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Designing and Building High Voltage Power Supplies

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Abstract— **High voltage researches and testing is more lively than ever and a lot of activity is expanded on the World in a great number of high voltage laboratories. For present industry production to perform fast advances toward more reliable, longer life, cost-effective power supplies, a better understanding and application of tests for electrical performance, mechanical, thermal, and environmental tensions must be imposed by the statement of work and applicable specifications.**

This study shows the summary which outlines many requirements and specifications that are either unnoticed or taken for granted during the evaluation and production of high voltage power supplies (HVPS). The study contains the design summary, production and manufacture of prototype of the HVPS. Also high voltage guidelines to minimize failures were researched in the study.

Keywords—**high voltage, power supply, designing.**

I. Introduction

There is an urgent need for long-life, affordable, high-energy density power supplies. Production technology, standardization programs, and workshops that have been implemented to emphasize the need for lighter weight, smaller volume, increment of reliability and, in many cases, lower cost. At first, many programs come forwarded to bring inventions toward higher reliability and longer life, only to find that life and reliability were good for the few power supplies delivered for the progress program. There are two reasons for the reliability and life releasing from its initial state. First, the initial orders were provided using special production techniques to build a few already designed power supplies. Second, the supplier did not include the required changes for the developed design in the production and test procedure because of cost and timing. Due to developments in design, production and test must be either specified at contract initiation or a new contract for following changed power supplies must be published [1].

Electrical design, packaging, materials and processes, production and test are equally important to the life, reliability, and cost effectiveness of a compact power supply. Until now, no single electrical or packaging design has all the ideal electrical, thermal, and structural properties for all applications; thus, the engineers must accept that each application has a set of designs both satisfy the electrical performance and meet the environmental and structural constraints. The designer must evaluate concessions when selecting the correct packaging techniques for electrical insulation and processing for a reliable, compact, lightweight, HVPS [2, 3].

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II. High Voltage Power Supplies

A HVPS is a low voltage power supply with some special high voltage sub circuits and parts. This means that many circuits within a HVPS are similar the low voltage power supply. Similar circuits include the input filter, switcher, control and built-in test equipment (BITE) and automatic test equipment (ATE).

The special high voltage circuits include a high voltage transformer rectifier or voltage multiplier, high voltage filter, high voltage control sensors and output connector [1].

Series strings of diodes have been used for decades to rectify the output of high voltage transformers to obtain HVDC. More recently, other solid-state power semiconductors are being used in series in a variety of high voltage applications. For example, series-connected SCRs (Silicon Controlled Rectifiers) are being used in crowbars [4] as a replacement for ignitrons. Series-connected IGBTs are in use as fast on–off high voltage switches [5, 6].

A HVPS is defined as any unit having voltage equal to or higher than 300 volts, peak. High voltages, including transients, are subject to corona breakdown and partial discharges. Partial discharges and corona can occur at low voltages. That is, as frequency increases, the corona initiation voltage occurs at low value. At 200 MHz, corona initiation can be as low as 50 volts peak. Therefore, effects of frequency must be considered in the design of all high voltage and low voltage switching power supplies.

Corona and partial discharges initiate more failures in high voltage electrical insulation designs than any other cause. The designer must be aware of this fact and insist that the encapsulating materials are compatible with parts insulating circuit boards, and the metal structure.

A. Design Summary

Although design of the HVPS is very important, it is usually done by electrical, electronic and mechanical engineers. Corona and partial discharge problems cannot be fully removed in all applications, but they can be kept to an acceptable level. An acceptable level is one where all large gaps that grow rapidly and break down insulation are eliminated. Very small discharges in micro gaps will destroy the insulation, but it may take years of continuous operation.

The desired features of a HVPS are as follows: fast recovery time, extraordinary crowbar unit at the load end to avoid complications and minimize failure risk, minimal indoor/outdoor space requirements and high performance, high availability target [7].

An encapsulated high voltage circuit in a HVPS with comfortable coated low voltage circuits can be developed with small weight penalty. It will be easily cooled and the potted

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module or modules can be kept fairly small in size. The output connector will be larger than that for a low voltage power supply. Low power display and other applications that use a simple high voltage, high-frequency transformer voltage multiplier, filter, and voltage control divider can be potted into one or two modules of very small volume in many cases. High voltage units may have the rectifier built into the transformer winding to save weight and volume. The only problem with this technique is rectifier cooling. Often the rectifier and attached winding turns become very hot and reduce the insulation life significantly if not designed with heat transfer.

The electrical characteristics should not change more than 3% to 5% percent. This is very important for voltage dividers. All materials, metal and coatings must be compatible with the insulating materials used in the design. Corona and partial discharges must be tested for all parts to indicate they are acceptable. All cores must be rounded to form smooth surfaces.

Corona testing of transformers is very important. All high voltage transformers should be tested, at operating frequency, in the active state. These tests should be made between spins, between the spins in next layers of a winding, between windings, and between the windings and core or other ground or metallic surfaces. Transformer cores, after potting, must be thoroughly temperature cycled to determine whether thermal tensions have caused insulation cracking or core cracking. An active corona test at operating frequency is suggested to determine the insulation condition.

Potting materials must be tested for suitability with all other parts boards and metals to be contained. Also the materials should meet or successfully pass the tests of electrical, mechanical, thermal and out gassing. Selection of a high voltage potting material must be left to the design and materials organization so they can choose common materials that they have assurance. Some of the selected materials will not meet the -55 ^{0}C temperature cycling tension test. By adding the material with fillers, some suspicious materials will meet the 55 ^{0}C temperature tension test.

The electric and magnetic field must be calculated to determine the electrical stress within an insulation system near the leads and sharp edges of parts cases. The electric field stress should be less than 150 to 350 volts/mil at the surface of the smallest radius, depending on the potting material, its thickness and flexibility. Many parts must be mechanically positioned during potting so they will not move during encapsulation. High voltage circuits must be isolated or protected from low voltage circuits to avoid propagated or conducted pulses from damaging low voltage circuit susceptible parts. Special care must be taken with protected cabling to ensure excellent bonding without gaps at the protect insulation interface [1, 8].

The solid state devices available for both higher voltages and higher switching frequencies have several advantages to replace traditional system like extended life, higher efficiency, easy and reliable operation. Further series connection of elementary power modules does not require direct series connection of semiconductor devices. Thus each module is designed for 1.2 kV DC approximately. Module components are low voltage devices, low cost and each step of the voltage is lower than the allowable peak-to-peak ripple and provides an additional degree of freedom in the dimensioning of output filter. It also provides complete flexibility since the number of switched-on modules in quantized steps of voltage controls the output voltage. The design also aims to enhance reliability, decrease costs, plug-in modularity, provide redundancy, components de-rating, components standardization and easy availability. However the above advantages come at the cost of relatively high complexity of multi secondary transformer and cabling of multiple power modules [7].

B. *Prototypes*

Developing a prototype is the best method for attesting design confirmation. The purpose of the prototype is to show the breadboard circuit can be packaged in a high-density volume with the least waste space and minimum volume, while meeting all the electrical input and output characteristics before and after exacting environmental and mechanical stressing.

The prototype unit or units should be produced using shop installation and test personnel. It should not be a handmade unit developed using specialized technicians and engineers. Engineers and technical specialists should be called on to solve difficult or modified installation and test techniques. These modifications should be reflected as drawing changes to the design. When parts or materials are involved, it must be shown that the modifications will satisfy or exceed all the original mechanical, environmental, and electrical test characteristics.

All parts, boards, wire, and materials must be of high quality and approved reliability. Traceability must show that all parts and materials have satisfied performance acceptance characteristics for the practicable environment and power and voltage levels to which they will be subjected. That includes cleaning before and after visual and quality control examination. No parts shall be tested in silicone liquid or similar liquid that cannot be easily clean from the surfaces. Tests and controls for parts, wires, boards and metals include the contamination by oils or wreckage, sharp corners, corona and partial discharges, electrical characteristics, environmental tests, dielectric strength and resistivity.

Several in process tests should take place during the prototype installation to prove production and installation production processes and procedures. A final installation test is compulsory to prove flight acceptance. Some tests that should be imposed include: high voltage corona and partial discharge tests at the design operation frequency for the transformer, voltage multiplier, transformer rectifier, filter and high voltage sensors, leakage current and arc tolerance, overvoltage and under voltage, short circuit, electrical characteristics, maximum transients at maximum voltage input and output, environmental altitude, temperature, shock, and vibration, electromagnetic interference (EMI) tests.

High voltage tests are usually misinterpreted. The first misrepresentation is the dielectric withstanding voltage (DWV) or high pot test. The specification reads that the high potential is to be applied at a voltage of two times the

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operating voltage plus 1000 volts for high voltage parts and circuits. That value is still used by the power industry for voltages where the stress levels will not damage the electrical insulation. For very high voltage, over 115 kV smaller maximum voltage stress values are used. Because high voltage power supplies are developed with high stress levels, the DWV test should not exceed two times the operating voltage.

Corona starting voltages and extinction voltage are non-destructive tests that indicate the probability of gaps, cracks, and limitation in parts boards and wiring. Corona tests should be performed before temperature cycle and post temperature cycle. Changes in the size or quantity partial discharges indicate gaps or insulation cracking at the surface of parts. Any increase in the partial discharge characteristic is cause to fail the test. Arc resistance and short-circuit tests should be mandatory high voltage tests. First, corona tests of the high voltage cable must be done and then the short circuit tests must be done. For some voltage multiplier designs, the arc resistance test can overstress the final capacitor in the circuit or the voltage divider circuit. Any defects in the insulation will be detected by the corona test.

Environmental tests for high voltage power supplies should be almost the same as for low voltage power supplies. The one basic difference is the high voltage circuits. Safety rules must be applied finely to provide no dangers to humans are encountered. For example, the high voltage circuits must be completely grounded and remain grounded along the shock and oscillation tests unless otherwise directed. Special feedthroughs, connections, and interconnects must be designed for operating. These designs must all be safety approved.

EMI, radio frequency interference, and electromagnetic pulse may all require test and evaluation. These tests should be made in shield rooms using certified, qualified test evaluation equipment. The low voltage circuits as well as the high voltage circuits must pass all tests and requirements to be fully accepted [1, 9].

C. *Production*

High voltage power supplies are bothered by pollutants, wreckages, incorrect installation procedures and processes, and testing. Cleaning, excellent inspection and test procedures, trained personnel and good test equipment and test procedures are very important to appropriate production with high-quality, highly reliable, long-life power supplies.

Parts, subassemblies, wiring and the power supply must be controlled, installed and handled using clean room techniques. When the parts are received from the suppliers and inspected, they should be bagged or placed in clean receptacles for storage before distribution to the assemblers.

All installation personnel should be instructed to wear white cotton, lint-free gloves or equivalent when combining the parts on the boards, and combine in the final installation. Those who assemble low voltage, charge-sensitive parts must be instructed to work at electrostatic discharge workstations. They too should wear white cotton, lint-free gloves.

All incoming receiving high voltage parts should be subjected to 100% control. Parts should be checked and tested for specification compliance and to eliminate all early failures before they can be combined. This saves a lot of rework and early failures. Many solid-state devices, capacitors, transformers, and voltage dividers should have a required bum-in test. This will select most early failure parts. Many parts suppliers do their own bum-in tests. When a supplier does the burn-in test, the procedure, time and characteristics test values should accompany critical parts such as capacitors, transformers and solid-state devices [10].

Specified personnel to the high voltage installation area should be trained to do the special installation and solder techniques required for high voltage installations. Job training may require coaching from engineering as well as shop instructors. Training by engineering is especially important for quality control, inspectors, and test personnel. The purpose is to motivate the installation personnel to do high-quality, efficient work.

There are many ways to cover or pot a high voltage subassembly or installation. Most result in many failures and rejects. Two methods are used with excellent success: vacuum impregnation with overpressure cure, and vacuum injection molding with cure under pressure. The pressure cure keeps bubbles from forming during cure. Tests should be performed to ensure that the vacuum pressure times and cure temperature are optimum for the material.

Lack of cleaning control of workroom causes poor vacuum impregnation results in gaps and poor workmanship results in high field stresses, partial discharges and failures. The corona test is the best test technique to determine these failure mechanisms. Much has been said about inspection and test. Three things that show up as overstress are sharp-edged parts, boards, and subassemblies. They are difficult to find because they do not occur in all components. Tests bring out three failure modes found in high voltage subassembly and power supply production. They are cleaning, poor vacuum impregnation and workmanship [11].

III. High Voltage Guidelines to Minimize Failures

High voltage power supply production and design is greatly affected by cost, time, and workmanship. Some urgently designed and produced equipment, developed at low cost, may result in overstressed insulation. This section discusses major causes of overstress and failure during the design and manufacture process. This discussion is followed by regenerative guidelines to minimize the probability of overstress and unfortunate failures.

A. *Technical Exchanges*

Technical exchanges in design should be held between the contractor and the power supply producers, production and test personnel. The purpose of these technical exchanges is to search for problem areas and find solutions that result in highly reliable, long-life power supplies. The most important guideline to follow is to estimate future failure modes and

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prevent them. For example, a whole new development program is in progress for high-density power supplies. Power supplies developed for airplanes before 1985 had relatively low efficiency and were overtired with thermal problems.

When determining the power density of a power supply, all parts must be included. That is the input and output connectors, switchers, rectifiers, filters, controls, BITE and ATE, heat removal, and structure to fit into the mainframe.

Dielectric parameters critical to high voltage design are temperature, material thickness, humidity, area, dielectric constant dissipation factor, degree of dielectrics between surfaces, component electrode configuration, and gaps. Unconformity of dielectrics within an insulation system is caused by placing the low dielectric constant material next to a small radius conductor in a multiple dielectric system. The greatest impact is for gas-filled gaps next to a curled wire conductor. The ionized gas heats the dielectric, and causes gradual impairment of the solid material.

The correlated physical parameters with components and the completed power supply that caused problems follow:

- Similar materials for stressing in large components such as transformer coils, high voltage solid-state power devices, transformer cores, and base plates.
- Placing low voltage sensitive circuits in a high voltage compartment.
- High voltage and low voltage wire separation.
- Lack of corona shields around nuts, screws, sharp-edged components and terminations.
- Bonding of multi dielectric systems such as epoxies and silicones.

B. *Stress Interactions*

Design stress interactions are reconciled with the electronic design, selection of materials and components, the packaging design, the design of the production fixtures, and the testing parameters. Production stresses can be caused by wrong mixing, potting, and curing of the materials, component and module installation, workmanship, and production facilities and environment.

The problems associated with installation and tests are caused by the production procedures developed by engineering, the production and installation of the components and equipment, and the in-process installation and acceptance tests. Areas of concern in packaging high voltage solid systems are given in Table I.

Solid insulation has electrical, mechanical, thermal, and chemical properties. These and other various properties are detailed in Table II. Sometimes materials are specified to be transparent so that the packaging engineer can assess parts stressing and bonding. Weight, water absorption, and out gassing are often specified. Most important for all categories of high voltage insulation is life, which depends on electrical stress and the environment [12].

- Contamination by waxes, greases and oils after cleaning.
- Mounting parts on circuit boards with exceptionally small gaps, which prevents filling with the encapsulant.
- Circuit board configuration. Potted, densely populated, long, wide circuit boards that crack at low temperature.

Table I. AREAS OF CONCERN IN PACKAGING HIGH VOLTAGE SOLID SYSTEMS

Potential problem	Effect	Method of Prevention
Voltage stress across surfaces	Corona creepage	Layout to minimize surface voltage stress. Creepage barriers. Select arc-resistant material.
Voltage stress exceeding material breakdown	Corona arcing	Maintain spacing between routed wires. Increase package size. Select higher strength dielectric. Solder balls. Hardware selection to avoid exposed sharp edges. Use of voltage shields. Large diameter conductors. Insulation dielectric strength compatibility (AC). Insulation resistivity compatibility (DC).
Excessive temperature	Component failure and insulation degradation	Layout to minimize insulation degradation thermal paths within the module. Use of loaded insulating materials (higher conductivity). Use of thermal spreaders. Minimize thermal resistance from module to ambient. Increase package size. Select thermally stable material.
Gaps in insulation	Corona arcing	Packaging geometry to allow easy fill and gas escape. Packaging design to accommodate cure shrinkage. Process control to avoid bubbles.
Cracks and delamination during thermal cycling	Corona arcing	Packaging delamination during configuration to thermal cycling accommodate insulation shrinkage and expansion (physical constraints). Coefficient of expansion compatibility. Material compatibility to promote adhesion. Low bulk modules if material is severely constrained.
Part or solder joint failure during thermal cycling	Shorts or opens. Corona arcing	Component mounting to provide stress relief. Soft conforming coat of sensitive components.
Particulate contamination	Corona arcing	Packaging design to allow easy cleaning. Process control.

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Table II. PROPERTIES OF INTEREST FOR INSULATING MATERIALS

Mechanical Properties	Tensile, compressive, shearing, and bending strengths. Elastic module. Hardness. Impact and tearing strengths. Viscosity. Extensibility. Flexibility. Machinability. Fatigue. Resistance to abrasion. Stress crazing.
Electrical Properties	Electric strength. Surface breakdown strength. Liability to track. Volume and surface resistivity. Permittivity. Loss tangent. Insulation resistance. Frequency coefficient of other properties.
Thermal Properties	Thermal conductivity. Thermal expansion. Primary creep. Plastic flow. Thermal decomposition. Spark, arc and flame resistances. Temperature coefficients of other properties. Melting point. Pour point. Vapor pressure. Glass transition.
Chemical Properties	Resistance to reagents. Effect upon adjacent materials. Electrochemical stability. Stability against aging and oxidation. Solubility. Solvent crazing.
Another Properties	Specific gravity. Refractive index. Transparency. Color. Porosity. Permeability to gases and vapors. Moisture absorption. Surface absorption of water. Resistance to fungus. Resistance to aging by light.

IV. Conclusion

The guidelines of design and production are proposed for use by low voltage and HVPS designers, technicians, program managers, and production technologists. Because a designer has successfully developed an excellent power supply is insufficient for continued success. New, high-density, high efficiency power supplies must be developed with an entirely new set of problems and solutions. The purpose of the study is to give the industrial designer and manufacturer, engineering and technical personnel a better insight into problems and solutions for high voltage power supplies. Thus in this study, problems encountered in the design and prototype development of HVPS and solving of these problems have been focused on. It has been also examined technical changes can be made and the stress interactions was investigated. It is estimated that about several years would be required to deliver all the HVPS, which includes simulation studies, engineering design, making of first prototype.

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