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(Course Coordinator: W. Sarjeant)





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HIGH VOLTAGE/PULSE POWER TECHNOLOGY

GRADUATE COURSE EECS596

University of New Mexico

## LECTURE INDEX

## PREFACE

With the recent increase in technological needs and the interest in the power conditioning arena, one of the problems facing workers in the field is the lack of texts or notes describing recent progress, particularly in the area of repetitive power conditioning. For this reason and because of expanding internal requirements, the University of New Mexico (UNM) and the Los Alamos Scientific Laboratory (LASL) have created a set of lecture notes based upon the graduate course taught recently at UNM. The objective of these notes is to create a record of many of the advances in the field since the last text in the field was published just after World War II. In this context, the lectures presented are oriented toward an introduction of the reader to each of the areas described and present sufficient background information to explain many of these advances. They are not intended to serve as design engineering notes, and thus the reader is referred to the references at the end of each lecture for detailed technical information in specific areas.

The preparation of these writings is a result of a considerable teamwork effort on the part of LASL and Sandia staff. In particular, Cathy Correll, in conjunction with Jo Ann Barnes and the rest of her efficient word processing staff, carried the major responsibility for preparation of the lectures while the lecturers did the proofreading and revisions. As course coordinator, it is a pleasure to acknowledge the strong support of Ray Gore, our E-Division Leader, and Shyam Gurbaxani who is the UNM Graduate Center Director, Los Alamos Campus.

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Los Alamos, New Mexico
October 3, 1980

LECTURE 1

# INTRODUCTION TO POWER CONDITIONING

LECTURE 1

INTRODUCTION TO POWER CONDITIONING

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Lecture 1

An Introduction to Power Conditioning Systems

by

W. J. Sarjeant

## 1. Scope of the Course

The purpose of the course is to present an overview of the power conditioning aspects of energy transfer systems. The objective, then, is to develop an understanding and appreciation of the physical processes that govern the performance of these systems, including the role of such elements as switches, capacitors, inductors, and resistors. Secondly, to discuss where are the sources of information once a problem area has been identified? A major effort in this course will be to transfer this information in key areas to you as hand-outs. All the information will be current and state-of-the-art, and directed toward these pulse components, with particular emphasis on the area of high-repetition-rate systems, as these are taking on ever increasing significance.

Walt Willis, Bob Butcher, and Bill Nunnally will cover the areas within this course on "Power Conditioning Systems" (PCS) with which they have had considerable experience. Jim Sarjeant will handle the course integration and the discussions of the component technology-base (for example, the present status of power conditioning systems and thyratron switching in general). As we progress, it will be arranged for several experienced individual to come in and discuss special topics. Some such suggested topics are grounding and shielding, safety, accelerators, and E beams. Ken Prestwich will discuss E-beam accelerators, and Gerry Rohwein will present detailed information on pulse transformers and high-voltage insulation. Tom Boyd and Don Swenson will discuss accelerator systems with us, noting in particular current PCS needs arising from present accelerator research.

The text on which the course is based is Pulse Generators by Glasoe and Lebacqz, the World War II radar modulator text, primarily concerned with charging capacitors or pulse-forming networks (PFN), and then discharging the energy stored therein at high repetition rates, either directly or through a transformer into a load. The secondary load was generally a magnetron. This text will serve as a reference base and then technology developments over the subsequent 30 years will be molded around it. Extensive use will be made of handout information to bring the overall technology base up to date.

The field of "Power Conditioning" is fraught with differing definitions as to what it means, as well as defining the branching points within each area. For the purposes of this course, we will define the concept of "Power Conditioning" as "the shaping of electrical power from the conventional 60- to 400-Hz mains, into temporally well-defined pulses of electrical energy having reproducible voltage and current time histories." (See Figure 1.) In this context there is no specific mention of the repetition rate at which these pulses of energy are deposited into whatever the load may be. Normally, such systems are divided into single-shot (several times per hour or day) and repetitively pulsed (1 Hz upwards), primarily depending upon load requirements. A "Power Conditioning System" (PCS) can then be defined as "an energy transfer system that stores energy, either mechanically or electrically, and then discharges a determined fraction of this as electrical energy into the load." There are two main types of energy storage techniques:

1. Mechanical: The mechanical energy, $W_r$, is stored in rotary motion of machinery, such as a flywheel dc source device or a pulsed compensated alternator:

$$W_r = \frac{1}{2} I_0 \omega^2$$

# INTRODUCTION TO POWER CONDITIONING SYSTEMS

**DEFINITION:**

AN ENERGY TRANSFER SYSTEM THAT STORES ENERGY, EITHER MECHANICALLY OR ELECTRICALLY, AND THEN DISCHARGES A DETERMINED FRACTION OF THIS AS ELECTRICAL ENERGY INTO THE LOAD.

**MECHANICAL**

ENERGY, $W_R$, IS STORED IN ROTARY MOTION OF MACHINERY.

$$W_R = \frac{1}{2} I_0 \omega^2$$

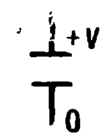
**ELECTRICAL**

ENERGY IS STORED IN ELECTROSTATIC OR MAGNETIC FIELDS.

ELECTROSTATIC:

$$W_E = \frac{1}{2} \int_{volume} \bar{D}\cdot\bar{E}\ dv$$

E.G. FOR CAPACITOR OF CAPACITANCE C: $W_E = \frac{1}{2} CV^2$




MAGNETIC:

$$W_M = \frac{1}{2} \int_{volume} \bar{B}\cdot\bar{H}\ dv$$

E.G. FOR INDUCTOR OF INDUCTANCE L: $W_M = \frac{1}{2} LI^2$

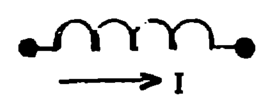



FIG. 1

2. Electrical: The energy is stored in electrostatic or magnetic fields:

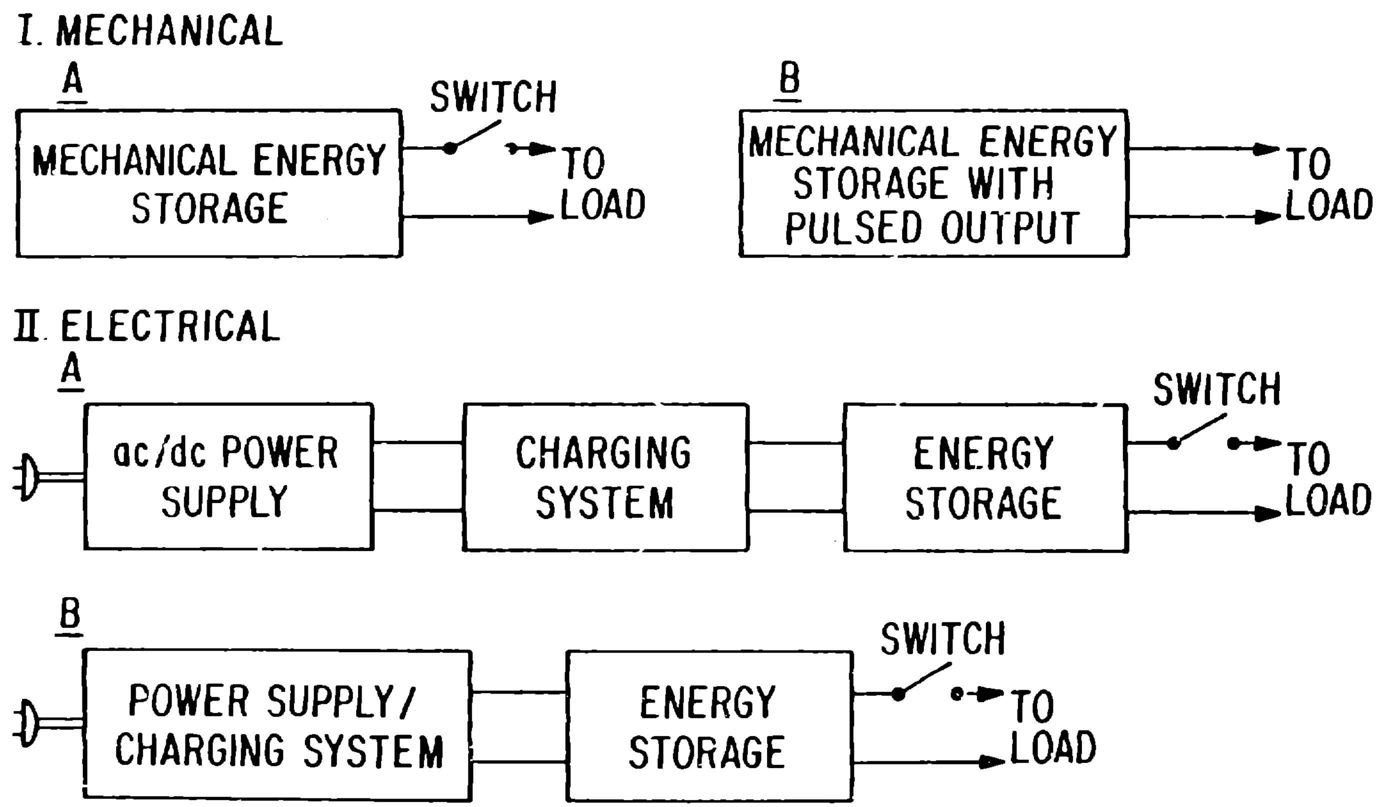
Electrostatic: $W_e = \frac{1}{2} \int_V \bar{D} \cdot \bar{E} \, dv$ For example, for a capacitor, $W_e = \frac{1}{2} CV^2$

Magnetic: $W_m = \frac{1}{2} \int_V \bar{B} \cdot \bar{H} \, dv$ For an inductor, as an example, $W_m = \frac{1}{2} LI^2$

These two classes of PCS, mechanical and electrical, are schematically illustrated in the block diagram in Fig. 2. Mechanical energy PCS of both types A and B are being actively pursued at the Naval Research Laboratory (NRL) and the University of Texas at Austin, the latter under Lawrence-Livermore Laboratory (LLL) support. It has been projected that these devices will be capable of transferring energies of up to 100 megajoules per unit, in a time span of several hundred microseconds for flashlamp pumping applications. It may be possible to extend the concept of a compensated pulsed alternator (type B in Fig. 2) to pulse-charging applications, up to 10-kHz repetition rates, for charging times around 10 microseconds. If this is possible, these devices, following the normal time scale of high technology development, may well make excellent second-generation (1985-1990) charging units for fusion reactor drivers -- charging high-energy-density transmission lines, which could then be discharged either in microseconds for laser drivers of the $CO_2$ type or in tens of nanoseconds for Electron Beam/Light Ion driven (EB/LI) or excimer (e.g., KrF) laser-driven fusion systems. It is far from clear that the leakage flux of these rather low voltage alternators can be reduced to the level that will allow efficient operation in the required ≈10 microsecond time scale. This point is currently under study at the University of Texas.

The electrical PCS fall into two categories, differing primarily in how the energy storage capacitors and/or transmission lines are charged.

# POWER CONDITIONING SYSTEMS



For purposes of illustration we shall discuss them with particular reference to some of the present repetitive PCS work underway at both LASL and Sandia. In the type II-A of Fig. 1, a conventional dc power supply feeds energy into the energy-storage unit through the charging system. For single-shot systems, the latter may only be a string of charging resistors (giving a 50% energy-charging efficiency), while for repetitively pulsed applications, the unit is usually an inductive type of resonant charge network to ensure near-unity energy transfer efficiency. These inductive charging systems, with several high-regulation variations, are currently under development at LASL for laser isotope separation (LIS) applications, pulsed medical accelerators, the free-electron laser, and also are under study for use in the very large PCS required for high-reliability fusion laser systems. In addition to the above, pulse-charging transformers form a third charging technique used primarily where high-voltage gains and efficiencies are required. The development of large-scale air-core pulse-charging transformer techniques was pioneered at Sandia for high-voltage gain, fast charging (0.1 to 1 microsecond) and triggering applications. They have developed an extensive expertise in these air-cored transformers, which are complementary to the iron-cored units under research and development at LASL. These compact iron-cored transformers, designed with very high coupling coefficients and transfer efficiencies, have the potential of being vital components in future high-efficiency, cost-effective multikilohertz lasers as well as in numerous related applications, such as research accelerators.

The energy storage device required for high-reliability, long-life systems will likely remain capacitors for some considerable period of time until other technologies become sufficiently mature to displace them in a cost-effective way. At LASL, research and development is underway on capacitor structures directed towards satisfying the very long lifetime requirements in LIS, laser fusion, accelerators, and nuclear particle diagnostic systems. These efforts have clearly identified the need for a considerable technology base development and effective laboratory-industry technology transfer in this area, which may soon take on considerable strategic significance. It has been recognized, through a number of LASL programs, that the future systems evolving from the research described above will demand component performance levels vastly beyond those obtainable from our current technology base. For this reason, the research emphasis is being placed upon the two weakest areas in PCS, namely, capacitors and switches for lifetimes in the region of $10^{10}$ to $10^{12}$ hots, as needed in the mature versions of all the above systems. In this field of high-repetition rate capacitor development there has been exceedingly sparse data available in the area of long lifetime systems except for small radar modulator mica capacitors developed for the F-111 ($\gg 10^{11}$ shot life) and polysulfone/polypropylene-silicone oil capacitors ($>10^{10}$ shot life) specifically created for driving industrial $CO_2$ TEA lasers. The results of the work to date here have shown that the present research and development approach to developing very long lifetime capacitor systems can be applied to PCS requirements for full-scale fusion laser driver applications.

In the area of switching, several laboratories are working on complementary parallel efforts. At this time it appears that the first feasibility demonstration fusion reactor systems, operating in the 1- to 10-Hz region can be cost effectively switched utilizing spark gaps under development at Sandia and at LASL. At Sandia, components are currently being tested in the 30-kW range and will soon be into the >100-kW test-stand configurations. These are all Marx Bank devices and the Sandia facility will yield valuable scaling and lifetime data. Studies at LASL have shown that it is highly probable that alternative PCS configurations can be developed, utilizing extensions of adiabatic Blumlein techniques to continuous operation in the 10- to 40-Hz region as noted above, but yielding an MTBF of 3 to 5 years in contrast to months to a year ($\approx 10^7$ shots) for spark gap systems. For second generation fusion drivers of the future, further development of switch and capacitor technology from the base currently being established through present programs is necessary to achieve industrial reliability levels for these systems.

The repetitive switching techniques undergoing research and development at LASL primarily utilize thyratron technology, because programmatic needs demand long lifetime operation in all of the high-repetition-rate systems, (although some systems can function with spark gap switches to meet near-term objectives). Through LASL contract support, the demonstration of current pulse switching rates comparable to many single-channel spark gaps has been accomplished this year at a level in excess of $10^{12}$ A/s. Scaling these new thyratron structures to exceedingly large power levels has been carefully studied by both EG&G and LASL staff. It has been concluded that sufficiently large devices could be developed to allow a full-scale $CO_2$ fusion laser driver or EB/LI pulse-charging unit to be switched with only a few thyratrons (two to six depending upon voltage needs), each passing multimegawatts of average power. It is to be noted that these thyratrons represent a direct scaling from megawatt devices produced through the ERADCOM program and the ultrafast tubes being developed for the LASL LIS program and show the significant offshoot benefits of both technology-base development programs.

As noted above for thyratrons, military tube developments are underway to meet adiabatic applications from 50 to 120-Hz repetition rates, for 60 to 90 seconds on-time, long off-times, and a limited number of total cycles (a few hundred). Thus, all components -- thyratrons, capacitors, charging systems, and power supplies -- need to be lightweight and of limited life. These conditons are diametrically opposed to the long-life needs of all long-life, industrial systems as well as numerous other program needs as described above, and dramatically illustrate the need for a research and technology base development program to create systems meeting these conditions that are so at variance with the military requirements.

In part II-B of Fig 1, the power supply/charging system is shown as one block, connected directly to the mains. This type of configuration was chosen to illustrate charging systems utilizing high-frequency inverters and polyphase cycloinverters, which directly charge the capacitor banks in times somewhat shorter than the pulse repetition period. In the area of large-scale inverter technology, this is primarily at the research level (Gilmour, University of Buffalo). Cycloinverters are well established in the power industry (AC-DC and vice versa) and they may have application to single-shot systems. In most cases, their cost is so high that it is unclear just where they could be effectively deployed.

A Power Conditioning System (PCS), then, stores electrical or mechanical energy and, on command, deposits a predetermined amount of this energy into a load (either a resistor, an inductor, or a more complex load system). As we saw above, storage can be either electrical or mechanical and either all or a portion of the energy can be discharged into the load. This includes, for example, rotating machinery, pulsed alternators, and the like as storage elements. In the mechanical sense, we're thinking of rotational energy, stored in rotary motion. In the electrical case above, there are two classes: (1) storing the energy as electrostatic energy in the dielectric of the medium and (2) in a magnetic case, where the magnetic energy is stored in the magnetic fields inside on the inductor. This discussion does not take into account time-varying capacitance or time-varying inductance. These relations above (Fig. 1) apply, then, to geometrically invariant systems, not varying in spatial dimensions or position with time. Otherwise, the C or L cannot be moved from under the integral sign. If one is dealing with nonlinear cases or time-varying C and L, it is necessary to return to the complete formulation of Maxwell's equations.

Let us expand somewhat upon several facets of the above pulse power systems. In mechanical systems, mechanical energy is often stored in a rotating machine and then discharged through a switch that couples the storage component to a load. A pulsed mechanical energy discharger, being developed at the University of Texas (Austin) is called a compulsator. It is essentially a magnetic-flux compressor. When the flux is compressed to a maximum amount, a burst of energy is emitted into the load. The real advantage of this system is the enormous amount of energy that can be stored. At NRL, several megajoules have been routinely stored in a rotary machine. Mechanical stress analysis indicates that storage of up to several hundred megajoules in a superconducting rotary motion machine, or 100 megajoules in a straight mechanical wheel, is possible. The present difficulty with this system is the repetition rate for a fixed energy per pulse: they are extremely slow to recharge, with bursts once every second to once every two minutes.

As discussed in the Introduction above, electrical systems are of two major types: firstly (II-A), the PCS can have an AC or DC power supply (AC is relatively rare), connected to a charging system that charges the energy storage device (capacitor, inductor, or transmission line) until the assigned stored energy is reached. At that time the output switch is turned on and the energy is dumped into the load. (Fig. 2) The second electrical case (II-B) is the high-frequency inverter power supply. It charges the energy system in a few milliseconds, permitting very high rep rates. Some other types of systems in this class are the constant-current DC supplies that use series vacuum tubes, and command charging systems that use a series tube in the output or a thyratron turned full on to initiate the start of the (resonant) charge cycle. The system then charges the energy storage system in a very short period of time, the series tube turns on is turned off, and the output switch then closes, transferring the stored energy into the load.

If the energy storage device is charged rapidly, the probability of switch prefire is reduced, as it is proportional to the time the switch is at full voltage. When it is necessary to stress the switch to the maximum voltage, charging must take place very quickly (to decrease this prefire probability). Corona formation times are on the order of 1-10 microseconds. If the system is charged in times of that magnitude the probability of the switch itself having a significant internal corona current, which gives you a small electron density and thus a prefire, is quite small. The other advantage of pulse charging is that the dielectric strength of the energy storage medium is increased significantly (up to a factor of four higher for the same lifetime in a rep-rate system). The device can then be made several times smaller for the same lifetime, appreciably reducing the system inductance. This has considerable advantage for airborne devices, portable devices, or systems where extremely low internal impedance on the order of a few tenths of an ohm is required.

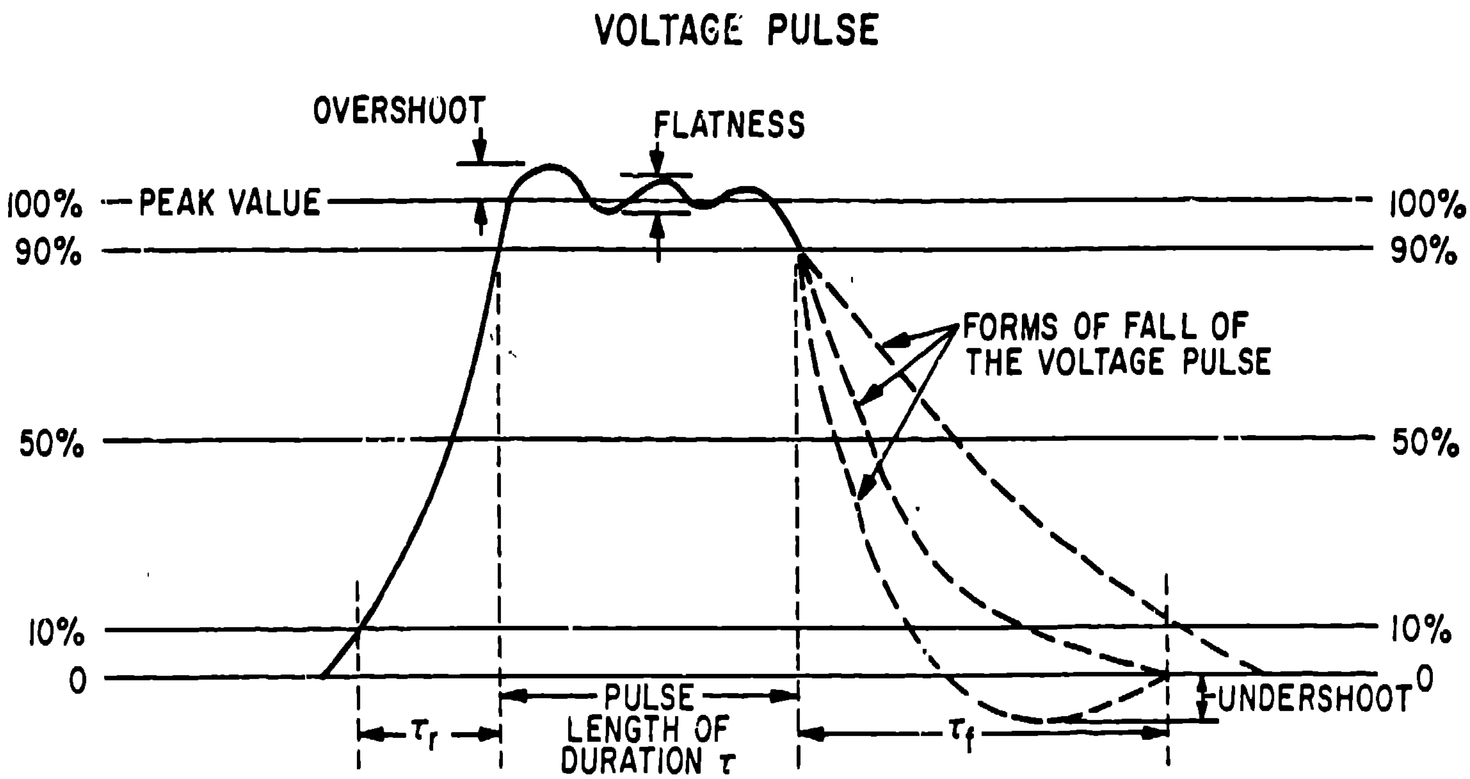
Each system has its own problem areas and performance limitations. When the switch closes, all the stored energy, if there isn't perfect energy transfer, is not dissipated in the load. Then, when the switch tries to open again, at the zero of voltage, the small voltage perturbations from the energy stored in residual inductance and stray capacitance of the system generate very high frequency transients in the system discharge loop and in the energy storage system. These transients must be dampened, otherwise the switch will generally reclose and fault the system power supply. This is the main reason why the early high-rep-rate TEA lasers were so very difficult to operate at rep rates above a kilohertz. There was enough energy stored in the loop inductances and stray capacitances in the system so that, whenever the switch started to open, there was sufficient inverse voltage applied to the thyratron switch (25 kv or so) to immediately fault it. It then acted as its own spark gap, tripping off the power supply. These transients can cause significant internal damage to triode thyratrons. Tetrode tubes are far more immune. Spark gaps, on the other hand, if they turn on again, stay on, and fault the power supply suffering no permanent damage Ignitrons will also tolerate such treatment if they have proper anode and "keep-alive" auxiliary electrode materials and will then withstand significant current reversals. The ignitron auxiliary electrode is pulsed with a very large trigger pulse and a relatively high energy is dumped into this auxiliary electrode (which keeps the pool ionized during the reversal period) so the mercury pool becomes the anode instead of the cathode. The only disadvantage is that high rep-rates cause a tendency for the reverse arc to track along the surface of the anode insulator, destroying the tube hold-off capability and reducing lifetime.

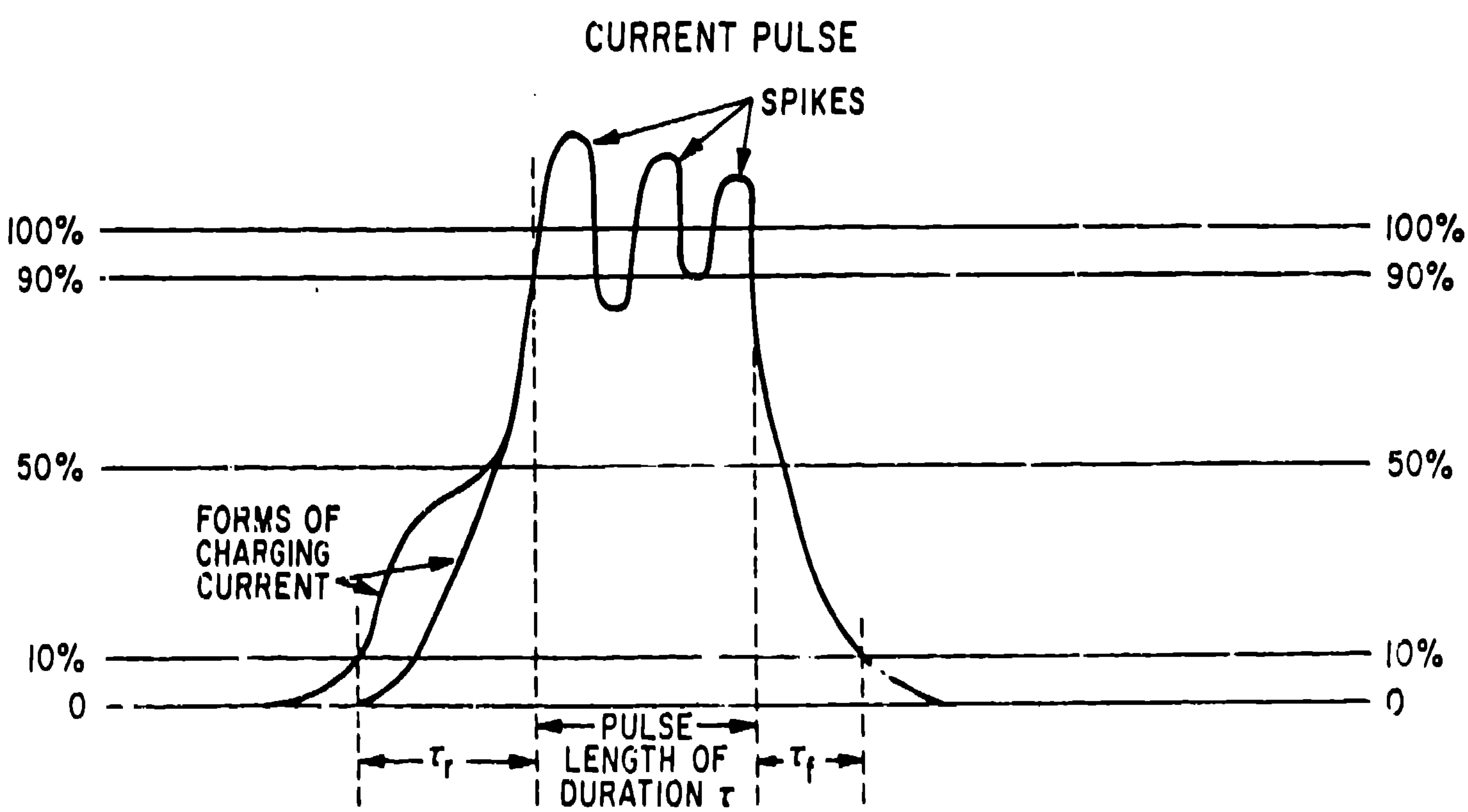
## 2. CHARACTERISTICS OF PULSE SHAPES.

In generating a voltage pulse, there are a number of parameters that are important in engineering, such as the peak value of the voltage and of the current through the load. These and other pulse shape parameters are summarized in Fig. 3, and their determining factors, described in greater detail below, are shown in Fig. 4. One area of considerable interest is the rate of rise of the voltage pulse on the load $\tau_r$; the second area is the rate of fall of the voltage, called $\tau_f$. The required smoothness of the top of the voltage pulse is determined by the load characteristics. In the case of magnetrons, klystrons, and similar systems, this particular fluctuation of voltage and subsequent fluctuation in current causes a tendency toward frequency pulling in the device, and results in a time-varying RF spectrum from the system.

Now, rates of rise can be defined in a number of ways. For these discussions, it will be defined as the time it takes the voltage to rise from 10% to 90%, rather than the e-folding time (i.e., the time it takes the pulse at an amplitude level of 1/e of its peak to fully fold back upon itself to zero initial amplitude). The same applies to the fall time. When the output switch is turned on, the voltage rate of rise is determined not only by the properties of the PCS, but also by those of the load. In the case of a magnetron or laser, until the voltage rises to 50-60% of the peak value, the load is almost an open circuit. The slope of this voltage curve at the beginning can then determine how the current begins to rise through the system and this can have several forms, depending upon the stray capacitances in the system and the load impedance. For a magnetron or laser, when the thyratron is first turned on, the PCS discharges into an equivalent shunt capacity across the laser

FIG. 3: PULSE SHAPE PARAMETERS



PULSE

# PARAMETERS DESCRIBING POWER CONDITIONING SYSTEMS

## A. FUNDAMENTAL

1. PULSE SHAPE:
   - A) $\tau_r$: FROM 10-90%: RATE OF RISE
   - B) SPIKES AND OVERSHOOT
   - C) FLATNESS
   - D) $\tau_f$: FROM 90-10%: RATE OF FALL
   - E) $\tau$: DURATION AT 90% POINTS
   - F) PEAK VALUE: $V_{PK}$ AND $I_{PK}$

2. PEAK PULSE POWER:

   $P_{PK} \equiv V_{PK} \times I_{PK}$

3. ENERGY:

   ENERGY, $W_L$, DELIVERED INTO THE LOAD OVER THE PULSE DURATION VS THE TOTAL ENERGY DELIVERED INTO THE LOAD, $W$, DURING THE INTERPULSE INTERVAL.

4. PULSE REPETITION FREQUENCY:

   $PRF = \frac{1}{T}$ : PROBLEM IS GENERALLY ONE OF INTERPULSE SWITCH RECOVERY TO PREDISCHARGE, QUIESCENT STATE.

## B. DERIVED

5. DUTY FACTOR $\equiv \tau/T \equiv DF$
   (DUTY RATIO)

6. AVERAGE POWER:

   $P_{AV} = \frac{\tau}{T} \times P_{PK}$

7. IMPEDANCE LEVELS:

   ESPECIALLY IMPORTANT FOR TIME-VARYING LOADS IN ORDER TO MAINTAIN HIGH EFFICIENCIES.

FIG. 4

electrodes or magnetron, in series with some equivalent series inductance; this forms a series-resonant circuit with some damping in the equivalent inductance, allowing the output voltage to ring up rather quickly to values well in excess of the storage element charging voltage (overshoot). In fact, significant overvoltages can thus occur in these types of systems, which is often of a considerable advantage in the actual operation of a laser system but generally causes additional insulation problems.

The falling characteristics of the pulse really depend upon the way in which the impedance of the load varies with time. The discussion up to this point has generally assumed that there was a well-defined resistive impedance acting as the load for the PCS. As the voltage starts to decrease, for example, in the case of a magnetron, a point is reached at some voltage where suddenly the magnetron ceases to draw any current and the load in the equivalent circuit for the PCS then becomes the shunt stray capacitance in series with the loop inductance, L. This resonant circuit has an energy of $1/2 \, Li^2$ stored in this L at the moment of current decay that can then give rise to significant voltage ringing across the load. It is the damping of this ringing that is one of the most awkward problems in very high rep-rate PCS design.

The pulse duration, $\tau$, for our applications will be defined as the duration of the pulse at the 90% of peak-pulse amplitude. Note that there is a $\tau$ for the current and for the voltage pulse, which are often significantly different.

The various parameters that can be used to describe power conditioning systems can now be summarized. The fundamental parameters for the voltage and current pulses were previously discussed, e.g., the risetime and also the rate of rise of voltage (of interest in the formation of glow discharges in lasers and in the initial turn-on conditions for klystrons and magnetrons) and are unique to each particular application. In the case of magnetrons, for example, the $\tau_r$ has to be slower than a critical value or a problem called "mode hopping" (a shift from one rf frequency to another during the time the current is building up) arises.

The second area of interest is spiking. Spikes are a major problem, even for relatively well-defined loads, such as the magnetrons and klystrons, as well as for laser systems, because these can give rise to arcing in the system when the voltage stresses are too high. If, too, the current oscillations are excessively large, they can cause the discharge in some laser loads to effectively quench as the current goes down through zero. This produces a system in which the switch will try to reclose and will no longer be operating in the proper mode, generally causing the switch or laser to arc and fault the system.

The pulse flatness is of primary consideration in applications requiring accurate voltage pulses for driving loads like Pockel's Cells and other electro-optic light modulators. On the other hand, this flatness isn't terribly important in many laser devices, which generally tend to behave as constant-voltage loads, smoothing out these peaks. As long as the energy is deposited into the resistive phase of the discharge in these systems (where the impedance is roughly constant), there's generally little advantage in efficiency for the applied voltage and current to have perfectly flat pulse shapes, provided the applied voltage is sufficiently above the threshold for efficient excitation laser kinetics. This has been a point of some considerable discussion and analytical work in the case of the $CO_2$ lasers in the course of the last few years. Work at LASL has shown that for an E-beam laser system with a very carefully controlled rectangular voltage and current pulse shape from the PCS into it, for which the gain is measured in the medium, this gain starts to grow up to some peak value above which deactivation processes begin to dominate. In contrast, take, then, the area under the power curve, which is some energy W deposited in the gas up to the gain peak and then deposit the same energy in the same time, but without a sophisticated, complicated network. Rather, what one uses is an inductor and a series capacitor; so then the energy is deposited in something like a $\sin^2 \omega\tau$ fashion, and measurement and calculation show that almost the same peak gain is obtained as for the carefully shaped flat pulse case. It's a very interesting observation for laser systems. As long as the energy is deposited into a constant-resistance system (glow-discharge) and the applied voltage is above some critical value,in general, it appears that one doesn't have to be very sophisticated about the pulse shape. This applies to systems primarily where electron attachment and recombination are the dominant mode in which the electron density decreases during this portion of the pulse. In the case of some of the ultraviolet laser systems, that argument isn't quite valid. This explains why you can get away with so much in driving most laser devices, in terms of pulse shape, and still have a relatively high efficiency. Whereas, in contrast, magnetrons and klystrons are very pulse-shape dependent for efficiency, particularly for very large pulsed klystrons.

There are three derived parameters in pulse shape characteristics. One is the duty factor, the ratio of the duration of the pulse to the interperiod spacing. This is usually written as DF in most of the texts. If you multiply that by 100, this gives the percentage of time during which a system is actively discharging energy. The duty factor can be used to calculate the average power, which is basically the duty factor times the peak power through the load per pulse, $P_{PK}$. A comment: that does not necessarily mean that that the total energy discharged into the load per pulse is useful energy. It says that there is some type of time history of the power flowing into the load and now all the energy that was stored in the energy storage device has been removed from the latter. The characteristic of the load device (laser, magnetron, or whatever) may be such that the input energy, beyond some point, alters the load characteristics and all this energy that is the flowing later on into the system (i.e., beyond this point in time) is lost, so far as efficiency is concerned. This is a significant difference from the PCS requirements of yesterday. In the 1950s one had well-defined loads, such as magnetrons and there were few efficiency problems. The model of a magnetron in this case was a resistor in series with a reverse-biased diode, which worked out quite accurately and efficiencies for these systems were often greater than 70%. Today, energy transfers in lasers are typically 20 to 50%. (That's the ratio of the energy stored in the PCS to the useful energy delivered into the load.) This fact can often be cause for considerable concern. This energy that is being delivered into the load that is useful energy and is producing either photons or RF power or the other output characteristics desired is often much less than the energy that is stored in the energy storage device of the PCS. Normally, this ratio is desired to be one. For a number of new systems of considerable interest today, it's much less than one. Therefore, the overall system efficiency that was formerly around 80% has decreased to 20-35%. When one considers devices where it is desired to put in hundreds of kilowatts of useable average power, this means that the total input power must be on the order of megawatts. Another reason this point is becoming important is that a number of the load interface considerations in previous systems now change because there is a great deal of resistive power (Joule heating) to dissipate in the load. One must transfer that thermal energy to somewhere else. This means either wasting energy in heating the gas laser or load medium or wasting it in the load device generating, say, RF radiation, giving rise to a very severe thermal load problem. If, for example, 70% is lost energy, at a megawatt of average power flowing into the system, there is, then, 700 kW of undesired power in the load, which must be disposed of. It's not useful. Such thermal loading can cause significant problems.

The peak pulse power, $P_{pk}$, is the product of the voltage and the current at the point at which $P_{pk}$ has a maximum value. More sophisticated definitions can be generated because of load characteristic shifts, but the convention suggested is that we look at $P_{pk}$, at the voltage peak, then we look at $P_{pk}$ at the current peak, and define the peak power to be the larger number of the two.

The energy $W_L$ is delivered into the load over the pulse duration, but it may not be the same as the total energy delivered into the load, W. That difference significantly affects, then, the efficiency of the overall system.

The Pulse Repetition Frequency (PRF, or sometimes Pulse Repetition Rate - PRR) is a perfectly good parameter to use in systems that are repetitive at a given frequency (i.e., there is a constant period of time from one pulse to the next, say 100 pulses per second). There are some difficulties when one considers, for example, modulators or pulsers with pulse rep-rate agility. These are normally hard-tube (vacuum tube) switched systems, where, upon commands into them a series of output pulses is generated at this certain externally defined interpulse spacing, which can be varying all the time; as well, the pulse width of the pulses can be varying all the time according to some predisposed computer program. In that particular case, the concept of PRF doesn't apply.

The main problem in all of these power conditioning systems is the one of interpulse recovery to the predischarge quiescent state. If there is some post-discharge energy left in the PCS, oscillations can arise in the discharge loop, and switches stay on that shouldn't and components often subsequently become overstressed. What is desired is to recharge the energy storage elements after all switches are fully recovered.

The load being reproducible on every pulse means that the system output pulse shapes are perfectly reproduceable on every pulse. For example, the impedance with time might have a specific shape, but in engineering a system to work at even a single shot, you assume that this does not vary from pulse to pulse. The next pulse that comes along, then, varies the same way with time, providing that everything is charged to the same voltage.

Comment: in high-rep-rate systems, particularly lasers and some RF tubes, this is not the case. A residual degree of ionization is left inside the system so the impedance profile per pulse may experience a different time history until equilibrium is reached. That is an important problem in very high rep-rate systems. In small, high-rep-rate magnetrons, or in klystrons, this does happen, but to a lesser degree. In that particular case this is primarily a result of the space-charge saturation limitation in the cathode region. As you come up to cathode operating temperatures from start-up, there's a small shift of the available charge per pulse available from the cathode. The time-history of impedance, then, changes slightly. It is meaningful to emphasize this point because, in a number of the systems under consideration now, this will become a significant factor in PCS design for high-efficiency of energy transfer. In $CO_2$ TEA lasers operating at multikilohertz rep-rates, this particular impedance pulse shape is primarily determined by a combination of gas heating combined with the effects of residual, interpulse, ionization left in the system. Then it is necessary to choose which is the most efficient load profile in time to match into for maximum output energy for the specific experiment under consideration. If a very long operating time is not required, one could choose the start-up load impedance, but if long runs are needed at maximum efficiency it will be necessary to utilize a pulse-forming network that will maximize the energy transfer into the system at the equilibrium impedance level.

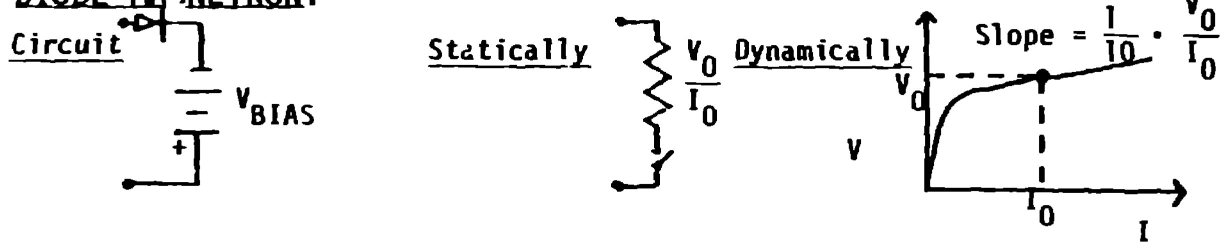
These, then, are some of the different types of loads often found connected to PCS. A summary of their characteristics is presented in Fig. 5. Pure resistive, capacitive, and inductive loads are relatively straightforward to handle. The diode magnetron, on the other hand, has an equivalent circuit of a reversed biased diode that turns on at some standard voltage. When it turns on, then the voltage-curve is almost flat with time. The dynamic impedance is quite low, basically like that of a glow-discharge, constant-voltage device.

In a magnetron the dynamic (slope) impedance is about a tenth the static value at the operating point. In the case of lasers, there is generally a combination of this load behavior, with a time-varying

LOADS FOR POWER CONDITIONING SYSTEMS

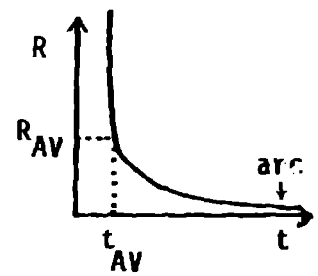
1. A) RESISTIVE: B) INDUCTIVE: C) CAPACITIVE:

2. DIODE MAGNETRON:




V-I Characteristic

3. LASER:
DIODE MAGNETRON LOAD OFTEN COMBINED WITH TIME VARYING RESISTANCE, R:




4. TIME VARYING LOADS:
DISPERSIVE LOADS AND LOADS WHOSE "L" AND/OR "C" CHANGES WITH TIME:
-- "INDUCTIVE" AND "RESISTIVE" PHASES DURING THE DISCHARGE TIME.
E.G. FERRITE SHOCK LINES, ARCS AND SPARKS, HIGH PRESSURE DISCHARGE LAMPS, EXCIMER LASERS.

NOW: THE CHOICE OF THE PCS INTERNAL IMPEDANCE DEPENDS UPON:
1) LOAD IMPEDANCE 2) PEAK POWER LEVEL 3) PRACTICAL CONSIDERATIONS OF CIRCUIT ELEMENTS : (CAN ALSO USE PULSE TRANSFORMERS).

FIG. 5

component in the impedance. Fig. 5 shows a rough sketch of what the impedance with time looks like for an attachment-dominated excimer laser system (e.g., KrF*, XeCl*, or XeF*). Evidently, the impedance decreases dramatically with time, but if one could put most of the energy into the system at times when the field intensity is sufficiently high for efficient pumping, then the laser system would work well and with high efficiency. Unfortunately, when this is attempted, a point is reached later in pumping time where the system arcs internally. This is normally caused by a thermally-induced instability. In terms of load classes, one of the most difficult, then, is the attachment-dominated laser discharge, which also happens to be rather interesting as an optical radiation source. In the copper vapor laser, for example, the impedance-with-time curve is somewhat shallower and alters dramatically as the rep-rate is increased. (The copper vapor laser is a longitudinal, abnormal glow discharge excited with ring electrodes, one at each end of a ceramic tube.) Closing the switch in the PCS generates a voltage pulse that initiates a discharge, dumping the energy stored in a relatively small capacitor into the discharge tube at a rep-rate of up to 25 kHz. By keeping the energy per pulse sufficiently small it is possible to obtain a uniform, longitudinal discharge. Unfortunately, as the rep-rate is increased even farther, thermal instabilities and kinetic effects constrict the discharge, raising the current, and increasing the drop in impedance with time, reducing the system efficiency.

The fourth class is formed by time-varying loads. Dispersive loads change their permeability or dielectric constants with time, as energy is deposited into them. An example is a shock-excited ferrite transmission line (e.g., a coaxial transmission line with the center conductor covered by a ferrite material.) Driving the line could be a capacitor with a switch connected to the line input. Closing the switch starts energy flowing down the line saturating the ferrite and steepening the rising edge of the voltage pulse as the wave front progresses down the line. As the ferrite saturates, a sharpening of the pulse is found. The sharpening is caused by the expenditure of energy in saturating the ferrite. Once the ferrite is saturated, the permeability is one and, since the dielectric constant is rather low (12-15), the balance of the foreshortened pulse travels down a much higher impedance line. For more details of this, Martin Maley wrote a report on the subject. In a sense, such systems can be represented by lumped-element transmission lines, where the L and the C per unit length are time varying. This is a nonlinear problem and can be numerically solved with iterative solutions to Maxwell's equations. There is no analytical solution to the problem. With these systems, it has been fairly straightforward to generate pulses of 5-10 kV with risetimes of 1-2 ns. With more optimal ferrite materials, one may be able to reach 100 to 200 ps risetimes. Unfortunately, there are serious reflection problems in these systems, making the generation of very accurate pulses a difficult and empirical design matter. This is very good technique for generating a very sharp pulse at the end of a coaxial cable.

Another type of load is the "spark discharge" used as a radiation source for short wave-length UV spectroscopy. Basically, the spark discharge is a point optical source and it is excited by a switch discharging a charged, single-wire transmission line into the spark load. As the line capacitance is discharged, a wave is launched along this line (of about 150 ohms impedance) providing the prompt energy for the spark discharge during the two-way transit time of the line. The spark is not a linear load with time and behaves similarly to the excimer laser loads discussed above. The difference in this case is that the arcing point is at the spark turn-on and it is this arc that provides the optical radiation source. The last area is high-pressure discharge lamps, CW or pulse for driving glass lasers and UV process curing lamps, Hg discharge lamps and other such systems, and these are operated in the glow (cw) or abnormal glow (pulsed) mode, all as optical radiation sources.

Ignitrons are a much maligned switch, generally ideal for crowbar applications. There are modest rep-rate applications (< 100 Hz) at low energies requiring an inexpensive switch that can handle substantial current reversal. This is a good application for ignitrons. One problem with them is the rather sophisticated trigger generators needed for reliable triggering. Normally, about a joule per pulse must be dumped into the igniter, basically through a constant-current source, causing some heating problems at high rep-rates.

The internal PCS impedance selected depends primarily upon three parameters: the load impedance time history, the peak power level (and concomitant useful energy), and, thirdly, the practical considerations in selecting available circuit elements. Capacitors for low rep-rates are readily available. For high rep rates ($\geq$ 1kHz), low-inductance, high-energy, long-life capacitors are not yet here. For fast discharges ($\approx$50 ns) capacitors generally behave as transmission lines. The liquid-impregnated, insulating-film capacitor is made of sections of paper, plastic film, and foil wrapped up with connections on either end. At the self-resonant frequency this is a parallel-plate transmission line with a surge impedance of a fraction of an ohm. Discharging this capacitor into a short circuit, the limiting transmision line discharge time for almost all such capacitors becomes $\approx$100 ns. The only way to make faster discharge capacitors is to develop capacitor geometries or new types of energy storage devices with shorter internal discharge times. Single-shot assemblies with discharge times of 40-50 ns have been developed, but are presently unsuitable for high-repetition-rate operation.

There are two categories of power conditioning systems, as shown in Fig. 6:

1. Ones in which a small amount of energy is dumped from the storage device into the load. These are generally hard-tube power conditioning systems, series vacuum tube switches, crowbar storage devices, and mechanical power conditioning systems, like the compulsator. The advantage of these devices is that they generally utilize an analog switch element, so you can, if desired, modulate the energy flow into fixed and time-varying load impedances as a function of time. Note that the X-ray flux from the high vacuum systems at the 30 kV level and above can be quite considerable.

2. The second class is one in which all the stored energy is transferred into the load every pulse. These are line-type power conditioning systems, Blumlein generators, Marx banks, etc.

## 3. SWITCHES

Normally, a switch is closed during discharge and opened during the recharge time (Fig. 7). During the recharge period, a closed switch would then short the charging system. The required characteristics of that switch then depend on whether all the stored energy is dumped into the load in each pulse. If one needs to transfer all the energy out of the storage system, at a constant output voltage for a predetermined period of time, a transmission line or a pulse-forming network needs to

## POWER CONDITIONING CATEGORIES OR CLASSES

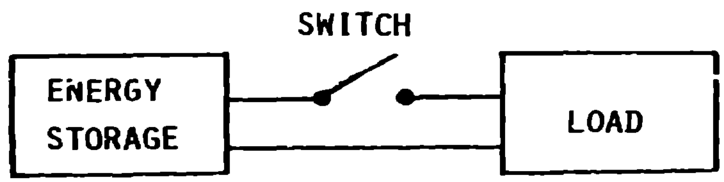
A) THOSE IN WHICH STORED ENERGY IS PARTIALLY TRANSFERRED EACH PULSE:
E.G., HARD-TUBE PCS, CROWBAR STORAGE BANKS, MECHANICAL PCS.
-- GENERALLY REQUIRE AN ANALOG SWITCH ELEMENT.

B) THOSE IN WHICH ALL STORED ENERGY IS TRANSFERRED EACH PULSE:
E.G., LINE-TYPE PCS, BLUMLEIN SYSTEMS, MARX BANKS.

FIG. 6

## SWITCHES

- GENERALLY A SWITCH IS CLOSED DURING THE DISCHARGE AND OPEN DURING THE RECHARGE TIME.




- SWITCH CHARACTERISTICS DEPEND UPON WHETHER OR NOT ALL THE STORED ENERGY IS TRANSFERRED PER PULSE.

  NOTE: PULSE SHAPING IS NECESSARY IN MOST DISCHARGE CIRCUITS WHERE ALL THE STORED ENERGY IS TO BE TRANSFERRED PER PULSE.

- NOTE ON CHARGING: SINCE THE INTERPULSE PERIOD IS MUCH LONGER THAN THE DISCHARGE TIME, IN GENERAL THE DISCHARGE CIRCUIT CAN BE LOGICALLY DISCUSSED SEPARATELY FROM THE CHARGING CIRCUIT.

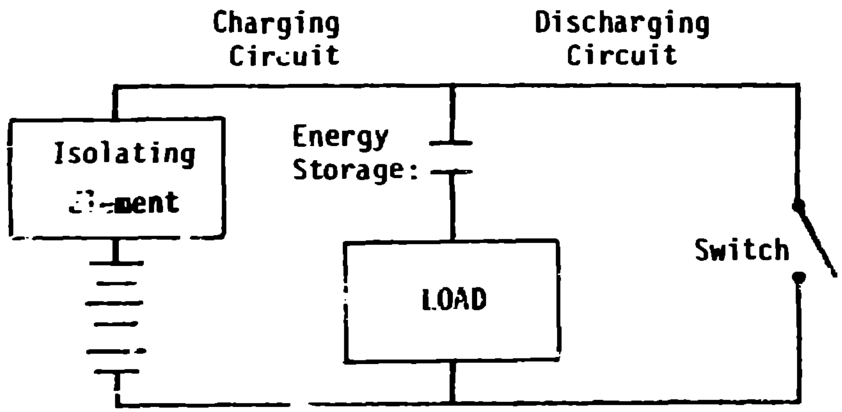
FIG. 7

be employed as the energy-storage device. Since the recharge time is almost always much longer than the discharge time, the discussion of the discharge part can be separated from that of the charging circuit. This approximation is not verv good, however, for systems such as the copper vapor laser with its 25-30 kHz operation -- the discharge time is a fraction of a microsecond and the recharge time is a microsecond or so. On that time frame, there are many other problems, particularly keeping the switch turned off during the recharge.

## 4. PC CONDITIONING SYSTEMS: HARD-TUBE AND LINE-TYPES

Hard-tube power conditioning systems are still alive and well. They are very useful in relatively small, low-voltage (<200 kV) systems. In a hard-tube PCS (Fig. 8), a large energy-storage capacitor is charged from a DC supply through an isolating element. The capacitor is connected to the load by a switch. If the switch is closed, energy is discharged into the load, and the isolating element serves to prevent the DC supply from discharging into the discharging circuit loop as well. The switch, however, opens to see almost the full potential of the DC power supply, since, for good voltage regulation, only a small portion of the stored energy is discharged into the load on each pulse. The switch generally then needs to be a high-vacuum tube or a vacuum interrupter. Hard-tube power conditioning systems are commonly used today in the region of a few kilovolts at subnanosecond risetimes. They have a great advantage in terms of pulse-width agility and rep-rate control. At high rep-rates they are very useful and the drive requirements are not severe. The real advantages of the hard-tube PCS are the variable pulse width and the high PRF capabilities at modest efficiencies. Large hard-tube power conditioning systems (1000 A at 200 kV) exist. At these high voltages, the switching time is rather long and the cost can be very high indeed. They cannot generally be replaced with thyratrons, ignitrons, or spark gaps in these applications. On the other hand, they have limited di/dt capability because the vacuum tubes have a saturation resistance of a few hundred ohms, and that resistance limits the charging

# HARD TUBE POWER CONDITIONING SYSTEMS




ENERGY STORAGE:

GENERALLY, ENERGY IS STORED IN A LARGE CAPACITOR AND ONLY A SMALL FRACTION OF THIS ENERGY IS TRANSFERRED TO THE LOAD PER PULSE.

-- THE SWITCH MUST HAVE VERY GOOD RECOVERY CHARACTERISTICS AS WELL AS HOLD-OFF CHARACTERISTICS: E.G., VACUUM TUBE.

NOTE: PULSE TAILORING CAN READILY BE PROVIDED WHEN USING A VACUUM TUBE SINCE THE GRID CONTROLS THE TUBE RESISTANCE.

FIG. 8

rate of whatever stray capacitances there are across the load. Their efficiency is nowhere near that of the line-type pulser (see Fig. 9).

Line-type pulsers are quite different (Fig. 10). The energy is stored in a continuous or lumped-element transmission line, sometimes called an artificial transmission line in the lumped-element case. Since this is the energy-storage element during the pulse discharge as well as the pulse shaper, the general designation of "Pulse-Forming Network," or PFN, was coined by someone during WWII.

There are two main classes of line-type pulsers: voltage fed and current fed. In the case of the voltage-fed pulser, the energy, $W_e$, is stored in the total capacitance of the transmission line or PFN ($W_e$ = 1/2 $CV^2$, where C is the total RFN capacitance and V is the charge voltage). In the case of current-fed systems, a current is placed into the pulse-forming network and at the peak current value, 1/2 $Li_{pk}^2$ of energy is stored in the system. On the charging side is a closed series switch that can be opened at that point. As soon as the switch opens it must withstand the full discharge voltage.

There are two general classes of voltage-fed line-type PCS (Fig. 11). The first is a continuous transmission line that is charged from a voltage source. It has a switch at one end, and, when the line is charged to voltage V, the switch is closed, discharging the energy stored in the transmission line into the load. If the load impedance equals the line impedance then $V_L$ = 1/2 V. On the right side of Fig. 11 is sketched a time history of a typical charge and discharge cycle. The energy storage system is charged to the voltage V with a charging network. At the peak voltage, V, the switch is closed and pulse of energy flows out of the system and into the load. The pulse length is twice the one-way transit-time value of the continuous transmission line and all the stored energy is transfered to the load. That's for a matched system.

## CHARACTERISTICS OF
## HARD TUBE POWER CONDITIONING SYSTEMS

ADVANTAGES:

- VERY HIGH PRF AS WELL AS APERIODIC OPERATION POSSIBLE.
- PULSE TAILORING.
- RAPID FAULT CLEARING.

DISADVANTAGES:

- LIMITED DI/DT CAPABILITY BECAUSE OF RATHER HIGH TUBE-ON RESISTANCES (≈100Ω).
- COST GENERALLY VERY HIGH COMPARED TO OTHER PCS.

FIG. 9

# LINE TYPE POWER CONDITIONING SYSTEMS

1. THE ENERGY IS STORED IN A CONTINUOUS OR LUMPED ELEMENT (I.E., "ARTIFICIAL") TRANSMISSION LINE.
   - SINCE THIS SERVES AS THE ENERGY STORAGE ELEMENT DURING THE DISCHARGE PULSE AS WELL AS THE PULSE SHAPING ELEMENT, THE GENERAL DESIGNATION IS:

"PULSE FORMING NETWORK" OR "PFN"

2. <u>CLASSES OF LINE TYPE SYSTEMS</u>

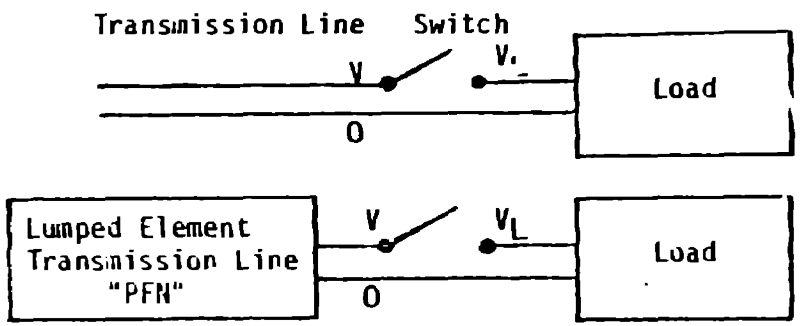
THERE ARE TWO CLASSES:

| VOLTAGE FED | CURRENT FED |
|---|---|
| - $W_e = \frac{1}{2} CV^2$ | - $W_e = \frac{1}{2} LI^2$ |
| - CLOSING SWITCH USED | - OPENING SWITCH USED |

FIG. 10

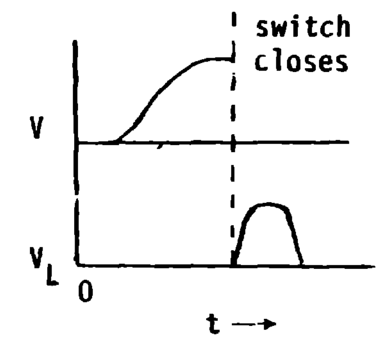
# VOLTAGE FED LINE TYPE POWER CONDITIONING SYSTEMS

**TYPES**




$$W_e = \frac{1}{2} CV^2$$

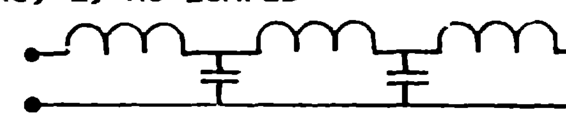
WHERE C IS TOTAL LINE CAPACITANCE AND V IS THE PEAK CHARGE VOLTAGE.




**NOTES:**

1. PFN CONSISTS OF A NUMBER OF CAPACITORS, C, AND INDUCTORS, L, AS LUMPED CIRCUIT ELEMENTS:

TYPE E PFN:



2. VALUES AND NUMBER OF ELEMENTS IN PFN DEPEND UPON THE:
   A) DESIRED PULSE SHAPE
   B) LOAD IMPEDANCE
   C) COMPONENT AVAILABILITY

3. WHEN $Z_{LOAD} = Z_{PFN}$ (OR $Z_{LINE}$) THERE IS MAXIMUM ENERGY TRANSFER AND EFFICIENCY, ASSUMING A "PERFECT" SWITCH IS USED. OTHERWISE SOME ENERGY IS LEFT IN THE PFN AT THE END OF THE DISCHARGE TIME OF THE PFN CAUSING PROBLEMS IF THE MISSMATCH IS SEVERE; E.G., SWITCH RECOVERY, FAULTING, LOAD ARCS.

FIG. 11

The second-class of line-type PCS uses a pulse-forming network comprised of a number of lumped elements of inductances and capacitors and a type E network is shown for illustration in Fig. 11. The designer chooses, basically, the L and C for the given load impedance and a number of sections in the line depending on the pulse fidelity required. With only one section, an L-C discharge network is formed. As more sections are added, the second begins to discharge into the load concurrently with the first section and a more rectangular pulse is formed in the load. With five or six sections, good pulse fidelities with ripples of about 4-5% are possible. Coupling between the inductances is possible and some PFNs, such as the Type E, are built that way. In this case, the different sections communicate in the flow of energy. Some classes of time-varying loads can be accommodated by the addition of additional coupling inductors between elements of the lines. These inductors are generally saturating inductors with ferrite cores. Years ago, there was some work done in far infrared laser driver systems using that particular mode of operation. Such a direct electron pumped far-infrared laser maintains high conversion efficiency as long as the voltage across the laser load exceeds a critical value. To keep the electron temperature high, elements were chosen depending upon the laser impedance time history and component availability to preserve a rectangular voltage pulse shape.

It is intended that we will spend a significant amount of time discussing the current state-of-the-art in components, as they represent the major limiting factors in the technology base of PCS, particularly at high repetition rates and long lifetimes.

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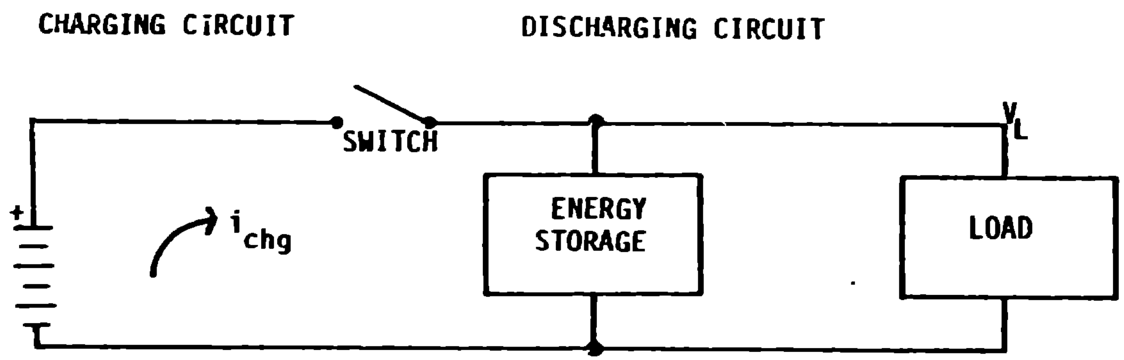
Current-fed power conditioning systems will see considerable use in the future as improved opening switches become available. In a current-fed PCS, in contrast to a voltage-fed pulser, the switch closes to allow current to flow through the battery ($V_{DC}$) to the energy storage (Fig. 12). When the peak current is reached the switch opens and a negative pulse is generated across the load. The switch then experiences a very large voltage across it. Many current-fed power conditioning systems in small modulators are formed with relatively fast switching transistors, and they can be used to generate relatively high-voltage pulses with modest charging voltages. An inductor can be put in series with a transistor with a transmission line or capacitor across it. When the transistor is turned off the energy stored in the inductor collapses and generates a voltage spike, which is useful for voltage multiplication. There are some very useful circuits in Electronics Design for voltage multiplying using this technique.

The pulse length, then, is forced to be determined by the characteristics of the energy-storage device. Either a capacitor or a current-fed transmission line can be used. The latter has been studied extensively by a student of Tom Burkes' over at Texas Tech. Provided that the switch technology can be improved, this particular approach may be of some value in the 10-50 kV region. At peak current, the switch is opened and conservation of energy gives a voltage across the load impedance equal to the peak charge current times the load impedance over 2. But, again, a major problem is switch recovery. There is another problem, in that when analysis of this sort of circuit is done, it is assumed that the switch is an ideal switch. In fact, what is normally used in this type of circuit is either a fast transistor, a series

## CURRENT FED POWER CONDITIONING SYSTEMS




NOTES:

1) THE CURRENT BUILDS UP IN THE INDUCTANCE OF THE ENERGY STORAGE ELEMENT (TRANSMISSION LINE, PFN, OR TRANSFORMER).

2) AT THE PEAK CURRENT, THE SWITCH IS OPENED AND A HIGH VOLTAGE, $V_L$, APPEARS ACROSS THE LOAD.

$$V_L = \frac{Z_L}{2} \cdot i_{chg}\text{[PEAK VALUE] : FOR MATCHED IMPEDANCES}$$

3) THE SWITCH MUST RECOVER VERY QUICKLY TO HOLD OFF THE PEAK LOAD VOLTAGE.

FIG. 12

high-vacuum tube, or a vacuum interrupter. The equivalent resistance of the device increases as the current through it increases; in some cases, a nonlinear increase is found, increasing the charging losses. One other type of switch technique is to use a forced-commutation thyratron switch or a vacuum current interrupter. An auxiliary circuit can be placed across the switch, then discharged through the switch at the point of peak charging current so that the switch carries no net current and the switch then rapidly recovers. This is a method of turning off a switch that normally only recovers at zero current.

## 5. IMPEDANCE MATCHING

Matching the load impedance to the pulse-forming-network impedance is done primarily to obtain maximum power transfer (Fig. 13). The disadvantage, of course, is that only half the charging voltage is obtained. If the pulse-forming network is charged to 100 kV, only a 50-kV pulse is generated with typical efficiencies of 80-90%. The other point is that if the load and PFN impedances are not equal, reflections between the load and the PFN occur at the end of the discharge period of the PFN. If the load impedance is lower than the PFN impedance, a current reflection follows and the current flow continues on for a long, long time in an oscillatory manner. If the load impedance is larger than the PFN impedance, the load voltage, $V_L$ is V/2 for the discharge time, $\tau$, and, depending upon the reflection coefficient (related to the ratio between the load impedance and the PFN impedance), a number of steps in the voltage pulse as a function of time can occur. Each step is $\tau$ seconds long. This points out one of the problems when the load impedance is much higher than the PFN impedance, namely that there's current flowing through the switch for a relatively long period of time. It's a unidirectional current, but takes a long time to die away. In such a case, switches such as spark gaps can revert from an arc to a glow and stay lit like a light bulb with milliamps of current through them. The actual power put into the switch can, operating under these conditions, be very significant. This is a strong argument for trying to

# IMPEDANCE MATCHING OF POWER CONDITIONING SYSTEMS TO THEIR LOADS

1. NEARLY MATCHED IMPEDANCES ARE REQUIRED FOR
   A) MAXIMUM EFFICIENCY
   B) PULSE SHAPE FIDELITY
   C) MINIMUM POST-DISCHARGE VOLTAGE STRESSES ON SWITCH AND PFN.

2. IF $Z = Z(t)$ THEN THERE ARE PROBLEMS IN OBTAINING HIGH EFFICIENCIES.

3. IMPEDANCE INCREASES ARE OFTEN HANDLED BY PULSE TRANSFORMERS.
   - PRESENCE OF MANY 50 OHM COAXIAL CABLES TENDED TO MAKE THIS IMPEDANCE AN OFTEN-USED ONE FOR THE PFN.

4. FOR VOLTAGE-FED NETWORKS, THE VOLTAGE, UNDER MATCHED CONDITIONS, DECAYS TO ZERO AT THE END OF THE PULSE.
   - VERY GOOD SWITCH IS ONE THAT RECOVERS AT ZERO CURRENT AND NEAR ZERO VOLTAGE. E.G., SPARK GAP, IGNITRON, THYRATRON, SCR.
   - THE RECOVERY CHARACTERISTICS OF THIS SWITCH ALSO DETERMINE <u>ALMOST EXCLUSIVELY</u> THE NATURE OF THE INTERFACE TO THE CHARGING SYSTEM.



FIG. 13

match or slightly undermatch ($Z_L \leq Z_{PFN}$) the load to the PFN impedance.

If the load impedance is less than the pulse-forming-network impedance, the post-discharge voltage pulse oscillates about zero. Then, the unidirectional switch turns off at the first voltage zero. A problem occurs if the load happens to short, generating a very large voltage reflection, then exceeding the switch-recovery voltage, thus causing it to fault unless a voltage-limiting network immediately shunts the energy away from the switch. A second class of problem arises when the load impedance is variable with time. A time-varying load impedance can move the operating point from a matched regime to unmatched as the time increases. This is particularly true in the case of lasers. It is also true in some high-current density discharge lamps. So, matching isn't really then practical: depositing the maximum amount of energy into the system in the relevant time frame is the most efficient approach. In terms of designing for this regime of operation, it is far easier because of the voltage reversal across the switch, in the latter case. This is in contrast to the case $Z_L \geq Z_{PFN}$ where a small unidirectional current is flowing through the switch for a very long period of time. The switch starts trying to recover in the zero current and zero voltage regime and any small oscillations in the pulse-charging system will tend to inhibit this recovery. If the switch detects any appreciable positive voltage near the zero of current, it will not recover, faulting on and dumping the high-voltage power supply during recharge. This regime of operation was formerly referred to as "positive mismatch." It was a favorite of many of the WWII radar modulator designers and is totally unnecessary today with the availability of modern inverse-voltage-control networks and considerably increased thyratron inverse-voltage ratings (up to -20 kV).

There were a number of applications, in the mid 1950s, where relatively high voltages in the region of 100 kV or 200 kV were needed at tens to hundreds of amps peak for driving large klystrons. (Klystrons needed physical length to accelerate the electrons vs the available electrical stress that the system permitted (electrical stress inside the system).) At that time, most switch tubes (thyratrons, ignitrons) were limited to 20-30 kV. The voltage thus had to be increased with a pulse transformer. The transformer technology for 1-5 microsecond pulse lengths is relatively well-established if the risetimes are on the order of fractions of a microsecond. When sub-hundred-nanosecond risetimes at significant average power levels are required, efficient design becomes very difficult. (With a sacrifice in efficiency, 20-30 ns risetimes are possible, but these are very sophisticated transformers with poor energy transfer (about 20-30%).) Few transformers are known that can handle significant energies at such risetimes: one is a special version of a transformer developed by Gerry Rohwein at Sandia. It is a very low leakage tape-wound air-core transformer. The other was proposed by RCA to drive a very large load and to produce a quarter of a megavolt with an extremely fast risetime, at an average power of 30 megawatts. The primaries and secondaries were relatively thin copper foil and water flowed through the copper foil, which was edge graded to prevent significant corona. The intention was to discharge 300 individual PCS into the primary of that transformer.

Pulse transformers were used so much in modulator design because they were straightforward to design at the 50-ohm primary impedance level. Fifty ohms was chosen, so the story goes, because there was 50-ohm cable. This cable existed because it was determined in the 1940s that working at the 50-ohm level gave you the highest available stress in the cable system along with minimal dispersion, and the cable was also easy to make.

Cables normally have rubber, polyethylene, or air-gap dielectrics. For most PCS applications, air-gap dielectrics are not practical. In the case of rubber dielectric cables, there are serious heating problems in short-pulse-length, high-repetition-rate applications. Rubber is not a good high-frequency insulator as it has considerable loss. In terms of physical flexibility and mechanical lifetime rubber is still the best choice for general-purpose applications, with a design lifetime of many years at a modest PRF. Polyethylene cable, on the other hand, is rather more fragile. It tends to have microbubbles filled with easily ionized water vapor in it. If these bubbles are undisturbed, they cause no damage. If the bubbles crack they propagate and internal treeing and shorts develop.

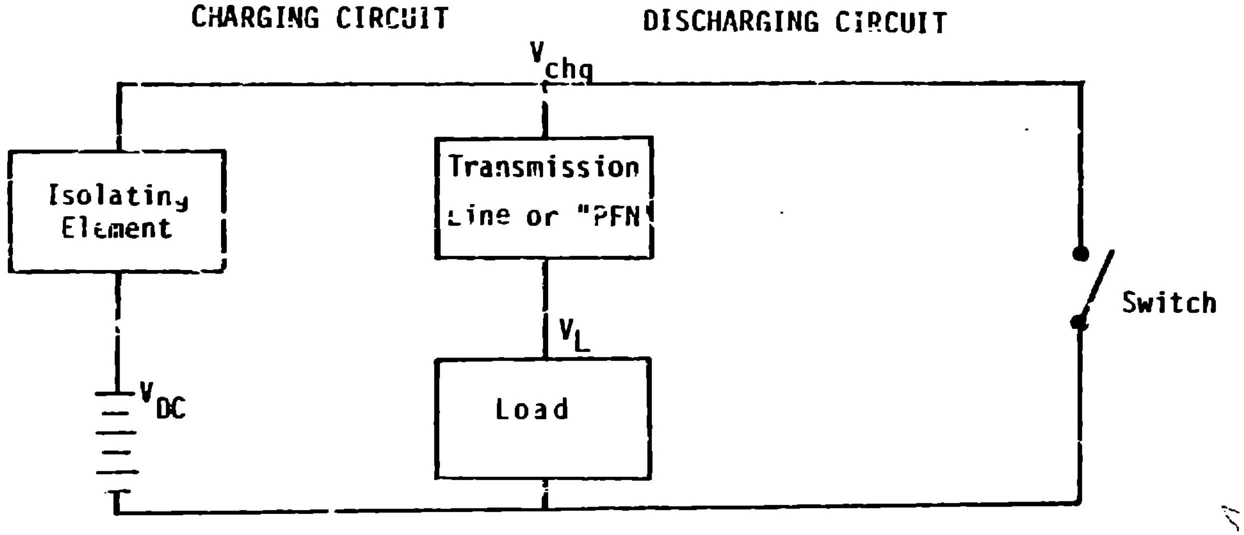
In the case of the matched load, maximum energy transfer and efficiencies are possible, given a perfect switch (Fig. 13). However, very few switches are anywhere near perfect. An imperfect switch changes a linear circuit to a time-varying one. Spark gaps initially turn-on as high-value resistors, but the resistance decreases dramatically with time, and, as an arc column then forms, it expands or contracts with the current and acts then as an inductor. A switch, then, can be a nonlinear element in the PCS. For short-discharge time, low-inductance systems, switch-limited pulse lengths are on the order of 20-100 ns for single-channel devices (thyratrons, spark gaps, etc.). The switches then become limiting components of the system. The alternate approach is to use a multi-channel spark gap or the very large-discharge area thyratrons currently under development.

If the switch isn't perfect and even if the load impedance is matched to the generator impedance, some energy is left over at the end of the discharge pulse, and this can cause oscillations in the system and give rise to switch-recovery problems. In other words, when you think you have zero current through the switch you often don't.

## 6. CHARGING SYSTEMS FOR PULSE-FORMING NETWORKS

In the charging system, the switch is open during the charging period and the charging time is much longer than the discharge time (Fig. 14). This is a general assumption applicable to most PCS. When the

# CHARGING SYSTEMS




SINCE:

1. SWITCH IS AN OPEN CIRCUIT DURING CHARGING OF THE PFN OR TRANSMISSION LINE
2. THE CHARGING TIME IS MUCH LONGER THAN THE DISCHARGE TIME

THEN:

THE CHARGING SYSTEM CAN BE TREATED AS PLACING CHARGE ONTO THE LINE/PFN TOTAL TERMINAL-TO-TERMINAL CAPACITANCE, C.

ISOLATING ELEMENTS:

1. RESISTIVE:  CHARGING INDUCTOR

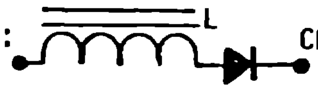
2. INDUCTIVE:  CHARGING DIODE


FIG 14

switch is open, a charge, q, is placed on the transmission line, charging up the total line capacitance, C to voltage V. There are now a number of choices for isolating elements. For a resistive-isolating element, generally used in single shot PCS, the energy-transfer efficiency is always 50% or less. In the case of an inductive isolating element of inductance L, the capacitor and inductor form a resonant circuit, and, at the point of zero current through the charging loop, the charge voltage is equal to twice the DC voltage on the battery. The time for this to occur is $\pi\sqrt{LC}$, and the energy-transfer efficiency is very close to 100%. Most of the losses are resistive losses in the charging inductor and they can be made relatively small, with wall-plug efficiencies of 70-80% possible in the PCS. If the period is chosen to be equal to the above time, this is called the resonant charging configuration, in which the discharge switch is turned on exactly at the zero-charging-current point. To work at other repetition rates, one may insert a blocking or charging diode in the charging loop. Once the voltage has come up to $2V_{DC}$, the current goes to zero, the voltage across the inductor collapses, the diode is reverse biased, and the $2V_{DC}$ remains on the PFN to be discharged at will at any rep rate up to $(\pi\sqrt{LC})^{-1}$. If this rep-rate is exceeded, there will be some DC current flowing through that choke at all times; that causes heating problems in choke design. As well, there is a net DC current through the discharge loop at all times and the rate at which the voltage is reapplied to the switch and transmission line is quite a bit faster than in the resonant case. Switch recovery problems then emerge. Operating at these rep-rates is called linear charging. This had some advantages in early modulator design, but is not very useful today.

Constant current or power charging systems use a high-frequency inverter (usually a push-pull type) with a rectifier bridge (Fig. 15). The DC current, fed through an isolating inductor, charges the pulse-forming network and a closed-loop feedback system is used to

## OTHER CHARGING SYSTEMS

A) <u>CONSTANT CURRENT OR POWER</u>

UTILIZES HIGH FREQUENCY INVERTER/RECTIFIER WITH CLOSED LOOP FEEDBACK:

- LEVELS UP TO 1 KJ/SEC CAN BE BOUGHT
- CAN ALSO USE A SERIES REGULATING SATURABLE REACTOR IN THE TRANSFORMER PRIMARY OF A NORMAL DC SUPPLY.

B) <u>COMMAND CHARGING</u>

- USES A SERIES SWITCH, EITHER VACUUM TUBE, IGNITRON, OR THYRATRON, TO CONNECT A RESONANT CHARGING NETWORK TO THE DC SUPPLY RESERVOIR CAPACITOR.
- ALLOWS MAIN PCS SWITCH TO FULLY RECOVER BEFORE CHARGING VOLTAGE IS APPLIED.

C) <u>AC RESONANT CHARGING</u>

- SATISFACTORY IF PRF IS LESS THAN TWICE THE AC FREQUENCY.
- TROUBLESOME FAULT MODES AND LITTLE PRF AGILITY LIMIT APPLICABILITY.
- LOWEST COST CHARGING SYSTEM AS ONLY A TRANSFORMER AND POSSIBLY SOME DIODES ARE REQUIRED.

FIG. 15

control the frequency of the inverter. Frequency regulation thus provides very accurate charging currents, and essentially very accurate voltages on the PFN. Charging units up to the order of a kilojoule per second can be bought as commercial units. They're small devices, but expensive.

Alternatively, in constant-current charging systems, a magnetic regulator can be used in series with the primary of the power supply transformer. For single-shot work this was often used in some of the charging networks for fusion PCS. The current is controlled through the primary, charging the capacitor bank through an isolating network, and the bank final voltage can be held to a very accurate level. The other real advantage to this system is that, when it is first turned on, the peak current through the system is rather low. The equivalent circuit is then a magnetic regulator in series with the high-voltage transformer, feeding a solid-state diode and a series resistor that connects the power to the capacitor bank. With the magnetic regulator in the primary, a high series impedance at turn-on is obtained, much larger than the reflected load impedance, so the current flow is very small. The secondary charging current and voltage can be used to control the regulator. Magnetic regulators have a number of advantages in protecting the components and form an unusually rugged charging system.

Command charging, on the other hand, uses a series switch in series with the battery or DC supply filter capacitor and the PFN. The switch is closed on command and the PFN is charged up through some other isolating device -- usually series a resonant network. In that case, charging is completed to $2V_{DC}$, the series switch opens, and then the PFN is discharged through the load using the main shunt discharge switch. The real advantage of pulse charging is that the PFN discharge switch is allowed to fully recover and then the voltage is reapplied to it and the pulse-forming network. This means that the PFN discharge switch will experience an enormous decrease in its fault rate as the high-voltage on-time is reduced. The problem with pulse charging is normally that it requires a floating deck series switch, with a large number of items placed at high voltage.

The last type of charging is AC resonant charging. Removing the diode and adding some extra inductance in a normal power supply (if desired) gives an LC resonant circuit with the PFN capacitance, C. The voltage on the PFN rings up and then it is discharged into the load. The disadvantage is that one must work only at this resonant frequency. If lower frequencies are attempted, the fault modes are simply horrendous. This technique was, however, used in several fixed-PRF WWII spark-gap pulsers. Some quite large modulators were built that had no explicit resonant charging network. They used a three-phase AC supply with adequate leakage inductance in the high-voltage transformer and charged three PFNs, using three switches to discharge them all into one load. The system for fixed-frequency operation can then be very compact.

## 7. Comparison of Hard-Tube and Line-Type PCS

Fig. 16 is a comparison between the hard-tube and the line-type PCS. The range in wall-plug efficiencies that the hard-tube systems work in is 10-15%, sometimes 20%. The first generation of line-type power conditioning systems ran at 50-60% efficiency: A lot of power was lost in dissipation in the pulse-forming network components and in the spark gap switches, and even in the thyratron switches. Today, a typical figure for a complete line-type PCS is an overall wall-plug efficiency in excess of 80%. The hard-tube PCS have increased their efficiency to about 20% because they then used three-phase or twelve-phase rectifiers with tubes requiring significant heater power. In addition, series high-vacuum switch tubes of somewhat higher efficiencies are available today. The real advantage of the hard-tube PCS is its pulse shape and rep-rate control. For varying load impedances one can generate a well-controlled pulse shape from a hard-tube PCS. Currently, for small systems running around the 10 to 50 ohm impedance range, the risetime is

FIG. 16
COMPARISON OF THE CLASSES OF REPETITIVE POWER CONDITIONING SYSTEMS

| Characteristics | Hard-tube PCS | Line-type PCS |
|---|---|---|
| Efficiency | Lower; more power lost in tube heating, and in dissipation in the switch tube. | High, $\geq$80%, particularly when the pulse-power output is high. |
| Pulse shape | Better rectangular pulses. Shape control by input pulse in analog fashion. | Poorer rectangular pulses, particularly through pulse transformer. |
| Impedance-matching | Wide range of mismatch permissible. | Small range of mismatch permissible ($\approx$20-30%). Pulse transformer will match any load, but power input to non-linear load cannot be varied over a wide range. |
| Interpulse interval | May be very short; as for coding beacons (i.e., $\approx$1 nsec). | Must be several times the deionization time of discharge tube (i.e., 2-300 μsec). |
| Voltage supply | High-voltage supply usually necessary $\approx V_L$. | Lower-voltage supply, particularly with resonant charging. |
| Change of pulse duration | Determined directly by input pulse shapes. | Requires high-voltage switching to a new network. |
| Time jitter | Negligible time jitter ($<$1 ns). | High-power line-type pulsers with a hydrogen thyratron give a time jitter of $\leq$2 ns. |
| Circuit complexity | Greater, leading to greater difficulty in servicing and high cost. | Less, permitting smaller size and weight. |

<1 ns, increasing to around 20 ns risetime in large systems. There are scalability limitations in the hard-tube PCS dictated by component availability for high average power systems.

SUMMARY

Pulse risetimes and the flatness characteristics suffered significantly as a result of long resistive phase turn-ons of early switch tubes. What can be achieved to date in sub-ohm impedance circuits are current risetimes of 20 ns at current rates of rise, circuit-limited, in excess of 1.2 MA/microsecond with new thyratrons under development. Five hundred kA/microsecond thyratron switch tubes are now available. One can now consider designing a number of line-type power conditioning systems for long-life operation at kilohertz rep rates that previously were thought of as impractical. The equivalent inductance of the switch thyratrons has concurrently been reduced by a factor of 20.

In the case of impedance matching one can modulate the equivalent resistance of hard-tube modulators in an analog fashion, so it is possible to accommodate very large impedance mismatches and time-varying loads. This was the reason for the first large-scale efforts to drive high-rep-rate $CO_2$ systems with hard-tube PCS. (They can operate at Megahertz rep-rates.) In this way the decreasing discharge impedance with time could be accommodated. The mismatch range of 20-30% is one over which the efficiency of the system doesn't vary a lot. Going beyond that, for PFN type PCS, all of the additional stored energy must be disposed of elsewhere if it is not deposited into the load in a time equal to one discharge time of the pulse forming network. It is desired to deposit as much of that energy as possible in the discharge time of the PFN.

Typical recovery times today for small tetrode thyratron devices are one or two microseconds. The WWII-design triode thyratrons that you can buy commonly now have a much longer recovery time. They also suffer recovery-time degradation with age because of their internal construction. It takes a long t for the plasma from the cathode to lose communication with the anode. Today, one can go down to a microsecond recovery time in modest sized thyratrons discharging millicoulombs/pulse.

In terms of high-power spark gaps, recovery times are hundreds of microseconds and haven't changed. If one wishes very fast recovery in spark gaps it is possible to go to a device that adopts some internal quenching mechanism to get rid of the residual ionization. An example is the work done on Hydrogen quench gaps, which are essentially a pair of electrodes separated by a number of fine meshes. In discharges through the device at a modest pressure of Hydrogen, the presence of the mesh cools the ionized gas in gap very quickly, enhances recombination around each mesh causing little globs of isolated plasma to form. These gaps can then work at a hundred kilohertz rep-rate or above, discharging a few hundred picofarads capacitance per pulse. However, because all the current is passing through the screens it's difficult to flow high average powers through the device.

This covers the introduction to pulse power systems, with an orientation toward higher rep-rate devices.

QUESTION: What dissipating mechanism were you using in the first class of loads in Fig. 5?

ANSWER: None. One can obtain a relatively high Q (>100) in circuits where the characteristic frequencies are on the order of a few megahertz. Normally, if just one discharge cycle is needed and the stored energy requirements are not too large (≈100 J), nonlinear thyrites or metal oxide varistors are very effective shunt elements for damping. The alternative choice that works well for inductors is to crowbar the voltage across the inductor with either a thyratron or a spark gap so that as the discharge current starts to reverse through it, the balance of the stored energy is then bypassed into a resistive dump. There is often a problem in timing the crowbar initiation.

Question: Will the course notes be available?

A report with all the diagrams from this course will be out by next Christmas. It will include a considerable bibliography and an expansion of many of the areas from the course. Later, a set of notes, in book form, may become available with a lot of detail in some of the specialty areas that, of time necessity, are briefly discussed in class.

GENERAL REFERENCES

1. G. N. Glasoe and J. V. Lebacqz, Pulse Generators (McGraw-Hill, New York, 1948).

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Lecture 1

# INTRODUCTION TO POWER CONDITIONING SYSTEMS

by

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