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L. Ducimetière
D.C. Fiander

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COMMUTATION LOSSES OF A MULTIGAP HIGH VOLTAGE THYRATRON

L. Ducimetière, D.C. Fiander
CERN, Geneva, Switzerland

Summary

Commutation loss measurements have been made on an EEV CX1171 three gap ceramic thyatron. It was operated in a $15\ \Omega$ impedance system, switching square pulses derived from a cable pulse forming network (PFN) directly into a matched load. The flat top current reached 2.6 kA at 80 kV charging voltage with a rise time of about 35 ns. Losses were measured from $\int u \cdot i \cdot dt$, u and i being the tube voltage drop and current respectively. Variable parameters were PFN voltage and reservoir voltage. Further investigation of voltages appearing on the intermediate gradient grids has allowed a better understanding of the commutation process and a localisation of the losses within the tube.

Ferrite saturable reactors have been series connected to the thyatron, primarily to reduce the commutation loss, but also to improve the di/dt . Both single and multi-turn devices have been tested. At best a reduction in the commutation loss by almost an order of magnitude has been obtained. A comparison of thyatron losses as a function of PFN voltage is given for both single and multi-turn reactors and also without saturable reactor. With a single-turn reactor an average rate of rise of 200 A/ns has been obtained against a typical figure of 65 A/ns for the same tube in the same operating scenario but without reactor. Possible disadvantages arising from the use of a saturable reactor in a cable PFN generator have also been investigated.

Introduction

Many present-day pulse power applications, including kicker magnets of particle accelerators, require ever higher repetition rate and di/dt from their thyatron switches. Commutation losses then assume an importance which is absent from lower frequency applications, leading to problems of anode heating, gas rarification and gas clean-up.

This paper seeks to investigate commutation losses of a multi-stage high voltage thyatron in a circuit of intrinsically high di/dt and to establish the relationship between these losses and operating voltage and tube gas pressure. It also aims to test out methods for the reduction of commutation loss whilst at the same time preserving or improving the switch di/dt capability.

Test Conditions

The thyatron under test was installed in an existing $15\ \Omega$ impedance generator (Fig. 1). This generator had been conceived for

Fig. 1: Test circuit.

the investigation of inverse conduction in hollow anode thyatrons [1] and in consequence was arranged for negative charging with the test thyatron anode at ground potential. This arrangement had the advantage in the present study of facilitating the connection of saturable inductors in series with the tube anode but the disadvantage of producing a large initial overshoot due to parasitic capacitance of the isolating transformer and grid drive components of the cathode region. The presence of this overshoot should be borne in mind when considering the absolute values of the commutation losses measured.

The PFN voltage was provided by a pulsed resonant power supply, adjustable in the range 25 to 80 kV. Flat top current at 80 kV was 2660 A, the initial peak due to the above mentioned capacitance being some 40% higher. The pulse duration, determined by the PFN cable length, was 300 ns.

Fig. 2 shows the thyatron with the $14\ M\Omega$ resistors for equal distribution of voltage over the three gaps and the four capacitive pick-ups for voltage measurement at its anode, cathode and two gradient grids. The drift spaces were closed by $540\ \Omega$ resistors of time constant $< 7\ ns$. Throughout the whole investigation the grid 1 current was maintained at 50 mA and the grid 2 bias at -150 V.

Fig. 2: Thyatron electrode arrangement.

The tube tested was a 3-inch ceramic device, EEV type CX1171. It had been manufactured in 1980 but was virtually unused prior to the present measurements. Its rise time performance may be slower than that of currently produced tubes of the same type because of detail improvements since introduced by the manufacturer.

Measurement method

The thyatron current was measured by a Pearson 110 current transformer in the anode to ground connection. Voltages were measured by integration of the signals derived from the low capacitance pick-ups, using a $140\ \mu s$ integrator time constant; the bandwidth extended from 2 kHz to 200 MHz. The voltage pick-up (Fig. 3) was formed from two coaxial cylinders with layered Kapton polyimide film and epoxy insulation. The external cylinder was connected to the point of measurement and the signal to be measured

was derived from the internal one, which was thus shielded from cross-talk with adjacent pick-ups. Inter cylinder capacitance was 10 pF. This method of voltage measurement was preferred to a resistive voltage divider because of its compactness and generally better frequency response. The extremely high electrical stress in the pick-up did not prove a problem provided that care was exercised in its fabrication.

Fig. 3 : High voltage coaxial capacitive pick-up.

Signals were processed on a Gould 4074 oscilloscope, allowing simultaneous digitising of four channels at 400 Msamples/s in single shot mode. Vertical resolution was 8 bits and bandwidth 100 MHz.

Losses were determined from $\int u \cdot i \cdot dt$ where u and i are respectively the instantaneous tube voltage drop and current. The processing facilities of the oscilloscope were able to evaluate these losses from the displayed voltage drop and current waveforms. Because the thyatron has a small finite inductance it stores reactive energy during the current rise and restores it only during the current fall. To neutralise this reactive energy the analysis was extended from the start of the leading edge to the end of the trailing edge of the current pulse.

Conduction losses are difficult to assess from such measurements because of the markedly reduced voltage scale at which they occur. Investigation of conduction losses was made with a high sensitivity, high offset Tektronix oscilloscope which permitted a voltage drop of the order of 300 volts to be accurately measured at 80 kV PFN charging level.

Normal Commutation

In the case of normal, magnetically unassisted commutation, the losses can be predicted from the following simplified model :

Provided that the voltage collapse and current rise occur synchronously, have the same duration and are linear then the commutation loss P is given by

$$P = \frac{UIt}{6} \quad (1)$$

or expressed in terms of the more usually quoted 10-90% rise time t_r

$$P = \frac{UIt_r}{4.8} = 0.21UIt_r \quad (2)$$

The voltage drop and current waveforms of Fig. 4 show that the above assumptions are largely respected excepting for the linearity of current rise. The lower trace of Fig. 4 shows the computed loss from the two upper waveforms. Three time zones can be distinguished :

- i) the switching time of about 50 ns - the commutation losses appear, supplemented by reactive energy stored in the tube inductance.
- ii) the current flat top of about 250 ns - the integral is not increased by conduction losses because the associated voltage drop is too small to be detected on this voltage scale.
- iii) the current-fall region - the reactive energy is restored, decreasing the loss integral to its final stable value.

Fig. 4 : Normal commutation at 80 kV.

These measurements were made for the tube operating at various reservoir voltages and over a PFN charging voltage range of 25 to 80 kV. The 10 - 90% current rise time was determined for each measurement. The results are presented in Fig. 5

A useful loss coefficient C can be derived from the curves of Fig. 5 such that

$$C = \frac{P}{UIt_r} \quad (3)$$

where P is the commutation loss
 U is the switched voltage
 I is the peak switched current
 t_r is the 10 - 90% rise time to current flat-top.

This coefficient C is plotted in Fig. 6, showing that it remains essentially constant for all reservoir voltages and PFN charging voltages considered. The measured coefficient of 0.15 is at variance with the theoretical coefficient of 0.21 of equation (2) mainly because of the non-linearity of the switched current. It is concluded that the loss coefficient of Fig. 6 permits a reliable prediction (+/- 10%) of the commutation loss, knowing the voltage and current being switched and the current rise time.

Fig. 5 : Rise time and losses for normal commutation.

The energy stored in the inter-electrode capacitance of the thyatron, and which is lost in the commutation process [2], is initially equal to $0.17 CU^2$ but rises to $0.68 CU^2$ as the gaps of the tube successively break down. (C is the interelectrode capacitance of one gap and U is the total voltage being switched). Most of this loss is included in the measurements of Fig. 5, only that part of the capacitive current not passing through the current transformer as the early gaps fire failing to contribute to the measured loss. The resulting error is negligible because the total capacitive stored energy amounts to only 3% of the recorded losses of Fig. 5.

Conduction loss, evaluated from independent voltage drop measurement during the flat top was found to be only 8% of the commutation loss at 80 kV for the specific pulse length of 300 ns of these measurements. Typical conduction voltage drops were 200 V at 30 kV PFN voltage and 260 V at 80 kV PFN voltage. In the present operating scenario the pulse length would have to be 4 μ s for conduction losses to equal commutation losses at 80 kV PFN charging level.

Fig. 6 : Derived loss coefficient.

Measurement of the voltages appearing simultaneously on the cathode and both gradient grids has allowed a better understanding of the commutation process (Fig. 7). About 200 ns after triggering G2 the gap closest to the cathode was conducting and the full PFN voltage began to be shared between the centre and anode gaps. After a further 50 ns the centre gap was starting to conduct and the full PFN voltage was building up on the anode gap which in turn started to conduct 50 ns later. The loss measurements previously reported for the whole thyatron can be applied gap by gap on the assumption that the current recorded in the Pearson current transformer represents correctly that in each gap. The results show 20% of the total loss associated with the cathode gap, 10% with the central gap and 70% with the anode gap. The difference between the losses of the cathode and central gaps is possibly due to the presence of the grid structures in the cathode gap. That the most significant loss is in the anode gap is fully expected as it is this gap which is the final closing switch.

Fig. 7 : Commutation process.

The inductance of the thyatron in its coaxial housing can be deduced from the waveforms either from the reactive energy ΔE restored at the end of the pulse ($L = 2\Delta E/I^2$) or from the negative voltage ΔU induced across the tube at the end of the pulse ($L = \Delta U dt/di$). Both methods lead to the same value of 80 nH.

This inductance was found to remain sensibly constant independent of reservoir voltage or PFN charging voltage. It was also reasonably equally distributed over the three gaps of the tube.

Fig. 8 : Commutation process in presence of "dark current".

Commutation losses decrease with increasing reservoir voltage (Fig. 5) but this process has its limits because of the onset of "dark current" in the cathode gap. At a reservoir voltage of 5.65 V the lack of symmetry of the voltage distribution across the gaps is clearly shown in Fig. 8 with respect to Fig. 7, where the reservoir voltage was 5.55 V. Further increase of the reservoir voltage to 5.80 V resulted in self firing of the tube under test.

Magnetically assisted commutation

Magnetic assistance is more and more used in high power, high repetition rate switching applications involving either gas filled or solid state switches [3 to 6]. It was therefore considered interesting to study quantitatively the effects of such assistance on the commutation speed and losses of the CX1171 thyatron, maintaining the same mounting and circuit conditions as for the previously reported normal switching.

The principle of magnetic assistance is to connect a saturable reactor in series with the switch, generally on the anode side. This saturable reactor holds off the majority of the voltage from the beginning to the end of the switch closure and then itself allows the circuit current to rise to full value by saturating [7]. The circuit rise time then depends on its saturation speed, resulting in a degree of improvement over the natural circuit rise time with normal switching depending on the reactor design (unsaturated inductance, squareness of magnetic material B-H loop etc.). Theoretically the commutation losses can be zero with "zero voltage switching" but in practice this does not materialise because the ionisation within the switch is completed only when the current is established. Nevertheless a substantial commutation loss reduction should be possible by maintaining a high circuit impedance with the saturable reactor during the initial switch commutation.

Two designs of saturable reactor were tested; a single turn and a three turn device, both using rings of Philips type 4H1 ferrite (Fig. 9). Their main characteristics are given in Table 1. The volt-seconds were judged adequate for the reactors to hold off the voltage during the whole of the thyatron commutation period. They were available without the need for pulsed or d.c. bias of the cores.

Table 1

	Single-turn	Multi-turn	Unit
Volt-second product	2.1	2.0	mV.s
Unsaturated inductance	50	72	μ H
Saturated inductance	370	660	nH
Saturating current	64	26	A

Fig. 9 : Single and three-turn reactors.

Ferrite main characteristics :

$$\begin{aligned} \mu_{\text{ini}} &= 600 & B_{\text{sat}} &= 0.3 \text{ T} \\ \mu &= 1200 & H_{\text{sat}} &= 400 \text{ A.m}^{-1} \end{aligned}$$

Figs. 10 and 11 show respectively the commutation process of the CX1171 thyatron with the single and multi-turn reactors connected between anode and ground. In both cases all electrodes of the tube assume virtually the same potential before there is any build-up of main circuit current.

Fig. 10 : Commutation with single-turn reactor.

Fig. 11 : Commutation with three-turn reactor.

The upper traces of Fig. 12 show, for 80 kV charging, the cathode voltage, the voltage across the anode reactor and the switched current. The lower traces are the tube anode to cathode voltage and the switched current. The small amplitude of the voltage across the tube during the current build-up is indicative of significantly lower commutation loss, particularly as this voltage is partly due to the reactive energy storage.

Fig. 12: Thyatron and single-turn reactor waveforms at 80 kV

Fig. 13 shows the effect of increasing the voltage-time integral of the single turn core by pre-bias; no bias was used for the upper traces whereas for the lower traces the core was biased by -50 A prior to application of the pulse. Apart from the longer delay time there is no difference in the commutation process when pre-bias is used. In practice even with unipolar pulses some core-resetting occurs due to bipolar reflections in the post pulse period. The rise time and loss results of Fig. 14 were all obtained without recourse to core biasing.

Fig. 13: Effect of pre-biasing on saturation delay.

In Fig. 14 the rise times obtained from magnetically assisted switching are compared with those of normal operation, all other drive parameters being unchanged. With magnetic assistance the rise times decrease with increasing PFN voltage due to the relatively faster saturation of the cores. In absolute terms the single turn reactor gives a three-fold improvement at 80 kV over normal switching. The multi-turn reactor hardly improves the normal rise time but this is because of limitations imposed by the large saturated inductance. From Fig. 14 the very considerable reduction in losses when using magnetic assistance can be appreciated. This reduction is most marked at the highest voltages and amounts to a factor of 8 at 80 kV. The loss reduction is sensibly independent of the rise time, being the same for the single and multi-turn reactors. Ferrite losses are small and approximately half those of the commutation losses.

Fig. 14: Comparison of rise times and losses.

Whereas the preceding results clearly demonstrate the positive aspects of magnetic assistance it must also be pointed out that a significant negative voltage appears across the reactor at the trailing edge of the current pulse (Fig. 12). This voltage easily attains 30% of the PFN voltage and it sets up reflections within the cable PFN. Whether or not these pass through the switch in the post pulse

period depends on their magnitude and the magnetic state of the switch. Fig. 15 shows the current in the Pearson transformer for the three cases of normal, single turn and multi-turn reactor switching. Whilst the first two are reasonably free from post-pulse reflections the multi-turn reactor generates significant negative pulses. Interestingly the first expected negative pulse does not materialise, presumably because the core has been left in the positive remanent state. The post pulse "tails" generated by the inductance of the anode reactor are visible in Fig. 15.

Fig. 15 : Post-pulse disturbance.

Magnetic assistance can be said to offer a very large reduction in the commutation loss of the CX 1171 thyatron. Provided that the saturated inductance can be kept low there can also be a significant improvement in the di/dt capability without increase of jitter. There is no advantage in increasing the voltage-time integral of the magnetic core above that needed to cover the commutation period. The physical core size required depends on whether or not core biasing is used. Some degradation of fall time and post pulse ripple can occur but these negative effects can be minimised, and the positive aspects previously mentioned maximised, by using a single turn reactor.

Conclusion

Commutation losses of thyratrons can be determined from accurate measurement of the current and voltage drop during the switching period. A loss coefficient can be obtained for any given tube which allows prediction of the losses under a wide range of operating conditions. For short pulses of up to a few hundreds of nanoseconds the conduction losses are negligible compared to those of the initial commutation.

Typical commutation loss for the CX 1171 thyatron operating without magnetic assistance in a 15Ω circuit at 80 kV is 2.8 joules. This can be reduced to about 0.4 joules if a ferrite saturable reactor is connected in series with the tube. Rise time improvement also results if the reactor is of low saturated inductance, indicating the choice of a single turn reactor in most applications. Care must be exercised concerning post pulse reflections when using saturable reactors, particularly if these have significant saturated inductance.

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