Medium Voltage Laboratory for Load Break Switch Development

Erik Jonsson and Magne Runde

***Abstract*—A new, directly powered laboratory for studying current interruption in medium voltage load break switches has been designed, built and tested. Since the current amplitude and the initial part of the transient recovery voltage (TRV) in general are found to be the most important factors for whether an interruption will be successful or not, the test circuit has been made with this in mind. It is demonstrated that the TRVs up to the first peak voltage of the so-called ”mainly active load current duty” of the IEC 62 271-103 standard can be accurately replicated for all voltage classes from 7.2 to 52 kV by using a relatively small and inexpensive 600 kVA laboratory transformer delivering 6.9, 12, 13.8 and 24 kV. Test currents span from 400 to 1 250 A (only to 630 A for the lower voltage classes). The values of the inductances, resistances and the capacitance of the test circuit are adjustable over a wide range, as this is required to achieve such a great versatility. The laboratory is well suited for empirical investigations of interrupting capabilities of switchgears, for example by varying one factor (rate of rise of recovery voltage, TRV amplitude, current amplitude, point on wave, etc.) at the time, while keeping the others constant.**

***Keywords*: Load break switch, switchgear, medium voltage laboratory, transient recovery voltage, IEC type test.**

I. Introduction

CURRENT interrupting tests constitute an important part of the process of developing and qualifying new high voltage switchgear designs and products. Such tests require extensive laboratory facilities and are time consuming and expensive, in particular when considering equipment for high ratings. Consequently, the tests are often focusing strongly on the type test requirements specified in the standards, and to a lesser extent aiming at fully understanding the behavior of the device.

Investigating and in detail exploring the interrupting capabilities of a switchgear require a test facility that can vary the most important circuit parameters over a rather wide range. The essential parameters in this context are the current levels and the transient recovery voltage (TRV), in particular the TRV steepness immediately after the arc has been extinguished and the current is interrupted. Such investigations may give a better understanding of the properties and behavior of the device, and identify critical features for further design improvements.

For studying current interruption in high voltage circuit breakers the amplitudes of the currents and voltages involved are often so large that in most cases so-called synthetic test circuits have to be applied [1]. The supply current and the recovery voltage are here generated by two separate circuits. Due to this, synthetic circuits normally provide great flexibility, but careful timing is necessary for generating a realistic TRV during the crucial thermal interruption part, i.e., in the first tens of microseconds after current zero.

Such difficulties do not arise if the test circuit is directly powered from the grid. Hence, for testing switchgear of more modest current and voltage ratings, a directly supplied test circuit is a better option. The device is then subjected to stresses of a nature exactly as in service.

The present paper describes a directly powered laboratory for research on load current interruption at the medium voltage (MV) level. MV load break switches typically have interrupting capabilities up to around 1 kA and are installed in large numbers in distribution networks [2]. It will be shown that by carefully selecting the parameter ranges for the inductances, resistances and capacitance of the test circuit, a very flexible and versatile laboratory can be obtained with a reasonably rated and not too expensive power transformer.

Only the initial part of the TRV is addressed, as re-ignition at a later stage usually is less of a problem for MV load break switches [3], [4]. The International Electrotechnical Commisson (IEC) type test conditions for ”mainly active load current duty” [5] form the basis for the laboratory layout. It will be demonstrated that the first few hundred microseconds of the TRV for all IEC voltage classes from 7.2 to 52 kV for a wide range of currents can be generated by using one transformer delivering 6.9, 12, 13.8 and 24 kV.

Initially, the circuit providing the considered IEC test duty is analyzed, and the TRVs are determined for the different voltage classes. Then follows a description of the design of the laboratory components, including their parameter ranges. Finally, measurements confirming that a wide range of TRVs can be achieved this way are shown.

This new laboratory is located at the Norwegian University of Science and Technology in Trondheim, Norway.

II. Analysis of the IEC 62 271-103 MV Standard

The MV load break switch standard issued by IEC [5], prescribes several test duties, including rated load current

This work is supported by the Norwegian Research Council.

E. Jonsson is with the Department of Electrical Power Engineering, Norwegian University of Science and Technology (NTNU), 7491 Trondheim, Norway (e-mail: erik.jonsson@elkraft.ntnu.no).

M. Runde is with the Department of Electrical Power Engineering, Norwegian University of Science and Technology (NTNU) and with SINTEF Energy Research, 7465 Trondheim, Norway.

Paper submitted to the International Conference on Power Systems Transients (IPST2013) in Vancouver, Canada July 18-20, 2013.

interruption, closing at full short circuit current, as well as dielectric withstand test for open position. Moreover, some load break switches are designed for special purposes, and special type tests exist for these cases. However, for the vast majority of load break switches, the mainly active load current duty is the dimensioning current interruption test. The associated test circuit is defined by the following requirements [5]:

- The test circuit should consist of a supply circuit and a load circuit.
- The load should contain a resistor and a reactor in parallel. The impedance of the load should have a power factor of 0.7±0.05.
- The supply circuit should contain a resistor and a reactor in series. The impedance of the supply circuit should be 15±3% of the total impedance and have a power factor less or equal to 0.2.
- The prospective TRV should have a peak value U_c with a time coordinate t_3, specified for each rated voltage.

Fig. 1 shows the test circuit according to the requirements. The implications of the first three requirements are clear, while the last one needs some elaboration.

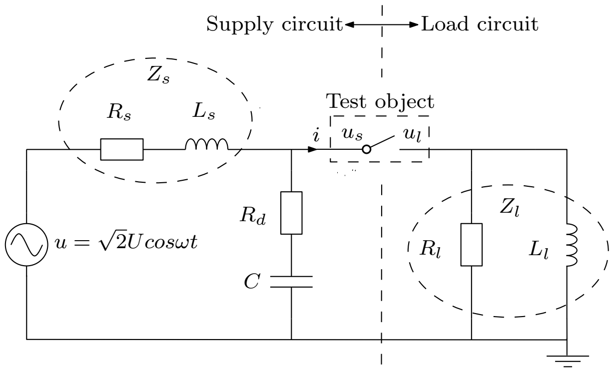

Fig. 1. Single phase circuit for IEC "mainly active load current duty". The voltages at the terminals of the test object are referred to as u_s (supply side) and u_l (load side).

Define the supply impedance as $Z_s = R_1 + jX_1$ and the load impedance as $Z_l = R_2 + jX_2$. The following set of equations can then be established with basis in the requirements listed above.

$$\begin{cases} (R_1 + R_2)^2 + (X_1 + X_2)^2 = |Z_{tot}|^2 \\ \sqrt{R_1^2 + X_1^2} = 0.15 \cdot |Z_{tot}| \\ \cos\left(\arctan\frac{\mathrm{X_1}}{\mathrm{R_1}}\right) = 0.2 \\ \cos\left(\arctan\frac{\mathrm{X_2}}{\mathrm{R_2}}\right) = 0.7, \end{cases} \tag{1}$$

where $Z_{tot} = Z_s + Z_l$.

For a three phase test the supply voltage u should be the rated voltage. For a single phase circuit the first-pole-to-clear factor of 1.5 needs to be included, and the supply voltage becomes the rated voltage multiplied by $(1.5/\sqrt{3})$.

For rated voltage and current of 24 kV / 630 A, (1) has the solution

$$R_1 = 0.99\ \Omega, X_1 = 4.84\ \Omega, R_2 = 20.5\ \Omega,_2 = 20.1\ \Omega.$$

In a 50 Hz system the values for the circuit components then become

$$R_s = 0.99\ \Omega, R_l = 40.7\ \Omega, L_s = 15.4\ \text{mH}, L_l = 129.4\ \text{mH}.$$

In order to comply with the IEC requirements for the TRV, the supply side of the circuit must also have a capacitor and a damping resistor. The damping resistor can be placed in series (as in Fig. 1) or in parallel with the capacitor. Most commonly used is the series damped circuit since the resistor then experiences much less ohmic dissipation. The series damped case gives a steeper start of the TRV, and the current interruption becomes slightly more difficult compared to the parallel damping case. In the present work only the series damped case will be considered.

The shape of the mainly active load type test TRV is not explicitly specified in the standard, but is defined by means of the prospective TRV. (The prospective TRV is the resulting TRV when the load is short-circuited.) It is not practical to adjust the prospective TRV using full rated voltage, since the resulting current and TRV will exceed the rating of the switch and the other test circuit components. Hence, normal procedure is to scale down all voltages when tuning the supply circuit parameters to obtain the prescribed prospective TRV. Alternatively, the circuit impedances can be determined by numerical simulations, here done with ATPDraw.

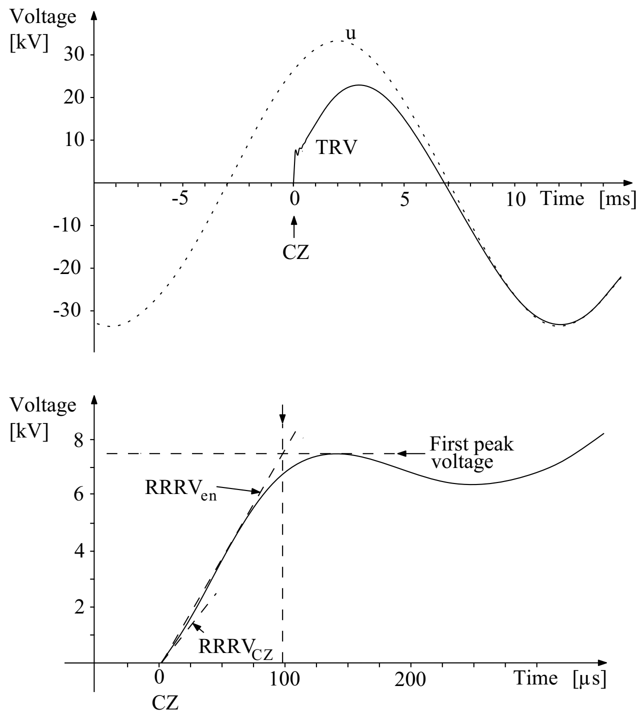

Fig. 2. Voltage waveforms from a typical 24 kV single phase mainly active load type test. Time t = 0 corresponds to CZ and current interruption. The lower part shows the first 350 μs of the TRV.

Fig. 2 shows the supply voltage and the simulated TRV for a successful 24 kV single phase type test. For more exact characterization of the initial part of the TRV, two additional parameters are also presented; the envelope rate of rise of recovery voltage (RRRV$_{en}$) and the initial rate of rise of recovery voltage (RRRV$_{CZ}$). The latter is the tangent of the voltage curve at current zero (CZ).

For the 24 kV voltage level, the IEC standard specifies that the prospective TRV should have a first peak voltage of U_c = 41 kV with a time coordinate t_3 = 88 μs. The values for the capacitor and the damping resistor yielding this voltage waveform can be calculated or experimentally determined by an iteration process to C = 0.147 μF and $R_d = 216$ Ω.

As can be seen in Fig. 2, with the load connected the resulting first peak voltage for the type test is about 7.6 kV which corresponds to 19% of the prospective value, since 85% of the source voltage is now over the load. The resulting TRV is the difference between the supply and load side voltages, but in the beginning the supply side dominates and the load side only contributes with a relatively slow exponentially decaying voltage. The shift of the time coordinate from 88 to 96 μs is mainly a consequence of changing the power factor from about 0.2 to 0.7, affecting the location of the CZ relative to the source voltage.

The same procedure is carried out for other voltage classes, and the results are given in Table I. The first peak voltages for the prospective TRV and the TRV with load are referred to as U_c and U_c', respectively. The same notation is used for the time coordinates t_3 and t_3'.

For a load break switch the thermal phase (first microseconds after CZ) usually poses the most difficult part of the interruption. Thus for more precise description of the stresses, the values for both RRRV$_{en}$ and RRRV$_{CZ}$ are included in Table I.

TABLE I
TRVS FOR IEC MAINLY ACTIVE LOAD TYPE TEST DUTY

Rated voltage [kV]	Prosp. TRV [5] U_c [kV]	t_3 [μs]	TRV (with load) U_c' [kV]	t_3' [μs]	RRRV$_{en}$ [V/μs]	RRRV$_{CZ}$ [V/μs]
7.2	12.3	52	2.1	56	38	34
12	20.6	60	3.6	65	55	50
24	41	88	7.6	96	80	72
36	62	108	12.0	116	103	93
52	89.2	138	18.5	152	123	111

All values in Table I are calculated for a current of 630 A, but other currents yield nearly identical results. Hence, the TRVs of the values in the table apply for all relevant current ratings.

III. Laboratory Circuit for Switchgear Development

A. Testing with Reduced Supply Voltage

In total 13 different MV classes, from 3.6 to 52 kV, are listed in the IEC standard. Providing type test conditions for only the five classes of Table I is in itself demanding for a laboratory, typically requiring a large, flexible and thus expensive transformer solution.

Furthermore, the IEC mainly active load type test requires a low impedance at the supply circuit side. For the 24 kV / 630 A example above, the supply side inductance should be 15.4 mH. This value also includes the inductive part of the short circuit impedance of the connected power system, of which the leakage inductance of the test transformer constitutes a major part. (The resistive part of the short circuit impedance is negligible in this context.) To be able to deliver a sufficiently large current for type testing of the important 24 kV / 1 250 A class load break switch, an even lower supply side inductance of around 8 mH is required. Again, this is not easily achieved, and adds on to the cost and complexity of the test transformer.

Simpler solutions can be obtained by taking advantage of the fact that the stresses occurring during the first few hundred microseconds after interruption are decisive for whether an interruption will be successful or not. Thus for switchgear development purposes it is largely sufficient to carry out tests with the correct current and the correct "IEC TRV" up to the first peak voltage, see Fig. 2. If the TRV is as defined by the parameters of Table I for the considered test voltages, the stresses on the device during these critical parts of the interruption are almost identical to the type test stresses. The shape and amplitude of the recovery voltage later on is of considerably less importance as dielectric re-strikes milliseconds after CZ is a rare occurrence in MV load break switches.

An important implication of this approach is that the supply voltage of the test circuit can be reduced compared to that of the true type test conditions. Furthermore, a higher test transformer leakage inductance can be accepted, and these factors substantially bring down investment costs.

For creating a wide range of test conditions, the circuit components need to have sufficiently wide tuning ranges. In addition, a detailed understand how the various components affect the TRV is required to fully exploit the potential of the laboratory.

B. Creating Different TRVs

Even though the test circuit only contains six impedances it is not straight forward to analytically derive the relationships between the circuit parameter values and the resulting TRV waveform and current amplitude. However, by understanding a few basic principles of the circuit behavior, the desired TRV can relatively easily be found after a few iterations.

At the moment of interruption, u_s and u_l (see Fig. 1) are the same and given by the voltage division between Z_s and Z_l. The supply side is a damped series RLC circuit. After the arc has extinguished the supply side terminal experiences a voltage step, and u_s starts a damped oscillating around the supply voltage u. The load side voltage u_l decays exponentially. Fig. 3 shows both u_s and u_l after CZ.

The first peak amplitude and the steepness of the TRV are primarely related to the following three parameters:

- The voltage step U_{step} (see Fig. 3).
- The frequency of the supply side oscillation.
- The damping of the supply side oscillation.

The voltage step U_{step} is determined by the supply voltage, the voltage division between load and supply side, and the

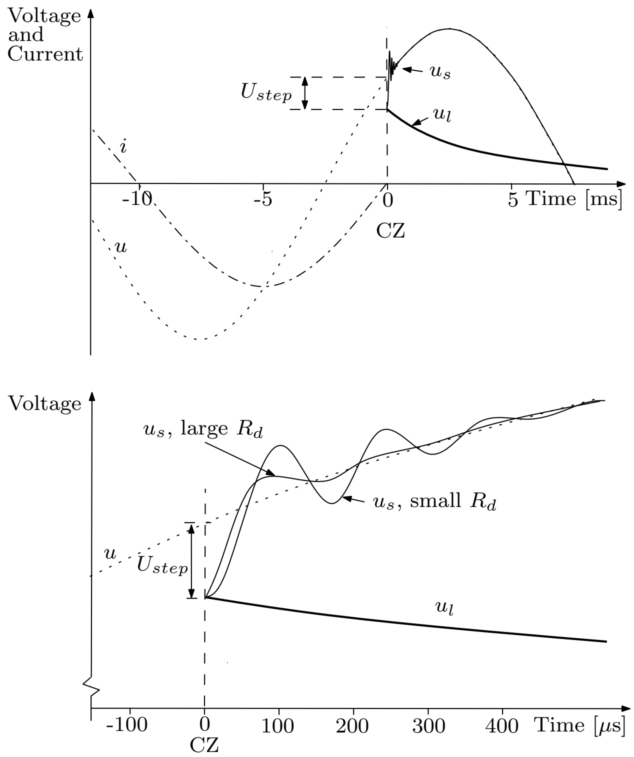

Fig. 3. Typical current and voltages during a current interruption. The two contributions to the resulting TRV, u_s and u_l are shown separately. U_{step} is the voltage across the supply side impedance at CZ. The lower graph shows the first part of the TRV and the effect of changing the damping resistance.

phase angle. Changing the ratio between load and supply side impedances changes U_{step}, and thus also the TRV amplitude.

From the general theory of a damped oscillation the frequency of the supply side oscillation is given by

$$f = \frac{1}{2\pi}\sqrt{\frac{1}{L_s C} - \left(\frac{R_d}{2L_s}\right)^2}. \tag{2}$$

The minute contribution from R_s is here neglected.

Unless the circuit is over-damped the first term of (2) is dominating over the second. Since the value of the capacitor can be adjusted without significantly changing the current through the test object, this is a convenient way of changing the time coordinate and frequency of the TRV.

Adjusting the damping has several effects on the TRV. For example, when increasing R_d the first peak voltage U_c' decreases, the time coordinate t_3' decreases, and the initial part becomes steeper, as shown in Fig. 3.

IV. Building the Laboratory

With basis in the considerations above, a laboratory for MV switchgear development was designed and built. The three phase laboratory transformer is directly powered from the 11.4 kV distribution system in the area, but the secondary side test circuit is only for single phase experiments. Fig. 4 shows the circuit diagram where the short circuit resistance R_{sc} and inductance L_{sc} of the test transformer and the external network are drawn together with the circuit components. The resistance R_s of Fig. 1 should be small and is not critical for tuning the TRV. In the realization of the test circuit R_s is simply taken as the short circuit resistance R_{sc}. (That is, R_{sc} is not a physical component.)

The operating mechanisms of both the laboratory circuit breaker (CB) and the test object have installed equipment for synchronizing the contact opening with the supply voltage. This makes it possible to control the contact position at the moment of current interruption and thereby efficiently study the effects of different arc lengths and arcing times.

For simplifying the TRV measurements the ground point is located at the load side terminal of the test object. This does not influence the TRV since the neutral point of the transformer is floating.

Even though it is not the objective to perform IEC type testing, it is still advantageous to have a laboratory transformer with a low leak inductance, as this gives greater flexibility for making different TRVs. The thermal rating of the transformer, on the other hand, is less of a concern as typical current interruption tests only last a few power cycles. A three phase 600 kVA transformer with a low short circuit impedance, providing 6.9, 12, 13.8 and 24 kV was designed, built and installed. Although being a customized device, the size and cost of this test transformer is small compared to what would be needed for a transformer able to power a full IEC mainly active load test duty.

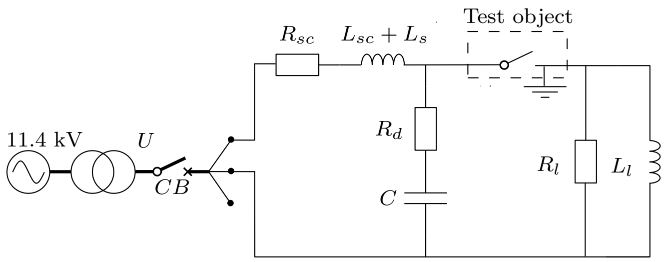

Fig. 4. Laboratory circuit diagram. The short circuit inductance L_{sc} and resistance R_{sc} are drawn as circuit components. Several disconnectors and earthing switches installed for personnel safety reasons are omitted from the diagram.

To generate the correct current amplitudes and the associated TRVs corresponding to a wide variety of IEC MV test levels, the components of the test circuit need to be adjustable over a wide range and with fairly small steps. Table II lists the ranges and resolution of the resistances, the inductances and the capacitance of the laboratory components.

TABLE II
Laboratory Components Values

	Symbol	Range	Step lenght
Load reactor	L_l	30-390 mH	1 mH
Load resistor	R_l	5-95 Ω	0.5 Ω
Supply reactor	L_s	0-70 mH	1 mH
Capacitor	C	0-9.676 μF	2 nF
Damping resistor	R_d	0-1 000 Ω	5 Ω

The reactors and resistors are all designed and built in-house, whereas the capacitor unit is assembled from commercially available devices. Obviously, the main challenges are to allow for fine tuning of the component values over a wide range, and at the same time avoid excessive dielectric stresses or excessive ohmic heating in any part.

The load reactor L_l consists of two separate air core coils connected in series, one with nine coarse steps of 30, 70, 110, ... 350 mH and one with 40 fine steps of 1 mH each. The two coils are about 0.6 m in diameter and 1.7 m tall, and are shown in Fig. 5.

The supply side reactor L_s is also made up by two coils in series. These have similar design as L_l, but are only about 1 m tall.

The coils are wound with a 2.1x4.5 mm cross section copper wire, in total about 5 km for all four coils. The wire is insulated with two layers of polyamide film, giving a partial discharge tolerant insulation up to stresses of 10 kV between neighboring turns. The copper wire is wound in 3-5 cm deep and 2.5 cm wide slots machined into a thick-walled polyethene pipe.

The coils are designed to not heat up more then 15°C during an interruption experiment of 1 250 A lasting for ten power cycles. For improving the mechanical strength and integrity, the windings are impregnated with glass fibre reinforced epoxy.

Fig. 5. Load reactor (in the 390 mH setting). The left coil is for coarse tuning and the right coil for fine tuning.

The load resistor R_l is shown in Fig. 6. It consists of 82 resistance elements, stretched up in a 4x2x1 m large frame, made of a non-flammable material. This component also has two sections connected in series, one for coarse and one for fine tuning.

Each resistance element consists of two equally long, parallel FeCrAl wires, of diameter in the range of 2-4 mm. These are wound as two springs, with opposite winding directions, one placed outside the other and with glass fiber fabric between. This design gives virtually no inductance. In the middle of each element a pipe of pressed mica provides structural support and restricts sideway movements.

With a current of 1 250 A for ten power cycles some of the resistance elements heat up 150°C. Substantially higher temperatures, probably up to around 1000°C, can be handled in a safe manner. This permits repetitive usage without too long cooldown times.

The damping resistor R_d is also made of FeCrAl wires. The current through this component is never exceeding a few ampere over a few milliseconds, making it much smaller than the load resistor.

Fig. 6. Load resistor.

The capacitor is assembled from 13 commercially available capacitors with the following values: 2, 4, 8, 16, 32, 64, 100, 150, 300, 600, 1 200, 2 400 and 4 800 nF. These can be connected in parallel in any combination, giving values from 2 nF up to almost 10 μF.

V. Results

Fig. 7 shows corresponding TRV and current waveforms obtained from a current interruption test replicating the initial and most important part of the 24 kV / 630 A IEC mainly active load current duty. An interval of some 400 μs around CZ is included. Since the supply voltage is only 13.8 kV, the shape of the TRV is similar to the type test conditions only for about the first hundred microseconds after interruption. The TRV is here nearly identical to the simulated waveform of Fig. 2 and well within the 3% margins given in the standard.

By changing the transformer setting and adjusting the parameter values of the test circuit components, the initial part of the TRV has been tuned to replicate 12 different IEC test conditions. As shown in Table III, voltage classes from 7.2 to 52 kV are included, each with two or three current ratings. The output voltage of the transformer and the associated short circuit inductances and resistances are listed in the table, as are the set values for the test circuit components. Finally, the last five columns of Table III list the measured current amplitude and the characteristic parameters of the resulting TRV. Comparing these numbers with those presented in Table I demonstrates that it is possible to obtain a wide variety of test conditions this way. The results in Table III are merely examples; the TRV of any other intermediate current and voltage values can certainly also be achieved.

The short circuit impedance of the different voltage settings in the transformer limits the current to around 700 A for 7.2, 12 and 24 kV levels. For the higher voltage levels, the current can be varied in the range 400 to 1 250 A, while

TABLE III
CIRCUIT SETTINGS AND MEASURED CURRENT AMPLITUDES AND TRV CHARACTERISTICS

Rated values		Transformer parameters			Circuit component values					Measured current and TRV characteristics				
Voltage [kV]	Current [A]	U [kV]	L_{sc} [mH]	R_{sc} [Ω]	L_s [mH]	L_l [mH]	R_l [Ω]	C [nF]	R_d [Ω]	I [A]	U_c' [kV]	t_3' [μs]	RRRV$_{en}$ [V/μs]	RRRV$_{CZ}$ [V/μs]
7.2	400	6.9	1.5	0.5	5	72	21	126	150	398	2.09	55	38	38
	630	6.9	1.5	0.5	3	47	13	208	150	625	2.20	57	39	39
12	400	6.9	1.5	0.5	8	79	18	108	35	403	3.61	66	55	44
	630	6.9	1.5	0.5	5	45	12	182	35	632	3.57	65	55	46
24	400	13.8	10	1.0	15	138	36	74	250	410	7.49	97	77	68
	630	13.8	10	1.0	7	86	22	102	200	634	7.50	92	83	71
36	400	24	25	2.8	14	225	63	64	100	399	11.51	119	97	62
	630	24	25	2.8	0	143	42	80	200	638	11.52	112	103	81
	1250	13.8	10	1.0	5	40	18	230	150	1 271	11.95	116	103	93
52	400	24	25	2.8	39	240	51	62	350	398	18.60	149	125	98
	630	24	25	2.8	17	134	30	100	250	632	18.47	149	124	91
	1250	13.8	10	1.0	13	94	16	250	150	1 240	18.50	154	120	99

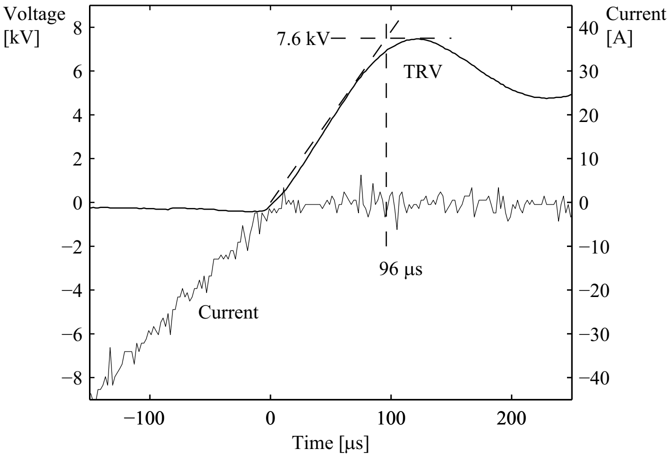

Fig. 7. Unfiltered measurement data of current and TRV during a successful load current interruption test. The sampling frequency is 5 MHz. The amplitude and the time coordinate of the first voltage peak of the TRV correspond to the values resulting from the IEC test requirements for the 24 kV / 630 A case, see Table I.

complying with the type test TRV requirements up to the first peak voltage.

VI. DISCUSSION AND CONCLUSION

Design, building and testing of a directly powered new MV laboratory devoted to current interruption research and development on load break switches have been described. It has been demonstrated how the initial and crucial part of the TRV of the considered type test duty for load break switches rated from 7.2 to 52 kV can be generated with a modestly rated test transformer, provided that the values of the inductances, resistances and the capacitance of the test circuit can be varied over a wide range.

The flexibility of the laboratory also makes it well suited for parameter studies and more fundamental investigations of current interruption at the MV voltage level. For example, a test series where the rate of rise of the recovery voltage just after current zero crossing is gradually increased while the current is kept constant, can provide information about the interrupting capability of a switching device and identify crucial design parameters. Similarly, tests where the current is increased in small steps while keeping the TRV unaltered may also give insight into basic aspects of arc quenching, and thus contribute to improving and optimizing a MV switchgear.

ACKNOWLEDGMENTS

The authors greatfully acknowledge the contributions from Nina Sasaki Aanensen, Bård Almås, Tor Bratsberg, Horst Førster, Hans Kristian Høidalen, Vladimir Klubicka, Oddvar Landrø, Odd Lillevik and Niklas Magnusson.

REFERENCES

[1] R. D. Garzon, *High Voltage Circuit Breakers Design and Applications*, New York: Marcel Dekker, 1997.
[2] B. M. Pryor, "Distribution switchgear," in *High Voltage Engineering and Testing*, H. M. Ryan, Ed., 2nd ed., London, UK: The Institute of Electrical Engineers, 2001.
[3] E. Jonsson, N. S. Aanensen and M. Runde, "Current Interruption in Air for a Medium Voltage Puffer Load Break Switch, to be published.
[4] D. Birtwhistle, G. E. Gardner, B. Jones and R. J. Urwin, "Transient recovery voltage and thermal performance of an airblast circuit breaker," *Proc. IEE*, vol. 120, no. 9, 1973.
[5] *High-voltage switchgear and controlgear - Part 103: Switches for rated voltage above 1 kV up to and including 52 kV*, IEC International Standard no. 62 271-103, ed. 1.0, 2011.