INSTITUTE OF PHYSICS PUBLISHING JOURNAL OF PHYSICS D: APPLIED PHYSICS

J. Phys. D: Appl. Phys. **37** (2004) 2107–2111 PII: S0022-3727(04)78571-X

Pseudosparks in the nanosecond range of operation: firing, jitter, and current disruption

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Received 31 March 2004
Published 14 July 2004
Online at stacks.iop.org/JPhysD/37/2107
doi:10.1088/0022-3727/37/15/009

Abstract
The operation of pseudosparks (thyratrons with cold cathodes) of the TDI1-150k/25 type was investigated in the nanosecond time range of control and switching. Their most important characteristics are their reliability of firing—practically in 100% of cases, a jitter time—less than 4 ns, and the possibility of them switching off (interruption of a current) at a particular moment (after the first half of a discharge cycle). Investigations have shown that the TDI1-150k/25 device has all the above characteristics (which meet the current industrial demands) if the proper operational regimes are chosen. We have proven its parameters with a set of four switches working in parallel at the current level of a few hundred kiloamperes at our installations of the Dense Plasma Focus type, having an energy of several kilojoules.

1. Introduction

Switching of high currents is one of the most important processes developed in the framework of modern pulsed power technology. There are only very few switch types that can be used with high currents. The pseudospark (PS), based on a hollow cathode discharge (the so-called 'thyratron with cold cathode'), is a very efficient switch (PS switch (PSS)) for high current devices. For example, one of its modifications, namely the PSS of the TDI1-150k/25 type, can produce commutation currents well above a hundred kiloamperes [1]. Moreover the total charge transferred with it is more than 10^6 C, which gives a lifetime of the PSS at this level of commutated current (e.g. for Dense Plasma Focus (DPF) devices [2] of several kilojoules stored energy) more than one million shots. This is necessary for meeting specific industrial demands, viz the energy supply system of an industrial device must work for a reasonable period of time. As an example, the DPF, working with this system in a repetitive mode of operation (say 10 Hz) for x-ray microlithography [2], must operate for a week without undergoing repairs.

But there are several issues that have not been investigated yet for PSSs of such a kind. Of these the important ones are connected with the operational characteristics demonstrated by these devices in the nanosecond time range of control and switching. This is very important for relatively small installations, in which the 'communication time' between the main power elements (e.g. capacitors) has to be short compared with the switching time and consequently lies in this range [2]. An independent problem is the parallel operation of several PSSs with a small jitter. It is essential for a synchronous start of all the power elements, which is necessary for trouble-free operation of the main device and, obviously, from the emergency point of view. The last problem means that if one of the capacitors working in parallel with others has a breakdown, the rest of the bank has to be discharged onto a load—not to this capacitor. This circumstance leads to the above-mentioned demand to have the jitter shorter than the communication time between capacitors because in this case the safeguard system may be much simpler. It was not clear whether the PSSs working in the above-mentioned range can cope with the above-mentioned industrial demands.

The problems under discussion are the reliability of PSSs' firing and their jitter time, especially when several such devices operate in parallel in one installation. Also, a quite intriguing issue is the possibility of switching off the PSSs, i.e. a complete current disruption, possibly produced by these devices at a particular moment of time. If this is realized, such a PSS can preserve the rest energy in the bank, thus increasing the system efficiency and the capacitors' lifetime. It was obvious that in pursuing these goals we had to find for the PSSs the proper operational regimes. We performed our experiments with currents of a few hundred kiloamperes at our installations, of the DPF type, NX1 (Singapore) and PF-6 (Poland), each of them equipped with four PSSs working in parallel from one master spark (firing system). These DPFs are both of the Maither type [3]. They have four capacitors of the KMK-7 type (7 μF, 30 kV, 8 nH), each switched on by these four PSSs. Let us discuss some particular features of the PSSs' operation in this scheme.

2. Firing circuit of the PSS

A schematic view of our PSS is presented in figure 1.

The principles of operation of PSSs and in particular of the TDI1-150k/25 in the microsecond range are described in the literature (see e.g. [4, 5]). A heater is used in this device for heating a hydrogen generator, which releases the working gas inside the PSS chamber. Its final pressure depends on the voltage applied. We have found during our use of the TDI1-150k/25 in the *nanosecond range* that the reliability of its *firing* strongly depends on two main factors—the *pressure* of the working gas (i.e. on a current in a heater of PSS) and on the reliability of the *firing system*, which strongly depends on its design.

Our experiments have shown that the operation of the PSS becomes reproducible within a certain range of heater current values, which is approximately 20% of the maximal magnitude (for the voltage applied to the heater it is about 5–6 V). Below this range the PS may not be fired in each shot, whereas at the higher voltage self-breakdowns may take place. But within the 'working interval' the PSS demonstrates perfect operation. But one takes into consideration that the heater current depends on the resistivity of the PS heater, which is changed during the initial period of time (approximately 10 min) after the heater is turned on. So it has to be controlled over this period of time.

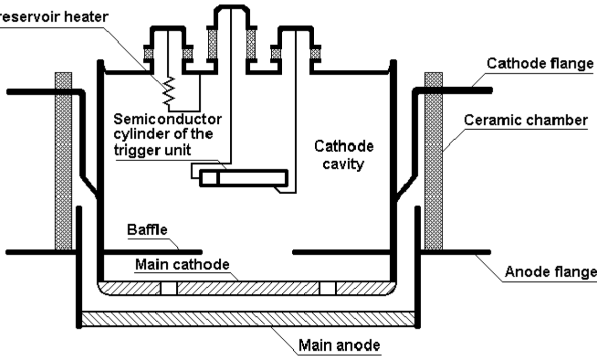

Figure 1. Design of the TDI1-150k/25.

We have tested two types of firing system. The first one was based on a single-pass cable, high-voltage discharge of a spark in nitrogen producing a triggering pulse for the PSS (figure 2(*a*)). Here four channels of this type work in parallel with one master spark gap that has been fired either with the help of an external trigger through the triggering electrode (TE) or simply due to its self-breakdown.

The other design was essentially the same as the previous one except that the Blumlein line [6] was used for this purpose. The first scheme is simpler. Fulfilling the demands on the rise-time and the trailing edge of the pulse formed by it is also easier here. The Blumlein scheme has the advantage that it may operate at a voltage two times lower than the previous one. But the point of pulse extraction must be designed very carefully for this construction to preserve the fast characteristics of the pulse. We have found several important points here.

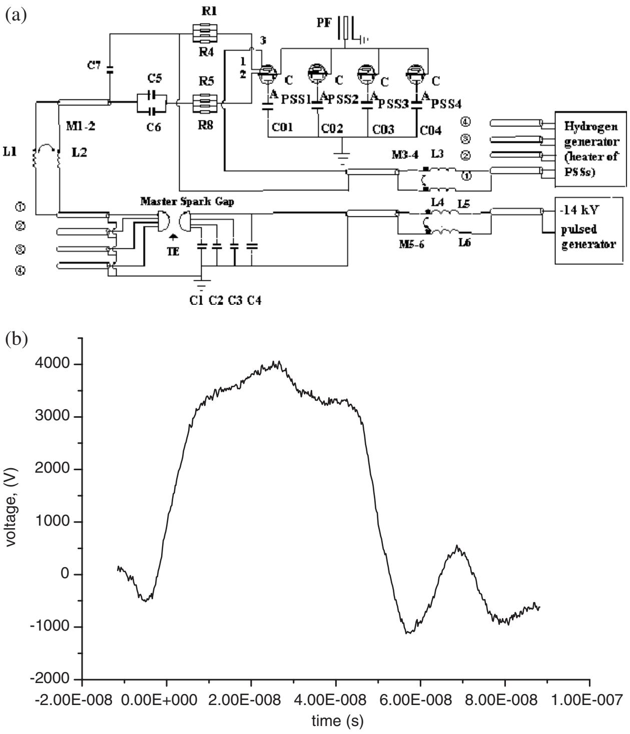

Figure 2. (*a*) Firing system based on four single-pass cables; here $R_1, \ldots, R_8 = 100\,\Omega$, 11 W; $C_{01}, \ldots, C_{04} = 7.8\,\mu$F, 30 kV; $C_1, \ldots, C_4$, capacitances of 6-m coaxial cables; C_5, $C_6 = 30$ pF, 30 kV; $C_7 = 1$ nF, 16 kV; $L_1, \ldots, L_6$, inductors; TE, triggering electrode of the master spark gap; $\mathrm{PSS}_1, \ldots, \mathrm{PSS}_4$, pseudospark switches; A, anode; C, cathode; 1, trigger connector (+); 2, trigger connector (–); 3, hydrogen heater connector; four trigger lines are used, ends going to PSS_1, PSS_2, PSS_3, PSS_4, respectively; one trigger line is shown, whereas the other three trigger lines are similar and are not shown. (*b*) Trigger pulse.

First, it appears that good and reliable operation is possible in both types of firing system only when the rise-time of the trigger pulse applied to the spark is shorter than 10 ns. We have found this parameter in both schemes to be within the limits of 4–10 ns (figure 3).

The same value has to be valid also for the trailing edge of the firing pulse. Note that the above-mentioned communication time between our capacitors is determined by the lengths of our cables between the bank and the current collector of the DPF chamber, and it was approximately 10 ns.

Second, we have found that the moment of switching on of a PSS (start of the main bank discharge through it) usually coincides exactly with the trailing edge of the trigger pulse (see figure 4). In the first scheme (in the case of the single-pass cable spark) we work with a charging voltage of the cable of about 8–9 kV (i.e. with the discharging voltage ∼4 kV) and with the cable length 6 m (i.e. at a pulse duration of 60 ns). It is interesting that the duration of the trigger pulse and its shape are both the same for the cases when this system is connected with the PSS and with an open end. Just the opposite result is observed for the Blumlein line. We have a cable length longer here than in the previous scheme, so that the pulse duration was approximately 80 ns. In this situation, for the same charging (and consequently discharging in this case) voltage the pulse shape strongly depends on the above conditions (see figure 3): when the firing system is connected to the PSS the pulse decreases in amplitude at the rise-time to half the amplitude and at the trailing edge almost to zero. Evidently it is a consequence of the matching conditions between the cable impedance and the input resistance of the PSS as well as the time of the discharge development inside the PSS. Nevertheless the start of the main bank discharge takes place at the end of the trailing edge of the pulse, as if the Blumlein line were disconnected.

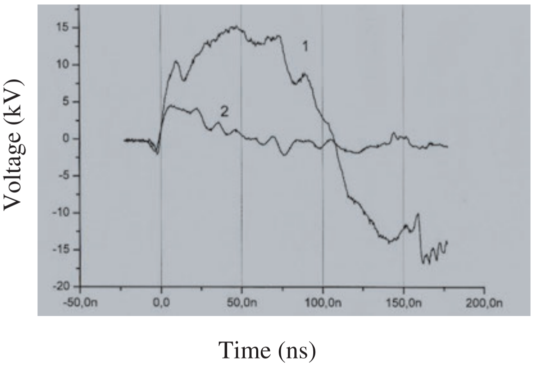

Figure 3. Trigger pulses in the cases of connected (1) and disconnected (2) firing systems.

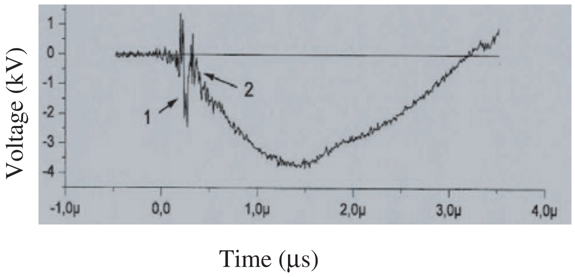

Figure 4. Trigger pulse (1) and discharge current (2) (negative polarity recording).

3. Jitter

Usually switching jitter for one PSS as well as for the whole set does not exceed the duration of the trailing edge of the pulse (i.e. 4–10 ns). But in the beginning of the conditioning procedure (usually needed for PSSs and taking approximately 100 shots), we have observed sometimes a certain delay in the start of the discharge of one of the PSSs (up to 200 ns) as is seen in figure 5(*b*). Note that one has to distinguish the situation of figure 5(*a*), arrow '1', where the current derivative curve decreases monotonically all the time in spite of the peculiarity of the breakdown phenomena, from that of figure 5(*b*), arrow '3'. In the last case the curve increases after evident additional late switching of one of the PSSs. But an increase in the heater's current, introduced to reach a value close to the upper limit of the allowable range (close to the self-breakdown value), as well as several conditioning shots, usually eliminate this delay.

Here, we should mention that during the first period of the PSSs' operation (several thousands shots) one has to follow the current (voltage) characteristics of the heaters very carefully as a heater's current should be tuned from time to time. But after this cycle the situation becomes normal without any tuning.

Through the above experiments we have shown that a perfectly organized firing procedure may ensure practically 100% firing at a proper gas pressure with the jitter

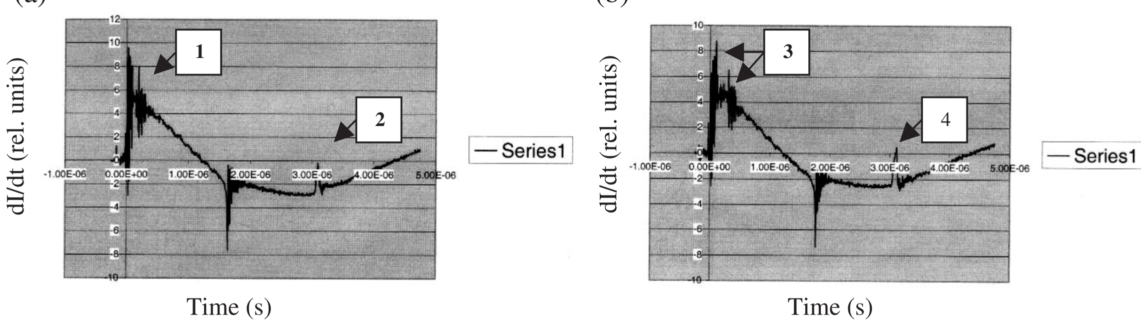

Figure 5. Current derivative for two shots of PF-6 with simultaneous (*a*, arrow '1') and with one delayed PSS (*b*, arrow '3') operations; one may also see short periods of current disruptions: arrows '2' and '4' for (*a*) and (*b*), respectively.

approximately 4–10 ns for four (in our case) concurrently operating PSSs.

4. Current disruption

In the course of our experiments we observed from time to time unexpected peculiarities (of the pulse valley type) on a current derivative of the main discharge looking as shown in figures 5(*a*) and (*b*). These peculiarities, short in duration (about 50 ns), always reached a zero line and took place when the current passed its zero value. Thus such a phenomenon is observed right at the end of the first half of a discharge cycle. We have supposed that it is a sort of current disconnection (disruption) taking place at a zero current and with the voltage across the PSS having the highest value, opposite in sign to the charging one. Thus we have decided to search for the conditions when the PSS can provide this disconnection of a circuit (current disruption) after the first half of a period completely. This possibility is of great importance because potentially it might ensure retention of energy inside a capacitor bank and an increase in the efficiency of a high-current discharge (e.g. of the DPF type).

In this connection various experiments have been undertaken to find the main reasons (basic factors) influencing the effect. Now we present some results of the work.

First we looked through many experiments related to these pulse valleys, trying to find whether any correlation exists between this phenomenon and the above-described delay (jitter) in operation of different PSSs of our device. We suppose it is because in many of our primary shots we had this delay (as in figure 5(*b*)). But an accurate examination of many such oscillograms has shown that with time, after several series of conditioning shots, this initial delay (non-simultaneous PSSs switching) disappears but the pulse valley does not (figures 5(*a*) and 6(*a*)).

Our second supposition was connected with the 'quality' of the plasma-focus formation. In a number of experiments we have seen that if the peculiarity of the main DPF discharge current at a pinching time is 'good', i.e. its amplitude is high and stretches in both the positive and negative directions (figure 6(*a*), arrow '1'), we have this pulse valley in our oscillogram without fail (figure 6(*a*), arrow '2'). In these good shots at this very moment ('1') we also had a short current disruption resulting from the appearance of the anomalous plasma resistivity inside the pinch column [7] and generation of a high (nominal) yield of hard radiation. This is a specific feature of DPF operation. The DPF plasma becomes turbulent at this time, and its resistivity increases. So the idea was that probably this phenomenon takes place inside the DPF chamber and results in a redistribution of the voltage throughout the electrical circuit, provoking later on—at the highest voltage across the PSS—the same situation inside the PS.

But inevitably we have observed here that sometimes even with worse plasma focusing (figure 6(*b*)), i.e. at a poor peculiarity on the dI/dt at a pinching time and with the hard radiation yield 4–5 times less than the nominal one, the duration of the pulse valley (i.e. the time of disconnection) may be even increased in comparison with a good plasma focusing shot (figure 6(*a*)). Thus the focusing quality is not responsible for the effect.

Then we decided to change the current of the PSS heaters, i.e. to decrease the working gas pressure inside the PSS chamber. And here we found that the lower the heating current, the better this disruption phenomenon (see figures 7(*a*) and (*b*)). And this is in spite of the fact that we may lose good jitter in these shots. The time period of the current disruption in our experiments reaches 1.5 μs. Thus we have found a clear correlation between the number of current carriers of the discharge inside the PSS and the appearance and duration of the main current disconnection. But a further decrease in the heater's current does not result in complete current disruption. Instead we found a regime of the PSS operation with misfiring.

But the most interesting situation appeared when we started to test our device in a high repetition mode of operation. And for the sake of the experiment we changed our DPF chamber into a dummy load having a constant chamber inductance slightly lower than that of the DPF. In our experiments we measured the voltage across the PSS. We found that if two shots are produced one after another with a short delay ($\leqslant 1$ s), each successive shot will demonstrate the desired complete current disruption (see figure 8).

Prolongation of a sequence of shots resulted in the same phenomena in the sequence of firing the subsequent discharge. Of course we had moderately diminished the pressure inside the PSSs before this set of shots by decreasing its heater's current.

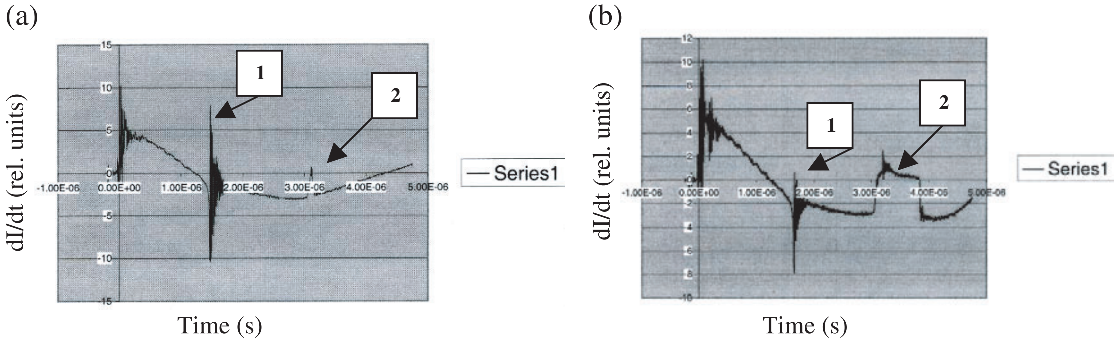

Figure 6. Current derivative for good (*a*) and moderate (*b*) shots with the current peculiarities responsible for the DPF plasma pinch phenomena (arrow '1') and for the current disruption at the PSS (arrow '2').

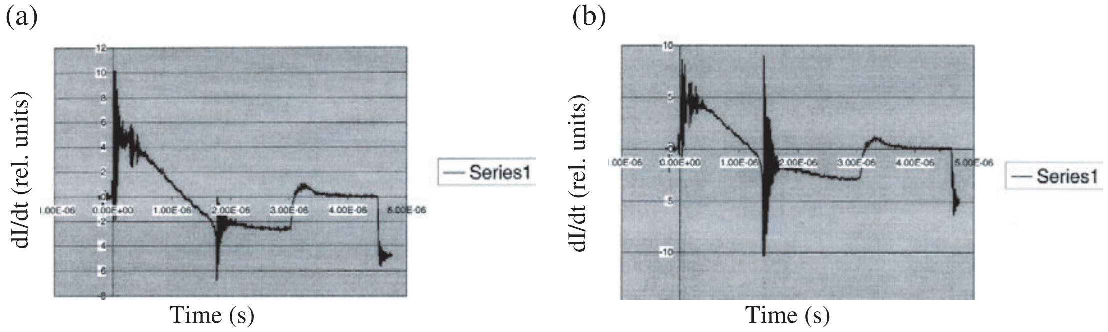

Figure 7. Current derivative with long period of current disruption, reached at the reduced value of the current flowing through the PSS hydrogen heater.

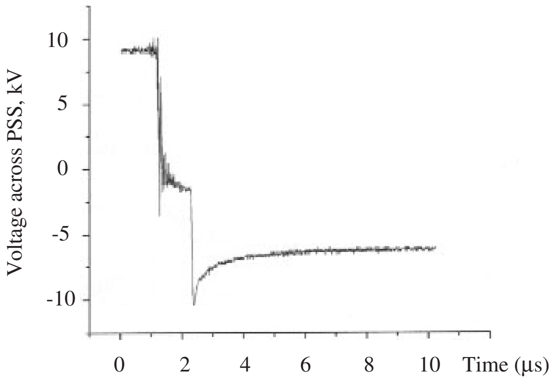

Figure 8. Voltage across the PSS at the second shot in a repetition mode of DPF operation; the appearance and conservation of the inverse voltage after a time period equal to half of the discharge cycle (≅1.3 μs) is seen.

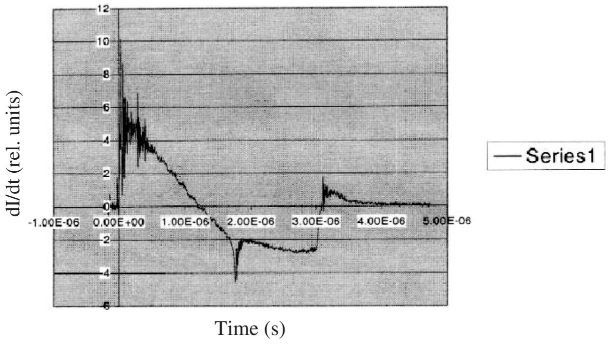

Figure 9. Current derivative with the complete current disconnection, reached at the reduced value of the current flowing through the PSS hydrogen heater and at the repetitive regime of its operation.

To verify this situation we have decided to measure again the current derivative of the DPF discharge at its operation with PSSs in a high repetition rate mode. And again in these measurements in each second (third, forth etc) shot we have observed this complete disruption of the main electrical circuit after the first discharge cycle (figure 9).

It is clear that certain current instabilities play an important role in this case. And excess over a critical current in this experiment [8], which depends on the density of the plasma inside the PSS, is also an undoubted fact. But it is difficult to deduce at this moment the particular physical model of such an interesting behaviour of the PSS, especially when it works in a repetitive mode. The mechanisms of the current cutoff phenomena taking place in plasma current breakers are not understood completely yet, as stated in [8].

Acknowledgments

This work is supported by the International Atomic Energy Agency under contract Nos 11940/R, 11941/R and 1192/R.

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