratios in both modes the microgrid should be modelled, if possible, and measured with accurate power quality equipment. Since inverter-based DERs inherently do not have large short circuit capability and active filters are not common in single phase or residential applications, mitigating power system harmonics can be a challenge. Proper power distribution planning and applying as needed passive solutions such a line filters are a couple key tools to help address these challenges. With a sound approach and the right tools, a residential microgrid with non-linear loads can operate with acceptable power quality.

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