International Journal of
Advances in Scientific Research and Engineering (ijasre)

E-ISSN : 2454-8006

DOI: http://dx.doi.org/10.7324/IJASRE.2018.32630

Volume 4, Issue 3
March - 2018

Determination of Fault Location in Shunt Capacitor Bank through Compensated Neutral Current

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ABSTRACT

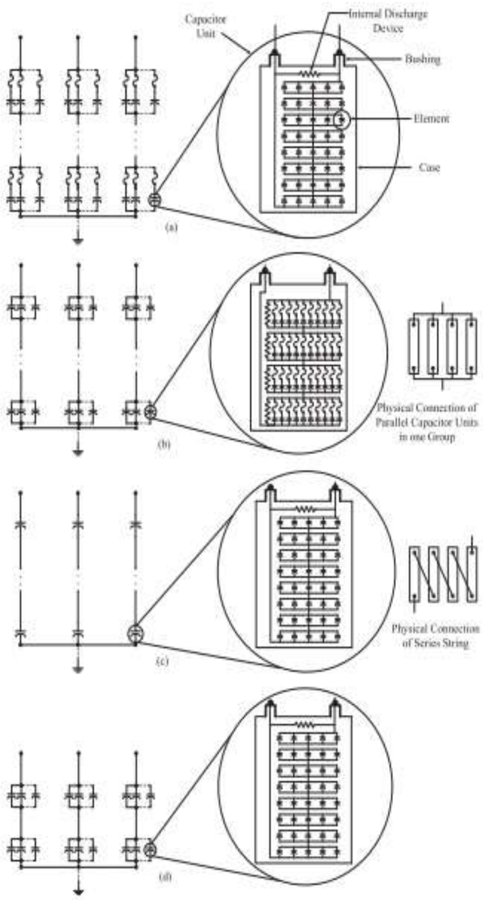
Shunt capacitor bank in power transmission are essential in providing reactive power support and improvement of voltage profile at any required point within the grid system. The failure of shunt capacitor bank due to unbalance capacitance caused reactive power and voltage losses to the power transmission network. The time taken to identify the location of capacitance failure require a lot of time due to no physical indication failure in shunt capacitor bank. This paper is focused on investigating the fault location in shunt capacitor bank in high voltage system mainly at power system transmission through compensated neutral current method. The investigation is focused on the internal failure of capacitor unit in shunt capacitor bank which caused by capacitance element failure. The configuration of shunt capacitor bank applied in this research used the common type of configuration which is ungrounded double wye connection and internally fused type of capacitor unit. This type of shunt capacitor bank configuration will affect the development of mathematical modelling as the algorithm for identifying the location and number of element failure in shunt capacitor bank. The investigation is done by developing the mathematical modelling and simulation through MATLAB software for neutral current at the neutral point of shunt capacitor bank. The output results of neutral current are used to determine and identify the location and number of element failure in shunt capacitor bank. Through neutral current result, the angle of neutral current is compared with corresponding or equivalent phase current to determine the faulty section thus determine the location of element failure in shunt capacitor bank. The ratio between neutral current and equivalent phase current will determine the number and type of element failure occurred in a section of shunt capacitor bank. The comprehensive analysis was done to determine the relationship between number and type of element failure to the number and type of faulty capacitor unit in shunt capacitor bank.

Key Words: *Shunt capacitor bank, Ungrounded double wye, Internally fused, Element failure, Neutral current.*

1. INTRODUCTION

Shunt capacitor bank in power system transmission played an important role in electrical utilities and industries especially for reactive power support and voltage profile improvement in power system network. Shunt capacitor bank was the preferred option as reactive power support in power system due its more economical and faster installation, and able to install nearly any location in transmission grid substation [1]. Shunt capacitor bank in high voltage system mostly constructed in single or double wye connection, H-bridge connection and each unit of capacitors in capacitor bank were arranged in series or parallel connection in order to achieve desired voltage and reactive power (Var) rating [1]. The capacitor unit itself was designed with externally or internally fused, fuseless, or unfused capacitor unit as shown in Figure 1. Shunt capacitor bank also can be configured as ungrounded wye or grounded wye configuration. Normally shunt capacitor bank have its own protection schemes to isolate the capacitor bank from the power system due to faulty of capacitor unit. This protection scheme known as unbalance protection. The unbalance protection for shunt capacitor bank commonly divided into several methods by depending on current or voltage measurements, which are unbalance protection for ungrounded with single wye banks connection, ungrounded with double wye banks connection, grounded with single wye banks connection and grounded with double wye banks connection [2].

Finding and locating the defected of faulty capacitor unit due to element failure during shunt capacitor bank tripping or breakdown at 132 kV high voltage power transmission substation which mainly focus on 132 kV power system network became a major problem when the faulty capacitor unit do not indicate any sign of visual or physical failure such as oil leakage at the capacitor bushing or burn marks due to capacitor element failure. Due to unknown estimated location of faulty capacitor unit, all the capacitor units in the shunt capacitor bank need to be measured in terms of capacitance value in order to make sure all the capacitance meet the rated value and shunt capacitor bank still in balance system. Measurement of capacitance value for each capacitor unit in shunt capacitor bank will take longer time which at least a day if the weather in good condition. This is because the capacitor bank is the outdoor type located in air insulated switchgear (AIS) substation and have average a hundred units of capacitor to be measured. This type of shunt capacitor banks used series and parallel combination connection of capacitor units with ungrounded and double wye connection which consisted of six section of capacitor banks. Each of the capacitor unit in this shunt capacitor bank used internally fused design. Each section was symmetrical to other section which consisted of 18 capacitor units. For average 20 hours of outage or shutdown time taken considered with good weather, 60% of 20 hours which are total 12 hours have been used to measure the capacitance value of each capacitor unit in order to locate the faulty capacitor unit, and with the average 2 hour have been used to measure each section of capacitor bank. If the location of faulty capacitor unit able to be estimated at least which section, average 10 hours could be saved which reduce 50% of outage or shutdown time. The delayed outage or shutdown time due to time taken to locate the faulty capacitor unit will affect the functionality and reliability of shunt capacitor bank for reactive power support and voltage improvement purpose.



i. Externally fused capacitor unit

ii. Internally fused capacitor unit

iii. Fuseless capacitor unit

iv. Unfused capacitor unit

Figure 1: Type of capacitor unit.

Currently, unbalance protection for double wye shunt capacitor bank connection with ungrounded used two types of methods which are the measurement of unbalance neutral current or unbalance neutral voltage. This unbalance protection scheme are required to protect the shunt capacitor bank from faults occurred inside the capacitor bank. These faults mainly occurred due to faulty capacitor elements in the capacitor unit. The detection of this unbalance protection was based on the differences of neutral current or voltage. Previous research [1,9] shows that neutral voltage unbalance protection for ungrounded double wye shunt capacitor bank configuration was limited to identify the phase of the capacitor bank only but cannot identify the section where the fault occurred in shunt capacitor bank. Since neutral current unbalance protection was the most common unbalance protection used for double wye shunt capacitor bank [9] and it also been used for the existing shunt capacitor bank that have been studied, it will much easier to focus instead make a recommendation to new unbalance protection installation which require a cost.

Previous research had use Real Time Digital Power System Simulation (RTDS) software to study the unbalance current through output from neutral and also phase angle position of unbalance current [2]. From the simulation, it will able to locate the faulty capacitor unit at possible phase. The capacitor unit used was fuseless type which element in the capacitor unit will consider failed when the element was shorted.

The objectives of this research are to simulate and verify detection technique by using compensated neutral current method to identify the location and number of faulty capacitor unit due to element failure in shunt capacitor bank at 132 kV power transmission system. Thus, able to minimize the outage or shutdown time due to shunt capacitor bank breakdown caused by unbalance capacitance value.

2. METHODOLOGY

The compensated neutral current in shunt capacitor bank was derived through the output measurement of neutral current at neutral point of shunt capacitor bank with ungrounded double wye. The shunt capacitor bank also assumed to be symmetrical of each section of shunt capacitor bank.

2.1 Proposed Fault Location Algorithm

The derivation of neutral current unbalance protection method was shown in Figure 2. By referred to left section of shunt capacitor bank, the measured neutral current using Kirchhoff's Current Law:

$$I_N = I_{la} + I_{lb} + I_{lc} \tag{1}$$

And by applied current division method in equation (1):

$$I_N = \frac{Z_{ra}}{Z_{ra}+Z_{la}} I_A + \frac{Z_{rb}}{Z_{rb}+Z_{lb}} I_B + \frac{Z_{rc}}{Z_{rc}+Z_{lc}} I_C \tag{2}$$

The impedances value in equation (2) was converted into capacitive reactance:

$$I_N = \frac{X_{ra}}{X_{ra}+X_{la}} I_A + \frac{X_{rb}}{X_{rb}+X_{lb}} I_B + \frac{X_{rb}}{X_{rb}+X_{lb}} I_C \tag{3}$$

Then the measured neutral current equal to:

$$I_N = K_A I_A + K_B I_B + K_C I_C \tag{4}$$

Where the K factor of compensated neutral current:

$$K_\phi = \frac{X_{r\phi}}{X_{r\phi}+X_{l\phi}}, \quad \phi\text{: phase A, B or C.} \tag{5}$$

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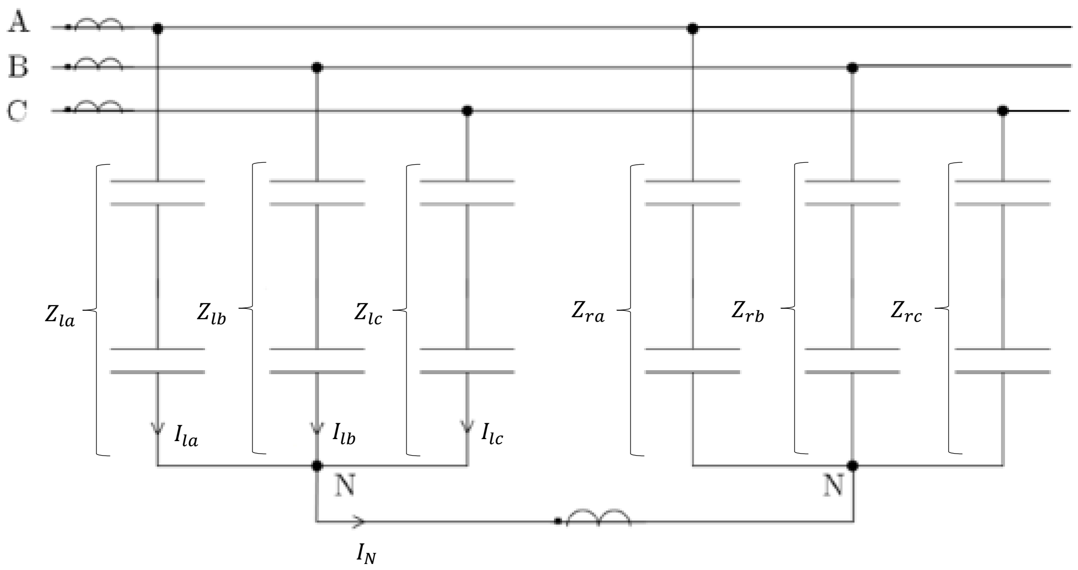

Figure 2: Ungrounded double wye shunt capacitor bank with neutral current unbalance protection.

Assumed there was element failure at left section of phase A, which cause changes value of reactance, X_{la} noted as X_{laF}. The X_{laF} produce new K factor for phase A noted as K_{AF}:

$$K_{AF} = \frac{X_{ra}}{X_{ra} + X_{laF}} \quad (6)$$

Then the new neutral current equation after element failure:

$$I_{NF} = K_{AF}I_A + K_BI_B + K_CI_C \quad (7)$$

Thus, the resulted compensated neutral current:

$$I_{Ncomp} = I_{NF} - I_N \quad (8)$$

$$I_{Ncomp} = I_A(K_{AF} - K_A) \quad (9)$$

And by substitute equation (5) and (6) into equation (9):

$$I_{Ncomp} = I_AX_{ra}(\frac{X_{la} - X_{laF}}{(X_{ra} + X_{laF})(X_{ra} + X_{la})}) \quad (10)$$

For symmetrical double wye shunt capacitor bank, the impedances or reactance of left section were equal to the right section of shunt capacitor bank during balance or non-fault condition, where:

$$X_{la} = X_{ra} \quad (11)$$

The simplified equation of compensated neutral current:

$$I_{Ncomp} = \frac{I_A}{2}(\frac{X_{ra} - X_{laF}}{X_{ra} + X_{laF}}) \quad (12)$$

Due all the reactance used same frequency, the equation (12) can be expressed in capacitance value which provide the final equation of compensated neutral current for elemeent failure at left section phase A:

$$I_{Ncomp} = \frac{I_A}{2}\left(\frac{C_{laF} - C_{ra}}{C_{laF} + C_{ra}}\right) \quad (13)$$

The element failure in the capacitor unit for internally fused type causes the fuse that connected to the failed element blown [3]. This cause open circuit to the failed element and reduced the total capacitance of capacitor unit. From compensated neutral current final equation, the equation of capacitance value:

$$\frac{C_{laF} - C_{ra}}{C_{laF} + C_{ra}} = \text{Negative (-) value sign indication} \quad (14)$$

The result phase angles of compensated neutral current from equation (14) indicate negative value which show the phase angles of compensated neutral current will be out of phase compared to the phase A current:

$$\angle I_{Ncomp} = -\angle I_A \tag{15}$$

Similar to right phase A, the element failure causes changes value of reactance, X_{ra} noted as X_{raF}. The X_{raF} produce new K factor for phase A noted as K_{AF}:

$$K_{AF} = \frac{X_{raF}}{X_{raF} + X_{la}} \tag{16}$$

With similar derivation, final equation of compensated neutral current for elemeent failure at right section phase A:

$$I_{Ncomp} = \frac{I_A}{2}\left(\frac{C_{la} - C_{raF}}{C_{la} + C_{raF}}\right) \tag{17}$$

As the failed element cause the total capacitance of capacitor unit to reduce, the equation of capacitance from equation (17):

$$\frac{C_{la} - C_{raF}}{C_{la} + C_{raF}} = \text{Positive (+) value sign indication} \tag{18}$$

The result phase angles of compensated neutral current from equation (18) indicate positive value which show the phase angles of compensated neutral current will be in phase compared with phase A current:

$$\angle I_{Ncomp} = +\angle I_A \tag{19}$$

The derivation of compensated neutral current at left and right section phase A after element failure also applicable to other phases.

2.1 Determination for Number of Capacitance Element Failure in Shunt Capacitor Bank

The previous equation (13) was applied when there is an element failure at left section phase A of shunt capacitor bank. From this equation, the result of compensated neutral current value was depended to the value of equivalent phase current. However, the phase current flow through shunt capacitor bank may varies and not consistent due to loading system in power system transmission network. By taking the value of equivalent phase current alone may cause difficulties to determine number of element failure in shunt capacitor bank. To solve this problem, the estimation number of element failure in shunt capacitor bank were able to determine by taking the ratio value between compensated neutral current with the equivalent phase current. By referred to equation (13), the ratio of compensated neutral current to the equivalent phase current at left section phase A:

$$\frac{I_{Ncomp}}{I_A} = \frac{1}{2}\left(\frac{C_{laF} - C_{ra}}{C_{laF} + C_{ra}}\right) \tag{20}$$

Then for element failure at right section phase A as referred to the equation (17):

$$\frac{I_{Ncomp}}{I_A} = \frac{1}{2}\left(\frac{C_{la} - C_{raF}}{C_{la} + C_{raF}}\right) \tag{21}$$

Similar for element failure at other phases, where the element failure at left section for each phase:

$$\frac{I_{Ncomp}}{I_\phi} = \frac{1}{2}\left(\frac{C_{l\phi F} - C_{r\phi}}{C_{l\phi F} + C_{r\phi}}\right), \ \phi\text{: phase A, B or C.} \tag{22}$$

And for element failure at right section for each phase:

$$\frac{I_{Ncomp}}{I_\phi} = \frac{1}{2}\left(\frac{C_{l\phi} - C_{r\phi F}}{C_{l\phi} + C_{r\phi F}}\right), \ \phi\text{: phase A, B or C.} \tag{23}$$

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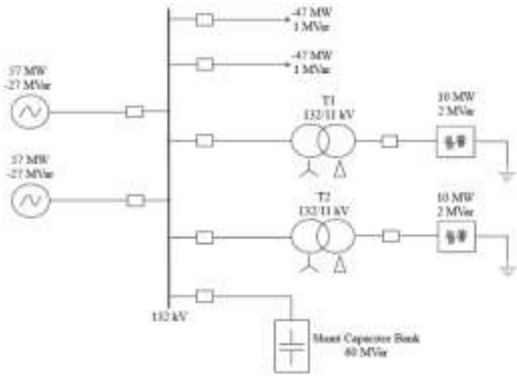
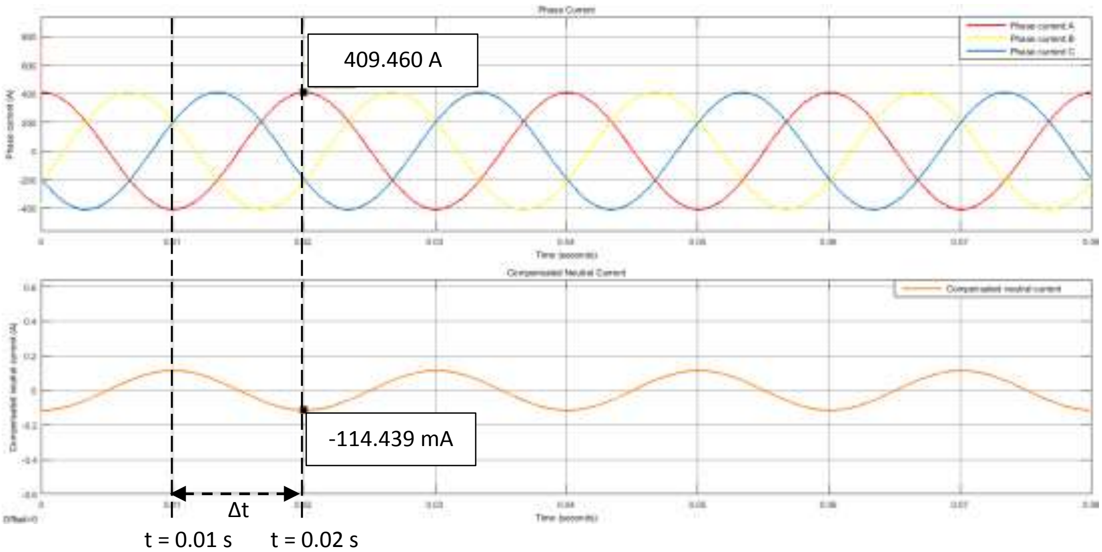


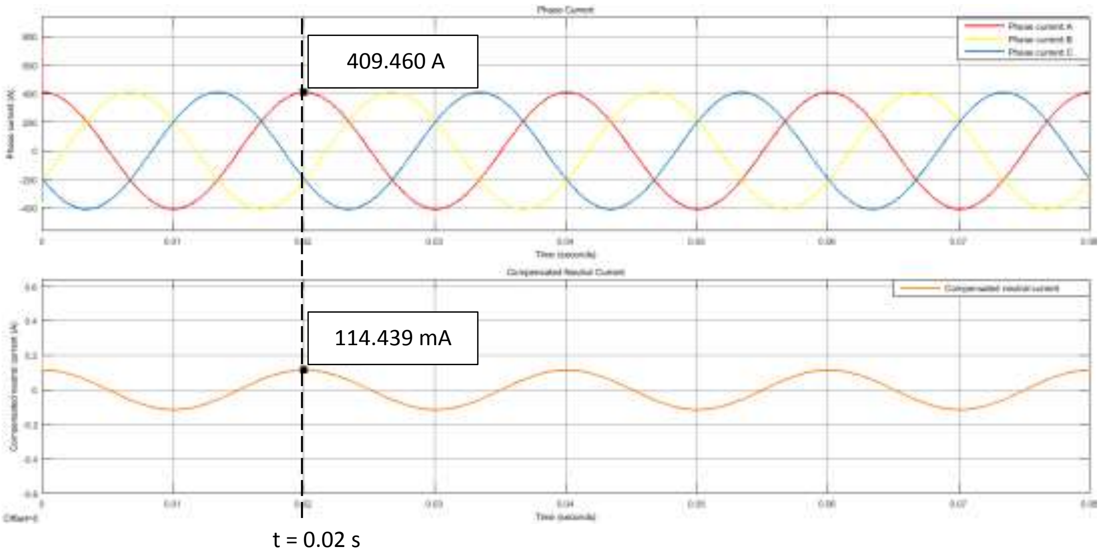
Figure 3: Modelled power system for shunt capacitor bank at 132 kV transmission substation.

3. RESULT AND DISCUSSION

The result of compensated neutral current (I_{Ncomp}) measurement compared with phase current (I_{ϕ}) after single element failure occurred at phase A in shunt capacitor bank were shown in Figure 4.



i) Single element failure at left section phase A



ii) Single element failure at right section phase A

Figure 4: Result of I_{Ncomp} compared to I_{ϕ} after single element failure at phase A.

In Figure 4, the occurrence of single element failure at phase A cause the existence value of I_{Ncomp} which indicate the unbalance current was existed due to unbalance impedance in shunt capacitor bank. For element failure at left section phase A, the angle of I_{Ncomp} was out of phase compared to phase current A (I_A) with angle difference 180^0 while the element failure at right section phase A cause the angle of I_{Ncomp} in phase with I_A. The ratio of compensated neutral current to phase current A ($\frac{I_{Ncomp}}{I_A}$) can be determined by taking the sample value of I_{Ncomp} and I_A at t = 0.02 s. Then by using equation (20) and (21):

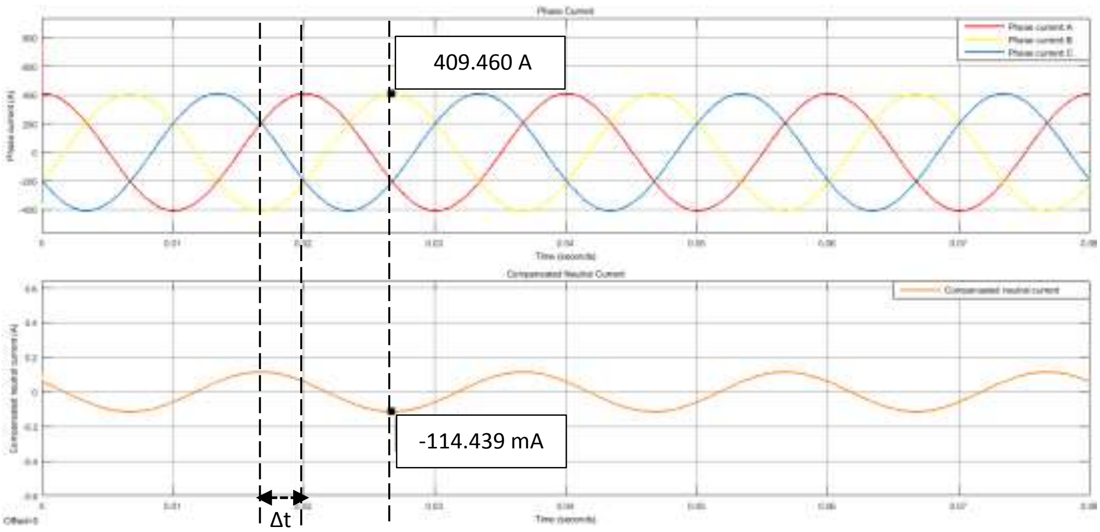
i) Left section phase A (Figure 4.i):

$$\frac{I_{Ncomp}}{I_A} = \frac{-114.439x10^{-3}}{409.460} = -0.2795\,x10^{-3} \tag{24}$$

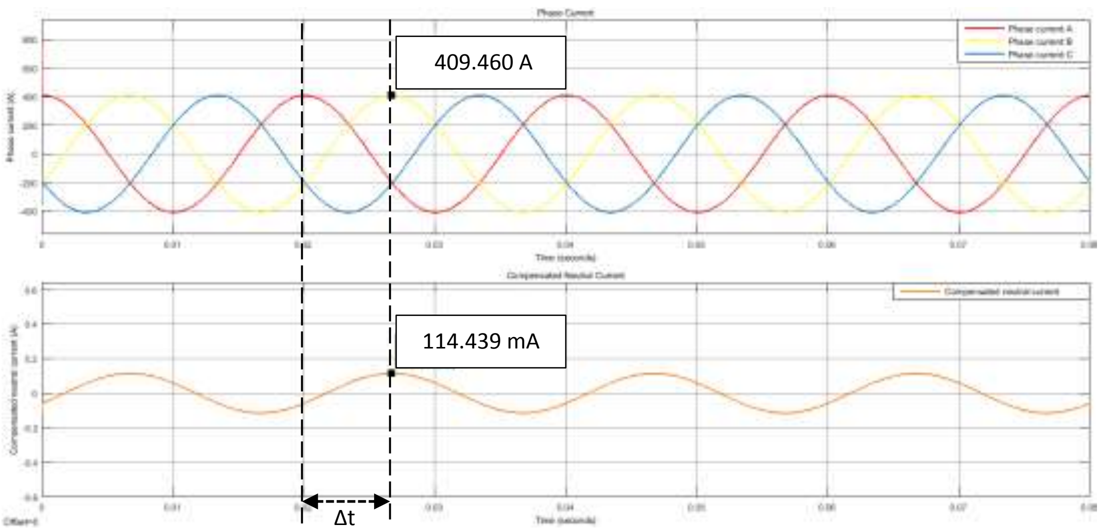
ii) Right section phase A (Figure 4.ii):

$$\frac{I_{Ncomp}}{I_A} = \frac{114.439x10^{-3}}{409.460} = 0.2795\,x10^{-3} \tag{25}$$

The negative or positive value in equation (24) and (25) provide indication for section location in a phase A. The result of I_{Ncomp} after single element failure at other phases were shown in Figure 5.



i) Single element failure at left section phase B



ii) Single element failure at right section phase B

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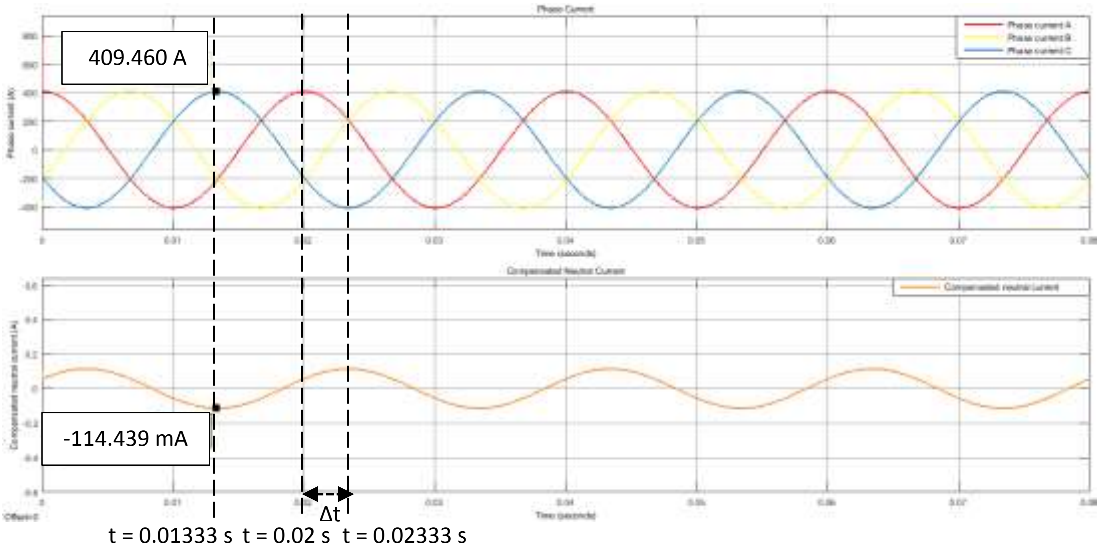
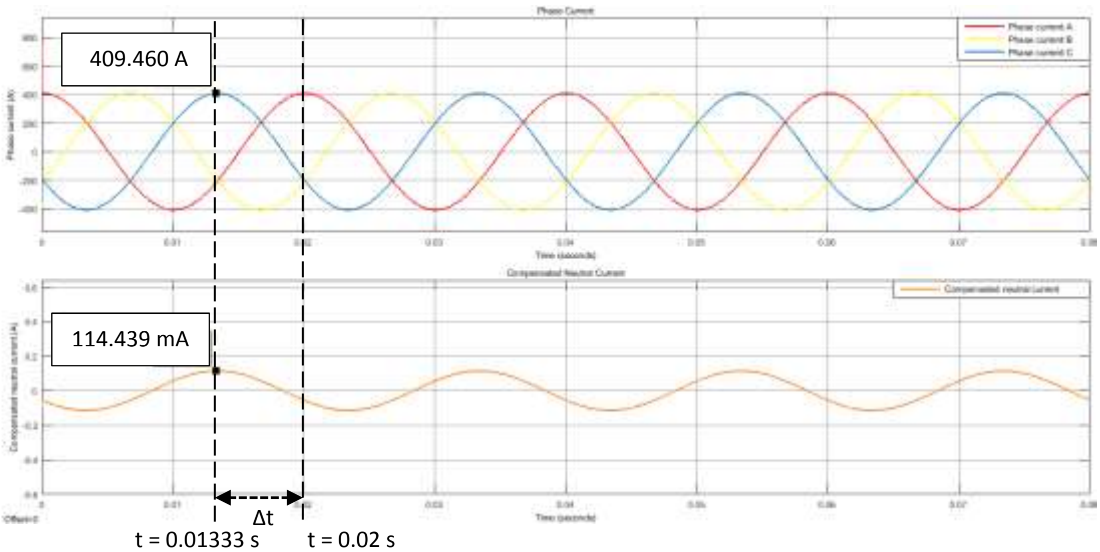


iii) Single element failure at left section phase C



iv) Single element failure at right section phase C

Figure 5: Result of I_{Ncomp} compared to I_{ϕ} after single element failure at phase B and C.

The result of I_{Ncomp} in Figure 5 also shows that the angle of I_{Ncomp} always out of phase or in phase with the equivalent I_{ϕ} depended on the location of element failure in shunt capacitor bank. As this research used positive sequence current, the result of I_{Ncomp} due to element failure at left section phase B or C always have angle difference of 60^0 compared to I_A as shown in equation (27) and (29):

i) Angle of I_{Ncomp} due to element failure at left section phase B compared to I_A (Figure 5.i):

$$\angle I_{Ncomp} = \frac{\Delta t}{T}.360^0 = \frac{0.02-0.01667}{1/50}.360^0 \tag{26}$$

$$\angle I_{Ncomp} = \frac{3.33x10^{-3}}{0.02}.360^0 \approx 60^0 \tag{27}$$

ii) Angle of I_{Ncomp} due to element failure at left section phase C compared to I_A (Figure 5.iii):

$$\angle I_{Ncomp} = \frac{\Delta t}{T}.360^0 = \frac{0.02-0.02333}{1/50}.360^0 \tag{28}$$

$$\angle I_{Ncomp} = \frac{-3.33x10^{-3}}{0.02}.360^0 \approx -60^0 \tag{29}$$

The positive or negative value of 60^0 indicate that the I_{Ncomp} was leading or lagging I_A with 60^0. For element failure at right section phase B or C, the result of I_{Ncomp} always have angle difference of 120^0 compared to I_A as shown in equation (4.8) and (4.10):

iii) Angle of I_{Ncomp} due to element failure at right section phase B compared to I_A (Figure 5.ii):

$$\angle I_{Ncomp} = \frac{\Delta t}{T}.360^0 = \frac{0.02-0.02667}{1/50}.360^0 \quad (30)$$

$$\angle I_{Ncomp} = \frac{-6.67x10^{-3}}{0.02}.360^0 \approx -120^0 \quad (31)$$

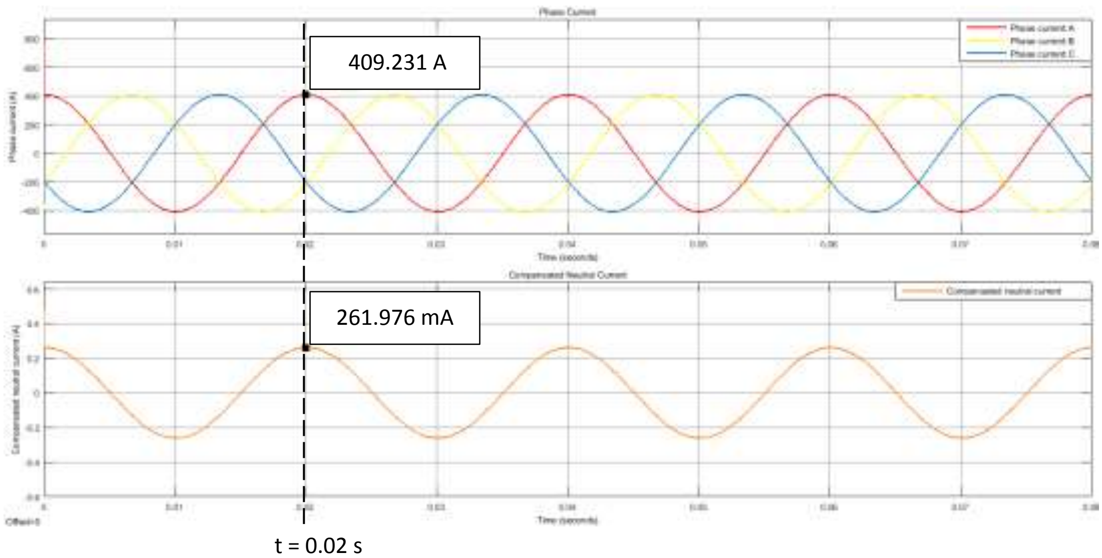
iv) Angle of I_{Ncomp} due to element failure at left section phase C compared to I_A (Figure 5.iv):

$$\angle I_{Ncomp} = \frac{\Delta t}{T}.360^0 = \frac{0.02-0.01333}{1/50}.360^0 \quad (32)$$

$$\angle I_{Ncomp} = \frac{6.67x10^{-3}}{0.02}.360^0 \approx 120^0 \quad (33)$$

The positive or negative value of 120^0 indicate that the I_{Ncomp} was leading or lagging I_A with 120^0. Hence, the result in Figure 4 and 5 proved the phase angle relationship between I_{Ncomp} and equivalent I_ϕ for each phase and sections after element failure for capacitor unit with internally fused type. The $\frac{I_{Ncomp}}{I_\phi}$ also equal to the value of equation (24) and (25) which are $-0.2795\ x10^{-3}$ and $0.2795\ x10^{-3}$ for left and right section since it has same magnitude value of I_{Ncomp} and equivalent I_ϕ after single element failure in shunt capacitor bank.

The increased of element failure in single group of parallel elements in a capacitor unit cause higher value of $\frac{I_{Ncomp}}{I_\phi}$. Figure 6 shows the result of I_{Ncomp} with increased value of element failure in single group of parallel elements in a capacitor unit.



i) 2 element failures in single group of parallel elements in a capacitor unit

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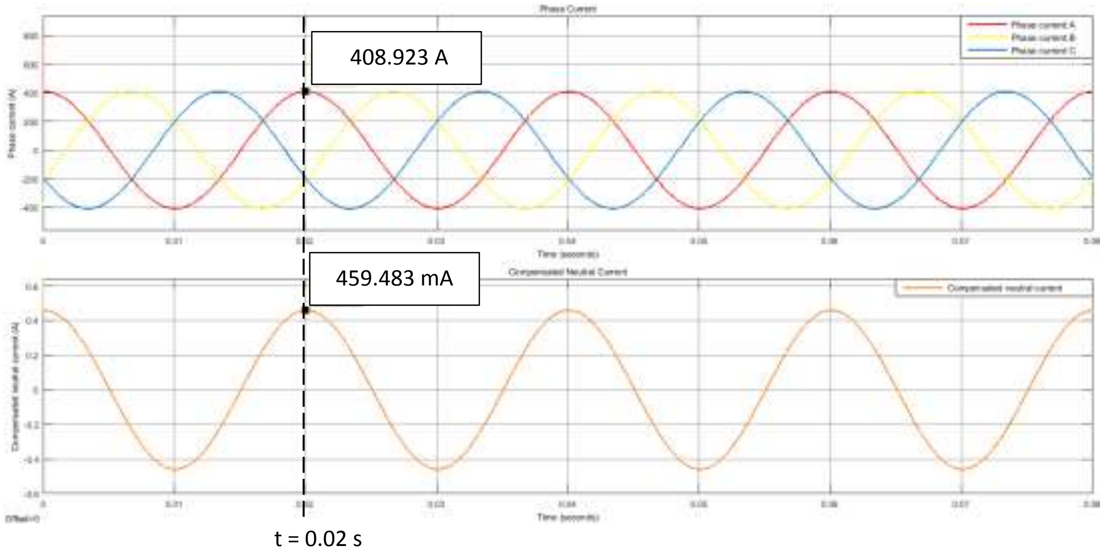

ii) 3 element failures in single group of parallel elements in a capacitor unit

Figure 6: Result of I_{Ncomp} compared to I_{ϕ} when element failures increase in single group of parallel elements in a capacitor unit at right section phase A.

The result in Figure 6 shows that the increased value of element failures in single group of parallel elements in a capacitor unit cause the increased value of I_{Ncomp} and decreased value of I_{A}. The $\frac{I_{Ncomp}}{I_{\mathrm{A}}}$ value for element failures at right section phase A by using equation (21):

i) 2 element failures in single group of parallel elements in a capacitor unit (Figure 6.i):

$$\frac{I_{Ncomp}}{I_A} = \frac{261.976x10^{-3}}{409.231} = 0.6402\ x10^{-3} \tag{34}$$

ii) 3 element failures in single group of parallel elements in a capacitor unit (Figure 6.ii):

$$\frac{I_{Ncomp}}{I_A} = \frac{459.483x10^{-3}}{408.923} = 1.1236\ x10^{-3} \tag{35}$$

The equation (34) and (35) shows that the increased value of element failures in single group of parallel elements in a capacitor unit also cause the value of $\frac{I_{Ncomp}}{I_{\mathrm{A}}}$ to increase. The value of $\frac{I_{Ncomp}}{I_{\mathrm{A}}}$ in Figure 6.ii was 4 times higher than $\frac{I_{Ncomp}}{I_{\phi}}$ value for single element failure in single group of parallel elements in a capacitor unit.

4. CONCLUSION

Generally the unbalance capacitance value due to element failure in a capacitor unit caused unbalance impedance and created unbalance neutral current in shunt capacitor bank system. This concept was used to study and proposed the mathematical modelling to identify location and number of faulty capacitor unit in shunt capacitor bank. The simulation result by using MATLAB software had verified and proved the proposed mathematical modelling through neutral current measurement which defined as compensated neutral current for this research. This detection technique by using neutral current measurement method was able to minimize the outage or shutdown time consumption during shunt capacitor bank breakdown to identify the location and number of faulty capacitor unit in a section of shunt capacitor bank.

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