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Overvoltage Transient Analysis of Vacuum Circuit Breaker Switched Arc Furnace Installation

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Abstract- Frequent Switching of arc furnace in steel company causes a great effect on the insulation of arc furnace transformer winding which in turn may causes a shutdown of production for long periods of time. Therefore, it is necessary to study and analyze the causes of these outages and design an adequate protective device. In this paper the transient overvoltage resulted from vacuum circuit breaker switching arc furnaces of El-Delta for metal and steel company connected to the Egyptian distribution network is presented and discussed. The resulted overvoltage at the circuit breaker contacts can be as high as 3.0 p.u. While at the transformer terminals, the overvoltage reaches a high value, which can be as high as 2.44 p.u. A Fast Fourier Transform (FFT) analysis is used to analyze the overvoltage transients to determine the critical frequencies which must eliminated by the protective devices**.**
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Index Terms- Switching Transients, ATP Simulation, Vacuum Circuit Breakers, arc Furnaces.

I. INTRODUCTION

Switching transients associated with vacuum circuit breakers (VCB) have been observed for many years. With the wide-spread application of vacuum circuit breakers for transformer switching, recently this phenomenon has been attributed to a significant number of transformer failures [1].

It is well known that during switching of highly inductive loads like transformers, under specific conditions, multiple restrikes in the circuit breaker can occur. Multiple restrikes are fast voltage surges which proceed along the cable and reach transformer terminals. Because of different surge impedances at terminals, a wave reflection and absorption takes place.

Voltage oscillations which proceed toward windings are continuously superposed by new voltage waves from generated surges. Hence, voltage waveforms along the transformer winding within a particular time interval can have very different amplitude and rate of rise. Their oscillations contain a broad frequency range, i.e. from a few kHz up to a few MHz. This is unwanted phenomena, because it can causes deterioration and failure to the electrical equipment insulation [2].

Vacuum circuit breakers (VCB) have excellent interruption and dielectric recovery characteristics, and can interrupt the high frequency currents, which result from arc instability. The interruption of these high frequency currents leads to multiple reignitions at the breakers opening. Severe voltage escalations may occur under certain network conditions [3], especially when vacuum circuit breaker used to switch electric arc furnace transformers. This case rises in concern because of their inductive currents. High frequency transients and overvoltages are resulted when the vacuum breaker exhibits virtual current chop and multiple reignitions [4].

The overvoltage usually happen during switching on and switching off operations, that in this kind of application occur very frequently (up to one hundred times per day). Another important task of transformer protection devices is to prevent current re–striking when interrupting the circuit and the consequent voltage escalation phenomenon [5].

The purpose of this paper is to discuss the problem of switching transients concerning industrial electric arc furnace transformers, particularly regarding the eventuality of breaker re–striking during the switching operation.

II. VACUUM CIRCUIT BREAKER MODELING

An overvoltage is generated across vacuum circuit breaker contacts when it interrupts current in arc furnaces circuit Due to the special properties of vacuum. The generated overvoltages are different nature than those generated in the same conditions by another types of circuit breakers (air, SF6, oil, etc.). When the contacts of a breaker open just before current zero, high frequency current transients will occur under certain network conditions. Vacuum circuit breakers have been modeled using an ideal controlled switch, as shown in figure (1).

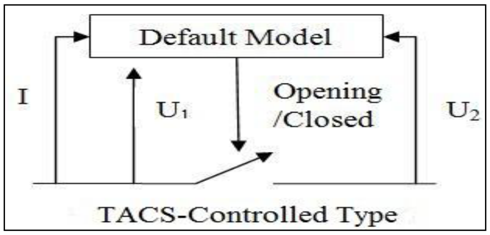


Figure (1) vacuum circuit breaker model

The Default Model of ATP-EMTP is used to generate opening or closed signal to TACS-Controlled Type 13 Switch. After each switching operation of VCB, the default Model judges and executes the next output signal by analyzing the current and two terminal voltages from the Type 13 Switch.

After the contacts of VCB are opened, the dielectric strength of vacuum gap will increases with the time, and a 'race' between the transient recovery voltage and the dielectric strength develops. If the increase of transient recovery voltage (TRV) is faster than the increase of dielectric strength, the re-ignition will occur and the default model will send a closed signal to Type 13 Switch. When the changing rate of HF current in zero point is smaller than the quenching capability of VCB, the default model will give an opening signal to Type 13 Switch and the high frequency HF current will be extinguished. If further re-ignitions occur, the above procedure will repeat until the dielectric strength could withstand the TRV [6].

A random event is taken for different switching operations of VCB, whereas the arcing time is the time between the contacts separation and instant of reaching the current to zero [3]. So, the opening time could be located at any point of one electrical period. In order to model the arcing time, the uniform distribution is used to generate random opening time in one electrical period. Then, the defined opening time is recorded in default model to calculate the arcing time [7].

The actual chopping current is not specified, however earlier research established different mean chopping levels for different load currents and contact material. In this paper, the mean chopping current is estimated according to the equation [7, 8]:

$$I_{ch} = (\omega . i . \alpha . \beta)^q \quad (1)$$

Where $\omega = 2 . \pi . f$

i = amplitude of the 50 Hz current.

$\alpha = 6.2\text{E}^{-16}$ s

$\beta = 14.3$

$q = (1 - \beta)^{-1}$

The chopping current depends on the moment of breaker contacts separation. The closer the contact opens to current zero, the higher the chopping current. In this simulation the statistical nature of the chopping current is represented by a Gaussian distribution with 15% standard deviation from the calculated value of equation (1). The breaker current is assumed to be chopped immediately once the absolute value of the current exceeds the statistically determined value.

There are two breakdown mechanisms [7]; the first one is the breakdown of a cold gap, while the second one refers to a gap which has reignition. In the second mechanism the residual charge carriers exist near the cathode and the breakdown occurs at lower voltages. In this study, the cold gap breakdown is considered. In this mechanism the relationship between the value of dielectric strength and the time is linear; and the typical representation is shown by the following equation [9]:

$$V = A\,(t - t_{open}) + B \quad (2)$$

Where; t_{open} is the moment of contact separation and A, B are constants.

A re-ignition occurs when the TRV exceeds the dielectric strength of the breaker contacts. The actual frequency of the high frequency current associated with arc stability of the breaker is determined by a model comprising inductance and capacitance. This high frequency current will superimpose on the power frequency current. When the high frequency Current gets larger in magnitude than the power frequency current, it can force the current to zero at times other than those expected to occur normally with power frequency current. Most VCBs have the ability to quench this high frequency current and therefore the current may be quenched in one of its zero crossings at high frequency.

The rate-of-change of the current at a current zero determines whether or not there is a successful extinction. The high frequency quenching capability of typical vacuum circuit breakers is found in the range of several hundred A/μs [10]. This value can be a constant or a function of the time after contact separate as shown in equation (3):

$$\frac{di}{dt} = C\,(t - t_{open}) + D \quad (3)$$

Where t_{open} is the moment of contact separation. It is assumed that when the absolute value of the rate-of-change of the current at a current zero above the di/dt limit, arc extinction will not occur.

III. OVERVOLTAGE TRANSIENT ANALYSIS

An actual case in Egyptain distribution network is used to analyze the voltage transients produced and choosing the convienent tools for overvoltage transients mitigation. El -Delta for metal and steel arc furnaces was used as a case study, where it is connected to Egytian distribution network at a 11 kV bus feeds from bahteem station, and uses a Δ/Δ connnected arc furnaces transformer rated 15MVA, 10.5kV/160V. The connected cable is a three core XLPE cable of 59m in length and having an indctance of 0.0283 mH. The no load current of the arc furnaces transformer is 17% and its leakage impedance is 18.8%. The arc furnaces transformer is switched by1200-A vacuum circuit breakers. A single line diagram of the arc furnace bay is shown in figure (2). Each parameter in the equivalent model of the plant under study must be evaluated carefully, where the protection device parameters are strongly affected by the plant parameters [10, 11]. Figure (3) shows the arc furnace circuit modeling in ATP package.

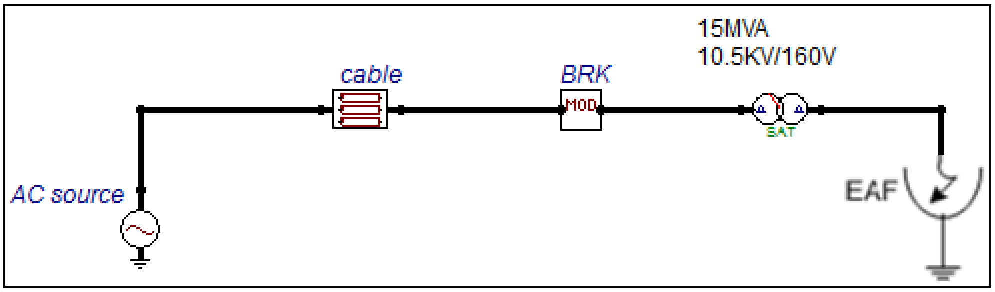


Figure (2) Single line diagram for El- Delta for metal and steel arc furnace.

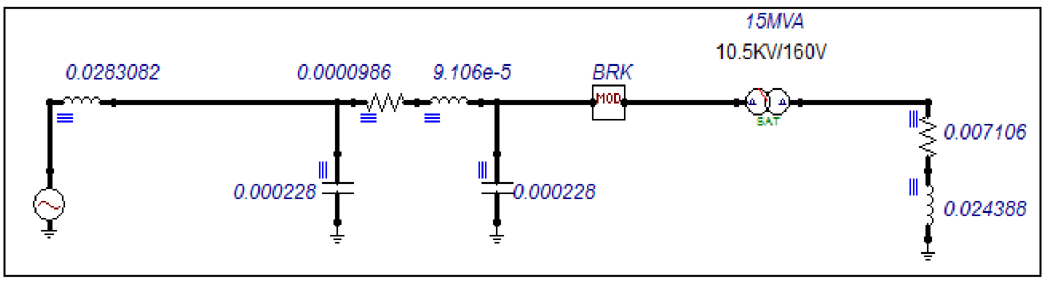
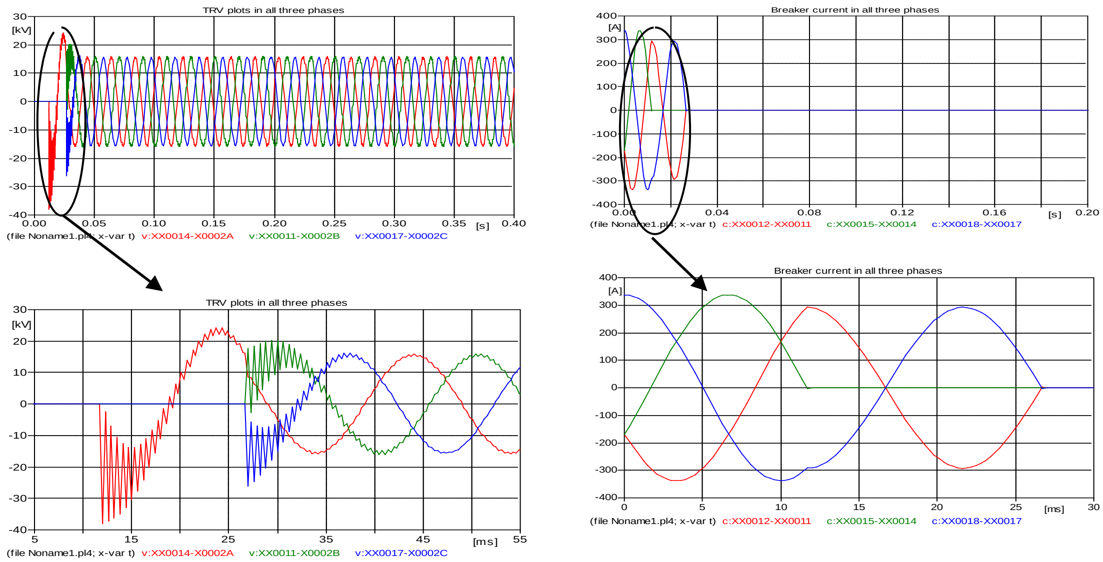


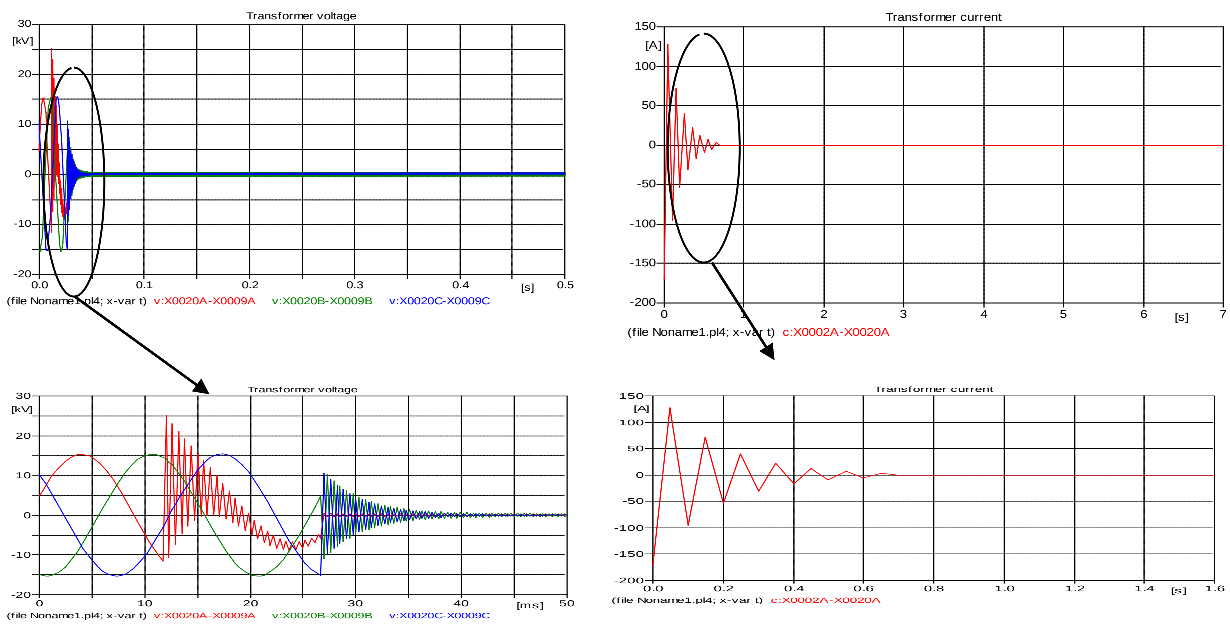
Figure (3) El-Delta for metal and steel Arc furnaces circuit in ATP simulation

According to equation (1), the chopping current is equal to about 4.79A. Initially, Rate of Raise of Dielectric Strength (RRDS) is set to 20V/µs and the quenching capability is set to 100A/µs. When the current reached to the chopping current value, the arc in the VCB becomes unstable and extinguished. At this moment, the current will sharply falls to zero, and VCB will be opened, a transient overvoltage will produce. The TRV across breaker contacts and the breaker current are shown in figure (4). It is observed that the first current zero has occurred in phase A. Due to the transient in phase A, high frequency currents have developed which flow through the other two healthy phases B and C. These high frequency currents have forced the power frequency current in phase A to reach zero value as shown in Figure (4). The power frequency current at this instant is 320A. This lead to TRV of 37.965 kV in phase A, which is equal to 2.44p.u. The induced overvoltage across circuit breaker contacts will lead to breaker failure. The voltage at the transformer is reached to 25.189 kV, which exceeds the BIL of the transformer winding (15 kV), and in turn will lead to a transformer insulation failure. The transformer voltage and current are shown in figure (5). This voltage will lead to transformer insulation failure after many cycles, which lead to transformer malfunction for long period of time. So, it is necessary to use surge arrestor and RC suppressor to reduce the transient overvoltage to the permissible limit.



(A) (B)

Figure (4) plots showing TRV across breaker contacts and breaker current



(A) (B)

Figure (5) Voltage and current across the transformer.

IV. EFFECT OF ARCING TIME

The severity of such overvoltage depends on several factors e.g. the instant of interruption, the parameter of the vacuum circuit breaker etc. The interruption times are mostly random in nature [4]. Therefore, two different values are taking into account and the results are presented and discussed.

The arcing time is set to 600µs, RRDS is set to 20V/µs and the quenching capability is set to 100A/µs. The generated TRV across VCB contacts as a result of VCB switching is shown in figure (6). The results showed that a re-ignition occurs with such lower value of rate of rise of dielectric strength (RRDS). This result can be explained as follows; the generated transient overvoltage across the VCB is much faster than the RRDS of the circuit breaker, which leads to a re-ignition. Also, due to the lowest value of arcing time, the dielectric strength is not sufficient to withstand TRV, then a second re-ignition will occur which is interrupted successively. It is noticed that the first re-ignition occurred in phase A. The high frequency current superimposed on power frequency current of phase A is high enough to affect that of phase B via capacitive coupling between both phases. The sequence is repeated to phase C also, thus all phases will suffer re-ignition. TRV produced is equal to 51.108kV which is equal 3p.u. This value is high enough to effect on vacuum circuit breaker and transformer insulation. Also, it is noticed that the transformer voltage is reached to35.424kV, which is high enough to cause transformer insulation failure, which lead to malfunction of transformer. The overvoltage transients generated on the arc furnace transformer is shown in figure (7).

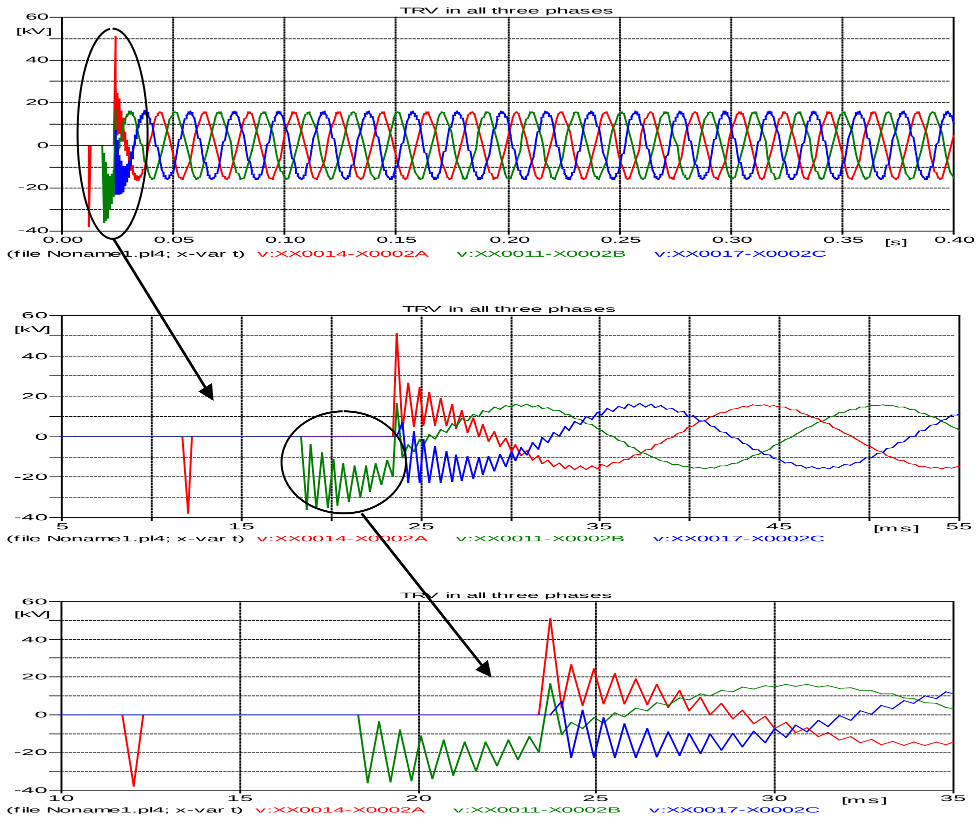


Figure (6) TRV across contact of vacuum breaker at arcing time=600µs (RRDS=20 V/µs, Quenching capability = 100A/µs).

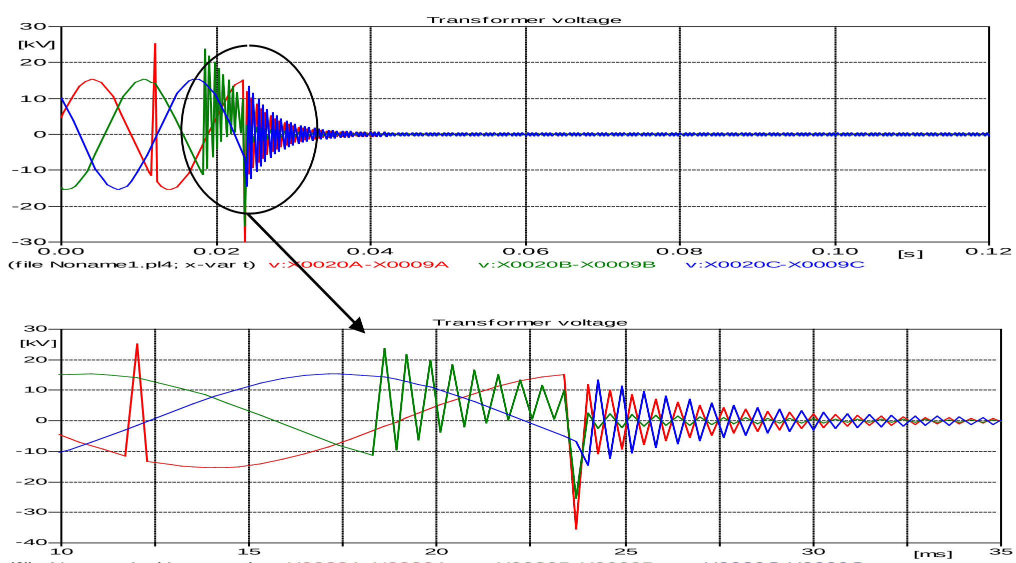


Figure (7) Transformer voltage at arcing time=600µs (RRDS=20 V/µs, Quenching capability = 100A/µs).

Now, the arcing time is set to 1600µs, RRDS is set to 20V/µs and the quenching capability is set to 100A/µs. The generated TRV across VCB contacts as a result of VCB switching is shown in figure (8).

The results showed that VCB is capable to interrupt the circuit successfully after the first re-ignition. This can attribute to the fact that, the RRDS is higher than the generated transient recovery voltage. The higher value of arcing time led to the fact that the high value of dielectric strength is sufficient to withstand TRV. It is noticed that the re-ignition firstly occurred in phase A. The high frequency current superimposed on the power frequency current of phase A, which can be high enough to effect on phase B via capacitive coupling between both phases. This sequence is repeated to phase C, thus all phase will suffer re-ignition. The TRV produced will be equal to 37.965kV which is equal 2.44p.u. This value is very high enough to effect on vacuum circuit breaker and transformer insulation. Figure (9) shows the overvoltage transients on the transformer windings. It is noticed that the transformer voltage reached to 25kV. This value is high enough to cause failure of transformer winding insulation, which leads to malfunction of arc furnace transformer.

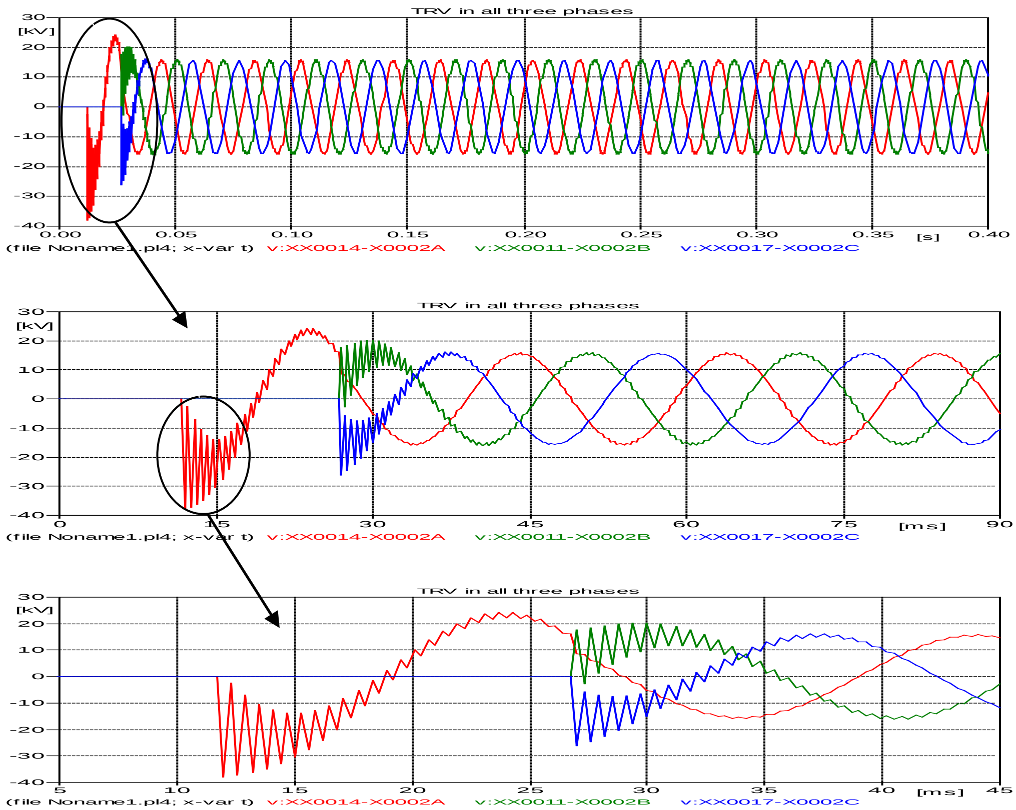


Figure (8) TRV across contacts of vaccum breaker at arcing time=1600µs (RRDS=20 V/µs, Quenching capability = 100A/µs).

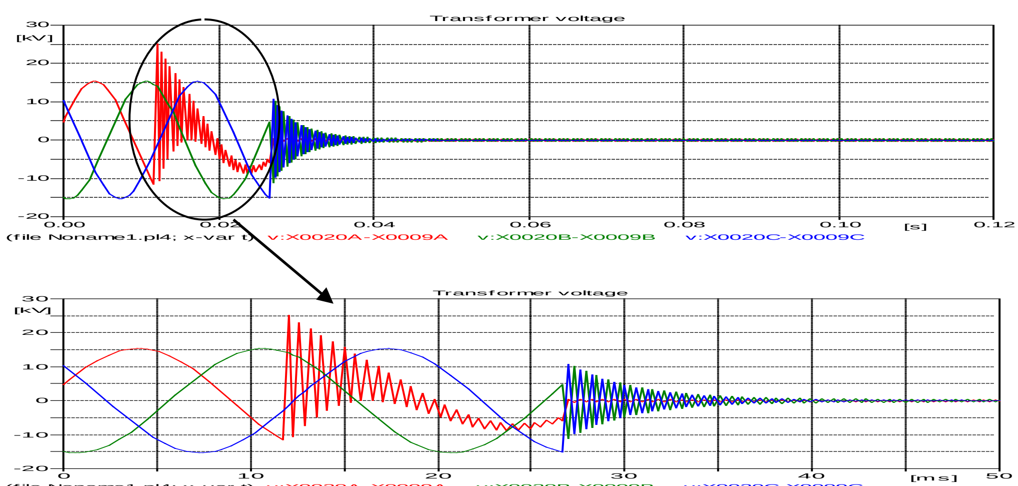


Figure (9) transformer voltage at arcing time=1600µs (RRDS=20 V/µs, Quenching capability = 100A/µs).

V. HIGH FREQUENCY SPECTRUM ANALYSIS

Fast Fourier Transform (FFT) was used to analyze the overvoltage transient generated due to VCB switching processes in arc furnace circuit to determine the critical frequency which must be removed to protect the sensitive equipment.

Frequency spectrum analysis across the contacts of the VCB showed that the overvoltage transient occurs at the power frequency, shown in figure (10.a), while at the other frequencies the voltage approaches a zero value. Figure (10.b) shows that the peak value of the overvoltage transients at the arc furnace transformer, about 25kV, occurs at the power frequency; while a second overvoltage with a magnitude about 15 kV occurred at a frequency of 1650 Hz, which exceeds the acceptable limit. This TRV is unacceptable and indicates the need for an additional protective tool in addition to a surge arrester.

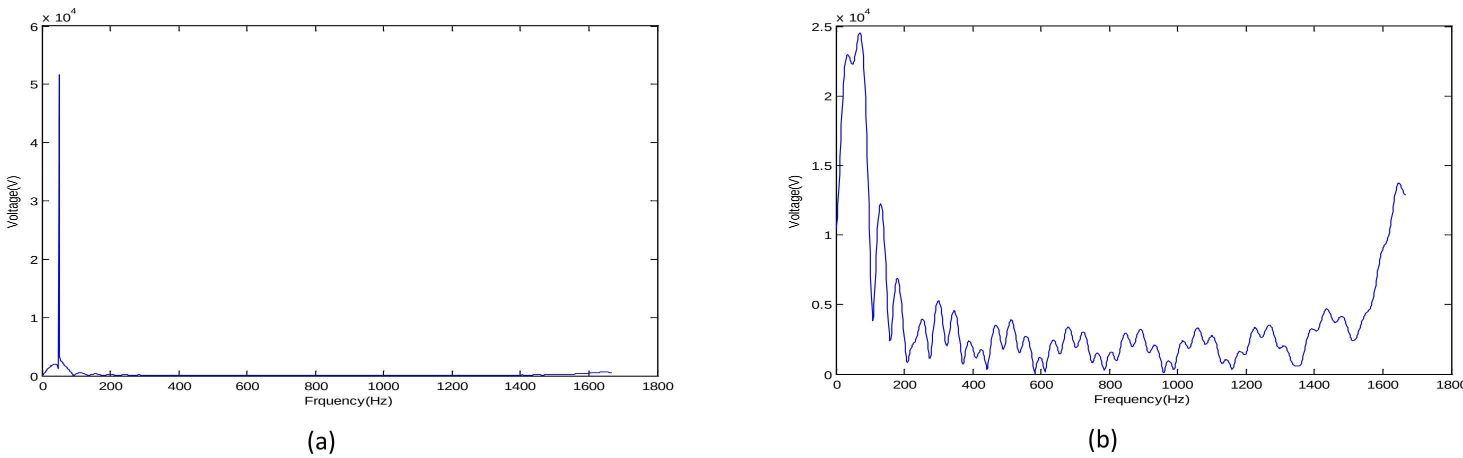


Figure (10) Frequency spectrum of phase voltage “B”
(a) Across contacts of VCB (b) At the transformer

VI. CONCLUSION

Digital simulation proved that severely degradation of an arc furnace transformer insulation of steel making factory as a result of overvoltages arising from VCB operation. The following points can be concluded from this study;

1. A transient recovery voltage and a high frequency current have developed across VCB. The TRV generated in phase A is about 2.44p.u., which lead to breaker failure. The voltage at the transformer is reached to 25.189 kV, which exceeds the BIL of the transformer winding, and in turn will lead to a transformer insulation failure.
2. The results showed that a re-ignition occurs with the lower value of rate of rise of dielectric strength (RRDS), i.e. 20V/μs.
3. Due to lowest value of arcing time, i.e. 600μs, the dielectric strength is not sufficient to withstand TRV, causes a second re-ignition to occur which is interrupted successively.
4. With using FFT, the peak value of the overvoltage transients at the arc furnace transformer, about 25kV, occurs at the power frequency; while a second overvoltage with a magnitude about 15 kV occurred at a frequency of 1650 Hz, which exceeds the acceptable limit..

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