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Design and Development of Power Module for A Six Pulse a.c to d.c Controlled Converter

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Abstract

The paper deals with the design problems encountered in the selection of semiconductor parts, their protection against temperature raise, over current, surges and reverse recovery and so on for a medium power six pulse controlled converter. Manufacturers manuals and data sheets were extensively referred to, to solve these problems to complete a successful design and development process. The design process presented is akin to a tutorial so that fresh design engineers can take recourse to this approach.

Keywords: *Power module, controlled converter, thermal design, snubber, surge suppression.*

Introduction

Six pulse a.c to d.c controlled converters are extensively used for charging large battery systems used in telephone exchanges, generating and receiving stations, UPS systems used in large computer installations and in electric vehicles and so on. Normally 380V-50 Hz-3 phase industrial a.c power supply from utility is used as input to the converter to produce the required d.c voltage and current. The design of the power module poses a challenge as it is the heart of the converter. The design process outlined below is given in a step-by-step fashion so that fresh designers can adopt and modify to suit their needs. The procedure outlined here was developed by the author for a course given to graduate students specializing in power electronics. The designed converter was actually constructed in the Department of Electrical Engineering and tested partly to validate the design.

Power Module Design Process

Specifications

The power module was designed to meet the following specifications:

Input a.c Supply: 380V +5% or –10%, 3-phase 50Hz industrial supply.

Output d.c: Voltage 0 – 400Vmax, Current 100A max.

Duty: Continuous operation with outlet cooling air temperature not more than 55°C.

Cooling: Forced air cooling of the heat sink with a fan.

Overload Protection: By semiconductor fuses.

Other Protections: The module must have the protection against surges, over voltages, reverse recovery, switch on and switch off transients.

Device Selection

The topology chosen was a six-pulse fully-controlled bridge. SEMIKRON thyristor module SKKT162-16E was chosen. This module consisted of two silicon-control rectifiers (scrs) packaged together with gate and annode-cathode connections brought out. Three modules were used to construct the bridge converter. Each scr in the module was rated for 1600V-160amp with a dv/dt of 1000V/μs. There are many other manufacturers who can supply similarly rated thyristor modules: for example International Rectifier, Fusi, GE International, to mention a few. What is the rationale behind choosing the 1600V module? The max. rms voltage an scr has to block is 420V (600V peak). Under transient conditions the expected peak voltage may reach 2.5 times the normal (1500V) and hence we have gone for 1600V device.

Heat Sink Design

Having chosen the thyristor modules, the next step was to design a suitable heat sink on which to mount the modules. The purpose of the heat sink is to dissipate the power loss generated in the modules during operation and limit the steady state temperature rise of the devices. Also the heat sink forms the structural part of the power module which may be used to mount some of the protection components. Forced cooling of the heat sink was necessary in this particular case as the dissipated power reaches 300W as we shall see later on. Basically in the heat sink design, we have to arrive at the required thermal resistance R_{Thsa} from sink to ambient. Then we chose a commercially available heat sink to meet the required thermal resistance and also the desired shape.

It was assumed that the power module has a continuous current rating of 100A d.c with 120° conduction angle. Hence average current per thyristor was 33.33A. Taking a safety factor of 1.25, we got I_{TAv} = 33.33 x 1.25 = 42A. Take I_{TAv} = 45A/thyristor. Referring to SEMIKRON Manual, pages B1-66, Fig.1(b), we got average power dissipation per thyristor P_{TAv} as 50 watts. Taking ambient temperature T_{amb} = 40°C, we got junction to ambient thermal resistance from the same Fig.1(b) as R_{Thja} =1.7°C/W. Again from the data sheet of SKKT 162.-16E given in page B1-65, for 120° pulse, we got R_{Thjc} =0.20°C/W per thyristor. Also the thermal resistance from case to heat sink was R_{Thch} =0.10°C/W per thyristor. Total number of thyristors in the power module N = 6. The heat sink to ambient thermal resistance was calculated from the formula:

$R_{Thha} = (R_{Thja} - R_{Thjc} - R_{Thch}) / 6$ given in page A-27.

It worked out to be 0.23°C/W. We must choose a heat sink whose thermal resistance was less than this. In order to limit the weight and length of the heat sink, forced cooling had to be used as the power loss was reasonably high-300W. Referring to SEMIKRON Manual, pages B13-14/15 we found that the heat sink P3/180F was suitable. However, the heat sink length of 180mm was found to be inadequate as we decided to mount three BUSSMANN fuse links on the heat sink itself so as to make the module compact. Hence a non-standard length of 220mm was chosen and the heat sink was designated as-P3/220F.

Cooling of the Heat Sink P3/220F: A cooling fan was to be fitted to the heat sink on one end to force air through the fins. It was found that the cooling fan DP 209WR was suitable for this purpose as it could be fitted in line with the heat sink. Given below is the calculation to show that the air delivery of this fan was adequate to take away the heat of 300W without excessive rise in the outlet air temperature. From the data sheet of this fan the air delivery is given as 75CFM(127.4m^3/hr) Taking 60CFM(102m^3/hr) as realistic air delivery we got the amount of air delivered as 36.83gm/ sec. The heat carried by air per second per °C rise is given by

Q = 4.2M S Joules per second per °C rise where M= mass of air in gm, S = sp.heat of air

Q=36.83x0.24x4.2 =37.12 J/s/°C.

From power point of view this is equivalent to 37.12W/°C rise. Let us take it as 30W/°C rise. Assuming inlet air temperature as 40°C, the rise in air temperature would be 10°C for carrying 300W power loss. It could be noted that adequate safety margin was given in this design so that short term over loads can be sustained without excessive temperature rise. Incidentally P3 heat sink weighs 17.6kg/m. The designed heat sink weighed 17.6 x 0.22 = 3.9kg.

Semiconductor Fuse Selection

The method of selecting a fuse for overload protection of a power semiconductor device such as a thyristor is different than that adopted for the protection of electrical equipment. This is mainly due to the very small thermal capacity of the semiconductor wafer. Hence manufacturers give a special rating for these power semiconductors called I^2t rating. For the SKKT 162-16E module the I^2t rating as given on page B1-65 by SEMIKRON (1998) for a junction temp. of 125°C for 50/60Hz half cycle basis is $125000A^2$-s. The fuse chosen must have an I^2t rating less than this value but must be capable of carrying full load current continuously. BUSSMANN-make semiconductor fuses had been chosen. The fuse selected is 170M 2666. This fuse has European square body satisfying DIN 43653. This fuse is rated for 160A and has $I^2t = 13000A^2$-s. In all three fuses are required on the a.c side. It should be noted that the fuse and its holder cost as much as the semiconductor being protected.

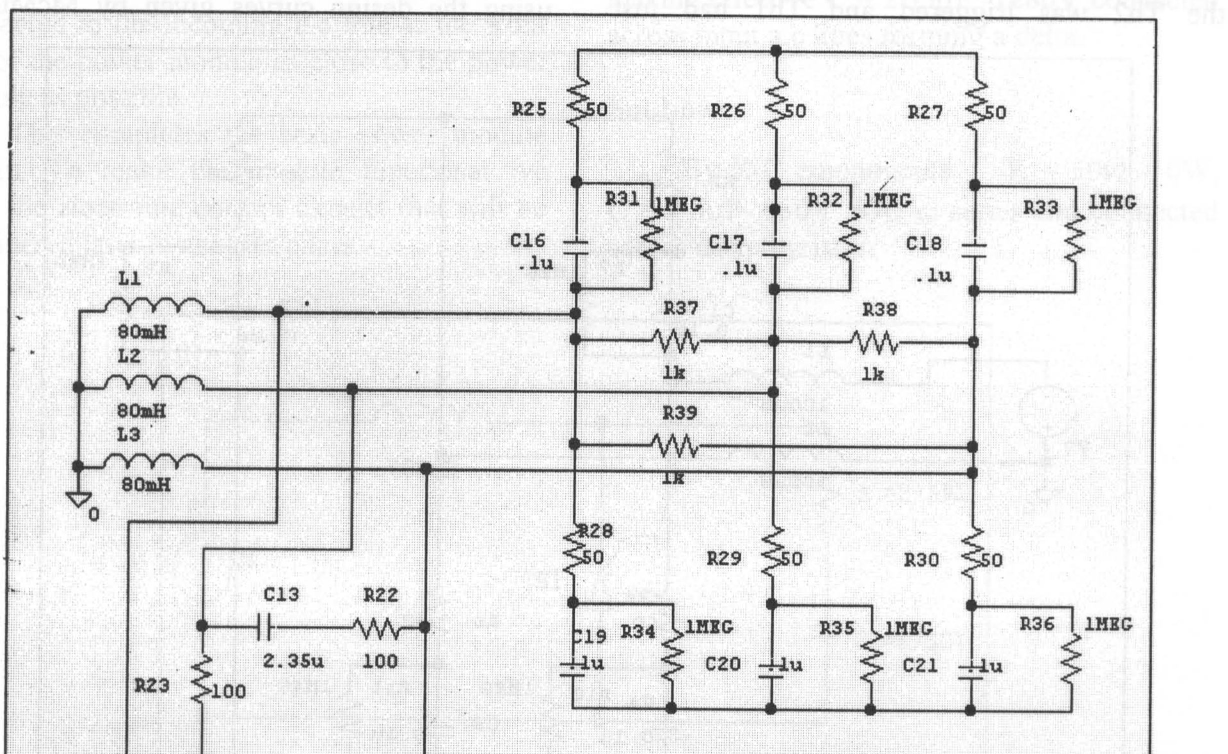
Switch-Off Surge Protection

Normally the converter a.c supply is given through a distribution transformer. When the converter is to be taken out of service, d.c load is reduced and then the primary of the transformer is disconnected from supply. This switch off can create a surge of voltage due to the trapped magnetic energy arising from the magnetizing current that existed in the three phases prior to switch off. Since primary is open, the currents get transferred to the secondaries and the associated energy is to be absorbed without excessive rise in voltage at the terminals of the power module. Normally R-C components are connected across lines but close to the power module. The method of estimating the required values is outlined below.

It was assumed that the converter was supplied from a 250kvA, 380V, 3 phase 50Hz transformer. The magnetizing current for this rating was about 2.3% (SIEMENS, p. 426 Table156). Therefore $I_{mag} = 8.75A$ rms and the magnetizing inductance $L_m = 80mH$. The required capacitance to absorb this magnetic energy was given by Sen (1988, p. 195):

$$0.75\ L_m\ I^2_m = 1.5\ C\ [V_{RM}^2 - (\sqrt{6}V_S)^2]$$

where V_{RM} = non repetitive peak reverse voltage of thyristor which was taken as 1200V for safety. The capacitance worked out to be 2.66µF and for reasonable damping the required series resistance $R > 2\ (\sqrt{3L_m/C})$ and works out to be nearly 100Ω. These values were estimates only as mentioned earlier. Hence pspice simulation was performed to find optimum values to limit over shoot and had reasonable damping. The values arrived at are R



Equivalent Circuit for Switch off Transient

= 50Ω - 50W, C = 2.35μF - 1280V. The surge suppressor was connected between lines and forms a delta connection. For those who are interested in the pspice simulation, the circuit used for this purpose is given below with the condition that the R-phase magnetizing current is maximum at the time of transformer disconnection.

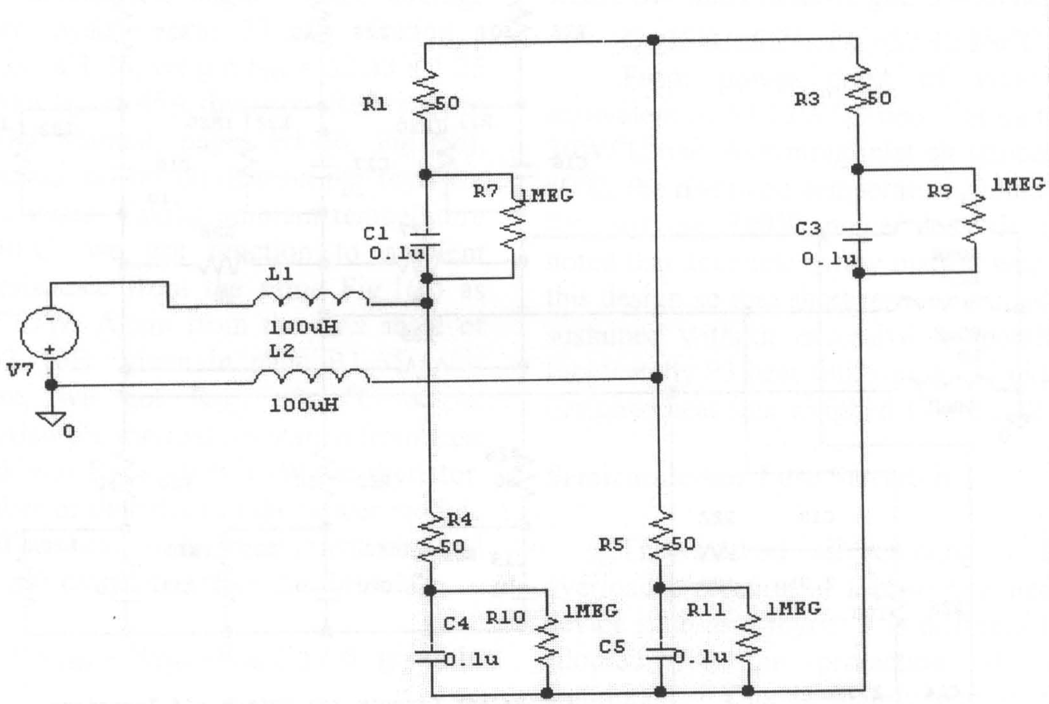
R-C Snubber Design For Optimum Reverse Recovery

The equivalent circuit of the power module with R-C snubber across each thyristor is shown in figure below. L_1, L_2, L_3 represent the stray leakage inductances present in each line. These values were calculated from the short circuit impedance of the transformer supplying the power module that was about 5% for 250kVA rating. The leakage inductance was going to be100μH. This was the value considered in the design of the snubber. Also the current through each device was assumed to be 100A constant during conduction period. The reverse recovery phenomenon of Thl was considered. The conduction sequence was 1-5, 1-6, 2-6, 2-4, 3-4, 3-5, 1-5, ----. Assume that the Th2 was triggered and Thl had just recovered and blocking. Th6 continued to conduct. The reverse recovery current of Thl was trapped in the line inductance. The equivalent circuit of the power module under these conditions is shown below.

The solid lines in legs 2 and 3 indicate that the thyristors 2-6 are now carrying the load current. However the circuit configuration was valid only for the study of the reverse recovery of Th1. This circuit can easily be reduced to the following equivalent circuit shown in figure (on Reverse Recovery of Thl-equivalent circuit) in the next page for further study. In this circuit R_1 and C_1 were values of each of the thyristor in the Bridge Rectifier.

The reverse voltage applied to Thl by Th2 when it was fired was taken as V_S = 465V which actually depended on the working firing angle of the power module. The di/dt is now 465/200 = 2.33A/μs. For this di/dt the recovered charge Q_{rr} was found from SEMIKRON page B1-68 Fig. 5 as 130μC and the reverse recovery current from Rashid (1997), page 24 as $I_{RR} = \sqrt{(2Q_{rr}\ di/dt)}$ and substituting the values we got I_{RR} =25A.

There were many ways to go from here for the design of the snubber. The author was using the design curves given by McMurray



Reverse Recovery of Thyristor 1

(1972). Limiting the peak transient $V_P = 2V_S$ the current factor from the curves d = 1.4 and optimum damping δ =0.24. The snubber capacitance $C = L\,(I_{RR}/\,d.V_S)^2 = 200 \times (25 / 1.4\times465)^2 = 0.3\mu F$. The snubber resistance $R = 2\delta\sqrt{(L/C)} \approx 12.5\Omega$ and $w_o = \sqrt{(1/LC)} = 13 \times 10^4$ rad/s, $(di/dt)/V_S$. W_O at t=0 is equal to 1.2 from design curve. So dv/dt at t=0 is 72.5V/µs. Initial reverse voltage across Th1 is $I_{RR} \times R = 25 \times 12.5 = 312.5V$. The actual snubber values were obtained by working back as $C_1 = 3/5\,C = 0.18\mu F$ and $R1 = 5/3\,R = 21\Omega$ and L1 =100µH. These values give us an idea and to be actually verified by simulation for the performance of the snubber. Finally the following values were decided for the snubber $R_1 = 50\Omega$-50W, $C_1 = 0.15\mu F$-1000V.

Apart from this it was essential to suppress the mains borne transients, spikes, etc. by using metal oxide varistors (MOV). Harris Semiconductors make MOV type V 480LA40A whose ratings are as follows: maximum continuous voltage 480Vrms / 640Vd.c, clamping voltage V_c = 1240V @ I_P = 50A, energy transient = 105J(10/1000µs) and varistor voltage at 1mA = 750V. Three varistors were connected in delta and connected to the incoming a.c line at the front end of the power module as close to the power module as possible.

This completes the basic power module design. To make the module functional we need the electronic control circuits that will be considered later in another paper.

Summary of the Designed Parameters for the Power Module

Power Devices

SEMIKRON-make semipack Thyristor modules SKKT162-16E-3 numbers in all.

Heat Sink

P3/220F weight 3.9kg

Cooling Fan

DP 209WR-220V 50Hz operation, air delivery 75CFM

Fuses

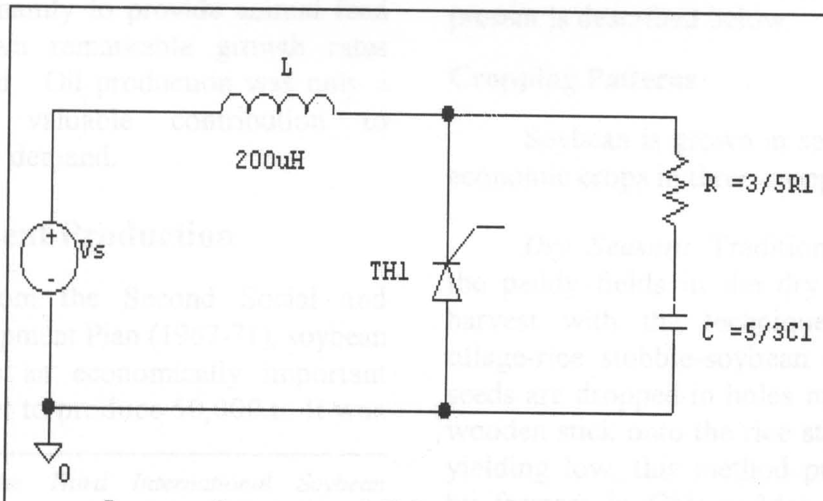
Semiconductor type, BUSSMANN-make 170M 2666 three numbers connected one each in the a.c lines

Surge Protection

By R-C components. R = 50Ω - 50W aluminum housed and mounted on heat sink, C = 4.7µF-640V with two capacitors in series making effective C = 2.35µF -1280V connected across input a.c lines forming a delta.

Snubber

By R-C components. R = 50Ω -50W, C = 1.5µF- 930V. R-C in series and connected across each thyristor.



Reverse Recovery of Th1-equivalent Circuit

MOVs

Three MOVs are used across the input a.c lines. Part number V480LA40A, Harris Semiconductor make.

Conclusion

The design process outlined above shows how the theoretically obtained values are to be modified so as to arrive at a practical design. Also design is impossible to perform without referring to the manufacturers Data Manuals and hence these manuals must be available to the designer at hand. Transient performance of the designed surge suppressor, snubber, and so on, cannot be tested in the laboratory ordinarily as they require sophisticated test and measurement systems. Hence one way to test the designs is to simulate using software such as pspice that is resorted to in the design process outlined above. Those who are interested in the simulation results may contact the author. The power module was constructed as per the designed values and tested in the department of Electrical Engineering partly as the required load to carry 100A d.c was not available. However the module was tested for switch on and switch off transients repeatedly and has performed well and none of the devices failed during this testing process.

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