Studying the Effect of Non-Linear Loads Harmonics on Electric Generator Power Rating Selection

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Abstract

Non-linear loads connected to an electric power system produce Harmonic currents, harmonics are introduced into the system in the form of currents whose frequencies are the integral multiples of the fundamental power system frequency (50/60 Hz). The harmonic currents interact with the supply system impedance causing distortions in supply output voltage and current, which has a very bad effect on all other loads connected to the system and the power supply itself, such as overheating, increasing powers losses in the system, and malfunction of protection and control devices connected to the system. This paper presents a study to analyze the effect of voltage and current harmonics resulting from non-linear loads such as variable frequency drive, uninterruptable power supply, and battery chargers on operation and power rating of synchronous generator. The study introduces an optimized method for selecting the suitable generator power rating to withstand harmful harmonics effects for a safe operation of the generator, saving its lifetime, and to improve the power quality of the power system. The method depends on analyzing the effect of increasing the supply generator power rating on the THVD produced from non-linear loads harmonics connected to the system. By calculating the THVD for each case of a generator power rating, a mathematical relationship between generator power rating and TVHD can be found. So, the relationship between generator power rating and total harmonic distortion in the power system will be discussed clearly.

Keywords: Generator power rating, Harmonics, Non-linear loads

Introduction

Applications of power electronic type devices are increasing by a significant way in all power system applications, these applications have non-linear voltage-current characteristics, which results in increasing harmonics in the power systems (H. Ortmeyer, 1985)

Nowadays, a high concern to power quality is the harmonic distortions of voltage and current waveforms. The ideal power supply is characterized by perfect sinusoidal waveforms of voltage and current. The presence of harmonics causes many harmful effects on the power supply and power system components (Serb, 2016)

Power system harmonics are introduced into the system in the form of currents whose frequencies are the integral multiples of the fundamental power system frequency. Harmonic currents are produced by non-linear loads connected to electric power systems such as static power converters, arc discharge devices, saturated magnetic devices. Static power converters are the largest non-linear loads used in industry in many applications, such as electrochemical power supplies, variable speed drives, and uninterruptible power supplies. The harmonic current interacts with the supply system impedance causing distortions in supply output voltage and current, which affect all other loads connected to the system and the power supply itself (Qiu Hongbo, 2015)

The principle of how the harmonic components distort the fundamental waveform is shown in Fig. 1.

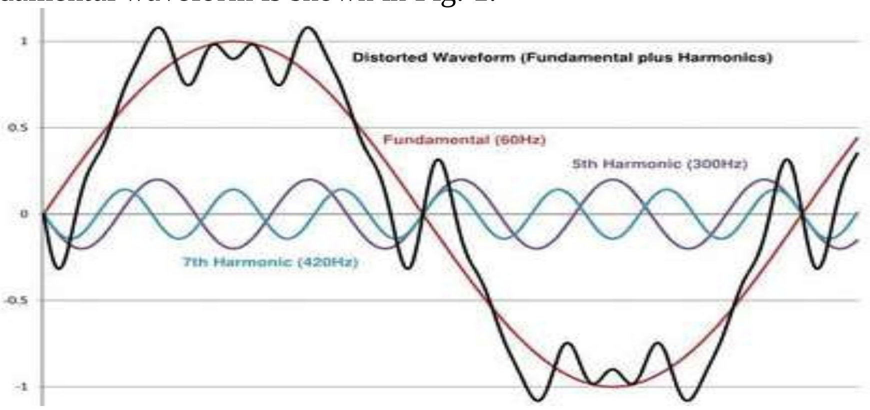

Figure 1: Distorted waveform due to harmonics.

The harmful effects of harmonic distortions are: (H. Ortmeyer, 1985), (Serb, 2016), (Qiu Hongbo, 2015)

1) Increase stress on insulation due to voltage effects.

2) Thermal stress and overheating to electric machines, capacitors, and solid state equipment.

3) Increase power loss in machine windings and conductors due to additional harmonic current flow.
4) Disruption (abnormal operation or failure) caused by voltage or current harmonics such as stray torques generated in electromechanical devices and malfunction or failure of electronic devices, switchgear and relays.
5) The high-frequency electrical noise which causes large voltage spikes in the power system ground which can damage sensitive electronic equipment such as computers, programmable logic controllers, and circuit's boards.
6) Increase the generator losses and temperature, which could decrease machine lifetime. Due to its high energy density and small size, the generator losses in the unit volume will be large, the cooling area will be small, and so the cooling will be difficult.

Harmonic current will cause also eddy current losses in the rotor, which will increase the rotor temperature and affect the efficiency seriously.

Studying harmonics effect is very important for generator supplying non-linear loads because if the harmonics increase above a certain limit, it will cause reduction of generator lifetime if it is not correctly rated and applied (Elias Kyriakides, 2015).

There are three main methods used to solve harmonics problems (www.trane.com, 2006):
1) Harmonic filters (Tuned Harmonic Filters, Broadband Blocking Filters, and Active Filters).

This method eliminates harmonic distortion of current and voltage, but it has some disadvantages:

- Higher cost.
- Separate mounting and protection devices are required.
- Attention should be taken to ensure that the filter will not be overloaded.
- The increase in the voltage due to over compensation that may happen. Leading power factors could happen during lightly loaded conditions.

2) Harmonic mitigating transformers

It develops phase shifts between sources of harmonics which results in the elimination of some harmonic orders. It's disadvantages:

- High cost due to the usage of additional equipment.
- Impedance matching is critical to performance.
- Transformers requires separate mounting.

3) De-rating the generator to withstand the harmonic currents.

Harmonic voltage and current distortion are greatly dependent on the power supply impedance. In comparison with utility power supplies, the effects of harmonic voltages and harmonic currents are significantly very high for stand-alone generators due to their source impedance being typically three to ten times that of utility power system. The major impact of voltage and current harmonics is to increase the machine heating due to increased iron losses and copper losses. To reduce the effect of harmonic heating and torque pulsations with torsional vibrations, the generators supplying non-linear loads are required to be up-rated (Larger generators are required because as generator rating increases, its impedance decreases) (www.trane.com, 2006), (Iverson, 2016).

The advantage of this method is it's the least expensive methods to deal with harmonics on the power system (Iverson, 2016).

The disadvantage of this method is that it solves only the effect of current harmonics on voltage waveform (decrease voltage harmonic distortions only and the current harmonic distortion stay as it) what will appear clearly from results in this paper.

Selection of suitable generator power rating

Selection of suitable generator power rating supplying non-linear loads presents a very challenging problem. Generator supplying non-linear loads is required to be de-rated if the voltage and current harmonics exceeded certain limits that will cause harmful effects on generator as discussed before. These harmonic limits are recommended by IEEE Std 519™-2014, as shown in tables 1, 2.

This study will determine the effect of up-rating generator power on voltage total harmonic distortion, in order to select the correct generator power rating to supply non-linear loads with a safe operation such that the standard limits of harmonic distortion shown in tables1, 2 are not exceeded.

The harmonic analysis is done using ETAP program. The circuit diagram of the system used for the simulation process is shown in Fig.3. It consists of a three phase synchronous generator rated at 595 KVA supplying nonlinear loads as shown in Fig.3. The detailed data about the generator is given in the Appendix.

Table 1 Voltage distortion limits

	Bus voltage			
	$V_B \leq 1kV$	$1Kv < V_B \leq 69kV$	$69Kv < V_B \leq 161kV$	$161Kv < V_B$
Individual harmonic %	5	3	1.5	1
Total harmonic distortion %	8	5	2.5	1.5

Table 2 Current distortion limits for systems rated 120 V through 69 kV

	Individual harmonic order				
	$3 \leq h < 11$	$11 \leq h < 17$	$17 \leq h < 23$	$23 \leq h < 35$	*TDD*

$I_{SC}/I_L < 20$	4	2	1.5	0.6	5
$20 < I_{SC}/I_L < 50$	7	3.5	2.5	1	8
$50 < I_{SC}/I_L < 100$	10	4.5	4	1.5	12
$100 < I_{SC}/I_L < 1000$	12	5.5	5	2	15

Where:

$I_{SC:}$ is the maximum short-circuit current.

$I_{L:}$ is the maximum demand load current (fundamental frequency component) under normal load operating conditions

h: is the harmonic order.

This study will determine the effect of up-rating generator power on voltage total harmonic distortion, in order to select the correct generator power rating to supply non-linear loads such that the limits of harmonic distortion shown in tables1, 2 are not exceeded.

The harmonic analysis is done using ETAP program, the circuit diagram of the system used for the simulation process is shown in Fig.3. It consists of a three phase synchronous generator non-linear loads as shown in Fig.2

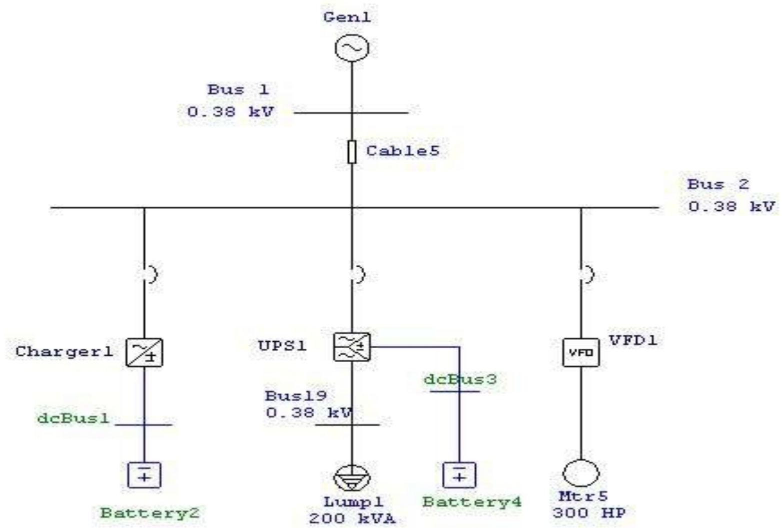

Figure 2: Simulation system model.

Simulation results

Case 1: 550 KVA non-linear loads with 6 pulse rectifiers supplied from 595 KVA synchronous generator (Generator 1) of parameters given by the manufacturer (www.abb.com, 2016)

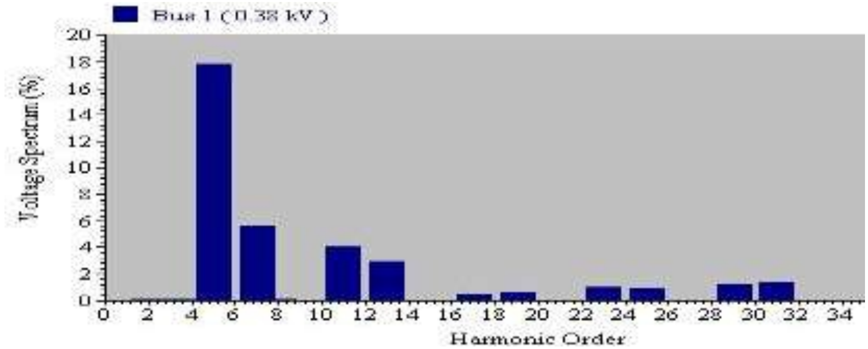

Figure 3: Bus 1 harmonics voltages as a percent of fundamental voltage (Case 1)

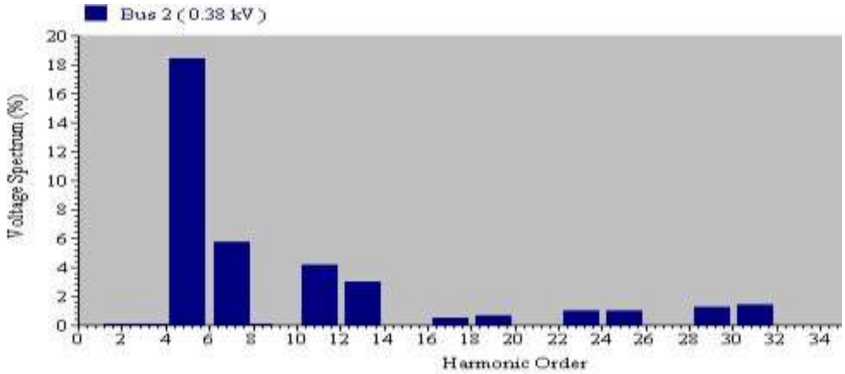

Figure 4: Bus 2 harmonics voltages as a percent of fundamental voltage (Case 1)

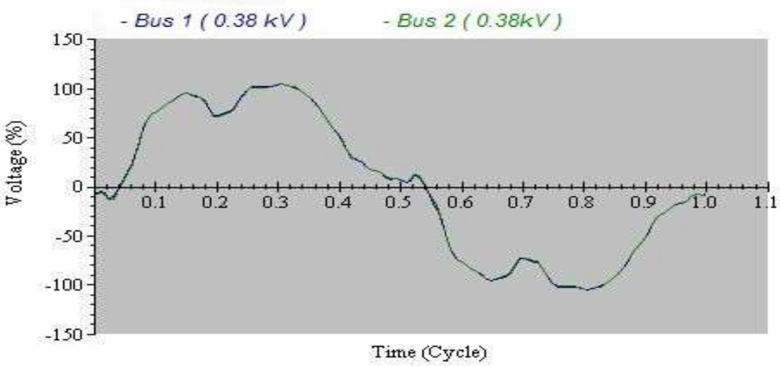

Figure 5: Generator 1 output voltage waveform.

Table 3 Buses percentage total harmonic voltage distortion (Case 1)

Bus		Voltage Distortion			
ID	kV	Fund. %	RMS %	ASUM %	THD %
Bus 1	0.380	100.00	101.88	136.15	19.48
Bus 2	0.380	99.44	101.46	136.76	20.22

Table 4 Buses percentage total harmonic current distortion (Case 1)

	Current Distortion			
To Bus ID	Fund. Amp	RMS Amp	ASUM Amp	THD %
Bus 2	820.53	836.90	1058.57	20.07
Bus 1	820.53	836.90	1058.57	20.07

Case 2: 550 KVA non-linear loads with 6 pulse rectifiers supplied from 1190 KVA synchronous generator (Generator 2) of parameters given by manufacturer (www.abb.com, 2016).

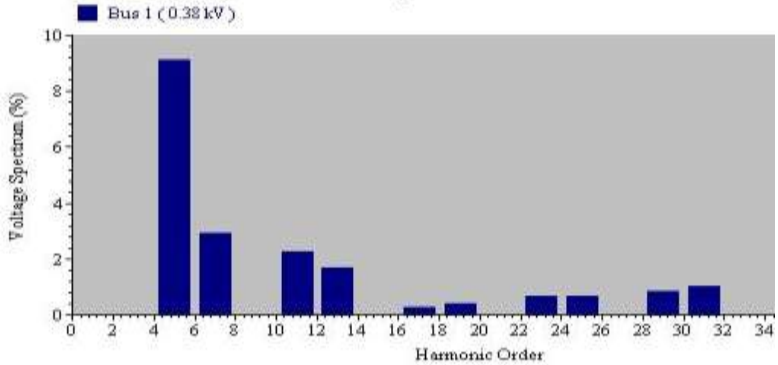

Figure 6: Bus 1 harmonics voltages as a percent of fundamental voltage (Case 2)

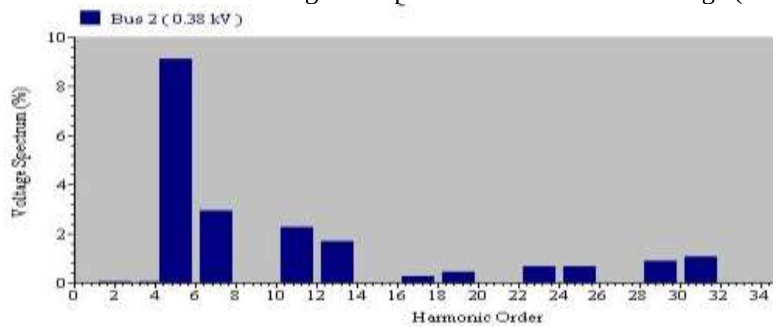

Figure 7: Bus 2 harmonics voltages as a percent of fundamental voltage (Case 2).

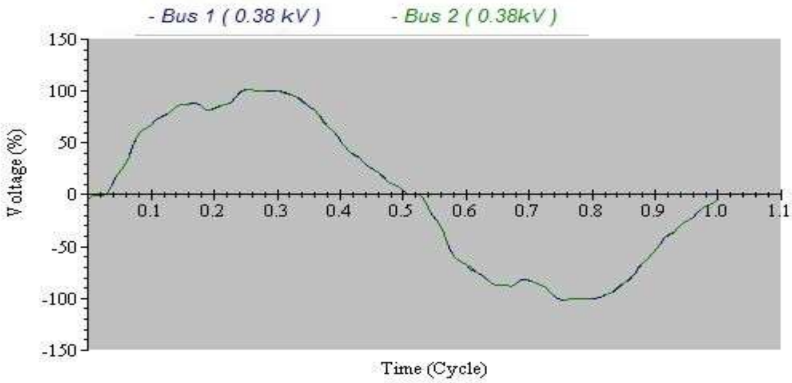

Figure 8: Generator 2 output voltage waveform.

Table 5 Buses percentage total harmonic voltage distortion (Case 2).

Bus		Voltage Distortion			
ID	kV	Fund. %	RMS %	ASUM %	THD %
Bus 1	0.380	100.00	100.51	120.05	10.11
Bus 2	0.380	99.72	100.23	119.85	10.18

Table 6 Buses percentage total harmonic current distortion (Case 2).

	Current Distortion			
To Bus ID	Fund. Amp	RMS Amp	ASUM Amp	THD %
Bus 2	818.43	837.05	1081.17	21.45
Bus 1	818.43	837.05	1081.17	21.45

Case 3: 550 KVA non-linear loads with 6 pulse rectifiers supplied from 1430 KVA synchronous generator (Generator 3) of parameters given by manufacturer (www.abb.com, 2016).

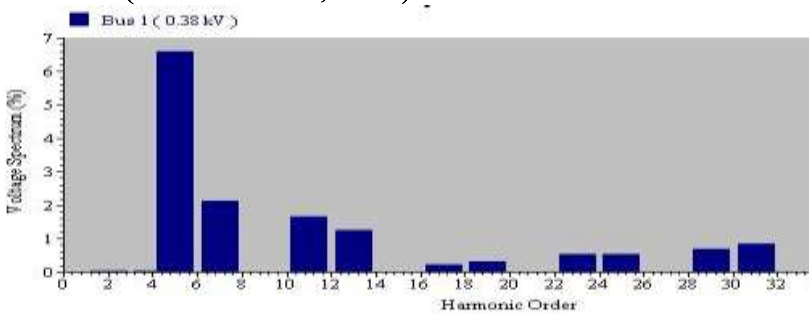

Figure 9: Bus 1 harmonics voltages as a percent of fundamental voltage (Case 3).

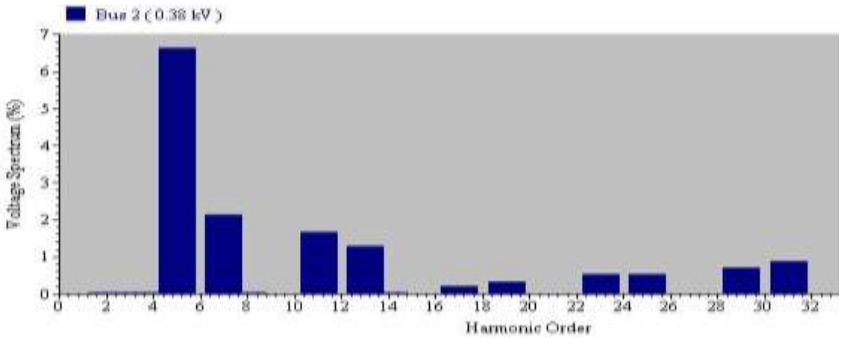

Figure 10: Bus 2 harmonics voltages as a percent of fundamental voltage (Case 3).

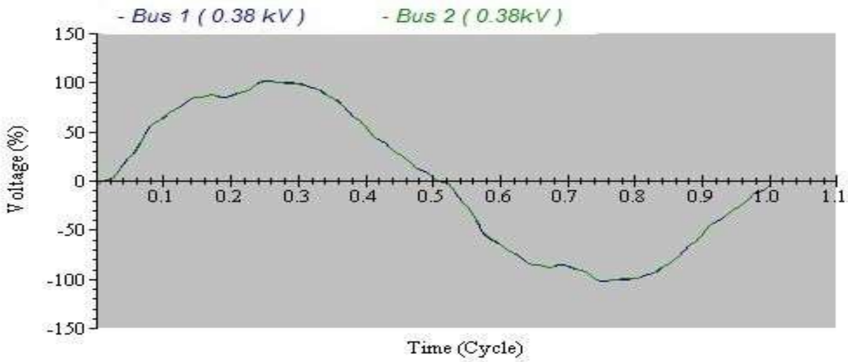

Figure 11: Generator 3 output voltage waveform.

Table 7 Buses percentage total harmonic voltage distortion (Case 3).

Bus		Voltage Distortion			
ID	kV	Fund. %	RMS %	ASUM %	THD %
Bus 1	0.380	100.00	100.27	114.85	7.36
Bus 2	0.380	99.72	99.99	114.65	7.43

Table 8 Buses percentage total harmonic current distortion (Case 3).

	Current Distortion			
To Bus ID	Fund. Amp	RMS Amp	ASUM Amp	THD %
Bus 2	818.43	837.05	1081.17	21.45
Bus 1	818.43	837.05	1081.17	21.45

Case 4: 550 KVA non-linear loads with 12 pulse rectifiers supplied from 550 KVA synchronous generator (Generator 4) of parameters given by manufacturer (www.abb.com, 2016).

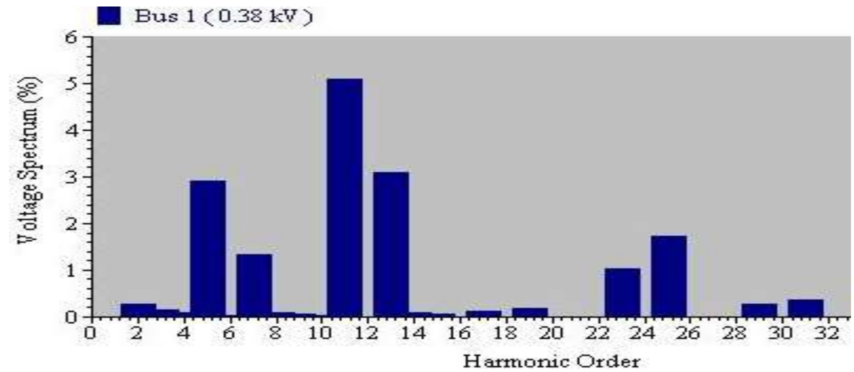

Figure 12: Bus 1 harmonics voltages as a percent of fundamental voltage (Case 4)

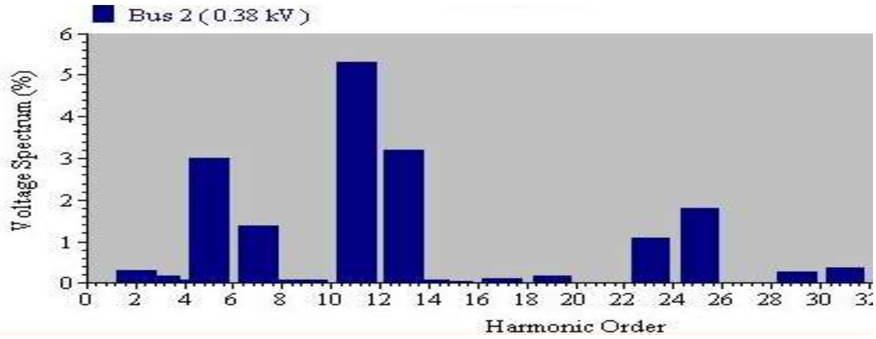

Figure 13: Bus 2 harmonics voltages as a percent of fundamental voltage (Case 4)

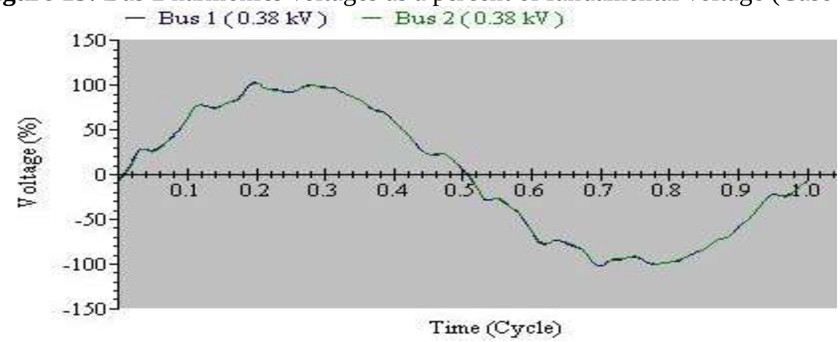

Figure 14: Generator 4 output voltage waveform.

Table 9 Buses percentage total harmonic voltage distortion (Case 4)

Bus		Voltage Distortion			
ID	kV	Fund. %	RMS %	ASUM %	THD %
Bus 1	0.380	100.00	100.25	116.88	7.09
Bus 2	0.380	99.44	99.71	117.00	7.39

Table 10 Buses percentage total harmonic current distortion (Case 4).

	Current Distortion			
To Bus ID	Fund. Amp	RMS Amp	ASUM Amp	THD %
Bus 2	820.53	821.83	935.16	5.63
Bus 1	820.53	821.83	935.16	5.63

For the non-linear loads with a 6-pusle rectifier, it is clear from the simulation results that as the power rating of the electric generator increases, the value of total percentage harmonic voltage distortion (THVD) of generator output voltage waveform decreases. The value of total percentage harmonic current distortion (THID) is approximately constant (as described in Section I). The most suitable generator for the previous case is the 1430 KVA generator, as the THVD is 7.4% which is below the standard limits shown in Table 1.

For the non-linear loads with 12-pusle rectifier, it is clear that the 550KVA generator can supply the 550 KVA non-linear loads without a need to be up-rated as THVD is 7% and all individual harmonics do not exceed 5% which is below the standard limits shown in Table 1.

The relation between generator power rating and THVD is shown in Fig. 23.

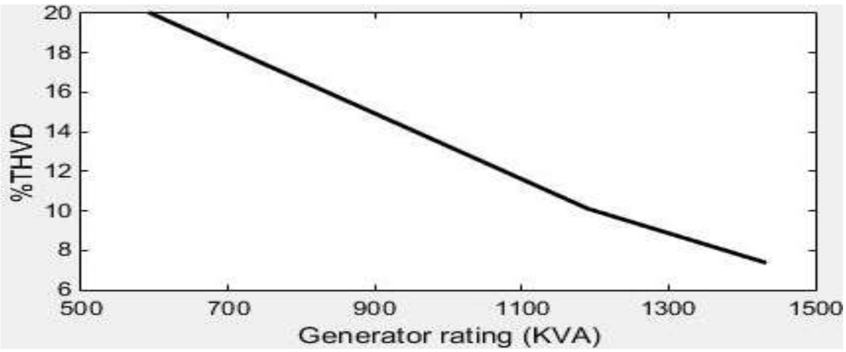

Figure 15: Effect of increasing Generator power rating on THVD

The up-rating factor (UF) required for the generator rating can be calculated as:

$$\mathrm{UF} = S_G/S_L \qquad (1)$$

Where:

S_G: is the generator rated complex power (KVA).

S_L: is the non-linear loads complex power (KVA).

The de-rating factor (DF) needed for generator power rating is the reciprocal of the up-rating factor.

The relation between UF and percentage THVD is shown in Fig. 24.

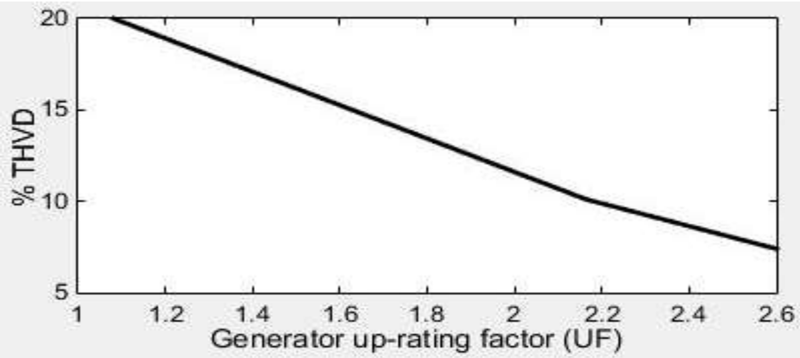

Figure 16: Effect of increasing Generator power rating on THVD

Applying curve fitting technique using MATLAB program to obtain a mathematical relationship between the needed generator UF and the value of % THVD, we get the following equation:

$$UF = 0.0041(THVD)^2 - 0.23(THVD) + 4.1 \quad (2)$$

So, the correct generator rating supplying non-linear loads can be calculated as:

$$S_G = UF * S_L \quad (3)$$

From (3), the required UF for a generator such that the THVD do not exceed the required limit (8%) as shown in Table 1 is 2.5. this comply with data given by generator manufacturers (Consulting-Specifying Engineer, 2008) (Caterpillar, 2008).

Analyzing temperature rise on the generators due to harmonics:

The total harmonic power losses can be calculated from (H. Ortmeyer, 1985):

$$P_h = \frac{3R_2}{\sqrt{2}(X_l)^2} \sum_{n=5}^{\infty} \frac{V_n^2}{n^{1.5}} \quad (4)$$

Where:

R_2: Equivalent negative sequence resistance in ohms

X_l: Effective leakage reactance in ohms.

Vn: Per phase harmonic voltage in volts.

n: Harmonic order.

For generator 1

The values of Vn are shown in fig. 3 and fig. 4, substituting in (4) we get:

$$P_h = \frac{3 * 0.00816}{\sqrt{2} * (0.027)^2} [\frac{((17.83/100) * 220)^2}{5^{1.5}} + \frac{((5.58/100) * 220)^2}{7^{1.5}} + \frac{((4/100) * 220)^2}{11^{1.5}} + \frac{((2.93/100) * 220)^2}{13^{1.5}}] = 3533 \text{watt}$$

The temperature rise in generator windings due to harmonics is:

$$T_r = P_h \theta \qquad (5)$$

Where:

T_r: Temperature rise in °C.

θ: Thermal resistivity of copper in (m°c/w).

Tr = 3533*(1/401) =8.8 °C.

Similarly, for generator 2:

$P_h = 1046.5$ watt

Tr = 1046.5*(1/401) =2.6 °C

Similarly, for generator 3:

$P_h = 684$ watt

Tr = 684*(1/401) =1.7 °C

So, it is clear that as the power rating of the selected generator increases, the harmonics thermal effect on generator decreases by an effective value.

Conclusion

This paper proposed a method to select the most suitable generator output power rating to operate safely with non-linear loads was studied clearly. Importance of reducing this impact is illustrated to guaranty safe operation of the electric generator and saving its lifetime. The methods depends on analyzing the effect of increasing the supply generator power rating on the THVD produced from non-linear loads harmonics connected to the system. By calculating the THVD for each case of a generator power rating, a mathematical relationship between generator power rating and TVHD was found. The required up-rating factors for a generator power rating (UF) were calculated in each case and as a result, a general mathematical relationship between TVHD and UF was found.

The thermal effect on generator due to harmonics was analyzed, by calculating the temperature rise in generator windings for each case. The results indicates that as the power rating of the selected generator increases, the harmonics thermal effect on generator decreases by an effective value.

References:

1. H. Ortmeyer, K. R. Chakravarthi, Aly A. Mahmoud (1985) The Effects of Power System Harmonics on Power System Equipment and Loads. *IEEE Transactions on Power Apparatus and Systems* Vol. PAS-104, No. 9.
2. Petropol Serb Gabriela Dana and Petropol Serb Ion (2016) Study of the harmonics of current and voltage for a synchronous generator in the context of railway Constraints. *International Symposium on Power Electronics, Electrical Drives, Automation and Motion,* IEEE.
3. Qiu Hongbo, Yi Ran, Li Weili, and Jin Nan (2015) Influence of Rectifiers on High-Speed Permanent Magnet Generator Electromagnetic and Temperature Fields in Distributed Power Generation Systems. *IEEE Transactions on Energy Conversion*, Vol. 30, No. 2.
4. Elias_Kyriakides, Siddharth Suryanarayanan, Vijay_Vitta (2015) Electric Power Engineering Research and Education. *Springer International Publishing, Switzerland*, ISBN 978-3-319-17189-0.
5. Engineering Bulletin CTV-PRB011-EN (2002). [Online] www.trane.com. Accessed on November 2016.
6. Jim Iverson (2007) Power topic #7007: How to size a genset. [online] http://power.cummins.com/. Accessed on November 2016.
7. IEEE Recommended Practice and Requirements for Harmonic Control in Electric Power Systems (2014) IEEE Std 519-2014.
8. Generators technical specifications (2012). [Online] http://new.abb.com/motors-generators/generators/generators-for-diesel-and-gas-engines/low-voltage-generators-for-industrial-applications/amg-0355?_ga=1.78441686.39063645.1473974022, Accessed on November 2016.
9. Generator Sizing Pitfalls Consulting-Specifying Engineer, *Generac Power Systems, Inc. (*2008). Accessed September 2016.
10. Application and installation guide, Electric Power Applications, Engine & Generator Sizing Caterpillar, (2008) http://www.cat.com/en_US/products/new/power-systems/electric-power-generation/diesel-generator-sets.html, Accessed on November 2016.