High Voltage Power Supplies

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High voltage power supplies are special type of DC/DC converters used as power sources in many applications. They are special in that their design and fabrication involves exercise of extra care. Good design techniques result in high voltage power supplies of good reliability.

Following paragraphs give an overview of high voltage (HV) design fabrication and the special care which must be taken to evolve a reliable HV supply.

HV converter

A HV converter can be defined as a power supply where a DC at a lower level is transformed into a DC at higher level.

Basic HV converter can be thought of as being an inverter and a rectifier connected in series as shown in Fig. 1.

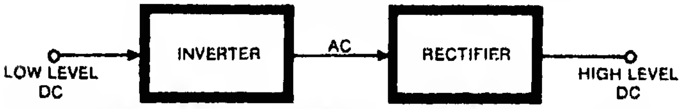

Fig. 1: Block diagram of a basic HV converter.

The inverter converts the DC at lower level to a higher level AC, by first changing the lower level DC to a lower level AC and then using a step-up transformer to get an AC at a higher level. Thus inverters are a special type of oscillators.

The rectifier at the output of inverter changes the stepped-up AC voltage to a DC voltage at higher level. To this basic HV converter, voltage multipliers are added optionally to get still higher voltages, than that got by a transformer without causing its breakdown. Filters and regulators can also be part of HV power supplies like any other low voltage power supplies.

Hence we have the following basic circuits to be discussed for a high voltage power supply (HVPS):

1. Oscillators
2. Rectifiers and voltage multipliers
3. Filters
4. Regulators
5. Controllers

OSCILLATORS

Out of the many circuits which can be used for inversion, the most popular are:

(a) Self-oscillating types. Here again we have two sub-sections: (i) chopper or push-pull circuits, and (ii) blocking oscillators.

(b) Driven types.

Self-oscillating circuits

In this type, no external drive is given to the switching transistors and they work on the principle of regenerative feedback. A portion of the switching voltage is fed back to drive the transistors.

A general form of push-pull type circuit is shown in Fig. 2. Both the primary and feedback windings are centre-tapped; the secondary can be centre-tapped, if required. T1 and T2 are used as switches to alternately cut on and off the DC (i.e. VCC) to produce chopped output at the primary and hence at the secondary. Due to the feedback action, either T1 (or T2) will be conducting at a time and T2 (or T1) will be off. Once T2 (or T1) cuts off, T1 (or T2) will start conducting. This produces a symmetrical square waveform at the T1, T2 collectors and secondary as shown in Fig. 3.

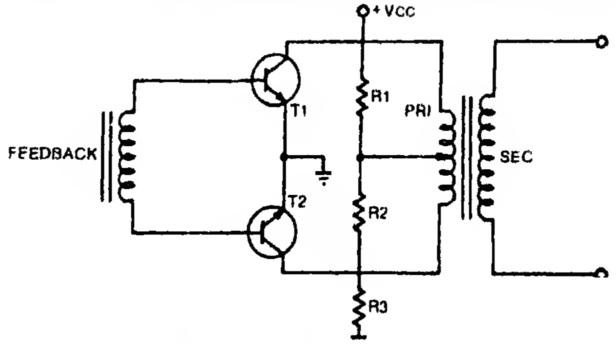

Fig. 2: A typical push-pull circuit.

This circuit has advantages, that (a) very symmetrical waveforms are observed at the output, and (b) core satura-

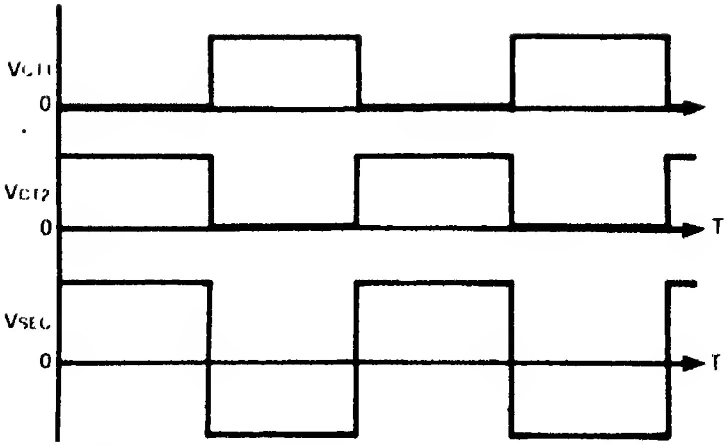

Fig. 3: A symmetrical square waveform produced by a push-pull circuit.

tion is avoided because the transformer is centre-tapped and the core is driven equally in both the directions.

However, the circuit has the disadvantage of higher standby losses and the centre-tapped transformer winding design requiring bifiliar arrangement of wires.

A general form of blocking oscillator circuit is given in Fig. 4. With power on, there is a zero bias on the transistor (T). The collector current starts with leakage in the transistor. Primary rate of change of current induces a voltage in the feedback, which gradually drives 'T' to saturation. At saturation, change in collector current ceases, feedback stops and transistor cuts off, negative voltage existing on the capacitor at the base gets discharged through R, and again the above process repeats.

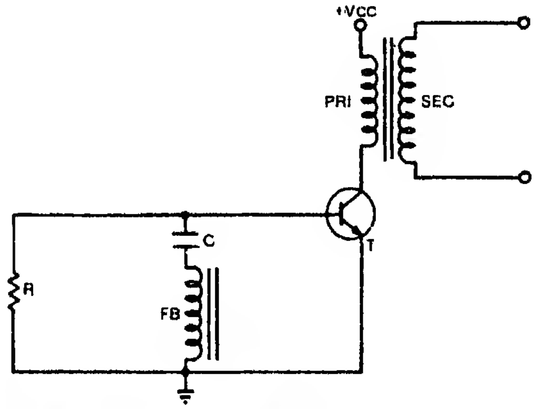

Fig. 4: A typical blocking oscillator circuit.

This produces waveforms at collector of T and secondary as shown in Fig. 5.

As seen in the waveforms at Fig. 5, blocking oscillator design produces slightly unsymmetrical pulses. Even this could be improved by redesigning and adding some other circuit elements, at the cost of extra power. This exercise is not really necessary. The slight asymmetry in the waveform does not matter much, because finally the AC is going to be converted back to DC. More important, standby power can be kept at a lower level in certain low power applications.

Driven type oscillators

This is characterised by an external oscillator driving the final on/off switches connected to the transformer primary. Here also there are two types, single-ended and push-pull, as depicted in Figs 6(a) and 6(b) respectively.

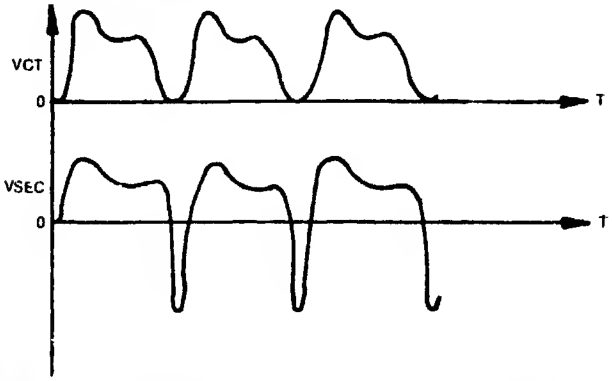

Fig. 5: Output pulses from the collector blocking oscillator transistor.

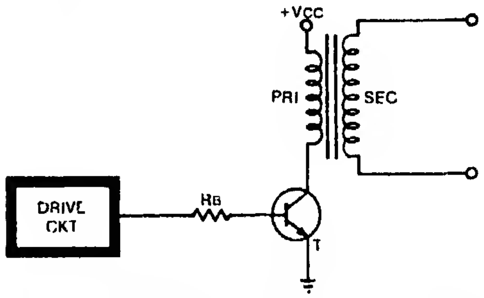

Fig. 6(a): Single-ended driven type oscillator circuit.

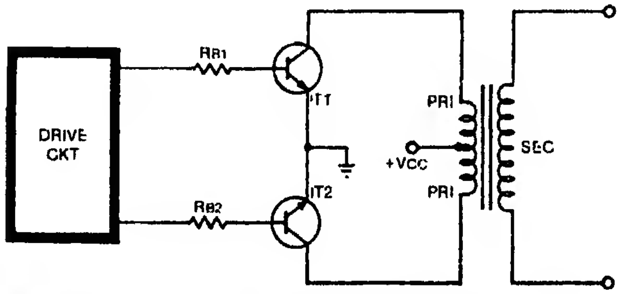

Fig. 6(b): Push-pull driven type oscillator circuit.

Driven-type oscillators have higher standby losses compared to the self-oscillating circuits.

Based on the above discussion, it can be said that, self-oscillating blocking oscillator circuits are used for low-power converters; self-oscillating push-pull types are for medium power applications and driven-type circuits are used for high power sources. In lower power applications, it is necessary to see that the circuit losses do not become comparable with the output power.

Thus the design of an oscillator consists of the following elements:

(a) Choice of switching transistors;
(b) Choice of switching frequency; and
(c) Choice of core and design of transformer.

Choice of transistors

The basic requirements regarding this are: (i) it should be a high frequency transistor, and (ii) it should have higher breakdown voltages.

The second requirement is necessitated because of inductive reactances encountered in the circuit at the primary and feedback. That is to say, transistor should be capable of withstanding high back-emf spikes produced during switch-off of inductors. A rule of thumb is that $V_{CE(max)} = 2V_{CC}$.

If $V_{CC} = 15V$; then $V_{CE(max)} = 15 \times 2 = 30V$.

Further, in switching applications, it is taken that switching power can be about eight times the normal class-A power rating, because during switching operation, the current flow is not continuous.

Hence $P_{SW} = 8P_{AV}$

If P_{AV} = 800 mW, then $P_{SW} = 8 \times 0.8 = 6.4W$.

That is, a transistor of 0.8W power rating can be expected to switch up to a maximum of about 6.4W.

A medium hfe transistor can be chosen, since amplification is not a criterion here.

Choice of frequency

This is a trade-off between various aspects. If the frequency is too low, then core size tends to increase; if it is too high, then standby losses in oscillator and core increase. The oscillator frequency is also likely to interfere with other systems, through conducted and radiated emission. So a careful selection, avoiding of frequencies of other systems connected to the same power line, is required.

In general, a frequency of around 2 kHz is used for low power applications, whereas a frequency of about 20 kHz is taken as suitable for medium power applications. Still higher frequencies are being tried out for higher power applications, with power MOSFETs as switches.

Choice of core and design of transformer

There are many types of cores available such as laminated cores, ferrite cores and toroidal cores.

Laminated cores have higher losses at the operating frequencies of the converters and hence they are avoided.

Ferrite cores are fragile; they cannot withstand vibrations and shocks. When reliability is important, ferrite cores fail to satisfy the conditions.

Toroidal cores are best suited for converter applications. These are also known as tape-wound cores. They have minimum flux leakage and hence losses because of their closed magnetic loop structure. A typical cut-away section of torodail core is shown in Fig. 7.

Tape material of the core may vary, as also the tape thickness. Tape material is usually an alloy of iron like deltamax, mumetal, permalloy etc. Tape thickness determines the maximum usable frequency of the core.

As an example, a kind of molybdenum-permalloy has 80 per cent Ni-Fe and 4 per cent Mo as its major constituents. It is recommended for high frequency applications and saturable reactors. Its speciality is that it has high initial permeability, low core loss, low coercive force etc. Regarding tape thickness, some manufacturers have specified that a 0.025mm thick tape can be used for frequencies up to 10 kHz; 0.013mm can be used up to 20 kHz etc.

The core breakdown strength is also an important factor while designing HVPS. It should be at least twice the peak-to-peak voltage appearing across the transformer secondary.

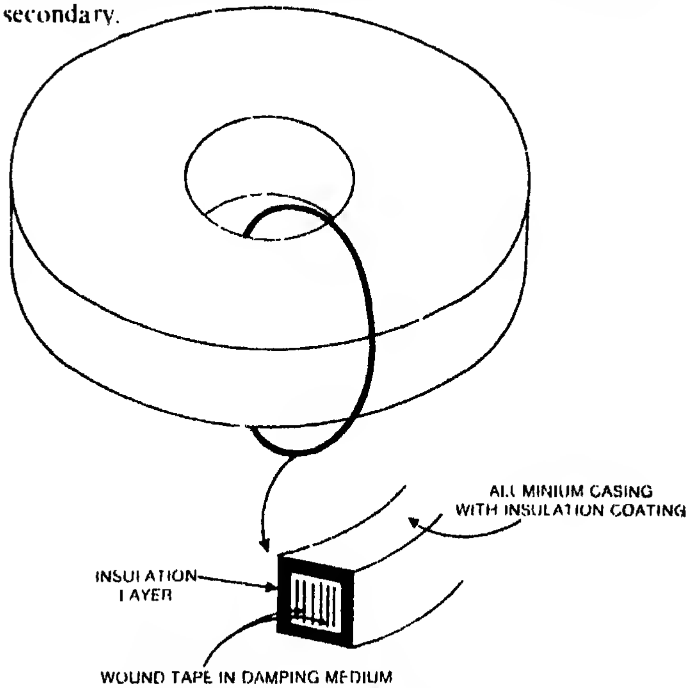

Fig. 7: Cut-away section of a toroidal core.

Enamelled copper wires of suitable SWG are wound on the core. Overlapped winding configuration can be used with primary, feedback and secondary coming one above the other. Bifiliar winding gives better results. The size of the core depends on the power output, window area, the turns ratio etc. Turns ratio depends on the output voltages required and output power determines the guage of the wire. In HVPS a turns ratio of 1:20 is not uncommon.

The step-up ratio, if too high, causes breakdown in the secondary winding and hence very high step-up ratios are avoided. Insulation tapes are provided between different layers in the secondary of the transformer. Transformer design starts with the design of primary number of turns. Knowing the frequency of operation, supply voltage and core flux density (B_{max}, specified by the manufacturer) we can calculate the primary turns by the given formula

$$N_P = \frac{E_{(av)}}{4 B_{max} f \times 10^{-8}} \quad \text{for non-sinusoidal waveforms}$$

To calculate the feedback turns (N_F), the following rule of thumb is used

$$\frac{1}{5} < \frac{N_F}{N_P} < 1$$

that is, feedback turns must be more than one-fifth but less than the number of turns in the primary.

To decide the secondary number of turns, it is required to know secondary current, guage of wire, window area of the core etc. 'Window area' is the area in the core which can accommodate all the three windings. Therefore when winding the secondary, the area already occupied by primary and feedback has to be taken into account. With thinner guages of wires it is found that practically a ratio of 30 to 40 can be accommodated, depending on the step-up ratio required, i.e.

$$\frac{N_s}{N_p} \simeq 30 \text{ to } 40$$

RECTIFIERS AND MULTIPLIERS

Any of the rectifiers used for low voltage power supplies could be used for HVPS as well. However, care has to be taken for device selection of higher ratings. Minimum two times the worst case operating condition of a device can be taken as a good device derating factor. For example, if a HV capacitor is subjected to say 600V DC as the worst-case condition, then the minimum working voltage of that capacitor has to be 1.2kV DC.

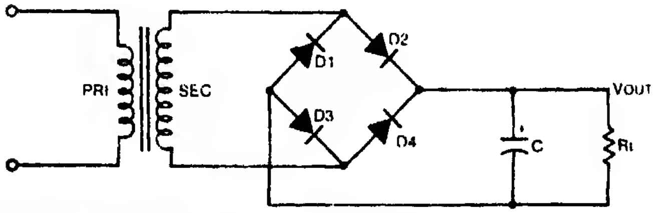

Fig. 8: A full-wave bridge circuit for HVPS.

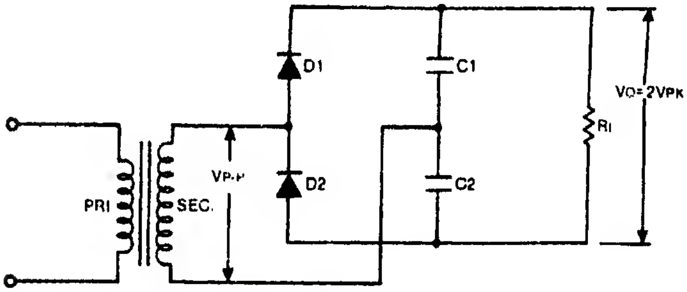

Fig. 9: A conventional voltage doubler circuit.

Depending on the application, a half-wave, full-wave, doubler or tripler can be used in HVPS. For example, a full-wave bridge circuit for HVPS shown in Fig. 8 is no different from that for a low voltage power supply. Note that D1-D4 and C are high voltage diodes and capacitor respectively.

In most cases, the secondary voltage is doubled, tripled or [illegible]ly multiplied. A conventional voltage doubler circuit is given in Fig. 9.

However, in practice an n-stage multiplier will be used to get higher voltages. Two most popular circuits in this are parallel multipliers and series multipliers (cockroft-walton circuit).

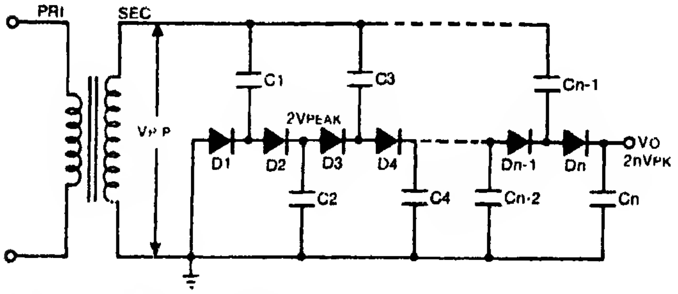

Fig. 10: The circuit for parallel multiplication.

As can be seen in the parallel multiplier circuit (Fig. 10), devices at the later stages have to be of higher voltage rating (almost load voltage). Further, there is no advantage with respect to device reduction or ripple. Hence series multipliers are used.

In a series multiplier circuit (Fig. 11), a maximum voltage of 2 VPK only appears across any device. Hence this circuit is advantageous in using devices of lower ratings. The capacitors used in this are approximated by $C=9\,V_O^2\,I_L/2f(V_{p\text{-}p})^3$, where I_L is the load current, f is the converter frequency and Vp-p is the peak-to-peak (2VPK) secondary voltage.

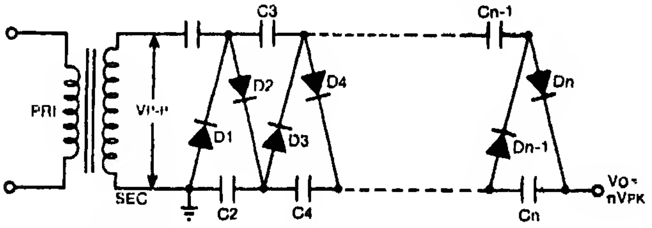

Fig. 11: The series multiplier circuit.

The following points are worth noting with respect to multipliers:

(a) For a given load, as the number of stages are increased, the efficiency goes down;

(b) Increase in number of multiplier stages increases the

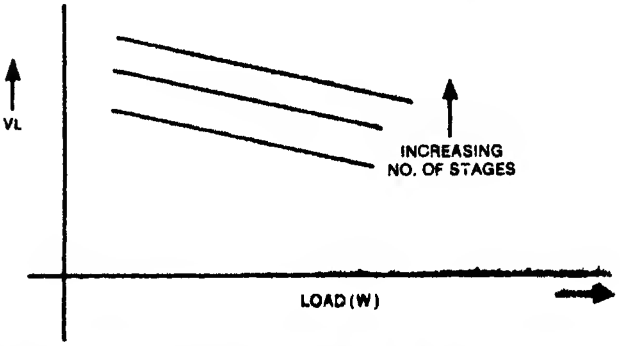

Fig. 12: Load supply vs load consumption characteristics for different number of multiplier stages.

output but the output power that could be supplied comes down linearly (Fig. 12).

Thus the number of multiplier sections have to be optimised. Taking into account the losses encountered in the high voltage sections and to supply any bleeder current, if required, an extra section or two can be incorporated.

FILTERS

Once the DC is available at the output, the next problem is to reduce the AC content in it. That is, filtering. This can be achieved by any one of the standard filter circuits.

Even though L-C filters can be used, by their very nature inductors are bulky which increases weight and space of the system. At lower currents, R-C filters are effective and can be used with advantage.

Simple R-C filters shown in Fig. 13 will serve the purpose. The number of R-C stages required depends upon the ripple that is tolerable in the system. The R and C values can be optimised by referring to charts of ripple attenuation versus RCF for different filter sections. One such useful chart is available in 'Electronic Engineer Handbook' by Landee and Davis (McGraw Hill), whose general form is shown in Fig. 14.

At low-current applications, four to five sections of filters reduce the ripple to acceptable values of 10-20mV. Also, it is found that, metal film resistors in place of carbon composition resistors give improved noise performance because of their uniform structure. Good grounding and shielding is also required. Shielding between multipliers and filters as also between oscillators and filters gives good improvement regarding ripple characteristic.

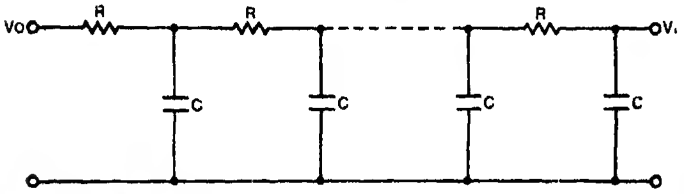

Fig. 13: Simple RC filters.

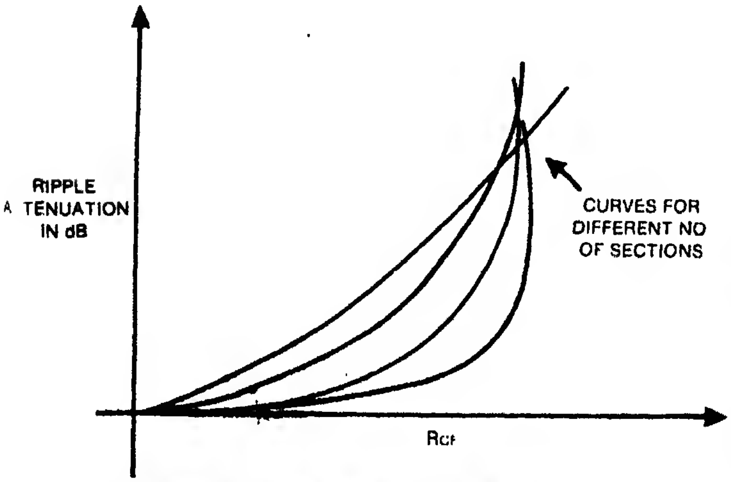

Fig. 14: General waveforms of ripple attenuation.

REGULATORS

Here we can study two types of regulators:

(a) Gas-tube regulators (VR tubes), and

(b) Feedback regulators.

In gas tube regulators, the phenomenon of gas breakdown is utilised for regulating the load voltage. Gas tube is the vacuum tube counterpart of zener diodes. Tubes are connected as shown in Fig. 15. When there is an increase in the voltage, the current (I_Z) through the tube adjusts in such a way that load voltage is kept constant.

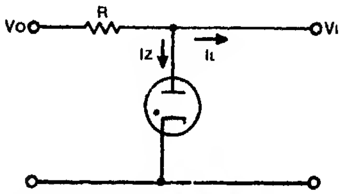

Fig. 15: Vacum tube regulator circuit.

However, tubes are bulky, fragile and occupy more space. Also, since the tubes work in open-loop mode, they do not regulate voltages lower than their own rated voltages. Further, tubes require biasing currents for gas breakdown and regulation. This adds to no-load losses.

Feedback techniques are preferred because they are closed-loop error detection and correction methods. If designed properly, they give very good regulation. Here an amplifier is used in the feedback. Load conditions are sampled and the sample is summed at the input of the amplifier with a constant reference. The amplifier output is made to vary in accordance with load conditions. Here again there are two types, namely voltage controlled and current controlled systems. The general form of voltage controlled system is shown in Fig. 16.

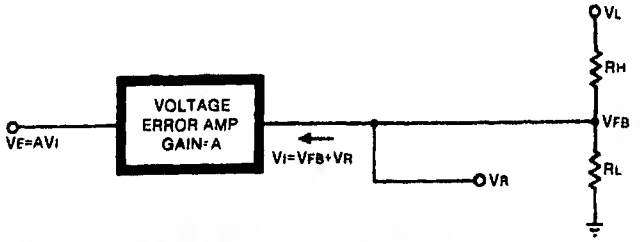

Fig. 16: A typical voltage controlled system.

Load voltage is sampled at V_{FB} using high value resistor R_H and low value resistor R_L. This is summed at V_I with a stable reference voltage V_R. Since the reference is constant, V_E varies in accordance with load voltage V_L.

Current mode control feedback loop system is more com-

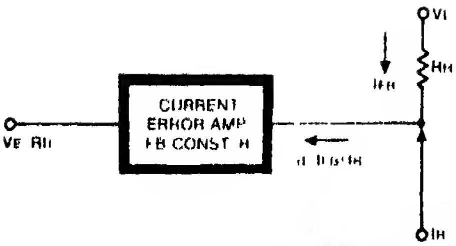

Fig. 17: The circuit for current mode control feedback loop system.

monly used as this simplifies the feedback loop to a one-pole system, which provides reduced phase shift and a more stable loop. Fig. 17 is the general form of this type of circuit.

Load current is sampled using a high value of resistor (R_H). This current (I_{FB}) is combined with a stable reference current (I_R), giving a total current of I_I which is transformed to a voltage (V_E) using an error amplifier acting as a current-to-voltage converter. When there is a change in load, bleeder current (I_{FB}) increases or decreases depending on the load conditions. This causes a change in error current (I_I) which in turn changes error voltage (V_E).

This error voltage change from either of the systems described above is made to control the drive of the oscillator circuit in such a way that, depending on load changes, the drive to the oscillator increases or decreases and hence the terminal voltage remains at a constant level.

CONTROLLERS

Drive control can be either by amplitude variation or by frequency variation.

The simplest form of amplitude controller is a series pass transistor as shown in Fig. 18. The base drive of transistor is varied by V_E which gives a varying V_A at the emitter. Hence the input supply voltage V_{CC} is varied in accordance with error voltage to give a controlling output. The disadvantage here is the power dissipated in the series pass transistors. But the control is simple.

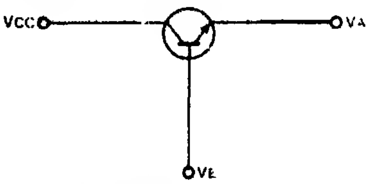

Fig. 18: A simple form of amplitude controller.

In frequency control methods, on/off times of the output transistors are varied in accordance with error voltage. Higher the error, more is the transistor on time. This gives a higher output, correcting the reduced output voltage. This method is advantageous as it gives better regulation and efficiencies. Known as pulse width modulation (PWM) technique, it is the latest in the field of high-power, high-efficiency switchers. A single IC does the job of this PWM.

Now we can see some of the miscellaneous aspects, problem areas and special precautions to be taken in HVPS.

Losses

Following are the losses encountered:

(a) Losses in regulating circuits, error amplifiers etc (i.e. losses in associated circuitry).

(b) Losses in the transformer cores.

(c) Losses in diodes, capacitors and resistors of high voltage multiplier and filter sections (switching losses).

(d) Losses due to stray capacitance in the transformer windings.

Avoiding HV discharges

Corona and arcing are the most common problems under HV discharges. Following steps have to be taken to avoid these:

(a) HV sections are to be separated from low voltage sections in the power supply.

(b) Isolation has to be provided with input transformers and optocouplers.

(c) HV components have to be highly derated and choosing components specially manufactured for HV applications is a better design practice.

(d) Surfaces of cards etc where HV sections are wired, have to be clean and without any deformities.

(e) HV printed circuit card layouts have to be specially done to avoid any sharp corners, as this may lead to corona discharges.

(f) HV lines and ground lines have to be spaced as wide apart as possible to avoid arcing.

(g) Components spacing should also be taken care of so that the HV points and low-voltage points do not come nearby.

(h) HV transformers have to be well insulated.

(i) Solid encapsulants or potting compounds have to be used to cover the HV sections.

(j) Voids or discontinuities in the potting compounds have to be eliminated.

(k) To avoid damage to the components because of corona or arcing, additional circuitry has to be incorporated to detect these and shut off the HVPS.

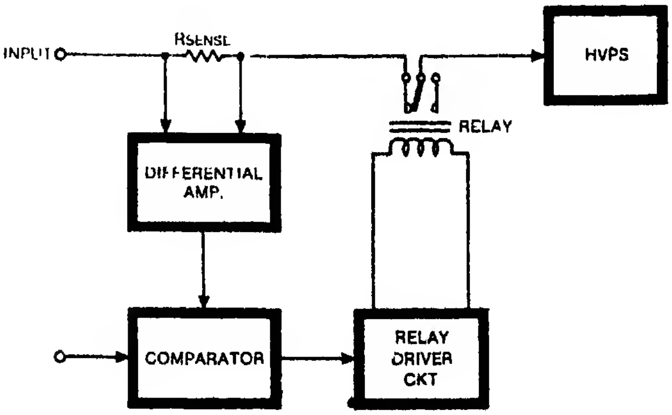

Fig. 19: The current sensing circuit to detect sudden rise or fall in current.

Incidentally, corona/arcing is detected by either a sudden rise in the input current or a drop in load voltage. To detect this, a simple current sense circuit at the input can be incorporated as shown in Fig. 19.

Safety procedures in testing and handling of HVPS

(a) HVPS have to be located at isolated places where there is minimum movement of personnel in the testing area.

(b) Red danger boards have to be made in both local language and English, and they have to be displayed at prominent places while HV testings are being carried out.

(c) HVPS should never be kept on in the absence of testing personnel and HV points should be well insulated.

(d) Persons should be educated about the hazards of HV shocks.

(e) Well insulated and rated equipment have to be used for HV measurements.

(f) Built-in bleeders have to be provided for discharging HVPS when put off in the absence of loads.

(g) Only qualified pesonnel should handle HVPS.

(h) Special HV cables have to be used for HV connections, thus avoiding any leakages.

Finally, we study some aspects which are considered crucial in the functioning of HVPS. Here an attempt is made to define and differentiate some of the terms which are mostly heard in connection with power sources.

Corona

When the voltage gradient between two electrodes exceeds a certain critical value, there is ionisation of air surrounding the conductors, and a luminous discharge occurs. This is known as Corona.

Corona onset voltage is governed by a law known as Paschen's Law. Paschen's Law states that, in a uniform field the corona onset voltage is dependent on both the pressure and the distance between the electrodes. Thus,

$V_s = f(p,d)$

The general form of corona onset voltage as a function of pressure times distance is given in Fig. 20.

We can see that as the pressure is decreased or distance between electrodes is decreased, corona can occur at lower voltages. But after reducing the pressure to a certain level, the corona onset voltage again increases. This is because at higher vacuum, there will be lesser number of free molecules to cause corona.

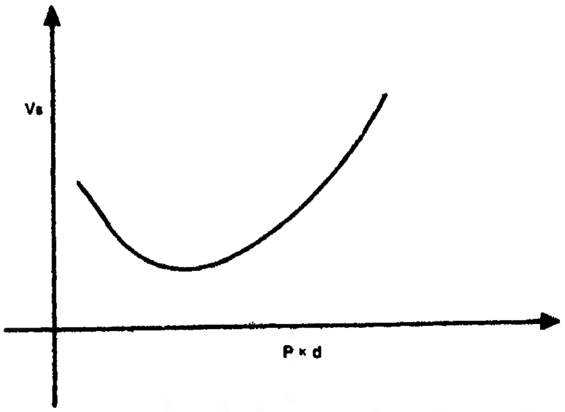

Fig. 20: A curve indicating the general form of corona onset voltage.

Corona is a localised discharge and is limited to the region surrounding the conductor in which the electric field exceeds a certain value.

Corona is characterised by a bluish purple glow in the vicinity of the electrode with smaller radius of curvature. Also, there is an abrupt increase in the current flow from one electrode to the other.

For a self-sustaining corona discharge, the ratio of effective local field to gas pressure is an important factor. It occurs in the nearness of conductors of small radius of curvature subjected to non-disruptive, intense electric fields such as electrical power lines, sharp points at high voltages, etc.

Though corona is responsible for power loss, RF noise and insulation faults, it finds applications in dust precipitation, electrostatic painting, commercial generation of ozone, telecopying etc.

Arc

This is defined as a discharge of electricity through a gas, normally characterised by a voltage drop in the immediate vicinity of the cathode approximately equal to the ionisation potential of the gas.

Arcing is a continuous luminous discharge of electricity across an insulating medium. During arcing usually there is a partial volatisation of the electrodes. Fig. 21 shows a typical curve, which indicates the transition to arcing.

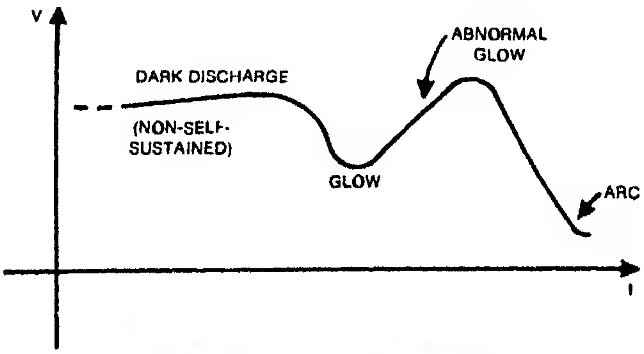

Fig. 21: A typical curve indicating transition to arcing.

Dark discharge sets'on with breakdown voltage. After this voltage, the current increases rapidly. With the occurrence of space charge phenomenon, the discharge passes through various stages of glow discharge, and finally when the voltage increases again discharge goes into arc region.

It should be noted that the power supply connected to the electrodes should have both a high voltage and sufficient power for the maintenance of an arc and that the highest voltage has to be applied for the short duration. Thus an arc can be formed by making the two electrodes come into contact with each other and then separating them. The thermionic emission at the cathode forms the arc and because of power supply, arc is sustained when electrodes are moved away.

Arc is characterised by high current density, high luminosity and fast-potential changes in front of the electrodes. Also, if the gap between the electrodes is already ionised, a lower voltage is required to strike an arc.

Spark

It is a disruptive discharge. Sparking occurs when there is a sudden and large increase in current through an insulating medium due to the complete failure of the medium under dielectric stress. Spark generation is by the physical contact of two electrodes at different potentials. Sparking is a discontinuous or a non-sustaining phenomenon in that once the electrodes are firmly in contact with one another, sparking ceases to exist till the time the electrodes are separated again. Only at the time of making or breaking an electrode-to-electrode contact sparks are observed.

Sparking is characterised by brilliantly luminous phenomenon of a short duration With sparking there is a flash of light. Sparking is also known as sparkover. □