A CASE STUDY OF INDUCED CURRENT UNBALANCE AS A RESULT OF CAPACITOR FAILURE

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Abstract: Capacitor banks rated 132 kV/ 72 MVAr are installed at the Durban North Substation of Ethekwini municipality to compensate for inductive power losses. The POW or synchronous switching technique is used for on-line switching of these banks, in a bid to minimise high magnitude induced transient voltage and current. in this study, the voltage waveform records and the percentage current unbalance, measured on and six months post commissioning of the capacitor banks are analysed in order to test the effectiveness of POW switching method, when implemented with mechanically linked 3-phase, 3-pole SF_6 circuit breakers. The results obtained indicate that within 6 months of commissioning, capacitive impedance of the banks failed, as result of high magnitude induced transient current and voltage, and the percentage unbalance level observed in the neutral current grew from 2.3% to 5.7%.

Key words: Point on wave switching, capacitor bank, transient voltage, current unbalance, SF_6 circuit breakers.

1. INTRODUCTION

Capacitor banks are commonly used in electrical networks to provide leading reactive power [1]. This practice is fundamentally intended to provide compensation for inductive losses in order to improve the load system power factor, and thus to stabilise the bus voltage [2-3]. These units are automatically or manually switched on line during peak inductive load time. The continuous on and off switching of capacitor banks usually induces high magnitude transient current and voltage [4]. The point on wave (POW) switching technique, whereby capacitor banks are switched on line at or near zero crossing of the supply voltage waveform, is commonly applied for successful mitigation of induced switching transients.

In this case study, high voltage capacitor banks with POW on-line switching, installed at the Durban North substation of Ethekwini municipality, are tested to be aggravating current unbalance six months after commissioning. Voltage and current measurement records obtained on and after commissioning of capacitor banks at the substation are analysed. The results indicate that a shift on the mechanically linked 3-pole circuit breaker causes transient voltage to be induced, which in turn cause capacitor cans to fail and thus creating current unbalance in the system.

2. DESCRIPTION OF THE CAPACITOR BANKS

The capacitors connected at the Durban North Substation consist of 132 kV/ 72 MVAr banks. Each capacitor bank is made up of 216 capacitor units or cans. The on-line switching is POW based. This is basically achieved using a 3-phase, 3-pole circuit breaker having a mechanical link staggered to satisfy 120 electrical degrees. The switching sequence is ideally meant to synchronise with the zero crossing instants of the 3-phase supply voltage. Therefore, considering the mechanical link as the horizontal axis, the first or reference pole is positioned at 27 degrees, while the second and the third ones are positioned at 88 degrees and 52 degrees of the horizontal axis, respectively. This setting ensures that all poles, and therefore capacitor banks are switched on line at zero crossing of the voltage waveform. The 3-pole SF_6 circuit breakers are used in this case study. Figure 1 depicts ideal POW or synchronous switching technique.

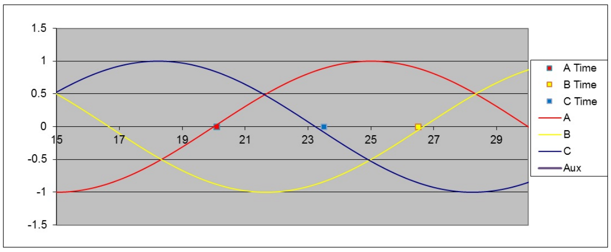

Figure 1: Ideal point on wave switching technique

For the purpose of dampening the switching transient, some value of inductance and resistance are present in the switching circuitry of capacitor banks. therefore, 0.6 mH inductor and 10 Ω resistor are measured. The complete capacitor bank to be connected on each line is shown in figure 2. To monitor the level of current unbalance, the neutral current is constantly measured using a current transformer (CT) and an unbalance relay. The CT transforms the measured neutral current (I_n) to a lower

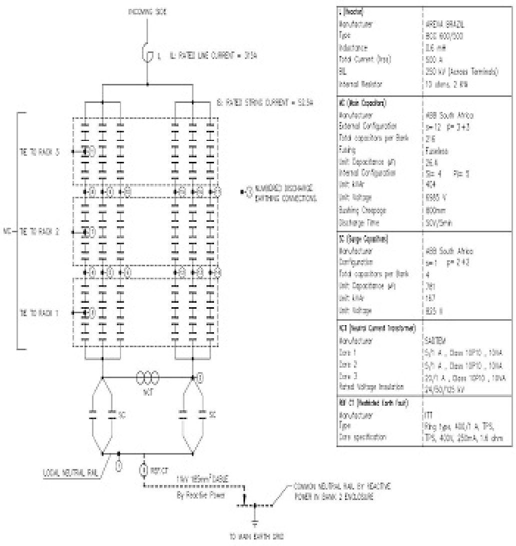

Figure 2: Line capacitor bank

scale, which is fed to the unbalance relay.

3. POINT ON WAVE SWITCHING AND CURRENT UNBALANCE

The POW switching of circuit breakers is mainly dependant on the breaker switch contact velocity, the time difference between contact closing and the breaking of the dielectric strength of the contacts' gap as a result of the applied voltage [5]. This could be expressed in terms of the following relationship:

$$\frac{U_m}{\sqrt{2}}\angle\phi = E\cdot v\cdot(t_s - t_b) \qquad (1)$$

Where:

$\frac{U_m}{\sqrt{2}}$ = rms value of phase voltage
ϕ = phase angle
v = switch contact velocity
E = dielectric strength of the contact gap
t_s = breaker's contact closing time
t_b = time to overcome the dielectric strength of the contact gap

Successful implementation of this technique therefore requires the following conditions to be met:

1. The time difference $(t_s - t_b)$ must be less than 5 electrical degrees: $(t_s - t_b) \leq 5$ electrical degrees

2. The switching phase voltage must be less or equal than the product of the dielectric strength and the velocity of the contacts: $E\cdot v \geq \frac{U_m}{\sqrt{2}}\angle\phi$

For the purpose of this study, the contacts of the SF_6 circuit breakers are mechanically linked and actuated upon reception of a closing command from a switching relay. The shift of the breaker's poles observed in this case study is shown in figure 4. This therefore results in transient voltages and current being induced, as well as steady state current and voltage unbalance in the system.

$$i(t) = \frac{u(t) - u(0)}{\sqrt{\frac{L_s}{C}}}\cdot sin\omega_o t \qquad (2)$$

Where:

$i(t)$ = instantaneous transient current
$u(t)$ = instantaneous transient voltage
$u(0)$ = instantaneous transient voltage when t=0
L_s= system inductance
C = capacitance of the bank
ω_o = $\sqrt{1/L_sC}$

Under steady state conditions, aggravated current unbalance is likely to emerge as an immediate consequence of transient voltage and current in this case study. Line or phase current unbalance occurs when the magnitude of line or phase currents becomes unequal as a result of change in the load phase impedance [6]. This results in the presence of negative and zero sequence in the system current. The percentage current unbalance factor (IUF) could be estimated using the ratio of the negative sequence to that of the positive components, given in equation 3:

$$IUF = \frac{I_2}{I_1} = \frac{I_R + a^2I_Y + aI_B}{I_R + aI_Y + a^2I_B}\times 100 \qquad (3)$$

Where:

I_2 = negative sequence component of the neutral current
I_1 = positive sequence component of the neutral current
I_R = rms magnitude of current in the red phase
I_Y = rms magnitude of current in the white phase
I_B = rms magnitude of current in the blue phase
a = $1\angle 120°$
a^2 = $1\angle 240°$

The neutral current (I_n) could therefore be expressed as follows:

$$I_n = 3I_0 + \left(1 + a^2 + a\right)I_1 + \left(1 + a + a^2\right)I_2 \qquad (4)$$

The unbalance relay monitors the degree of current unbalance on the basis of the percentage IUF in the neutral current. Under tolerable unbalanced current condition, generally related to load imperfection, the percentage IUF should not exceed 5 % [7]. Therefore, the settings of the unbalance relay in this case study could be summarised as follows:

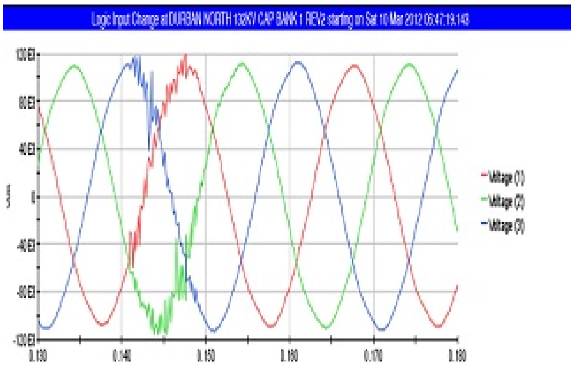

Figure 3: Transient voltage six months after commissioning

1. Unbalance relay trip conditon: $IUF\{I_n\} > 5$ %
2. Unbalance relay restrain condition: $IUF\{I_n\} < 5\%$

The implementation of these relay setting conditions, on and after commissioning of the capacitor banks, are shown in figures 5 and 6, respectively.

4. RESULTS AND DISCUSSION

The voltage waveforms recorded six months after commissioning show the existence of transients in all the phases upon line switching of capacitor banks. This is shown in figure 3.

Since the presence of transients implies that the POW switching principle is either not or inadequately implemented, The switching positions or the closing positions of the 3-pole SF_6 circuit breakers are compared on and after commissioning. This reveals a position shift of about 15 or more electrical degrees (green arrow) from the initial position. This theoretically implies that the time difference $(t_s - t_b)$, which in fact is the arcing time, has become too long than required, and thus causing the switching to take place beyond zero crossing. This is the basis of the transients induced in the waveform. Therefore, the transients observed in the voltage waveforms could be attributed to the displacement of the mechanical linkage between the circuit breaker poles, indicated in figure 4.

The neutral current measured after commissioning proved to have higher unbalance factor as compared to initial measurement. The results obtained are shown in figures 5 and 6. This relates to the fact that almost no transient voltage and current are induced on commissioning as compared to higher magnitude induced six months post commissioning of the capacitor banks.

The increase in the level of unbalance in the neutral current is a direct consequence of aggravated change in the impedance of capacitor banks, which are triggered by induced switching transients. This is indeed proven by testing the capacitance of the bank. This testing revealed

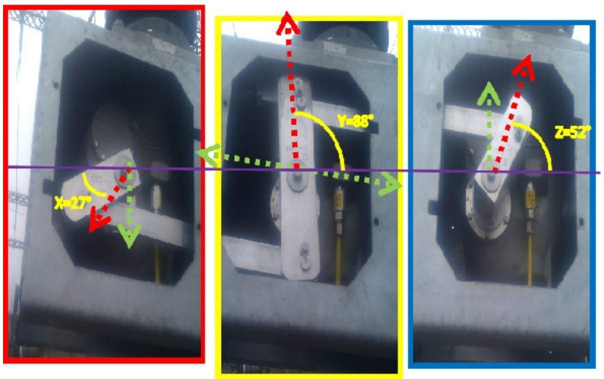

Figure 4: Shift of the mechanical linkage of the 3-pole circuit breakers

Figure 5: Current unbalance level on commissioning

Figure 6: Current unbalance level after commissioning

that seven capacitor units of the bank had failed due to resulting high magnitude transient voltage and current. Capacitor units failure occur as a result of increasingly high frequency voltage and current transient. This inrush amount of transient energy has the effect of causing the electrodes of the capacitor unit to short circuit. Since, the transient state lasts only for a few cycles, the resulting steady state overall capacitance and capacitive impedance of the capacitor bank will therefore be compromised. This implies therefore aggravated unequal current and voltage distribution across the phases. The level of unbalance measured in the neutral current in this study, happens to be 5.7% six months post commissioning, against 2.3% on commissioning of the capacitor banks.

It is worth noting that the root cause of induced transient voltage and current as well as current unbalance is the shift of the mechanical linkage between the poles of the circuit breaker.

5. CONCLUSION

The effectiveness of POW switching using mechanically linked 3-phase, 3-pole circuit breakers, for the purpose of transient voltage and current mitigation, when capacitor banks are switched on-line, is analysed in this case study. The voltage waveforms recorded and the level of unbalance measured in the neutral current, six months after commissioning, point to the following:

1. The transient voltage and current induced result from the shift of the mechanical link. This causes switching to take place beyond zero crossing.
2. The inrush transient energy into the bank is likely to damage capacitor units.
3. The increase in the neutral current unbalance level could be seen as the steady-state consequence of the damage effected on the bank as a result of high magnitude transient voltage and current.
4. The magnitude of the resulting transient current is dependent on the initial conditions of the contacts of the breakers.

These observations indicate that POW switching of capacitor banks using mechanically linked 3-phase, 3-pole SF_6 circuit breakers, is prone to induce transient current and voltage which in turn aggravate current unbalance resulting from capacitance failure in the bank. The fundamental source of these problems remains the shift of the linkage between the breakers which tends to occur in a very short period of time, and thus making this technique non effective.

Recent Developments in this field of study tend to promote electronic based POW switching technique of capacitor banks.

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