NOTES ON HIGH VOLTAGE PULSE TRANSFORMERS
INSULATING OIL CARE AND ACCIDENTAL TRANSFORMER OVER-VOLTAGES

Pearson pulse transformers feature a minimum of solid insulation in regions of high electric field. This type of construction prevents damage to the transformer by accidental flashovers due either to poor oil or to overvoltages beyond the typical 50 to 100% safety factor built into the transformer. The intentional weakest region is between the high voltage corona ring and the core. These are metal surfaces and flashovers between them have negligible effect on the surfaces for the energies involved in even the highest power line-type pulsers.

In spite of the voltage stand-off safety factor built into the transformer, and the feature of being able to withstand reasonable flashovers without damage, there are still occasional cases of damaged transformers. On inspection these units invariably show that they have been operated in oil that was dirty or there have been enormous over-voltages, sometimes approaching a million volts for a unit rated at a small fraction of this value. It is hoped that the following notes will help the user avoid these difficulties.

The necessity for good oil is generally accepted, but often the specific precautions necessary are not understood. Pulse modulator malfunction is not so generally appreciated as an important and frequent cause of accidental over-voltages. In fact, it is often a major source of trouble. Over-voltages can be difficult to detect and the causes difficult to diagnose.

INSULATING OIL

Ordinary transformer insulating oil supplied by the major oil and electrical companies is basically satisfactory for high voltage pulse use. The problems that arise are most frequently due to contamination by dirt, air and water. The condition of the oil as initially installed must be good. Once installed satisfactorily, one must assure that it stays good.

Dirt During Installation

Reasonable effort should be made to be sure the transformer itself, the tank, and the other parts in the oil are free from dust, lint, chips, etc. before filling. It is difficult to get all the parts absolutely clean. The slightest amount of dirt in the oil can be a potential source of flashover when it drifts through a region of high electric field.

Filtering the oil is normally indicated at this point.

Filtering After Installation

The oil filter element should be of a type that filters very small particles. "Fuller's Earth" filters, or equivalent, capable of filtering fine particles are necessary. If a filter unit is part of the transformer tank assembly, running the filter unit for a period of a few hours before operation will clean up most of the dirt particles. If there is no continuous filtering unit, placing the inlet and outlet hoses of the pump and filter in diagonally opposite corners of the tank will give most rapid filtering of the oil volume.

Keeping Dirt Out of the Oil

Once the oil is clean, several precautions should be taken:

1. Put a lid on the tank and keep it there. Remove only for short periods of time for initial inspection if necessary. Once operation of the unit is going smoothly, the cover and gasket should be bolted in place.

2. Do not put hands in oil without filtering the oil afterwards. Even clean hands and arms seem to deteriorate the oil.

3. If an accidental over-voltage results in a flashover, the oil will have a small amount of carbon in it, weakening the oil. Filtering is a wise thing to do if any spark-overs occur.

4. If the oil should inadvertently become so carbonized that it becomes perceptibly darkened, then the oil is weakened to the point where corona tracks can be established on the solid insulation on which the transformer windings are wound. Once corona tracks are established, which can happen at less than rated voltage once oil is badly weakened, the tracks will grow until complete breakdown occurs.

Occasional Sparkover in First Few Hours of Operation

Sometimes it is found that, although performance of the modulator is perfect and the oil very clean, a sparkover may occur after several hours of running time. This can be explained by the presence of a lone piece of dirt, perhaps a nearly invisible piece of lint, which is drifting slowly about in the transformer tank. It can take hours of drifting before it enters a region of high electric field. The sparkover demolishes the particle, and the resultant flashover contaminants may become so disbursed as to cause no further trouble.

Continuous Filtering

In a stably operating system, with no over-voltages, thoroughly clean oil, sealed tank, and no undetected corona from some sharp high voltages points in the tank, there should be no need for continuous filtering. But if all these conditions are not certain to prevail at all times, the expense of downtime and its attendant mess can be largely avoided by continuous filtering.

Oil Testing

A standard 60 Hz oil tester can be used to check pulse transformer oil. The breakdown point of the oil should be at least 30 kV rms for a standard oil cup with electrode spacing of 0.1 inch.

The oil test cup (and also any other vessel used for dipping up the oil) should be rinsed in clean oil, other than the oil to be tested, so as to avoid possible contamination of the oil to be tested. Oil should be taken from the transformer tank as used in operation. Repeated tests should be made. The lowest reading is the significant one since the density of contaminants can be low.

Air Contamination

Air contamination is not as frequent a source of trouble as dirt, but can cause problems. A certain amount of air is always absorbed in the oil and causes no problem. Free bubbles in the oil that are in the high electric fields will be certain to cause breakdown. Some of the ways in which bubbles get in the oil are as follows:

1. On pumping oil into a transformer tank the oil, on striking the open oil surface, or a hard surface, captures air bubbles. This lowers the breakdown value of the oil markedly. Some of these bubbles float back to the surface and burst. Others are absorbed into the oil. Allowing the oil to stand for a day will bring it back to full test. A useful technique is to let the oil flow almost parallel to the surface of a tank wall so that the stream spreads out without capturing bubbles. Then when the depth of oil is sufficient the hose is lowered beneath the surface of the oil.

2. At the start of oil pumping there is often a certain amount of air trapped in the pumping system. This gets churned up into bubbles when pumping starts. If a spare drum of oil is available, this start-up process can be done in it and the hoses then transferred to the transformer tank.

   If a circulating pump is an integral part of the tank assembly, this churning sometimes cannot be avoided. A compensating feature is that the pump will suck up bubbles along with the oil and take them out of the tank.

   A leak in the negative pressure side of the pumping system will pull in air. This is broken into bubbles which end up in the transformer tank.

3. The core warms up during high average power transformer operation. It can then release air trapped in the laminations. These air bubbles can drift up through the transformer and enter the regions of high electric fields. Pearson transformer cores are impregnated with oil under vacuum to remove this air.

Water Contamination

As with air, oil contains a small amount of water which under normal laboratory room temperature and humidity, and over a long period of time, reaches an equilibrium that does not normally harm the oil. However, if the oil is in storage or in use in areas where the temperature and humidity are not held within bounds, water will condense and collect on the bottom of the container. Oil-breakdown value suffers under this condition.

Water is widely used for cooling. All too often mishaps occur and water is spilled in the oil or small undetected water leaks drip water into the oil. Where this is a factor it is best to specify a divided tank, so that the transformer compartment can be sealed against entry of moisture.

If water drops or puddles should exist on the bottom of a transformer tank or storage drum, and pumping should pickup some of this water, it will be broken up and emulsified with the oil. The water droplets can then stick to the surface of the transformer. High voltage operation under this condition will result in breakdown of the solid insulating material of the transformer.

If water is standing in the bottom of a container, the oil should be pumped off until a remainder which includes the water can be thrown away. Then a heater immersed in the oil for a long period (days) will gradually drive off the moisture. Other methods (all requiring special equipment) for removing moisture are:

1. Water absorbing filter.
2. Distillation type oil refiner.
3. Centrifugal type oil refiner.
4. Spraying heated oil into an evacuated chamber.

ACCIDENTAL OVER-VOLTAGES

It is possible for the pulse modulator to malfunction in such a way as to result in over-voltaging the transformer, as well as other important components such as the PFN and the switch. Some of the possible causes are:

1. A combination of too-low load resistance and an inadequate PFN reverse charge removal circuit.
2. A switch that fires spontaneously during interpulse periods.
3. Continuous conduction of the switch.
4. Load resistance too high.
5. A combination of two or more problems listed above.

This list is only a partial one. There are undoubtedly many more possible sources of trouble.

Combination of Too Low Resistance and Inadequate Discharge Circuit for Removing Reverse Charge

This problem is covered (*Vol. 5* p. 417 f.) of the M.I.T. Radiation Laboratory Series, Glasoe, etc., and is a problem that normally receives attention. One possible difficulty is that the reverse charge discharge circuit does not remove the reverse charge fast enough. It should do this even for complete load short circuit at full charging voltage. What can happen then is that the charging cycle can get well under way before the reverse charge is completely removed.

Successive pyramiding of the charging voltage can occur.

A simple test that may help show whether this circuit is operating adequately is to momentarily short circuit the load. The peak charging voltage should not rise. If a full voltage test of this sort is ruled out, a low voltage test could be performed. This would show whether the discharge circuit is properly proportioned. It would not show whether the current capabilities of the discharge diode were adequate.

Switch Fires Spontaneously During Normal Interpulse Periods

This problem is one of the most serious causes of component over-voltaging. It is also one that is difficult to avoid and difficult to cope with. With the tendency toward ever-higher peak and average pulse powers, the problem of securing a completely adequate switch becomes increasingly difficult. This is coupled with the necessity for keeping costs within limits so that completely adequate instrumentation and protective circuits are not always included as a matter of course in the design of the pulse modulator.

If a pulse switch has any tendency toward spontaneous firing during the interpulse period and there is no positive type of protection included specifically for this malfunction, then the pulse transformer and other components will certainly be overvoltaged.

Consider the following explanation. If the switch closes while charging current is flowing, a normal or subnormal pulse voltage will appear at the load. Oftentimes the switch will then conduct continuously and the normal over current breaker protection will have to operate, but there will not necessarily (see below) be an over-voltage. If the switch should clear at the end of the pulse as it normally does, a new charging cycle is started. But this new charging cycle starts with finite current. For an initial charging current greater than zero, the next charging voltage crest will be higher. Then if the switch is closed again at it's normal time a larger voltage pulse appears at the load.

Of course, if the switch has a tendency to close spontaneously for normal charging voltage, then it will be still more apt to close spontaneously at the higher than normal charging voltage. If this continues, enormous voltages can be generated.

If, on the other hand, the switch should close spontaneously some time after the charging cycle was completed, but before the next normal pulse, then a normal pulse will be formed. A normal charging cycle will then be started. But while this cycle is in progress, the normal trigger occurs, the switch closes, and then the process for over-voltage goes into operation since now a charging cycle is started with finite charging current already flowing.

Transformer Over-voltage Prevention

A simple device that will help prevent over-voltaging the transformer (but not necessarily other components) is a fast over-voltage sensing circuit that will automatically prevent the next and all succeeding triggers from being applied to the switch if the charging voltage rises above a predetermined value. A voltage divider giving faithful waveform division is necessary here. A bleeder resistance for draining off the PFN charge should be part of the circuit too. It is prudent also to turn off the power supply automatically at the same time (see section on continuous conduction).

Other protective measures are possible. One is a spark-gap and low resistance in series across the primary, with the gap set to fire for any amount of over-voltage. Another is thyrite across the primary. Both of these are inherently imperfect but are better than nothing.

Pulse Switches

Obviously a switch with adequate voltage hold-off capability is called for and every effort should be made during design to assure this. Series operation of switches is a possibility, but one that should usually be avoided. One of the problems that has been encountered with series switches is that of making certain that the charging voltage is equalized between the series tubes. This means that the capacitances as well as resistances must be equal since the charging voltage has ac components as well as dc. The capacitances should be measured in an actual circuit to be certain that stray capacitances are not upsetting the balance. Individual triggering of all series switches is recommended for positive closing of the individual series switches. This is relatively simple to do with an appropriate multi-secondary trigger transformer or separate, paralleled-primary trigger transformers.

Continuous Conduction of the Switch

Another difficulty that may occur is that the switch may conduct continuously. An over-voltage is not created initially. However, the charging inductance and the filter capacitor go through a half cycle of oscillation. At the end of the half cycle the current is stopped by the charging diodes. Now the voltage is reversed on the filter capacitor. Current now flows from the power supply to recharge the filter capacitor. But this is a situation completely analogous to resonant charging a PFN having a reverse charge, except that the capacitive element is now the filter capacitor and the inductive element is the inductance. The result is a tendency to charge the filter capacitor to more than double the normal power supply value. Of course, all the succeeding pulse components are then correspondingly over-voltaged. Obviously, the power supply circuit breakers and current sensing circuits should be fast-acting for the case of continuous conduction of the switch.

Load Resistance Too High

Proper instrumentation and calibration is expensive in money and time. Sometimes the temptation is to make assumptions regarding the load resistance. Voltage dividers and pulse current transformers should be used on the load to be certain that the load resistance is correct at full operating voltage. Dummy loads whose resistances vary with temperature should be watched. A mismatch on the high side for the load can allow the transformer voltage to be too high even though the charging voltage is an appropriate value.

Combination of Problems

A common failing on the part of an engineer or technician trying to locate trouble in a malfunctioning pulse system, is the tendency to assume there is only one system malfunction. Actually, it is more common that there are several problems co-existing in the equipment. In testing to see if a particular malfunction exists, as much of the circuit that can be eliminated or replaced by simpler components should be. An example would be that of first operating a pulse modulator into a resistive load at full peak and average power. Then add the transformer operating into a resistive load, again at full power. Then the diode type load can replace the resistive load. This process can partially avoid assigning of the trouble to the pulse transformer or the diode load or the reaction of these on the circuit when the fault may have been somewhere else.

Detecting Overvoltages

Detecting overvoltages can be difficult. Sometimes all that is known is that the pulse transformer sparked over. It is easy to conclude that the transformer is defective, since that was the only obvious thing that happened.

The first check is to be certain the oil is up to standard. Then one should watch for larger than normal secondary and primary pulses. This can be difficult, because the malfunction may occur just the moment one takes his eyes off the scope. Also a single high pulse will often not occur during the normal triggered sweep time of the scope trace. One better way is to monitor the PFN voltage with a reliable voltage divider. A high charging cycle here can be detected more easily. Another possibility that does not require such close watching is to position the normal scope trace so that it is just off the scope screen. By turning the intensity very high and using a scope screen that has some persistence (e.g. P2) an overvoltage will fall on the visible part of the screen and the intensity of the spot and the persistence of the screen will allow viewing after the event.

Bifilar Heater Current Protection

A rare problem, but one worth including, is for the case of a bifilar transformer carrying heater current, that sparks between the two legs of the bifilar. There is normally not enough current in the pulse circuits to damage the transformer windings. But the high-voltage spark is followed by a heavy current arc fed by the heater supply. If not properly fused or circuit-breaker protected, this heavy current arc can burn the transformer windings through, resulting in an open winding. If pulsing is continued, this break in the winding will spark over continuously with the pulses, rapidly carbonizing the oil and causing further breakdowns.