ＳＬＦ合成回路条件における油中しゃ断再起電圧

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Transient Recovery Voltage Reproduced in Oil Media under Artificial Short-Line Fault Conditions

Iwao MIYACHI and Kamal M. SHEBL*

The interruption of current in liquid oil under very short-line fault (SLF) conditions within a distance of 1 km long has been performed using 10 sections of π-type artificial line. It has been found that, under the suitable number of used sections between 4 and 8, the ideal triangular shape of the transient recovery voltage (TRV) can also be obtained even for the moment of current interruption in oil as is usually the case with air-blast circuit-breakers. Reducing the value of line capacitance, to obtain the higher value of the surge impednace of the line, will reproduce the triangular waveform at a wide range of used sections. The sudden change of arc voltage, or the deformation of current before its zero (current chopping is also included here) affects the shape of the triangular voltage oscillation after interruption. The deformation in current was considerably reduced, compared with the formerly reported breaker-terminal fault conditions, by the insertion of the artificial line into the test circuit. But the amount of damping of the line-side TRV may vary from test to test, and occasionally these oscillations disappear completely, which characterizes the interrupting phenomena in oil.

1. Introduction

In the particular case of the short-circuit fault being some few kilometers distant from the circuit-breaker of a modern substation where a large number of transmission lines is concentrated, an extremely onerous fault conditions result[1]. At the moment of current zero, the voltage on the line-side terminal of circuit-breaker is equal to the reactance voltage drop along the faulted-line section. On interruption of current, the line remains charged at that ramped voltage. The stored energy of the line is then dissipated by means of travelling voltage waves along the line length in high-frequency voltage transient of a sawtooth waveform impressed on the circuit-breaker terminal. These line-side transient oscillations, when added to the bus-side recovery voltage, may prove the current difficult to be interrupted, on account of the initial build-up sharpness of restriking voltage not represented by cosine type but by linear rate of rise, by some types of circuit-breakers even within the range of nominal breaking capacity.The frequency of these oscillations is inversely proportional to the distance from the breaker to the fault[2], and the magnitude of the crest voltage is directly proportional to the distance[3].

Test interruption under short-line fault (SLF) conditions would be more practical if the actual line were replaced by an artificial one composed of certain number of links. In this matter there are always questions about the types of these links as the suitable number of them to reproduce the ideal sawtooth waveform of the transient recovery voltage (TRV) under the short-line fault conditions.

As the interruption process in oil is considered to be physically complex, it is generally said that the TRV in oil is so different to be determined uniquely by experimental work because of its diversity of waveforms which might be speculated by appropriate calculations. The behavior of current and voltage waveforms just before current zero has been discovered to exert an influence on the reproduced TRV under SLF condition. Because of the fact that the oil circuit-breakers are still popular in the electric power systems of so many countries in the world with their mechanical simplicity and low cost, it is really important to clarify the fundamental phenomena about current interruption in liquid oil media under most difficult conditions.

* Department of Electrical Engineering, Mansoura University, Egypt

2. Experimental Procedure

The schematic diagram depicted in Fig.1 shows the details of the test circuit components that have been used to detect the transient recovery voltage under short-line fault conditions. The basis of operation of this system, is the injection of a current into the main circuit, where the current is obtained from the discharge of the capacitor bank C mainly through the inductance L. The values of both capacitance and inductance have been chosen to produce an interrupted current frequency of about 50 Hz ($1/2\pi\sqrt{LC}$). R_V and C_V are the control resistance and capacitance for the reproduced source-side transient recovery voltage. In this experiment, with the consideration of the practical cases, the following values are selected for those constants: $C=730\ \mu F$ charged up to 1000 V-DC, $L=14$ mH, $R_V=395\ \Omega$ to obtain the amplitude factor as 1.3 and $C_V=0.05\ \mu F$ to have a frequency of 6 kHz.

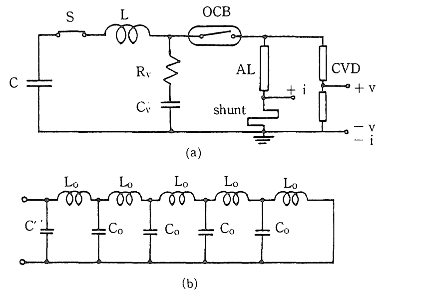

Fig. 1 Test circuit for SLF conditions
(a) test circuit arrangement for line-side TRV
(b) artificial line (AL)

The capacitive voltage divider (CVD) and the shunt are to be grounded at the only one point grounding of the whole circit connection. The tripping circuit ensures the opening of the oil interrupter to interrupt the flowing current during its first half cycle after closing the relay switch S.

The used interrupter here is a small-oil volume type circuit-breaker with rated voltage of 3.5 kV, and 600 A as rated current.

3. Description of Artificial Line

An artificial line is needed to act instead of the actual one. With respect to the construction of the artificial line, there are many different schemes which are suitable for reproducing the sawtooth waveforms[4]. Among these schemes, the π-section type has been chosen as the changing of the connection of the artificial line can be done rapidly and due to the symmetrical characteristics of the elements. As for the construction of the artificial line, it consists of 10 identical sections in total, and the coils are of the air-cored type with a diameter of about 28 cm, having an inductancce L_0 of 0.156 mH. Each capacitor has a capacitance C_0 of 1000 pF except that one C' connected to the first section has 500 pF. These arrangements are roughly representing a transmission line of 1 km long with each section corresponding to a length of 100 m whose surge impedance being 395 Ω.

The main coils of the artificial line are suspended and connected in series along an insulated straight support and, in order to avoid the mutual magnetic coupling among them, are arranged so as to fix the axes of the adjacent coils in perpendicular position one after another like x, y and z directions of three dimensional rectangular coordinates.

To reproduce the conditions for the short-line fault, the artificial line has been inserted in the main circuit of the test connection, as shown in Fig.1, in series with the oil interrupter to ensure that the breaking-current will flow through it.

4. TRV under Different Number of Sections of Artificial Line

Fig.2 shows the transient recovery voltage waveforms across the contacts of the interrupter reproduced under short-line fault conditions upon interruption in liquid oil according to the shown scheme in Fig.1. It has been noticed that the sawtooth oscillations have been reproduced with rounded tip as shown in case (a). This TRV waveform was obtained when all sections of the 10 π-type artificial line ($n=10$) were used with the surge impedance of 395 Ω as mentioned above. The peak value of the current to be interrupted in this case was 228 A. The rate of rise of the transient recovery voltage was measured as 85 V/μs in case of $n=10$, where the frequency of the sawtooth oscillations was estimated as 50 kHz. By decreasing the number of the used sections of the

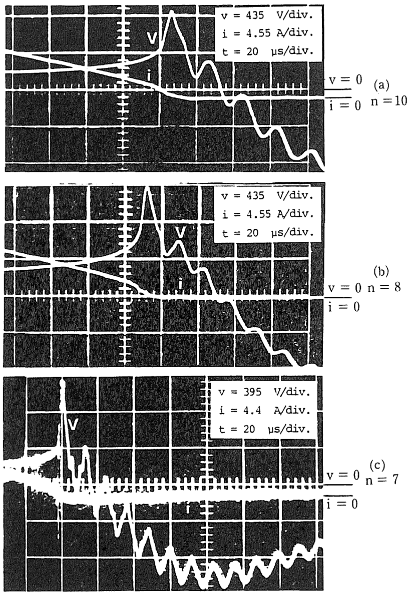

Fig. 2 Voltages across interrupter contacts under SLF conditions $C'=500$ pF $C_0=1000$ pF

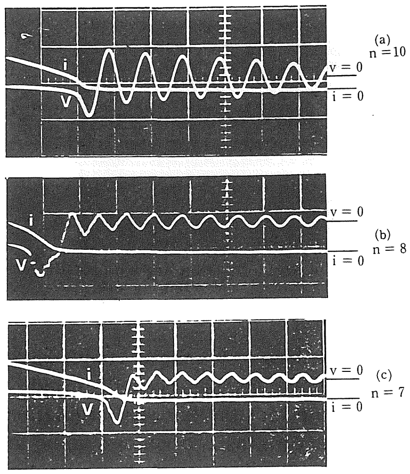

Fig. 3 Line-side transient recovery voltage.
$C'=500$ pF $V=165$ V/div.
$C_0=1000$ pF $i=4.55$ A/div.
$t=20$ μs/div.

artificial line, with the same surge impedance, to n=8, Fig.2b shows the TRV where the frequency of the oscillations has been increased to about 72 kHz and the rate of rise of its initial part increased to a value of 98 V/μs. In case of using 7 sections, Fig.2c has been obtained, where the first few cycles have been distorted due to some higher frequencies superimposed on them but the rest of oscillations are nearly identical with the sawtooth waveform. The corresponding line side TRV's are shown in Fig.3.

As it is known that the first capacitor of the π link immediately after the interrupter may cause the testing error because it is considered to be effective even before current zero and may influence both the arc path conditions at and after the current zero, it was suggested to increase the value of the capacitance of first link from 500 pF to 1000 pF. Fig.4 shows the line-

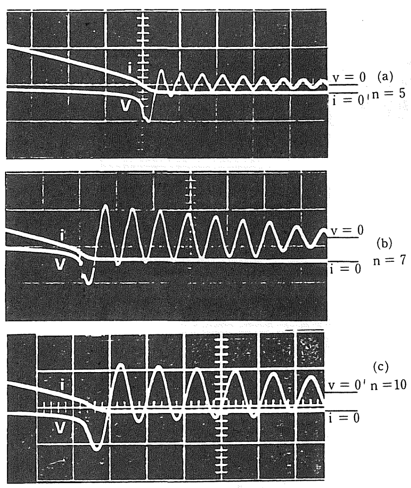

Fig. 4 Line-side transient recovery voltage after increasing the value of C'.
$C'=1000$ pF $V=165$ V/div.
$C_0=1000$ pF $i=4.55$ A/div.
$t=20$ μs/div.

side oscillations at $C'=1000$ pF. It can be noticed that the case at n=5 is the nearst one to the sawtooth waveform, where that case at n=7 shows very small deviation, and the case of n=10 shows much deviation with a rounded-peak oscillations. Remarkable changes are not likly to be recognized on the line-side voltage oscillations.

In order to survey the effect of the surge impedance Z_n of the artificial line upon the reproduced transient recovery voltage, the value of capacitance of each section has been reduced, by 20 %, from 1000 to 800 pF to obtain $Z_n=442\ \Omega$. Fig.5 shows the line-side TRV

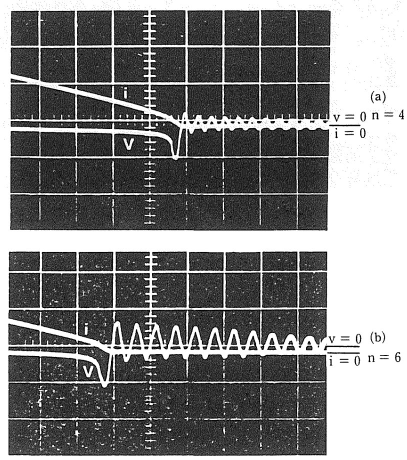

Fig. 5 Line-side transient recovery voltages in case of increased surge impedance.
$C'=400$ pF $V=165$ V/div.
$C_0=800$ pF $i=4.55$ A/div.
$Z_n=442\ \Omega$ $t=20$ μs/div.

at n=4 and n=6 where both of them show a nearly sawtooth waveform without any irregular oscillations superimposed. The results show the ideal sawtooth waveform of TRV can be reproduced, for higher line-side surge impedance even by using a smaller number of sections between four and six.

Fig.6 shows the relation between the number of sections of the artificial line and the interrupted current peak. It can be concluded, from the results shown in the figure, that the higher the number of sections, the lower the interrupted current corres-

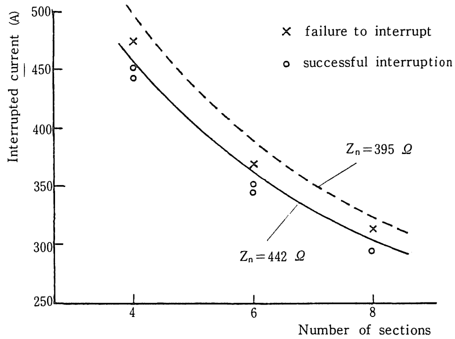

Fig. 6 Interrupted current versus the number of used sections.

ponding to the simulated line length. This curve was drawn for a surge impedance value of $Z_n=442\ \Omega$. By reducing the surge impedance of the artificial line to $Z_n=395\ \Omega$, the dotted curve of Fig.6 has been obtained in a higher position with respect to that for the previous one.

Fig.7 shows an example of a failure-to-interrupt case in oil under short-line fault conditions. It can be

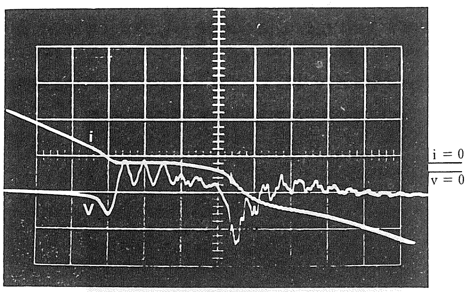

Fig. 7 Example of failure-to-interrupt case in oil.
$I_p=456$ A, $V=165$ V/div.
$n=6$, $i=4.55$ A/div.
$C'=400$ pF, $t=20$ μs/div.
$C_0=800$ pF

seen that the current after reaching its zero level, it sustains at that level for about 32 μs where it reignites and increases gradually in the opposite polarity. The instant at which the reignition had occurred can be easily recognized as the amplitude of the line-side TRV oscillation decreases rapidly and its frequency has been changed.

5. Relation between Arc Voltage and SLF Oscillations

As it has been noticed during interruption in oil[5] that the arc voltage, after contact separation, starts to build up gradually, and a few microseconds before current zero it increases to a relatively high value. The rate of rise, just before current zero, differs from case to case.

It has been discovered during interruption in oil under SLF conditions, that the reproducing of the ideal sawtooth waveform is obtained in the case where the arc voltage has rather small value, [see Fig.3b,c, Fig.4a, and Fig.5a] , whereas in the cases that the arc voltage displays high value, the sawtooth waveform almost comes with a rounded peak [see Fig.3a, and Fig.4c]

By comparing the two cases of Fig.5, it can be observed that in case (a), the amplitude of the first peak of TRV oscillations is 57 V where the arc voltage peak shows −150 V. In case (b) the first amplitude increased to 95 V according to the increased arc voltage of −190 V. It concludes that the amplitude of the high-frequency oscillations is approximately in direct correlation to the amplitude of the arc voltage.

Fig.8 shows that the arc voltage at the end of its period has increased suddenly with some fluctuations

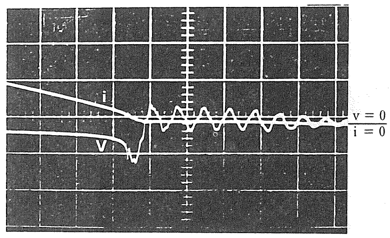

Fig. 8 Effect of arc voltage on line-side oscillations.
$n=8$, $V=165$ V/div.
$C'=400$ pF, $i=4.55$ A/div.
$C_0=800$ pF, $t=20$ μs/div.

on its waveform. As a result, the sawtooth waveform, especially the first one, has been distorted. These examples indicate that the line-side oscillations are seriously affected by the arc voltage value and its sudden increase before current zero, as the line voltages start to oscillate at a certain voltage value rather than that in the case without arcing voltage.

6. Effect of Current Deformation on TRV

In actual system operation the triangular restriking waveform that associated with short-line faults may not be too readily distinguishable due to the interaction between the line and the interrupter concerned[6]. Apart from the obvious differences in restriking voltage waveforms under SLF conditions already discussed before, it was felt that the presence of a relatively large capacitance shunting the interrupter would affect the current flowing in the interrupter gap in the period immediately before and after the nominal current zero[5]

Fig.9 shows, in case (a), that the first two cycles of sawtooth waveform have been distoted following a deformation in current before its zero in a shape of current chopping. In case (b), the current is falling towards its zero with a constant rate at first, but at about 28 μs before current zero it increases again

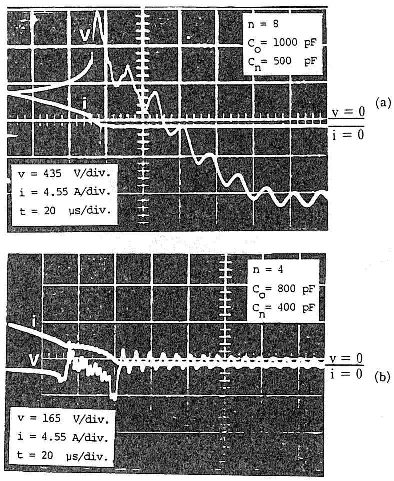

Fig. 9 Effect of current deformation on TRV.
(a) voltage across contacts
(b) line-side TRV

while at last falling towards zero level with an increasing rate, and small oscillations have appeared on its path. As a result, the arc voltage waveform was greatly distorted and the line-side TRV has been deformed accordingly. In comparing the current waveforms in case of SLF conditions with that for breaker-terminal fault (BTF) conditions[5], it is also recognized that the insertion of the artificial line in the circuit connection, to achieve SLF conditions, will result in the considerable reduction of the current deformation.

On the other hand, in some interrupting cases, it has

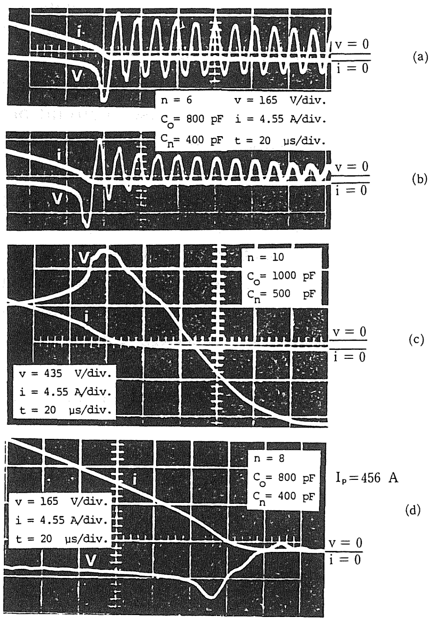

Fig. 10 Damping effect on sawtooth oscillations.

been noticed that the line-side TRV is highly damped and the amount of damping varies greatly from test to test under the same conditions as shown in Fig.10(a,b). The first peaks in these two cases have almost the same value, but there has been considerable damping in case (b) in comparison with case (a) especifically for the first two cycles. In extreme cases, these line-side oscillations have completely disappeared as shown in cases (c) and (d). The non-oscillatory TRV thus occasionally found is characteristic for the cases of current interruption in oil probably because of the residual conductance between the contacts which depends upon the physical property of the turbulent oil-gas mixture at the moment of current zero.

It can be said, with the help of the results discussed before, that the suitable construction of an artificial line is not the only factor to decide the reproduction of the transient waveform, but there are also the other factors, as the current and the voltage characteristics of the arc near current zero that depend on the interrupter itself, affecting the reproduction of TRV under SLF conditions.

7. Arc Resistance Characteristics just before Current Zero

As the arc voltage, during interruption in oil, rises sharply a few microseconds before current zero, it will be usefull to discuss the behavior of arc resistance during that period.

Fig.11 indicates the examples of the time variation

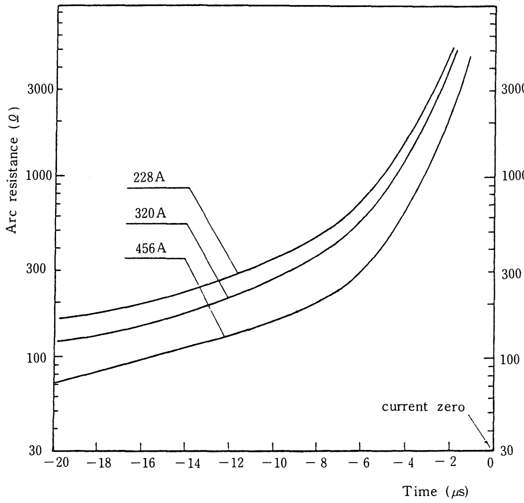

Fig. 11 Examples of time variation of arc resistance as a function of interrupted current.

for the arc resistance in oil at three different values of interrupted current. The arc resistance in oil, generally, increases gradually but at the last 7 microseconds before current zero it increases with a very high rate. At any instant before current zero, it increases with the decrease in the interrupted current value. It varies from 5000 to 2000 ohms for the interrupting current of 228 through 456 A at 2 μs before current zero.

8. Conclusions

To interrupt a current in oil under very short-line fault conditions, an artificial line has been constructed. In this matter there were questions about the type and the number of links of that line in order to reproduce the characteristic triangular voltage waveform. The π-type air-cored line has been chosen as the changing of elements is easy. As for the number of links, it was found that 4 through 8 sections are nearly enough to reproduce the sawtooth waveform. Twice increasing the capacitance value of the first-section capacitor does not result in the remarkable changes on the line-side triangular waveform. Thus the experiments verified the existence of the severe sawtooth waveform on line-side TRV when interrupting the current by oil interrupter under SLF conditions.

To observe the effect of the surge impedance of the artificial line, the capacitance of each section has been reduced by 20 % so as to change the impedance from 395 to 442 Ω. The sawtooth waveform can be reproduced by using smaller number of sections for higher line-side surge impedance.

The current and the arc voltage waveforms during the final 20 μs before current zero affect the reproduced line-side TRV. The sudden change of arc voltage just before current zero has deformed the triangular oscillations, and the peak of those oscillations was found to be in direct correlation to the value of the arc voltage.

The deformation of current before its zero (current chopping is also included here) affects the shape of the triangular oscillations.

The amount of damping of the line-side TRV may vary from test to test, and in extreme cases these oscillations disappear completely which is characteristic for current interruption in oil. Of course, the triangular waveform during the transident state of the recovery stage will shift over the steady state sinusoidal one during the lapse of time.

The arc resistance in oil increases sharply before the current zero, but decreases with the increase of the value of the interrupted current.

The authors hope the present paper will contribute to have some definite ideas about the current interruption in oil under SLF conditions in the actual power systems. They also wish to express their sincere gratitude to Dr. Masayuki YODA who kindly prepared and carefully revised the typescript.

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