Analysis of IEEE Harmonic Limits under Resonance Conditions

George Eduful and Ebenezer A. Jackson

Abstract— Resonance represents a potential threat to the integrity of power delivery system. Many examples of power system components destroyed by resonance abound in literature. It is usually associated with large voltage and current that can cause severe stress on the insulation of power system components and subsequently results in system failures. To deal with the phenomenon, harmonic current levels in power systems need to be managed. The IEEE standard 519 is widely used to limit harmonic levels in power system. Whilst this standard addresses harmonic voltage distortion at point of common coupling (PCC), it is unable to mitigate the impact of harmonic resonance in some cases. The paper examines the IEEE harmonic limits under resonance conditions and revises aspects of the IEEE limits found to have induced dangerous resonance.

Keywords— Ferroresonance, Cable-fed transformers, EMTP RV, Regression Analysis.

I. INTRODUCTION

A system is in harmonic resonance when its natural frequency is reinforced by a harmonic source of the same frequency [1] [2]. High levels of harmonic current can thermally stress or damage equipment [3]. The likelihood of such effects occurring is greatly increased if a resonant condition occurs. The extent of equipment damage from harmonic resonance is dependent on magnitude of individual harmonic current in the harmonic spectra. While harmonic resonance induced by high harmonic current can be very damaging, harmonic resonance produced by low harmonic currents may have little or no effect.

To prevent harmonics from negatively affecting equipment, nationals and international standards have established limit on harmonic emissions. IEEE standard 519 is widely used to control harmonics in power delivery system. The standard was introduced in 1981 and was revised in 1992 [4]. It clearly established limits for both voltage and current distortion. Whilst these limits address harmonic voltage distortion at point of common coupling (PCC), it is unable to control harmonic resonance.

Conventionally, natural frequencies are detuned to avoid harmonic resonance. However, this method is more challenging as detuned natural frequencies create further parallel resonant points that are destructive. Usually, resonant frequency swings around depending upon the changes in the system impedance. Similarly an expansion or reorganization of the distribution system may bring out a resonant condition where none existed before. Even if a capacitor bank in a system is sized to escape current resonance conditions, immunity from future resonance conditions cannot be guaranteed owing to system changes [5].

It is however noted that the destructive power of resonance is a function of harmonic current magnitude. Therefore the effective way of controlling resonance is to rely on harmonic emission levels that reduce the impact of resonance. The paper therefore, examines the IEEE harmonic limits under resonance conditions and revises aspects of the IEEE limits found to have induced dangerous resonance.

II. THEORETICAL FRAMEWORK

The term resonance generally refers to oscillation of large amplitude of a system produced in response to a relatively small oscillation having a frequency that is the same or near the natural frequency of the system [10]. In harmonic resonance, natural or resonant frequency is excited by harmonic current from electronic device. In power delivery system, there are two forms of harmonic resonance which can occur: parallel resonance and series resonance.

Parallel resonance occurs when a harmonic frequency produced by a non-linear load closely coincides with a power system natural frequency [6-12]. In parallel resonance, the impedance of a circuit is high which leads to extremely high overvoltage. Parallel resonance is common when there are capacitor banks or long AC lines connected with large transformers [2].

Figure 1 shows an example of a parallel harmonic resonance circuit. Parallel resonance occurs when SW1 is closed and the harmonic source (AC1) is connected parallel to the inductive (L1) and capacitive (C1) components.

George Eduful is with the Electricity Company of Ghana, P.O. Box AN 5278, Accra-North, Ghana. (phone: +233-246-132-736; e-mail: georgeeduful@yahoo.com

Ebenezer A Jackson is with Jackson Educational Complex, Teacher Training Department. 115 Ayeduase Road, Kumasi-Ghana. e-mail: jacksonea1@yahoo.com

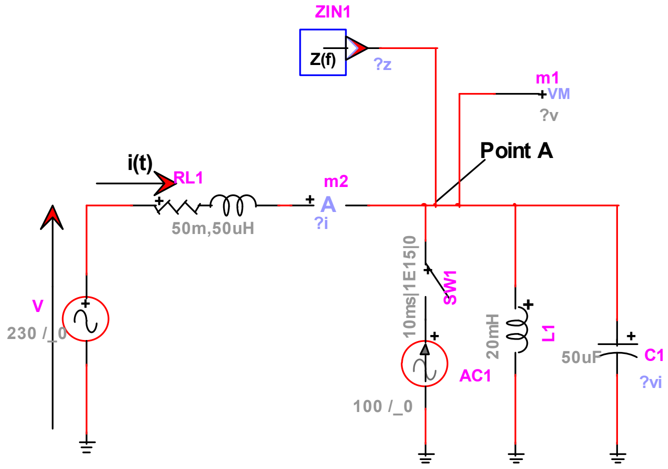


Fig 1: Example of parallel resonant circuit

A plot of the equivalent system impedance and frequency scan as seen from Point A in Fig 1 is shown in Fig 2. It can be seen that the circuit presents high impedance (20-ohms) at its resonant frequency of 3200Hz.

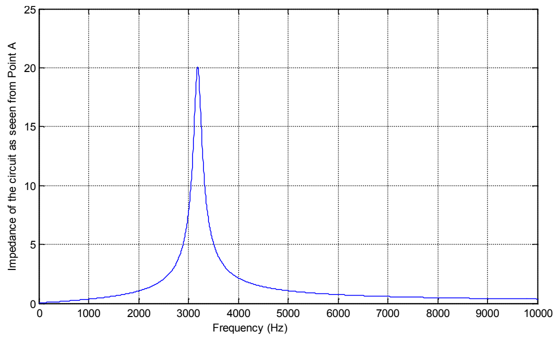


Fig 2: Frequency scan and impedance as seen from Pont A

To observe the effect of resonance in Fig 2, harmonic current source (100A) of a frequency equal to the resonant frequency of the circuit was injected into the circuit. The resonance effect can be seen in Fig 3: voltage and current in the circuit amplify or multiply themselves by 9.8 and 62 times respectively.

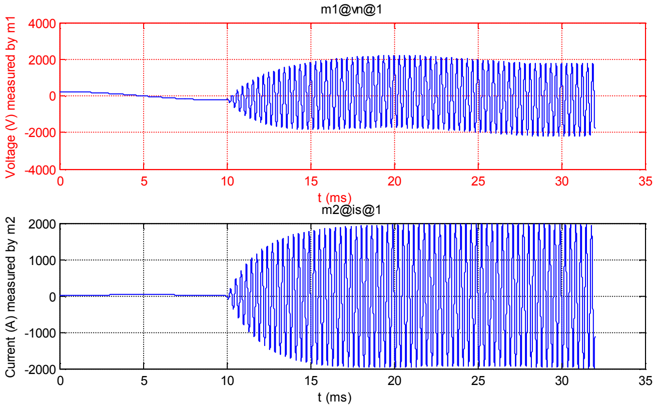


Fig 3: Voltage and Current amplification under resonance condition

Series Resonance

To prevent resonance from becoming dangerous, the system natural frequency point must be forced below harmonic frequencies measured in the system [3]. To do this, series resonant circuit is used. It is a situation where an inductor is usually connected in series with a capacitor to tune or force the natural frequency away from the harmonic source. Series resonance differs from the parallel resonance in its low impedance at a resonance frequency. The case is similar to the parallel resonance, but instead of high voltages, high currents flow through a low impedance circuit. Essentially, series resonant is a harmonic filter tuned at a fixed frequency to reduce or drain harmonic currents and consequently reduce harmonic distortion.

An example of series resonant circuit is shown in Fig 4. The effect of the series inductance can be seen in the frequency-impedance plot shown in Fig 5. The series circuit produces a low impedance path to the initial resonant frequency of 3200Hz and now moves the resonant frequency point to 2260Hz.

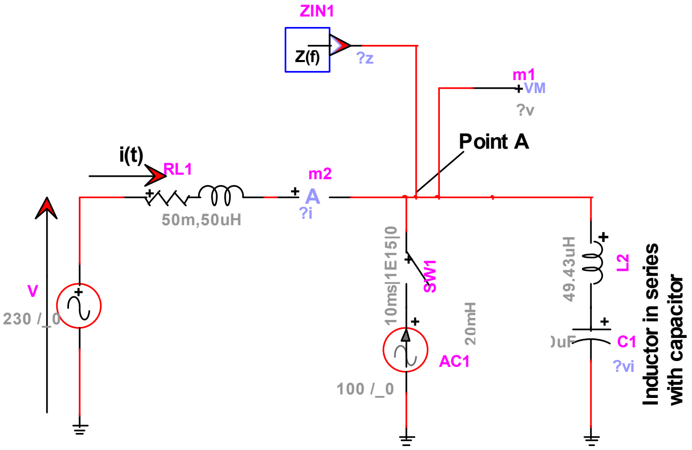


Fig 4: Example of series resonant circuit

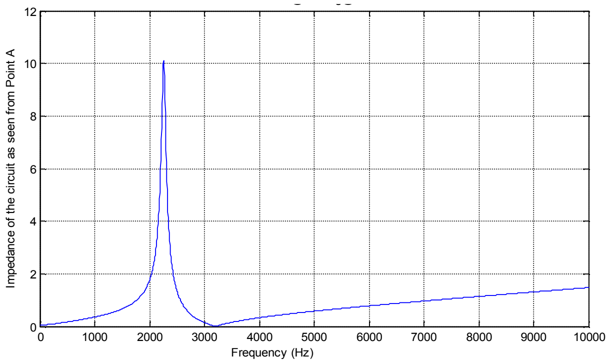


Fig 5: Frequency scan and impedance as seen from Bus-1 (reference Fig 4).

The effect of the series resonant circuit or the series filter can be observed in Fig 6. Voltage spike is seen at the instant the harmonic source was energised. This could be destructive but can be managed with a surge arrestor. Compared with the case of the parallel resonance, the series inductor has significantly reduced the current and the voltage magnifications.

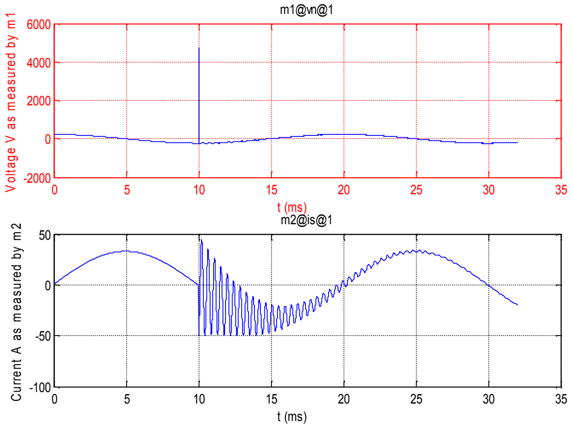


Fig 6: Reduction in voltage and current magnifications

From the above discussion, it can be noted that reducing harmonic levels in power system is key in resonance impact management. In the subsequent sections, the IEEE harmonic emission limits as given by IEEE Standard 519 will be examined under resonance conditions and where necessary, revise specific harmonic limits found to induce dangerous resonance.

III. METHODOLOGY

This section presents method used to examine the IEEE harmonic limits. The study was based on modelling and simulation using the EMTP RV. The method used in modelling the system components and running the resonance simulations are explained.

A. Frequency Scan Technique

In the harmonic resonance analysis, frequency scan technique was used. This technique is also called the impedance scan. It is normally the first step of the harmonic analysis. Its principal objective is to detect the possible resonance frequencies in the electrical network [13].

B. IEEE Short-Circuit Ratios

The IEEE standard 519 establishes limits for harmonic emissions in power delivery system. The emission limits are based on short-circuit ratios (SCR) at point of common coupling PCC. The short circuit ratio (I_{SC}/I_L) is the ratio of short circuit current (I_{SC}) to the customer's maximum load or demand current (I_L) at the point of common coupling. The ratios are in five different ranges, each giving harmonic distortion limit for individual harmonic components as well as total harmonic distortion, see Table 1.

Table 1 : Current Distortion Limits (in % of IL) for General Distribution Systems (120-69,000V) [ ]

I_{sc}/I_L	<11	11≤h<17	17≤h<23	23≤h<35	35≥h	TDD
<20	4	2	1.5	0.6	0.3	5
20-50	7	3.5	2.5	1	0.5	8
50-100	10	4.5	4	1.5	0.7	12
100-1000	12	5.5	5	2	1	15
>1000	15	7	6	2.5	1.4	20

C. Capacities of Transformers Used

Five transformers of different capacities namely 100, 200, 315, 500 and 2500kVA were selected and modelled for the resonance simulations. Transformer ratings from 100 to 500kVA were classified as a distribution transformers and the 2500kVA transformer classified as a power transformer.

For each of the selected transformers, the original intention was to examine the IEEE harmonic limits at all the given SCRs in the IEEE 519. However, it was found that the distribution transformers could not deliver the required maximum demand at SCR of less than the 20 range. The maximum demand required was more than the capacity of the transformers.

It was also found that at SCRs of 100 to 1000 and SCR range greater 1000, the maximum demands required were too small to be considered for the study. As a result, the distribution transformers were used to examine the IEEE harmonic limits at the 20-50 and 50-100 SCRs only.

In the case of the power transformer, it was possible to examine the IEEE harmonic limits at all the five SCRs. It appeared as if the SCRs are more applicable to power transformers.

D. Short Circuit Current

The EMTP RV was used to simulate the short circuit currents. This was done by connecting a conducting link from the bus bar to the ground through switch-2, see Fig 7.

E. Short Circuit Ratio Chosen for the Analysis

In each of the five ranges of the SCRs, one fixed ratio was selected. The transformers were then loaded to a maximum demand calculated from these fixed ratios. The respective fixed ratios and their corresponding loading are given in Table 2.

Table 2: Fixed ratios and their corresponding maximum demands

IEEE Short-Circuit Ratio	Fixed Ratio Used	% of Transformer loading corresponding to the fixed ratios
<20	15	90.5
20-50	45	30.3
50-100	75	18.2
100-1000	100	13.6
>1000	1050	1.3

F. Network Modelling

In modelling the network, appropriate power system components in the EMTP RV library were used.

Source Modelling

The source was represented as Thevenin equivalent with an X/R value of 3.7. The short circuit power was 150MVA at a base voltage of 11kV.

ISBN: 978-988-19253-4-3
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

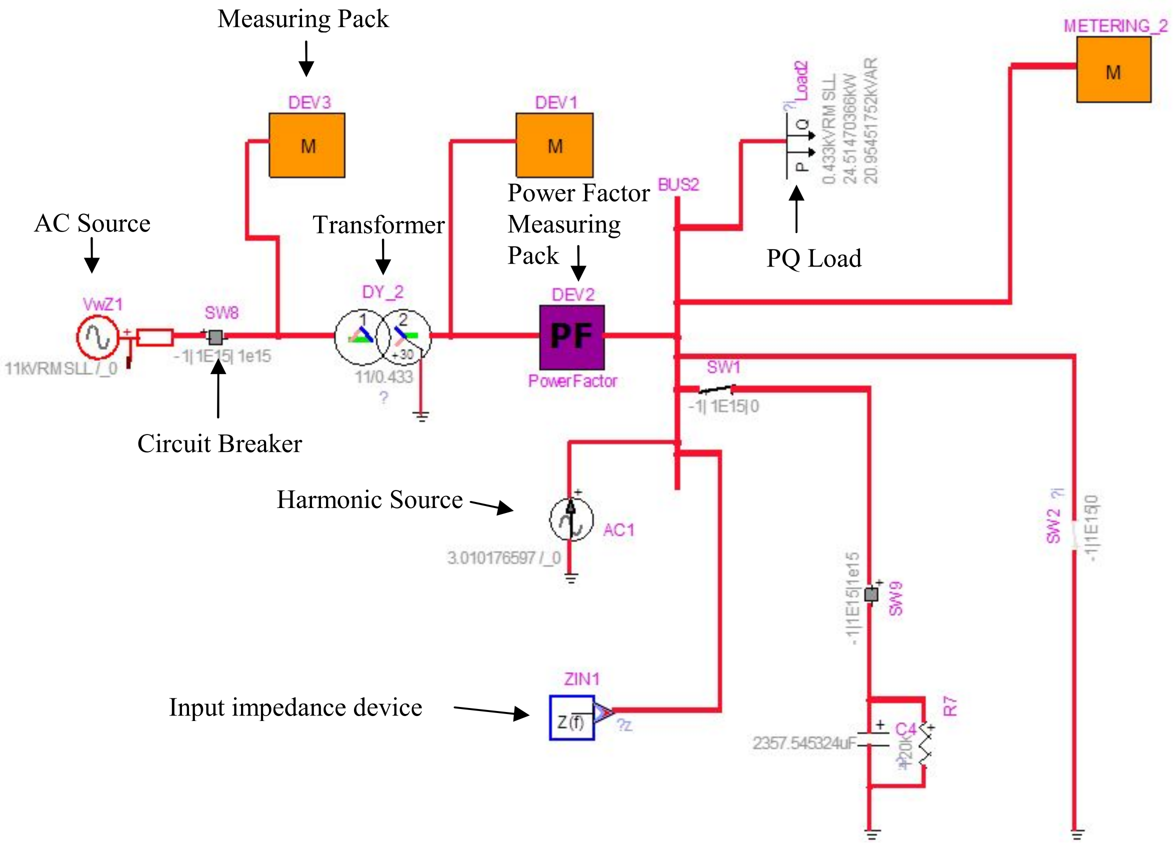


Fig 7: Representation of the Network as Modelled

Table 3: Saturation Curve used in Transformer Modelling

Current (PU)	0	0.0321	0.0524	0.063	0.0776	0.0894	0.0974	0.1098	0.124	0.1484	0.1684	0.2371
Flux (PU)	0	0.012	0.0252	0.0333	0.0445	0.0544	0.061	0.0698	0.0785	0.0892	0.0946	0.1057

Transformer Modelling

The transformers were modelled with their primary winding connected in delta configuration and their secondary winding connected in star configuration. For the 100 to 500kVA transformers, percentage impedance used for each transformer was 4.5%. And for the 1250 and 2500kVA transformers, 5 and 8% percentage impedance were used respectively. The percentage impedance is normally given by manufacturers. However, in this study the percentage impedances were obtained from a suit of transformer specification used by the Electricity Company of Ghana.

Transformer Saturation Curve

Current-flux curve, also known as magnetization curve or saturation curve is often used to represent non-linear characteristics of the transformer iron core. Data for the magnetization curves is usually supplied by manufacturers. A good magnetization data should result in some level of distortion in current waves due to harmonic generations. In this study, a magnetization data, obtained from a manufacturer was used. The data is given in Table 3.

As a form of ascertaining the quality of the data, it was used (the data) to initially model a 200kVA transformer. Harmonic analysis of the current wave through the transformer is shown Fig 8. The presence of harmonic contents in the harmonic spectrum confirms the goodness of the magnetization data.

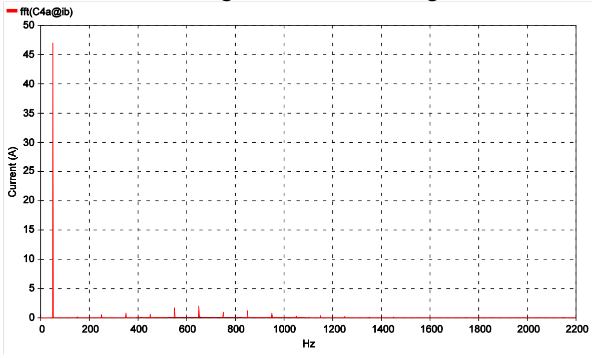


Fig 8: Harmonic Spectrum

Harmonic Current Source

A current source component from the EMTP RV library was used to model the harmonic current source.

Other Components Used in the Network

The big M's shown in the network are measuring device. They are modelled to measure voltages, in per unit, at the various points in the network. The power factor of the network was measured with a measuring device labelled PF in the Fig 7. Input impedance device *Z(f)* was used for frequency scanning analysis. The device injects current amplitude of 1A in to the network. The impedance seen at the point of the current injection is run through a set of frequencies. The result is a plot of magnitude of impedance versus harmonic frequency.

IV. RESULTS AND DISCUSSIONS

Results of the simulations were obtained in waveforms. However, for clarity, peak values of current amplification in resonance conditions were noted and subsequently analysed with the Microsoft Excel program. Figure 9 shows an example of how a typical simulation results were displayed.

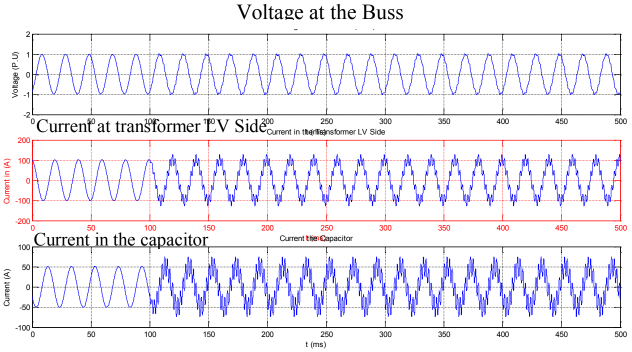


Fig 9: Results of Voltage and Current Amplification at 5th harmonic resonance simulation with 100kVA transformer

In the resonance simulations, current amplifications were observed in the modelled capacitors. This is because, in harmonic resonance, capacitors always experience the worst current magnification. As a result, current amplifications were expressed as percentage of current rise relative to nominal capacitor currents. However, it should be noted that current magnification resulting from resonance is not only harmful to capacitors or capacitor banks, transformers and other system components are equally at risk and may eventually fail when subjected to resonance prone environments.

A. Current Amplification Behaviour with Different Transformer Ratings

Using the IEEE harmonic limits at short circuit ratios (SCRs) of 20-50 and 50-100, current amplifications were observed in resonance conditions. Results of the amplifications are shown in Fig 10 and Fig. 11. As can be seen, current amplifications at SCR 50-100 are higher compared to amplifications at SCR 20-50. This is consistent with the IEEE harmonic emission limits – harmonic emissions limits at higher SCR are not as strict as limits pertain to a low SCR.

In the case of the distribution transformers, the trends and magnitude of the amplifications were same. However, in relation to the power transformer, some damping in amplification magnitudes can be observed. Considering the parameters used in the modelling, it was believed that the impedance of the power transformer may have accounted for the damping effect as the value was higher compared to the impedances of the distribution transformers.

It is important to note that in both cases, there were instances where amplifications assumed levels dangerous to system components. According to IEEE [2][3] and other standards [14], capacitor banks are designed to operate continuously at 135% of their rated current. Operating capacitors beyond this limit could result in violent failure.

In order to reduce the levels of current magnifications to the acceptable and safe limits, the IEEE 519 harmonic emission limits at these ratios need to be revised. To do this, Fig 10 and Fig 11 provide a clue: current amplifications in distribution transformers are higher compared with power transformer. This means harmonic emission limits that is able to control resonance in distribution transformer would automatically control resonance in power transformers with higher margin of safety. Revision of the IEEE harmonic emission limits is considered later in this chapter.

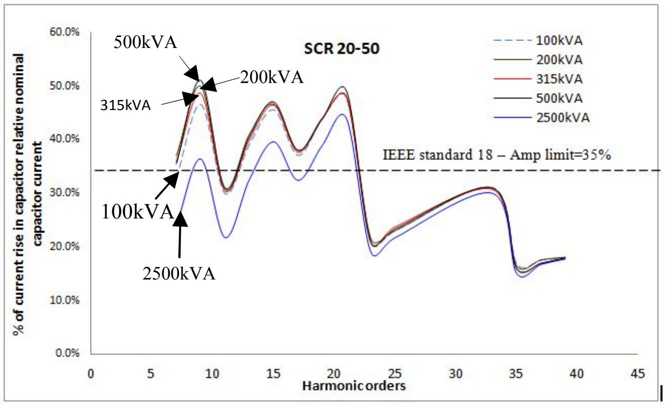


Fig 10: Current amplification with different transformer ratings at IEEE Ratio of 20-50

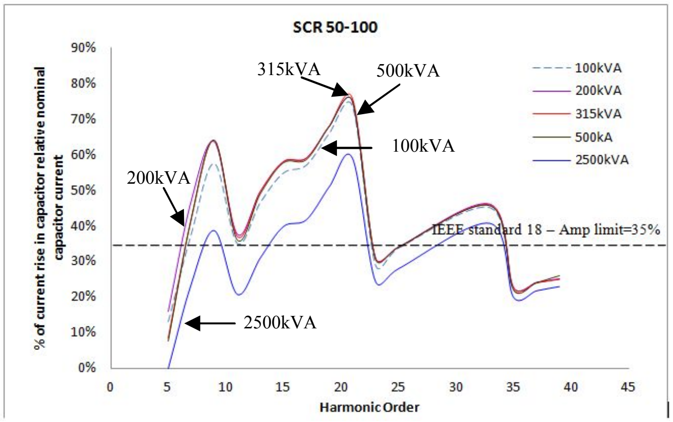


Fig 11: Current amplification with different transformer ratings at IEEE Ratio of 50-100

B. Examining the IEEE Harmonic Emission Limits with the 2500kVA transformer

The power transformer (2500kVA) transformer was used to examine the IEEE harmonic emission limits at all the five SCRs. This is because at some SCRs, either the maximum demands required were too small to make practical and economic sense or were more than the capacities of the distribution transformers. In other words, some of the SCRs are not applicable to distribution transformers.

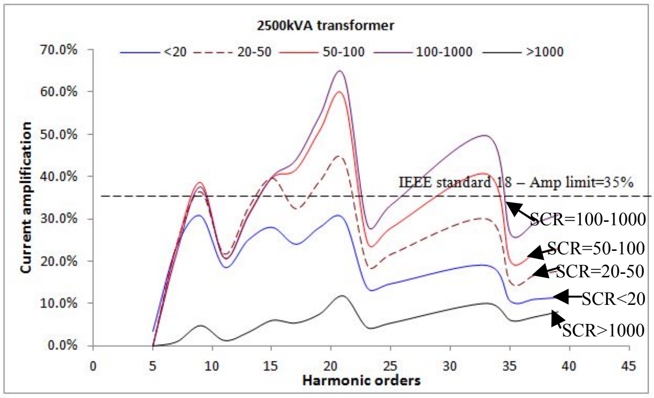


Fig 12: Current amplification curves at all the five ranges of the IEEE short circuit ratios

Current amplification at the various harmonic components at each range of the short circuit ratios (SCR) are shown in Fig 12. As can be seen, the worst current amplifications occurred at 50-100 and 100-1000 ranges of SCRs. Most of the amplification values are destructive -they are above the maximum specified current operating limit of the capacitor. More importantly, it should be noted that the amplifications are caused by resonance which is a steady state phenomenon. The phenomenon usually corrects itself by either a fuse blow-outs or components failure which is undesirable.

In the SCR of 20-50, the amplification values went beyond the safety limits only at four harmonic orders namely 9th 15th 19th and 21st harmonic orders. Nonetheless, these are still considered destructive. The amplification values at these SCR are shown in Table 4. It can be observed that in all the SCRs, the amplifications drop markedly to the safe operating zone at the 35th harmonic order. Based on the amplification curves and following the trends, the level of current amplification is negligible and harmless at and beyond the 35th harmonic order.

Table 4: SCRs and Destructive Amplification values

SCR h	9th	15th	17th	19th	21st	33rd
20-50	36.40%	39.60%		38.90%	43%	
50-100	38.70%	39.80%	41.70%	51%	59%	40.70%
100-1000	37.60%	40%	44%	54.40%	64%	49%

On the other hand, current amplifications observed in SCR (less than 20) and in SCR (greater than 1000) are all within the permissible operating zone. The IEEE harmonic emission limits at these limits are therefore safe to operate with. Based on the results and the analysis so far, it could be established that the IEEE harmonic emission limits at some SCRs could result in dangerous current amplification in resonance. In Table 5 below, SCRs and their respective harmonic limits status are shown.

Table 5: SCRs and their respective harmonic limits status

SCR	<20	20-50	50-100	100-1000	>1000
Limit status	safe	Distructive	Distructive	Distructive	safe

C. Controlling Harmonic Current Amplification in Resonance

As explained in chapter four, harmonic emission limits in relation to SCRs (20-50 and 50-100) were revised based on resonance conditions using the distribution transformers. This is because the ratios were found to be more applicable to distribution transformers. At SCR 100-1000, harmonic limits were revised based on the power transformer. Harmonic limits at SCRs (less than 20 and greater 1000) were found safe and therefore were not revised.

The revision was done by carefully reducing the limits and observing the resulting current amplifications. The reductions were managed such that values of the amplifications stayed within the safety zone.

The revised limits are shown in Table 6 and the corresponding amplification levels are shown in Fig 5.4. As can be seen, the revised limits have now brought the magnitudes of the current amplifications to safe levels. Consequently, the debilitating effect of resonance is managed and controlled at these limits.

Table 6: Limits Revised in SCRs (20-50, 50-100, 100-1000)

Current Distortion Limit (in % of I_L)							
SCR h		<11	11≤h<17	17≤h<23	23≤h<35	35≥h	TDD
<20	Existing limits	4	2	1.5	0.6	0.3	5
20-50	Existing limits	7	3.5	2.5	1	0.5	8
	Revised limits	5	2.5	1.5	1	0.5	6
50-100	Existing limits	10	4.5	4	1.5	0.7	12
	Revised limits	5.5	2.5	2	1	0.7	7
100-1000	Existing limits	12	5.5	5	2	1	15
	Revised limits	11	4.5	2.5	1	1	12
>1000	Existing limits	15	7	6	2.5	1.4	20

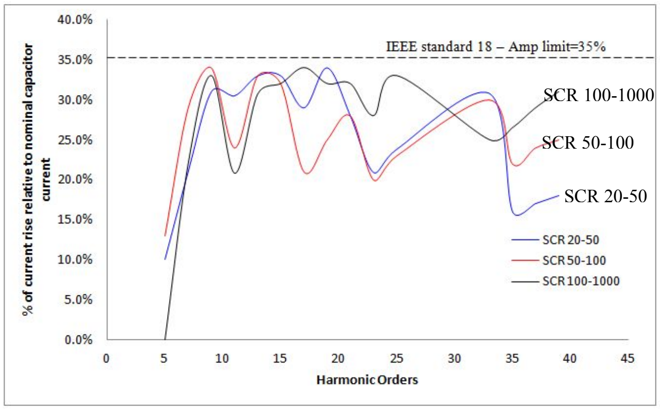


Fig 13: Amplification Levels from Revised Limits

As can be seen in Fig 13, all the amplifications are now within the safety operating zone.

V. CONCLUSION

The paper has presented and analysed results obtained from the harmonic resonance studies. The IEEE harmonic limits were examined under resonance conditions. The following are conclusions from the studies:

1. Application of IEEE harmonic emission limits at short circuit ratios (SCRs) of 20-50, 50-100 and 100-1000 can be destructive under resonance conditions.
2. Distribution transformers cannot be used to examine IEEE harmonic limits at some short circuits ratios.
3. Power transformers could be used to damp about 35% current amplification in resonance.
4. To control resonance, harmonic limits at some of the SCRs were revised. The reduction resulted in lower current amplifications that were safe to system components.
5. The most effective way of controlling harmonic resonance is to reduce harmonic currents to levels such that even in resonance, current amplification will not assume dangerous levels. The revised IEEE harmonic limits in this paper are recommended for resonance control

Reference

[1]. C. Sankaran, Power Frequency Disturbance, 2002: Online source. Available at www.crcnetbase.com/doi/pdf/10.1201/9781420041026.ch2: CRC Press LLC.

[2]. Thomas Blooming et al, 2005: "Capacitor Failure Analysis: A Troubleshooting Case Study," Online source, date accessed 5th January, 2013. Available at www.asocem.org.pe/bivi/sa/dit/icem/05_04-2005.pdf.

[3]. T. Blooming, 2008: "Capacitor Application Issues," IEEE Transaction on Industry Applications, vol. 44, no. 4, pp. 1013 - 1026.

[4]. S. A. Ali, 2011: "Capacitor Banks Switching Transients in Power Systems," Energy Science and Technology , Vols. 2 , No.2, pp. 62-73.

[5]. E. Issouribehere, 2007: "Measurements and Studies of Harmonics and Switching Transient in Large HV Shunt Capacitor Bank," IEEE Power Engineering Society General Meeting.

[6]. L. Layton, "Electric Distribution Overvoltage Protection," Online source, date accessed 15th May, 2011. Available at www.pdhengineer.com/pages/E-002.htm, 2011.

[7]. T. A Short, 2014: Electric Power Distribution Handbook, Washington D.C: CRC Press.

[8]. Issouribehere etal, 2007: "Measurements and Studies of Harmonics and Switching Transient in Large HV Shunt Capacitor Bank," IEEE Power Engineering Society General Meeting.

[9]. "IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems," IEEE, 1992.

[10]. D. Trumper, 2.003 Problem Archive, Online Source, date accessed: 7th May, 2014. Available at http://ocw.mit.edu/courses/mechanical-engineering/2-003-modeling-dynamics-and-control-i-spring-2005/assignments/archive.pdf, 2005.

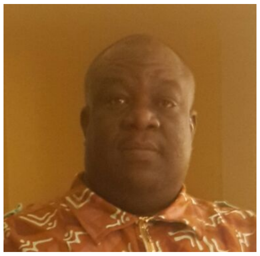
[11]. S. Mohitkar, "Harmonic Measurement and Analysis of Variable Frequency Drive (vfd) in Industry," International Journal of Research in Advent Technology, pp. 309-309, 2014.

[12]. D. J. Carnovale, 2004: Price and Performance Considerations for Harmonic Solutions, IEEE, 2004.

[13]. K. Rauma, 2012: Electrical Resonances and Harmonics in a Wind Power Plant, Espoo: Master's Thesis, 2012.

[14]. C. Gebs, 2013: Protection of capacitor banks, Trondheim: Norwegian University of Science and Technology.

BIOGRAPHIES



George Eduful is a Chartered Engineer by profession. He holds the Graduate Diploma from the Senior Awards Division of City and Guilds, London, the Honours Graduate Diploma from Cambridge International College, the Master's Degree from Kwame Nkrumah University of Ghana and presently a PhD candidate at the University of Mines and Technology. George was once a District Manager of the Electricity Company of Ghana. As a District Manager, he was responsible for commercial and technical operations of the company at the district level. His duties also included revenue management at the district. He is presently the Manager in charge of Research and Development Department of the Electricity Company of Ghana (ECG). He is responsible for investigating disturbing electrical phenomenon, work practices, processes and systems, piloting of new materials and equipment prior to adoption. He also develops and reviews all technical documentation in ECG. The documentation includes specifications for all materials and equipment used in ECG or proposed to be used, system Planning Manual, Design Manual, Construction Guidelines, Maintenance Manuals, Operations Manual etc. George Eduful has presented a number of papers at national and international fora and has more than 25 papers published in reputable international journals. His field of interest includes lightning protection, grounding system, harmonics and resonance in power delivery system. He is now the National Chair, IEEE Ghana Section.