Research Journal of Applied Sciences, Engineering and Technology 7(9): 1900-1909, 2014
DOI:10.19026/rjaset.7.480
ISSN: 2040-7459; e-ISSN: 2040-7467
© 2014 Maxwell Scientific Publication Corp.
Submitted: June 28, 2013 Accepted: July 08, 2013 Published: March 05, 2014

Research Article

Using a Fixed and Switched-Capacitor Bank to Investigate Harmonic Resonance and Capacitor Bank Switching in a Distribution Network

J.C. Attachie and C.K. Amuzuvi
Department of Electrical and Electronic Engineering, University of Mines and Technology,
Tarkwa, Ghana

Abstract: Harmonic resonance often manifests as high harmonic voltages in a power system. This produces losses and affects other consumers in the grid negatively. Capacitance switching applications also involve not only interrupting capacitive currents, but also the energizing of capacitor banks, cables and overhead lines. The applications of capacitors are extensively used in power systems for voltage support and power factor correction. However, the main concern arising from the use of capacitors is the possibility of system resonance. This study investigates the frequent capacitor bank tripping and damages in one of the distribution substations of the Electricity Company of Ghana (ECG). The study was conducted using the Electromagnetic Transient Program (EMTP) software for the simulation. The results showed that, the failures were related to harmonic resonance. Selected series connected inductors were recommended to shift the resonant frequencies of the network below characteristics harmonic frequencies.

Keywords: Capacitance switching, capacitor banks, characteristic harmonics, distribution substations, harmonic resonance, resonant frequency, simulation

INTRODUCTION

Power systems contain lumped capacitors such as capacitor banks for voltage regulation or (and) power factor improvement and capacitors that are part of filter banks to filter out higher harmonics. In addition, cable networks on the distribution system level form a mainly capacitive load for the switching devices. Capacitive switching requires special attention because, after current interruption, the capacitive load contains electrical charge which can cause a dielectric re-ignition of the switching device. When this process occurs repeatedly, the interruption of capacitive currents emerges and causes high over-voltages (Ciok, 1962; Khan *et al*., 1994; Ware *et al*., 1990).

The application of shunt capacitors for voltage support and power factor correction is a common practice in the power industry. With the proliferation of harmonic-producing loads (such as adjustable speed drives and uninterruptible power supply) and the increasing awareness of harmonic effects, the possibility of system-capacitor resonance has become a routine concern for shunt capacitor applications. Whenever a shunt capacitor is to be added to a network or resized, system planners are interested in knowing if the proposed capacitor installation would resonate with the system. If there is a resonance, then the problem is much severe.

A commonly used method to verify if a capacitor resonates with its supply system is to determine the ratio of the system fault level to the capacitor size (IEEE Standard 519-1992, 1994). Resonance frequency can also be estimated from this ratio. Our experience shows that this method is obsolete to be practically useful. This ratio is based on the assumption that the system harmonic reactance is proportional to its fundamental reactance determined from the fault level. There is no guarantee that this assumption is valid for practical interconnected power systems. Furthermore, one cannot determine the severity of the resonance as not all resonance conditions will cause setbacks. However, engineering judgment must be used when applying capacitors in power systems with high harmonic currents. Capacitors might not survive long enough in such environments if they are inappropriately applied (Ronald, 2005).

The objective of this study is to investigate the frequent tripping and occasional failure of fixed and automatically switched-capacitor banks in the ECG's distribution network. The network has a number of 33/11 kV power distribution substations with shunt capacitor banks installed. The main purpose of

Corresponding Author: J.C. Attachie, Department of Electrical and Electronic Engineering, University of Mines and Technology, Tarkwa, Ghana
This work is licensed under a Creative Commons Attribution 4.0 International License (URL: http://creativecommons.org/licenses/by/4.0/).

installing the capacitors was to minimize system losses, improve the system power factor and release the capacity to enable transfer of maximum power. However, upon commissioning, some of the capacitor banks were reported to have tripped persistently on over voltages and in some cases capacitor failure had occurred.

In this study, a distribution substation was used as a case study to aid in the investigation of the problem. Power disturbance analyzer was installed at the stations to monitor and measure power quality parameters. Harmonic currents measured were observed to be significant. Consequently, the network was modeled and examined using the EMTP software to help identify the exact disturbing electrical phenomenon. It was found that the failures were strongly related to harmonic resonance.

MATERIALS AND METHODS

Resonance phenomena: The reactance of an electrical network is dependent on the frequency. At certain frequencies, the inductive and capacitive components of the network begin to resonate with each other at the resonance frequency. That frequency is the natural resonance frequency that is determined by the combination of the inductances and capacitances of the components. The resonant frequency for a particular inductance/capacitance combination can be computed from a variety of different formulae depending on what data are available. The basic resonant frequency equation is:

$$f = \frac{1}{2\pi}\sqrt{\frac{1}{LC}} \tag{1}$$

where,

L = The inductance

C = The capacitance of the network (Lukasz *et al.*, 2009)

At high voltages, the resistance of a network is usually small compared to the capacitance and inductance and therefore, the impedance can change considerably. The situation becomes severe when the resonance frequency coincides with a frequency of any harmonic current or voltage. If this occurs, the harmonic current or voltage will be amplified, which can lead to damage of some network components. Most often, resonance frequencies occurs between harmonic frequencies (inter-harmonic resonance) (Gunther, 2001). One system can have several resonance frequencies depending on the grid configuration (Patel, 2010). A relatively small distortion at resonance frequency can lead to serious consequences, which emphasizes the importance of the advance analysis of harmonics (Arana *et al.*, 2009). Two different types of resonance can be identified; parallel resonance and series resonance (Wakileh, 2001).

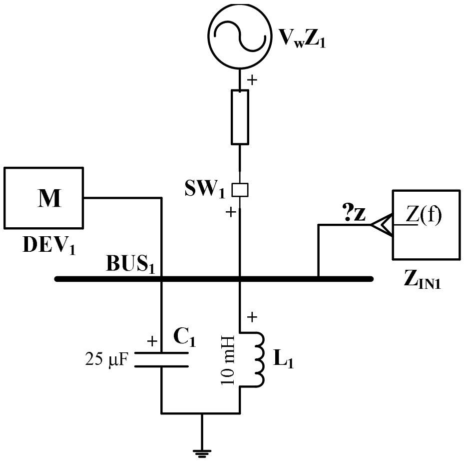

Fig. 1: Example of parallel resonant circuit

Parallel resonance: In parallel resonance, the impedance of the circuit is high. In an ideal resonance (circuit without resistance), impedance becomes infinitely high, which leads to extremely high overvoltage. At parallel resonance frequency, the voltage obtains its highest possible value at a given current (Young and Freedman, 2011).

Parallel resonance can occur when a source of a harmonic current is connected to the electrical circuit that can be simplified as a parallel connection of inductive and capacitive components (Zheng, 2010). In an extreme case, a relatively small harmonic current can cause destructively high voltage peaks at resonance frequency (Aro *et al.*, 2003)

Parallel resonance is common when there are capacitor banks or long AC lines connected with large transformers. In this case, large capacitances and inductances start to resonate with each other (Lukasz *et al.*, 2009). Figure 1 shows an example of a parallel harmonic resonance circuit.

Figure 2 shows a plot of the equivalent system impedance and frequency scan as seen from BUS_1 (Fig. 1). Figure 1, the circuit has high impedance at its resonant frequency: impedance of the circuit as seen from BUS_1 is 147 Ω at 630 Hz using EMTP. Under normal condition, this should not pose any threat to the system at all and therefore a clean sine-wave voltage was recorded, using the measuring device M, at BUS_1. However, it becomes a problem only if a harmonic source exists at or near this frequency.

Parallel resonant equation: The parallel resonant frequency of a system involving a transformer can be estimated. At a secondary side of a transformer, resonant frequency of a network can be determined using the following relation (Thomas *et al.*, 2013):

$$h = \sqrt{\frac{kVA_{transformer}}{Z_{transformer} \times kVAR}} \tag{2}$$

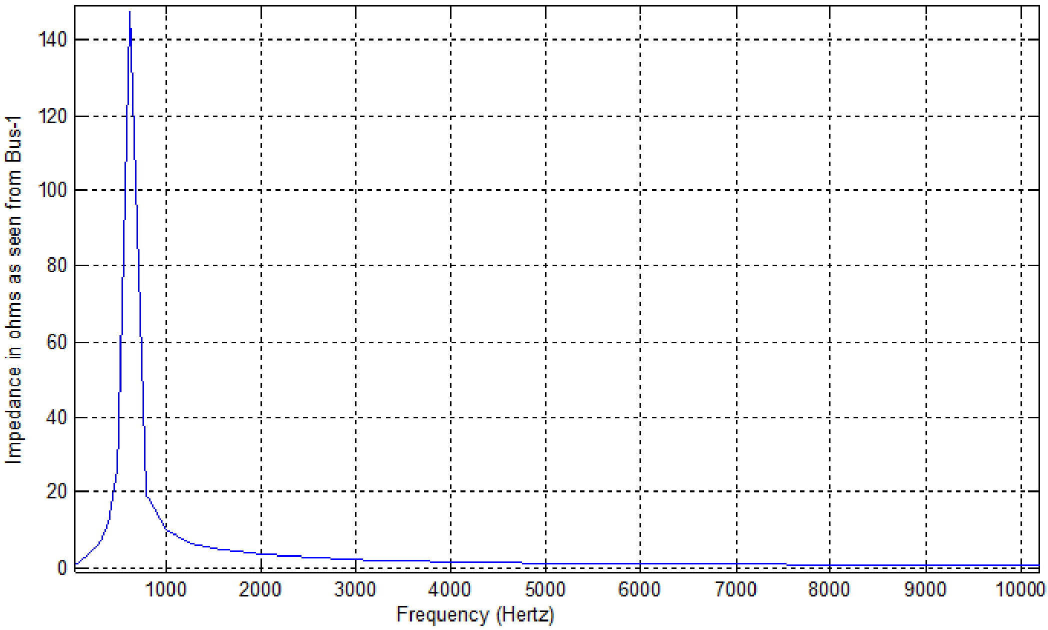

Fig. 2: Frequency scan and impedance as seen from BUS$_1$

where,

h = The harmonic frequency in per unit
Z = Impedance of the transformer in percent
kVA = The power rating
kVAR = The reactive power rating of the capacitor bank

Series resonance: Series resonance differs from the parallel resonance in its low impedance at a resonance frequency. At the resonance frequency, the inductive and the capacitive reactance at a certain point becomes equal (Sankaran, 2002). In this case, the capacitive reactance annuls the inductive reactance and the network impedance only consists of the resistance of the network. As the cable resistances are normally very low, the reduction of impedance can be seen as noticeably high currents (Aro *et al*., 2003). The case is analogous to the parallel resonance but instead of high voltages, high currents flow through a low impedance circuit.

To prevent the resonance from becoming dangerous, the system natural frequency point is forced below any of the frequencies where significant current harmonic distortion occurs. To do this, the series resonant circuit is used. In a series resonance circuit, the inductive reactance components are in series to a source of harmonic current. Essentially, series resonant is a harmonic filter tuned at a fixed frequency to attract harmonic currents and consequently reduce harmonic distortion. An example of the series resonant circuit is shown in Fig. 3.

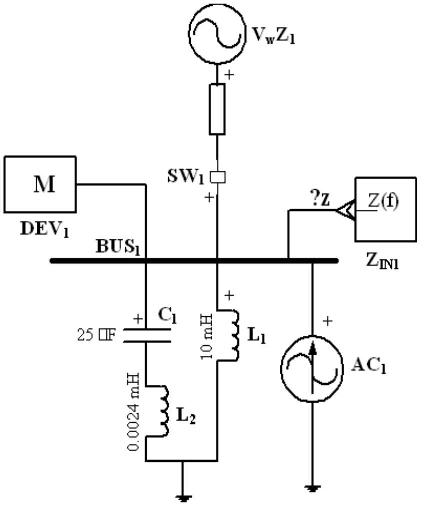

Fig. 3: Example of series resonant circuit

A plot of the impedance as a function of frequency in the series resonance circuit is illustrated in Fig. 4 (for the circuit of Fig. 3). The effect of the series inductance can be seen as: while the parallel resonant circuit produces a high impedance of 147-ohms at the 13th harmonic current, the series circuit, tuned to 13th harmonic order, produces a low impedance path to the 13th harmonic current and changes the resonant frequency point. The resonant frequency is now moved to the 8th harmonic order which is considered not detrimental.

Figure 5 depicts the effect of the series inductor on the bus voltage and current amplification in the capacitive circuit. At the instant the harmonic source was energized, a voltage spike was observed. This can be destructive but can be managed with a surge arrestor. Compared with the case of the parallel resonance, the

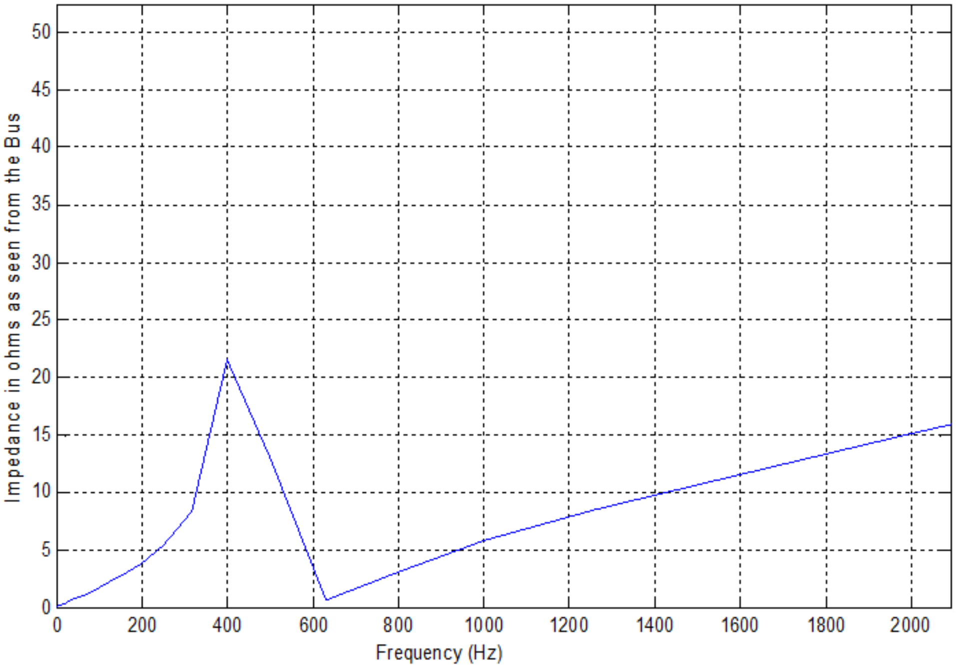

Fig. 4: Frequency scan and impedance as seen from BUS$_1$ (reference Fig. 3)

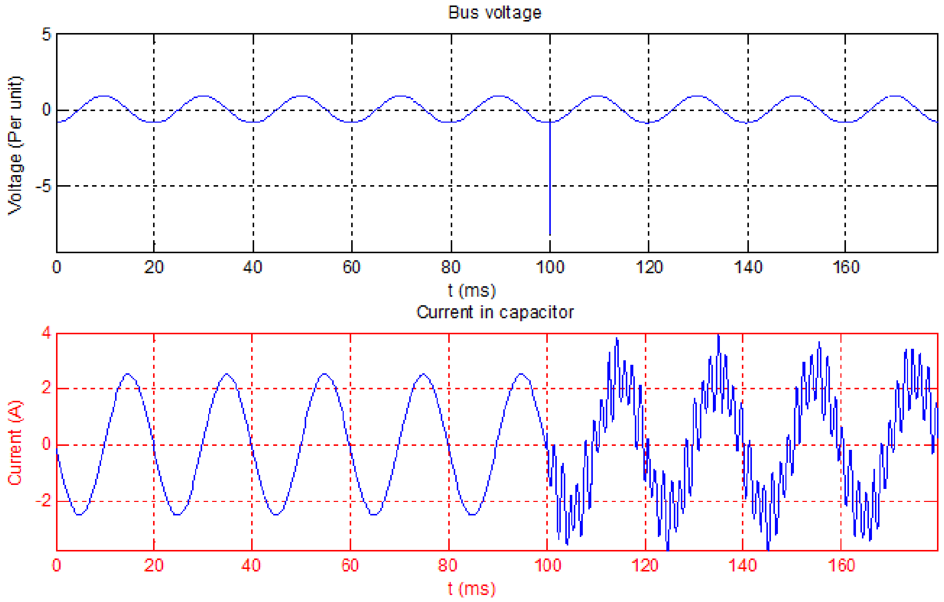

Fig. 5: Bus voltage and current amplification

series inductor has significantly reduced the current to a tolerable range. It is important to note that, the primary purpose of the series resonant is not essentially to reduce the harmonic distortion but to ensure that the capacitor does not resonate with the impedance of the circuit (IEEE Standard 519-1992, 1992).

Series resonant equation: The value of the inductance required to tune or move a circuit's natural frequency away from a characteristic harmonic frequency, can be determined using the following relation:

$$X_L = \frac{X_C}{h^2} \tag{3}$$

where,

Xc = The capacitive impedance of all the capacitors connected to the secondary bus of the transformer

X_L = The inductive impedance of the transformer

RESULTS AND DISCUSSION

At the substation, a fixed and an automatically switched capacitor banks are installed. Depending on the load, the switched capacitor bank commutates, i.e., switches on and off. The purpose was to support the fixed capacitor in reactive power compensation. It was reported that the switched capacitor trips on instant overvoltage once it was energized. In order to determine the cause of the tripping in this case, the EMTP is used to simulate the energization of the switched capacitor.

The circuit data: The source was represented as Thevenin equivalent with an X/R value of 3.15. The short circuit power is 1800 MVA and voltage of 33 kV as base. The 20 MVA, 33/11 kV transformer at the station was represented with 10% impedance. PQ load of the station are 5,569 kW and 2,130 kVAR with a lagging power factor of 0.93. The equivalent network of the station is shown in Fig. 6.

Simulation results and discussion: Initially, a frequency scan was performed to determine the resonant frequency of the station: with and without the switched capacitor bank. The impedance and frequency of the network at the two scenarios are shown in Fig. 7 and 8. Whilst the impedances at the two scenarios were the same, the resonant frequencies were different. The resonant frequency of the network with only the fixed capacitor bank was at the 15th harmonic order. This is a characteristic frequency which is a source of concern. Fortunately, when the fixed capacitor is closed, then the resonant frequency point is moved to the 10th harmonic order which is a harmless frequency. However, it is important to examine the network under the fixed capacitor condition at the 15th harmonic order of 50 A because it is also found in the measured harmonic content of the substation. Subsequently, the extent of voltage and current amplification was examined.

When the current source is closed at 100 ms, a harmonic current of 50 A in the 15th harmonic order is injected into the network from the 11 kV bus. In Fig. 9, the voltage amplification was about 5% which according to IEEE standard 18-2002 is tolerable.

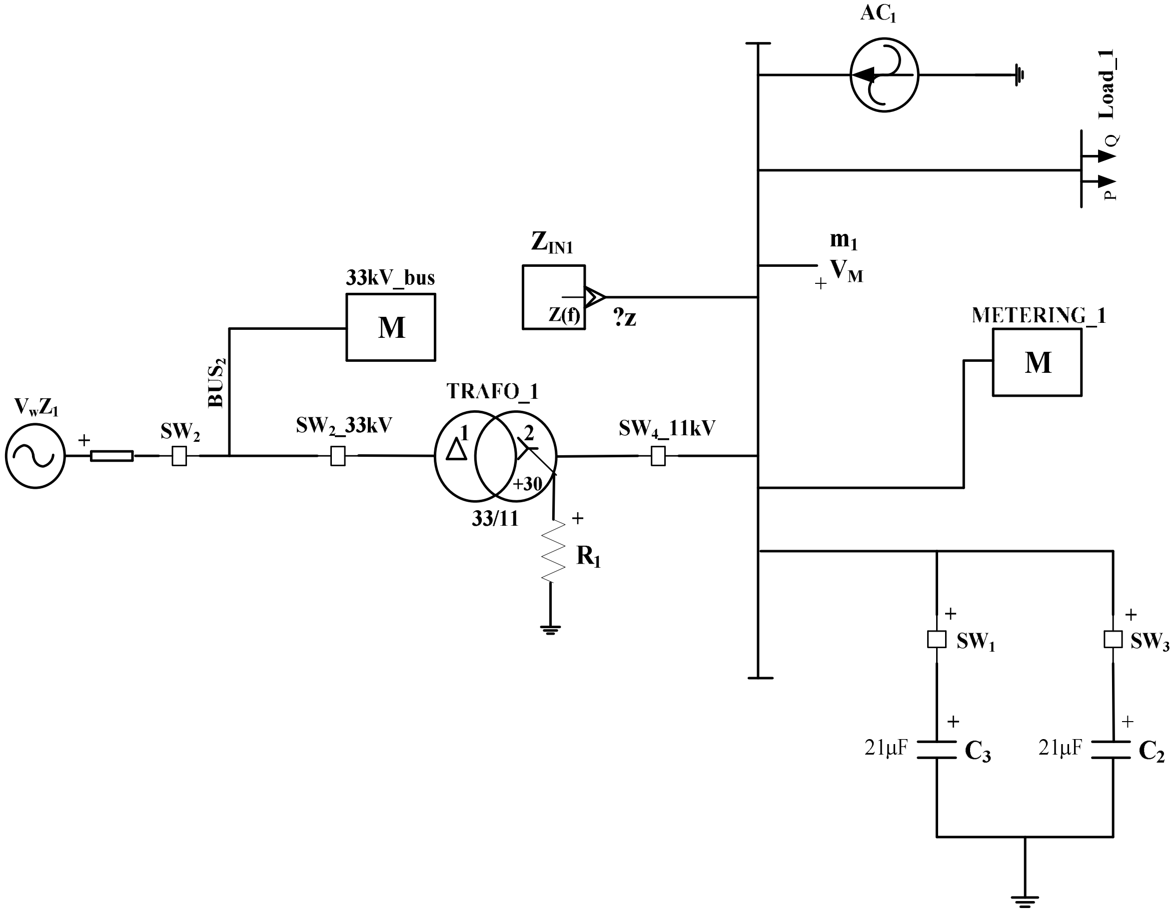

Fig. 6: Equivalent network of substation

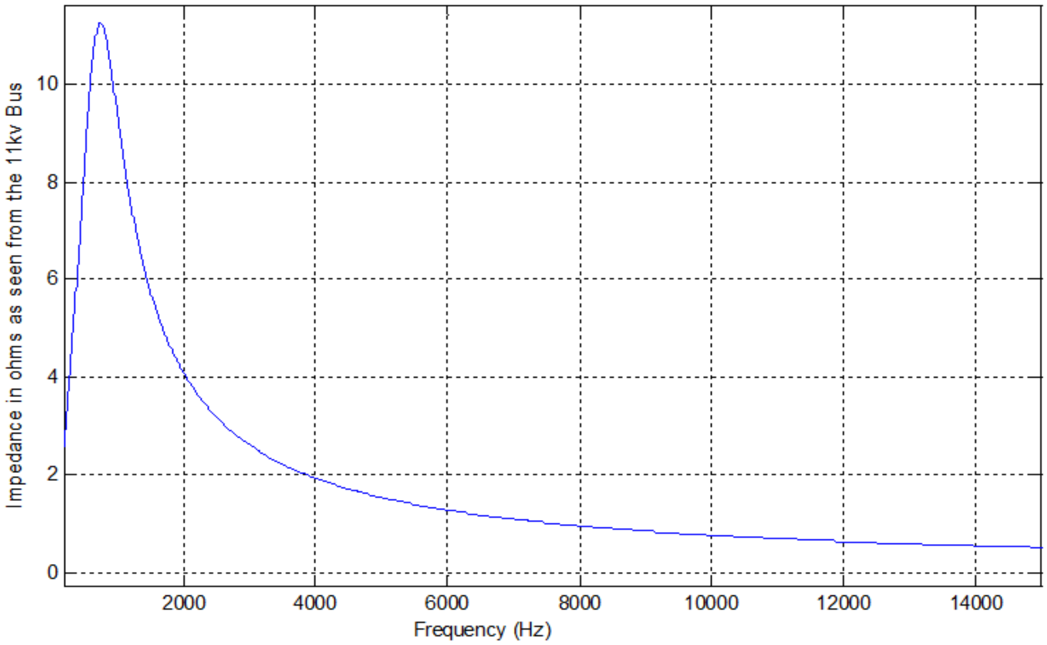

Fig. 7: Impedance-11.2 ohms and frequency-749 Hz (only fixed energized) at the 15th harmonic order

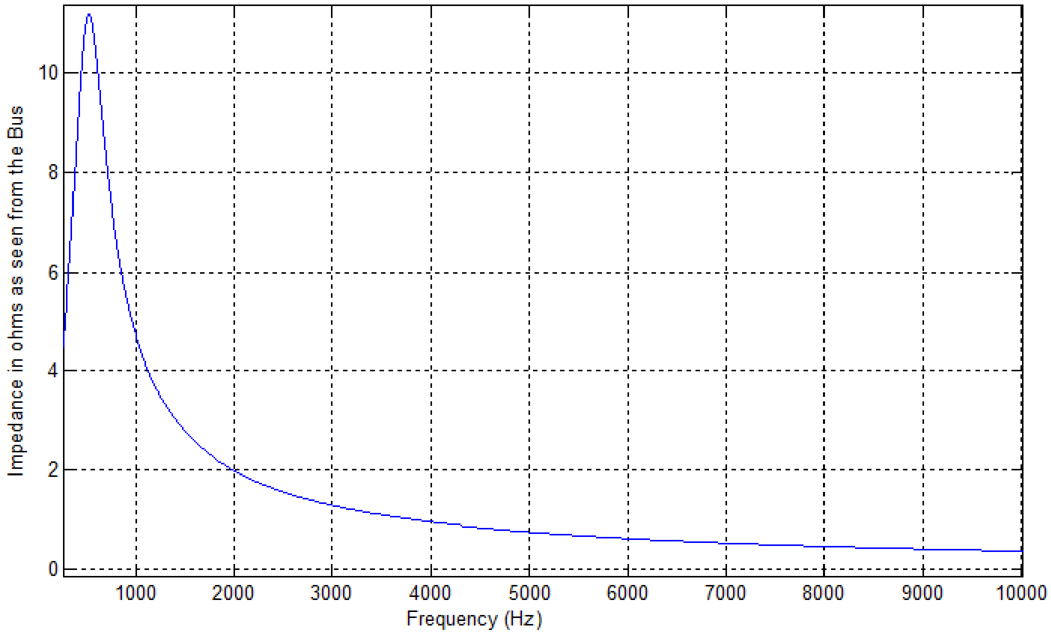

Fig. 8: Impedance-11.2 ohms and frequency-513 Hz (fixed and switch on) at the 10th harmonic order

However, the problem, as illustrated in Fig 10, is with the current amplification. Current amplification of about 2.8 times the nominal current was noted. This far exceeds the inrush current limit allowed by IEC 60871 and AS 2897. Such level of current may trip or damage the capacitor bank.

The effect of switching the automatically switched-capacitor bank: In order to examine the effect of the switched-capacitor, the switched-capacitor was energized at 100 ms of the simulation time. The resultant effect on the bus voltage was marginal (Fig. 11). However, the inrush current was over 1500 A. This explains why the switched-capacitor trips instantly each time it was energized. From the analysis, it is expected that the tripping should be as a consequent of over-current and not on overvoltage. We suspect that the overvoltage related tripping might be due to a problem with the overvoltage relay settings.

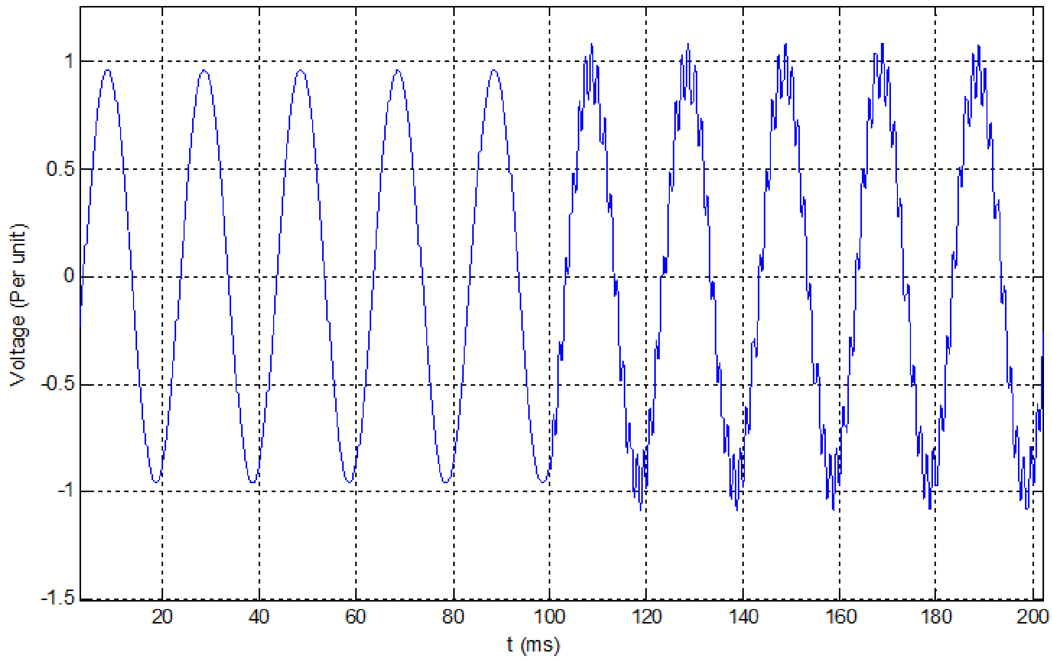

Fig. 9: Only fixed cap on with voltage amplification

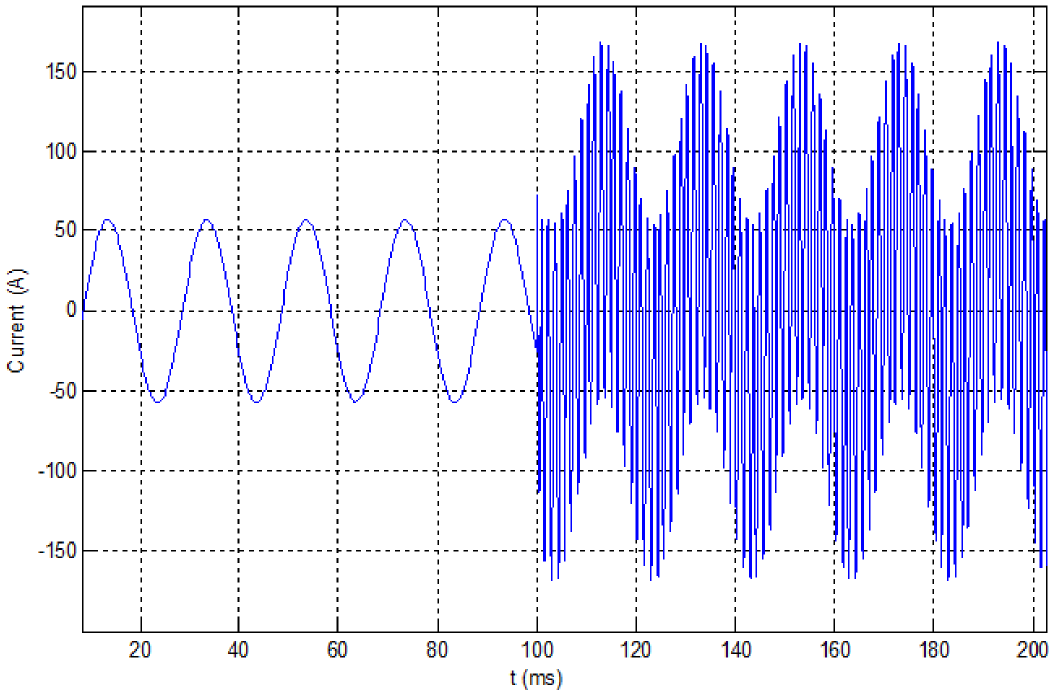

Fig. 10: Only fixed cap on with current amplification

A hypothetical situation was examined where the fixed capacitor was tuned to the 15th harmonic order leaving the switched-capacitor unturned. The result is shown in Fig. 12. Again, the transient disturbance on the 11 kV voltage was tolerable.

The amplification in both the fixed and the switched capacitor banks was about 400%. This level of current amplification is unacceptable by the IEEE standard 18-2002.

From the analysis made, it is obvious that in order to address the problem, both the fixed and the switched-capacitor need to be tuned. The fixed capacitor bank was tuned to the 15th harmonic order because the resonant frequency occurs at this harmonic frequency.

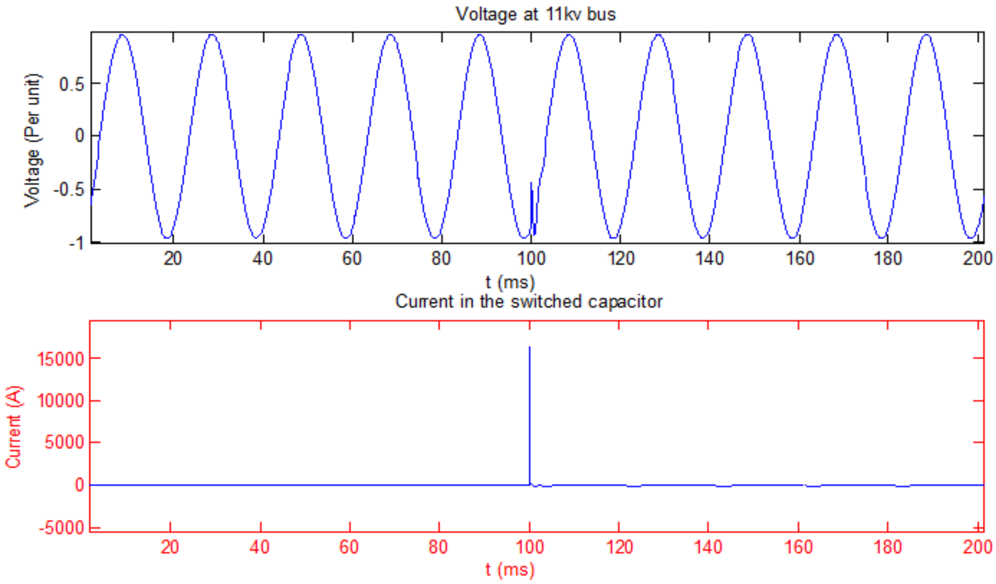

Fig. 11: Voltage and current during energization of switched-capacitor bank

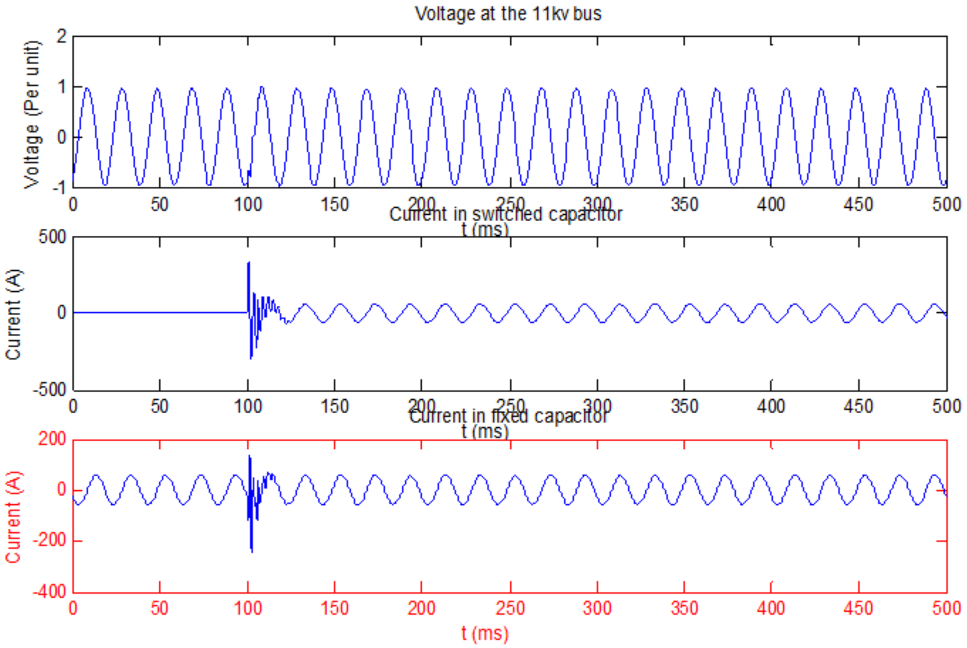

Fig. 12: Bus voltage and current in fixed and switched capacitor banks (with only fixed capacitor tuned to the 15th harmonic order

In relation to the switched-capacitor bank, even though it pushes the resonant frequency to the 10th harmonic order, it was recognized that the 10th harmonic filter may produce a parallel resonance near the 9th harmonic.

The best preventative approach recommended by research articles is to tune or select a filter that ensures that the systems natural frequency point is moved below any of the frequencies where significant current harmonic distortion occurs. Accordingly, the switched-capacitor was tuned to the 4.7th harmonic order. This is a standard filter that also provides filtering at higher frequencies such as the 7th, 11th, 13th etc., the impedance against tuned frequencies of the network is shown in Fig. 13.

The size of the series inductors as calculated for the tuned 4.7th and the 15th harmonic order are 0.022 and 0.00214 H, respectively. The effect of these inductors on both the bus voltage and the current drawn by the capacitor banks are shown in Fig. 14.

From Fig. 14, the inrush current, especially in the switched-capacitor has been limited to about 90% of the nominal current of the capacitor.

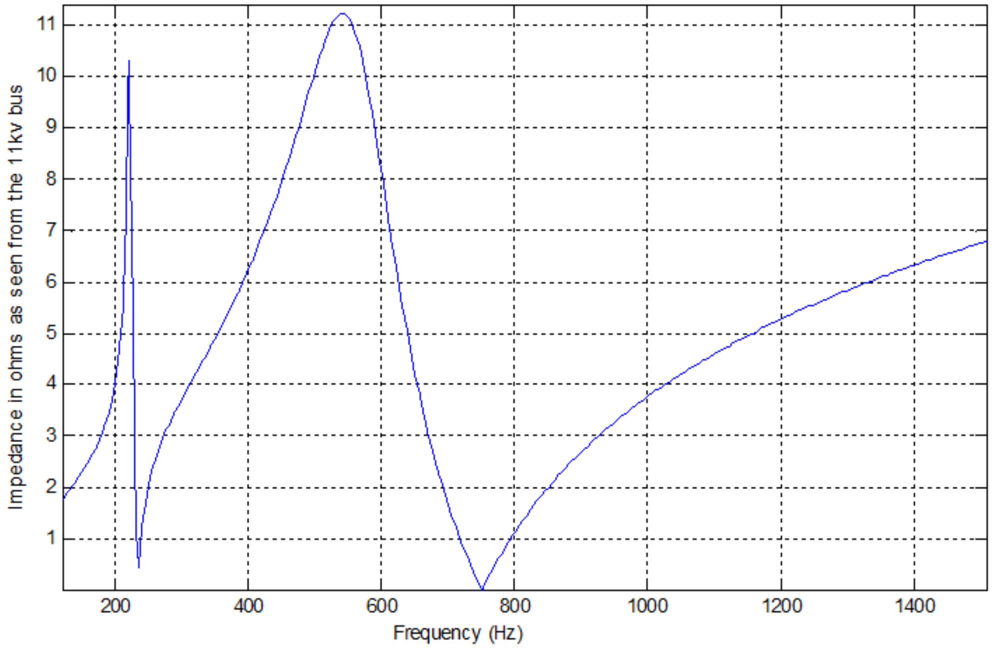

Fig. 13: Impedance against frequency graph of the tuned network as seen from the bus

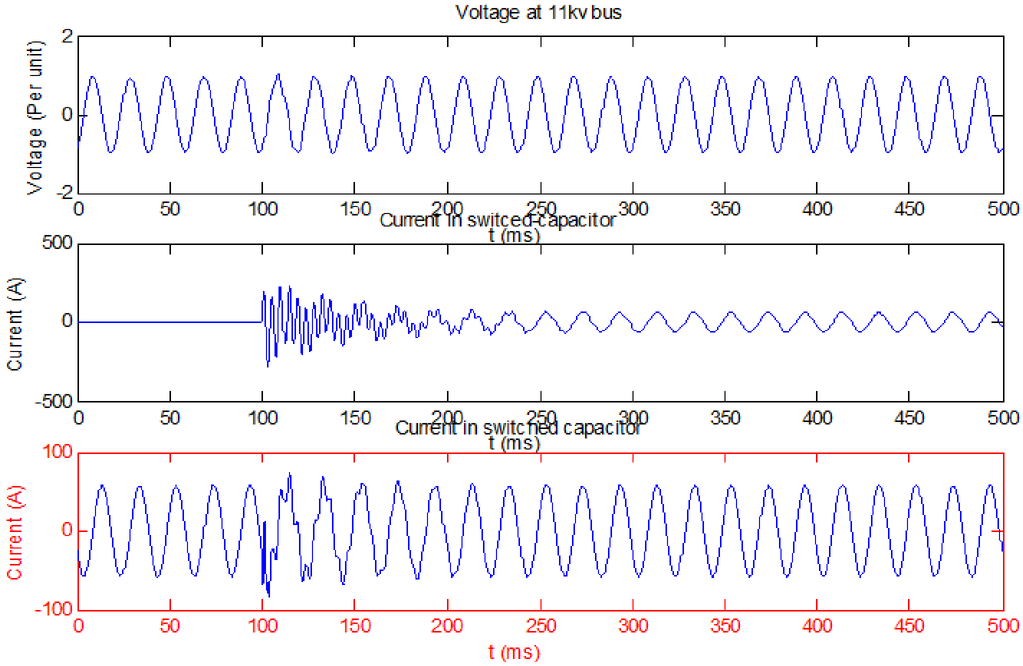

Fig. 14: Effect of these inductors on both the bus voltage and the current drawn by the capacitor banks

This amplification is within acceptable inrush current limits.

CONCLUSION

The widespread use of nonlinear loads by all customers results in unavoidable harmonic generation throughout distribution systems. Power system harmonics, nowadays, cause many problems like equipment failures and plant shutdowns. Accordingly, mitigation of these harmonics is important especially for industrial applications where, any small downtime period may lead to great economic losses. Additionally, the applications of capacitors are also extensively used in power systems for voltage support and power factor correction. This study investigated the frequent capacitor bank tripping and damages in a distribution substations of the ECG. The study was conducted using the EMTP software for the simulations. The results showed that, failures were related to harmonic resonance.

In many cases, it may be more economical to control the voltage distortion experienced by all customers by changing the frequency response of the system. This can be accomplished with a tuned capacitor bank on the distribution system.

ACKNOWLEDGMENT

The authors wish to express their heartfelt gratitude to George Eduful of the Electricity Company of Ghana for his immense assistance and efforts during the data collection and analysis and Georgina Attachie and Bridget Brown.

REFERENCES

Arana, I., L. Kocewiak, J. Holboll, L. Bak and A.H. Nielsen, 2009. How to improve the design of the electrical system in future wind power plant. Proceeding of the Nordic Wind Power Conference (NWPC2009), Bornholm, Denmark.

Aro, M., J. Elovaara, M. Karttunen, K. Nousiainen and V. Palva, 2003. High Voltage Engineering. Helsinki, Otatieto, ISBN: 9789516723207.

Ciok, Z., 1962. Non-Simultaneous short-circuits in three phase networks with special consideration to the effect upon the operation of circuit-breakers. Report No. 120, CIGRE Session.

Gunther, E.W., 2001. Inter-harmonics in power systems. Proceeding of the IEEE Power Engineering Society Summer Meeting 2001, 2: 813-817.

IEEE Standard 519-1992, 1992. IEEE Recommended Practice and Requirements for Harmonic Control in Electric Power Systems. Published by IEEE.

IEEE Standard 519-1992, 1994. Power System Harmonics Causes and Effects of Variable Frequency Drives Relative to the IEEE 519-1992 Standard. Square D Product Data Bulletin, Bulletin No. 8803PD9402.

Khan, A., D.S. Johnson, J.R. Meyer and K.B. Hapke, 1994. Development of new synchronous closing circuit breaker for shunt capacitor bank energization. Proceeding of the 61st Annual International Conference of Doble Clients, Berlin, Paper 5E.

Lukasz, H.K., J. Hjerrild and C.L. Bak, 2009. Harmonic models of a back-to-back converter in large offshore wind farms compared with measurement data. Proceeding of the Nordic Wind Power Conference 2009, Bornholm, Denmark.

Patel, D., 2010. Impact of wind turbine generators on network resonance and harmonic distortion. Proceeding of the 2010 23rd Canadian Conference Electrical and Computer Engineering (CCECE).

Ronald, H.S., 2005. Misapplication of power capacitors in distribution systems with nonlinear loads: Three case histories. IEEE T. Ind. Appl., 41(1).

Sankaran, C., 2002. Power Quality. CRC Press, Boca Raton, FL, ISBN: 0849310407.

Thomas, M.B. and D.J. Carnovale, 2013. Capacitor Application Issues. Retrieved from: http://electrical-engineering-portal.com/ download-center/ books-and-guides/ power-substations/ capacitor-application-issues, (Accessed on: January 18, 2013).

Wakileh, G.J., 2001. Power System Harmonics: Fundamentals, Analysis and Filter Design. Springer, ISBN: 3540422382.

Ware, B., J. Reckleff, G. Mauthe and G. Schett, 1990. Synchronous switching of power systems. Report No. 13-205, CIGRE Session.

Young, H.D. and R.A. Freedman, 2011. Sears and Zemansky's University Physics with Modern Physics. Addison-Wesley, San Francisco, ISBN: 0201603365.

Zheng, R., 2010. Harmonic resonances due to a grid-connected wind farm. Proceeding of the 14th International Conference on Harmonics and Quality of Power (ICHQP), Bergamo, Italy, pp: 1.