Investigating Damaged Capacitor Bank at a Quarry Processing Plant

George Eduful, *MEMBER*, *IAENG*, Kivlyn N. Asante and Ebenezer A Jackson

***Abstract*— This paper investigates capacitor bank failure at a quarry processing company in Ghana. The company had blamed the Electricity Company of Ghana (ECG) for the cause of the damage. According to the company, the damage was due to frequent power fluctuations and outages experienced from the ECG distribution network. Analysis of the failure, using the EMTP RV, links the failure to harmonic resonance emanating from the company's power system. The paper presents and discusses techniques applied to investigate the problem and reports the results achieved. For safe and reliable operation of capacitor banks, it is recommended that harmonic content of an electrical installation is measured, analyzed and a good engineering judgment made before installation.**

***Index Terms*— Harmonic order, natural frequency, resonant frequency, resonant step.**

I. Introduction

In this paper, capacitor bank failure in a quarry processing company is investigated. On 20th November, 2012 the company lodged a complaint with the Public Utility Regulatory Commission (PURC) blaming the Electricity Company of Ghana (ECG) for damaging their power factor correction capacitor bank. The capacitor bank was installed on 28th September, 2012 and got damage on 8th November, 2012. According to the company, the cause of the damage was due to frequent power fluctuations and outages experienced from the ECG distribution network. They are therefore praying the PURC to compel ECG to pay for the cost of the capacitor bank and in addition restrain ECG from surcharging them for operating at low power factor.

This report presents and discusses techniques applied to investigate the problem and reports the results achieved. It was found that the damage of the capacitor bank was related to harmonic resonance due to high harmonic currents being generated by the company.

II. System configuration

Fig.1 shows equivalent representation of the power distribution network of the company. 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 2MVA, 33/0.433kV transformer at the station was represented with 6 % impedance. PQ load of the station are 390 kW and 547kvar respectively.

The PQ loads are mainly AC motors with variable speed drives. These drives are intermittently called into operation as the process demands. On the average, the 2MVA transformer is about 30% load with a maximum load of 630kVA. The drives are the only significant harmonic sources on the bus.

The capacitor bank contains six steps of varying kvars. Step1 and 3 are each 56kvar. The rest of the steps are each 112kvar. The combined kvars of the six steps is 560kvar. All of the kvar ratings are at 750V maximum voltage. None of the steps are configured as harmonic filters. Each of the steps is protected by a 160A current limiting fuse. The steps switch in and out of service automatically based on the power factor correction control algorithm in the bank.

III. Methodology

A. Power Quality Measurements

Megger power analyzer, model PA-9 Plus, was used for power quality measurements at the company. The power quality at the premises was monitored for a period of five days. The main electrical parameters tracked included power frequency, harmonics, transients and voltage fluctuations. From the power quality measurements, transient overvoltages were not found. Accordingly, our discussions on the electrical parameters were limited to power frequency, harmonics and voltage fluctuations.

B. Effect of power interruptions

Frequent power interruption was one of the factors the company cited as being responsible for the capacitor failure. As a result, effect of power interruption on the capacitor bank was examined. This was done by simulation using EMTP RV. The EMTP RV is an engineering software used for power system studies.

C. Outage statistics

The company reported that on the day the capacitor failed, six successive outages were recorded within a minute, followed by a loud explosion at their substation. To investigate this claim, statistical record of outage on the feeder serving the company was obtained and studied.

Manuscript received February 25, 2013; revised April 04, 2013. This work was supported in part by the Electricity Company of Ghana.

George Eduful is with the Electricity Company of Ghana, System Planning Division. P.O. Box AN 5278, Accra-North, Ghana. e-mail: eduful@ieee.org

Kivlyn N. Asante is with the Electricity Company of Ghana, System Planning Division. P.O. Box AN 5278, Accra-North, Ghana. e-mail: knaasante@engineer.com

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

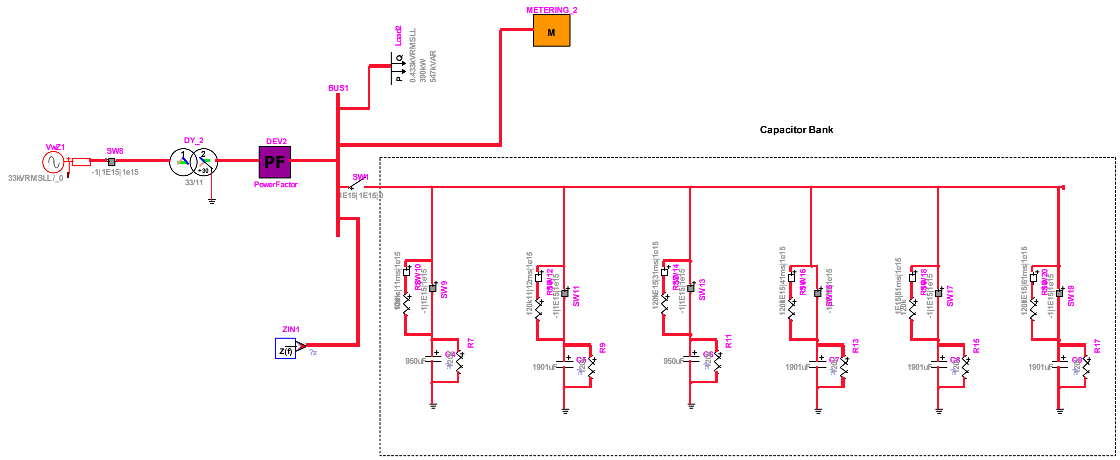


Fig.1: A single line diagram of the company's distribution network

IV. Results and Discussion

A. Voltage Fluctuation

Voltage limits are based on overall permissible voltage range allowable under standards. ECG operating voltage (in low voltage network) ranges from a maximum of 253V to a minimum of 207V. This is based on a nominal voltage of 230V representing ±10%. Fig.2 shows voltage envelope as measured by the analyzer. Operating voltage range of 235 to 242V was recorded. This represents a voltage variation of 2-5% in comparison to ECG nominal voltage. The variation was therefore within the acceptable operating voltage limits.

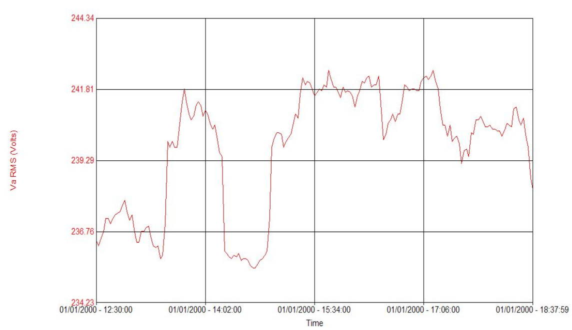


Fig.2: Voltage envelope as measured b the power analyze

B. Frequency

The term power frequency disturbance describes events that are slower and longer lasting compared to electrical transients. Power frequency disturbance can be harmful to electrical equipment [1]. The extent of damage varies from one piece of equipment to another and depends on the extent of the disturbance. One of the most common power frequency disturbances is voltage sag.

From Fig.3, frequency variation of about 0.5% was noted. Effect of this variation reflected as 2% voltage sag in Fig.2. The 2% voltage variation was within the tolerable and acceptable ECG operating voltage limit.

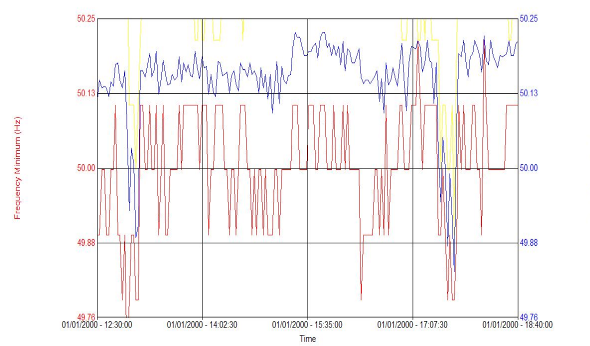
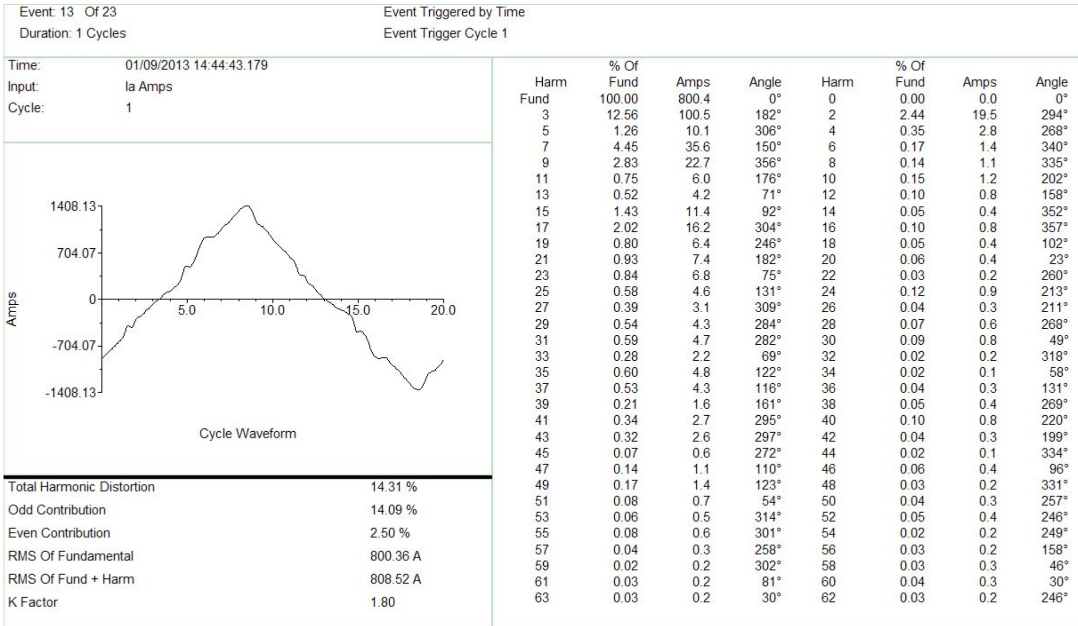


Fig.3: Frequency graph as measured

C. Harmonics

Harmonics is one of the possible causes of capacitor failures and fuse operations [2]. Measurements were performed to quantify the harmonic voltages and currents in the capacitors in order to study whether harmonics were the cause of the failures. Result of the harmonic measurement at full load of the company is shown in Fig.4

ISBN: 978-988-19252-8-2
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)


Event: 13 Of 23
Duration: 1 Cycles
Event Triggered by Time
Event Trigger Cycle 1

Time: 01/09/2013 14:44:43.179
Input: Ia Amps
Cycle: 1

Total Harmonic Distortion	14.31 %
Odd Contribution	14.09 %
Even Contribution	2.50 %
RMS Of Fundamental	800.36 A
RMS Of Fund + Harm	808.52 A
K Factor	1.80

Harm	% Of Fund	Amps	Angle	Harm	% Of Fund	Amps	Angle
Fund	100.00	800.4	0°	0	0.00	0.0	0°
3	12.56	100.5	182°	2	2.44	19.5	294°
5	1.26	10.1	306°	4	0.35	2.8	268°
7	4.45	35.6	150°	6	0.17	1.4	340°
9	2.83	22.7	356°	8	0.14	1.1	335°
11	0.75	6.0	176°	10	0.15	1.2	202°
13	0.52	4.2	71°	12	0.10	0.8	158°
15	1.43	11.4	92°	14	0.05	0.4	352°
17	2.02	16.2	304°	16	0.10	0.8	357°
19	0.80	6.4	246°	18	0.05	0.4	102°
21	0.93	7.4	182°	20	0.06	0.4	23°
23	0.84	6.8	75°	22	0.03	0.2	260°
25	0.58	4.6	131°	24	0.12	0.9	213°
27	0.39	3.1	309°	26	0.04	0.3	211°
29	0.54	4.3	284°	28	0.07	0.6	268°
31	0.59	4.7	282°	30	0.09	0.8	49°
33	0.28	2.2	69°	32	0.02	0.2	318°
35	0.60	4.8	122°	34	0.02	0.1	58°
37	0.53	4.3	116°	36	0.04	0.3	131°
39	0.21	1.6	161°	38	0.05	0.4	269°
41	0.34	2.7	295°	40	0.10	0.8	220°
43	0.32	2.6	297°	42	0.04	0.3	199°
45	0.07	0.6	272°	44	0.02	0.1	334°
47	0.14	1.1	110°	46	0.06	0.4	96°
49	0.17	1.4	123°	48	0.03	0.2	331°
51	0.08	0.7	54°	50	0.04	0.3	257°
53	0.06	0.5	314°	52	0.05	0.4	246°
55	0.08	0.6	301°	54	0.02	0.2	249°
57	0.04	0.3	258°	56	0.03	0.2	158°
59	0.02	0.2	302°	58	0.03	0.3	46°
61	0.03	0.2	81°	60	0.04	0.3	30°
63	0.03	0.2	30°	62	0.03	0.2	246°

Fig.4: Harmonic Measurement

At a secondary side of a transformer, resonant frequency of a network can be determined using the following relation [3]:

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

Where

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

Natural frequencies of the company's network at the respective steps of the capacitor bank were computed and have been reported in Table-1. As can be seen, the natural (resonant) frequency of the network changes with the steps of the capacitor bank.

	Step-1	Step-2	Step-3	Step-4	Step-5	Step-6
kvar	56	168	224	336	448	560
Resonant frequency	26	15	13	10	9	8
Measured Harmonic Current (A), refer to Fig.3						
	0	11.4	4.2	0	22.7	0

It can be seen that the network is switched into resonance with step 2, 3 and (or) 5 engaged. This is because the natural frequency of the network at these steps (hereafter referred to as resonant steps) coincides with 15th, 13th and 9th harmonic content of the network. Effect of the resonant steps on the capacitor bank was examined by simulation using the EMTP RV.

Simulation

Harmonic current of 11.4, 4.2 and 22.7A associated with 15, 13 and 9th harmonic order were in turn injected into the network. Voltage at the LV bus and current drawn by the respective steps were observed. The worst resonance occurred at engagement of step-5. However, effect of the resonance was more pronounced in the step-3 capacitor bank. As can be seen in Fig 5, current amplification of about 170% of the normal current was observed in step-3 capacitor bank. This was about 160A drawn by step 3 capacitor bank: just equal to the size of the associated protecting fuse. IEEE standard 18-2002 allows 135% of capacitor nominal load but this is intended for contingencies and not intended for normal continuous load. From this stand point, it could be clearly seen that the magnitude of the current amplification is destructive.

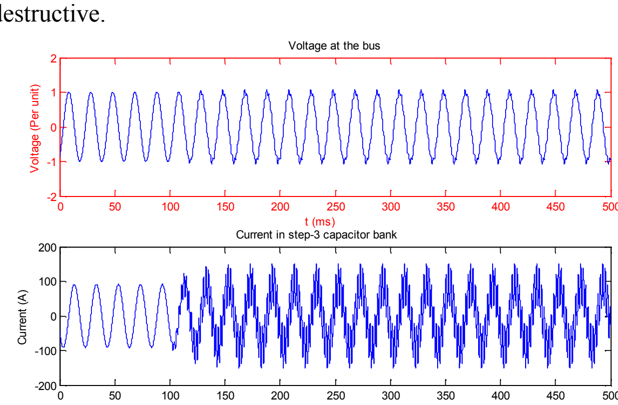


Fig.5: Voltage at bus-1 and current in step-3 capacitor bank

ISBN: 978-988-19252-8-2
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

It is important to note that normally fuse start fusing from 125 to 165% of it rated current [4]. Therefore, it was expected the 160A current limiting fuse of the capacitor bank should operate from 200 to 264A. This means the 160A fuse would not blow under the resonance condition. The capacitor will therefore, be expected to fail before the fuse blows.

Again, it is important to note that capacitor fuses are deliberately oversized to take care of capacitor switching transient and prevent excessive nuisance blow-outs [3]. Although the fuse may blow at certain resonance condition, capacitor fuses are not primarily sized to take care of resonance conditions. It is therefore important to measure and analyzed harmonic contents of an electrical installation and take preventive decision before installing a capacitor bank.

D. Power interruptions

Effect of power interruptions on the capacitor bank was examined. Overvoltage and inrush currents in the capacitor bank during restoration of power were studied. As can be seen in Fg.6, overvoltage induced from the power restoration was 1.5 per unit and this lasted for 1.8ms. IEEE standard 18-1992 and IEEE standard 1036-1992 allow overvoltage of 1.7 per unit for 1 second. It is obvious that the overvoltage induced by the power restoration was well within the standard safety limits and therefore, should have no effect on the capacitor bank.

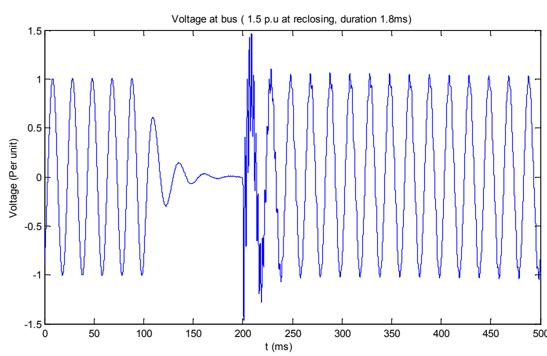


Fig.6: Overvoltage resulting from power restoration

Fig.7 shows inrush current drawn by step 2 and step 3 capacitor banks. Step 2 and step 3 give a representative result because they are made up of 112 and 56kvar respectively. Recall that each step in the bank is either 56kvar or 112kvar.

Inrush currents drawn by step 2 and step 3 capacitor banks were 1342A and 623A respectively. IEC 60871-1 standard establishes that the peak value of the overcurrent due to switching operations should be limited to a maximum of $100xI_N$ [5]. Where I_N is the rms value of nominal current. By this standard, the maximum inrush current limit for the 112kvar and 56kvar are 19600A and 9100A respectively. Consequently, it can be seen that the current drawn by the capacitors during the power restoration were far less compared with their maximum inrush current limits.

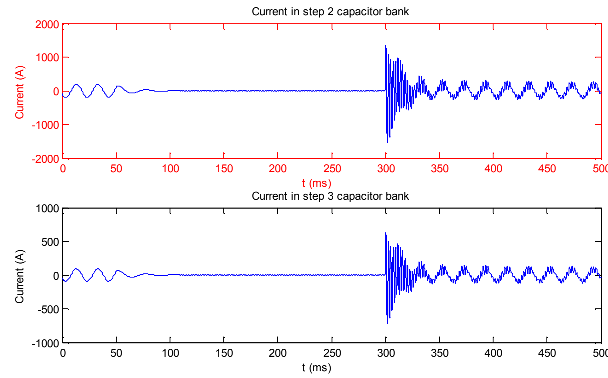


Fig.7: Inrush currents in the capacitor bank as a result of power restoration

V. Conclusion

1. It is not true that the capacitor bank got damaged from power fluctuation. Voltage operating envelope measured at the company's substation ranged between 2 to 5% of the nominal voltage.
2. Upon power restoration, transient overvoltage of 1.5 per unit occurred and lasted for 1.8ms. This overvoltage was within standard safety regulation.
3. No harmonic study was conducted before the capacitor bank was installed. The total harmonic distortion being produced by the company is 15%. This is at variance with ECG standard limit of 5% required from customers.
4. The capacitor got damage from harmonic resonance. This was caused by high harmonic current produced by a 9^{th} harmonic order.
5. From our analysis, it is obvious that the cause o the capacitor damage was self inflicted since harmonic studies were not carried out.

Reference

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

[2]. M. B. P. Thomas, "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,* 2005.

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

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

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

ISBN: 978-988-19252-8-2
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)