Transient Recovery Voltages Measurement and Surge Protection of the LV Vacuum Circuit Breakers

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Abstract: - In low voltage power electrical circuits where switching operations are made through the contactors or vacuum circuit breakers, switching transient overvoltages (TRV) occurs. When disconnect a vacuum contactor in between this device and consumer electromagnetic energy accumulates and thus overvoltages are generated which additional overcharge the electrical insulation. To prevent undesirable switching overvoltages while switching inductive circuits, the transient overvoltages must be limited to the lowest possible values and for this dedicated devices are known as transient surge suppressors or transient voltage suppressors (TVS). A measuring circuit for transient switching overvoltage allows determination of their shape and maximum values obtained from using new types of transient voltage suppressors. The study was performed using a data acquisition board connected to a PC via a USB connection and HP VEE Pro 8.0 software, also used to design the theoretical model of switching transient overvoltages parameters.

Key-Words: - Circuit simulation, Transient analysis, Vacuum breakers, Overvoltages, Surge suppressor, HP VEE Pro 8.0

1 Introduction

Disconnecting an electrical circuit via a vacuum contactor, each of the networks at eider side of the breaker proceeds to redistribute its trapped energy. As a result of this energy distribution, each network will develop a voltage that appears simultaneously at the respective terminals of the breaker. The algebraic sum of these two voltages represents the transient recovery voltage [1].

\[ u(t) = \frac{U_{d}}{Z} \cdot \sin(\omega t + \varphi) \]

The recovery voltage phenomenon depends on the conditions that prevail at the moment of the current interruption and has an oscillatory amortized shape because of the RLC network components. Documentation model that reflects this switching off situation consists of an RLC group disconnected from the load resistance by the K breaker as shown in figure 1, which has significance for testing laboratories, where the resistance R, inductance L and capacitance C are concentrated elements values [2]. In case of network faults, those elements are evenly distributed and it should be noted that damping in laboratory testing conditions is determined by the resistance R, while damping for real networks, resulting largely from the corresponding resistance of the dielectric losses and the corona effect. It follows therefore that the principle circuit is sufficiently accurate for testing in laboratories equipped with synchronous generators, as its own source of energy.

Differential equations after disconnecting the circuit breaker, taking into account that because of the short circuit at \( t = 0 \), the capacitor has not been charged with electric charge, are:

\[
\begin{align*}
\dot{U} \sin(\omega t + \varphi) &= Ri + L \frac{di}{dt} + u \\
i &= C \frac{du}{dt}
\end{align*}
\]

(1)

Transient recovery voltage is established between the terminal voltage circuit breaker, after disconnecting the short circuit and his expression has two components namely periodical component and a periodical component given by (2).
A simplified transient recovery voltage (8) can be obtained using simplifying hypothesis like:

- Short circuit current interruption occurs when passing through the natural zero value;
- Phase shift between voltage and current is $\pi / 2$;
- Alternative voltage is considered constant and equal to the voltage peak $U^\prime$.

$$u(t) = \frac{\hat{U} \sin(\omega t + \varphi_0)}{\sqrt{R^2 + \frac{1}{C \omega^2}}} - D\hat{U} e^{-\alpha t} \sin(\omega t - \gamma)$$

Equation 1 elements represent:

$$\delta = \frac{R}{2L}; \delta_0 = \frac{1}{L C}; \omega = \sqrt{\omega_0^2 - \delta^2}; \omega = 2\pi f$$

$$D = \sqrt{A^2 + B^2 - 2AB \cos(\beta - \alpha)}$$

$$A = \sqrt{1 + \frac{\omega}{\omega_0} + \left(\frac{\delta}{\omega}\right)^2}; B = \sqrt{1 - \frac{\omega}{\omega_0} + \left(\frac{\delta}{\omega}\right)^2}$$

$$\alpha = \varphi_0 + \varphi; \beta = \varphi_0 - \varphi; \varphi = \arctan(\omega L / R)$$

$$\varphi = \arctan\left(\frac{2\omega_0\delta}{\omega_0^2 - \delta^2}\right), \varphi_0 = \arctan\left(\frac{\delta}{\omega - \omega_0}\right), \varphi_t = \arctan\left(\frac{\delta}{\omega + \omega_0}\right)$$

$$\tan \gamma = \frac{A \sin \alpha - B \sin \beta}{A \cos \alpha - B \cos \beta}$$

For $\delta << \omega e$, the sinus term can be neglected and the approximate transient recovery voltage waveform is presented in Fig. 4 and has the following expression:

$$u(t) \approx \hat{U}(1 - e^{-\alpha t} \cos \omega t)$$

In Fig. 4 is presented the approximate transient recovery voltage waveform at 500 rated volts, with the help of HP VEE Pro 8.0 software.

![Figure 3. Exact solution of the TRV.](image)

![Figure 4. Transient recovery voltage approximate solution.](image)

2 Experimental model for virtual TRV measuring

The magnitude of transient overvoltages can be reduced to harmless values by means of surge suppressors. In order to experiment some surge suppressors types and to measure transient overvoltages a testing laboratory model was developed like in Fig. 5.

Vacuum contactor (CV) is switched using a button K and makes disconnections of the power user Zs, in this chase an electrical motor. The electronic suppressor is connected between the three phases and downstream from the contactors contacts. This suppressor has an important influence over the transient recovery overvoltage when the load user is...
switched. Connection between the voltage divisor respectively the connector (Con1) and the data acquisition board (DAQ).

![Figure 5. Transient recovery voltage measuring setup](image)

Information is applied to analog inputs and all analog data are connected to analog ground (AGND) of the data acquisition board. Data connections must be realized with shielded wires and connected to one ground terminal of the measuring system (GND). All six voltages defined by the upstream potentials contacts and the downstream potentials contacts are applied to the connector terminals (Con1). Voltage information is obtained from the voltage divisor for every part of the circuit terminals. Voltage information from the connector (Con1) is carrying over to analogical inputs of the Data Acquisition Board using cover cables. All this cables will be connected to the measuring circuit earthy terminal [3].

2.1 Surge suppressor using passive components

In fig. 7 is presented the first version of a surge suppressor (transient voltage suppressor – TVS) accomplished using metal-oxide varistors. This type of devices was use because they provide an excellent protective device for limiting surge voltages in absorbing energy pulses and is a non-linearly resistance (Var) whose peak current and voltage values basically depend on the current/voltage characteristic. Varistors are voltage dependent resistors whose resistance decreases drastically when voltage is increased. It is a well-known fact that a sudden break in an inductive circuit causes an overvoltage which can seriously damage the electrical motor insulation.

![Figure 7. Schematic diagram of the automatic protection device switching surge transient](image)

In fig. 8, 9 are presented measurements of the limited overvoltages on the positive edge. Numerous measurements indicate that the transient recovery voltages have random values based on the switching moment.

![Figure 8. Measurement of the cut-off overvoltages (using surge suppressor with passive components)](image)

![Figure 9. Switching-off transitory overvoltages developed across the contacts.](image)
Using the passive elements surge suppressor transient recovery voltages reach maximum 1000V, which is not a dangerous level for the motor insulations.

Figure 10. Measurement of the cut-off overvoltages (using surge suppressor with passive components)

Figure 11. Switching-off transitory overvoltages developed across the vacuum contacts.

2.2 Surge suppressor using active components

This chapter presents two surge suppressors prototypes containing active components.

2.2.1 Surge Suppressor with transistor and Zener diode

To limit undesirable effects of the transitory overvoltages over the electrical motors insulations, was designed a device for automatic protection against switching surge transients that occur in electrical low voltage circuits were the switching process is done through the vacuum circuit breakers. In fig. 12 is given the schematic diagram of the automatic protection device against transient switching overvoltages which contains a three-phase rectifier bridge that transform the three-phase transient recovery voltages in to a continuous transitory voltage that supply a dynamic load constituted from an electronic multi-junction device (T) and a ballast resistance (R2). Breakdown voltage of the electronic device is programmed through the Zener diode (DZ) and limiting resistance (R1).

Figure 12. Version 1 of surge suppressor schematic using active components

Bring into service delay of the multi-junction device and its protection against false drive is provided through resistance (R3) connected in parallel with capacity (C). In fig. 13 is presented the measurement recordings concerning the switching transient overvoltages.

Figure 13. Measurement of the cut-off overvoltages (using version 1 surge suppressor)

In the graphical interfaces is shown the voltages at either side of the breaker, V1 being one of the three...
phase voltages from the electrical network. The other three voltages \( V_1', V_2' \) and \( V_3' \) respectively represent the voltages from the other side of the vacuum circuit breaker.

In fig. 14 and fig. 15 are presented the phase voltages and the transitory recovery voltages developed across the contacts for the first part of the phenomena from fig. 13 namely connection of vacuum contactor and the last part of it namely disconnection of the circuit breaker.

\[ \text{Figure 14. Switching-on transitory overvoltages developed across the vacuum contacts} \]

\[ \text{Figure 15. Switching-off transitory overvoltages developed across the vacuum contacts} \]

**2.2.2 Surge Suppressor with Breakover Diode**

In fig. 16 is presented the surge suppressor schematic against transient switching overvoltages which contains a three-phase rectifier bridge which transform the three-phase TRV into a continuous transitory voltage that supply a dynamic load constituted from an electronic multi-junction device (T).

\[ \text{Figure 16. Version 2 surge suppressor diagram using active components} \]

In fig. 17 is presented the measurement recordings concerning the switching transient overvoltages limited with the second version of surge suppressor.

\[ \text{Figure 17. Measurement of the cut-off overvoltages (using version 2 surge suppressor)} \]

\[ \text{Figure 18. Switching-on transitory overvoltages developed across the vacuum contacts} \]
It can be observed that the switching transient overvoltages appear even on the connection of vacuum contactor (i.e. 600V). Breakdown voltage of the electronic device is programmed through the breakover diode (IXBOD) who is the main device of this surge suppressor. Voltage-current characteristic of the surge suppressor is nonlinear type and it has a breakdown voltage of the central electronic device - breakover diode - that can be programmed at certain value and a negligible saturation voltage compared to the saturation voltage of the equivalent industrial surge suppressors.

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Figure 19. Switching-off transitory overvoltages developed across the vacuum contacts.

In the fig. 18 and fig. 19 are given the phase voltages and the transitory recovery voltages developed across contacts and the particularity is that the shape of TRV is not amortized oscillating. Due to the characteristic shape, the proposed surge suppressor fully and quickly dissipates electromagnetic energy that circulates in the power circuit, limiting the maximum amplitude of transient overvoltage and protecting the electrical insulation.

4 Conclusion
The purpose of the paper is to present surge suppressors used to prevent and reduce the switching overvoltages implications over the low voltage electrical consumers that use vacuum contactors for switching. Transitory overvoltages were simulated and measured also, using data acquisition board and a synthesized HP VEE Pro 8.0 program.

Objective of the experimental measuring system was to display the switching transient overvoltages waveforms when different types of surge suppressors are used. Using a laboratory measuring system, transient overvoltages can be measured on different types of vacuum low voltage contactors and surge suppressors can be tested and also. Amplitude of the resulting voltage spikes depends on breaker type and circuit characteristics and if exceeds the basic insulation level of the motor, overvoltage protection circuits should be installed. Using active components in developing surge suppressors some advantages were identified as efficient limitation of the vacuum switching overvoltages and dissipation of the electromagnetic energy during transitory phenomena.

Comparing the experimental surge suppressors, it results that the first version, using passive devices, offers an optimal harmonic dissipation of the transitory energy.

References: