Advances in Semiconductor Devices and Their Growing Use in Electrical Circuits and Systems

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Abstract: - The main aim of this investigation is to assess the suitability of modern power semiconductor devices for pulse power applications. Pulse power system involves the storage of energy, which is released in form of high power pulse to the load by means of a switching device. Hence the basic components of pulse power system are an energy storage element, a switch, and a load circuit. The energy storage is usually either an inductive or capacitive nature. The limiting device in a pulse power system is often the switch, which limits the pulse peak power and the repetition rate. The switch element in this case is very special and falls into two basic categories:
1-Vacuum and gas filled switching tubes,
2- Solid-state (semiconductor) switches.
The conventional approach in pulsed power designs is to use spark gap and gas filled switches such as thyratron and ignitron, because they truly possess the required characteristics for high power application. However, these devices have limited lifetime, high cost, low repetition rate and high losses. On the other hand high power semiconductor devices have under gone continued improvement in switching speed, voltage and current ratings and thus are replacing the conventional gas filled devices in some applications. Solid state devices are considered environmental friendly since they do not contain nasty gases and have perceived higher reliability than gas filled devices.
In this paper, a complete overview of vacuum and gas filled switches and solid-state switches will be given.
Very rarely these types of power semiconductor devices are characterised for pulse power applications and so the task of dimensioning a device simply from the datasheets is somewhat difficult and time consuming. Different methods for assessing their suitability will be described and a new technique to rapidly dimension the semiconductor device for pulse power application will be presented.

Key-Words: **-** Pulsed power, Gas-filled devices, Electro-thermal models, Simulation, Power semiconductor devices.

1 Introduction

Pulse power is an elite branch of power electronics. This is because the main use of pulse power is confined to research (such as research in particle physics) and military applications (such as rail gun). However in recent years pulse power technology is being used in some industrial applications such as water purification, materials treatment, food sterilisation and some special medical types of equipment.

Pulsed Power Technology (PPT) is used to generate and apply energetic beams and high-power energy pulses. It is distinguished by the development of repetitive pulsed power technologies, x-ray and energetic beam sources, and electromagnetic and radiation hydrodynamic codes for a wide variety of applications.

Some examples of these applications are:

- Nuclear survivability and hardness testing
- Measurement of material properties
- Materials processing
- Waste and product sterilisation and food purification
- Electromagnetically-powered transportation
- Interpreting data from x-ray binaries and galactic nuclei
- Electric Pulse rock crushing
- Laser supplies : Excimer, CO2 , Nitrogen, Copper Vapour
- Plasma immersed Ion implantation

- Klystron/Magnetron supply
- Particles accelerators

A Pulse Power System generally involves the storage of energy, which is released in form of a high power pulse to the load by means of a switching device (Figure 1). Hence the basic components for pulse power system are an energy storage element, a switch and a load circuit. The energy storage is usually either of an inductive or capacitive nature. The limiting device in a Pulsed Power System is often the switch, which limits the pulse peak power and the repetition rate. The switch element in this case is very special and falls into two basic categories:

- Vacuum and Gas filled switching tubes
- Solid-state (semiconductor) switches

The conventional approach in Pulsed Power designs is to use a gas filled switch such as a thyratron, ignitron or spark gap. However these devices have limited lifetime, high cost, low repetition rate and high losses. On the other hand high power semiconductor devices have under gone continued improvement in switching speed, voltage and current rating and thus are replacing the conventional gas filled devices in some applications.

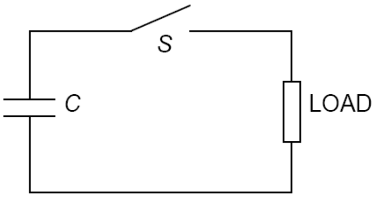

Figure 1. Basic pulse generator topology

2 Vacuum and gas-filled devices

Two primary distinguishing features can classify these types of switches:

- the source of free electrons within the device and
- the gaseous filling (or lack of it) within the tube envelope

A vacuum tube is a device with a vacuum (very low pressure gas) filling. And a gas filled device is, as the name would suggest, filled with gas that might be at a pressure somewhat above or below atmospheric.

The type of gas used is also an important feature, particularly in switching tubes where a wide variety of fillings are encountered. The source of the free conduction electrons in the device may be either thermal such as a heated filament physically associated with the cathode of the device – a hot cathode, or alternatively a simple consequence of a high voltage gradient across the device, resulting in auto-emission from the cathode. A device employing this latter method is known as a cold cathode device and is used in many high-voltage switching applications.

2.1 Thyratrons

A thyratron is a type of gas filled tube used as a high energy electrical switch. Triode, Tetrode and Pentode variations of the thyratron have been manufactured in the past though most are of the triode design. Gases used include mercury vapor, xenon, neon, and (in special high-voltage applications or applications requiring very short switching times) hydrogen. Unlike a vacuum tube, a thyratron cannot be used to amplify signals linearly.

Thyratrons evolved in the 1920s from early vacuum tubes such as the UV-200, which contained a small amount of argon gas to increase its sensitivity as a radio signal detector; and the German LRS Relay tube, which also contained argon gas. Gas rectifiers which predated vacuum tubes, such as the argon-filled General Electric "Tungar bulb" and the Cooper-Hewitt mercury pool rectifier, also provided an influence. A thyratron is basically a "controlled gas rectifier". Irving Langmuir and G. S. Meikle of GE are usually cited as the first investigators to study controlled rectification in gas tubes, circa 1914[1,2]. The first commercial thyratrons didn't appear until circa 1928.

A typical hot-cathode thyratron uses a heated filament cathode, completely contained within a shield assembly with a control grid on one open side, which faces the plate-shaped anode. When positive voltage is applied to the anode, if the control electrode is kept at cathode potential, no current flows. When the control electrode is made slightly positive, gas between the anode and cathode ionizes and conducts current. The shield prevents ionized current paths that might form within other parts of the tube. The gas in a thyratron is typically at a fraction of the pressure of air at sea level; 15 to 30 millibars (1.5 to 3 kPa) is typical.

Both hot and cold cathode versions are encountered. A hot cathode is an advantage, as ionization of the gas is made easier; thus, the tube's control electrode is more sensitive. Once turned on, the thyratron will remain on (conducting) as long as there is a significant current flowing through it. When the anode voltage or current falls to zero, the device switches off.

Small thyratrons were manufactured in the past for controlling electromechanical relays and for industrial applications such as motor and arc-welding controllers. Large thyratrons are still manufactured, and are capable of operation up to tens of kiloamperes (kA) and tens of kilovolts (kV).

Modern applications include pulse drivers for pulsed radar equipment, high-energy gas lasers, radiotherapy devices, and in Tesla coils and similar devices. Thyratrons are also used in high-power UHF television transmitters, to protect inductive output tubes from internal shorts, by grounding the incoming high-voltage supply during the time it takes for a circuit breaker to open and reactive components to drain their stored charges. This is commonly called a “crowbar” circuit.

Thyratrons have been replaced in most low and medium-power applications by corresponding semiconductor devices known as Thyristors (sometimes called Silicon Controlled Rectifiers, or SCRs) and Triacs. However, switching service requiring voltages above 20 kV and involving very short risetimes remains within the domain of the thyratron. Variations of the thyratron idea are the krytron, the sprytron, the ignitron, and the triggered spark gap, all still used today in special applications.

2.2 Ingnitron

An ignitron is a type of controlled rectifier dating from the 1930s. Invented by Joseph Slepian[3] while employed by Westinghouse, Westinghouse was the original manufacturer and owned trademark rights to the name “Ignitron”.

It is usually a large steel container with a pool of mercury in the bottom, acting as a cathode. A large graphite cylinder, held above the pool by an insulated electrical connection, serves as the anode. An igniting electrode (called the “ignitor”) is briefly pulsed to create an electrically conductive mercury plasma, triggering heavy conduction between the cathode and anode.

Ignitrons were long used as high-current rectifiers in major industrial installations where thousands of amperes of AC current must be converted to DC, such as aluminium smelters. Large electric motors were also controlled by ignitrons used in gated fashion, in a manner similar to modern semiconductor devices such as silicon-controlled rectifiers and triacs. Many electric locomotives used them in conjunction with transformers to convert high voltage AC from the catenary to relatively low voltage DC for the motors.

Because they are far more resistant to damage due to overcurrent or back-voltage, ignitrons are still manufactured and used in preference to semiconductors in certain installations. For example, specially constructed pulse rated ignitrons are still used in certain pulsed power applications. These devices can switch hundreds of kiloamperes and hold off as much as 50,000 volts. The anodes in these devices are fabricated from a refractory metal, usually molybdenum, to handle reverse current flow during ringing (or oscillatory) discharges without damage. Pulse rated ignitrons usually operate at very low duty cycles. They are often used to switch high energy capacitor banks during electromagnetic forming, electrohydraulic forming, or for emergency short-circuiting of high voltage power sources (“crowbar” switching).

2.3 Krytron

The Krytron is a cold-cathode gas filled tube intended for use as a very high-speed switch and was one of the earliest developments of the EG&G Corporation.Unlike most other gas switch tubes, the krytron uses arc discharge to handle very high voltages and currents (several kV and several kA peak), rather than the usual low-current glow discharge. The krytron is a development of the triggered spark gaps and thyratrons originally developed for radar transmitters during World War II.

There are four electrodes in a krytron. Two are conventional anode and cathode. One is a keep-alive electrode, arranged to be close to the cathode. The keep-alive has a low positive voltage applied, which causes a small area of gas to ionize near the cathode. High voltage is applied to the anode, but primary conduction does not occur until a positive pulse is applied to the trigger electrode. Once started, arc conduction carries a considerable current. In place of or in addition to the keep-alive electrode some krytrons may contain a very tiny amount of radioactive material (usually nickel-63) which emits beta particles (high-speed electrons) to make ionisation easier. The amount of radiation in a krytron is very small and not harmful.

This design, dating from the late 1940s, is still capable of pulse-power performance which even the most advanced semiconductors (even IGBT transistors) cannot match easily. The vacuum-filled version is called a Sprytron and is designed for use in environments where high levels of ionising radiation are present (because the radiation might cause the gas-filled krytron to trigger inadvertently).

Krytrons and their variations are still manufactured by Perkin-Elmer Components, and used in a variety of industrial and military devices. They are best known for their use in igniting the exploding-bridgewire detonators and slapper detonators in nuclear weapons, their original application, either directly or by triggering the higher-power spark gap switches. They are also used to trigger large flashlamps in photocopiers, lasers and scientific apparatus, as well as firing ignitors for industrial explosives.

2.4 Over voltage spark-gap

The Over voltage spark gap is essentially just two electrodes with a gap between. When the voltage between the two electrodes exceeds the breakdown voltage of the gas, the device arcs over and a current is very rapidly established. The voltage at which arcing occurs in these devices is given by the Dynamic Breakdown Voltage, which is the voltage at which the device will breakdown for a fast rising impulse voltage. Note that this voltage may be as much as 1.5 times greater than the static breakdown voltage (breakdown voltage for a slowly rising voltage.) how much greater than the static breakdown voltage the actual breakdown voltage is will be depends almost entirely on how rapidly the voltage rise, a shorter rise time means a higher breakdown voltage. Commutation times for these devices are exceptionally low (sometimes less than 1nanosecond).

Overvoltage gaps are primarily used for protection. But in combination with the other devices mentioned here they are commonly used to sharpen the output pulses (decrease the rise times) of very high current pulses form triggered switching devices e.g. Thyratrons. The size of these devices is almost entirely dependent upon how much current/voltage they are intended to switch, There is really no limit as to the size of these devices they can be as small as krytrons, however they can also be very big, and devices intended to switch MA will be just that.

2.5 Triggered spark-gap

The triggered spark gap is a simple device; a high voltage trigger pulse applied to a trigger electrode initiates an arc between anode and cathode. This trigger pulse may be utilized within the device in a variety of ways to initiate the main discharge. Different spark gaps are so designed to employ one particular method to create the main anode to cathode discharge. The different methods areas follows-

Triggered spark gap electrode configurations:

i) Field distortion: three electrodes; employs the point discharge (actually sharp edge) effect in the creation a conducting path

ii) Irradiated: three electrodes; spark source creates an illuminating plasma that excites electrons between the anode and cathode.

iii) Swinging cascade: three electrodes; trigger electrode nearer to one of the main electrodes than the other.

iv) Mid plane: three electrodes; basic triggered spark gap with trigger electrode centrally positioned.

v) Trigatron: trigger to one electrode current forms plasma that spreads to encompass a path between anode and cathode.

The triggered Spark gap may be filled with a wide variety of materials, the most common are:

Air, SF6, Argon and Oxygen.

Often a mixture of the above materials is employed. However a few spark gaps actually employ liquid or even solid media fillings. Solid filled devices are often designed for single shot use (they are only used once- then they are destroyed). Some solid filled devices are designed to switch powers of 10TW (10000 GWatts) such as encountered in extremely powerful capacitor bank discharges.

Except (obviously) in the case of solid filled devices the media is usually pumped through the spark gap. Some smaller gaps do not use this system though. Usually Gas filled spark gasp operate in the 20-100kV / 20 to 100kA range though much higher power devices are available. I have one spec for a Maxwell gas filled device that can handle 3 MA – that's 3 Million Amperes! But then it is the size of a small car!! More commonly gas filled devices have dimensions of a few inches. Packages are often shaped like large ice pucks though biconical, tubular and box like structures are also seen.

Sparkgaps are often designed for use in a certain external environment (e.g. they might be immersed in oil). A system for transmitting the media to the appropriate part of the device may sometimes be included. Common environments used are:

(a) Air (b) SF6 (c) Oil

Spark gaps are damaged by repeated heavy discharge. This is an inevitable consequence of such high discharge currents. Electrode pitting being the most common form of damage. Between 1 and 10 thousand shots per device is usually about what is permissible before damage begins to severely degrade performance. EG&G make miniature triggered spark gaps specially designed for defense applications. These devices are physically much smaller than normal spark gaps (few cm typical dimensions) and designed for use with exploding foil slapper type detonators.

Laser switching of spark gaps: The fastest way to switch a triggered spark gap is with an intense pulse of Laser light, which creates plasma between the electrodes with extreme rapidity. There have been quite a few designs employing this method, chiefly in the plasma research area. Triggered spark gaps tend to have longer delay times than Thyratrons (their chief competitor, at least at lower energies) However once conduction has started it reaches a peak value exceptionally rapidly (couple of nanoseconds commutation.)

3 Solid-state Power Semiconductor Switches

Solid state switches in pulse power refer to power semiconductor devices. These generally fall into three categories viz. bipolar devices (such as diodes, transistors, thyristors), unipolar devices (such as Schottky diodes and Power MOSFETS) and bi-mos devices such as IGBTs (which is a combination of MOSFET and bipolar).

3.1 Power Diodes

Diodes are basically two terminals (anode and cathode) uncontrolled switches and they are turned ON and OFF by the action of the electrical circuits. A fundamental property of a diode is its rectifying characteristics as shown in figure 2. This means it has two modes of operation, i.e. forward conduction mode (ON state) and reverse blocking mode (OFF state). In the ON state it conducts a current ION and has a finite on-state voltage drop VON. This results in significant power dissipation in the diode and consequently limits the maximum current handling capability. In the reverse blocking mode it exhibits a finite blocking current and also supports a finite maximum reverse voltage (reverse breakdown voltage BVR). Power loss due to blocking current is small but can become significant at higher operating temperature. A diode also has finite switching times during turn-on and turn-off leading further power losses in the device.

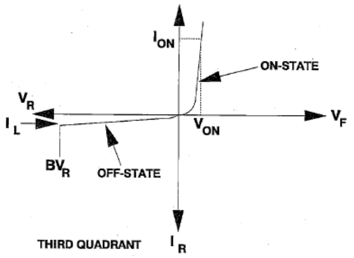

Figure 2. Rectifying Characteristics of a diode

There are basically two types of power diodes, a p-n junction diode and a Schottky barrier diode. A p-n junction diode is a two-layer semiconductor device usually formed by diffusing p-type layer into n-type silicon. The interface between p-type and n-type silicon is called p-n junction and hence the p-n junction diode. With this type of structure very high current and very high voltage diodes can be manufactured (> 10,000A and >9kV).

Power diodes are supplied in variety of packages e.g. metals, plastics and ceramic housings. For high power pulse applications devices in ceramic housing are of interest.

The Schottky barrier diode is formed by producing a metal-semiconductor junction as a Schottky barrier (unlike p-n junction in semiconductor to semiconductor junction). This structure results in very fast switching device with low forward voltage drop. However Schottky diodes based on silicon material gives low reverse blocking characteristics (~50V) and hence not quite suitable for very high voltage application. However recent development is replacing silicon in favour of other semiconductor material such as silicon carbide and diamond to improve the reverse blocking characteristics of these diodes.

The main application of power diode is rectification of AC to DC power and commutation of inductive power in many power conversion circuits[4].

3.2 Power Thyristors

The thyristor is a solid-state semiconductor device with four layers of alternating N and P-type material. They act as a switch with three terminals (anode, cathode and gate), conducting when their gate receives a current pulse, and continue to conduct for as long as they are forward biased. Thyristor has three modes of operation (Figure 3), the forward blocking mode, the reverse blocking mode and forward conduction mode when triggered on. That is why it is also known as silicon-controlled-rectifyer (SCR).

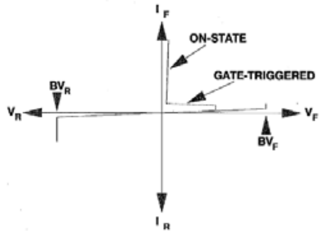

Figure 3. Thyristor output characteristics

Thyristors are well suited for AC circuit applications because they have forward and reverse blocking characteristics and when triggered on in the forward direction they turn off naturally upon reversal of the anode voltage.

The thyristor can be made to operate in DC circuit but some external means to turn off is required such as commutation circuit. For DC circuit applications, it is preferable to be able to turn-off the current flow without reversal of the anode voltage. This has been achieved in a structure called the Gate Turn-Off (GTO) Thyristor. Other useful structures belonging to the thyristor family are the ASCR asymmetrical thyristors, IGCT — Integrated gate commutated thyristor, LASCR — light activated SCR, or LTT — light triggered thyristor.

3.3 IGBT Modules

Insulated Gate Bipolar Transistor (IGBT) combines the simple gate drive characteristics of the MOSFET with the high current and low saturation voltage capability of bipolar transistors by combining an isolated gate FET for the control input, and a bipolar power transistor as a switch, in a single device. The IGBT is mainly used in switching power supplies and motor control applications.

Figure 4 shows the output characteristics of IGBT. IGBT has three modes of operation, forward blocking mode, reverse blocking mode and forward conduction mode. Most IGBTs on the market have asymmetrical blocking characteristics i.e. very little or no reverse blocking capability.

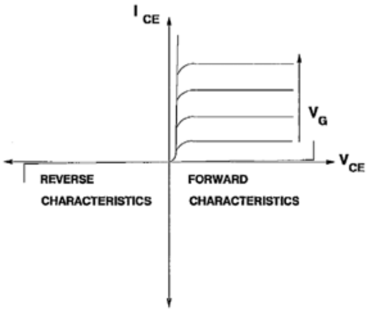

Figure 4. IGBT output characteristics

Figure 5. IGBT module

The IGBT is a recent invention. The “first-generation” devices of the 1980s and early ‘90s were relatively slow in switching, and prone to failure through such modes as latchup and secondary breakdown. Second-generation devices were much improved, and the current third-generation ones are even better, with speed rivaling MOSFETs, and excellent ruggedness and tolerance of over-loads. The extremely high pulse ratings of second- and third-generation devices also make them useful for generating large power pulses in areas like particle and plasma physics, where they are starting to supersede older devices like thyratrons and triggered spark gaps.

Figure 5 shows IGBT module which houses several IGBT chips connected in parallel to obtain high current rating. For high voltage applications, series connection of IGBTs is required[5].

4. Dimensioning power devices for pulse power applications

The main aim of this investigation is to asses the suitability of modern power semiconductor devices such as power diodes, thyristors, gate turn-off thyristors and IGBT modules for pulse power applications. Very rarely these types of devices are characterised for abnormal applications such as pulsed power or surge riding capability and so the task of dimensioning a device simply from the datasheets is somewhat difficult and time consuming. Sometime it is required to build a special test rig to ascertain the device capability under required operating conditions. Again this approach is costly and time consuming. One of the methods adopted is to model semiconductor devices and simulate the device applications. There are several semiconductor devices modeling software available on the market and some of this also incorporate circuit simulator or stand alone circuit simulator like PSPICE can also be used. However these packages are crammed with many utilities and hence tend to be expensive and can also be slow. A novel approach is used to develop a dedicated software tool to rapidly dimension the semiconductor device for pulse power application. This requires developing suitable Electro-thermal model of the device, which then can be used with Microsoft Excel spreadsheet to obtain the desired output very quickly.

4.1 Simulation process

Most power semiconductor devices have junction temperature rating of 125°C for continuous current operation. However this limit can be exceeded and the junction temperature could rise much higher level (300~400°C) as long as the device blocking capability is not seriously degraded or the onset of thermal run-away is avoided. The electrical characteristics of the power devices are strongly dependent on junction temperature and therefore Electro-thermal simulation technique is required to estimate the electrical and thermal behavior of the power devices.

Numerous literatures can be sited for estimation of junction temperature for power semiconductor device [6-12] and methods for obtaining transient thermal curve. Recently computer modeling is used to simulate the transient thermal behavior of the power devices based on the geometry and the thermal properties of the materials used (FEM).

The method used here is to use two most important parameters given on the device data-sheets viz. the on-state voltage drop (which contributes towards power losses) and the transient thermal resistance (which dissipate these losses) to create an Electro-thermal model of the device. The variations of on-state voltage as function on of current and transient thermal resistance as a function time are used to extract model parameters.

To extract model parameters for the device electrical and thermal models the authors have used linear regression and solve functions readily available in the Excel spreadsheet. Finally to couple these models the power generated within the device is equated to the power dissipated within the device materials and the ambient. At this point device simulation process can begin. The input to the simulation is the time dependant current waveform and the output can be the time dependant junction temperature of the device or the temperature dependant on-state voltage or the voltage and current surge loops. The simulation process can be carried out very effectively on Excel spreadsheet. Using the visual basic and look-up table facility available on this spreadsheet one can construct a very powerful simulation tool for dimensioning power devices for pulse power and other applications.

4.2 Simulation models

For simulation purpose two basic models are required viz.-electrical model and thermal model. These two models are then coupled to give an Electro-thermal model to estimate the device junction temperature for reliable operation under pulse power duty.

4.2.1 Electrical model

All power devices generate power losses during conduction state and transition states (turn-on and turn-off). These losses are function of instantaneous current and device temperature. Therefore in order to predict the loss accurately the electrical model should be able to alter the device characteristics dynamically with variation of the device instantaneous temperature. The conduction loss is function of on-state resistance or on-state voltage. The switching losses are function of transient current and voltage waveforms. These are also function of switching frequency. At high frequencies the switching losses dominate the total power losses. Hence at frequencies below about 200Hz one can easily ignore the switching losses contribution to the total power losses. This could further simplify the device model. However with very short high current pulses when there is not sufficient time to dissipate the energy, switching losses could become significant factor in increasing the junction temperature and hence cannot be ignored.

Most device datasheets provide the on-state characteristics in form of a graph of on-state current against on-state voltage at two measured temperatures (usually at 25°C and 125°C). Figure 6 illustrates thyristor on-state characteristics provided in the device datasheets.

Bipolar devices such as diodes, thyristors, and gate turn-off thyristor exhibit very similar characteristics. However IGBTs have similar looking characteristics only in the linear ohmic region and also depends on the gate bias voltage. Once the IGBT saturates no further significant increase in forward current is possible for a given gate voltage. Operation in this region of the IGBT characteristics is generally avoided due to very high dissipation. In order to model on-state characteristics as shown in the Fig.6, one chooses either a physics based model or an empirical model which have proved to give good results.

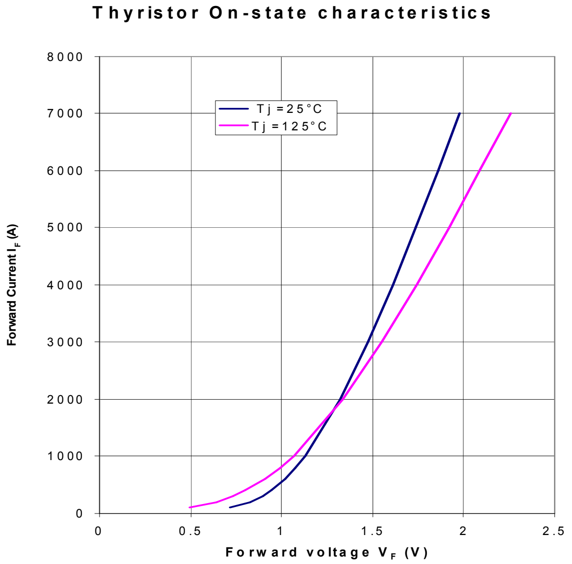

Figure 6. On-state characteristics

An empirical model which is commonly used by the manufacturers to model on-state characteristics for diodes, thyristors and GTOs is as follows:

$$V_{ON} = A+B*Ln(I_{ON})+C*I_{ON}+ D*\sqrt{I_{ON}} \qquad (1)$$

This relation is valid for a fixed temperature (isothermal) and a specified current range. The parameters A, B, C, and D are either given for 125°C or for 25°C and 125°C respectively. These are usually obtained by curve fitting measured on-state characteristics using regression method. This relation gives reasonable accuracy if self-heating is minimal. In pulsed power application the peak currents are much higher than the average current rating and the effect of self-heating is very evident. The authors have modified equation (1) and converted into a temperature dependant relationship by assigning a separate temperature coefficient element to the constants A, B, C and D. Thus:

$$V_{ON}(I,T_J) = (A + a(TJ)) + (B + b(TJ))*Ln(I) + (C+ c(T_J))*I+(D+d(T_J))*\sqrt{I} \quad (2)$$

Where a, b, c, and d are the temperature coefficient for the parameters A, B, C, and D respectively. The authors have found that all these coefficients can be obtained using regression method available in EXCEL Spreadsheet on values of on-state voltage obtained from the data sheets.

4.2.2 Thermal model

The main purpose of thermal modelling of power semiconductor is to determine the junction temperature of the device during steady state and or transient overloads situation in order to assess the risk of failure and the need for protection or circuit modification. There are various techniques available for this purpose and the choice depends on the accuracy needed, the amplitude and the shape of the power waveforms involved and whether it is necessary to couple a temperature dependent electrical model to the thermal model to adequately represent the system. Some of these techniques are listed below.

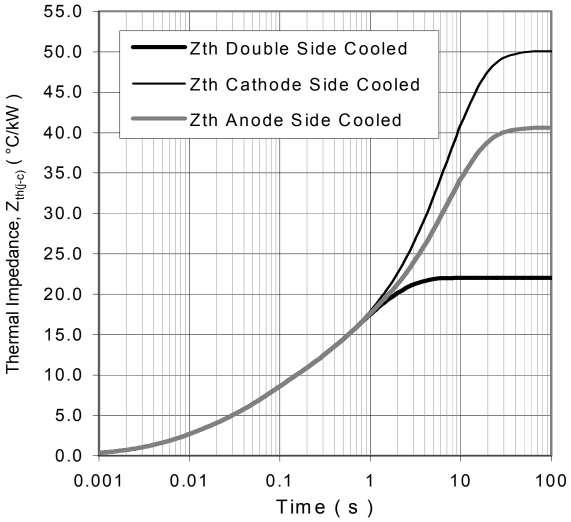

Figure 7. Transient thermal curve for a thyristor

1. Solving the thermal diffusion equation
2. Use of transient thermal impedance curve- Superposition
3. Use of transient thermal impedance curve - the convolution integral
4. The lumped R-C network model
5. The exponential series model

The model commonly given in the device datasheet is the exponential series model (Figure 7)

$$Z_{th}(t) = \sum_{1}^{n} A_n \bullet (1 - \exp(-B_n \bullet t)) \quad (3)$$

4.2.3 Electro-thermal model

The device electro-thermal model is obtained by coupling both the electrical model and the thermal model. This is done by equating the power generated in the device during the conduction-state to the power dissipated in the device materials, packaging and to the atmosphere.

$$P_{generated}=V_{ON}*I_{ON} \quad (4)$$

$$P_{dissipated}=(TJ–T_{ref})/Z_{th} \quad (5)$$

Hence equating (4) and (5) and rearranging,

$$T_J=Z_{th}*V_{ON}*I_{ON}+T_{ref} \quad (6)$$

where VON is a function of ION and TJ and ION and Zth could be time varying functions. Where as Tref is reference temperature and the junction temperature TJ is measured from Tref . Tref is usually the device case temperature or sometimes it is referenced from the heatsink or ambient.

4.3 Methodology and simulation example

For the purpose of illustration, a press-pack thyristor is chosen to outline the methodology used for the simulation. This method is also applicable to any power devices e.g. IGBT using suitable Electro-thermal model for the device. The chosen task is to calculate the instantaneous junction temperature of the thyristor for a given half-sinusoidal current pulse. Microsoft EXCEL spreadsheet is used for the mathematical process and built-in Visual Basic Application (VBA) for the programming. This process can also be carried out using stand alone mathematical software packages such as MATHCARD.

☐ To begin the process we need:

☐ Input current waveform (e.g. half-sine wave) in form of a mathematical equation or measured values with respect to time.

☐ Temperature dependant model for the on-state voltage (e.g. equation (2)) with model parameters extracted using data-sheet values (Table 1)

☐ Transient thermal impedance curve for the device given in the data-sheet is used for the thermal model. This is usually expressed mathematically as sum of exponential (equation (3))(Table 2).

Table 1 On-state voltage parameters

A	B	C	D
4.2	-3.9E-1	3.0E-4	1.62E-2
a	b	c	d
-1.36E-2	7.1E-4	-7.8E-8	2.3E-4

Table 2 Transient thermal impedance coefficients

n	**1**	**2**	**3**	**4**
A_n (°C/kW)	0.94	2.705	4.51	4.1546
B_n (s)	0.01	0.055	0.327	1.63

These three input items are then used to calculate instantaneous power and temperature rise at specified time intervals, e.g. 1ms using the relation

$$Tj(t)=Zth(t)\times V_{ON}(I_{ON},Tj)\times I_{ON}(t)+T_{ref} \qquad (7)$$

and the superposition theorem as follows.

1) Take the initial Tj at the start of the first 1ms period as Tj(1). Calculate average power in the first interval (P1).

2) From P1 and Zth(1ms) calculate the temperature rise in the first period and hence starting temperature for the second period Tj(2) where

$$Tj=Tj(1)+T_{rise}(1). \qquad (8)$$

3) Proceed to the second time period and use Tj(2) to calculate appropriate volt drop values and power in this period.

4) Use the average power in period 2 (P2) and the change in thermal impedance between 1ms and 2ms to calculate the rise in the second interval. This then gives the temperature at the end of the second interval, Tj(3).

5) Continue this procedure for as many time intervals as necessary.

The procedure is more clearly explained by considering a waveform with 5 time intervals (Figure 8).

$$\begin{aligned}Tj(6) = {} & P1[Z(T6-T1)-Z(T6-T2)] \\ & +P2[Z(T6-T2)-Z(T6-T3)] \\ & +P3[Z(T6-T3)-Z(T6-T4)] \\ & +P4[Z(T6-T4)-Z(T6-T5)] \\ & +P5[Z(T6-T5)] \qquad (9)\end{aligned}$$

By making the time interval narrower a better estimation of the junction temperature is obtained. The result of the simulation is plotted as shown in Figure 9. It is interesting to observe that the peak junction temperature does not coincide with the peak of the current waveform and this is due to the thermal lag of the system.

4.4 Verification of models and simulation process

Any modeling and simulation process requires to be verified independently in order to add credibility to the results of the simulation. The output of the simulation example so far described is the instantaneous junction temperature of a thyristor in response to a current pulse. The junction temperature of any semiconductor device is measured indirectly by measuring the temperature dependant parameters of the device such as on-state voltage or blocking-voltage current. Other methods such as the infrared radiation or attaching temperature probes can only measure the silicon chip surface temperature.

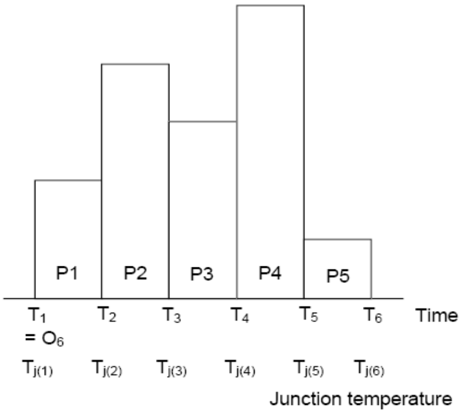

Figure 8. Calculation of junction temperature

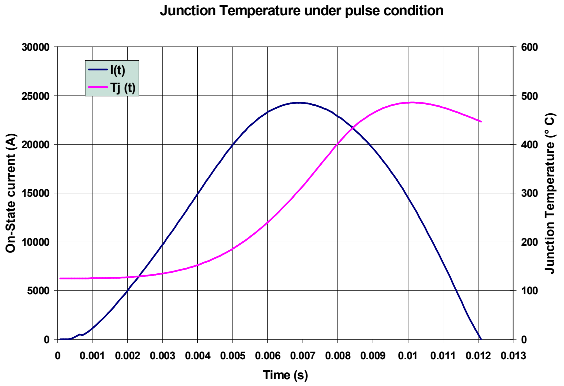

Figure 9. Temperature response of a single current pulse

The method used here was to measure temperature dependant on-state voltage of two thyristors with different voltage and current ratings for a 10ms current pulse of different amplitudes approaching the surge current limit. By comparing the on-state voltage obtained by the measurements with the simulation results one can validate the models used and the simulation process. This process was used on two 50mm thyristors with voltage blocking of 2800V (DCR1640F28) with surge current ratings of 21900A. The first step was to generate Electro-thermal models for these two thyristor types from the data sheet values. The second step was to randomly select a sample from each family and perform measurement for half-sinewave current pulse of 10ms with peak current just below the surge limit. Thyristors voltage and current waveforms were recorded on the digital oscilloscope. The digitized current waveform was then used in the simulator to obtain the simulated voltage waveform. By superimposing the simulated voltage waveform on the measured one can check the accuracy of the simulation.

Figures 10-12 show the results for DCR1640 Thyristor for peak current set up to 14 times the average current ratings. One can observe that for surge current values up to 8 times the average current value, a reasonable tracking of the on-state voltage is predicted by the simulation method. As the maximum surge current limit is approached the shape of the on-state voltage changes dramatically. This voltage now increases much faster for the given current increase. Clearly the model no longer predicts this behavior and hence sets the limit for the simulation boundary.

The verification tests of the simulation process suggests that it is safe to extrapolate up to eight times the average current rating of the device with the proposed device models. For higher current, the junction temperature approaches intrinsic temperature and the device behavior changes, which can no longer be predicted by the simple models, extracted from the data-sheet values. In any case, when device reaches intrinsic temperature, further operation beyond this point is regarded unsafe. Thus these models serve a very useful function beyond the rated current values if the simulation limit is set at eight to ten times the device rated current values.

Figures 10-12 show the thyristors on-state voltage as a function of time. Sometimes thyristor voltage and current are plotted and such a graph is called thyristor surge loop. By plotting measured and the simulated surge loops together as shown in Figure 13, one can also verify the simulation process as an alternative to previous method. These surge loops are for 10ms half-sine-wave pulse with peak currents of 8 and 14 times the average current ratings. It is clear from these plots that at very high currents the model does not exhibit the “beak” like behavior of the measured surge loops. This is because when silicon temperature reaches intrinsic temperature the device becomes more resistive. This behavior is not accounted for in the simple model used.

Figure 14 shows the schematic circuit for the laboratory test set up for the thyristor test. The capacitor is charged to the required voltage by a separate power supply and then discharged through step-up transformer to generate the required current pulse in the device under test (DUT). The current through the thyristor is measured using a current transformer and the voltage drop across the thyristor is monitored with a voltage probe. Both voltage and current are recorded on a digital oscilloscope. Note that during the simulation process it was assumed that the thyristor was fully turned on and hence comparing the measured values with the simulation, the turn-on phase of the thyristor is not included in the simulation.

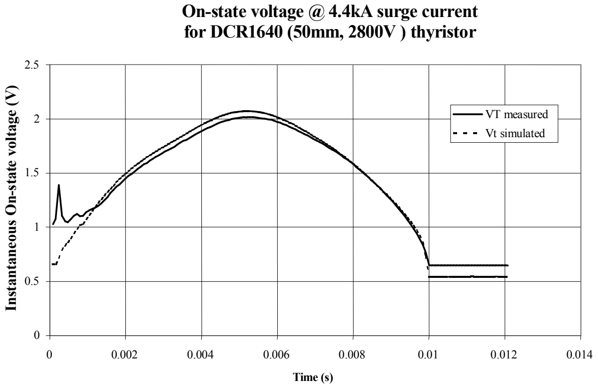

Figure 10. On-state voltage at ~ 3xIav

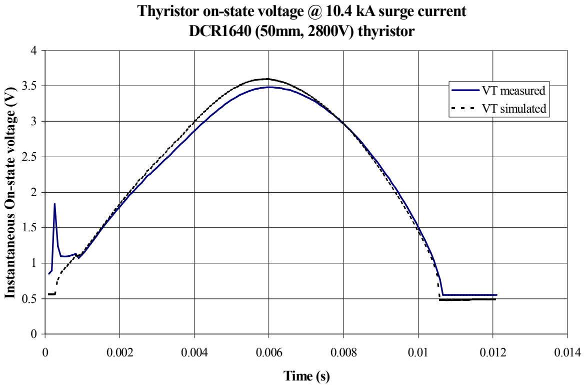

Figure 11. On-state voltage at ~ 8xIav

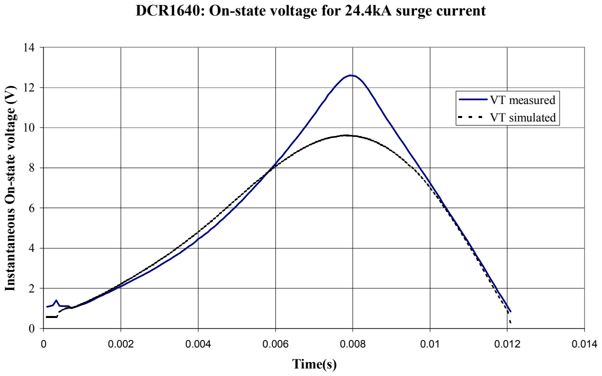

Figure 12. On-state voltage at ~ 14xIav

4.5 Pulse power applications

The pulse power application field is very wide and varied and the choice of power semiconductor switches depends on the operating conditions such as voltage, current, switching speed, pulse width and operating life. The suitable requirements for solid state power devices in pulse power applications fall within the following envelope:

- Blocking voltage: 5 to 60kV
- Peak current: 5 to 200kA
- Pulse widths: 100μs to 1s

This usually means that the power switches considered are at the top end of the power range with silicon diameter greater than 30mm, and invariably connected in series and parallel combinations. The general approach to dimension the power device for pulse power ratings is as follows:

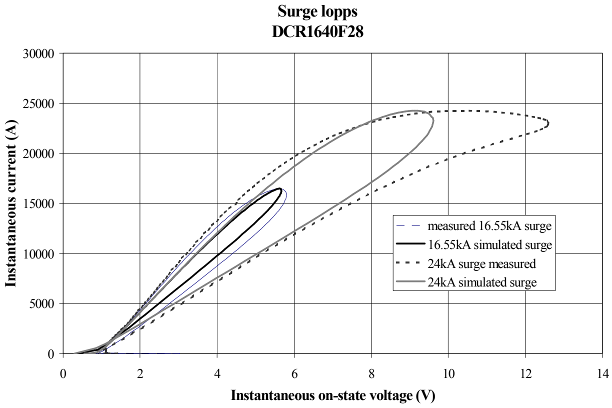

Figure 13. Thyristor surge loops for 10ms pulse

1. Voltage ratings: select device with appropriate forward blocking voltage (and reverse blocking if required) with overshoot safety margin (usually 50%). In many cases series connection several devices is need to fulfil the required voltage.
2. Current rating: use exact current profile needed for the application. Also ensure that device di/dt limit is not exceeded if thyristor/GTO switch is used. If IGBT is used make sure it is operating in the linear region of the output characteristics. In many cases a single device may not be able to withstand the required current pulse and so several devices in parallel may be required.
3. Electro-thermal model: use this model to determine device junction temperature and ΔTj. Under pulse conditions junction temperature can go much higher than 125°C (or device rated temperature) as long as device is not thermally running away. For thyristor it was shown that current pulse as high as eight times the average current rating is safe to use. Figure 15 shows a pulse current rating for a thyristor derived using the above procedure.

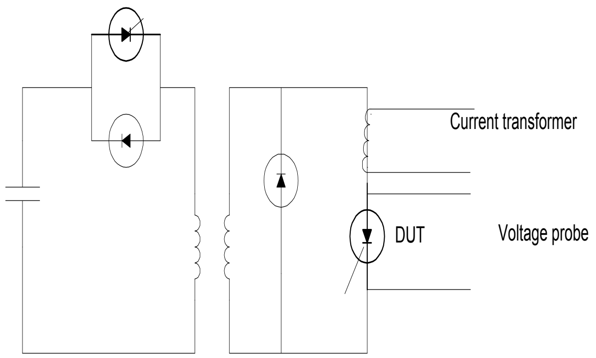

Figure 14. Laboratory Test circuit schematic

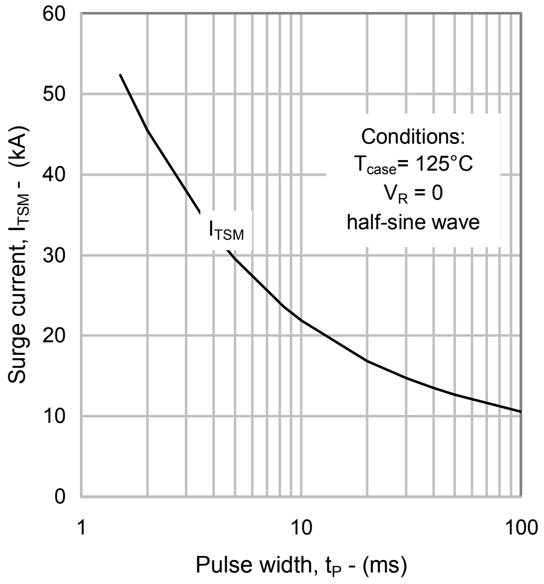

Figure 15. Pulse current rating of a thyristor

5 Conclusion

A complete overview of vacuum and gas filled switches and solid-state switches was given. A methodology for dimensioning power semiconductor devices using novel simulation has been described. The method involved creating Electro-thermal model for the power device based on temperature dependant on-state voltage and device thermal impedance. The model parameters can be extracted using datasheet values. The simulation process using this model can be executed on Excel spreadsheet. The simulation process resulted in variation of device junction temperature for input of current pulse. Model verification by tests and measurements was described and how far the model can be extrapolated. Some examples of use of this technique are given for deriving the abnormal current ratings of a thyristor. Also outlined the general approach to dimension the power device for pulse power applications using this simulation method.

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