A POWER STAGE FOR A 20kHz 10kW SWITCHED MODE POWER SUPPLY FOR THE INDUSTRIAL 380/440V MAINS

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INTRODUCTION

The theory of transistor converters operating from the single phase 220V mains is not the same as that for switched mode power supplies operating directly from the 380V and 440V mains and delivering an output power of more than 10kW. For the latter the increased technological constraints must be taken into account when designing such a converter. This paper explains the design of a 10kW - SMPS operating on the three-phase 380V - 440V mains and the solutions which have been found to resolve the technological problems.

CHOICE OF THE CONVERTER STRUCTURE

The converter has been designed for a supply from the 380V and 440V mains. It must provide an output voltage of 80V and an output power of 10kW. The operating frequency has been chosen to be 20kHz. There are several possible solutions for the topology of the converter. The choice of topology has been strongly influenced by technological considerations.

CONVERTER TOPOLOGIES FOR THE 10kW - POWER RANGE

Considering the high supply voltage and the switching frequency of 20kHz, converter topologies applying a voltage in excess of the supply voltage to the transistors, or necessitating a power transformer with a low leakage inductance have been eliminated. Transformers with a low leakage inductance that respect the insulation standards are difficult to manufacture. The one transistor "forward" converter and "push pull" converter are thus eliminated.

The choice of the converter topology is reduced to two converter types :

- The full-bridge (figure 1) which is a symmetrical structure with alternating magnetic polarisation.
- The asymmetrical half-bridge (figure 2) in which the magnetic polarisation is uni-directional.

Figure 1 : Full Bridge Converter.

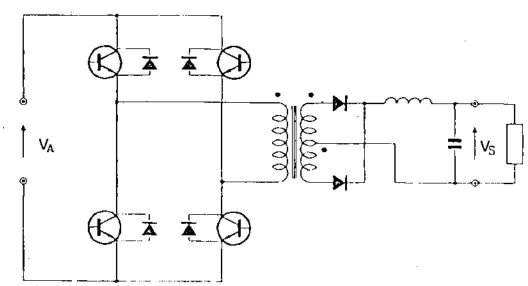
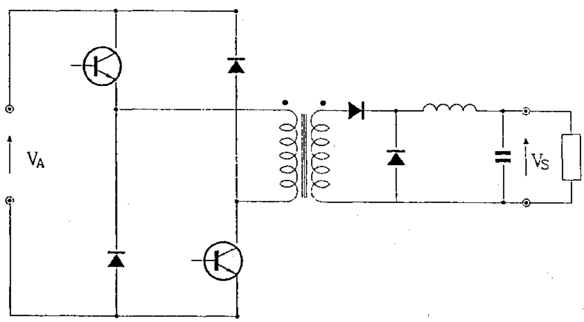


Figure 2 : Asymmetrical Half Bridge FORWARD Converter.



CHOICE CRITERIA

Theoretically the complete bridge is the solution for high output power : at equal output power the transformer is half as big as that of an asymmetrical half bridge.

In practice, there exist a certain number of secondary parasitic phenomena which reduce the advantages of a symmetric structure in comparison to the half bridge. One of these phenomena is that a full bridge is never perfectly balanced. A circuit to correct the symmetry must therefore be designed in and the transformer must be slightly larger to avoid saturation due to dissymmetry.

The full bridge necessitates the use of 4 bidirectional switches and therefore of 4 galvanically isolated drive circuits, whilst the half bridge only requires 2. Simple switching aid networks cannot be directly applied to a full bridge, due to the direct coupling between the upper and lower switches. Supplementary chokes therefore have to be added which would complicate the circuit considerably.

The asymmetrical half bridge does not have these problems. The input current of the asymmetrical half bridge has a bad form factor. Consequently and contrary to a full-bridge, the input filter capacitors of a half-bridge are subject to a high RMS-current.

These different considerations led us to choose an asymmetrical half bridge. The experiment has shown that our choice was reasonable and we think today that for an output power in the 10kW area, the asymmetrical half bridge presents the best technical and economical compromise.

For a substantially higher output power the full bridge seems to be preferable. Alternatively, 2 asymmetric half-bridge circuits can be used, operating in antiphase.

THE ASYMMETRICAL HALF BRIDGE

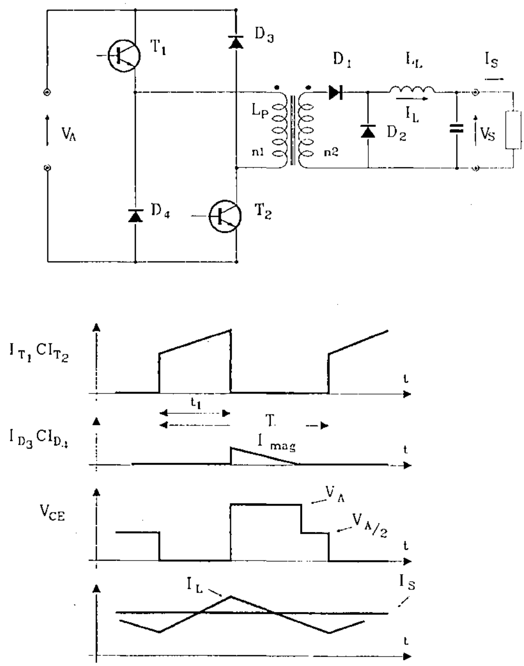
GENERAL CIRCUIT DIAGRAM

The figure 3 shows the basic circuit and the principal voltage and current waveforms of an asymmetrical half bridge.

In this converter, the transistors T1 and T2 are driven simultaneously. They conduct for a time τ and are off for the rest of the period, $T - \tau$.

The diode D1 on the secondary conducts while the transistors are conducting (time τ). The secondary current (during time τ) goes through the inductance L. The diode D2 operates as a free-wheel diode (time $T - \tau$).

Figure 3 : Forward Asymmetrical Half Bridge Converter.



THE MAIN FEATURES OF AN ASYMMETRICAL HALF BRIDGE

The main features of an asymmetrical half bridge are :

- The power transformer and ferrite core. Litz wire is used for the primary because of its reduced skin effect. The low leakage inductance is obtained by winding a half-primary and a half-secondary onto each leg of the transformer. A reduction of the duty cycle with increasing input voltage limits the magnetisation of the core. This reduces the transformer's volume to a minimum.
- The Power Switches. The simultaneously driven power switches must be fast. Their drive must not be disturbed by parasitic signals. To obtain a good voltage safety margin, turn-off snubbing networks are necessary.
- Rectifiers and filter components. The choke inductance is the principal component of the output circuit. As far as possible, the inductance must be high, so that the maximum current in the power switches and the recifier diodes is as low as possible. Fast recovery diodes are used to reduce the switching oscillations. The use of an RC network in parallel to each diode reduces the voltage ripple on the output.
- Safety. In power equipment, safety is a fundamental element which must be considered from the very first stages of design. The principal active safety elements we introduced are :

  a. current limitation for the power switches,
  b. a soft start,
  c. protection against overload on the output,
  d. control of auxiliary voltages,
  e. control of the transformer core magnetisation,
  f. minimum conduction time for complete discharging of the snubbers.
- Control. The control circuit was developed with an integrated circuit, the UAA4006. Amongst other things, this circuit contains several protection functions. The output voltage is detected by means of an extra winding on the filter choke. The free wheel diode is conducting during the demagnetisation phase of the filter choke. During that time interval the voltage across the filter choke is equal to the output voltage. This voltage is fed to the control IC. The control IC also provides the features a-f listed above for safe operation.

THE POWER SWITCHES

For the 10kW switched mode power supply operating from the 380V - 440V mains two fast power switches able to switch 100A with a maximum supply voltage of 700V are required.

There are two possible solutions when choosing the power transistors.

1. To choose transistors with V_{CEW} higher than the maximum voltage the switch has to sustain. Theoretically, this would allow a design without turn-off switching aid networks.
2. To choose transistors with V_{CEW} higher than half the maximum supply voltage and with a V_{CEV} rating higher than the maximum voltage the switch has to support.

The second solution has the advantage of better switching performance than the first one.

The switching times must be as short as possible since the minimum conduction time is of the order of 7μs and during a short circuit at the output about 2 to 3μs.

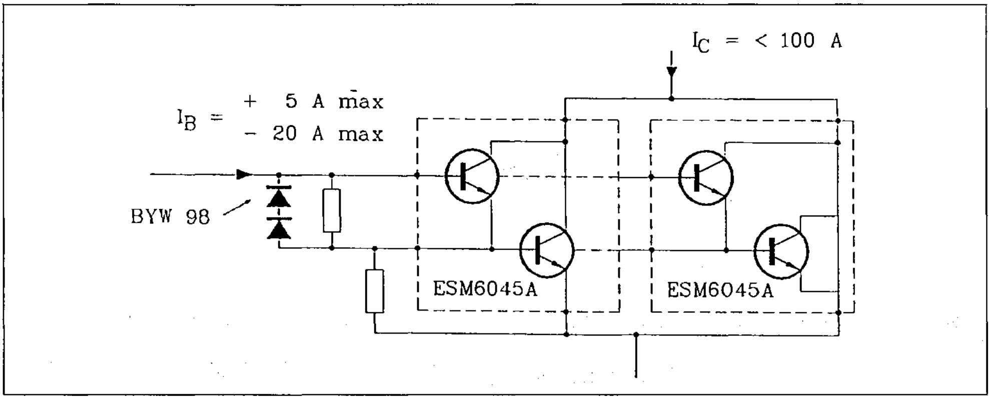
Our choice is a Darlington combination using ESM6045A (fig. 4).

PRINCIPAL CHARACTERISTICS OF THE TRANSISTORS USED

ESM6045A

- $V_{CEW} > 450V$
- $V_{CEV} > 1000V$ ($V_{BE} = -5V$)
- $V_{CEsat} > 2.0V$
- $t_{fi} < 0.6\mu s$
- $t_{si} < 6.0\mu s$ } $I_C = 60A$ and $I_B = 2.4A$
- $t_c < 2.0\mu s$ } $T_j = 100°C$

Figure 4 : Power Switch.



Note that this type of transistor is mounted in an ISOTOP package. The insulation voltage between the die and the bottom of the case is 2.5kV r.m.s. This avoids not only external insulation but also considerably reduces the capacitance between the transistor and the heat sink, hence gives a reduction in RFI.

A certain number of precautions are required when using transistors with V_{CEW} lower than the maximum voltage, to which the switch is subjected :

- A base-emitter resistance must be connected to each transistor (value stated on the data sheet), which insures a static blocking voltage of 700V and therefore protects the switch against any problem arising from the negative bias. Nevertheless the auxiliary voltage should be monitored.
- A turn-off switching aid network must be connected to each switch to insure that the load line stays in the RBSOA at switch off. In our case, the network has to be calculated so that the collector-current reaches zero before the collector-emitter voltage reaches 450V.
- The driver circuit must be capable of providing sufficient base current with an optimized waveform.
- The conduction time of each transistor will always have to remain higher or equal to the time necessary to discharge the snubber capacitor even in the case of an overload.

If these precautions are respected, the voltage safety margin is the same as if very high voltage transistors were being used.

BASE DRIVE CIRCUIT

The base drive turns the transistor switches on and off as determined by the electronic control and safety circuit.

The positive base drive is regulated in order to maintain the power transistors in quasi-saturation. This reduces the effect of parameter spread of the power transistors and simplifies the paralleling. The storage and fall times are also reduced by this means.

The base drive must have a high immunity to electrical disturbances (dV/dt for example). The input interface uses a driver transformer with a bobbin with two segments. The base drive circuit for one switch is shown in figure 5.

Figure 5 : Base Drive Circuit.

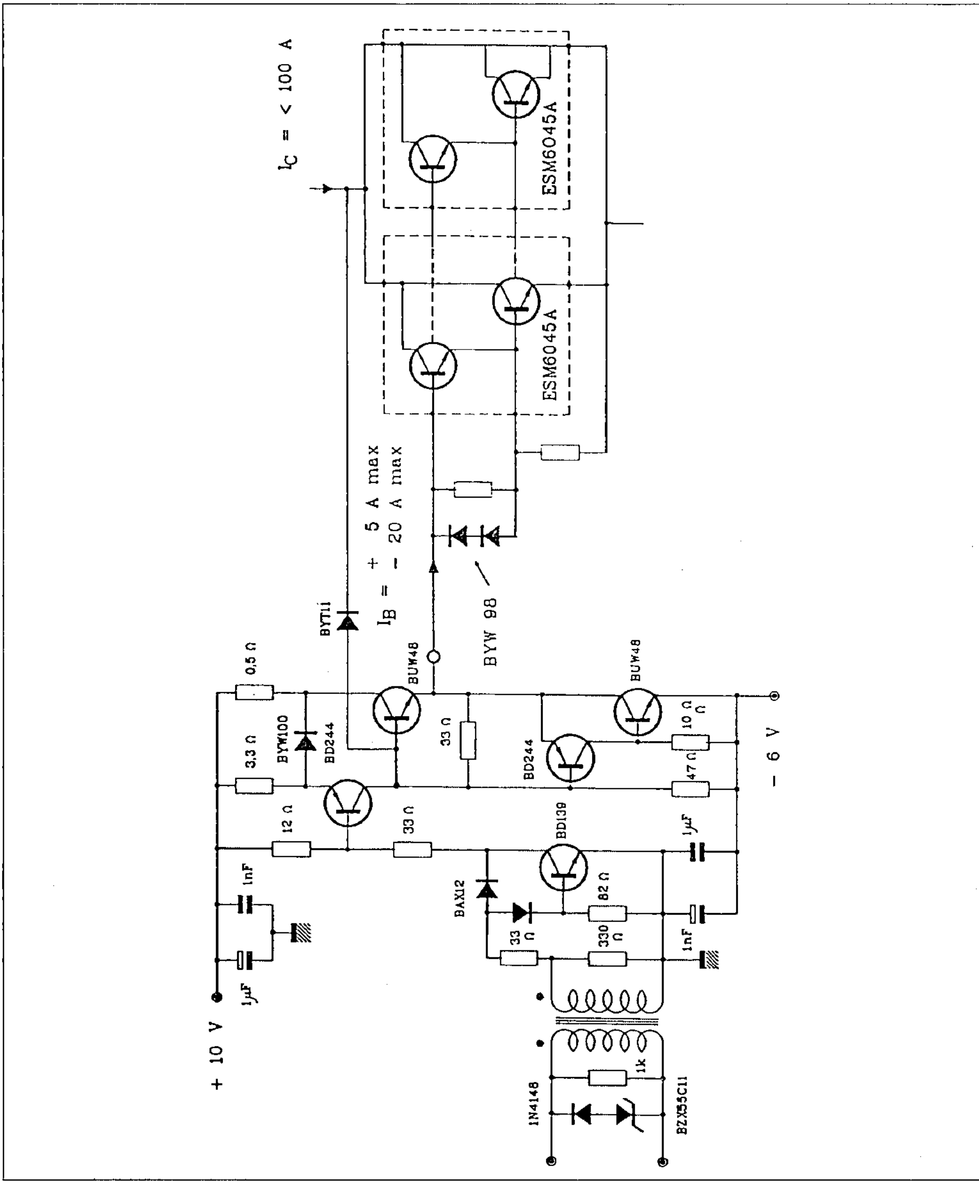
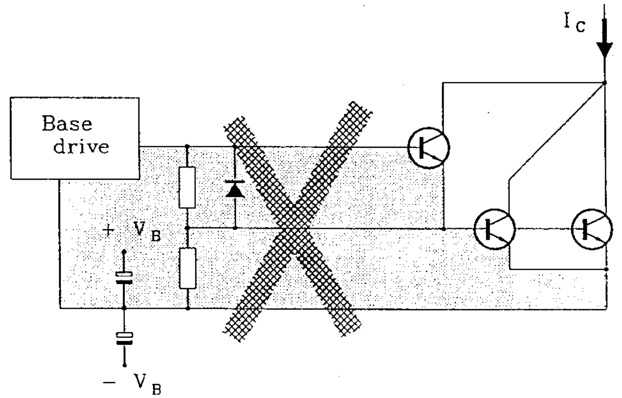
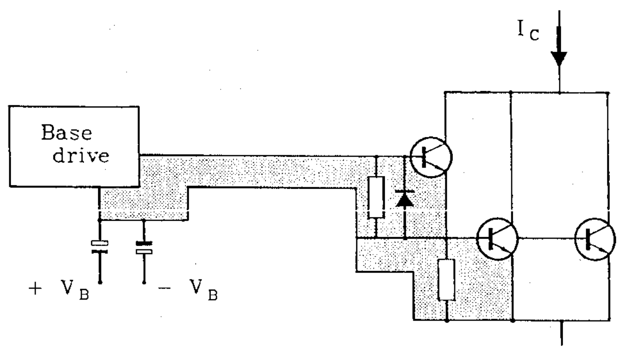


Figure 6 : Wiring for High Power Switching.

a) Base Drive with Poor Wiring.



b) Base Drive with Recommended Wiring.



WIRING PRECAUTIONS

Special care must be taken concerning the wiring of the fast high power switches. The switching speeds being in the order of 200A/µs (much more if they are not limited), current/voltage oscillations are induced in the leads.

It is therefore necessary to pay particular attention to the wiring to reduce the parasitic inductance :

- The connections between transistors, and to the drive must be as short as possible (figure 6) and form very small wiring loop areas.
- Try to obtain the highest symmetry possible between the paralleled transistors. The spread of the transistor -characteristics is only of second order, (for components of the same type and from the same manufacturer) the spread in switching times is essentially a result of the wiring dissymmetry.
- The reference point for the driver must be the emitter connection of the power transistor. Figure 6a shows an example where the zero point of the driver circuit is disturbed by voltages created by the fast rise and fall (dI/dt = 50A/µs) of the output current of the driver stage.
- The decoupling capacitors must be connected as close as possible to the switches.
- The decoupling capacitors must have low equivalent series inductances and resistances. To further reduce the impedance of the decoupling capacitor, multilayer film capacitors with low parasitic impedance have been connected in parallel to the electrolytic capacitors.

THE SNUBBERS

A turn-off switching aid network is needed due to the V_{CEW} rating of the switching transistors which is lower than the supply voltage. To obtain high efficiency from the power supply, switching aid networks with energy recovery have been choosen |2|.

Due to the reverse recovery behaviour of the diodes these snubbers do not operate in an ideal way. The reverse recovery current of the diode D_{AC3} (fig. 7) causes some problems.

The reverse recovery time, t_{rr}, is dependant on the diode technology and the switching conditions.

The reverse recovery current of this diode has several consequences.

- With a low load on the output of the power supply it produces a reverse collector-emitter current in the transistor. The transistor can be protected against this current by means of an antiparallel diode between collector and emitter.
- The reverse recovery current of D_{AC3} partially recharges the capacitor C1 (and discharges C2), figure 7.
- It also flows through the choke L. If the stored energy is not discharged it will generate overvoltages. The diode D_{AC4} clamps and limits this overvoltage to the supply-voltage. Unfortunately, the current through this "clamp" recharges C1 still more (fig. 8).

Diode D_{AC3} must be chosen with care. To reduce the parasitic phenomena it must have a very fast recovery characteristic. The type BYT30-1000 was used.

The resistor (R) parallel to the diode D_{AC1} allows the complete discharge of the capacitor C1 during the conduction time of the transistor (figure 8). This increases the snubber losses, but they are still significantly reduced (~ 30%) when compared to those of a conventional RCD-snubber.

These modifications to the snubber with energy recovery are justified with high switching frequencies (e.g. : 20kHz) and when the minimum conduction time is short. In this case the snubber must reset very rapidly and the parasitic phenomena of the components can no longer be neglected.

The other components of the snubber are chosen in the same way as those for the conventional RCD-snubber.

Figure 7 : Non Dissipative Snubber.

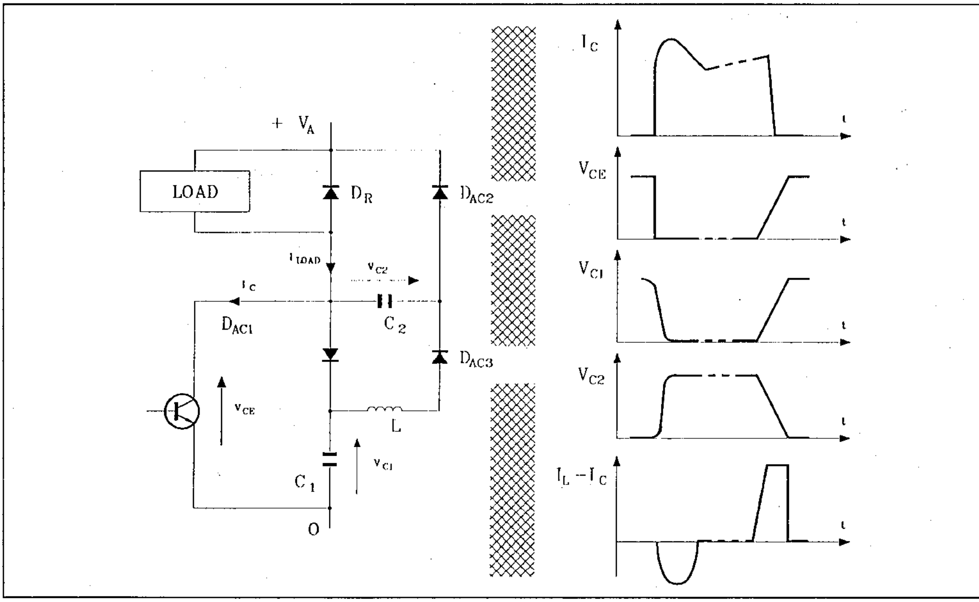
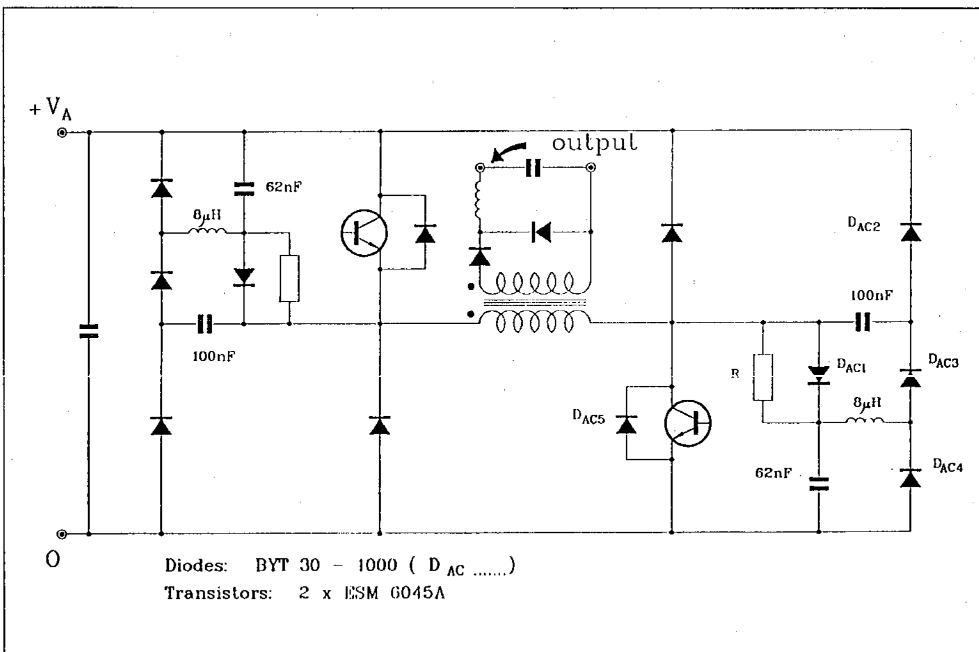


Figure 8 : Complete Diagram of a Power Converter Output Stage.



CONCLUSION

The technological constraints are very important in the design of converters supplied from the 380V - 440V mains.

The use of high voltage transistors with a V_{CEW} rating lower than the supply voltage requires certain precautions, but enables a fast switching speed to be achieved.

The magnetic components (transformer, filter-choke), technological choices are also important since they affect the overall performance of the equipment as well as their influence on the size of the active components.

Adding the snubber with energy recovery increases the efficiency of the power supply and the overall reliability.

This circuit constitutes a basis for the development of switched mode power supplies in the power range of 1 to 10kW for power supply, welding induction heating, battery charger and other high power applications.

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