진공차단기의 가상전류 쵸핑에 대한 컴퓨터 해석

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The computer analysis of the virtual current chopping in the vacuum circuit breaker.

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Abstract : The work is concerned with the analysis of the voltage escalation caused by the repeated restriking and extinguishing of the current when the vacuum circuit breaker interrupts the arc furnace load current.
The paper particularly concentrates on the protective measures that may be adopted to overcome the restriking problem and guidelines are evaluated.

1. Introduction

Vacuum has been known as an extraordinary interrupting medium and the vacuum circuit breakers (V.C.B.) are increasingly used in industrial systems.

The advantages of using vacuum circuit breakers are :

(a) Less checking in operation and refurbishing of components.

(b) Little contact wear and no need for adjustment.

(c) Small fire and explosion hazard.

(d) High speed of operation.

(e) Quiet operation with little mechanical shock.

(f) Short clearing time.

(g) Ability to handle the severe recovery transients due to fast recovery of dielectric strength following interruption.

(h) Capability of interrupting high currents.

(i) Compact arrangement due to reduced spacing.

Due to these advantages, the V.C.B. is finding application in the control of arc furnace transformers because of its ability to endure a large number of operations without maintenance.
Because of the circuit configuration involved in this application, problems have occurred due to multiple re-ignitions and interruptions of the circuit-breaker, leading to the production of high overvoltages and insulation failures in the transformer. The problem is due to its improved interrupting ability, which enables it to interrupt the high frequency currents which flow following a re-ignition in the circuit-breaker. This phenomenon has been termed 'virtual current chopping' because its effects are similar to those of current chopping in a circuit-breaker, although, in this particular case, chopping of the current is not a necessary condition for the phenomenon to occur.
Since the V.C.B. has been adopted for the industrial system, several arc furnace transformers suffered insulation failures. From the year 1972, attention has been paid to the cause of the failures.
Extensive field measurements were taken. The dielectric insulation, magnetic fields and switching transients in the transformers were studied and the overvoltages in the system in general and those associated with vacuum switching and also chopping of magnetising currents were reviewed. None of the individual investigations can explain the reason for the failures. It is not until recent years that we have an idea of what had actually happened.
The problems occur on industrial systems of arc furnace installations, where there are an exceedingly large number of switchings. By field tests, it was found that the overvoltages occur when loaded

furnace transformers were opened. This gives rise to a series of re-ignitions and clearings in the vacuum.

2. Solution using the Runge-Kutta-England method

Referring to Fig. 1 the differential equations representing the circuit are :

$sp1 = Z+RC/4$

$sp2 = Z-RC/4$

$HH = sp2/sp1$

$H_1 = (1+HH)/2$

$H_2 = (1-HH)/2$

τ : travelling time

Z : cable surge impedance

RC : cable resistance

$$E_{a1} = H_1.(V_2(t-\tau)+sp2.i_{14}(t-\tau))+H_2.(V_1(t-\tau)+sp2.i_{13}(t-\tau))$$

$$E_{a2} = H_1.(V_1(t-\tau)+sp2.i_{13}(t-\tau))+H_2.(V_2(t-\tau)+sp2.i_{14}(t-\tau))$$

$$E_{b1} = H_1.(V_6(t-\tau)+sp2.i_{16}(t-\tau))+H_2.(V_5(t-\tau)+sp2.i_{15}(t-\tau))$$

$$E_{b2} = H_1.(V_5(t-\tau)+sp2.i_{15}(t-\tau))+H_2.(V_6(t-\tau)+sp2.i_{16}(t-\tau))$$

$$E_{c1} = H_1.(V_{10}(t-\tau)+sp2.i_{18}(t-\tau))+H_2.(V_9(t-\tau)+sp2.i_{17}(t-\tau))$$

$$E_{c2} = H_1.(V_9(t-\tau)+sp2.i_{17}(t-\tau))+H_2.(V_{10}(t-\tau)+sp2.i_{18}(t-\tau))$$

$i_{13} = (V_1-E_{a1})/sp1$

$i_{14} = (V_2-E_{a2})/sp1$

$i_{15} = (V_5-E_{b1})/sp1$

$i_{16} = (V_6-E_{b2})/sp1$

$i_{17} = (V_9-E_{c1})/sp1$

$i_{18} = (V_{10}-E_{c2})/sp1$

$V_{14} = -RG.(i_1+i_5+i_9)$

$V_{15} = (V_4+V_8+V_{12})/3$

$di_1/dt = (V_A-V_{14}-V_1)/L_1$

$di_3/dt = (V_3-V_4)/AL_1$

$\vdots \qquad \vdots$

$di_{12}/dt = (V_{12}-V_{15}-R_3.i_{12})/L_3$

$dV_{13}/dt = (i_1+i_5+i_9-i_{13}-i_{15}-i_{17})/CG$

$dV_1/dt = (i_1-i_{13})/C_1+dV_{13}/dt$

$dV_2/dt = (i_2+i_{14})/BC_1$

$\vdots \qquad \vdots$

$dV_{12}/dt = (i_{11}-i_{12})/C_3$

$$di_2/dt = \frac{i_2}{(V_2-V_3)}\, d(V_2-V_3)/dt + \frac{i_2^2.(V_2-V_3)}{\theta_0 P_0\left(\frac{i_2}{V_2-V_3}\right)^{(k+\ell)}} - \frac{i_2}{\theta_0\left(\frac{i_2}{V_2-V_3}\right)^{\ell}}$$

where P_0, θ_0, k, ℓ : constants

The above complex nonlinear differential equation is a dynamic arc equation.

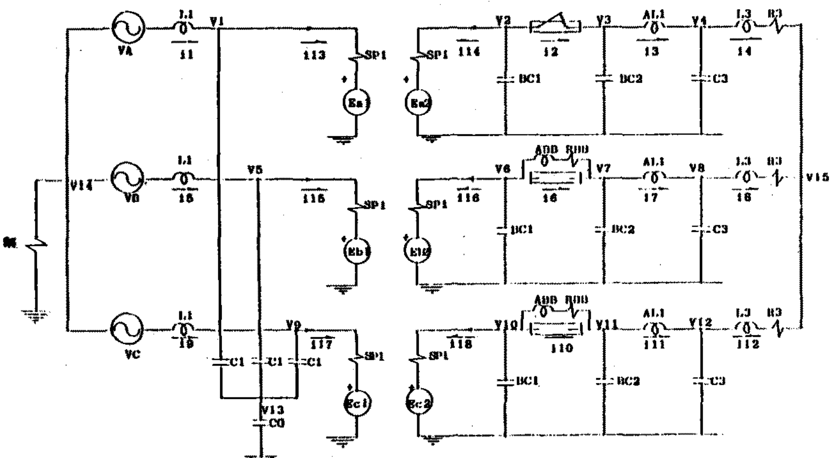
3. Surge Resistor-Capacitor

The purpose of the surge resistor-capacitor was to make the high frequency current aperiodic, resulting in the absence of a high frequency current zero by choosing the proper surge resistor.

The surge resistor-capacitor suggested by the Toshiba company has been known to be the most reliable surge protection method.

The author analysed the effects of the surge resistor by the travelling wave and the dynamic arc circuit concentrating on the effects of the stary capacitances BC1 and BC2.

The circuit is shown in Fig 2 and the cable length is assumed to be 100(m).



Refer to Fig. 2 for the meaning of characters

Fig. 1 Three phase equivalent circuit

The computer results are shown in Fig 3 and Fig 4.

4. Conclusion

In this paper, the author has concentrated on practical protective schemes to prevent repetitive re-ignitions from occurring in an arc furnace installation and has examined the surge resistor-capacitor effect.

Although the maximum overvoltage can be reduced to the safe value by the surge resistor, the high rate of rise of voltage of the arc furnace transformer winding due to the travelling wave of the high frequency re-ignition current might gradually damage the insulation of the transformer connected to the cable leading to the insulation breakdown as in Fig 4.

When the stray capacitances BC1 and BC2 are not small enough, the surge resistor-capacitor cannot prevent the rapid dV/dt of the transformer winding and the repetitive re-ignition from occurring.

It is not necessarily the magnitude of restriking overvoltage which damages the insulation but rather the rise time of the surge wave front.

Moreover, the vacuum circuit breaker for the arc furnace transformer must be operated frequently and both the rapid dV/dt and repetitive re-ignition might cause the damage of the transformer winding insulation gradually.

Therefore, the author suggests the following guidelines to operate the vacuum circuit breaker for the arc furnace transformer safely :

(a) Incoming cable should be connected directly to the circuit-breaker to reduce the stray capacitance.
If the incoming cable is connected to the circuit breaker via cubicle, then the stray capacitance might be increased.

(b) A busbar is recommended in preference of a cable for connecting the circuit-breaker to the arc furnace transformer to reduce the stray capacitance. If the cable is connected from the circuit breaker to the arc furnace transformer, the stray capacitance BC2 might be increased.

(c) Surge capacitor is recommended to be as high as possible to prevent the reignition from occurring.

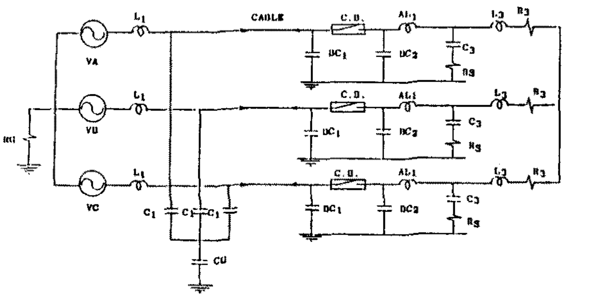
(d) Surge resistor is recommended to be above the critical damping value in the region of 1 to 2 times the critical value.

A knowledge of the power distribution system layout and parameters is necessary to enable selection of the proper capacitor and surge resistor.

If the above conditions are satisfactory, then the following results might be obtained.

(a) Re-ignition is prevented from occurring.

(b) If re-ignition occurs then the re-ignition current is aperiodic.
Therefore no current zero is found and repetitive re-ignitions do not take place.



L_1 : source inductance
AL_1 : connecting line inductance
R_3, L_3 : load resistance, inductance
C_1 : power factor capacitor
CG : stray capacitance of C_1
BC_1 : bus & C.B. capacitance
BC_2 : C.B. & connecting line capacitance
C_3 : surge capacitor
RS : surge resistor

Fig. 2 Installation of the Surge Resistor-Capacitor

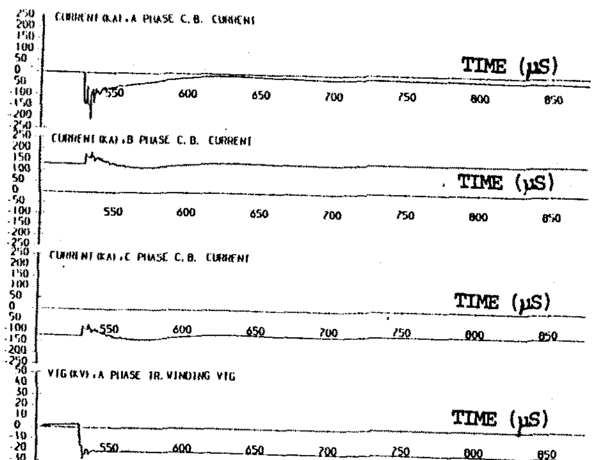


Fig. 3 Re-ignition currents & Tr. winding voltage
(BC1 & BC2 = .5(nF), 1 aperiodic restrike)

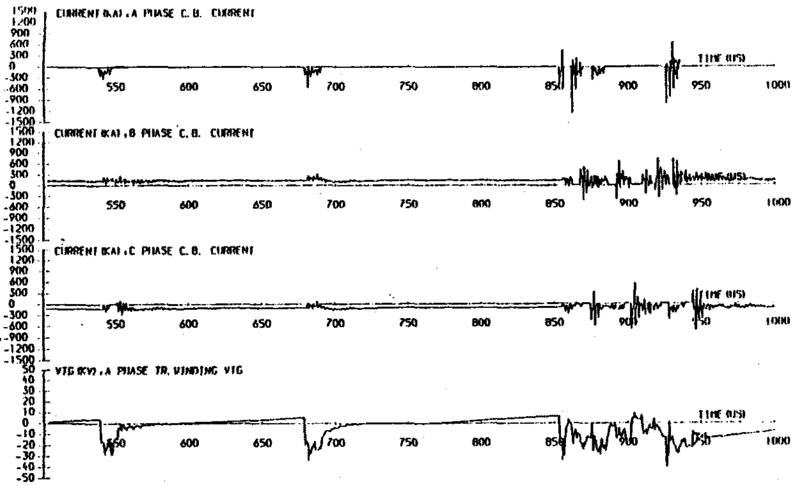


Fig. 4 Re-ignition currents & Tr. winding voltage
(DC1 & DC2 = 3.0 (nF), repetitive restrike)

Under such conditions, the vacuum circuit-breaker for the arc furnace transformer can be operated safely.

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