Capacitor Bank Switching and Resonance Studies in ECG Distribution Network

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***Abstract*— Application of capacitor bank to an electric power system provides well known benefit, including power factor correction, better voltage regulation and freeing up capacity to enable maximum power transfer. However, a major concern arising from the use of capacitors in power system is the possibility of system resonance. In this paper, frequent capacitor bank tripping and failures in two Electricity Company of Ghana (ECG) distribution substations have been investigated. The study was based on EMTP RV simulation. It was found that the failures were related to harmonic resonance. Purposefully selected series connected inductors were recommended to help move the resonant frequencies of the network below characteristics harmonic frequencies. The paper presents and discusses the techniques applied in the investigation and reports the results achieved.**

***Index Terms*— Harmonic order, natural frequency, resonant frequency, characteristic harmonics.**

I. INTRODUCTION

In power system, shunt capacitors increase power transfer capability without requiring new lines or larger conductors [1]. Shunt capacitor banks are relatively inexpensive and can be easily installed anywhere on a power distribution network. However, engineering judgment must be used when applying capacitors in power systems with high harmonic currents. Capacitors might not survive long in such environments if they are improperly applied [2]

This paper investigates frequent tripping and occasional failure of fixed and automatically switched capacitor banks in the Electricity Company of Ghana's (ECG) distribution network. The network has a number of 33/11kV distribution substations with shunt capacitor banks installed. The capacitors were installed with the main aim of reducing system losses, improving system power factor and releasing capacity to enable maximum power transfer.

However, upon commissioning, some of the capacitor banks were reported to have been tripping persistently on over voltages. In some cases capacitor failure had occurred. Using two of the substations as case studies, the problem was investigated. First, power disturbance analyzer was installed at the stations to monitor and measure power quality parameters including harmonic content. The network was modelled and examined using the commercially available EMTP RV software to help identify the exact disturbing phenomenon. It was found that the failures were strongly related to harmonic resonance.

To address the problem, purposefully selected series inductors were recommended to help move the resonant frequencies of the network below problematic harmonic frequencies. The paper presents and discusses the techniques applied to investigate the problem and reports the results achieved.

II. PARALLEL RESONANCE AND SERIES RESONANCE

There are two forms of resonance which can occur: parallel resonance and series resonance

A. Parallel Resonance

Parallel resonance occurs when a harmonic frequency produced by a non-linear load closely coincides with a power system natural frequency [2]. In a parallel resonance circuit, the inductive reactance and capacitive reactance impedance components are in parallel to a source of harmonic current. Fig.1 shows an example of a parallel harmonic resonance circuit.

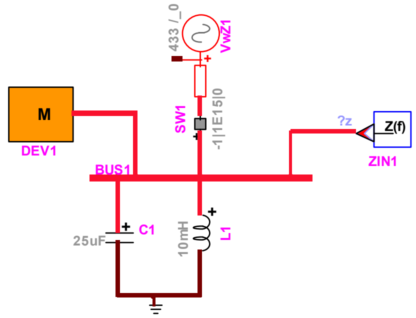

Fig.1: Example of parallel resonant circuit

Fig.2 shows a plot of the equivalent system impedance and frequency scan as seen from BUS-1. It can be seen that the circuit presents a high impedance at its resonant frequency: impedance of the circuit as seen from Bus-1 is 147Ω at 630Hertz. Under normal condition, this should not pose any threat to the system. A clean sine-wave voltage was recorded, using a measuring device M, at Bus-1. However, it becomes a problem only if harmonic source exist at or near this frequency.

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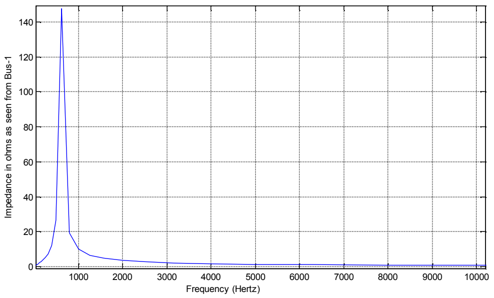

Fig.2: Frequency scan and impedance as seen from BUS-1

B. *Parallel resonant equation*

Parallel resonant frequency of 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 [3]:

$$h = \sqrt{\frac{kVA_{transformer}}{Z_{transformer} \times kVAR}} \qquad (1)$$

Where

h is harmonic frequency in per unit, Z impedance of the transformer in percent, kVA power rating and kVAR reactive power rating of the capacitor bank .

C. *Series resonance*

To prevent resonance from becoming dangerous, the system natural frequency point must be forced below any of the frequencies where significant current harmonic distortion occurs. To do this, 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 series resonant circuit is shown in Fig.3.

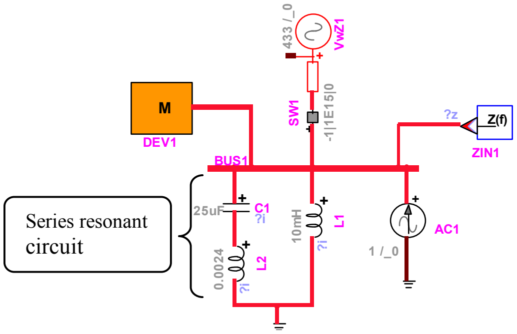

Fig.3: Example of series resonant circuit

Fig.4 shows a plot of impedance as a function of frequency in the series resonance circuit. The effect of the series inductance can be seen: compared with the parallel resonant circuit which 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 8th harmonic order which is considered harmless

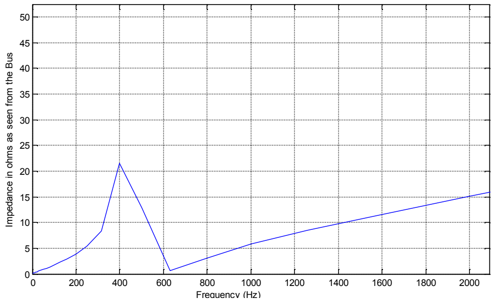

Fig.4: Frequency scan and impedance as seen from Bus-1 (reference Fig.3).

Effect of the series inductor on the Bus voltage and current amplification in the capacitive circuit can be seen in Fig.5. Voltage spike can be observed at the instant the harmonic source was energised. This could be destructive but could be managed with a surge arrestor. Compared with the case of the parallel resonance, the series inductor has significantly reduced the current to 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 [4].

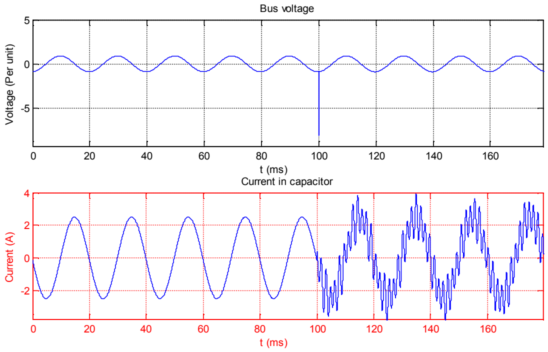

Fig.5: Bus voltage and current amplification

D. *Series resonant equation*

The following relation can be used to determine inductance require to tune or move a circuit's natural frequency away from a characteristic harmonic frequency.

$$X_L = \frac{X_c}{h^2} \qquad (2)$$

Where

Xc is the capacitive impedance of all the capacitors connected to the secondary bus of the transformer, and X_L is the inductive impedance of the transformer.

III. CASE STUDY 1: FIXED CAPACITOR BANK AT STATION S

This case investigates the cause of frequent tripping and occasional failure of a 2x400kvar fixed capacitor bank at Substation-S. Fig.6 is an equivalent representation of the network of the substation. The transformers were independently operated as the 11kV bus sectionalizer (circuit breaker) was kept normally open. Although the study considered two sections of the 11kV bus (Bus 1&2), to avoid repetition of procedures and ensure clarity, report of the analysis is limited to Bus-1.

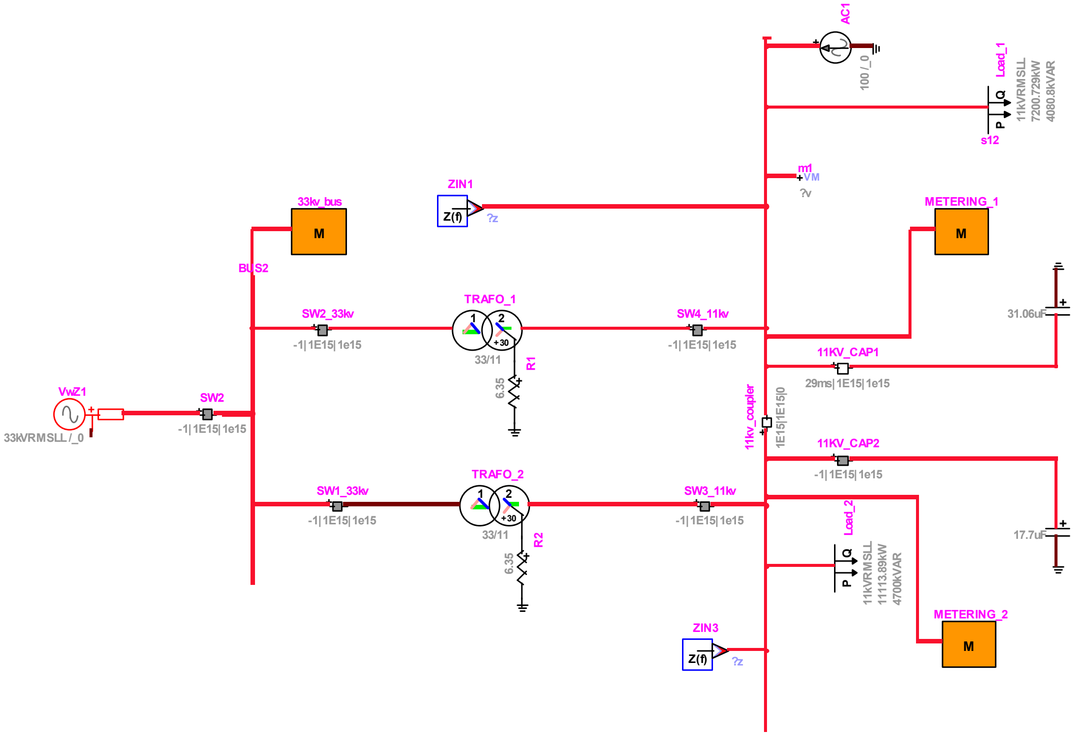

Fig.6 - A single line diagram of Substation-S

A. Circuit data:

The source was represented as Thevenin equivalent with an X/R value of 5.3. The short circuit power is 1800MVA at a voltage of 33kV as base. The 10 MVA, 33/11 kV transformer at the station was represented with 9.9 % impedance. PQ load of the station are 7200 kW and 4081 kvar with a lagging power factor of 0.87. The equivalent network of the station is shown in Fig.6.

B. Calculation of resonant frequency:

Resonant frequency of the network was calculated using equation (1).

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

Where

$kVA_{\text{transformer}} =$ 10, 000, $Z_{\text{transformer}}$=9.9%, *kvar*= 1400

h = 8.5

This means the system exhibits a resonant frequency that is close to a problematic frequency of 9th harmonic order.

The EMTP RV was used to confirm the calculated resonant frequency. Fig.7 shows frequency scan and impedance as seen from Bus-1. The network present a high impedance at a resonant frequency of 450Hz (9th harmonic order) which is in agreement with the calculated natural frequency.

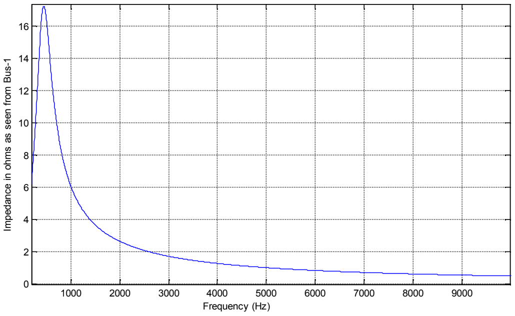

Fig.7: Frequency scan and impedance as seen from Bus-1

C. Simulation:

To determine harmonic resonant effect on the system voltage, harmonic current source of 34A of 9th harmonic order (value taken from the measured harmonic content of the station) was injected into Bus-1. As can be seen in Fig.8, the resulting overvoltage is about 30%.

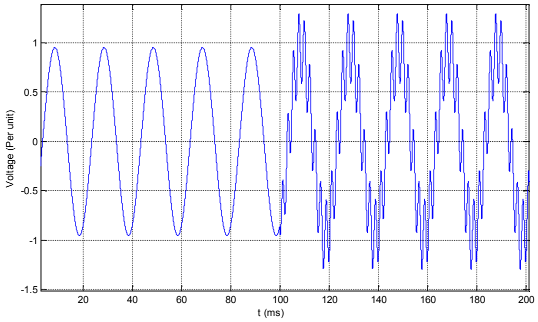

Fig.8: Harmonic effect on Bus-1 voltage

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The limit on steady- state voltage is generally taken to be 110% of the rated voltage. If the voltage is allowed to rise above this point, transformers will saturate and overheat. According to IEEE standard 18-1992 and IEEE standard 1036-1992, capacitor bank short time overvoltage of about 130% should be limited to 1minute. From this standpoint, we conclude that the existence of the 9th harmonic of such magnitude in the system explains why persistent tripping of the capacitors was experienced

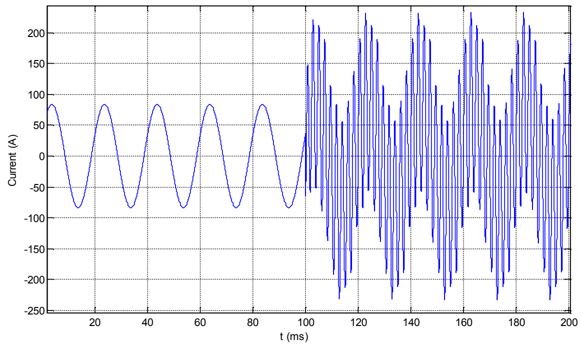

Fig.9: Current drawn by the capacitors under harmonic resonant condition

Current drawn by the capacitors under the harmonic resonant condition was also examined. As can be seen in Fig 9, peak current of about 270% of the normal current was drawn by the capacitors. Capacitor standards by IEC 60871 and AS 2897 indicate that capacitors should be able to withstand inrush currents up to 100 times nominal current. Large and high frequency steady-state current of about 270% is enough to damage the capacitors.

D. Recommended solution: Case-1

Having investigated the possible cause of the frequent tripping and the damage of the capacitor bank, our secondary aim was to find solution to the problem. As discussed earlier, problem with harmonic resonance can be solved by purposefully selecting and connecting inductor in series with the capacitor bank to help limit harmonic currents and consequently reduce harmonic distortion. At this stage, it is known that the network exhibits 9th harmonic resonant frequency. To solve the problem, inductance of 0.0059H was connected in series with the capacitor bank to drain all the 9th harmonic current.

The size of the inductor was calculated as follows:
First, consider frequency to tune the circuit to. In this case, we are tuning the capacitor bank to 9th harmonic order.
From equation (2),

$$X_L = \frac{X_c}{h^2} \quad \text{and} \quad L = \frac{X_L}{2\pi f}$$

Where,
L is the inductance in henries of the series inductor to be calculated, h = 9 (frequency to be filtered)

From Fig 14,
Xc=21µF
Therefore, L =0.00594H

As can be seen in Fig 10, the network now presents a very low impedance path to the 9th harmonic current. The resonant frequency of the network is now moved to 8th harmonic order which is considered a problem-free frequency.

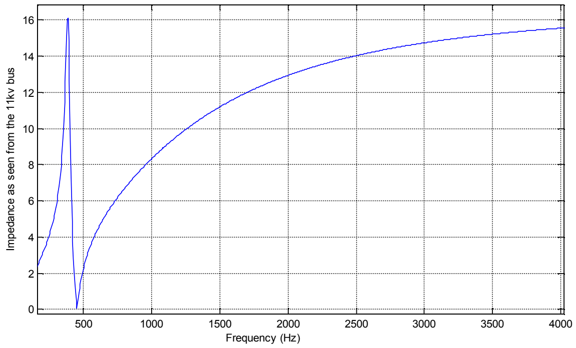

Fig.10: Frequency scan and impedance as seen from Bus-1

Effect of the series inductor on Bus-1 voltage is shown in Fig.11. It is clear that the 30% overvoltage effect occasioned by the parallel harmonic resonance condition in Fig. 8 has been removed by the series inductor.

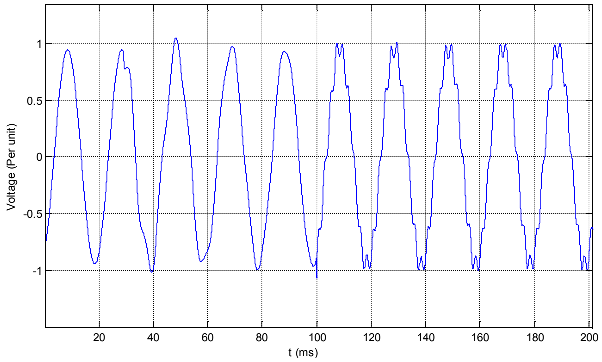

Fig.11: Bus voltage as a result of series inductor

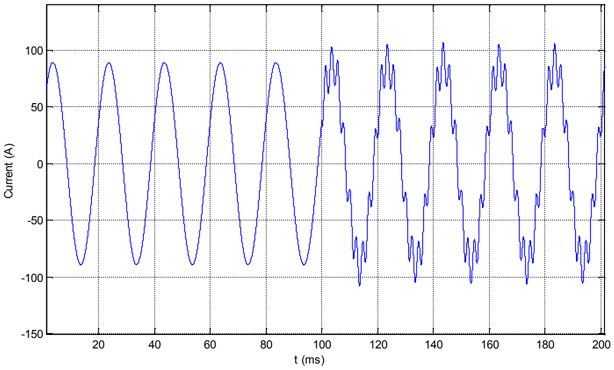

Fig.12: Current in the capacitor as a result of the series inductor

Fig.12 shows the effect of the series inductor in relation to current drawn by the capacitors. The harmonic induced peak current amplification is now reduced significantly from 270% to about 20%. According to IEEE standard 18-2002, shunt capacitors should be able to tolerate 135% continuous current overload. Hence, the 20% current amplification should be safe for the capacitors.

IV. CASE STUDY 2: FIXED AND SWITCHED CAPACITOR BANK SWITCHING AT STATION K

At this station a fixed and an automatically switched capacitor banks are installed. The switched capacitor bank switches on and off depending on the load. The aim was to support the fixed capacitor in reactive power compensation. It was reported that the switched capacitor trips on instant overvoltage once it was energised. In this case, the EMTP RV is used to simulate energization of the switch capacitor to determine the cause of the tripping.

A. Circuit data:

The source was represented as Thevenin equivalent with an X/R value of 3.15. The short circuit power is 1800MVA and voltage of 33kV as base. The 20MVA, 33/11kV 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.13.

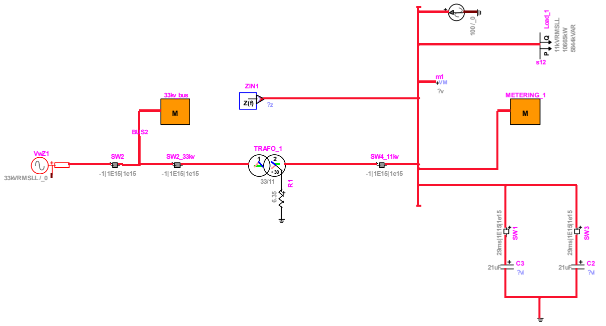

Fig.13: Equivalent network of the Station K

B. Simulation:

First, frequency scan was performed to determine the resonant frequency of the station with and without the switched capacitor bank. Fig 14 and 15 show the impedance and frequency of the network at the two scenarios. 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 15th harmonic order. This is a characteristic frequency which is a source of concern. Fortunately, when the fixed capacitor was closed, the resonant frequency point moved to 10th harmonic order which is considered a harmless frequency. It was however important to examine the network under the fixed capacitor condition as 15th harmonic order of 50A was also found in the measured harmonic content of the substation. Consequently, the extent of voltage and current amplification was examined.

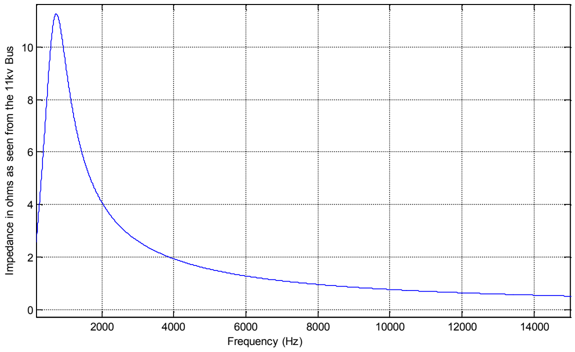

Fig.14: Impedance-11.2 ohms, frequency-749 (only fixed energized) 15th harmonic order

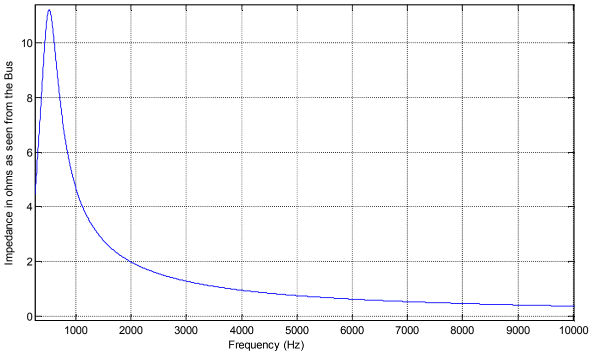

Fig. 15: Impedance-11.2 ohms, frequency-513 (fixed and switch on) 10^{th} harmonic order

Harmonic current source of 50A in 15th harmonic order was injected into the network from the 11kV bus. The current source was closed at 100ms. As can be seen in Fig. 16 the voltage amplification was about 5% which according to IEEE standard 18-2002 is tolerable. However, the problem, as seen in Fig 17, was with the current amplification. Current amplification of about 2.8 times the nominal current was noted. This far exceeds even inrush current limit allowed by IEC 60871 and AS 2897. Such level of current may trip or damage the capacitor bank.

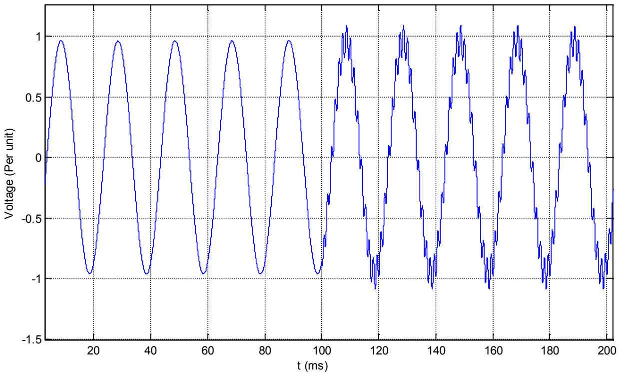

Fig.16: Only fixed cap on (injected harmonic current-50A)

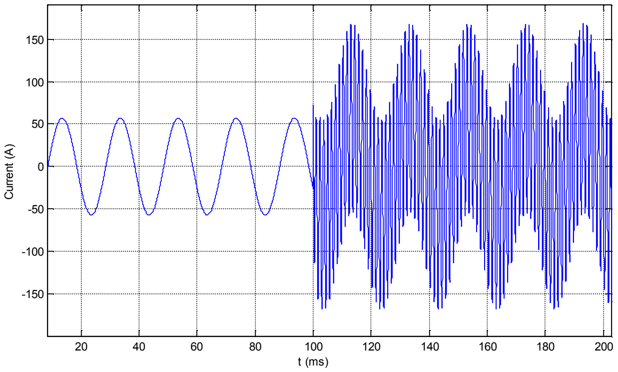

Fig.17: Only fixed cap on (injected harmonic current-50A)

C. *Effect of switching the automatically switched-capacitor bank:*

To examine the effect of the switched-capacitor, the switched-capacitor was energized at 100ms of the simulation time. As can be seen in Fig 18, effect on the bus voltage was marginal. However, the inrush current was over 1500A. This explains why the switched- capacitor trips instantly each time it was energised. From the analysis, it is expected that the tripping should be on over-current and not on overvoltage. It is our suspicion that the overvoltage related tripping might be due to problem with the overvoltage relay settings

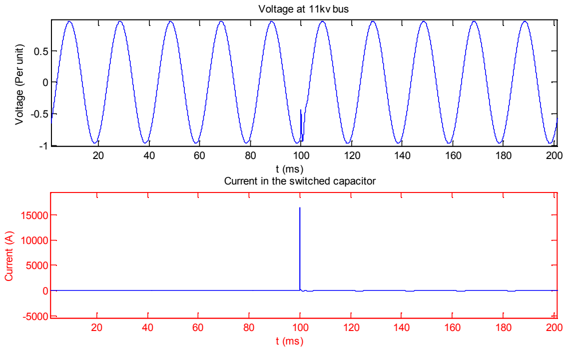

Fig.18: Voltage and current during energization of switched-capacitor bank

We examined a hypothetical situation where the fixed capacitor has been tuned to 15th harmonic order leaving the switched-capacitor untuned. The result is shown in Fig.19. Again, the transient disturbance on the 11kV voltage was tolerable. In relation to the current, even though the reduction compared with the above case was very significant, the amplification in both the fixed and the switched capacitor banks is about 400%. This level of current amplification is unacceptable by standards.

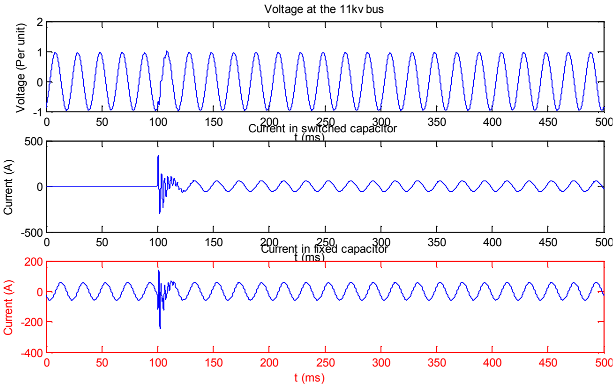

Fig.19: Bus voltage and current in fixed and switched capacitor banks (with only fixed capacitor tuned to 15th harmonic order.

D. *Recommended solution: Case 2*

From the above analysis, it is clear 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 15th harmonic order because the resonant frequency occurs at this harmonic frequency. In relation to the switched-capacitor bank, even though it pushes the resonant frequency to 10th harmonic order, it was recognised that 10th harmonic filter may produce parallel resonance near 9th harmonic. The best preventative approach recommended by research articles is to tune or select a filter that ensures that the system natural frequency point is moved below any of the frequencies where significant current harmonic distortion occurs. Accordingly, the switched-capacitor was tuned to 4.7th harmonic order. This is a standard filter that also provides filtering at higher frequencies such as 7th, 11th, 13th etc. Impedance and tuned frequencies of the network is shown in Fig.20.

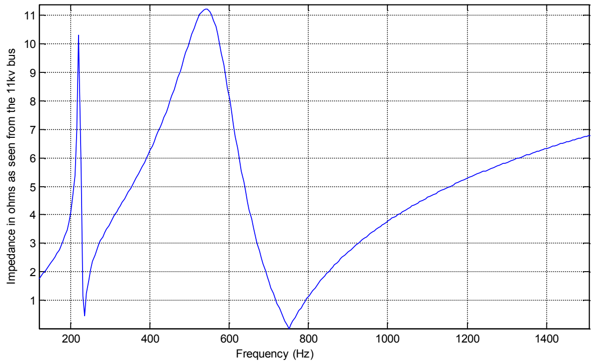

Fig.20: Impedance and frequency graph of the tuned network as seen from the Bus

The size of the series inductors as calculated for the tuned 4.7th and the 15th harmonic order are 0.022H and 0.00214H respectively. Effect of these inductors on both the bus voltage and the current drawn by the capacitor banks are shown in Fig.20. As can be seen, the inrush current, especially in the switched-capacitor has been limited to about 90% of the nominal current of the capacitor. This amplification is within acceptable inrush current limits.

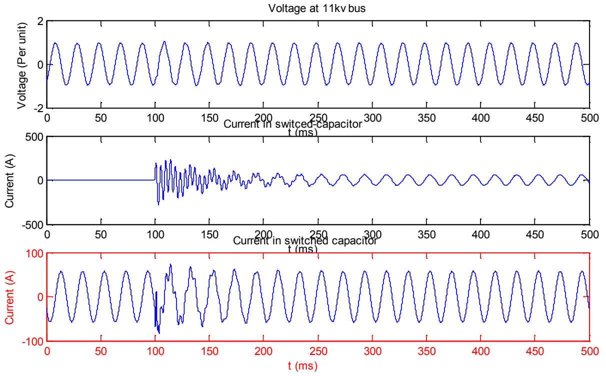

Fig.20: Effect of these inductors on both the bus voltage and the current drawn by the capacitor banks

V. CONCLUSION

Application of capacitor bank to an electric power system provides well known benefit, including power factor correction and freeing up capacity to enable maximum power transfer. However, a major concern arising from the use of capacitors in power system is the possibility of system resonance. In this paper, frequent capacitor bank tripping and failures in two ECG distribution substations have been investigated. The study was based on simulation using the EMTP RV. The failures were found to be related to harmonic resonance. To solve the problem, harmonic content of the substations were measured and the resonant frequency point of the network forced below the characteristic harmonic frequencies.

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