CLM-P823



# Pulsed power systems research at Culham Laboratory

T. E. James
J. W. Gray
M. J. Kear

UK ATOMIC ENERGY AUTHORITY

Culham Laboratory

CLM-P823

# Pulsed power systems research at Culham Laboratory

T.E. James
J.W. Gray
M.J. Kear

Culham Laboratory, Abingdon, Oxfordshire
OX14 3DB UK
(Euratom/UKAEA Fusion Association)

ABSTRACT

Culham Laboratory is the UK Centre for Nuclear Fusion and Plasma Physics Research and also undertakes contract research in the fields of electrotechnology, particle beams, lasers, space, defence and lightning simulation.

This paper reviews the Pulsed Power systems and the experimental facilities at Culham such as fast high current switching of multi-megajoule energy storage systems; modulated HV power systems for plasma heating applications (160 kV, 16 MW) and the Lightning Studies Unit.

Current studies include theoretical and experimental studies on Compulsators and Electromagnetic Launchers. Future experimental facilities are being considered for high performance, repetitive switching systems and high energy storage (∿ 50 MJ) for Electromagnetic Launchers based on the use of existing HV DC (160 kV 16 MW) and high current DC (100 kA, 30 MW) Power Supplies.

(Paper presented at 6th IEEE Pulsed Power Conference, Arlington, USA, June 1987).

June 1987

# FUSION PROJECTS

## Fusion Magnetic Field Power Systems

1. Most of the pulsed power systems used at Culham were originally developed to meet the requirements of magnetic fusion experiments. As the size of fusion machines has increased and the confinement time has improved from < 1 ms in the 1960s to approaching 1.0 s in the 1980s the magnetic field power system requirements have also changed very significantly. Fast high voltage (∿ 50 kV) capacitor banks [1][2] have generally been replaced by higher energy systems (100 to 1000 MJ) based on inductive storage and transfer backed up by kinetic energy storage in rotating machines and/or by static DC 'flat-top' supplies from the national network. This is especially so for Tokamak experiments [3] whereas current Reverse Field Pinch experiments [4] require a combination of relatively slow low voltage (∿ 8 kV) capacitor banks combined with inductive energy transfer and DC 'flat-top' supplies.

2. Typical parameters for these different fusion magnet power systems are summarised in Table 1. As a result of increases in the requirements for the pulse-time (by about $10^4$) and energy transfer (by about $10^2$ to $10^3$) a significant reduction in the switching system GVA rating (by about $10^3$) has occurred but with a large increase in coulombs/pulse (by about $10^2$).

3. In general, fusion experiments require a combination of different power systems operating in 3 phases as follows:

(a) 'charging' of capacitor or inductive energy storage.
(b) 'fast transfer' (or pulse compression) to produce plasma current.
(c) 'flat-top' to maintain magnetic field configuration.

For future large fusion projects [5] such as the 'Next European Torus' (NET) now being considered the 'flat-top' times envisaged are > 500 s. This would require DC convertor power supplies of > 6 GVA though by re-connecting individual units to different loads during the pulse it is expected that the convertors actually installed could be reduced to ∿ 2 GVA.

TABLE 1

FUSION PULSED POWER SYSTEMS

TYPICAL MAXIMUM PARAMETERS (Approximate)

| Power System (Application) | Volts Current Energy | Pulse Length Coulombs | Switching System Type, Rating |
|---|---|---|---|
| **Capacitor Banks** | | | |
| Fast HV [1] [2] (Theta Pinch) | 50 kV<br>16 to > 100 MA<br>1.0 to > 10 MJ | 50 μs (Crowbar)<br>1000 to 5,000 C | Closing Switches:<br>Spark Gaps<br>800 to > 5,000 GVA |
| Slow LV [4] (RFP) | 8 kV<br>50 kA<br>5 MJ | 50 ms<br>2500 C | Closing Switches:<br>Ignitron/Mech Switch<br>400 GVA |
| **Inductive Storage/Transfer** | | | |
| Poloidal Cct [3] (Tokamak) | 40 kV<br>80 kA<br>100 MJ | 125 ms<br>10,000 C | Opening Switches:<br>Cct Breakers<br>3.2 GVA |
| **Rectifier Convertors** | | | |
| HVPS [6]- Culham (Plasma Heating) | 20 to 160 kV<br>800 to 100 A<br>100 MJ | 10 s<br>8,000 C | Thyristors<br>Tetrode Mod./Reg<br>16 MW |
| LVPS - Culham Toroidal Cct (Tokamak) | 300 V<br>100 kA<br>35 MJ | 1 s<br>100,000 C | Thyristors<br>30 MW |
| **Rotating Machines** | | | |
| Main PS [3] (Tokamak) | 10 kV<br>100 kA<br>2,500 MJ | 2 s<br>200,000 C | Diodes<br>1.0 GVA |

Fusion Plasma Heating Power Systems

4. These systems include HV power systems for plasma heating by neutral beam injection (NBI), ion cyclotron RF Heating (ICRH) and electron cyclotron RF Heating (ECRH). Research work at Culham has been mainly concerned with the 80 keV 5 MW ion sources for the JET NBI system and the 2 MW ECRH system for the COMPASS tokamak experiment using ten 80 kV, 200 kW gyrotron oscillators.

5. To meet the wide range of plasma heating power system requirements a flexible high voltage DC power supply [6] has been installed at Culham to operate at full power (16 MW) at voltages of 20, 40, 80 and 160 kV (Refer Table 1). It consists of 4, 20/40 kV 4.0 MW units which can be re-connected remotely to achieve the required performance parameters in three different experimental locations.

6. The voltage control and protection of NBI sources and ECRH gyrotrons has required the development of systems based on a tetrode modulator-regulator [7] (150 kV withstand voltage, > 1.0 MW dissipation) which functions both as a regulator and a switch. It can interrupt the supply in < 10 μs in the event of a temporary fault and re-establish it after ∿ 1 ms.

7. Future development work associated with the fast switching of high voltage DC power systems is in progress based on the use of GTO thyristors. Following the development of a prototype these modular systems would be used to switch individual 80 kV gyrotron circuits to give more operational flexibility than with a tetrode modulator. It may also be possible to use them in future for very high voltage ion source applications at > 300 kV.

## INDUSTRIAL AND DEFENCE PROJECTS

### Lightning Studies

8. The Culham Lightning Studies Unit (CLSU) was set up about 12 years ago to provide a well equipped laboratory to undertake lightning and static electricity simulation for research, development and certification applied tc aircraft and terrestial structures. Studies include the damage mechanisms oi lightning currents such as hole burn-through, conductor vapourisation, arc forces and induced voltages by electromagnetic coupling. Electromagnetic analysis is undertaken using the INDCAL computer program. Consultancy work and advice is also provided to manufacturers, designers, certifying and procuring authorities.

9. A range of pulsed power systems up to 700 kV, 200 kA and 1.0 MJ (for high di/dt, current and coulomb tests respectively) providing waveforms whicl comply with the internationally agreed standards of simulation can be applie‹ to a wide range of experimental rigs. A portable capacitor bank is also available for off-site tests on whole aircraft such as the 'fly-by-wire' Jaguar. Other facilities include a static electricity charge ejector for testing aircraft windscreens and other dielectric components.

10. The theoretical and experimental expertise gained by CLSU in the interaction of electromagnetic phenomena with complex electronics equipment and structures is being increasingly applied to the study of EMP (Electromagnetic Pulse) effects in general.

### Compulsator Studies

11. As a result of a general review of pulsed power supplies with low volum and weight for defence applications the compulsator was identified for futur study and development as a pulsed power supply with a high repetition rate. A compulsator is a rotating machine with similar distributed windings on the stator, and rotor connected in series [8][22]. As the machine rotates a variation of inductance occurs which produces a corresponding variation in current in an external load connected in series with the windings.

12. Theoretical analyses of the magnetic field configuration using the PE2D computer program with a CRAY computer were completed and also systems studies involving non-linear loads. Experimental studies of a demonstration compulsator have been made on a rewound Schrage machine which had additional excitation windings on both rotor and stator to allow a wide range of excitation configurations and the effect of different capacitative and resistive loads to be studied. A slotted machine was used to maximise the inductance compression ratio. The experimental programme had the following objectives:

(a) Measurement of inductance as a function of rotational angle.
(b) Assessment of iron saturation effects.
(c) Optimisation of energy transfer as regards impedance and excitation angle.
(d) Operation with capacitative loads to examine the effect of a complex load impedance on energy transfer.

13. Typical experimental results with varying machine parameters compared with theoretical analysis are shown in Fig. 1 and demonstrate that compression ratios of 30:1 are obtained. Important features of the theoretical study were the inclusion of eddy current and saturation effects. It was shown that magnetic saturation reduces the minimum inductance and therefore increases the compression ratio and consequently the output current whereas eddy currents have the opposite effect. Papers on the above experimental and theoretical studies are also being presented at this conference [9][10].

<u>Electromagnetic Launchers</u>

14. The principal objective of research work on Electromagnetic Launchers is to accelerate 1.0 gm projectiles up to a velocity of 15 km/s. A hypervelocity test facility has been set up for this project using a railgun driven by an existing 8 kV capacitor bank. Pre-injection of the projectile has been achieved by electromagnetic forces produced by an auxiliary high current arc supplied from a small capacitor bank. Future studies will be concerned with the optimisation of the pre-injection system and the development of the mechanical and electromagnetic design of the railgun barrel.

SWITCHING SYSTEMS

15. The wide range of fusion power system requirements has had a major impact on the development of switching systems. These include fast high current low inductance closing switches for capacitor banks (ignitrons, spark gaps, solid dielectric switches) and opening switches for inductive stores (ignitrons, air blast and vacuum circuit breakers, thyristors).

16. Much of the development work at Culham has been associated with high performance closing switch systems using single or multiple arc pressurised spark gaps (50 to 100 kV) or ignitrons (up to 20 kV) as discussed below. For applications where an extremely low inductance ($< 5$ nH) is required in one switch multiple arc spark gaps and solid dielectric switches have been developed [11][12][13]. Fast Metal-to-Metal solid-dielectric switches with a contact width of $\sim$ 20 cm have also been used for crowbar duty where virtually zero resistance and inductance is required. A review of closing switch systems using these devices has already been published [1]. Their maximum performance parameters obtained at Culham are summarised in Table 2 though all parameters are not necessarily obtained simultaneously.

Pressurised Air Spark Gaps

17. The main problem to be overcome using large numbers of parallel spark gaps in high performance low inductance multi-megajoule banks (Table 1) is to achieve adequate system reliability by minimising their premature breakdown rate. This is best achieved by using the minimum number of high performance gaps. The Mk V gap 3-electrode field distortion gap was developed to meet this objective with the maximum performance shown in Table 2 (single arc). Its premature breakdown rate was about 1 in 5000 pulses [14] as shown in Fig 2. The number of gaps required in a given application was reduced by a factor of 10 to 36/MJ or less using the Mk V gap compared with about 300/MJ in previous systems.

18. The design of capacitor banks using MkV spark gaps is modularised [15] so that they can be built almost completely in industry and installed on site in a few weeks. Such a MJ bank was built for the SPICA screw-pinch experiment in Jutphaas (Netherlands) with metal-to-metal crowbar switches and has operated satisfactorily for $> 10$ years.

TABLE 2

MAXIMUM PERFORMANCE OF FAST CLOSING SWITCHES

| | Ignitron (Size E) [21] | Spark Gaps | | Solid-Dielectric | | Hybrid [20] Ignitron and Mechanical |
|---|---|---|---|---|---|---|
| | | Single Arc [14] | Multiple Arc [11] | Arc [12] | Metal-to-Metal [13] | |
| Voltage (kV) | 25 | 50 | 60 | 100 | 50 | 35 |
| Current (kA) | 100 to 230 | 1,000 | 1,000 | 2,000 | 2,000 | 50 |
| Coulombs/pulse | 400 to 1600 | 100 | 10 | 2,000 | 2,000 | 20,000 |
| Closing Time (μs) | 1.0 | 0.05 | 0.02 | 1.0 | 3.0 | 1.0 |
| Jitter (ns) | 100 | 5 | 1 | 200 | 300 | 10 |
| Inductance (nH) | 100 | 50 | 2 to 5 | 5 | 5 | 200 |

NOTE: The above parameters are the maximum obtained and are not necessarily achieved simultaneously.

19. The electrode life of high performance spark gap switches is very dependent on electrode erosion and jitter in breakdown time [14]. The former is critically dependent on the internal geometry of the gap and its insulation and the flow pattern of clean air through the gap between pulses. Maintaining low jitter in breakdown time is very dependent on keeping the same electrode and air gap dimensions in spite of very large amounts of electrode erosion. This is achieved in the Mk V gap by arranging that erosion of the trigger electrode successively moves the arc position on to new areas of the main electrodes. Studies of the variation of jitter in breakdown time with life indicates that this gap would continue to operate satisfactorily for a life of more than $10^6$ C and possibly aproaching $10^7$C with modified electrodes.

20. Multiple arc spark gaps are used where an extremely low switch inductance is required. The first multiple arc spark gap was developed in 1967 for a 1.0 MA 50 kV application to achieve an inductance of 5 nH as a start switch and 2 nH as a crowbar switch [11][16]. This also uses the field distortion electrode geometry but with straight electrodes ∿ 50 cm long though it has subsequently been referred to as a 'rail-gap'. To achieve multiple arc breakdowns a fast rising trigger pulse of about 4 kV/ns is required so that the breakdown time is less than the arc resistive phase decay time. The latter has been predicted theoretically [17] to be a function of electric field, gas density and transmission line impedance $Z_o$. Experiments with varying circuit conditions demonstrated good agreement between theory and experiment.

Ignitrons

21. Ignitrons have been used extensively over many years as closing switches up to 20 kV. Development studies at Culham have been concerned with the following aspects:

(a) Inverse-parallel operation in oscillatory circuits [18].
(b) Opening switch duty with an inductive store [19].
(c) Hybrid ignitron and mechanical switch for fast closing and very high Coulomb applications [20].
(d) Maximum current and Coulombs performance [21].

22. Inverse-parallel operation of ignitrons in oscillatory circuits is required for RFP toroidal field circuits. It requires reliable commutation of current from the forward ignitron to the reverse ignitron at current zero. Experimental studies at different peak currents and frequencies established that this will usually occur if the di/dt at current zero is $< 8.10^7$ A/S [18]. These studies also indicate the conditions for which an ignitron can act as an opening switch for inductive stores as proposed for the COMPASS poloidal field circuit [19].

23. Recent results [21] from tests on the size E (BK 496) ignitron indicate that a significant increase in the coulomb rating is possible beyond the manufacturer's nominal maximum ratings of 400 C and 100 kA. Satisfactory operation was obtained at 1600 C, 10 kA and at 200 C, 230 kA (to represent fault conditions). Measurements of the resistive voltage drop of size A, D and E ignitrons have also been made. These results will be published in the near future.

24. Some applications such as RFP toroidal field circuits require fast switching but with Coulombs/switch approaching 20,000 C. In this case a hybrid ignitron/mechanical switch is being developed in collaboration with industry to meet a wide range of switching and protection duties for the RFX project in Padua (Italy) [20].

## FUTURE PULSED POWER SYSTEMS

### High Energy Pulsed Power Facility

25. Consideration of the performance requirements of future pulsed power systems indicate that the following performance parameters could be required during the development and testing of new systems:

| | |
|---|---|
| Stored Energy: | 50 MJ (inductive) |
| Maximum Voltage: | 100 kV (to earth) |
| Peak Current: | 10 MA (output with resistive load) |
| Charging DC Supply: | 30 MW |

A technical study of such a High Energy Pulsed Power Facility is in progress to define the technical problems involved in setting up such a facility at Culham.

26. To minimise cost and space and enable an opening switch system to be studied, inductive energy storage is proposed using similar coils to those i the JET Tokamak magnetising circuit (refer Table 1) which store about 100 MJ To obtain an output current of up to 10 MA the inductive store would be inductively coupled to the output circuit. A simple equivalent circuit of this system is shown in Fig 3 with the DC power supply opening switch and typical high current load circuit also indicated. The existing LVPS DC supply at Culham (Table 1) would be suitable for charging the inductive store. Ultimately, this might be achieved with a pulsed rotating machine such as a compulsator subject to satisfactory further development up to the performance required.

27. One of the major outstanding pulsed power switching problems to be solved is that of high power opening switches of minimum cost, complexity an volume. The development and testing of new concepts for such opening switches would be a major objective of the development programme using this proposed high energy facility though existing opening switch techniques woul be used initially when using the facility as a high current pulsed power source.

28. Further development of Electromagnetic Launchers of the 'railgun' type requires the availability of pulsed power systems with current ratings of several MA at about 2 to 5 kV. The parameters of the proposed high energy facility are based on meeting these high current output requirements.

Repetitive Switching Studies

29. The repetitive operation of HV closing and opening switches represents a major problem still to be overcome satisfactorily. Assessment of the repetitive operation of high performance spark gaps and ignitrons (Table 2) is envisaged and also possibly new opening switch concepts. The requirements of a development facility for this purpose has been considered.

30. Such a development facility would require a multi-MW DC power supply for which it is proposed to use units of the existing HVPS at Culham (Table 1). This would enable the repetitive operation performance in Table 3 to be achieved with an 80 kJ energy store:

**TABLE 3**

**HVPS REPETITIVE OPERATION PARAMETERS (80 kJ/pulse)**

| HVPS Units/Power | Voltage | Operating Frequency |
|---|---|---|
| | | (approx) |
| 1/4.0 MW | 25 or 50 kV | 50 Hz |
| 2/8.0 MW | 50 or 100 kV | 100 Hz |

ACKNOWLEDGEMENT

31. The authors wish to acknowledge the contribution of the many engineers and scientists at Culham and in the JET project whose work is reviewed in this paper. The work on Electromagnetic Launchers is being sponsored by RAE Farnborough (UK MOD).

## REFERENCES


1. T. E. James, Fast High Current Switching Systems for Megajoule Capacitor Banks. Culham Laboratory Report, CLM–L23, 1973.

2. E. L. Kemp et al, The Design and Installation of Scyllac, 6th SOFT Aaachen, EUR 4593e, p.227, 1970.

3. E. Bertolini, Design, Installation and Commissioning of the JET Power Suppy System, 10th SOFE, Philadelphia, IEEE Cat No. 83CH1916-6NPS, p.1756, 1983.

4. G. Rostagni et al, The RFX Project: A Design Review, 13th SOFT, Varese, EUR9183EN, p.189, 1984.

5. J. B. Hicks, N. A. Mitchell, E Salpietro, NET Plasma Engineering and PF Coil Power Supplies, 14th SOFT, Cadarache, EUR10936EN, p.707, 1986.

6. R. J. Noyes, J. E. Partridge, J. H. Hay, J. Mowat, D. C. Edwards, Future AC and DC Power Systems at Culham, 13th SOFT, Varese, EUR9183EN, p.895, 1984.

7. J. B. Hicks, P. F. Gascoyne, D. P. Hammond, J. H. Hay and R. T. Pedley, HV Control and Protection for the Culham Multi-MW Beamline, 12th SOFT, EUR7893EN, p.419, 1982.

8. W. F. Weldon, Rotating Machinery for use in Pulsed Power, 3rd IEEE Pulsed Power Conference, Albuquerque, IEEE Cat No. 83CH1908-3, p.658, 1983.

9. M. J. Kear, J. W. Gray, J. L. Browning and D. J. Wilson, Demonstration Compulsator with Slotted Windings, 6th IEEE Pulsed Power Conference, Arlington, 1987 (this conference).

10. D. Putley, Analysis and Modelling of the Culham Experimental Compulsator, 6th IEEE Pulsed Power Conference, Arlington, 1987 (this conference).

11. T E James, High Current 60 kV Multiple Arc Spark-gap Switch, Proc IEE, Vol 117, No. 7, p.1448, 1970.

12. T. E. James, P. M. Barnes, K. Harries and J. Phillpott, A Multiple Arc 100 kV 2.0 MA Solid-Dielectric Switch, Proc, IEE, Vol 117 No. 1, p.250, 1970.

13. R. A. Burden, D. Bold and D. E. Skelton, Development Aspects of Fast Metal-to-Metal Solid Dielectric Switches, 6th SOFT, Aachen, EUR 4593e, p.365, 1970.

14. T. E. James and R. A. Burden, Statistical Performance Data for a High Current 60 kV Spark Gap Switch, 7th SOFT, Grenoble, EUR 4938e, p.389, 1972.

15. T. E. James, A Compact 1.5 MA 60 kJ Capacitor/Spark Gap Module. 2nd Int. Conf. on Gas Discharges, London, IEE Publication No.90, p.112, 1972.

16. T. E. James, J. E. Gruber and F. J. Kivlin, The Initiation of Multiple Arc Breakdowns in a 60 kV Low Inductance Spark Gap, 8th Int. Conf. Ionised Gases, Vienna, Springer-Verlag (Austria), p.208, 1967.

17. J. C Martin, Multiple-Channel Gaps, AWRE Aldermaston (UK) Report, SSWA/JCM/703/27, 1970.

18. P. M. Barnes, R. A. Burden and J. W. Gray, Ignitron Switching Problems Associated with a Large Reverse Field Pinch Experiment, 10th SOFT, Padua, EUR 6215, p.413, 1978.

19. J. H. Hay, D. Bold, D. C. Edwards, J. W. Gray, S. E. V. Warder, COMPASS Poloidal Field Power Supply System, 14th SOFT, Cadarache, EUR 10936 EN, p.847, 1986.

20. J. W. Gray, J. L. Browning, T. A. Mace and G. L. Varley, Protection and Switching System for the RFX Power Supply, 14th SOFT, Cadarache, EUR 10936 EN, p.841, 1986.

21. R. A. Burden and J. W. Gray, Ignitron Performance at High Coulomb Rating, Culham Laboratory Report (to be published).

22. J. D. Jukes, Rotary Pulse Generators; Basic Electrical Theory. Culham Laboratory Report No. CLM RR/M11/16, June 1986.

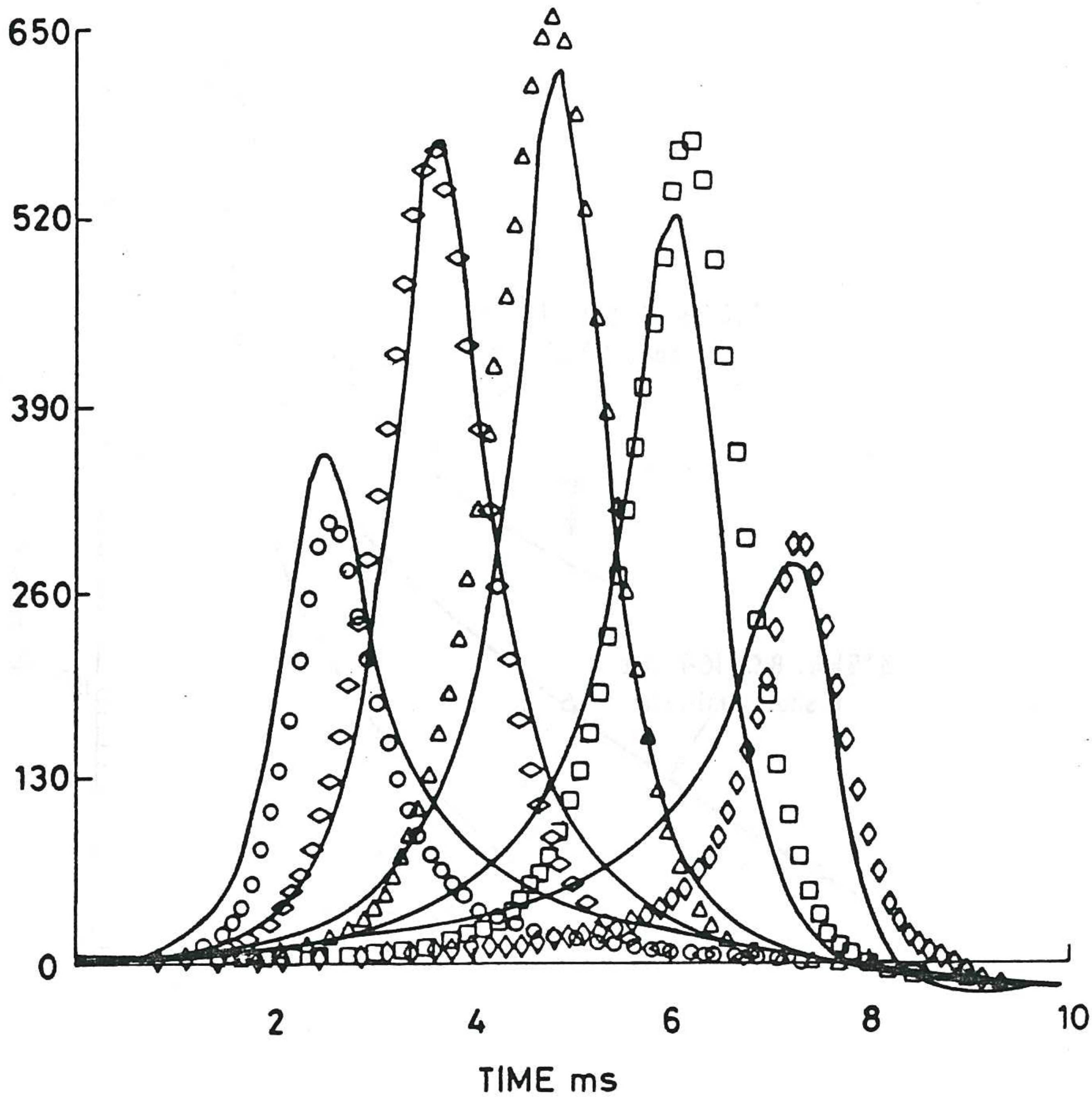


Fig. 1 Variation of Compulsator Excitation Phase Angle $\delta$ with Resistive Load
Theoretical: ————
Experimental: $\delta=0$
$\delta=\pm\pi/4$
$\delta=\pm\pi/2$

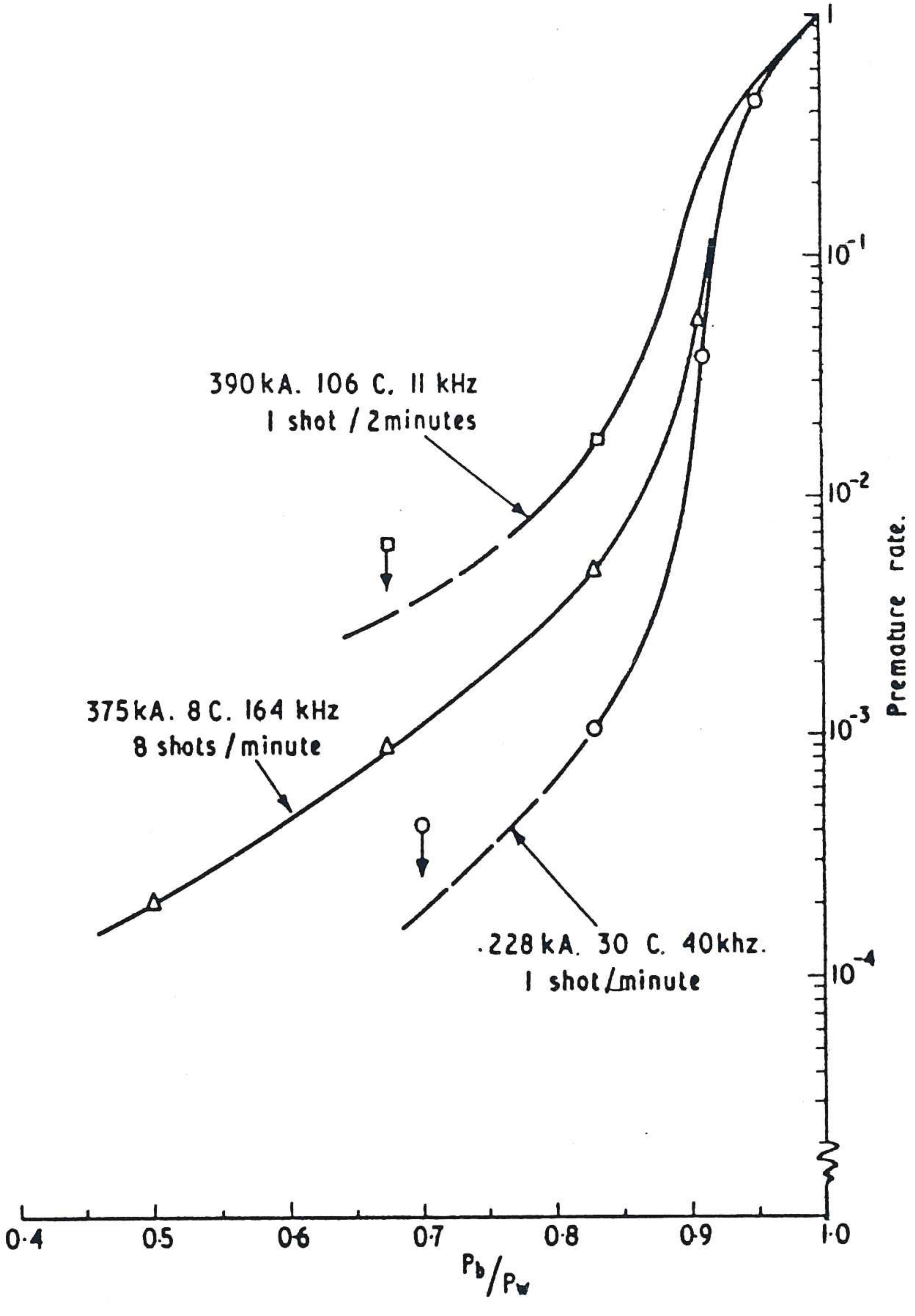


Fig. 2 MkV Field Distortion Spark Gap Premature Breakdown Rate

$\frac{P_b}{P_w} = \frac{\text{static breakdown pressure}}{\text{working pressure}}$

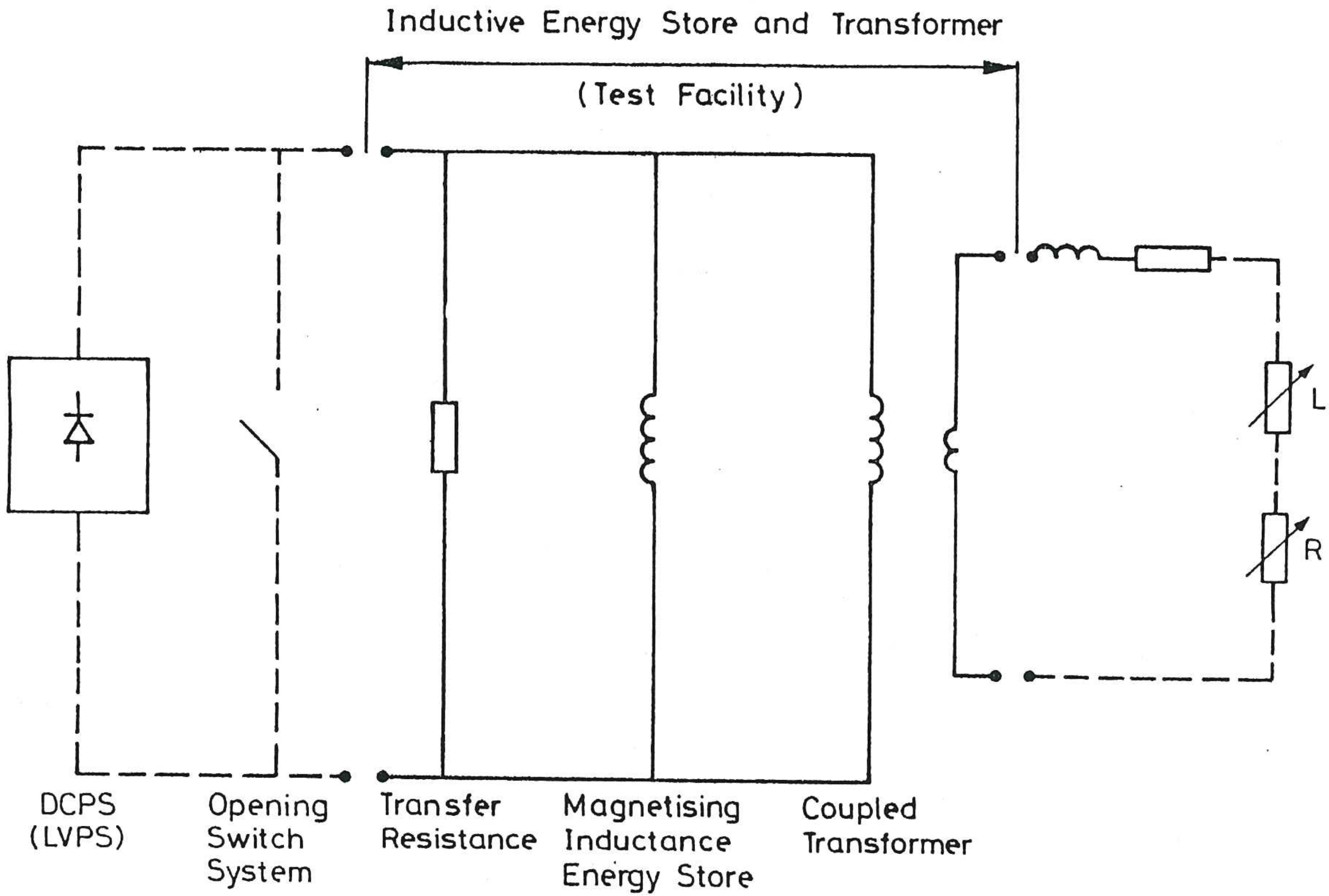


Fig. 3 High Energy Pulsed Power System